Available online at www.sciencedirect.com

Resuscitation

journal homepage: www.elsevier.com/locate/resuscitation

EUROPEAN RESUSCITATION COUNCIL

Clinical paper

Association of chest compression and recoil velocities with depth and rate in manual cardiopulmonary resuscitation

Digna María González-Otero [a,b], James Knox Russell [c], Jesus María Ruiz [a], Sofía Ruiz de Gauna [a,*], José Julio Gutiérrez [a], Luis Alberto Leturiondo [a], Mohamud Ramzan Daya [c]

[a] University of the Basque Country, UPV/EHU, Bilbao, Bizkaia, Spain
[b] BEXEN Cardio, Ermua, Bizkaia, Spain
[c] Oregon Health & Science University, OHSU, Portland, OR, USA

Abstract

Aim: Maximum velocity during chest recoil has been proposed as a metric for chest compression quality during cardiopulmonary resuscitation (CPR). This study investigated the relationship of the maximum velocities during compression and recoil phases with compression depth and rate in manual CPR.

Methods: We measured compression instances in out-of-hospital cardiac arrest recordings using custom Matlab programs. Each compression cycle was characterized by depth and rate, maximum compression and recoil velocities (*CV* and *RV*), and compression and recoil durations (total and effective). Mean compression and recoil velocities were computed as depth divided by compression and recoil durations, respectively. We correlated *CV* and *RV* with their corresponding mean velocities (total and effective), characterized by Pearson's correlation coefficient.

Results: *CV*/*RV* were strongly correlated with their corresponding mean velocities, with a median *r* of 0.83 (0.77–0.88)/0.82 (0.76–0.87) in per patient analysis, 0.86/0.88 for all the population. Correlation with mean effective velocities had a median *r* of 0.91 (0.87–0.94)/0.92 (0.89–0.94) in per-patient, 0.92/0.94 globally ($p < 0.001$). Total and effective compression and recoil durations were inversely proportional to compression rate. We observed similar *RV* values among compressions regardless of whether they were compliant with recommended depth and rate. Conversely, we observed different *RV* values among compressions having the same depth and rate, but presenting very distinct compression waveforms.

Conclusion: *CV* and *RV* were highly correlated with compression depth and compression and recoil times, respectively. Better understanding of the relationship between novel and current quality metrics could help with the interpretation of CPR quality studies.

Keywords: Cardiopulmonary resuscitation (CPR), Chest compression, Compression depth, Compression rate, High-quality CPR, Recoil velocity, Release velocity

Introduction

High-quality cardiopulmonary resuscitation (CPR) is key to improving outcomes of cardiac arrest victims.[1–3] CPR quality metrics of compression depth[4,5] and rate,[6] chest compression fraction,[7] and duration of peri-shock pause (compression cessation prior to and following electrical shock)[8,9] have been independently associated with survival to hospital discharge among victims of out-of-hospital cardiac arrest (OHCA). Complete chest recoil is another component

* Corresponding author.
E-mail address: sofia.ruizdegauna@ehu.eus (S. Ruiz de Gauna).

https://doi.org/10.1016/j.resuscitation.2019.07.023
Received 1 April 2019; Received in revised form 23 June 2019; Accepted 12 July 2019
0300-9572/

of high-quality CPR since rescuer leaning is common during resuscitation[10,11] and may compromise the blood flow generated by chest compressions.[12–14]

Measure of leaning requires force sensors usually built into bulky and expensive devices.[15] Chest compression release velocity has been proposed as an alternative indirect measure to identify leaning.[16,17] More affordable accelerometer-based devices characterize the movement of the patient's chest to provide feedback to the rescuers. The term *release velocity* has been used by some authors to refer to the maximum velocity achieved by the chest during the recoil phase as measured by these devices. However, since this measure characterizes how the chest moves rather than how the rescuer releases the force, we have suggested recoil velocity (*RV*) as a more accurate term.[18] A recent study with out-of-hospital CPR data concluded that, even though the probability of leaning was higher for lower *RV* values, there was a high overlap in the distributions, and thus *RV* was ineffective at predicting leaning.[18]

Recoil velocity has also been proposed for monitoring chest compression quality. Its influence on blood flow and blood pressure and its relation with end-tidal CO_2 levels during CPR have been studied in animal models of cardiac arrest.[19] The significance of *RV* as predictor of survival and favourable neurological outcome[20–22] and as predictor of achieved end-tidal CO_2 levels during CPR[23] has also been assessed in human models. Additionally, *RV* has been studied as a potential new CPR quality metric in children.[24]

When a new chest compression quality metric is proposed, its potential relationship with existing well-established metrics should be carefully analysed.[21] Understanding these relationships would ensure that studies are well designed and account for confounding factors when interpreting results. For this purpose, we performed a retrospective observational study using CPR data from OHCA episodes containing a large number of chest compression instances. Our hypothesis was that *RV* is strongly correlated with the mean velocity of the chest during recoil, which in turn is defined as compression depth divided by recoil time. We similarly analysed compression velocity (*CV*), defined as the maximum velocity achieved during chest compression. We introduce the concepts of effective compression and recoil times and analyse *CV* and *RV* in relation to them as well.

