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ORIGINAL RESEARCH

Causes of Chest Compression Interruptions During Out-of-Hospital Cardiac Arrest Resuscitation

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BACKGROUND: Interruptions in chest compressions contribute to poor outcomes in out-of-hospital cardiac arrest. The objective of this retrospective observational cohort study was to characterize the frequency, reasons, and duration of interruptions in chest compressions and to determine if interruptions changed over time.

METHODS AND RESULTS: All out-of-hospital cardiac arrests treated by the Seattle Fire Department (Seattle, WA, United States) from 2007 to 2016 with capture of recordings from automated external defibrillators and manual defibrillators were included. Compression interruptions >1 second were classified into categories using audio recordings. Among the 3601 eligible out-of-hospital cardiac arrests, we analyzed 74 584 minutes, identifying 30 043 pauses that accounted for 6621 minutes (8.9% of total resuscitation duration). The median total interruption duration per case decreased from 115 seconds in 2007 to 72 seconds in 2016 ($P<0.0001$). Median individual interruption duration decreased from 14 seconds in 2007 to 7 seconds in 2016 ($P<0.0001$). Among interruptions >10 seconds, median interruption duration decreased from 20 seconds in 2007 to 16 seconds in 2016 ($P<0.0001$). Cardiac rhythm analysis accounted for most compression interruptions. Manual ECG rhythm analysis and pulse checks accounted for 41.6% of all interruption time (median individual interruption, 8 seconds), automated external defibrillator rhythm analysis for 13.7% (median, 17 seconds), and manual rhythm analysis and shock delivery for 8.0% (median, 9 seconds).

CONCLUSIONS: Median duration of chest compression interruptions decreased by half from 2007 to 2016, indicating that care teams can significantly improve performance. Reducing compression interruptions is an evidence-based benchmark that provides a modifiable process quality improvement goal.

Key Words: cardiac arrest ■ cardiopulmonary resuscitation ■ defibrillation ■ emergency medical services

Out-of-hospital cardiac arrest (OHCA) is a major cause of mortality.[1] Survival is possible but relies on time-sensitive interventions that feature cardiopulmonary resuscitation (CPR) as the cornerstone. Minimally interrupted chest compressions are associated with greater coronary perfusion pressure and higher likelihood of return of spontaneous circulation and survival.[2–5] Conversely, prolonged interruptions in chest compressions are associated with poorer outcomes.[6] Hence, international guidelines recommend minimizing chest compression interruption as part of high-quality CPR.[7]

Compression interruptions are necessary to perform important tasks, such as rhythm checks and pulse checks. Longer interruptions have been attributed to moving patients, obtaining intravenous access, and performing endotracheal intubation.[8–10] Decreasing the number and duration of interruptions in chest

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CLINICAL PERSPECTIVE

What Is New?

- Cardiac rhythm analysis accounted for most interruptions in chest compressions in a high-performing emergency medical services system.
- Quality improvement efforts focused on reducing interruptions in chest compressions can result in high cardiopulmonary resuscitation performance.

What Are the Clinical Implications?

- High-performance cardiopulmonary resuscitation teams can deliver cardiopulmonary resuscitation fractions >90% in most resuscitation attempts by performing tasks such as airway management and vascular access without interrupting chest compressions.

Nonstandard Abbreviations and Acronyms

AED	Automated external defibrillator
BLS	Basic life support
CPR	Cardiopulmonary resuscitation
ECG	Electrocardiogram
EMS	Emergency medical services
EMT	Emergency medical technician
HP-CPR	High-performance cardiopulmonary resuscitation
IQR	Interquartile range
OHCA	Out-of-hospital cardiac arrest
SD	Standard deviation

compressions is a key performance goal and quality metric for emergency medical services (EMS) systems.

Few studies have comprehensively characterized chest compression interruption by EMS. We evaluated a large, population-based cohort of OHCAs to determine the distribution of causes, frequency, and duration of chest compression interruptions. We hypothesized that the duration of interruptions would decline over time because of ongoing quality improvement emphasis on minimizing interruptions in chest compressions.

METHODS

Data Availability Statement

The data and analytic methods that support the findings of this study are available from the corresponding author on reasonable request.

Study Design, Population, and Setting

The investigation was a retrospective cohort investigation of all people treated for OHCA by the Seattle Fire Department between January 1, 2007, and December 31, 2016. Treatment was defined by receipt of any chest compressions by Seattle Fire Department personnel. We excluded cases missing all defibrillator recordings. Cases with electrocardiographic rhythm recording but no audio recording were included as long as enough information (eg, chest wall impedance recording or audio recording from an automated external defibrillator [AED]) was available to determine when chest compressions were occurring. We also excluded children and cases without a single interruption in compressions as these patients were typically found to have pulses on the first pulse check or declared deceased before the initial 2-minute compressor rotation. The study was approved by the University of Washington Institutional Review Board, with waiver of informed consent.

The Seattle Fire Department is the sole provider of primary responding EMS in Seattle, WA.[11] The EMS system is a tiered response model. The first tier is provided by firefighters–emergency medical technicians (EMTs) who are trained in CPR and equipped with AEDs and arrive at the patient an average of 7 minutes

Table 1. Time Line for Development of High-Performance CPR

When	What
Fall 2003	Intensive CPR training at the beginning of every new paramedic training class
2004–2005	Clinical trial of AutoPulse mechanical CPR device: • Began training with Laerdal Skill Reporter manikins • Implemented 2 minutes of CPR before first AED analysis
December 2005	Begin implementation of "BLS continuous" CPR: • "BLS is responsible for CPR." • Eliminate 3 stacked shocks in favor of 1 shock • Compression rate 100/min • No compression interruption >10 s • Ventilations interposed between compressions 10:1 with or without endotracheal tube
April 2006	Paramedics precharge manual defibrillator before pausing compressions to view ECG rhythm
September 2010	Changed NO SHOCK protocol for LP500 to no further analysis or pulse checks every 2 minutes; LP500 reconfigured to accommodate new protocol
August 2011	BLS crews provided chest compressions while charging LP500
September 2014	Replaced LifePak 12 with LifePak 15 manual defibrillators
December 2014	LUCAS mechanical CPR device deployed to be used only during transport of patients with ongoing CPR

