The Influence of Scenario-Based Training and Real-Time Audiovisual Feedback on Out-of-Hospital Cardiopulmonary Resuscitation Quality and Survival From Out-of-Hospital Cardiac Arrest

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Study objective: We assess whether an initiative to optimize out-of-hospital provider cardiopulmonary resuscitation (CPR) quality is associated with improved CPR quality and increased survival from out-of-hospital cardiac arrest.

Methods: This was a before-after study of consecutive adult out-of-hospital cardiac arrest. Data were obtained from out-of-hospital forms and defibrillators. Phase 1 included 18 months with real-time audiovisual feedback disabled (October 2008 to March 2010). Phase 2 included 16 months (May 2010 to September 2011) after scenario-based training of 373 professional rescuers and real-time audiovisual feedback enabled. The effect of interventions on survival to hospital discharge was assessed with multivariable logistic regression. Multiple imputation of missing data was used to analyze the effect of interventions on CPR quality.

Results: Analysis included 484 out-of-hospital cardiac arrest patients (phase 1 232; phase 2 252). Median age was 68 years (interquartile range 56-79); 66.5% were men. CPR quality measures improved significantly from phase 1 to phase 2: Mean chest compression rate decreased from 128 to 106 chest compressions per minute (difference −23 chest compressions; 95% confidence interval [CI] −26 to −19 chest compressions); mean chest compression depth increased from 1.78 to 2.15 inches (difference 0.38 inches; 95% CI 0.28 to 0.47 inches); median chest compression fraction increased from 66.2% to 83.7% (difference 17.6%; 95% CI 15.0% to 20.1%); median preshock pause decreased from 26.9 to 15.5 seconds (difference −11.4 seconds; 95% CI −15.7 to −7.2 seconds), and mean ventilation rate decreased from 11.7 to 9.5/minute (difference −2.2/minute; 95% CI −3.9 to −0.5/minute). All-rhythms survival increased from phase 1 to phase 2 (20/231, 8.7% versus 35/252, 13.9%; difference 5.2%; 95% CI −0.4% to 10.8%), with an adjusted odds ratio of 2.72 (95% CI 1.15 to 6.41), controlling for initial rhythm, witnessed arrest, age, minimally interrupted cardiac resuscitation protocol compliance, and provision of therapeutic hypothermia. Witnessed arrests/shockable rhythms survival was 26.3% (15/57) for phase 1 and 55.6% (20/36) for phase 2 (difference 29.2%; 95% CI 9.4% to 49.1%).

Conclusion: Implementation of resuscitation training combined with real-time audiovisual feedback was independently associated with improved CPR quality, an increase in survival, and favorable functional outcomes after out-of-hospital cardiac arrest. [Ann Emerg Med. 2013;62:47-56.]

Please see page 48 for the Editor's Capsule Summary of this article.

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INTRODUCTION

Background and Importance

Communities in North America report wide disparities in outcomes from out-of-hospital cardiac arrest.[1,2] Although many report poor outcomes, several have achieved significantly higher survival rates[1,2] that are likely a result of multiple factors, with one possible component being out-of-hospital cardiopulmonary resuscitation (CPR) quality. There is preclinical and clinical evidence demonstrating that high-quality CPR (defined by the hemodynamically important components chest compression depth,[3-7] chest compression fraction,[8-13] preshock pause,[14-16] chest compression release velocity ["recoil"],[17-19] chest compression rate,[13,20] and ventilation[21]) improves outcomes. Although the 2010 American Heart Association (AHA) Guidelines place a clear emphasis on minimally interrupted, high-quality CPR, it remains to be determined whether individual communities can improve

Editor's Capsule Summary

What is already known on this topic

Despite decades of cardiac arrest research, functional survival after out-of-hospital cardiac arrest has not improved substantially.

What question this study addressed

Whether a "bundle" of a cardiopulmonary resuscitation training program emphasizing performance metrics and the use of real-time audiovisual feedback improves survival for out-of-hospital cardiac arrest victims.

What this study adds to our knowledge

In this before-after trial of 484 patients, unadjusted survival to discharge with favorable functional outcomes was 6.5% in the before group and 10.8% (difference 4.2%; 95% confidence interval [CI] −0.8% to 9.2%) after implementation of the bundle, and the adjusted odds ratio was 2.69 (95% CI 1.04 to 6.94).

How this is relevant to clinical practice

Within the limitations of a study design that is vulnerable to temporal confounding, this study suggests that this approach might be beneficial.

outcomes by systematically improving the CPR quality delivered by out-of-hospital providers.

In addition to novel approaches to CPR training, real-time audiovisual feedback has been shown to improve CPR quality in actual arrest scenarios both inside and outside the hospital.[6,7,22,23] Hostler et al[24] showed improvement in CPR quality metrics but not outcomes when real-time audiovisual feedback was used in the out-of-hospital setting. Edelson et al[6] demonstrated that real-time audiovisual feedback used for inhospital arrests improved CPR quality and increased rates of return of spontaneous circulation. For inhospital training, Wayne et al[25,26] and Wayne and McGaghie[27] showed significant improvement in CPR performance with simulations and a team approach.

Goals of This Investigation

Our a priori hypothesis was that an out-of-hospital initiative aimed at improving CPR quality by implementing (1) scenario-based CPR training, emphasizing a team approach to resuscitation and the importance of CPR quality metrics, and (2) real-time audiovisual feedback during CPR would improve CPR quality and survival from out-of-hospital cardiac arrest.