Materials and methods

Data collection

Data were extracted from adult (≥18 years) OHCA episodes collected from 2013 through 2017 by Tualatin Valley Fire and Rescue (TVF&R), an advanced life support fire agency that serves eleven incorporated cities in Oregon, USA. Episodes (one per patient) were collected as part of the Resuscitation Outcomes Consortium (ROC) Epistry effort at the Portland (OR, USA) site approved by the Oregon Health & Science University (OHSU) Institutional Review Board (IRB00001736). No patient identifying data were required for this study.

Each episode reflected the resuscitative efforts of multiple rescuers on the patient lying on a hard and stable surface, as recorded by the monitor-defibrillator during ALS treatment. Episodes were acquired with HeartStart MRx monitor-defibrillators with integrated Q-CPR technology (Philips Medical Systems, Andover, MA, USA). This technology is based on a compression monitor fitted with an accelerometry sensor and a force sensor, adhered to the chest of the patient during CPR, beneath the heel of the rescuers' hands. Force and acceleration signals are used by the monitor to provide real-time CPR feedback to the rescuers on chest compression depth, rate, and leaning. We selected those episodes containing concurrent chest acceleration and force signals during at least 200 chest compressions. Acceleration and force signals were resampled to 1000 samples per second. We computed compression depth and velocity signals from the acceleration signal using forward and reverse digital filtering to preserve phase.[18] Chest compressions were automatically identified in the velocity using a threshold of 25 mm/s, and were required to have a peak force of at least 5 kg-f. Additional rules excluded instances with

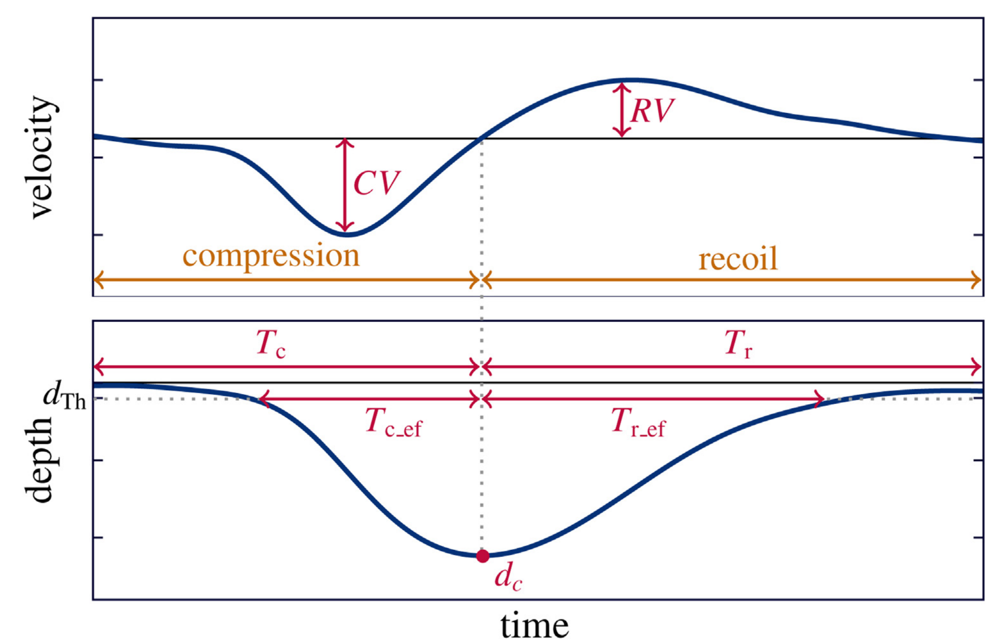

Fig. 1 – Metrics annotated from velocity and depth waveforms for each chest compression cycle.

highly irregular shapes. Leaning was annotated per each compression if the release force at the end of the recoil phase remained above 2.5 kg-f.[18] Compressions that demonstrated leaning were excluded from the study, as leaning results in inaccurate measurement of depth.[25]

Metrics calculation

Several metrics were annotated in the compression depth and velocity signals for each compression instance. A custom-made Matlab program was used to automatically annotate the metrics and to derive some additional measurements. Fig. 1 shows the velocity (top panel) and the compression depth (bottom panel) signals corresponding to a single compression cycle, with all the annotated metrics. Nomenclature and definition of each metric is described as follows:

- d_c: (maximum) compression depth. It corresponds to the quality metric recommended by resuscitation guidelines[26] (at least 50 mm but not exceeding 60 mm).
- T_c: duration of the compression phase.
- T_r: duration of the recoil phase.
- d_{th}: the threshold defining the effective compression cycle.
- d_{c_ef}: effective compression depth, i.e. the amount the compression depth exceeds the threshold d_{th}.
- T_{c_ef}: effective compression time, i.e. the time when the compression depth signal exceeds the threshold, d_{th}, during the compression phase.
- T_{r_ef}: effective recoil time, i.e. the time when the compression depth signal exceeds the threshold, d_{th}, during the recoil phase.
- *CV*: compression velocity, i.e. the maximum velocity achieved during the compression phase.
- *RV*: recoil velocity, i.e. the maximum velocity achieved during the recoil phase.