AED indicates automated external defibrillator; BLS, basic life support; CPR, cardiopulmonary resuscitation; and LP500, LifePak 500 AED.

after the 9-1-1 call is answered. The second-tier paramedics arrive an average of 4 minutes after the first tier and are trained in advanced life support, including ECG rhythm interpretation, manual defibrillation, placement of intravenous catheters, administration of medications, and endotracheal intubation. From the outset of resuscitation, EMS teams provide continuous chest compressions with a breath interposed every 10th compression.[12] Every 2 minutes, EMS providers are trained to interrupt compressions to assess rhythm to inform therapy (defibrillation, drug administration, or pulse check). Before and during the period of data collection, the EMS teams were trained to minimize chest compression interruptions. Interventions were implemented sequentially over the course of the 10-year study period (Table 1). Part of this training initiative involves quality improvement case review, whereby the crew receives a report that details interruptions and their causes. An example of a report is provided in Figure S1.

During the study period, the EMT firefighters used the LifePak 500 AED, from Physio-Control in Redmond, WA. The paramedics used either the LifePak 12 or LifePak 15, also from Physio-Control, in manual mode. All defibrillators record real-time audio, continuous ECG waveforms, and continuous transthoracic impedance. The defibrillator recordings are maintained in a secure electronic format for review.

Data Collection and Definitions

As part of quality improvement, the Seattle Fire Department maintains a registry of each treated OHCA. The registry includes demographic, circumstance, care, and outcome information and is organized according to the Utstein guidelines.[13] The defibrillator recordings were reviewed by a single coordinator using an abstraction form that recorded the timing of each start and stop of chest compressions and the associated cause of interruption.

Because the Seattle Fire Department uses a strategy of continuous compressions throughout resuscitation, regardless of placement of an endotracheal tube, an "interruption" was defined as any pause in chest compressions >1 second. Chest compression interruptions were classified into exclusive groups, appreciating that some interruptions may have been attributable to multiple causes (eg, rhythm analysis and pulse check).

Because the LifePak 500 AED may take >10 seconds to charge the capacitor for a shock, EMTs were trained to give 30 chest compressions while the AED was charging. Thus, EMTs paused compressions to allow the AED to analyze the rhythm while no one was touching the patient. This event was classified as an "AED analysis." Then, if a shock was recommended, compressions were resumed; and the shock was delivered during the next pause after 30 compressions without additional rhythm analysis or pulse check. This event was classified as an "AED shock." Sometimes, the EMTs paused compressions to check pulses without pushing the AED analysis button. Those events were classified as "pulse check."

Because audio recording was typically available, the reviewer of the recordings could classify the cause of compression interruptions. Sometimes during an interruption, the paramedics diagnosed a shockable rhythm and delivered a shock without anyone checking for pulses. Those events were classified as "rhythm analysis and shock." Other options included the following: "rhythm analysis and pulse check," often used if an organized rhythm was present; and "rhythm analysis alone," often used if asystole was diagnosed. If an interruption was unable to be classified into a cause because of missing audio recordings or difficulty interpreting an audio recording, then it was labeled as "unknown."

When >1 activity took place during an interruption in compressions, the event was classified using all of the activities during that interruption. We could not separate the pause cause in those cases into individual components because often activities overlapped (eg, "rhythm analysis and pulse check").

Outcome

The primary outcome was the total duration of chest compression interruption. Additional outcomes were the longest duration of interruption and the frequency of interruption.

Statistical Analysis

We used descriptive statistics to characterize the demographics, circumstances, and care to include the cause, timing, and frequency of interruptions. We evaluated the median duration for each type of interruption. We also measured the duration of the longest pause in each case, and the duration of pauses that >10 seconds. To control for possible impact on the duration of resuscitation efforts, we also calculated the interruption duration per 10 minutes of resuscitation.

We evaluated the temporal trends in interruptions according to each calendar year. We tested whether there was a temporal change in compression interruption using linear regression, examining the association between year as the independent variable and the appropriate dependent variable. For the chest compression level variables, *P* values were adjusted for clustering of observations within patients with the Huber-White sandwich estimator. We conducted

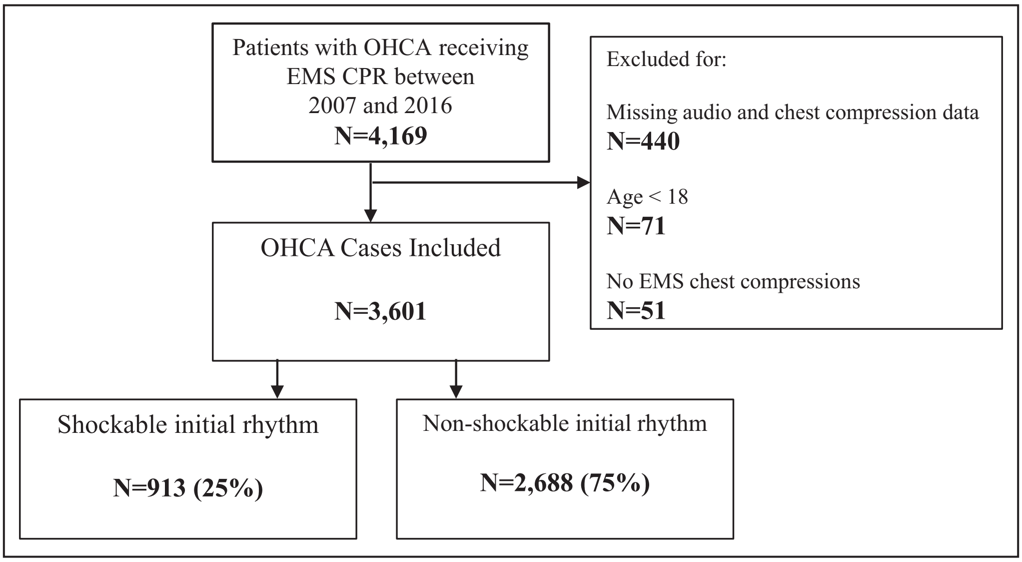

Figure 1. Patient inclusion criteria and initial rhythm status.
CPR indicates cardiopulmonary resuscitation; EMS, emergency medical services; and OHCA, out-of-hospital cardiac arrest.

sensitivity analyses stratified by shockable versus nonshockable rhythm to evaluate whether the temporal trend in CPR fraction differed according to initial rhythm. We used STATA 15 and Tableau 2019.2.3 to perform analyses.

