Chest Stiffness Dynamics in Extended Continuous Compressions Cardiopulmonary Resuscitation

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Abstract

Aim of the study

To characterize the effects of extended duration continuous compressions cardiopulmonary resuscitation (CPR) on chest stiffness, and its association with adherence to CPR guidelines.

Methods

Records of force and acceleration were extracted from CPR monitors used during attempts of resuscitation from out-of-hospital cardiac arrest. Cases of patients receiving at least 1000 compressions were selected for analysis to focus on extended CPR efforts. Stiffness was normalized per patient to their initial stiffness. Force remaining at the end of compression was used to identify complete release. Non-parametric statistical methods were used throughout as underlying distributions of all types of measurements were non-Gaussian. Averages are reported as median (interquartile range).

Results

More than 1000 chest compressions were delivered in 471 of 703 cases. Rate of change in normalized stiffness (S_n) was unrelated to patient age, sex or initial ECG rhythm, and did not predict survival. Most (76%) chests became less stiff over the course of resuscitation efforts. While the remainder (24%) exhibited increased stiffness, overall S_n decreased monotonically, declining by 31% through 3500 compressions. Rate adherence did not show a consistent trend with S_n. Depth adherence and complete release improved modestly with decreasing S_n.

Conclusion

Chest compressions during extended CPR reduced the stiffness of most patients' chests, in the aggregate by 31% after 3500 compressions. This softening was associated with modestly improved adherence to depth and release guidelines, with inconsistent relation to rate adherence to guidelines.

Introduction

Chest compression is an essential element of modern cardiopulmonary resuscitation (CPR) practice. The American Heart Association (AHA)[1] and the European Resuscitation Council,[2] regularly promulgate guidelines for its performance, including recommendations for rate, depth, complete release and hands-on time, based on consensus review of available evidence. Most evidence underlying these guidelines comes from experimental studies and from clinical studies of the initial 5 — 10 minutes of efforts,[3,4] or without regard to time.[5] Adherence to guidelines has been associated with improved patient outcomes.[6]

Continuous compression CPR, wherein interruptions in delivering compressions are minimized, is increasingly prevalent. Extended periods of CPR are increasingly common,[7] driven by data suggesting a minimum of 30 minutes for resuscitation efforts in the field.[8]

Chest compression is a forceful intervention. It may alter the stiffness of the patient's chest over the course of resuscitation efforts.[9] Limited clinical data has been published on chest stiffness. We sought to characterize changes in chest stiffness over the course of extended CPR efforts and to assess its impact on adherence to recommended guidelines for chest compression. These observations may have implications as to whether chest compression guidelines may require adjustment over the course of extended resuscitation efforts.

Methods

Force and acceleration signals were extracted from CPR monitors attached to defibrillator/monitors (MRx® with Q-CPR®, Philips Healthcare, Andover MA, USA) used in adult cases of out-of-hospital cardiac arrest (OHCA) attended by a single emergency medical service agency (Tualatin Fire and Rescue (TVF&R), Tigard, Oregon USA) from 2013 through 2017. During this time period, the TVF&R protocol for called continuous chest compressions with interposed ventilations for each 2 minute cycle of CPR. Data were extracted from CPR process files collected from episodes entered into the Resuscitation Outcomes Consortium Epidemiological Cardiac Arrest Registry (ROC Epistry-Cardiac Arrest)[10] approved by the Oregon

Health & Science University (OHSU) Institutional Review Board (IRB00001736). No patient private data were required for this study. All TVF&R personnel had completed training on the continuous compressions protocol by the end of 2012. Responders had access to real-time feedback on rate, depth and release throughout the study period. TVF&R responders are instructed to continue efforts in the field until sustained return of spontaneous circulation (ROSC) has been achieved or 20 minutes of efforts have been expended. TVF&R allows providers to terminate resuscitation efforts per protocol or following consultation with On-Line Medical Control physicians.

Contextual information about patient characteristics (age, sex, initial rhythm) and resuscitation outcomes (return of spontaneous circulation (ROSC), survival to admission, survival to discharge, modified Rankin Scale (MRS)) were extracted from prehospital care records and hospital medical records.

AHA guidelines introduced upper limits on recommended chest compression rate and depth in 2015. These limits were included as part of the annual refreshed training by TVF&R beginning in 2016.