Several measurements were computed from the annotated metrics:

- Compression rate: rate = $60/(T_c + T_r)$. It corresponds to the quality metric recommended by resuscitation guidelines (between 100 and 120 compressions per minute, cpm.[26])

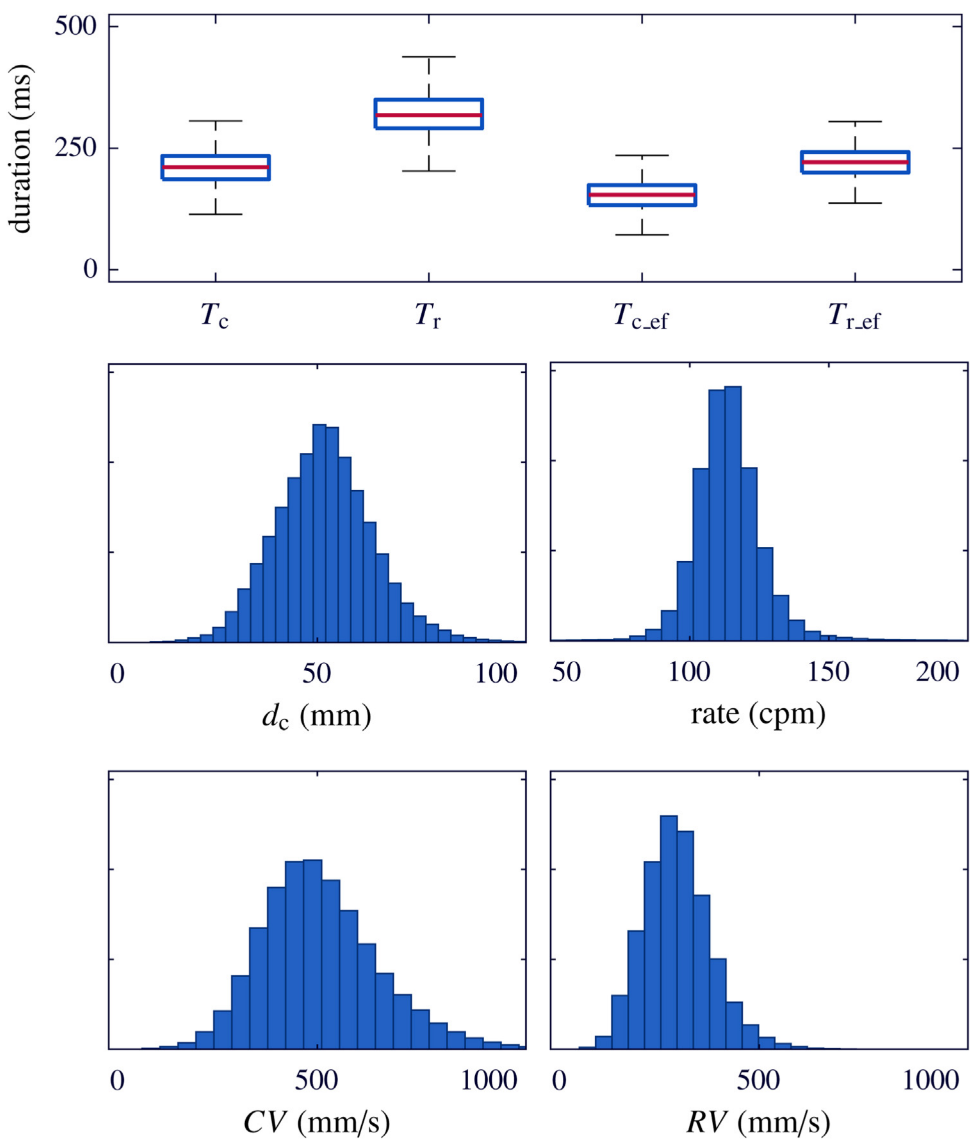

Fig. 2 – Distributions of some of the annotated metrics.

Additionally, we computed the mean (average) compression and recoil velocity per each compression (total and effective), as the compression depth divided by the corresponding compression or recoil time. Therefore:

- Mean compression velocity: $V_{cm} = d_c/T_c$.
- Mean recoil velocity: $V_{rm} = d_c/T_r$.
- Mean effective compression velocity: $V_{cm\_ef} = d_{c\_ef}/T_{c\_ef}$.
- Mean effective recoil velocity: $V_{rm\_ef} = d_{c\_ef}/T_{r\_ef}$.

Statistical analysis

Global distributions of the annotated and computed metrics were analysed using boxplots and histograms. Values were reported as median and interquartile range (IQR). Kruskal–Wallis Analysis of Variance was used to perform between-groups comparisons, and $p-$values < 0.05 were considered significant.

The linear relationship of *CV* and *RV* with associated mean velocities was modelled using univariate linear regression, according to the expressions:

$$\begin{aligned} CV &= k \cdot V_{cm} = k \cdot d_c / T_c && \text{(mm/s)} \\ CV &= k \cdot V_{cm\_ef} = k \cdot d_{c\_ef} / T_{c\_ef} && \text{(mm/s)} \\ RV &= k \cdot V_{rm} = k \cdot d_c / T_r && \text{(mm/s)} \\ RV &= k \cdot V_{rm\_ef} = k \cdot d_{c\_ef} / T_{r\_ef} && \text{(mm/s)} \end{aligned}$$

The linear relationships between compression and recoil times (total and effective) and rate were also examined per episode. Finally, linear relationships of *CV* and *RV* with compression depth were examined per patient and globally. Linear models were characterized by Pearson's correlation coefficient *r* both per patient and for all the population.