RESULTS

Of the 4169 OHCA patients treated during the study period, 568 were excluded, leaving 3601 cases for the primary study cohort (Figure 1). The cohort was 63.8±17.8 years old on average and 65% men. Of the 89% who were in arrest on EMS arrival, 53% received bystander CPR; and 11% arrested after EMS arrival. An initial shockable rhythm was present in 25%, and 84% had endotracheal intubation.

EMS teams performed 74 584 minutes of resuscitation that included 30 043 interruptions, accounting for 6621 minutes (8.9%). The median total interruption duration per case was 83 seconds (interquartile range [IQR], 46–145 seconds) and decreased over the 10-year period from 115 seconds in 2007 (IQR, 55–203 seconds) to 72 seconds in 2016 (IQR, 44–117 seconds) (P<0.0001, test for trend), even though the mean±SD number of interruptions per case increased from 7.8±5.7 interruptions in 2007 to 8.5±5.5 interruptions in 2016 (P<0.01) (Table 2). Resuscitation duration increased by 2.1 minutes from a median of 17.1 minutes in 2007 to 19.2 minutes in 2016 (P=0.04). Among all interruptions >1 second, overall median interruption duration was 9 seconds, and decreased from 14 seconds per interruption in 2007 to 7 seconds in 2016 (P<0.0001). Among interruptions >10 seconds, median interruption duration decreased from 20 seconds in 2007 to 16 seconds in 2016 (P<0.0001).

Long interruptions also decreased in frequency. There was a median of 2.6 interruptions >10 seconds per 10 minutes of resuscitation in 2007, compared with 1.1 per 10 minutes in 2016 (P<0.0001). The median duration of the longest interruption per case decreased from 33 seconds in 2007 to 19 seconds in 2016 (P<0.0001).

The most common interruption cause was manual rhythm analysis and pulse check, accounting for 41.6% of total interruption time over the study period, with an overall median interruption duration of 8 (IQR, 5–12) seconds (Table S1). Other causes comprising the top 5 highest fractions of total interruption time included AED analysis (13.7% of total interruption time [17 seconds; IQR, 13–23 seconds]), manual defibrillator rhythm analysis and shock (8.0% [9 seconds; IQR, 7–14 seconds]), unknown because of missing or unintelligible audio recording (5.5% [6 seconds; IQR, 4–11 seconds]), and attempted placement of an endotracheal tube (5.3% [19 seconds; IQR, 11–35 seconds]).

Most cause-specific interruptions demonstrated a temporal decrease (Figure 2 and Figure S2). Interruptions for manual rhythm analysis and pulse check decreased from a median of 11 seconds in 2007 to 7 seconds in 2016 (P<0.001). Interruptions for AED analysis decreased from 22 seconds in 2007 to 14 seconds in 2016 (P<0.001). On the other hand, median interruptions for manual rhythm analysis and shock delivery remained stable at 9 seconds in 2007 and 9 seconds in 2016; but the variation decreased (IQR, 6–18 seconds in 2007 and IQR, 7–13 seconds in 2016; P<0.01).

Table 2. Chest Compression Interruptions by Year

Variable	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Overall
Cases, N	322	357	351	324	325	379	388	381	390	384	3601
Pauses*	2512	2823	2871	2525	2803	3184	3281	3445	3498	3101	30 043
Pauses per case, mean ±SD†	7.8±5.7	7.9±5.7	8.2±6.2	7.8±5.9	8.7±6.0	8.4±6.0	8.5±5.7	9.0±6.1	9.0±5.9	8.5±5.5	8.4±5.9
Duration of all pauses, median (IQR), s‡	14 (8–23)	11 (7–19)	10 (6–18)	10 (6–18)	9 (6–15)	8 (5–13)	8 (5–13)	7 (5–12)	7 (5–11)	7 (5–12)	9 (6–15)
Duration of pauses >10 s, median (IQR), s‡	20 (15–28)	19 (14–26)	18 (13–26)	18 (14–27)	17 (13–25)	15 (12–22)	15 (12–22)	16 (12–22)	15 (12–22)	16 (13–24)	17 (13–25)
Duration of total pauses per case, median (IQR), s‡	115 (55–203)	102 (53–163)	97 (51–166)	86 (46–147)	90 (49–163)	72 (44–130)	78 (41–133)	70 (44–122)	74 (39–127)	72 (44–117)	83 (46–145)
Longest pause per case, median (IQR), s‡	33 (23–48)	27 (21–41)	28 (20–39)	27 (18–41)	26 (17–41)	21 (14–32)	21 (14–32)	19 (14–29)	19 (13–30)	19 (12–32)	24 (16–37)
Pauses >10 s per 10 min of resuscitation, median (IQR)‡	2.6 (1.9–3.4)	2.2 (1.4–3.0)	2.1 (1.3–2.9)	1.8 (1.0–2.8)	1.8 (1.1–2.5)	1.6 (1.0–2.3)	1.4 (0.8–2.1)	1.2 (0.5–1.9)	1.2 (0.5–1.7)	1.1 (0.5–1.8)	1.6 (0.9–2.5)
Duration of resuscitation, median (IQR), min*	17.1 (9.7–26.7)	18.6 (9.5–28.2)	17.9 (9.9–28.8)	18.5 (10.1–27.4)	17.9 (10.4–28.5)	16.9 (10.1–26.6)	18.4 (10.9–28.2)	20.4 (12.5–29.1)	19.9 (12.0–29.8)	19.2 (10.0–28.3)	18.5 (10.4–28.2)

IQR indicates interquartile range.
*$P<0.05$ using test for trend for change over all 10 years.
†$P<0.01$ using test for trend for change over all 10 years.
‡$P<0.001$ using test for trend for change over all 10 years.