We computed depth and velocity from acceleration[11-14] and identified chest compressions automatically where downward velocity crossed 25mm/s and force subsequently exceeded 5 kg-f (49 N). We selected cases that included at least 1000 compressions. We calculated stiffness as the ratio of peak force to peak depth and normalized stiffness (S_n) as the ratio of each patient's current stiffness to the median stiffness during their first 100 compressions. Compressions for which the final applied force exceeded 2.5 kg-f (24.5 N) were considered to exhibit incomplete release by the CPR provider, as in Fried[15].

Dependence of stiffness on number of compressions (count) and on patient variables such as sex, age, initial rhythm and outcomes were analyzed with Kruskal-Wallis ANOVA. Differences in counts were assessed with Fisher Exact tests. Trends with count and with S_n quintiles were assessed with Jonckheere-Terpstra tests[16]. P-values below 0.05 were considered statistically significant.

Signal processing and statistical analyses were performed with custom Matlab® (Natick, MA, USA) programs, using version R2020b.

Summary statistics are reported as median (interquartile range), except as specified.

Results

Of 703 cases responded to between 1 January 2013 and 31 December 2017 in which defibrillator/monitor recordings were acquired by TVF&R (cases where TVF&R arrived first and applied its monitors), 471 were from adult patients that received at least 1000 compressions (Fig. 1). Attended cases in which the first defibrillator/monitor device was applied by another responding agency, and cases with corrupted recordings were not included.

Patients in these cases were 66 (53 — 75) years of age, and 66% were males. The first recorded ECG rhythm was shockable (VF/VT) in 27% of cases with recorded initial rhythm (n = 468), pulseless electrical activity in 26%, and asystole in 47%, similar to the distribution of initial rhythms among all EMS treated non-traumatic OHCA (24%, 21%, 42% respectively) reported from the ROC-Epistry Cardiac Arrest.[17] ROSC sustained until hospital arrival was achieved in the field in 35% of the 437 patients receiving extended CPR for which ROSC status was recorded (Table 1).

Patients with extended CPR are a relatively challenging group with regards to outcomes. Of extended CPR patients with known disposition, 38% died in the field, 36% died in the emergency department, 21% died after hospital admission, and 5% survived to hospital discharge, in contrast to 40%, 28%, 19% and 13% respectively of the 688 adult cases of all lengths with recorded disposition. Of extended CPR survivors, 76% had a favorable MRS (3 or better) at the time of hospital discharge (Table 1). Most patients' chests decreased in stiffness (softened) over the course of resuscitation efforts (360 of 471, 76%), while the remainder (111 of 471, 24%) increased in stiffness. Patients whose chests softened were declared dead in the field less often than those whose chests stiffened (32% vs 56%, $p < 0.001$), but there were not significant differences between these subgroups with regards to survival to hospital admission, survival to hospital discharge, or in favorable MRS among survivors.

Differences in chest compression rate and depth after introduction of upper limits in 2016 training were minor (Table 2), and results from all years have been pooled for statistical analysis.

Cases with extended CPR included 2051 (1490 — 2864) compressions. Patients whose chests softened received more compressions (2158 (1509 — 3027)), compared to patients whose chests stiffened (1886 (1434 — 2351), $p < 0.001$). For all cases together, the 1000th compression occurred at the 11th (11 - 12) minute after the beginning of recorded compressions, the 2000th at the 22nd (20 - 23), the 3000th at the 32nd (31 - 34) and the 3500th at the 37th (35 - 39).

Case-wise median compression rate was 113 (110 — 117) compressions/minute. Case-wise median compression depth was 52 (46 — 57) mm. Complete release was present in 96 (90 — 99)% of compressions and hands on time averaged 87 (82 — 90)% (Table 2). There were no significant differences in rate, depth or percent of compressions with complete release between patients with chests that softened compared to those that stiffened. Patients with chests that stiffened experienced modestly higher hands-on time (89 (85 — 92)% vs 86 (80 — 90)%, $p < 0.001$) than patients with chests that softened.