MATERIALS AND METHODS

Setting

Data were collected from a single fire-based emergency medical services (EMS) agency located in Mesa, AZ, which responds to a suburban population of 439,000 residents, with approximately 70,000 911 calls annually.[28] The agency includes 19 fire stations staffed by 202 emergency medical technician (EMT)-paramedics and 171 EMT-basics. A typical responding crew includes 2 EMT-paramedics and 2 EMT-basics. Additionally, a privately contracted ambulance company assists the fire-based rescuers with patient transport to hospitals. The Mesa Fire/Medical Department participates in the statewide cardiac resuscitation public health initiative called "SHARE—Save Hearts in Arizona Registry and Education."[29] This department has used an innovative minimally interrupted cardiac resuscitation protocol as their standard approach to adult out-of-hospital cardiac arrest from suspected cardiac cause since 2006. Minimally interrupted cardiac resuscitation has been previously described.[10]

Out-of-hospital cardiac arrest has been designated a major public health problem by the Arizona Department of Health Services. SHARE is the designated public health program created to measure response to out-of-hospital cardiac arrest and improve outcomes. Thus, the SHARE Program initiatives and its data collection are exempt from the Health Insurance Portability and Accountability Act. By virtue of SHARE being a health department–sponsored public health initiative, the Arizona Department of Health Services' Human Subjects Review Board and the University of Arizona institutional review board have determined that neither the interventions nor their evaluation constitutes human subjects research and have approved the publication of deidentified data.

Study Design and Selection of Participants

This is a prospective, before-after, observational cohort study of consecutive adult patients (aged ≥18 years) with out-of-hospital cardiac arrest of presumed cardiac cause who had out-of-hospital initiation of CPR. Cases were excluded from analysis if resuscitation was not initiated, the patient had a do-not-resuscitate order, arrest was witnessed by EMS, or the cause of the arrest was presumed to be noncardiac.

Interventions

Eighteen months' worth of baseline CPR quality and outcome data (October 7, 2008, to March 31, 2010) were collected during phase 1 (before). Real-time audiovisual feedback was not enabled during phase 1. The subsequent intervention included 2 hours of didactic teaching, along with 2 hours of team-centered psychomotor practice using scenario-based training, and activation of real-time audiovisual feedback. Didactic education and scenario-based training repeatedly and explicitly emphasized a team approach to resuscitation and meticulous compliance with the parameters of high-quality CPR within their minimally interrupted cardiac resuscitation protocol. Providers were educated about specific positioning and the role of each team member in a "pit crew" model of resuscitation (Appendix E1, available online at http://www.annemergmed.com), with the intent that this model would be used during actual resuscitations. The prime importance of uninterrupted, high-quality chest compressions was stressed and

the "compressor" was trained to have an unobstructed view of the defibrillator to enhance the effectiveness of real-time audiovisual feedback. In addition to the initial training, 10-minute videos were shown for both 2- and 4-provider crews to reinforce the patterned approach to resuscitation (see http://azdhs.gov/azshare/ccr_share.htm). Providers were specifically trained to avoid excessive ventilation (both rate and volume) and were educated to use the CPR interval timer (on the defibrillator) to space ventilations properly (ie, deliver 1 ventilation every 6 seconds). The training emphasized the importance of applying the combination defibrillator pads/accelerometer without interrupting compressions.

The monitor-defibrillator used in this study provides real-time audiovisual feedback through both audio and visual prompts. The visual display allows the compressor to see multiple, real-time, compression-to-compression quality parameters, including absolute compression depth, absolute compression rate, and a measure that includes a weighted summary analysis of depth, rate, and compression fraction (Appendix E1, available online at http://www.annemergmed.com). When compressions are discontinued for at least 3 seconds, an idle timer is prominently displayed, reminding the compressor to resume CPR. Rate and depth measurements are displayed numerically on the monitor. If compressions are performed outside of the target depth or rate (ie, depth <2 inches, rate <90 or >120 compressions/minute), the parameter label (rate or depth) and its numeric value are illuminated with a distinct red highlight that serves as a visual "alarm." The text "Fully Release" is automatically displayed every 30 seconds. An audio metronome, set to 100 compressions per minute, sounds any time compressions are performed. All other audio prompts related to CPR quality (eg, "push harder," "good compressions") remained disabled in both phases. The "charge during CPR" feature was enabled during phase 2 (after) to automatically charge the defibrillator before the end of each 2-minute chest compression interval, with the goal of minimizing compression interruptions while waiting for the defibrillator to charge.

On April 6, 2010, a 4-hour training session was conducted with 9 "master trainers," who later trained the remaining 364 providers between April 7, 2010, and April 29, 2010. Phase 2 began on May 27, 2010, after training was completed and the real-time audiovisual feedback and new software were enabled on the monitor-defibrillators.

Methods of Measurement

Chest compression quality was measured during resuscitation with a monitor-defibrillator (E-series; ZOLL Medical, Chelmsford, MA) with Food and Drug Administration–approved accelerometer-based technology that measures chest compression fraction, depth, rate, and rate of recoil. The accelerometer is integrated into defibrillator pads that are used for patient monitoring and defibrillation. The defibrillator units are equipped with Food and Drug Administration–approved technologies that provide real-time audiovisual feedback on the quality of compressions.

