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Optimal Combination of Compression Rate and Depth During Cardiopulmonary Resuscitation for Functionally Favorable Survival

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IMPORTANCE Previous studies of basic cardiopulmonary resuscitation (CPR) indicate that both chest compression rate (CCR) and chest compression depth (CCD) each are associated with survival probability after out-of-hospital cardiac arrest. However, an optimal CCR-CCD combination has yet to be identified, particularly with respect to age, sex, presenting cardiac rhythm, and CPR adjunct use.

OBJECTIVES To identify an ideal CCR-CCD combination associated with the highest probability of functionally favorable survival and to assess whether this combination varies with respect to age, sex, presenting cardiac rhythm, or CPR adjunct use.

DESIGN, SETTING, AND PARTICIPANTS This cohort study used data collected between June 2007 and November 2009 from a National Institutes of Health (NIH) clinical trials network registry of out-of-hospital and in-hospital emergency care provided by 9-1-1 system agencies participating in the network across the United States and Canada (n = 150). The study sample included 3643 patients who had out-of-hospital cardiac arrest and for whom CCR and CCD had been simultaneously recorded during an NIH clinical trial of a CPR adjunct. Subgroup analyses included evaluations according to age, sex, presenting cardiac rhythm, and application of a CPR adjunct. Data analysis was performed from September to November 2018.

INTERVENTIONS Standard out-of-hospital cardiac arrest interventions compliant with the concurrent American Heart Association guidelines as well as use of the CPR adjunct device in half of the patients.

MAIN OUTCOMES AND MEASURES The optimal combination of CCR-CCD associated with functionally favorable survival (modified Rankin scale ≤ 3) overall and by age, sex, presenting cardiac rhythm, and CPR adjunct use.

RESULTS Of 3643 patients, 2346 (64.4%) were men; the mean (SD) age was 67.5 (15.7) years. The identified optimal CCR-CCD for all patients was 107 compressions per minute and a depth of 4.7 cm. When CPR was performed within 20% of this value, survival probability was significantly higher (6.0% vs 4.3% outside that range; odds ratio, 1.44; 95% CI, 1.07-1.94; *P* = .02). The optimal CCR-CCD combination remained similar regardless of age, sex, presenting cardiac rhythm, or CPR adjunct use. The identified optimal CCR-CCD was associated with significantly higher probabilities of survival when the CPR device was used compared with standard CPR (odds ratio, 1.90; 95% CI, 1.06-3.38; *P* = .03), and the device's effectiveness was dependent on being near the target CCR-CCD combination.

CONCLUSIONS AND RELEVANCE The findings suggest that the combination of 107 compressions per minute and a depth of 4.7 cm is associated with significantly improved outcomes for out-of-hospital cardiac arrest. The results merit further investigation and prospective validation.

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In recent clinical reports regarding cardiac arrest outcomes after closed-chest cardiopulmonary resuscitation (CPR), 1 factor strongly associated with worse outcomes has been inadequate performance of chest compressions.[1-7] Recovery with good neurologic function after out-of-hospital cardiac arrest (OHCA) is well-correlated with target ranges of chest compression rate (CCR) and chest compression depth (CCD).[3-7] In these studies,[3-9] favorable ranges of CCR or CCD were independently identified, with worse outcomes outside each of those respective ranges.

Despite these complementary but independent findings, there are interactions between CCR and CCD, such as a faster CCR being associated with compromised CCD.[9] Data are still lacking with respect to specifically identifying the optimal combination of CCR and CCD and whether the same CCR-CCD target combination should be applied to all patients irrespective of sex, age, presenting cardiac rhythm, or CPR adjunct use.[3-9] Knowing, monitoring, and confirming target CCR-CCD combinations would not only optimize treatment but also improve the study design and reliability of clinical studies.[7]

The specific hypothesis was whether a target CCR-CCD combination could be identified that would be associated with improved likelihood of favorable functional outcome after OHCA. It was also hypothesized that a different target combination might be delineated when comparing sex, age, presenting heart rhythms, or application of CPR adjuncts.