While males had higher initial stiffness values 0.98 (0.79 — 1.19) N/cm) than females 0.77 (0.66 — 0.92) N/cm), ($p < 0.001$), differences among age groups were not statistically significant ($p = 0.56$). Rate of change in stiffness per 1000 compressions was not significantly related to sex ($p = 0.55$) or age ($p = 0.89$), to presenting rhythm ($p = 0.95$), or to survival to discharge ($p = 0.19$).

Normalized stiffness varied with chest compression count ($p < 0.001$). It decreased monotonically through the first 3500 compressions by 36% ($p_{trend} < 0.001$, Fig. 2).

A series of compressions at 1, 10, 20, 30 and 40 minutes from a 68 year-old male illustrates how compressions changed in the presence of pronounced softening. Force applied by the CPR provider (in red) declined monotonically. Resulting depth (in blue) increased from 47 mm to 60 mm, yielding the measured decrease in S_n by 68% (Fig. 3).

Changes in adherence to 2015 AHA guidelines were associated with quintiles of S_n. Rates less than 100 compressions per minute (cpm) remained between 25% and 33%, while rates exceeding 120 compressions per minute (cpm) remained at 9%. Guideline adherent rates (>= 100 cpm, <= 120 cpm) were between 64% and 66% in quintiles 2-5, though only 58% in the softest quintile (quintile 1) ($p_{trend} = 0.03$, Fig. 4, top panel).

Depths of less than 50 mm increased from 40% in the 1st quintile to 52% in the 5th. Depths exceeding 60 mm remained between 33% and 35% through the first 4 quintiles, declining to 30% stiffest quintile. Depth adherence with guidelines (50 - 60 mm) declined from 27% in the 1st (softest) quintile to 17% in the 5th (stiffest) quintile ($p_{trend} = 0.007$, Fig. 4, middle panel).

Incidence of complete release decreased monotonically from 96% in the first quintile to 87% in the fifth ($p_{trend} = 0.007$, Fig. 4, bottom panel).

Concurrent adherence to the recommendations for compression form — rate between 100 and 120 cpm, depth between 50 and 60 mm, and complete release, remained between 19% and 23% without a trend across S_n quintiles ($p_{trend} = 0.16$).

Discussion

Chest compression during CPR is a highly forceful intervention. Resuscitation protocols calling for extended CPR on site when ROSC is not achieved in the field, up to 30 minutes or longer, are increasingly prevalent. During extended CPR, thousands of forceful compressions may be administered. Relatively little is known about their cumulative effects on the chest's response to force. There is legitimate concern about harm produced by chest compressions[18-20] since rib and sternal fractures are common during CPR.[20,21] We sought to characterize changes in patients' chest stiffness during extended CPR. We normalized stiffness (peak force/peak depth), to median stiffness during the first 100 compressions in order to combine patients with differing stiffness at the outset of resuscitation efforts.

Measurements of force and acceleration during chest compressions are challenging. They may be affected by orientation of the sensor, position of the subject and position of the responder's hands on the sensor.[11] Measurement of force is not available in most CPR monitors. Force, combined with displacement, is required to calculate stiffness. Estimation of displacement with an accelerometer requires integrating the measured acceleration twice, requiring high-pass filtering to avoid accumulation of any noise or measurement errors.[12,13] In the absence of a fixed frame of reference, interpretation of this displacement as depth references displacement to a local average minimum displacement whose location may be shifting in response to compressions,[12,14] a problem common to all CPR depth measurement derived from accelerometry. Interpretation of this depth as chest compression depth ignores possible motion of the substrate, which is not known in the absence of either a fixed reference frame (e.g. as available in the context of mechanical CPR[22]) or measurement of motion of the substrate.[11] Similarly, interpretation of measured stiffness as chest stiffness may be confounded by inclusion of a compliant substrate in the measurement, or by irregularities in the orientation of the subject and the compressions with respect to the local gravitational field.[11] These problems are pronounced if CPR is performed on a patient supported by a compliant mattress,[23] relatively uncommon in pre-hospital resuscitation efforts prior to transport, the setting in which our study data were collected.

Measured chest stiffness itself may also be affected by position of the sensor on the chest. Furthermore, we have no record of any compressions that may have been delivered by bystanders prior to arrival of the EMS providers with force recording monitors. Any such prior CPR may itself have induced some unmeasured change in chest stiffness. These issues may contribute to the considerable variation in measured stiffness we observed.