Chest compression fraction was measured as the percentage of time compressions were performed (when indicated) throughout the entire resuscitation event. Compressions were considered indicated any time a patient was without spontaneous pulses (as documented in the patient care report and confirmed by ECG) during out-of-hospital care (ie, excluded data after arrival at the emergency department [ED]) and when compression data were valid (ie, the pads were connected and adhered properly). Time was not allotted for the performance of interventions such as ventilation, defibrillation, or intubation (ie, the timer continued to run during all interventions). Preshock pause was calculated as the number of seconds without ongoing compressions before shock delivery for patients with a shockable rhythm (ventricular fibrillation/tachycardia). "Ongoing" compressions were defined as at least 5 back-to-back compressions. Recoil was measured as the peak chest compression release velocity (milli-inches/second) during each compression. Ventilation rates were averaged for each minute of postintubation EMS care without return of spontaneous circulation. Ventilations were captured with the end-tidal CO_2 waveform from a sidestream $ETCO_2$ adaptor (LoFlo Sidestream CO_2 Module; Philips/Respironics; Wallingford, CT), which was placed after intubation. $ETCO_2$ values were averaged for each case from all out-of-hospital minutes containing valid $ETCO_2$ data without return of spontaneous circulation. Minutes with $ETCO_2$ values greater than 40 mm Hg were not averaged because they may have been associated with return of spontaneous circulation.

The SHARE program has been previously described in detail and includes a voluntary Utstein-style out-of-hospital cardiac arrest EMS database linked with inhospital postarrest process and outcome data from hospitals.[29] Data collected from participating EMS systems and hospitals are entered into an ACCESS 2007 (Microsoft Corporation, Redmond WA) database maintained on a secure server at the University of Arizona. The SHARE database is mapped to the Cardiac Arrest Registry to Enhance Survival Registry, the largest national out-of-hospital cardiac arrest reporting system (http://www.mycares.net). The SHARE database has multiple logic constraints for out-of-hospital cardiac arrest data elements. For example, arrival in the ED cannot occur before collapse. When values outside the realm of physical possibility are encountered or are missing for any of the Utstein data elements, secondary and tertiary data sources (such as private ambulance transporting first care reports or hospital ED records) are referenced, which allows the backfilling of missing data elements or confirmation of suspected erroneous elements. Additionally, each record goes through a manual review before being committed to the data set. Minimally interrupted cardiac resuscitation protocol compliance was determined by all 4 components: 200 preshock chest compressions, 200 postshock chest compressions, delayed intubation attempt for 3 cycles of 200 compressions and rhythm analysis, and patients having received intravenous epinephrine in the first or second cycle of chest compressions.

Outcome Measures

The main outcome variables were survival to hospital discharge, favorable functional outcome (Cerebral Performance Category score of 1 or 2) as measured at hospital discharge by formally trained hospital personnel, and CPR quality. These outcomes were compared between study phases (phase 1 versus phase 2), the main independent variable. Additional confounders and risk factors considered were initial cardiac rhythm on EMS arrival (initial rhythm), EMS dispatch-to-on-scene arrival interval (response interval), age, sex, location of arrest, witnessed versus unwitnessed arrest, provision of bystander CPR, the use of therapeutic hypothermia, and minimally interrupted cardiac resuscitation protocol compliance.

CPR quality measures included the following: chest compression fraction, depth, rate, and release velocity; preshock and postshock pause; and ventilation rate.

Primary Data Analysis

For univariate analyses, Fisher's exact test (proportions), *t* test (means), or Kruskal-Wallis test (medians) was used, with $\alpha=.05$. Summary statistics are reported as percentages, means with 95% confidence intervals (CIs), and medians with interquartile ranges. Absolute differences with 95% CIs are reported for comparisons of means, medians, and proportions. To calculate crude and adjusted odds ratios (ORs) for survival and favorable functional outcome, we used multivariable mixed-effects logistic regression (xtmelogit, Stata version 12.1; StataCorp, College Station, TX), with the hospital providing final care as the random effect and all patients not transported treated as a single cluster. Covariates were included in the final model if the associated *P* value from the likelihood ratio χ^2 test was less than or equal to .05 or if they were judged to be a significant confounder (inclusion of covariate changed the coefficient for main risk factor >10%) of the relationship between the outcome variable and our main independent variable, pre- versus postperiod. We calculated the Hosmer-Lemeshow goodness-of-fit statistic and the area under the receiver operating characteristics curve for each final multivariable model, using the predicted probabilities incorporating the random effects from the mixed-effects modeling. We also explored model diagnostics for the mixed-effects model by examining final model residuals (Pearson, deviance, and Anscombe) to identify overly influential covariate patterns or outliers that could represent miscoded cases. We also examined model diagnostics (leverage, deviance, etc) for all final models, assuming no random effects (ordinary logistic regression), as an additional approach to identifying potential outliers. Fractional polynomial regression was used to examine the linear relationship of continuous variables with the outcome variables in the logit scale.

Univariate multiple imputation methods and approaches were explored to handle missing values for the chest compression quality metrics (mean depth, mean rate, recoil, compression fraction, percentage of compression ≥2 inches, mean preshock and postshock pauses), using the following variables as covariates for imputation: survival to discharge, pre/postperiod, out-of-hospital return of spontaneous circulation, age, sex, witnessed arrest, shockable rhythm (ventricular fibrillation/ventricular tachycardia), bystander CPR, location of arrest, and EMS response interval. The pattern of missing data was first explored with univariate analyses to examine associations between a patient's having missing data and study covariates. Because all CPR quality data were missing for a case with any missing CPR quality data, each CPR quality metric was imputed independently. Twenty imputed data sets were created for analysis with linear regression ("mi impute regress" with random number seed "4987"), and all chest compression quality metrics were compared between phase 1 and phase 2 with either linear or median regression, as appropriate, with associated 95% CIs for differences. Ventilation and $ETCO_2$ data were not amenable to imputation because we could not identify the time of intubation for all patients and thus were not able to determine which patients were intubated before sustaining return of spontaneous circulation. Thus, ventilation data are compared between the phase 1 and phase 2 with nonimputed data.