Methods

This cohort study used data from the National Institutes of Health (NIH) clinical trials network database. For the past 2 decades, the NIH and partner agencies sponsored multicenter clinical trials managed by the NIH Resuscitation Outcomes Consortium (ROC), which tested pharmacological, procedural, and device interventions for OHCA.[10] The ROC PRIMED (ROC Prehospital Resuscitation Impedance Valve and Early Versus Delayed Analysis) trial evaluated a CPR adjunct using a sizeable, diverse cohort of patients with OHCA treated across 150 US and Canadian emergency medical services (EMS) agencies participating in the ROC network between June 2007 and November 2009.[10-12] It was the first multicenter trial to use electronically documented measurements of CCR and CCD.[10-12] By enrolling 8718 adult-age patients with OHCA, a high percentage of women, and use of a CPR adjunct, the data set from this trial[12] was considered an appropriate vehicle for this present investigation.[11,12] The present study, undertaken independently of the NIH, involved analyses of data from the ROC PRIMED database that were obtained through the NIH Data Sharing Policy and Freedom of Information Act (https://grants.nih.gov/policy/sharing.htm). Published studies[3,5-7,9] examining either optimal ranges of CCR or optimal ranges of CCD have used similar approaches. The Human Subjects Committees at the University of Minnesota, Minneapolis, reviewed and approved the study; the study met exempt qualifications because this was an analytic review of a deidentified public database, and therefore informed consent was not required. Investigators followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guideline. Data analysis was performed from September to November 2018.

Key Points

Question During cardiopulmonary resuscitation, is there an optimal combination of chest compression rate and depth associated with an enhanced likelihood of favorable functional outcome, and does that optimal combination change with respect to age, sex, presenting cardiac rhythm, or use of a cardiopulmonary resuscitation adjunct?

Findings In this cohort study of data from 3643 individuals in the National Institutes of Health clinical trials network database, the optimal combination of chest compression rate was 107 compressions per minute and chest compression depth of 4.7 cm; this finding remained relatively consistent regardless of age, sex, presenting cardiac rhythm, or cardiopulmonary resuscitation adjunct use. Adjunct use was associated with significant improvements in outcome, but this was dependent on delivering the identified optimal chest compression rate and depth combination.

Meaning The findings suggest that the combination of 107 compressions per minute and a depth of 4.7 cm may be the optimal target for chest compression rate and depth, and that use of an adjunct may be associated with significantly enhanced outcomes if this target is used.

Study Design

For ROC PRIMED, both CCR and CCD data were collected electronically using measurement and recording sensors linked to the EMS agencies' electrocardiographic monitor defibrillators.[11,12] On the basis of previous publications,[11,13] the CCR-CCD data used here were the means of measurements taken during the first 5 minutes of recorded CPR, with CCR recorded to the nearest integer and CCD recorded to the nearest 0.5 cm. To avoid detracting outliers with CCR or CCD values indicating negligible odds of survival, data sets were trimmed to only include patients receiving CCR between 60 and 160 compressions per minute (cpm) and CCD between 2.0 and 8.0 cm.

Analyzed data included age, sex, presenting cardiac rhythm, and CPR adjunct use. The adjunct, methods, and primary results of the original trial are described elsewhere.[10-12] In brief, patients were assigned randomly in a blinded manner to receive conventional CPR using either an inactive (sham) impedance threshold device (ITD) or active-ITD providing 16 cm H_2O resistance (ZOLL Medical).[11,12] Each device was labeled with a numerical code known only to the data coordinating center for subsequent identification of sham-ITD or active-ITD assignments.

Patient Care Protocols

The EMS first-responders were instructed to apply ITDs by face mask or advanced airway while providing chest compressions and ventilation according to concurrent American Heart Association recommendations.[3,11,12,14] These recommendations stipulated 80 to 100 cpm, a compression depth of 4.0 to 6.0 cm, and using an advanced airway, 10 positive-pressure breaths per minute with approximately 600 mL tidal volume. The breaths were delivered in a 30:2 compression to breath ratio when using basic airways.[3,11,12,14] The ROC sites were permitted to only enroll persons after showing for several months that CPR could be delivered with these predefined metrics more than 50% of the time.[11,12]

Study Participants

Among 8718 ROC PRIMED patients, 6199 had recordings of CCR and 3750 had CCD recordings, but most lacked simultaneous measurements of CCR and CCD during the first 5 minutes of CPR. Eligible study participants were those with intact sets of simultaneous CCR-CCD recordings during the first 5 minutes of EMS-performed CPR. As previously stated, those with CCR-CCD values outside the proscribed ranges (60-160 cpm and 2.0- to 8.0-cm depth) were excluded from analyses.

Statistical Analysis

Statistical techniques were used to calculate the optimal CCR-CCD combination associated with a maximized probability of survival with a modified Rankin scale (mRS) score of 3 or less at the time of hospital discharge, examining the entire cohort of analyzed patients and the subset of survivors.[15] For both analyses, a 130-cell grid was constructed with 10 levels of CCR (ranging from 60-69 cpm to 150-160 cpm) and 13 levels of CCD (ranging from 2.0 cm to 8.0 cm using 0.5-cm increments). For the full cohort, the survival probability in each cell was calculated as the numerator of survivors in each cell divided by the denominator of patients within that individual cell. That survival probability was then multiplied by the reciprocal of its variance within each cell to create a set of weighted probabilities for each of those cells. For the survivors-only analyses, each of the similarly constructed 130-grid cells contained the corresponding proportion of survivors (with the sum of all 130 proportions equaling one).