In our study final normalized stiffness was > 1 in 24% of patients, that is their chests stiffened over the course of resuscitation efforts. Tomlinson et al[9] also found that stiffness increased in 18% of their 39 patients over the course of the initial 1000 compressions. Whether a chest stiffens or softens may depend on the nature and extent of thoracic injuries. Sternal fractures, combined with rib fractures, have been associated with lower incidence of ROSC than for rib fractures alone.[21] Unfortunately we have no information regarding thoracic injuries in our study subjects. We did not identify any characteristics that could predict patients whose chests became stiffer as opposed to those whose chests became softer. Patients whose chests became stiffer received fewer compressions, were more frequently declared dead in the field, and received higher hands-on-times. It is possible that CPR providers perceive futility of resuscitation efforts in these patients earlier than in patients whose chests soften. Better understanding of the differences between patients with stiffening as opposed to softening chests must await further study and additional data on the nature and extent of associated thoracic injuries.

Our measure of stiffness — peak force/peak depth in each compression — is intuitive, but novel. It includes measurements from two separate moments, as the peak of depth trails the peak of force (see Fig. 3 for examples). This approach avoids requiring that compressions meet any particular depth target (as in Tomlinson et al[9], Beesems et al[22]) and accommodates the lag in depth response to applied force attributable to the visco-elasticity of the chest.[24,25] In our dataset, peak depths lagged peak forces by an median of 19 (13 — 27) ms. Our results are robust to alternatives. For example, defining stiffness as the ratio of force to depth at the peak of response (at peak compression velocity), or as the ratio of force to depth both measured at the point of peak depth, provided essentially the same findings, with monotonic decreases in normalized stiffness over 3500 compressions reaching 32% and 41% respectively.

We found that despite the greater initial stiffness in males than in females, also documented by Tomlinson et al[9] though not Beesems et al[22], the rate of change in normalized stiffness did not depend on patient sex, nor was it influenced by patient age or initially recorded ECG rhythm, nor did it affect likelihood of survival. Analysis of stiffness normalized per subject to their initial stiffness is also novel. In a study of 91 patients using an experimental monitor that also measured force, Tomlinson et al[9] documented an average decline in stiffness, measured as the force required to reach 25 mm depth, over the course of the initial 1000 compressions. This observation is consistent with progressive softening, though without normalization to initial stiffness it is not direct support for softening in individuals. At that time (2004-5) the prevailing guideline for compression depth was 38 — 50 mm. Mean compression depth was 42 mm, less than currently prevailing guidelines and than our observed median of 51 mm, which may have resulted in less cumulative impact on the subjects' chests. Despite differences in methods, their reported aggregate mean reduction in stiffness over 1000 compressions of 6.2% (calculated from the reported regression relation) was remarkably similar to our observation of mean individual reduction in stiffness over the initial 1000 compressions (5%, averaging S_n for compressions 990 - 1010), though substantially less than our observation of median individual reduction in stiffness over the same interval (11%), reflecting the sensitivity of analysis to assumed linearity. Our observations show that reduction in stiffness continues as compressions continue to accumulate. Reduction in stiffness increased monotonically through the first 3500 compressions to 36%.

Perhaps due to real-time feedback from the CPR monitor, reducing stiffness had only modest impact on adherence to guidelines for chest compressions. Chest compression during CPR is physically challenging and, despite real-time feedback, adherence is limited.[26,27] Guidelines changed during the period of this study, with the addition of upper limits on recommended rate and depth of compressions, but this change did not appear to affect performance meaningfully. Regardless of S_n quintile, adherence to rate recommendations of 100 to 120 compressions per minute remained between 58 and 66%. Adherence to recommendations for depth of between 50 and 60 mm is evidently more challenging. Softening of chests led to somewhat deeper compressions, on average. Tomlinson et al[9] also noted deeper compressions in softer chests on average. The reduction in compressions that were too shallow resulted in increase of adherence to the depth recommendation from 17% in the stiffest (5th) quintile of S_n to 27% in the softest (1st) quintile. Complete release improved from 87% in the stiffest quintile to 96% in the softest quintile. Overall, concurrent adherence with all three recommendations, regarding rate, depth and release, remained modest (19 — 23%) throughout. This compression-by-compression assessment of adherence is not directly comparable to other reports using case-wise averages and omitting release[26] or assessing a single parameter[27] but is consistent overall with the disappointing levels of adherence reported in these other analyses.