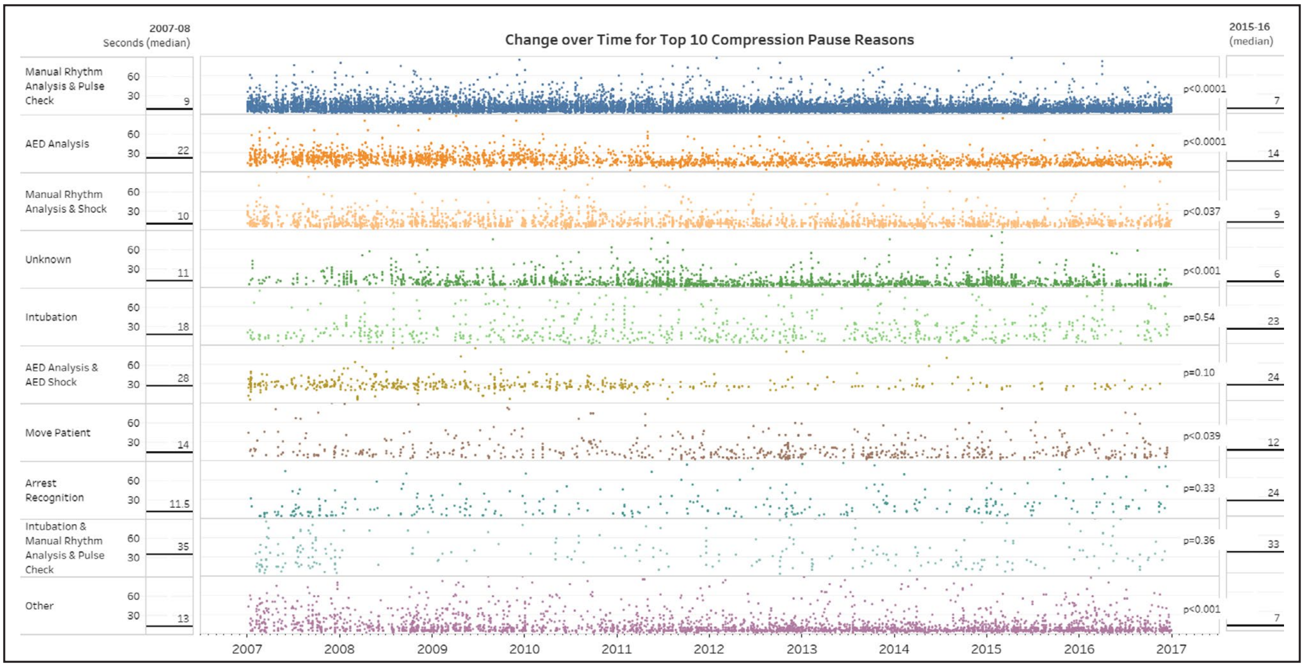

Figure 2. Median pause duration and frequency of common pause causes. The top 10 pause causes are plotted, showing median pause duration in seconds for each pause cause.

Each dot represents one pause. We tested whether there was a temporal change in compression interruption using linear regression, examining the association between year as the independent variable and pause duration as the dependent variable. *P* values were adjusted for clustering of observations within incidents with the Huber-White sandwich estimator. "Intubation" and "arrest recognition" have positive slopes but lack statistical significance over time. In a sensitivity analysis, the nonparametric Spearman ρ test was run and produced *P* values similar to those reported in the figure. AED indicates automated external defibrillator.

Over time, the proportion of cases in which an interruption in compressions included an attempt to perform endotracheal intubation was low and declined from 33.5% of cases in 2007 to 16.7% of cases in 2016 ($P<0.0001$ by χ^2 for trend statistic; Table S2). Simultaneously, the duration of interruptions that included an attempt at intubation remained stable. The median was 23 seconds overall, and was 24 seconds in 2007 and 31 seconds in 2016 (*P*=not significant) (Table S3 and Figure S3).

In an effort to limit interruptions, the single long interruption of the AED analysis, charge, and shock sequence (N=548; median, 27 [IQR, 24–32] seconds) was reengineered into 2 separate interruptions that leveraged the AED functions: AED analysis (N=2779; median, 17 [IQR, 13–23] seconds) followed by a period of chest compressions while the AED was charging and then AED shock delivery with a median interruption of 5 (IQR, 4–7) seconds. This change was implemented beginning in August 2011 (Table 1).

A sensitivity analysis stratified for shockable versus nonshockable initial rhythm using a linear trend model demonstrated that CPR fraction increased over time regardless of initial rhythm, although shockable initial rhythms had, on average, longer interruptions than cases with nonshockable initial rhythms (Figure 3).

DISCUSSION

In this population-based investigation of the cause, frequency, and duration of EMS chest compression interruptions, we observed a progressive temporal reduction in the duration of individual compression interruptions and total interruption per case even as the duration of attempted resuscitation increased over time. We found that the interface between the rescuer and the defibrillator performing rhythm analyses with or without consequent pulse checks or shock accounted for more than half of the interruptions.