We conducted a post hoc analysis to identify potential secular trends or a Hawthorne effect in all-rhythms survival and positive functional outcomes by dividing phase 1 into halves and comparing outcomes (survival and functional outcome) between them. In addition, we investigated the proportion of patients who were not transported to a hospital but were treated by EMS on scene in phase 1 versus phase 2 to assess whether this was associated with any outcome differences between periods. All statistical analyses and imputations were performed with Stata (version 12.1).

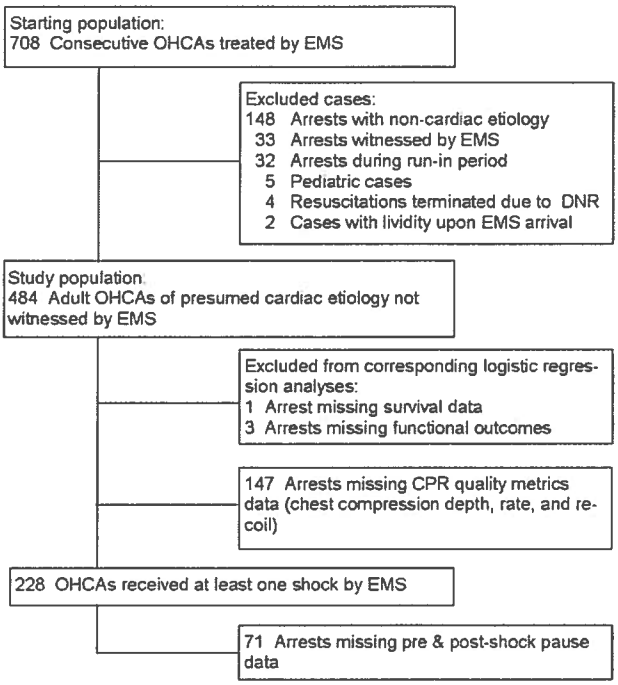

Figure. Study population inclusion/exclusion flow chart. *OHCA*, Out-of-hospital cardiac arrest; *DNR*, do not resuscitate.

Table 1. Demographics and outcomes by study period.

Characteristic	Overall	Preperiod	Postperiod	Absolute Difference to Post–Pre (95% CI)
Total, No. (%)	484 (100)	232 (47.9)	252 (52.1)	NA
Age, median (IQR), y	68 (56–79)	69 (59–79)	68 (55–79)	−1 (−5 to 3)
Male sex, No. (%)	322 (66.5)	149 (64.2)	173 (68.7)	4.4 (−4.0 to 12.8)
Witnessed arrest, No. (%)	192 (39.8)	98 (42.2)	94 (37.3)	−4.9 (−13.7 to 3.8)
Shockable rhythm on EMS arrival, No. (%)	150 (31.0)	79 (34.1)	71 (28.2)	−5.9 (−14.1 to 2.4)
Provision of bystander CPR, No. (%)	192 (39.7)	102 (44.0)	90 (35.7)	−8.3 (−17.0 to 0.5)
Location of arrest, No. (%)				
Residential	353 (72.9)	167 (72.0)	186 (73.8)	1.8 (−6.1 to 9.8)
Medical facility	68 (14.1)	32 (13.8)	36 (14.3)	0.5 (−5.7 to 6.7)
Public	63 (13.0)	33 (14.2)	30 (11.9)	−2.3 (−8.3 to 3.7)
EMS response interval, median (IQR), min	5 (4–6)	5 (4–6)	5 (4–6)	0
Use of TH, No. (%)	52 (10.7)	23 (9.9)	29 (11.5)	1.6 (−3.9 to 7.1)
MICR protocol compliance (complete vs partial), No. (%)	375 (77.5)	155 (66.8)	220 (87.3)	20.5 (13.2 to 27.8)
Return of spontaneous circulation, No. (%)	113 (23.4)	58 (25.0)	55 (21.8)	−3.2 (−10.7 to 4.4)
Survival to hospital discharge for all rhythms, No./total (%)*	55/483 (11.4)	20/231 (8.7)	35/252 (13.9)	5.2 (−0.4 to 10.8)
Survival to hospital discharge for witnessed arrests, shockable rhythms, No./total (%)*	35/93 (37.6)	15/57 (26.3)	20/36 (55.6)	29.2 (9.4 to 49.1)†
Favorable functional outcome (CPC score=1 or 2) for all rhythms, No./total (%)†	42/481 (8.7)	15/230 (6.5)	27/251 (10.8)	4.2 (−0.8 to 9.2)†
Favorable functional outcome (CPC score=1 or 2) for witnessed arrests, shockable rhythms, No./total (%)†	27/91 (29.7)	11/56 (19.6)	16/35 (45.7)	26.1 (6.6 to 45.6)

NA, Not applicable; *IQR*, interquartile range; *TH*, therapeutic hypothermia; *MICR*, minimally interrupted cardiac resuscitation; *CPC*, cerebral performance category.
*Missing 1 survival outcome.
†Missing 3 functional outcomes.
‡Discrepancy between the absolute difference and the subtraction of pre and post values is due to rounding.