Response Surface Modeling Approach

Both cohort and survivor samples were analyzed using response surface modeling to estimate the combination CCR-CCD values associated with optimized outcome. In these models, CCR was represented by the midpoint of the rate interval (eg, 95 cpm for the interval of 90-99 cpm), whereas CCD was defined by rounding to the nearest 0.5 cm as previously described.

A regression model with a linear and quadratic term for each of the rates and depths (and their interaction) was fitted to the data overall and then separately fitted for sham-ITD (inactive) and active-ITD groups. A stepwise method was used to identify the best-fitting model. From these models, optimal CCR-CCD combination values were calculated using numerical optimization techniques. The proposed optimal combination was evaluated further within a range that was within 20% of the identified CCR-CCD target.

Subgroup Analyses

Analyses were performed to determine whether optimal CCR-CCD targets varied by sex, age (using median age of the overall cohort: <70 years vs ≥70 years), or the presenting cardiac rhythm, specifically comparing ventricular fibrillation or ventricular tachycardia with other presenting rhythms or asystole. In addition, optimal CCR-CCD combinations for sham-ITD (standard CPR) and active-ITD (adjunct CPR) were estimated within each sham-ITD or active-ITD subgroup and across subgroups combined.

Contour Plot Approach

Contour plots were constructed to visually display optimal CCD-CCR combinations colorimetrically with separate displays for sham-ITD and active-ITD groups. These plots were designed to show the relative proportions of survivors across the survivor sample and the weighted survival proportions for the overall cohort within each cell, with the rate and depth categories forming a 2-dimensional plot. Colder zones represent the lowest (negligible) proportion of survivors or survival probability, cool zones represent slightly higher proportions, and warmer and hotter zones represent higher proportions of survivors or survival.

Descriptive statistics for continuous variables are reported as mean (SD) and categorical variables by frequency and percentage. Comparisons are reported as mean difference (95% CI) or odds ratio (OR) (95% CI); $P < .05$ (2-sided) indicates statistical significance. Analyses were performed in Stata, version 13.1 (StataCorp) and Minitab, version 17.3.1 (Minitab Statistical Software).

Results

Patient Characteristics

Simultaneous measurements of CCR and CCD during the first 5 minutes of CPR efforts were recorded for 3749 patients, with 106 patients (2.8%) having CCR-CCD values outside the trimmed ranges (60-160 cpm; 2.0-8.0 cm), leaving a study cohort of 3643 patients (mean [SD] age, 67.5[15.7] years; 2346 [64.4%] men). Although 35 (0.9%) achieved return of spontaneous circulation within that 5-minute period, their data before return of spontaneous circulation were included. Compared with those achieving return of spontaneous circulation after 5 minutes, these patients remained well-matched in terms of demographics, active ITD use, and survival.

Of the 3643 patients, 1527 (41.9%) had bystanders witness the OHCA with bystander-CPR performed for 1323 (36.3%); 1740 (47.8%) presented with asystole and 893 (24.5%) with ventricular fibrillation or ventricular tachycardia. First-in responders had a mean (SD) response interval of 5.7 (2.0) minutes (dispatch to street location arrival); 3316 patients (91.1%) received at least 1 prehospital dose of epinephrine, and 186 (5.1%; 93 controls and 93 active-ITD patients) had functionally favorable survival to hospital discharge (mRS ≤3).

When comparing 1832 patients (50.3%) assigned to sham-ITD and 1811 (49.7%) receiving the active-ITD, the demographic, clinical presentation, and treatment data confirmed well-matched subgroups and mimicked the overall study group (**Table 1**). The only statistically significant difference was frequency of epinephrine administration (sham-ITD vs active-ITD: 89.8% vs 92.3%; OR, 1.35; 95% CI, 1.07-1.70; $P = .01$).