During the study period, the Seattle Fire Department implemented substantial training in high-performance CPR (Table 1). High-performance CPR emphasizes teamwork among basic and advanced providers to reduce or eliminate interruptions.[14] The goal of the training was to limit interruptions throughout a resuscitation by engineering more efficient interface with the defibrillator (eg, charging the defibrillator during CPR) and coordinating EMS provider treatments (eg, designated timekeeper, rotation of compressor during rhythm analysis, placement of vascular access during compressions, and intubation during compressions). Consistent with these efforts, we observed a corresponding temporal decrease in compression interruptions, suggesting that programmatic efforts directed to limiting interruptions

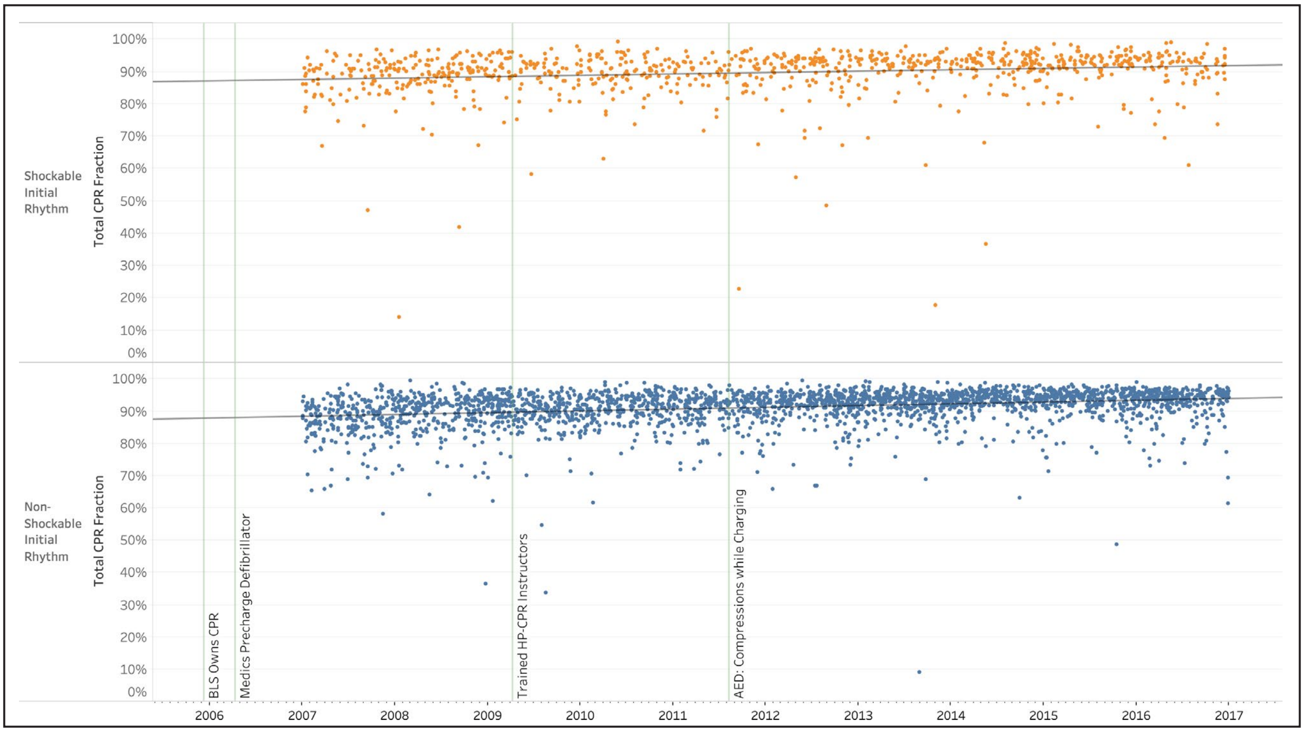

Figure 3. Change in cardiopulmonary resuscitation (CPR) fraction over time for initially shockable and nonshockable cases. Each dot represents a single case.
We examined the association between time and CPR fraction for initially shockable and nonshockable cases with linear regression. *P* values were adjusted for clustering of observations within incidents with the Huber-White sandwich estimator. The plotted linear regression lines show an association between time and increasing CPR fraction, for both the shockable initial rhythm ($P<0.0001$) and the nonshockable initial rhythm cohorts ($P<0.024$). There was a difference in trend in CPR fraction and time for shockable and nonshockable rhythm. Shockable rhythms were associated with lower CPR fraction over time ($P<0.0001$ by linear regression). AED indicates automated external defibrillator; BLS, basic life support; and HP-CPR, high-performance cardiopulmonary resuscitation.

can lead to improvements in CPR performance, even in a system where the baseline CPR fraction was >85%. Observational studies from the Resuscitation Outcomes Consortium from 2009 to 2011 showed that CPR fractions were commonly <80%.[14,15]

Given the real-time audio recording of the defibrillators, the causes of interruptions of compressions could be assessed. Consistent with international resuscitation guidelines, the EMS providers of the study community perform rhythm analysis after every 2-minute chest compression cycle. Ultimately, over half of the total interruption time was associated with rhythm analysis with or without consequent pulse checks or shocks.

Interruptions occurred with both AEDs and manual defibrillators. Others have shown that the probability of return of spontaneous circulation in OHCA patients with ventricular fibrillation or tachycardia decreased as preshock interruption time increased.[16] The creation and propagation of defibrillator technology that can analyze cardiac rhythm during chest compressions may be an important step toward reducing one of the most common reasons for interruptions in chest compressions.[17]

Over the course of the study, the frequency of interruptions to perform endotracheal intubation declined over time; and endotracheal intubation was achieved in most patients without any interruption in chest compressions. Notably, the duration of interruptions to perform intubation remained relatively unchanged, although the patients remaining with an interruption to perform intubation may have been more technically challenging (Table S3). A previous investigation of intubation during resuscitation reported a median interruption of 109 seconds.[18] Other evidence indicates that the duration of the single longest interruption per case is associated with lower chance of survival.[19] The current study experience indicates that best practices for endotracheal intubation that limit interruption in chest compression during resuscitation can be achieved systematically.

Vascular access is another intervention that can be effectively performed during chest compressions. During the course of the study, paramedics primarily used peripheral venous catheters; and intraosseous access was available beginning in 2010. Central venous catheterization often produced protracted case-specific cause of chest compression interruption (median, 32 [IQR, 17–77] seconds), but was uncommon

(N=58), resulting in only 0.8% of total interruption duration (Table S1).

Alternative approaches to vascular access using intraosseous needles have provided the means to reduce compression interruptions related to central venous access. Indeed, we observed a decrease over time in interruptions because of vascular access as the use of a central line decreased. Excluding central venous catheter placement, chest compressions were interrupted only 67 times during the study period exclusively for vascular access (0.2% of total interruption time; median, 11 seconds).