RESULTS

Characteristics of Study Subjects

A total of 232 consecutive, adult, non-EMS-witnessed, out-of-hospital cardiac arrests of presumed cardiac cause with resuscitation initiated in the field occurred in phase 1 and 252 in phase 2 (see the Figure for inclusion/exclusion flow chart). Among the 484 patients in this analysis, 1 was missing survival data and 3 were missing functional outcome scores. A total of 147 patients (30.4%) were missing CPR quality data, and 71 of 228 patients (31.1%) who received shocks were missing pre/postshock pause data. A comparison of demographics and standard Utstein data elements is presented in Table 1. Patient characteristics of phase 1 and phase 2 were similar. Overall, 113 of 484 patients (23.4%) achieved return of spontaneous circulation in the out-of-hospital setting and 55 patients (11.4%) survived to hospital discharge. Of patients with a witnessed arrest and a shockable rhythm, 35 of 93 (37.6%) survived to hospital discharge.

Main Results

Table 2 shows survival and favorable functional outcomes across study periods, along with crude and adjusted ORs. Survival increased from 8.7% (20/231) in phase 1 to 13.9% (35/252) in phase 2 (absolute difference 5.2; 95% CI −0.4 to 10.8), with a crude OR of 1.73 (95% CI 0.93 to 3.21) and an adjusted OR of 2.72 (95% CI 1.15 to 6.41), controlling for witnessed arrest, initial rhythm, provision of therapeutic hypothermia, age, and minimally interrupted cardiac resuscitation protocol compliance. Favorable functional outcome increased from 6.5% in phase 1 to 10.8% in phase 2 (absolute difference 4.2%; 95% CI −0.8% to 9.2%), with a crude OR of 1.76 (95% CI 0.88 to 3.52) and an adjusted OR of 2.69 (95% CI 1.04 to 6.94), adjusting for witnessed arrest, provision of therapeutic hypothermia, age, and minimally interrupted cardiac resuscitation protocol compliance. Age as a continuous variable was linear in the logit scale, as determined by fractional polynomial regression. The intraclass correlation (cluster effect) between both survival and favorable functional outcome and hospital was 0.125 (95% CI 0.018 to 0.528) and 0.140 (95% CI 0.023 to 0.532), respectively, and the likelihood ratio test P value comparing mixed effects versus ordinary logistic regression was .02 and .01, respectively, indicating a significant cluster effect and justifying mixed-effects logistic regression. For the final multivariable model for survival to discharge, the Hosmer-Lemeshow goodness of fit P value was .85 and area under the receiver operating characteristics curve for survival was 0.913. For the final model for positive functional outcome, the Hosmer-Lemeshow goodness of fit P value was .30 and the area under the receiver operating characteristics curve was 0.920. In witnessed arrests with a shockable rhythm, survival and functional outcomes improved significantly from phase 1 to phase 2 (survival 26.3% [15/57] to

Table 2. Final logistic regression models for survival and neurologic outcomes (all rhythms and witnessed/shockable).

	Survival to Hospital Discharge and Associated OR (95% CI)				Favorable Functional Outcome (CPC score=1 or 2), OR (95% CI)			
Characteristic	**No./Total (%)**	**Absolute Difference (95% CI)**	**Crude OR (95% CI)**	**Adjusted OR (95% CI)***	**No./Total (%)**	**Absolute Difference (95% CI)**	**Crude OR (95% CI)**	**Adjusted OR (95% CI)***
Study period								
Pre	20/231 (8.7)	5.2 (−0.4 to 10.8)	1 [Reference]	1 [Reference]	15/230 (6.5)	4.2 (−0.8 to 9.2)	1 [Reference]	1 [Reference]
Post	35/252 (13.9)		1.73 (0.93 to 3.21)	2.72 (1.15 to 6.41)	27/251 (10.8)		1.76 (0.88 to 3.52)	2.69 (1.04 to 6.94)
Witnessed arrest								
No	13/291 (4.5)	17.4 (11.1 to 23.7)	1 [Reference]	1 [Reference]	10/291 (3.4)	13.4 (7.7 to 19.1)	1 [Reference]	1 [Reference]
Yes	42/192 (21.9)		4.19 (2.12 to 8.30)	4.00 (1.72 to 9.28)	32/190 (16.8)		4.01 (1.86 to 8.65)	3.73 (1.45 to 9.59)
Initial rhythm								
Nonshockable	12/334 (3.6)	25.3 (17.7 to 32.8)	[Reference]	1 [Reference]	8/334 (2.4)	20.7 (13.7 to 27.7)	1 [Reference]	1 [Reference]
VF/VT	43/149 (28.9)		7.33 (3.59 to 14.99)	5.88 (2.59 to 13.36)	34/147 (23.1)		8.53 (3.68 to 19.73)	6.22 (2.43 to 15.92)
Use of TH								
No	25/431 (5.8)	51.9 (38.3 to 65.5)	1 [Reference]	1 [Reference]	18/429 (4.2)	42.0 (28.3 to 55.6)	1 [Reference]	1 [Reference]
Yes	30/52 (57.7)		14.60 (6.98 to 30.51)	11.87 (5.16 to 27.33)	24/52 (46.2)		13.46 (6.13 to 29.52)	9.26 (3.87 to 22.12)
Age, per year			0.97 (0.95 to 0.99)	0.98 (0.95 to 1.00)			0.96 (0.93 to 0.98)	0.97 (0.94 to 1.00)
MICR protocol compliance								
Partial	10/108 (9.3)	2.7 (−3.6 to 9.1)	1 [Reference]	1 [Reference]	10/108 (9.3)	−0.7 (−6.8 to 5.5)	1 [Reference]	1 [Reference]
Complete	45/375 (12.0)		2.02 (0.95 to 4.28)	1.16 (0.46 to 2.93)	32/373 (8.6)		1.31 (0.60 to 2.86)	0.62 (0.23 to 1.63)

VF, Ventricular fibrillation; *VT*, ventricular tachycardia.
*Adjusted for all variables listed in this table in final model (likelihood ratio *P* value for all variables included in final model ≤.05 or judged a significant confounder).