Results

Of 703 uses of monitor-defibrillators by TVF&R during 2013 through 2017, 18 cases were excluded because the patients were younger than 18 years of age, and 69 because very few (<200 compressions) or no CPR was administered. In the 616 episodes that met our inclusion criteria, with a median (IQR) duration of 32 (27–47) min, a total of 1,162,766 compression instances were automatically detected, a median of 1726 (1043–2609) compressions per episode. We discarded 86,262 (7%) compressions with leaning, a median of 64 (15–202) per episode. A total of 1,076,504 compressions were included in the study, a median of 1726 (1043–2609) per episode.

Fig. 2 shows the distributions of some of the analysed metrics. In the top panel, durations of the different phases of the chest compression cycle (T_c, T_r, T_{c_ef}, and T_{r_ef}) are depicted using boxplots. The threshold d_{th} was fixed to 5 mm. Median duration of the compression phase, T_c, was 211 ms (186–234), lower than the median duration of the recoil phase which was 318 ms (291–350) ($p < 0.001$). Similarly, median T_{c_ef} was 154 ms (133–174), lower than median T_{r_ef} which was 221 ms (200–242) ($p < 0.001$). In the middle panels, distributions of compression depth and rate are depicted. Median compression depth was 52 mm (44–59) and median compression rate was 113 cpm (107–120). Finally, the bottom panels show the distributions of velocities: median *CV* was 493 mm/s (409–590), significantly higher than median *RV* which was 299 mm/s (248–352) ($p < 0.001$).

CV was moderately correlated with compression depth, with a median correlation coefficient *r* of 0.67 (0.57–0.75) per patient, 0.71 globally, as was *RV*, with a median *r* = of 0.74 (0.66–0.80) per patient, and 0.82 globally. Correlation with compression rate was weaker: for

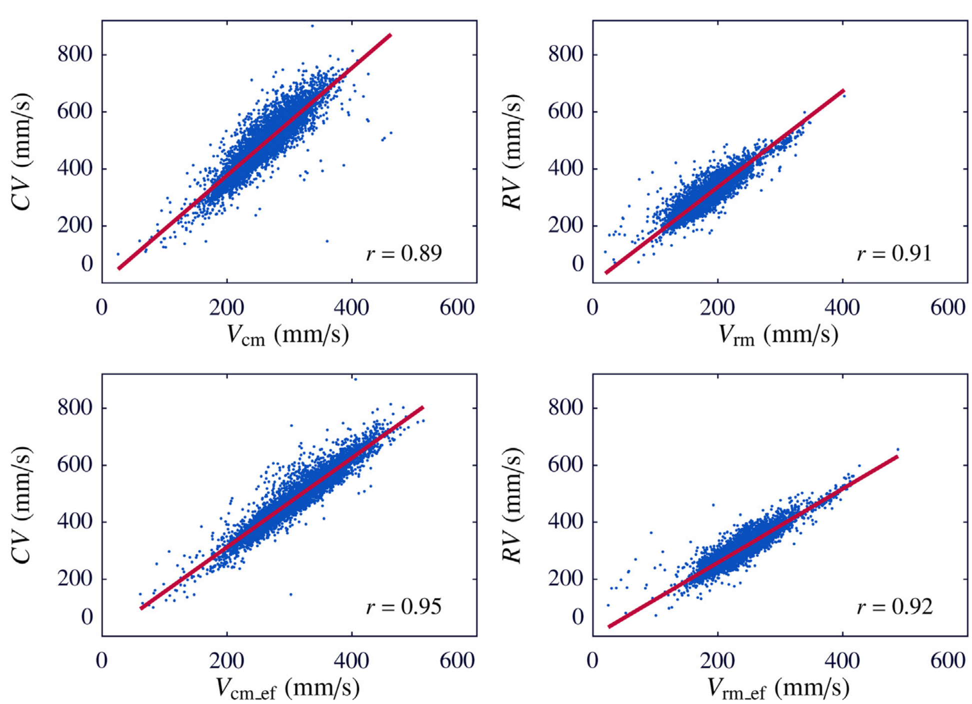

Fig. 3 – Linear relationship of *CV* and *RV* with the corresponding mean velocities, total and effective, for a single patient episode.

CV, median *r* = per patient was 0.37 (0.31–0.43), and 0.35 globally; for *RV*, median *r* = per patient was 0.41 (0.35–0.46) and 0.37 globally.

However, correlations were stronger with mean velocities (total and effective). Fig. 3 depicts the linear regressions between maximum and mean compression and recoil velocities (total and effective) for a single patient episode. Red lines show the linear model per each pair of analysed parameters, together with the correlation coefficient *r*.