Rotating chest compressors is another chest compression interruption cause of interest during OHCA. A study characterizing the reasons for interruptions during in-hospital cardiac arrest of older children and adolescents found that 57% of interruptions were attributable to switching personnel, accounting for 41% of total interruption time.[20] In the current investigation, the chest compressor switch occurs during the first AED analysis and after every 2-minute cycle of chest compressions thereafter. Teamwork coordinated by a designated timekeeper and preassigned roles enables this efficient rotation for chest compressions.

The current study has limitations. The investigation is a retrospective analysis of a single EMS system, so it may lack generalizability. Nevertheless, similar CPR fractions have been reported by other EMS systems, suggesting that the temporal improvement and interruption causes may be matched elsewhere.[21] We classified interruptions into categories, understanding that some interruptions may have had multiple causes. Moreover, classification of interruptions into categories may reduce detail-oriented information required to understand process improvement. However, the approach was necessary to present the information in a structured, actionable manner. The investigation evaluated the duration and causes for interruption but did not examine the details that enabled process improvement, including the relationship between interruptions and clinical outcome. Because of the large sample size, some results, while statistically significant, may not be clinically important.

These limitations should be considered in the context of the strengths of this investigation. We were able to evaluate a large population-based cohort of resuscitation using ECG, impedance, and audio recordings, providing for a comprehensive and detailed assessment overall and over time on a topic that is high priority for many EMS systems.

CONCLUSIONS

In this population-based cohort of OHCA, median duration of chest compression interruptions decreased by half from 2007 to 2016, indicating that care teams can significantly improve performance. Reducing compression interruptions is an evidence-based benchmark that provides a modifiable process quality improvement goal.

ARTICLE INFORMATION

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Supplementary Materials

Tables S1–S3
Figures S1–S3

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SUPPLEMENTAL MATERIAL

Table S1. Characteristics of Specific Pauses.

		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Overall
Manual Rhythm Analysis & Pulse Check	N Pauses	1,191	1,538	1,557	1,395	1,375	1,857	1,898	2,023	2,063	1,852	16,749
	Total Pause Duration (seconds)	15,426	17,108	16,418	15,278	14,894	17,886	17,363	16,920	16,900	15,181	163,374
	% of Total Pause Time	32.6%	38.4%	39.1%	41.0%	38.6%	48.9%	46.4%	46.5%	45.0%	42.7%	41.6%
	Pause Time (median [IQR])	10 [7-16]	9 [6-13]	8 [5-13]	9 [6-14]	8 [5-13]	8 [5-11]	8 [5-11]	7 [5-10]	7 [5-9]	7 [5-9]	8 [5-12]
AED Analysis	N Pauses	403	358	345	226	253	244	245	233	241	231	2,779
	Total Pause Duration (seconds)	9,221	8,334	7,489	4,559	4,900	4,116	4,185	3,641	3,895	3,620	53,960
	% of Total Pause Time	19.5%	18.7%	17.9%	12.2%	12.7%	11.3%	11.2%	10.0%	10.4%	10.2%	13.7%
	Pause Time (median [IQR])	22 [17-27]	22 [17-26]	20 [15-26]	18 [14-25]	15 [12-20]	14 [12-20]	15 [12-20]	14 [11-18]	14 [12-19]	14 [12-18]	17 [13-23]
Manual Rhythm Analysis & Shock	N Pauses	280	251	249	278	256	214	304	294	228	211	2,565
	Total Pause Duration (seconds)	3,798	3,256	2,870	3,883	3,260	2,459	3,356	3,136	2,357	2,884	31,259
	% of Total Pause Time	8.0%	7.3%	6.8%	10.4%	8.4%	6.7%	9.0%	8.6%	6.3%	8.1%	8.0%
	Pause Time (median [IQR])	9 [6-18]	11 [7-17]	9 [6-14]	10 [7-17]	10 [7-15]	9 [7-13]	8 [6-12]	8 [6-11]	8 [7-12]	9 [7-13]	9 [7-14]
Unknown	N Pauses	48	136	171	188	372	237	278	273	343	202	2,248
	Total Pause Duration (seconds)	709	1,943	1,577	2,348	3,980	1,517	2,289	2,131	3,144	1,831	21,469
	% of Total Pause Time	1.5%	4.4%	3.8%	6.3%	10.3%	4.1%	6.1%	5.9%	8.4%	5.2%	5.5%

		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Overall
	Pause Time (median [IQR])	13 [9-20]	11 [7-17]	7 [5-11]	8 [5-14]	6 [4-12]	4 [3-8]	5 [3-10]	6 [4-9]	7 [5-10]	5 [3-9]	6 [4-11]
Intubation	N Pauses	52	81	68	85	81	86	68	90	71	60	742
	Total Pause Duration (seconds)	1,386	2,061	1,987	2,447	2,613	1,985	1,930	2,234	1,785	2,222	20,650
	% of Total Pause Time	2.9%	4.6%	4.7%	6.6%	6.8%	5.4%	5.2%	6.1%	4.8%	6.3%	5.3%
	Pause Time (median [IQR])	16 [11-24]	19 [13-31]	22 [13-39]	18 [9-42]	20 [10-40]	15 [9-32]	20 [10-34]	19 [10-33]	17 [10-32]	29 [16-50]	19 [11-35]
AED Analysis & AED Shock	N Pauses	126	119	93	74	45	23	15	23	14	16	548
	Total Pause Duration (seconds)	3,850	3,385	2,638	2,112	1,166	686	469	721	339	404	15,770
	% of Total Pause Time	8.1%	7.6%	6.3%	5.7%	3.0%	1.9%	1.3%	2.0%	0.9%	1.1%	4.0%
	Pause Time (median [IQR])	28 [26-33]	27 [23-31]	27 [23-31]	28 [24-32]	26 [24-29]	26 [25-31]	26 [24-31]	27 [26-33]	25 [21-26]	24 [22-27]	27 [24-32]
Move Patient	N Pauses	48	49	50	47	61	107	82	85	56	65	650
	Total Pause Duration (seconds)	1,570	1,211	1,370	1,082	1,267	1,489	1,673	1,682	1,124	1,417	13,885
	% of Total Pause Time	3.3%	2.7%	3.3%	2.9%	3.3%	4.1%	4.5%	4.6%	3.0%	4.0%	3.5%
	Pause Time (median [IQR])	16 [9-36]	13 [9-24]	15 [8-37]	16 [11-26]	13 [5-27]	10 [5-18]	12 [7-19]	12 [6-22]	12 [8-28]	11 [6-19]	12 [7-23]
Arrest Recognition	N Pauses	56	32	29	23	32	36	30	29	40	33	340
	Total Pause Duration (seconds)	964	2,100	726	935	902	1,031	922	871	1,553	1,719	11,723
	% of Total Pause Time	2.0%	4.7%	1.7%	2.5%	2.3%	2.8%	2.5%	2.4%	4.1%	4.8%	3.0%
	Pause Time (median [IQR])	9 [4-17]	18 [13-48]	15 [7-30]	23 [11-47]	18 [8-33]	16 [8-39]	22 [10-40]	17 [11-28]	23 [12-36]	25 [18-65]	18 [9-35]