55.6% [20/36]; absolute difference 29.2% [95% CI 9.4% to 49.1%]; adjusted OR 3.81 [95% CI 1.23 to 11.80]; functional outcome 19.6% [11/56] to 45.7% [16/35]; absolute difference 26.1% [95% CI 6.6% to 45.6%], adjusted OR 3.83 [95% CI 1.11 to 13.13]). Adjusted ORs for both survival (Hosmer-Lemeshow *P* value=.89; area under receiver operating characteristics curve 0.811) and positive functional outcome (Hosmer-Lemeshow *P* value=.40; area under receiver operating characteristics curve=0.784) in witnessed arrests with a shockable rhythm were adjusted for provision of therapeutic hypothermia, age, and minimally interrupted cardiac resuscitation protocol compliance. Model diagnostic analyses for survival and functional outcome models (for all rhythms and witnessed shockable rhythms) showed no extreme outliers or overly influential covariate patterns.

Table 3 shows a comparison of the CPR quality metrics across study periods for both nonimputed and imputed data sets. All metrics showed a statistically significant improvement from phase 1 to phase 2 for both imputed and nonimputed data. Comparison of the imputed and nonimputed data sets showed that CPR quality metrics were generally lower in the nonimputed data set and that excluding cases with missing CPR quality data overestimates the difference in CPR quality metrics between the pre- and postperiod. Comparison of study variables between patients with complete and missing CPR quality metrics data is shown in Table 4. The association between missing data and the various covariates appears consistent with the underlying assumption of the multiple imputation method that data are "missing at random." This does not mean that there are no variables that are predictive of missing CPR quality metric data, but instead that the variables that are associated with missing data are included in the multiple imputation models.[30,31] Cases with missing CPR quality metrics had a significantly lower proportion of witnessed arrests, therapeutic hypothermia use, and return of spontaneous circulation than cases with quality metrics data (Table 4). Also, cases with missing CPR quality metrics data had a significantly higher proportion of phase 1 cases than cases with no missing CPR quality data. Although not statistically significant, cases with missing CPR quality metric data had fewer survivors to discharge, fewer positive functional outcomes, lower provision of bystander CPR, fewer shockable rhythms on EMS arrival, and higher median age.

Our post hoc analysis for potential secular trends or a Hawthorne effect showed that neither survival nor functional outcome increased from the first half of phase 1 to the second half of phase 1 (survival 10/109 [9.2%] to 10/122 [8.2%]; absolute difference −1.0% [95% CI −8.3% to 6.3%]; favorable functional outcome 9/109 [8.3%] to 6/121 [5.0%]; absolute difference −3.3% [95% CI −9.8% to 3.2%]). The proportion of patients who were not transported to a hospital but were treated by EMS on scene did not differ between phase

Table 3. CPR quality metric comparisons by study period for imputed and nonimputed data set.

CPR Quality Metrics	Preintervention		Postintervention		Absolute Difference, Post-Pre (95% CI) for Imputed Data Set*
	Missing Data Excluded	Imputed Data Set	Missing Data Excluded	Imputed Data Set	
	(N=146)	(N=232)	(N=191)	(N=252)	
Mean chest compression depth (inches), mean (95% CI)†	1.72 (1.66 to 1.80)	1.78 (1.71 to 1.85)	2.14 (2.10 to 2.20)	2.15 (2.09 to 2.22)	0.38 (0.28 to 0.47)
Mean chest compression rate, compressions/min, mean (95% CI)†	126 (124 to 128)	128 (125 to 131)	105 (103 to 107)	106 (103 to 108)	−23 (−26 to −19)
Mean chest compression recoil, milli-inches/s, mean (95% CI)†	1,174 (1,129 to 1,220)	1,205 (1,160 to 1,250)	1,306 (1,274 to 1,339)	1,315 (1,276 to 1,355)	110 (51 to 170)
Chest compression fraction, %, median (95% CI)**	65.6 (63.7 to 67.6)	66.2 (64.1 to 68.3)	83.7 (82.0 to 85.4)	83.7 (82.1 to 85.4)	17.6 (15.0 to 20.1)
Percentage of compression ≥2 inches, median (95% CI)**	14.8 (7.5 to 22.1) (n=82)	22.5 (14.0 to 31.1) (n=121)	67.5 (61.1 to 73.9) (n=75)	67.1 (61.2 to 73.0) (n=107)	44.6 (34.2 to 54.9)
Preshock pauses, s, median (95% CI)**	25.4 (22.4 to 28.3)	26.9 (24.0 to 29.9)	14.8 (11.7 to 18.0)	15.5 (12.3 to 18.7)	−11.4 (−15.7 to −7.2)
Postshock pauses, s, median (95% CI)**	17.3 (15.3 to 19.3) (n=52)	18.2 (15.8 to 20.6) NA	6.7 (4.6 to 8.8) (n=63)	7.2 (4.7 to 9.7) NA	−11.0 (−14.4 to −7.6)
Ventilation rate, ventilations/s, mean (95% CI)†	11.7 (10.3 to 12.9) (n=48)	NA NA	9.5 (8.4 to 10.6) (n=60)	NA NA	−2.2 (−3.9 to −0.5)§
$ETCO_2$, mm Hg, mean (95% CI)†	17.1 (14.5 to 19.7)	NA	21.9 (19.5 to 24.2)	NA	4.7 (1.2 to 8.3)§

NA, Not applicable.
*Differences are based on regression and rounded after analysis and may differ slightly from subtraction of rounded pre and post medians and means.
†Linear (least squares) regression results.
§From analysis of nonimputed data set only.
**Median regression results.