The survivor sample (n = 186) showed similar comparisons except that 1 statistically significant difference was a

Table 1. Characteristics of Patients Receiving Standard CPR (Sham-ITD) Compared With Those Receiving an Active-ITD

Characteristic	Sham-ITD (n = 1832)[a]	Active-ITD (n = 1811)[a]	Comparison of Active vs Sham, OR (95% CI)	*P* Value
Age, mean (SD), y	67.5 (15.5)	67.5 (15.8)	−0.03 (−1.04 to 0.99)[b]	.96
Male	1161 (63.4)	1185 (65.4)	1.09 (0.96 to 1.25)	.19
Public location	246 (13.4)	240 (13.3)	0.98 (0.81 to 1.19)	.88
Bystander witnessed	790 (43.1)	737 (40.7)	0.91 (0.79 to 1.03)	.14
Bystander performed CPR	678 (37.0)	645 (35.6)	0.96 (0.84 to 1.10)	.56
Time elapsed from dispatch to first EMS crew arrival, mean (SD), min	5.8 (2.1)	5.7 (2.0)	−0.10 (−0.24 to 0.03)[b]	.12
Time from dispatch to first arrival of ALS, mean (SD), min	8.7 (4.3)	8.5 (4.3)	−0.21 (−0.49 to 0.07)[b]	.14
Treated by ALS clinicians	1823 (99.5)	1808 (99.8)	2.98 (0.80 to 11.01)	.10
First cardiac rhythm presentation				
VF/VT	460 (25.1)	433 (23.9)	1 [Reference]	.43
Pulseless electrical activity	434 (23.7)	470 (26.0)	1.15 (0.96 to 1.38)	
Asystole	886 (48.4)	854 (47.2)	1.02 (0.87 to 1.20)	
AED applied but not used[c]	52 (2.8)	54 (3.0)	1.10 (0.74 to 1.65)	
Unknown or could not be determined	0	0	NA	
Epinephrine infused before arrival to hospital	1645 (89.8)	1671 (92.3)	1.35 (1.07 to 1.70)	.01

Abbreviations: AED, automated external defibrillator; ALS, advanced life support; cpm, compressions per minute; CPR, basic cardiopulmonary resuscitation; EMS, emergency medical services; ITD, impedance threshold device; NA, not applicable or estimable; VF/VT, ventricular fibrillation/ventricular tachycardia.

[a] Data are presented as number (percentage) of individuals unless otherwise indicated.

[b] Data shown are mean difference (95% CI).

[c] AED indicated no shock, but no recording was recovered to document asystole or pulseless electrical activity.

longer response interval for active-ITD patients (mean [SD], 5.4 [1.5] vs 4.9 [1.7] minutes for sham-ITD; mean difference, 0.49 minutes [95% CI, 0.02-0.95 minutes]; *P* = .04).

Rate and Depth Data

Across the 130 CCR-CCD combinations, the 100-109 cpm and 4.0 cm combination was the most populated whether for sham-ITD, active-ITD, or the overall cohort (**Table 2**). In the survivor group (n = 186), the most populated cell was the 90-99 cpm/4.5 cm combination.

Results From Response Surface Models

Table 3 provides the response surface modeling results for the 186 survivors. Terms for rate, depth, and their quadratic forms were kept in the final models for all groups with the interaction term between rate and depth not significant in any model.

The optimal combination of CCR-CCD associated with the greatest probability of favorable functional outcome was identified as 107 cpm and 4.7 cm with little difference across subgroups (age, sex, cardiac rhythm, or adjunct use). With CPR performed within 20% of this identified combination (86-128 cpm; 3.8-5.6 cm), survival probability was significantly higher (6.0% vs 4.3% outside that range; OR, 1.44; 95% CI, 1.07-1.94; *P* = .02). Corresponding comparisons for sham-ITD and active-ITD survivors (mRS ≤3) showed significantly larger numbers of survivors with the active-ITD (n = 60) vs the sham-ITD (n = 43) (OR, 2.11; 95% CI, 1.17-3.81; *P* = .01).

Results From Contour Plots

Contour plots were developed for the 93 sham-ITD (standard CPR) survivors (mRS ≤3) (**Figure**, A) and 93 active-ITD counterparts (Figure, A). Optimal CCR-CCD combinations were similar, with the cell with the highest proportion of survivors being 100-109 cpm and 4.5-5.0 cm. However, the peak proportion of survivors for the active-ITD group was significantly higher compared with the corresponding sham-ITD group, indicated by the hotter colorimetric zones and the only red zone findings. A similar pattern was shown when evaluating all 3643 patients combined (Figure, B). Despite the higher probability of survival with ITD use, the identified optimal CCR-CCD combination remained similar with or without the device.

When evaluating the 4 most populated combinations of CCR-CCD among survivors, survival (mRS ≤3) was 7.4% (**Table 4**). However, when stratified, survival probability was 9.6% for active-ITD use vs 5.3% for sham-ITD use (OR, 1.90; 95% CI, 1.06-3.38; *P* = .03).