Most CPR monitors provide feedback only on rate. One other technology does provide feedback on depth, but no other device provides feedback on release, infeasible without a force sensor. Without additional studies that measure all three of these factors, it is difficult to interpret the degree of adherence to all three recommendations that we observed other than to acknowledge that this appears to be quite challenging during manual CPR. Nonetheless, it is somewhat reassuring to learn that instead of degrading adherence, chest softening if anything enhances it a little. There is no basis in our observations to suggest that guidelines need to be adapted to the duration of CPR efforts.

Limitations

Our data is from a single EMS service. Guidelines for chest compression changed during the study period. We have no data on the duration and quality of any bystander CPR that preceded our data, which were acquired after EMS arrival. We also lack data on possible thoracic injuries the subjects may have sustained, the substrate for compressions or the precise positions of rescuers hands. Depth was estimated from a single accelerometer, with no fixed reference point.

Conclusions

Chest stiffness during extended CPR decreases monotonically through at least the first 3500 compressions. Its impacts on adherence to guideline recommendations are modest, moderately improving adherence to depth and release targets without consistently affecting adherence to rate recommendations or overall adherence. Adaptation of guidelines to duration of CPR on the basis of changing chest stiffness does not appear to be warranted.

Conflicts of interest:

Author Digna María González-Otero is employed by Bexen Cardio, a Spanish medical device manufacturer. Bexen Cardio had no role in study funding, or study design, data collection and analysis, decision to publish, or preparation of the manuscript. The other co-authors declare no conflict of interest.

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Figure Legends

Figure 1: Emergency responses with activation of defibrillator/monitors by Tualatin Valley Fire & Rescue, 2013 - 2017

Figure 2: Chest stiffness normalized (S_n) to median of stiffness in initial 100 compressions) by minutes of CPR

Figure 3: Softening in a 68 year old male. The patient presented with ventricular fibrillation, received 43 minutes of CPR in a single series including 8 defibrillation shocks prior to transport, and expired in Emergency Department.

Figure 4: Adherence by Moulding Quintile:

Rate (top panel): The proportion of compressions adherent to the recommended rate limits of between 100 and 120 compressions/minute (in red) peaks at the center, in the 3rd quintile at 66%, declining in both directions, reaching a minimum in the 1st quintile of 58%.

Depth (middle panel): The proportion of compressions adherent to the recommended depth limits of between 50 and 60 mm (in red) peaks in the 1st (softest) quintile at 27%, declining monotonically to 17% in the 5th (stiffest) quintile.

Complete release (bottom panel): The proportion of compressions adhering to the guidance for complete release, assessed as leaving < 2.5 kg-f (24 N) on the chest, peaks at 96% in the 1st (softest) quintile, declining monotonically to 87% in the 5th (stiffest) quintile.

Table 1: Patient characteristics and disposition of cases with extended CPR (> 1000 compressions)

Characteristic	Observed value
Age, y median (IQR)	66 (53 - 75)
Sex n (%)	
Male	312 (66)
Female	159 (34)
Presenting ECG rhythm n(%*)	
shockable (VF/VT)	125 (27)
pulseless electrical activity	122 (26)
asystole	221 (47)
not recorded	3
Return of spontaneous circulation (ROSC) n (%*)	154 (35)
Disposition n (%*)	
died in field	176 (38)
died in emergency department	168 (36)
died after hospital admission	98 (21)
discharged alive	24 (5)
unknown	8
Modified Rankin Score (of discharged alive) n (%*)	
1	2 (12)
2	3 (18)

3	8 (47)
4	4 (24)
5	0
unknown	4

* (of known)

Table 2: Extended CPR case characteristics for performance metrics and stiffness

Characteristic	median (IQR) 2013-5	median (IQR) 2016-7	median (IQR) all years
n	280	191	471
Duration of initial CPR series (minutes)	20 (14 — 29)	20 (15 — 26)	20 (15 — 28)
Compressions	1985 (1485 — 2817)	2155 (1511 — 2999)	2051 (1490 — 2864)
Compression rate (cpm)	113 (109 — 117)	114 (111 — 117)	113 (110 — 117)
Compression depth (mm)	51 (45 — 57)	52 (46 — 58)	52 (46 — 57)
Compression force (N)	419 (356 — 498)	419 (361 — 476)	419 (358 — 492)
Complete release (%)	96% (88 — 99)	97% (93 — 99)	96% (90 — 99)