For each individual patient episode, *CV* showed a linear correlation with mean compression velocity, V_{cm}, with a median correlation coefficient *r* of 0.83 (0.77–0.88). More importantly, correlation was significantly stronger between *CV* and mean effective velocity, V_{cm_ef}, with a median *r* of 0.91 (0.87–0.94) ($p < 0.001$). When the entire population was considered collectively, the correlation coefficient between *CV* and V_{cm} was 0.86, and increased to 0.91 when considering V_{cm_ef} instead. Thus, a good approximation to the actual *CV* value could be computed as a function of effective depth over mean effective compression time with the equation:

$$CV = 1.64 \cdot V_{cm\_ef} = 1.64 \cdot d_{c\_ef}/T_{c\_ef} \text{ENTITY NOT DEFINED !!!} (mm/s) \quad (1)$$

We obtained similar results when analysing *RV*. For each patient, the linear relationship between *RV* and mean recoil velocity, V_{rm} had a median *r* of 0.82 (0.76–0.87). Correlation was again significantly stronger when considering the mean effective recoil velocity, with a median *r* of 0.91 (0.87–0.94) ($p < 0.001$). When all population was considered jointly, the correlation coefficient between *RV* and V_{rm_ef} was 0.94, higher than 0.88 when V_{rm} was considered. Thus, the actual *RV* value could be estimated as a function of effective depth over mean effective recoil time with the equation:

$$RV = 1.43 \cdot V_{rm\_ef} = 1.43 \cdot d_{c\_ef}/T_{r\_ef} \text{ENTITY NOT DEFINED !!!} (mm/s) \quad (2)$$

We computed correlation results with varying thresholds. Using a lower threshold of 2.5 mm: for *CV*, factor *k* was 1.56 (*r* of 0.90 (0.86–0.93), and 0.92 considering the entire population), and for *RV*, factor *k* was 1.36 (*r* of 0.91 (0.89–0.94), and 0.94 considering the entire population). Using a higher threshold of 10 mm: for *CV*, factor *k* was 1.57 (*r* of 0.94 (0.94–0.96), and 0.95 considering the entire population), and for *RV*, factor *k* was 1.40 (*r* of 0.93 (0.91-0.95), and 0.96 considering the entire population).

Fig. 4 depicts the relationships of compression and recoil times (total and effective) with compression rate for a single patient. Negative correlation was observed since increasing rates corresponded to lower compression and recoil times.

Examples (A) and (B) in Fig. 5 illustrate how the same *RV* value can be achieved with very different chest compression morphologies. The chest compression instance in example (A) meets guideline recommendations regarding depth and rate. Example (B) is too shallow, but with a very short effective recoil time. It has a *RV* value similar to example (A).

Fig. 6 shows two compression instances with the same depth and duration (and therefore the same rate) but with significantly different *CV* and *RV* values. The compression waveform depicted with the thinner line (in red in the online version of the article) suggests a high-impulse pattern during compression and recoil, quite different from the compression depicted with the thicker line (in blue in the online version), presenting a more sinusoidal pattern.

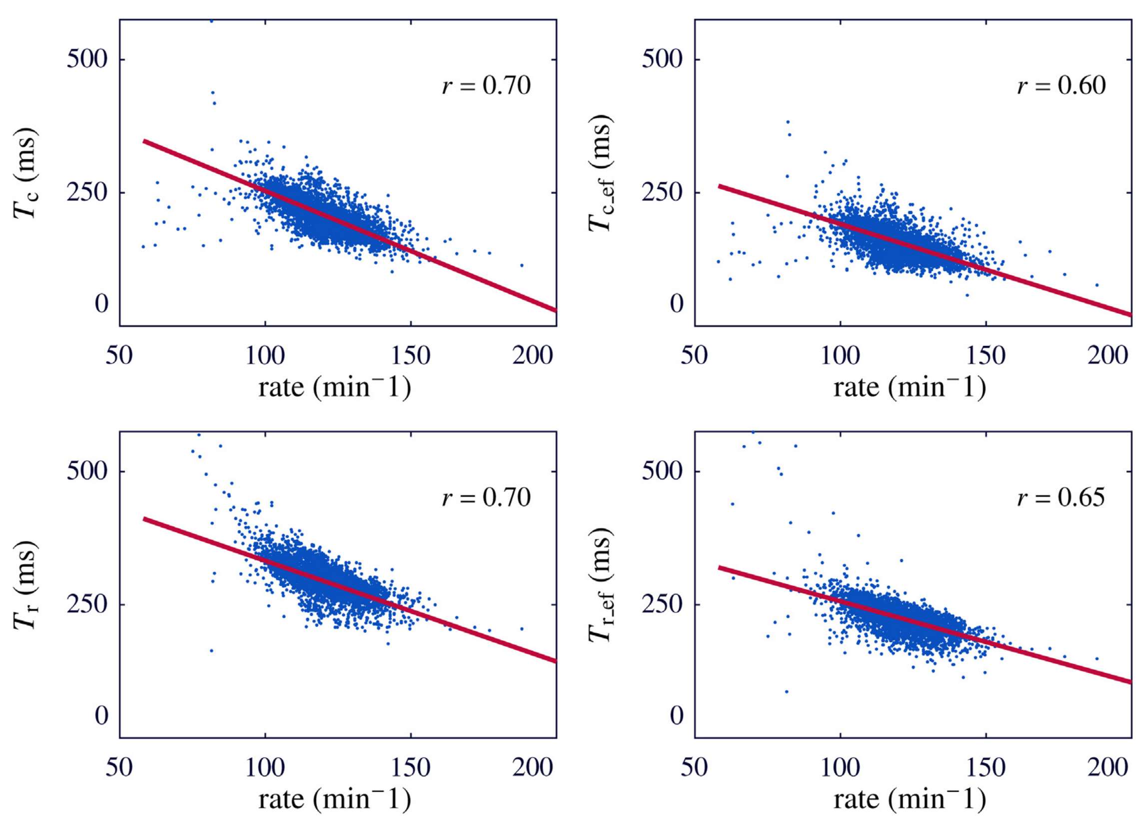

Fig. 4 – Linear relationship of compression times, total and effective, with compression rate for a single patient.