1 and phase 2 (81/232 [34.9%] and 92/252 [36.5%], respectively; absolute percentage difference 1.6% [95% CI −6.9% to 10.1%]).

LIMITATIONS

There are limitations to our study. First, this study was not randomized. We implemented an intervention targeting specific CPR quality metrics and improving survival from out-of-hospital cardiac arrest and as such did not believe it ethical to randomize the intervention. Thus, we chose a large, well-controlled, before-after observational study design as the best feasible methodology. This approach precludes claiming definitive causation and introduces the possibility that unknown confounders or the Hawthorne effect might, in part, have led to the improved outcomes measured. However, when we analyzed the preperiod (phase 1), we did not find statistical evidence of secular trend or the Hawthorne effect for survival or favorable functional outcomes. Second, we evaluated only 1 busy suburban EMS agency, using 1 type of CPR measurement and feedback device. The external validity and reproducibility of these results in other EMS systems using different devices remain unknown. Third, there were some missing CPR data elements, as is common in out-of-hospital CPR quality studies. However, the majority of missing data were for individual CPR quality metrics, and we used multiple imputation (with the exception of ventilations/minute) to evaluate a change in these metrics from phase 1 to phase 2. We believe this greatly reduced the chance of systemic bias in our study.[30,31] However, it is still possible that there were unmeasured confounders we did not account for that influenced our results.

Only 1 case was missing data for the main outcome measure of survival, and we were unable to obtain functional outcomes for only 3 subjects. Finally, in this analysis we are unable to determine the relative influence of each intervention (eg, didactic education, scenario-based training, real-time audiovisual feedback) or of each specific component of CPR quality (eg, rate, depth, pre/postshock pause, CPR fraction, ventilation rate). The operational, logistic, cognitive, and psychomotor aspects of resuscitation are complex and interrelated and may require the entire "bundle" of interventions to improve CPR quality enough to lead to improved outcome.

DISCUSSION

The thrust of the current literature supports the concept that CPR quality is an important factor in survival from out-of-hospital cardiac arrest.[3,21,32,35] This issue is strongly emphasized in the 2010 AHA guidelines.[32] This analysis demonstrates that a systematic and comprehensive approach to improving out-of-hospital CPR quality in a large EMS system was associated with achieving the 2010 AHA guideline recommendations for CPR quality, an increase in survival to hospital discharge, and favorable functional outcomes.

These results demonstrate an improvement in CPR quality performance in line with the 2010 AHA guidelines for all

Table 4. Demographic and outcome comparisons between patients with CPR quality metrics data and those with missing data.

Characteristic	Cases With Missing CPR Depth, Rate, Recoil, and Compression Fraction		Cases Not Missing CPR Quality Metrics Data		Absolute Difference, Not Missing-Missing (95% CI)
	N	%	N	%	
Total, No. (%)	147	30.4	337	69.6	NA
Study period, No. (%)					
Pre (phase 1)	86	58.5	146	43.3	15.2 (5.6 to 24.7)
Post (phase 2)	61	41.5	191	56.7	
Age, median (IQR), y	71	(58–80)	67	(56–78)	−4 (−8 to 0)
Male sex, No. (%)	91	61.9	231	68.6	6.6 (−2.6 to 15.9)
Witnessed arrest, No. (%)	49	33.3	144	42.7	9.4 (0.1 to 18.7)
Shockable rhythm on EMS arrival, No. (%)	39	26.5	111	32.9	6.4 (−2.3 to 15.1)
Provision of bystander CPR, No. (%)	53	36.1	139	41.3	5.2 (−4.2 to 14.6)
Location of arrest, No. (%)					
Residential	105	71.4	248	73.6	2.2 (−6.5 to 10.9)
Medical facility	25	17.0	43	12.8	−4.2 (−11.3 to 2.8)
Public	17	11.6	46	13.7	2.1 (−4.3 to 8.4)
EMS response interval, median (IQR), min	5	(4–6)	5	(5–6)	0
Use of therapeutic hypothermia, No. (%)	9	6.1	43	12.8	6.6 (1.4 to 11.9)
MICR protocol compliance, No. (%)	110	74.8	265	78.6	3.8 (−4.4 to 12.1)
Return of spontaneous circulation, No. (%)	19	12.9	94	27.9	15.0 (7.7 to 22.2)
Survival to hospital discharge for all rhythms, No./total (%)*	13/146	8.9	42/337	12.5	3.6 (−2.3 to 9.4)
Favorable functional outcome (CPC score=1 or 2) for all rhythms, No./total (%)†	10/145	6.9	32/336	9.5	2.6 (−2.6 to 7.8)

NA, Not applicable.
*One outcome missing.
†Three outcomes missing.

metrics and, most important, increased adjusted odds of survival and favorable functional outcome in our postintervention group (Tables 2 and 3). According to current understanding of the effects of CPR during cardiac arrest and the quality of CPR in most actual resuscitations, our findings are both biologically plausible and logical. For example, one major contributor to the low survival rates in most settings is prolonged inadequate myocardial and cerebral blood flow.[36-38] During resuscitation efforts, the forward blood flow generated by CPR is marginal, and as such, any pause in compressions or compressions of inadequate depth have a significant negative effect on both defibrillation success and survival.[5,36-38] Cardiac output is the major determinant of carbon dioxide delivery to the lungs during CPR. In our analysis, the higher $ETCO_2$ in phase 2 provides strong evidence for improved CPR quality during phase 2 and was likely the result of increased perfusion.