Hands on time (%)	86 (81 — 90)	88 (83 — 91)	87 (82 — 90)
S_n decrease (%)	28 (2 — 45)	26 (2 — 44)	23 (2 — 44)

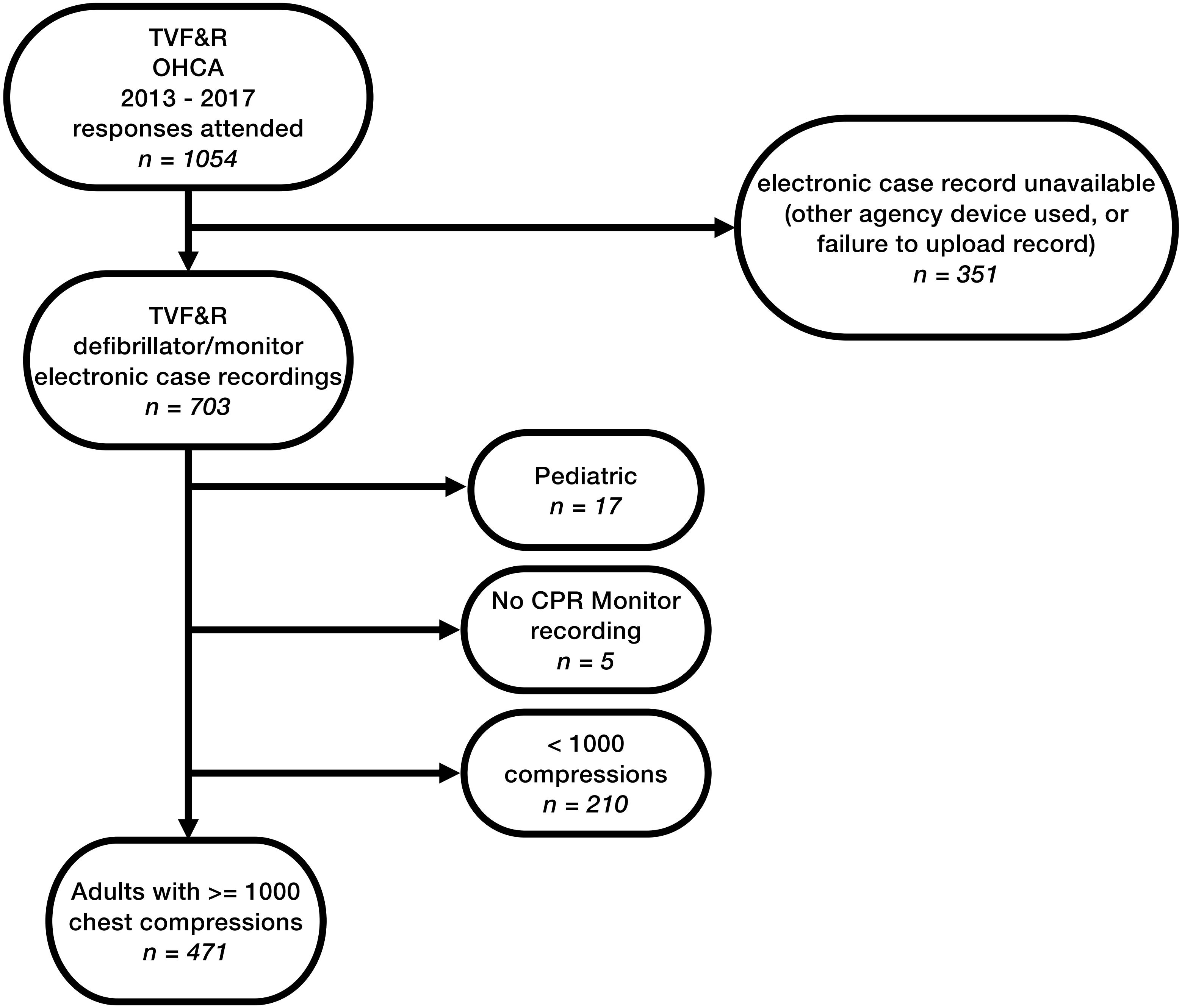

TVF&R
OHCA
2013 - 2017
responses attended
n = 1054
electronic case record unavailable
(other agency device used, or
failure to upload record)
n = 351
TVF&R
defibrillator/monitor
electronic case recordings
n = 703
Pediatric
n = 17
No CPR Monitor
recording
n = 5
< 1000
compressions
n = 210
Adults with >= 1000
chest compressions
n = 471