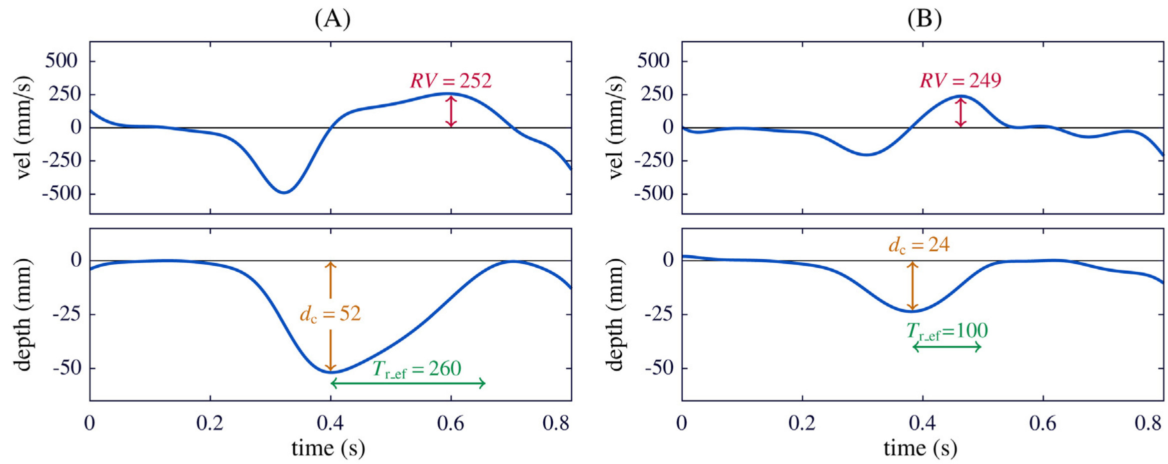

Fig. 5 – Examples of velocity and depth waveforms for different chest compressions. (A) Chest compression met the guidelines recommendations for depth and rate. (B) Too shallow chest compression with *RV* similar to (A).

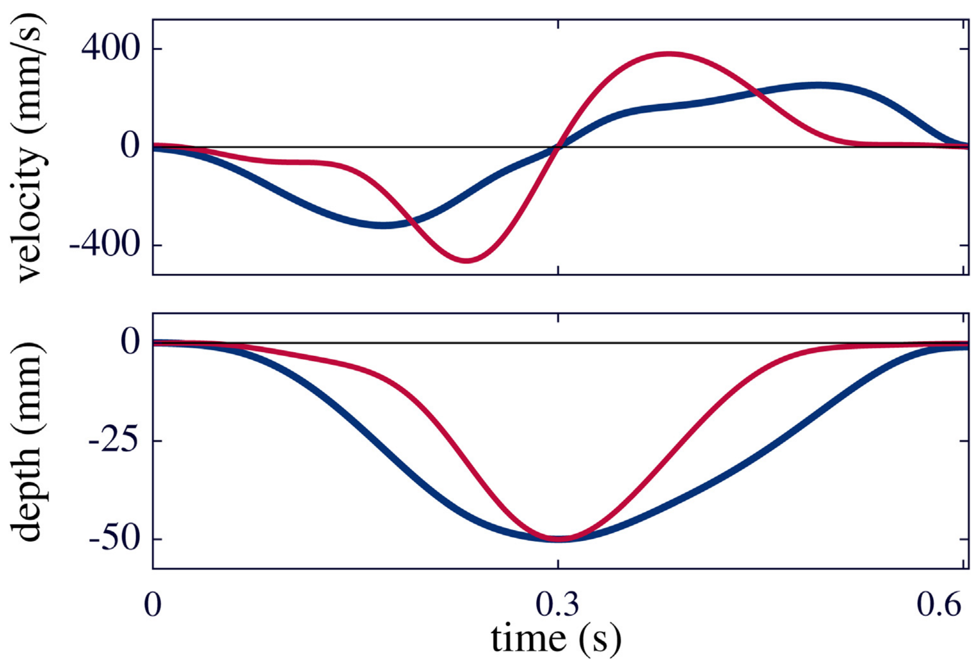

Fig. 6 – Examples of two chest compressions meeting guidelines but differing in waveform; the one depicted with the thinner line suggests a higher impulse compression and recoil pattern.