		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Overall
Other	N Pauses	45	31	41	35	24	33	31	33	24	32	329
	Total Pause Duration (seconds)	2,346	1,048	1,731	1,648	800	852	741	709	746	796	11,417
	% of Total Pause Time	5.0%	2.4%	4.1%	4.4%	2.1%	2.3%	2.0%	1.9%	2.0%	2.2%	2.9%
	Pause Time (median [IQR])	38 [23-63]	19 [12-30]	19 [11-36]	31 [19-57]	21 [12-40]	17 [12-26]	22 [13-29]	17 [12-26]	18 [13-28]	19 [12-36]	21 [12-38]
Intubation & Manual Rhythm Analysis & Pulse Check	N Pauses	80	13	11	14	20	27	24	29	18	27	263
	Total Pause Duration (seconds)	3,012	729	609	671	1,108	1,300	856	737	682	1,131	10,835
	% of Total Pause Time	6.4%	1.6%	1.5%	1.8%	2.9%	3.6%	2.3%	2.0%	1.8%	3.2%	2.8%
	Pause Time (median [IQR])	31 [17-50]	43 [34-71]	39 [29-74]	41 [31-57]	40 [31-50]	33 [23-70]	32 [20-42]	21 [16-31]	26 [18-53]	34 [26-58]	34 [20-54]
Shock	N Pauses	22	131	132	64	112	144	121	154	167	117	1,164
	Total Pause Duration (seconds)	192	1,086	907	397	871	905	729	1,023	999	660	7,769
	% of Total Pause Time	0.4%	2.4%	2.2%	1.1%	2.3%	2.5%	1.9%	2.8%	2.7%	1.9%	2.0%
	Pause Time (median [IQR])	5 [3-8]	6 [5-8]	6 [4-8]	5 [4-7]	5 [4-8]	5 [4-7]	6 [4-7]	5 [4-6]	5 [4-7]	5 [4-6]	5 [4-7]
Pulse Check	N Pauses	5	4	5	25	77	99	110	93	111	96	625
	Total Pause Duration (seconds)	37	53	48	196	671	769	1,133	683	638	621	4,849
	% of Total Pause Time	0.1%	0.1%	0.1%	0.5%	1.7%	2.1%	3.0%	1.9%	1.7%	1.7%	1.2%
	Pause Time (median [IQR])	7 [4-9]	10 [9-14]	10 [10-11]	7 [4-10]	7 [4-11]	6 [4-9]	7 [5-10]	5 [3-9]	5 [3-8]	6 [4-8]	6 [4-9]
	N Pauses	35	31	39	31	50	37	36	31	22	39	351

		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Overall
Check Breath Sounds	Total Pause Duration (seconds)	299	431	556	459	598	452	358	271	201	285	3,910
	% of Total Pause Time	0.6%	1.0%	1.3%	1.2%	1.5%	1.2%	1.0%	0.7%	0.5%	0.8%	1.0%
	Pause Time (median [IQR])	8 [6-11]	11 [9-18]	11 [7-18]	12 [9-17]	9 [5-13]	10 [5-13]	10 [7-13]	8 [6-10]	7 [5-11]	5 [3-10]	9 [5-13]
Apply LUCAS	N Pauses								8	59	80	147
	Total Pause Duration (seconds)								298	1,327	1,730	3,355
	% of Total Pause Time								0.8%	3.5%	4.9%	0.9%
	Pause Time (median [IQR])								32 [21-47]	16 [10-30]	17 [7-26]	17 [9-28]
Insert Central Line	N Pauses	6	10	19	12	5	5			1		58
	Total Pause Duration (seconds)	654	523	661	633	381	114			47		3,013
	% of Total Pause Time	1.4%	1.2%	1.6%	1.7%	1.0%	0.3%			0.1%		0.8%
	Pause Time (median [IQR])	125 [104-129]	31 [19-36]	28 [15-42]	32 [11-87]	71 [37-126]	25 [17-28]			47		32 [17-77]
Manual Rhythm Analysis & Pulse Check & Check Heart Sounds	N Pauses	22	5	13	1	6	7	5	4	5	2	70
	Total Pause Duration (seconds)	832	118	349	34	182	204	197	89	173	46	2,224
	% of Total Pause Time	1.8%	0.3%	0.8%	0.1%	0.5%	0.6%	0.5%	0.2%	0.5%	0.1%	0.6%
	Pause Time (median [IQR])	35 [21-44]	25 [15-28]	28 [13-38]	34	25 [16-27]	24 [18-42]	27 [22-46]	17 [15-24]	11 [11-48]	23 [21-26]	26 [16-41]
	N Pauses	12	6	6	3	2	4	2	2	1	3	41