Figure2

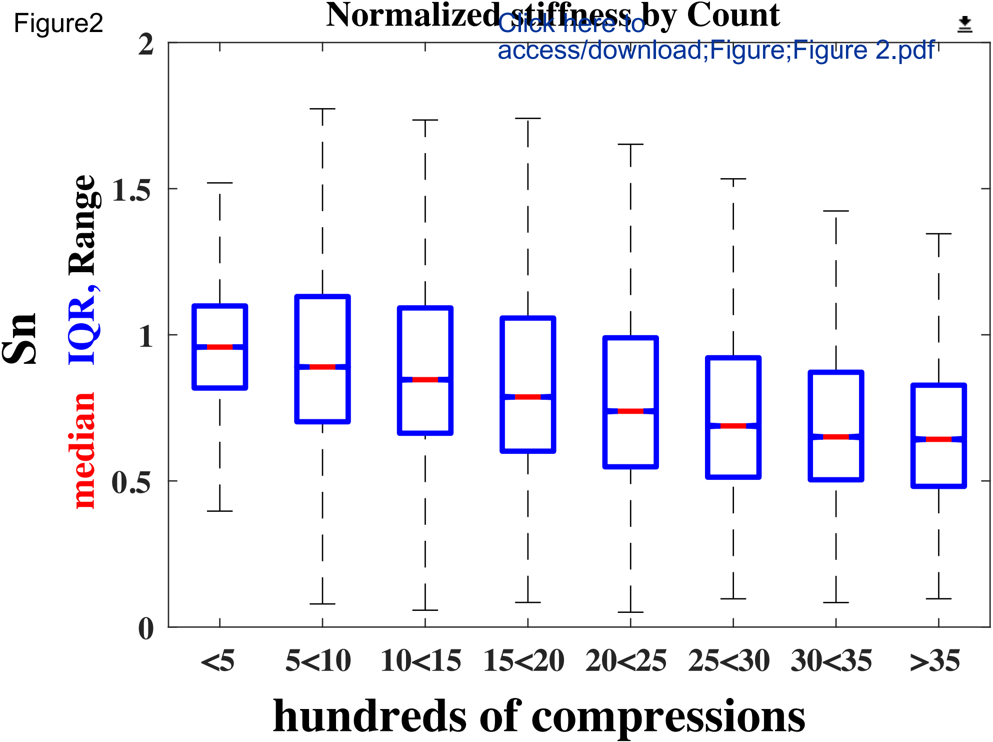

Normalized stiffness by Count
Sn median IQR, Range
2
1.5
1
0.5
0
<5
5<10
10<15
15<20
20<25
25<30
30<35
>35
hundreds of compressions