Discussion

Recoil velocity (*RV*), defined as the maximum velocity achieved by the chest during the recoil phase, has been proposed as a new CPR quality metric. In human studies, contradictory results have been presented. Kovacs et al. reported an independent association between *RV* and improved survival and favourable neurological outcome.[21] In another study by Cheskes et al., statistically significant differences in *RV* were reported between survivors and non-survivors on univariate analysis.[22] However, this association did not hold after adjusting for Utstein variables. Furthermore, Cheskes et al. reported a significant correlation between chest compression depth and *RV*, which led them to exclude compression depth from their model.[22] Kovacs et al. also reported on depth, but excluded it from their model without explanation.[21] In both studies, any differences in outcomes could be related to compression depth rather than to additional information provided by *RV*.

Our study showed that *CV* and *RV* are directly proportional to compression depth and inversely proportional to compression and recoil times, respectively. As rate increases, compression and recoil durations decrease, and *CV* and *RV* increase accordingly. This relationship was significantly stronger when considering effective compression depths and durations. This is explained by the fact that per each compression cycle there is an interval when only a residual force is applied, barely displacing the chest with a negligible velocity (defined as relaxation time in[18]). Thus, effective compression and recoil times reflect when patient's chest is effectively moving. These results were not sensitive to the depth threshold used to define the effective periods. Similar results were obtained for larger and smaller thresholds. The novel concept of effective compression and recoil times contributes to a better understanding of chest compression dynamics.

The clinical significance of our study is two-fold. First, when assessing the relationship between recoil velocity and outcome, knowledge of the dependency of *RV* on depth and rate is necessary for an accurate interpretation of the findings. Second, our model was able to predict the variation of recoil velocity from depth and recoil time when the compression rate was fixed[19] or not.[24]

Both compression and recoil velocities are explained by depth and rate to some extent, but this relationship is ambiguous: although higher depths are associated with higher *CV* and *RV*, chest compressions with different depths can produce similar *RV* values depending on the chest compression waveform (see Fig. 5). Conversely, two compressions with the same depth and rate but different waveforms may present very different *CV* and *RV* values, as illustrated in Fig. 6. In this example, for one of the chest compressions the chest achieved the same depth in less time (higher *CV*) and recoiled faster (higher *RV*), i.e. the compression was more *impulsive*. Animal studies using mechanical pistons analysed different compression/decompression patterns, and concluded that high-impulse compression and decompression improves blood flow.[27,28] However, the characteristics of the optimum compression waveform are still under investigation, and in fact a recent animal study challenges the concept of a single optimal chest compression waveform.[29] In future works, we plan to explore potential metrics capable of characterizing chest compression impulsiveness independently of rate and depth. The results of this study suggest that effective compression and decompression times could be good candidates to characterize impulsiveness of the compression and recoil phases, respectively.

Limitations

This study has some limitations. First, we did not assess changes over time for a given patient. Chest compression waveform could vary throughout an episode due to rescuer fatigue or potential changes in chest compliance with time, but in the present study we analysed all chest compressions in an episode jointly. Time variations will be studied in future works. Another limitation is reliance on the threshold for computing effective depths and durations. However, varying the threshold to lower and higher values had little impact on our results. Additionally, compressions with leaning were excluded from the study as their depth cannot be measured accurately from acceleration. Thus, our conclusions are only applicable to chest compressions that do not demonstrate rescuer leaning at the end of the cycle. Finally, only adult OHCA patients were included in our study, therefore results may not translate to patients under 18 years of age or patients with in-hospital cardiac arrest.

Conclusions

Recoil (or release) velocity has been proposed as a new CPR quality metric. In the absence of leaning, compression and recoil velocities are directly correlated with compression depth and inversely proportional to compression and recoil times, respectively. This relationship was significantly stronger when restricted to effective depth and durations. Understanding these relationships could help to better interpret the results of CPR quality studies related to recoil velocity.

Conflict of interest statement

Author Digna M González-Otero is employed by BEXEN Cardio, a Spanish medical device manufacturer that markets an accelerometer-based CPR feedback device.

The authors confirm that there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgements

Authors from the University of the Basque Country received financial support from the Basque Government through the grants IT1087-16 (for research groups) and 2018222012 (research projects oriented to health development). Author from BEXEN Cardio received financial support from the Spanish Ministry of Economy, Industry and Competitiveness through the program Torres Quevedo PTQ-16-08201.

We would like to thank the EMS providers and staff of Tualatin Valley Fire and Rescue for their dedication and efforts to support research on CPR quality.