The recognition of the importance of continuous blood flow and the consequences of interrupting myocardial and cerebral perfusion has led to great interest in CPR quality.[32] Numerous animal and clinical studies have demonstrated that CPR quality (chest compression depth,[3-7] fraction,[8-13] preshock pause,[14-16] recoil,[17-19] chest compression rate,[13,20] and ventilation rate[21]) has a significant effect on cardiac arrest outcomes. In 2007, Kramer-Johansen et al[39] proposed a rationale for establishing common definitions and a reporting template for CPR metrics. Despite the understanding of the importance of high-quality CPR, most out-of-hospital cardiac arrest victims still do not receive optimal CPR.[17,21,33-35]

Previous investigators have shown that real-time audiovisual feedback can improve CPR quality.[6,7,22,23] Our findings are consistent with these previous investigations and strongly support the current emphasis that the 2010 AHA guidelines place on high-quality CPR as a means to improve survival.[32] Although causality cannot be proven according to a nonrandomized trial, to our knowledge, this is the first study to demonstrate an association between a dedicated CPR quality initiative using real-time audiovisual feedback and out-of-hospital cardiac arrest outcomes. Furthermore, it is the first report to show an association between performance of the 2010 AHA CPR quality metrics and increased survival.[32] The interventions, which included didactic education, scenario-based training, and real-time audiovisual feedback, were specifically aimed at particular CPR quality metrics. The training emphasized the importance of CPR quality, a team approach to resuscitation, and real-time audiovisual feedback.

Hostler et al[24] recently performed a large (1,586 subjects) cluster-randomized study within the Resuscitation Outcome Consortium to assess the effect of real-time audiovisual feedback on CPR quality and outcomes. Although they found improvements in CPR quality with feedback on compared with feedback off (compression fraction 66% versus 64%, respectively, $P=.02$; depth 40 mm versus 38 mm, $P=.005$; rate

103 versus 108, $P<.001$; percentage with incomplete release 10% versus 15%, $P<.001$), they did not find improvements in rates of return of spontaneous circulation (44% versus 45%) or survival to hospital discharge (11% versus 12%). And although the study by Hostler et al[24] showed statistical improvements in CPR quality, the effect sizes were small and of questionable clinical significance and CPR quality data were missing in 26% of patients. There are several fundamental differences between the study by Hostler et al[24] and ours. First, the current investigation included (1) dedicated didactic and scenario-based training emphasizing CPR quality metrics, in addition to real-time audiovisual feedback as part of a bundled approach to improving CPR quality; (2) a major focus on the optimal use of the feedback-capable defibrillator; (3) a specified "pit crew" team approach to resuscitation; and (4) multiple imputation to reduce the likelihood of bias caused by excluding cases with missing CPR process data. Additionally, we used a different feedback device and our training included a targeted and standardized approach to resuscitation, with a focus on maximizing CPR quality.

In this study of out-of-hospital cardiac arrest, a carefully targeted CPR training curriculum in conjunction with real-time audiovisual feedback was independently associated with achievement of the AHA 2010 guideline-recommended metrics for CPR quality and an increased likelihood of both survival to hospital discharge and favorable functional outcome.

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Author contributions: BJB, TFV, AES, JMT, GAS, and DWS conceived and designed the study. BJB, AES, JMT, SAC, TKM, JS, and GAS supervised the conduct of the study and data collection. BJB, US, and AES managed the data, including quality control. BJB, TFV, US, AES, and DWS provided statistical advice on study design and analyzed the data. TFV drafted the article, and all authors contributed substantially to its revision. BJB takes responsibility for the paper as a whole.

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Appendix E1.

A

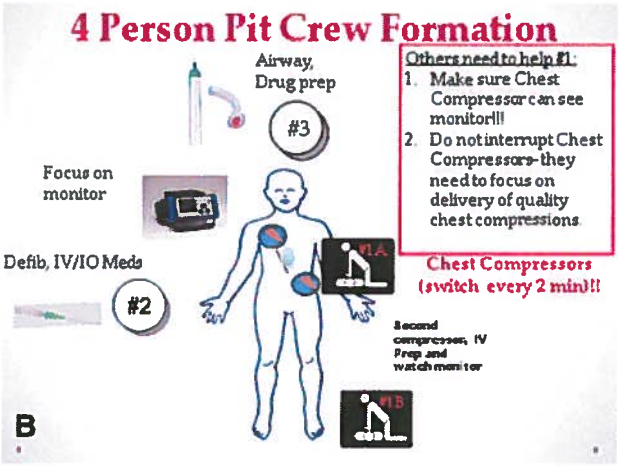

Figure E1. *A*, E Series Defibrillator Display with Real-Time Audiovisual Feedback Enabled (ZOLL Corporation, Chelmsford MA). *B*, Coordinated multiprovider resuscitation schematic.