Subgroup Analyses

Among 186 survivors (mRS ≤3), 133 (71.5%) were men. Although survival differences between men (5.7%) and women (4.1%) were significant (OR, 1.41; 95% CI, 1.02-1.95; *P* = .04), the identified optimal CCR-CCD combination remained consistent (Table 3). Older individuals (age, ≥70 years) appeared to benefit from a shallower CCD (Table 3), but differences were not statistically significant. Standard CPR (sham-ITD) patients with nonshockable presentations appeared to have a lower optimal CCR compared with counterparts presenting with ventricular fibrillation or ventricular tachycardia (99 vs 109 cpm), but definitive conclusions could not be drawn because of small sample sizes.

In general, there did not appear to be conclusive support for a variable favorable combination for any of the predefined subgroups compared with the overall findings.

Discussion

Despite reported interactive associations between CCR and CCD, data have been lacking with respect to determining a specific optimal CCR-CCD combination. Previous studies

Table 2. Persons Falling Within Each of 130 Combinations of Rate and Depth and Those With Functionally Favorable Survival Within Each of 130 Combinations of Rate and Depth

	Rate, cpm									
Depth, cm	60-69	70-79	80-89	90-99	100-109	110-119	120-129	130-139	140-149	150-160
Persons Within Combinations of Rate and Depth, No.										
2.0	2	6	4	16	18	17	9	6	9	2
2.5	0	10	14	20	39	37	31	16	10	3
3.0	3	7	31	57	81	76	48	26	8	11
3.5	7	12	37	112	164	113	51	37	15	5
4.0	7	12	56	189	229	138	69	31	8	5
4.5	5	16	47	174	190	117	55	23	7	8
5.0	6	12	46	128	133	76	33	7	4	1
5.5	1	11	27	77	80	46	20	11	8	0
6.0	0	8	25	41	41	25	9	3	2	0
6.5	4	3	20	19	18	15	14	1	1	0
7.0	0	5	10	20	17	6	0	2	0	1
7.5	1	0	8	5	10	5	2	2	0	0
8.0	1	0	0	5	5	4	2	0	0	0
Persons With Functionally Favorable Survival, No.										
2.0	0	0	0	2	2	0	0	0	0	0
2.5	0	0	1	1	1	0	0	1	1	0
3.0	0	0	1	0	2	1	0	0	0	1
3.5	1	1	2	1	9	6	1	2	1	0
4.0	1	0	2	7	13	10	2	1	0	1
4.5	1	1	5	16	13	6	3	2	0	0
5.0	0	0	3	4	12	3	2	0	0	0
5.5	0	2	1	3	8	2	0	1	0	0
6.0	0	0	1	1	5	1	1	0	0	0
6.5	0	0	1	0	2	1	2	1	0	0
7.0	0	0	1	1	1	1	0	0	0	0
7.5	0	0	1	0	1	0	0	0	0	0
8.0	0	0	0	0	1	0	0	0	0	0

generally addressed independent evaluations of optimal ranges for CCR or CCD.[3-9] Of importance, whether such an ideal CCR-CCD target would differ significantly depending on sex or age (anatomical and physiologic differences), the presenting cardiac rhythm (possible surrogate for more prolonged hypoxic event), or the use of a CPR adjunct (that might augment flow) has not been specifically addressed.

Although this was a secondary analysis of clinical trial data, the study included prospectively collected, well-defined data points from the OHCA experience of more than 150 EMS agencies in 2 countries including actual simultaneous recordings of CCR and CCD, constituting the best available data from the largest North American database on the subject. Recognizing the limitations of this analysis and that the findings may not be universally applicable, the results suggest a plausible value for an optimal CCR-CCD combination associated with a maximized probability of functionally favorable survival after OHCA. This optimal combination should now be further studied and validated in future prospective investigations. Although the combination may not be the eventual definitive answer regarding optimal rate and depth, it is an important step in the process of finding the best practice and determining whether the combination varies according to various factors.

The data from this analysis showed that, regardless of the presenting cardiac rhythm, age, sex, or use of a particular CPR adjunct, the optimal CCR-CCD combination remained similar. It is still possible that other interventions, such as various mechanical CPR devices or more prolonged arrest intervals, could have altered that finding. Therefore, evaluations of CCR-CCD combinations should be stratified accordingly in future studies of such interventions or conditions.

In this study, ITD use was associated with significantly improved survival likelihood when CPR was performed within or near the identified best combination, and this finding was dependent on that optimal performance of CPR. The other findings, such as the favorable associations for a shallower CCD in older patients or slower CCR for nonshockable rhythms were not conclusive because of the small sample sizes but could be considered hypothesis generating.