REFERENCES

1. Nolan JP, Nadkarni VM, Billi JE, et al. Part 2: International collaboration in resuscitation science: 2010 international consensus on cardiopulmonary resuscitation and emergency cardiovascular care science with treatment recommendations. Resuscitation 2010;81:e26–31.
2. Sasson C, Rogers MA, Dahl J, Kellermann AL. Predictors of survival from out-of-hospital cardiac arrest: a systematic review and meta-analysis, Circulation. Cardiovasc Qual Outcomes 2010;3:63–81.
3. Perkins GD, Travers AH, Considine J, et al. Part 3: adult basic life support and automated external defibrillation: 2015 international consensus on cardiopulmonary resuscitation and emergency cardiovascular care science with treatment recommendations. Resuscitation 2015;95:e43–69.
4. Stiell IG, Brown SP, Christenson J, et al. What is the role of chest compression depth during out-of-hospital cardiac arrest resuscitation? Crit Care Med 2012;40:1192–8.
5. Vadeboncoeur T, Stolz U, Panchal A, et al. Chest compression depth and survival in out-of-hospital cardiac arrest. Resuscitation 2014;85:182–8.
6. Idris AH, Guffey D, Aufderheide TP, et al. Relationship between chest compression rates and outcomes from cardiac arrest. Circulation 2012;125:3004–12.
7. Christenson J, Andrusiek D, Everson-Stewart S, et al. Chest compression fraction determines survival in patients with out-of-hospital ventricular fibrillation. Circulation 2009;120:1241–7.
8. Cheskes S, Schmicker RH, Christenson J, et al. Perishock pause: an independent predictor of survival from out-of-hospital shockable cardiac arrest. Circulation 2011;124:58–66.
9. Cheskes S, Schmicker RH, Verbeek PR, et al. The impact of peri-shock pause on survival from out-of-hospital shockable cardiac arrest during the Resuscitation Outcomes Consortium PRIMED trial. Resuscitation 2014;85:336–42.
10. Niles DE, Sutton RM, Nadkarni VM, et al. Prevalence and hemodynamic effects of leaning during CPR. Resuscitation 2011;82:S23–6.

11. Fried DA, Leary M, Smith DA, et al. The prevalence of chest compression leaning during in-hospital cardiopulmonary resuscitation. Resuscitation 2011;82:1019–24.
12. 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.
13. Sutton RM, Niles D, Nysaether J, et al. Effect of residual leaning force on intrathoracic pressure during mechanical ventilation in children. Resuscitation 2010;81:857–60.
14. Meaney PA, Bobrow BJ, Mancini ME, et al. Cardiopulmonary resuscitation quality: improving cardiac resuscitation outcomes both inside and outside the hospital: a consensus statement from the American Heart Association. Circulation 2013;128:417–35.
15. Gruber J, Stumpf D, Zapletal B, Neuhold S, Fischer H. Real-time feedback systems in CPR. Trends Anaesth Crit Care 2012;2:287–94.
16. Geheb F, Freeman GA, Boucher DR. Method and apparatus for enhancement of chest compressions during CPR. Google Patents; 2007. US Patent 7,220,235.
17. Johnson GR. Compression Depth Monitor with Variable Release Velocity Feedback. Google Patents; 2014. US Patent App 13/874,372.
18. Russell JK, González-Otero DM, Ruiz de Gauna S, Daya M, Ruiz J. Can chest compression release rate or recoil velocity identify rescuer leaning in out-of-hospital cardiopulmonary resuscitation. Resuscitation 2018;130:133–7.
19. Lampe JW, Tai Y, Bratinov G, et al. Developing a kinematic understanding of chest compressions: the impact of depth and release time on blood flow during cardiopulmonary resuscitation. Biomed Eng Online 2015;14:102 OnLine.
20. Indik JH, Conover Z, McGovern M, et al. Amplitude-spectral area and chest compression release velocity independently predict hospital discharge and good neurological outcome in ventricular fibrillation out-of-hospital cardiac arrest. Resuscitation 2015;92:122–8.
21. Kovacs A, Vadeboncoeur TF, Stolz U, et al. Chest compression release velocity: association with survival and favorable neurologic outcome after out-of-hospital cardiac arrest. Resuscitation 2015;92:107–14.
22. Cheskes S, Common MR, Byers AP, Zhan C, Silver A, Morrison LJ. The association between chest compression release velocity and outcomes from out-of-hospital cardiac arrest. Resuscitation 2015;86:38–43.
23. Murphy RA, Bobrow BJ, Spaite DW, Hu C, McDannold R, Vadeboncoeur TF. Association between prehospital CPR quality and end-tidal carbon dioxide levels in out-of-hospital cardiac arrest. Prehosp Emerg Care 2016;20:369–77.
24. Duval-Arnould J, Niles D, Insley E, et al. Characterization of a new CPR performance metric in children: chest compression release velocity. Crit Care Med 2018;46:151.
25. Ruiz de Gauna S, González-Otero DM, Ruiz J, Russell JK. Feedback on the rate and depth of chest compressions during cardiopulmonary resuscitation using only accelerometers. PLOS ONE 2016;11:1–17, doi:http://dx.doi.org/10.1371/journal.pone.0150139.
26. Monsieurs KG, Nolan JP, Bossaert LL, et al. European resuscitation council guidelines for resuscitation 2015 section 1. Executive summary. Resuscitation 2015;95:1–80.
27. Betz AE, Menegazzi JJ, Logue ES, Callaway CW, Wang HE. A randomized comparison of manual, mechanical and high-impulse chest compression in a porcine model of prolonged ventricular fibrillation. Resuscitation 2006;69:495–501.
28. Tømte Ø, Sjaastad I, Wik L, et al. Discriminating the effect of accelerated compression from accelerated decompression during high-impulse CPR in a porcine model of cardiac arrest. Resuscitation 2010;81:488–92.
29. Lampe JW, Yin T, Bratinov G, et al. Effect of compression waveform and resuscitation duration on blood flow and pressure in swine: One waveform does not optimally serve. Resuscitation 2018;131:55–62.