Figure 3

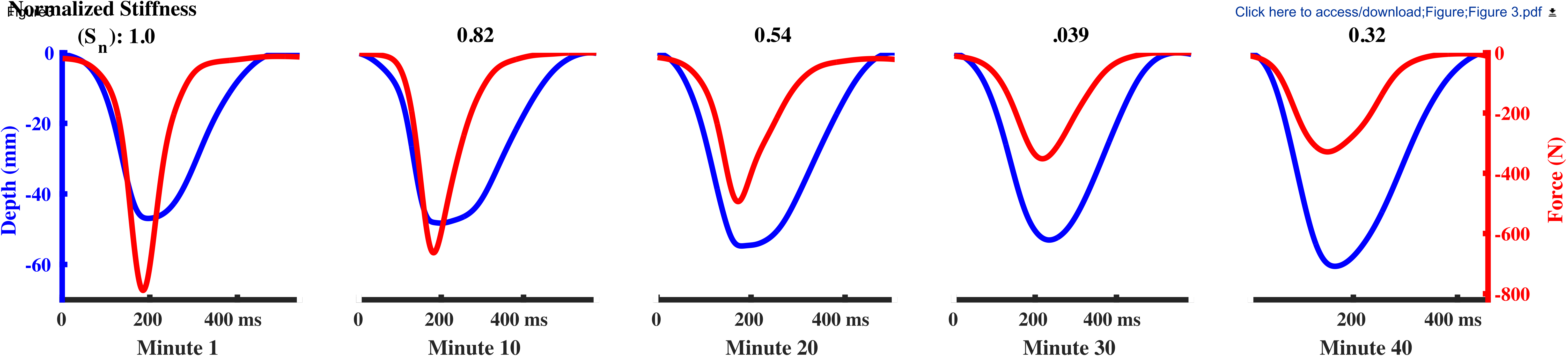
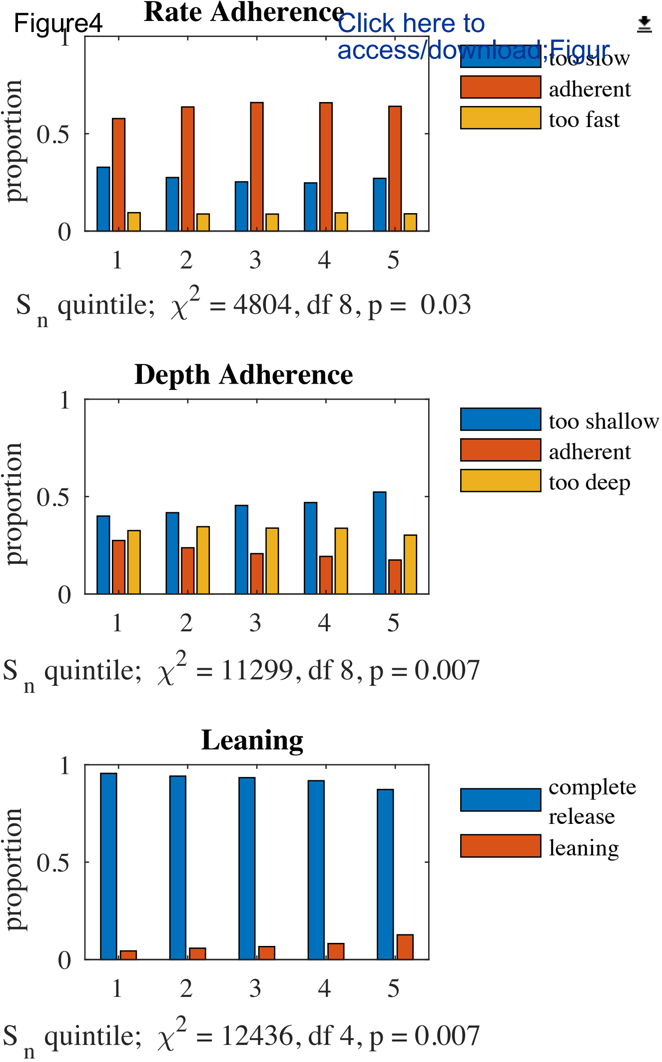

Normalized Stiffness
(S n): 1.0
0.82
0.54
.039
0.32
Depth (mm)
0
-20
-40
-60
Force (N)
0
-200
-400
-600
-800
0
200
400 ms
Minute 1
Minute 10
Minute 20
Minute 30
Minute 40

Figure4


Rate Adherence
proportion
1
0.5
0
1
2
3
4
5
too slow
adherent
too fast
S_n quintile; χ^2 = 4804, df 8, p = 0.03
Depth Adherence
proportion
1
0.5
0
1
2
3
4
5
too shallow
adherent
too deep
S_n quintile; χ^2 = 11299, df 8, p = 0.007
Leaning
proportion
1
0.5
0
1
2
3
4
5
complete release
leaning
S_n quintile; χ^2 = 12436, df 4, p = 0.007

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The other co-authors declare no conflict of interest.

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Sofía Ruiz de Gauna: Resources; Writing - review & editing; Supervision; Funding acquisition; Project administration.
Jesus María Ruiz: Resources; Methodology; Software; Funding acquisition.
Mohamud Ramzan Daya: Resources; Writing - review & editing; Supervision.