The wide variation in both CCR and CCD across the study cohort (Table 2) may indicate the challenges of optimizing manual CPR performance among numerous rescuers whose individual abilities to perform CPR properly may be variable, even in closely monitored EMS systems. One could therefore argue for real-time CPR feedback tools on a day-to-day basis and/or automated CPR devices to better ensure consistent

Table 3. Optimal CCR-CCD Among Cardiac Arrest Survivors Overall and for Predefined Subgroups

Group	Optimal Rate, cpm	Optimal Depth, mm	Survivors, No.
All survivors	107	47	186
Sham-ITD	108	46	93
Active-ITD	107	48	93
Men	107	47	133
Sham-ITD	108	47	65
Active-ITD	107	48	68
Women	107	45	53
Sham-ITD	108	45	28
Active-ITD	106	45	25
Younger age (<70 y)	107	48	135
Sham-ITD	107	47	72
Active-ITD	107	49	63
Older age (≥70 y)	107	44	51
Sham-ITD	110	44	21
Active-ITD	108	44	30
VF/VT (shock indicated)	108	47	154
Sham-ITD	109	47	79
Active-ITD	107	48	75
Other rhythm presentations (shock not indicated)	105	44	32
Sham-ITD	99	45	14
Active-ITD	108	43	18

Abbreviations: CCD, chest compression depth; CCR, chest compression rate; cpm, compressions per minute; ITD, impedance threshold device; VF/VT, ventricular fibrillation/ventricular tachycardia.

delivery of optimal CCR-CCD combinations. Studies such as this and follow-up investigations may provide presumptive guidance, but evolving factors such as bundled CPR approaches that include mechanical CPR and other adjuncts may also alter that optimal target.[16]

A unique feature of this analysis was the use of response surface models and contour plots. Response surface models provide a better estimate of the optimal combination of CCR and CCD to achieve the best survival; the contour plots are useful tools that enable direct visualization of the joint associations of CCR and CCD with survival for the whole grid of values.[17]

If our data are on target and the CCR-CCD combination of 107 cpm and 4.7 cm (within 20%) are proven to be the best approach, the 6% survival among those patients compared with the 4% survival outside the combination zone would translate into several thousands of additional lives saved each year in the United States alone. Furthermore, if the ITD were used within the optimum 4 best cells for survivors, the 9.6% neurologic-intact survival that we detected would conservatively translate into at least 10 000 more lives saved annually.

Limitations

The findings here may not be universally applicable. They need to be further validated and examined for modifications as certain variables change in the future.[16,18,19] It also involved EMS systems with presumably seasoned 9-1-1 agencies and well-monitored OHCA cases initially audited by the NIH ROC leadership and therefore not entirely representative of other circumstances. However, even if the results were simply reflective of a subset of EMS personnel more focused and trained well in resuscitative tasks with high-level performance, those factors should not only improve the results, but also serve largely to better reinforce reliability of the study's findings.

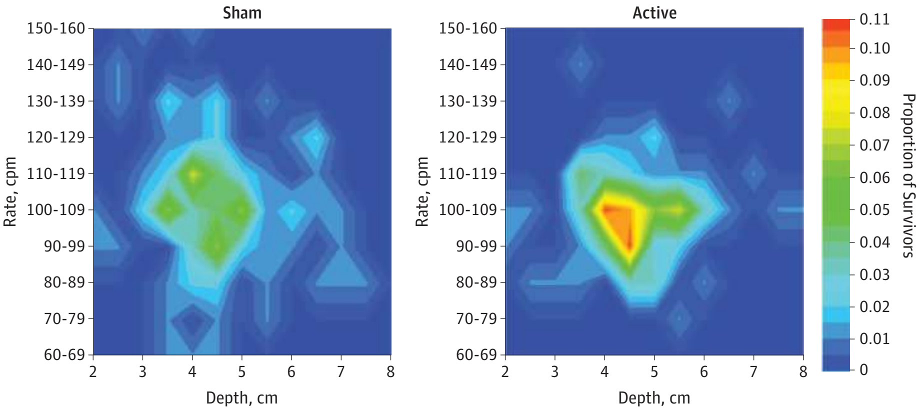
Cardiopulmonary resuscitation was not always performed optimally. Targeting rescuers charged with delivering a rate of 100 cpm (range, 80-100 cpm) and a depth of 4.0 to 6.0 cm might appear to be a form of selection bias. However, previous studies[3-9] have shown that even when the CCR was within a preferred range, CCD might not have been, or vice versa. We also sought to find the optimal CCR-CCD combination within that proscribed range and evaluate whether the preferred target changed according to age, sex, electrocardiographic presentation, or use of a flow-enhancing device (eg, ITD).

More than half the patients (53.2%) were found to be in CCR-CCD grids beyond a calculated optimal target combination range of within 20%, and 80% of the study population was outside the 4 most populated grids for survivors; those were grids that closely represented what the rescuers were expected to be providing. Also, most of the patients overall received CCR-CCD combinations that were below what were determined by this analysis to be the optimal grid zones for survivors (Table 2).

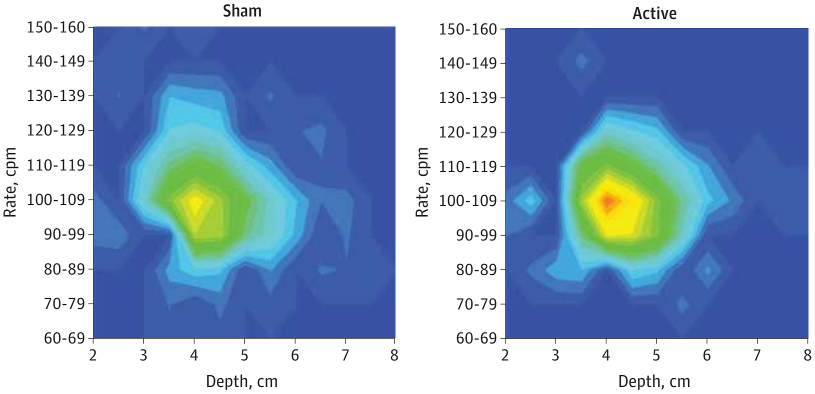
This study cohort was comprised of patients who had simultaneous recordings of CCR and CCD performed. This cohort was derived from within a larger cohort of study patients from the selected clinical trial.[12] In many settings and certain individual cases, CCR and CCD were not measured simultaneously during the proscribed initial 5-minute period or were not technically retrievable (approximately 57% of the source cohort). Although this might also create the concern for a potential selection bias, the present study cohort was shown to

Figure. Colorimetric Contour Plots Showing the Proportion of Patients With Functionally Favorable Survival and Weighted Survival Among Those in the Overall Cohort at Each Combination of Rate and Depth

A Proportion of patients with functionally favorable survival



B Weighted survival in overall cohort



A, Left panel, standard cardiopulmonary resuscitation (n = 93); right panel, addition of an active impedance threshold device (n = 93). B, Left panel, standard cardiopulmonary resuscitation; right panel, addition of an active impedance device. Survival scale is not shown because the data are derived from weighted units.

Table 4. Survivors and Survival in the Cohort Observed Within a 20% Range of the Identified Optimal CCR-CCD Combination of 107 cpm and 4.7 cm

Group	Rate Range, cpm	Depth Range, cm	Persons in Range, No.	Survivors, No./Total No. (%)	Survival, %	OR (95% CI)
Total	86-128	3.8-5.6	1704	103/186 (55)	6.0	NA
Sham-ITD	86-128	3.8-5.6	827	43/93 (46)	5.2	1 [Reference]
Active-ITD	86-128	3.8-5.6	877	60/93 (65)[a]	6.8	1.34 (0.89-2.00)
4 Cells with most survivors[b]	NA	NA	726	54/186 (29)	7.4	NA
Sham-ITD	NA	NA	360	19/93 (20)	5.3	1 [Reference]
Active-ITD	NA	NA	366	35/93 (38)	9.6[c]	1.90 (1.06-3.38)

Abbreviations: CCD, chest compression depth; CCR, chest compression rate; cpm, compressions per minute; ITD, impedance threshold device; NA, not applicable; OR, odds ratio.

[a] *P* = .01.

[b] The 4 most populated combination compression rate and compression depth cells among survivors are 100-109 cpm and 4.5 cm; 100-109 cpm and 4.0 cm; 90-99 cpm and 4.5 cm; and 100-109 cpm and 5.0 cm.

[c] *P* = .03.

be representative of the entire group when we compared the demographic and clinical presentations of the original clinical trial cohort.[12] The analyzed standard CPR and active-ITD groups matched especially in terms of demographics, clinical presentations, and treatment.

Another limitation is that the quality of chest wall recoil was not available and no information regarding the actual performance of assisted ventilation (frequency, tidal volume, timing, and squeeze duration) was provided.[13,18-20] All of these variables have been considered to be effect modifiers in terms of outcomes, and the optimal CCR-CCD target described in this study could shift if information related to optimal chest wall recoil, chest compression fraction, ventilatory parameters, or other modifiers were considered simultaneously when determining optimal CCR-CCD targets.[16,18-20]

With the consideration that the present study groups were so well matched, it is reasonable to assume that recoil and ventilatory aberrations were equally distributed and further optimization of recoil and ventilation would likely serve to improve survival chances even further at the optimal combination of CCR and CCD. Regardless, these measures are recommended factors to capture and evaluate as part of an optimal bundle of care delivery in future investigations.

In addition, although crude surrogates, the sex-based and age-based comparisons were performed to detect any potential anatomic and physiologic differences among those complex subcategories.[18,19] In future analyses, investigators might consider collecting more specific data regarding weight and height or body mass indices and document rib fractures occurring during CPR. Also, we used binary evaluations (men vs women; age, <70 vs ≥70 years). Validation studies might be improved with evaluations of more subsegmented or continuum data combinations of age and sex categories.

Conclusions

In this study, the optimal CCR-CCD combination associated with a favorable neurologic outcome after OHCA was 105 to 109 cpm and 4.5 to 5.0 cm, with an estimated peak at or near 107 cpm and depth of 4.7 cm. This same combination generally applied regardless of age, sex, presenting cardiac rhythm, or the use of an ITD. Moreover, improved survival with the use of the ITD appeared to be dependent on providing the optimal combination of CCR and CCD as identified here. Therefore, optimal CCR-CCD combinations merit further validation and should be important considerations in future CPR survival investigations, particularly those involving studies of CPR-dependent interventions.

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Invited Commentary

Push Hard, Push Fast, Do Not Stop— Optimal Chest Compression Rate and Depth

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The importance of chest compression rate and depth when performing cardiopulmonary resuscitation (CPR) has been known for many years. Compressions that are too fast will not allow for enough ventricular filling between compressions (which is similar to the problems seen in rapid atrial fibrillation), and compressions that are too slow do not provide enough forward flow. The recommended chest compression rate in adults is 100 to 120 per minute.[1] In addition, chest compressions that are too deep can cause substantial thoracic (and even cardiac) injury, while compressions that are too shallow do not provide the needed mechanical chamber movement and valve function for useful flow. Current depth recommendations are 5 to 6 cm.[1]

An intriguing article by Duval et al[2] in this issue of *JAMA Cardiology* explores whether an optimal combination of chest compression rate and depth might exist in the management of out-of-hospital cardiac arrest (OHCA). The authors conducted a secondary analysis of data from the Resuscitation Outcomes Consortium Prehospital Resuscitation Using an Impedance Valve and Early vs Delayed Analysis (ROC-PRIMED) study, which enrolled 8718 patients who experienced OHCA and were treated by about 150 emergency medical services agencies in the United States and Canada.[3] Of these patients, 3643 had both rate and depth of chest compressions continuously recorded for the first 5 minutes of CPR and were included in this secondary analysis. Through a variety of statistical and graphing techniques, a rate of 107 compressions per minute and a depth of 4.7 cm were identified as the optimal combination. Compressions delivered within 20% of these parameters were associated with survival with good neurologic outcome, a benefit that persisted across subanalyses of age, sex, and presenting heart rhythm. The authors[2] appropriately identify a number of methodologic limitations, but the study's underlying assumptions and findings seem reasonable, so let us assume for the moment that the proposed optimum combination is sound. In this case, how do we implement it?

At the recent International Conference on Emergency Medicine in Seoul, Korea, a number of presentations and subsequent question-and-answer discussions centered on the increasingly important role of the emergency telecommunicator in the recognition of, response to, and management of OHCA. The shift in terminology from *dispatcher* to *telecommunicator* illustrates that these personnel do much more than simply send ambulances out on calls. Interfacing with callers through a variety of new technologies (including text, video, and apps), correctly identifying the OHCA case, notifying nearby citizen responders of OHCA cases, locating nearby automated external defibrillators and directing lay responders to them, and providing dispatcher-assisted CPR instructions are all important responsibilities of the telecommunicator. While the concept of dispatcher-assisted CPR is not new,[4] it has been limited until quite recently to coaching the caller by voice over the telephone by using a scripted set of step-by-step instructions. While it is relatively easy for the telecommunicator to ensure the proper compression rate by calling out a metronome count over the telephone, assessing and managing compression depth over the telephone is a much greater challenge. Several Asian nations are taking on this challenge using video-calling technology. A mobile app being introduced in Taiwan allows the telecommunicator to coach the lay rescuer's compression rate and depth through video conferencing.[5] A similar pilot project is underway in the dispatch center of Chiba prefecture, Japan (https://www.youtube.com/watch?v=UGfaVdXUzB0). Additionally, a device roughly the size and thickness of a credit card has been developed in Singapore that is placed between the sternum of the patient and the hands of the rescuer and provides real-time feedback on both CPR depth and rate.[6] This is an option for a rescuer who is trained in CPR and does not need telecommunicator instructions.

So, there is now a proposed optimal rate and depth combination, and researchers are working on ways to implement it in the field once it is validated or refined. How best to validate the findings here? While several other large OHCA databases exist, including both national and international regis-