		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Overall
AED Analysis & Move Patient	Total Pause Duration (seconds)	505	242	257	154	56	115	84	56	21	166	1,656
	% of Total Pause Time	1.1%	0.5%	0.6%	0.4%	0.1%	0.3%	0.2%	0.2%	0.1%	0.5%	0.4%
	Pause Time (median [IQR])	45 [31-50]	40 [38-49]	42 [30-56]	50 [49-54]	28 [28-29]	29 [24-33]	42 [31-53]	28 [24-32]	21	38 [35-67]	38 [29-51]
Manual Rhythm Analysis & Pulse Check & Move Patient	N Pauses	3	4	4	4	6	6	6	14	7	5	59
	Total Pause Duration (seconds)	71	92	204	130	133	168	127	463	95	119	1,602
	% of Total Pause Time	0.1%	0.2%	0.5%	0.3%	0.3%	0.5%	0.3%	1.3%	0.3%	0.3%	0.4%
	Pause Time (median [IQR])	30 [18-33]	22 [21-25]	42 [32-62]	37 [31-38]	23 [14-25]	17 [6-31]	16 [12-27]	20 [11-37]	13 [9-19]	24 [11-35]	22 [12-35]
Manual Rhythm Analysis & Pulse Check & Check Breath Sounds	N Pauses	47	3	8	1	4	2	4	9	2	2	82
	Total Pause Duration (seconds)	817	67	264	10	73	25	35	176	34	35	1,536
	% of Total Pause Time	1.7%	0.2%	0.6%	0.0%	0.2%	0.1%	0.1%	0.5%	0.1%	0.1%	0.4%
	Pause Time (median [IQR])	17 [9-22]	17 [15-28]	28 [14-49]	10	19 [15-23]	13 [11-14]	7 [3-13]	13 [11-17]	17 [15-20]	18 [16-19]	16 [10-22]
Surgical Cricothyrotomy	N Pauses	1	1			1			1	1		5
	Total Pause Duration (seconds)	786	138			232			236	63		1,455
	% of Total Pause Time	1.7%	0.3%			0.6%			0.6%	0.2%		0.4%
	Pause Time (median [IQR])	786	138			232			236	63		232 [138-236]
Other Procedure	N Pauses	1	1	3			1	3		1		10

		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Overall
	Total Pause Duration (seconds)	248	9	77			238	172		395		1,139
	% of Total Pause Time	0.5%	0.0%	0.2%			0.7%	0.5%		1.1%		0.3%
	Pause Time (median [IQR])	248	9	27 [16-37]			238	49 [27-84]		395		48 [14-208]
Perform Pericardiocentesis	N Pauses	1	3	4		3	1	3	1			16
	Total Pause Duration (seconds)	100	165	278		228	79	215	71			1,136
	% of Total Pause Time	0.2%	0.4%	0.7%		0.6%	0.2%	0.6%	0.2%			0.3%
	Pause Time (median [IQR])	100	56 [51-60]	70 [47-92]		56 [40-102]	79 [79-79]	73 [69-75]	71			68 [55-82]
Manual Rhythm Analysis & Pulse Check & Apply LUCAS	N Pauses								2	17	15	34
	Total Pause Duration (seconds)								51	417	565	1,033
	% of Total Pause Time								0.1%	1.1%	1.6%	0.3%
	Pause Time (median [IQR])								26 [24-27]	19 [14-31]	26 [13-37]	23 [14-33]
DNR Clarification	N Pauses		1	2		1	1	1		1		7
	Total Pause Duration (seconds)		40	265		42	40	370		10		767
	% of Total Pause Time		0.1%	0.6%		0.1%	0.1%	1.0%		0.0%		0.2%
	Pause Time (median [IQR])		40	133 [71-194]		42	40	370		10		40 [25-149]
Clear Airway	N Pauses	2	5	5	2	6	2	3	2		1	28

		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Overall
	Total Pause Duration (seconds)	48	64	122	56	165	39	80	28		54	656
	% of Total Pause Time	0.1%	0.1%	0.3%	0.2%	0.4%	0.1%	0.2%	0.1%		0.2%	0.2%
	Pause Time (median [IQR])	24 [21-27]	6 [5-20]	13 [9-31]	28 [25-31]	29 [15-40]	20 [19-20]	13 [12-35]	14 [13-15]		54 [54-54]	19 [12-32]
Manual Rhythm Analysis & Pulse Check & Insert Central Line	N Pauses	6	2	4	2							14
	Total Pause Duration (seconds)	114	135	371	25							645
	% of Total Pause Time	0.2%	0.3%	0.9%	0.1%							0.2%
	Pause Time (median [IQR])	18 [14-26]	68 [65-70]	94 [72-115]	13 [11-14]							29 [15-70]
Intubation & AED Analysis	N Pauses	8	1	1	1				1			12
	Total Pause Duration (seconds)	320	105	27	59				85			596
	% of Total Pause Time	0.7%	0.2%	0.1%	0.2%				0.2%			0.2%
	Pause Time (median [IQR])	36 [25-46]	105	27 [27-27]	59 [59-59]				85			43 [27-66]
Other Vascular Access	N Pauses	3			6	3	8	7	4	3	3	37
	Total Pause Duration (seconds)	45			87	52	70	131	50	80	25	540
	% of Total Pause Time	0.1%			0.2%	0.1%	0.2%	0.4%	0.1%	0.2%	0.1%	0.1%
	Pause Time (median [IQR])	12 [12-17]			12 [9-23]	23 [13-25]	7 [4-13]	11 [7-30]	11 [6-18]	15 [10-38]	9 [7-10]	11 [5-19]
	N Pauses									1		1

		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Overall
Intubation & Surgical Cricothyrotomy	Total Pause Duration (seconds)									523		523
	% of Total Pause Time									1.4%		0.1%
	Pause Time (median [IQR])									523		523
Insert IV	N Pauses	2	6	8	3	3	2	3	1		2	30
	Total Pause Duration (seconds)	22	113	140	48	25	26	12	7		25	418
	% of Total Pause Time	0.0%	0.3%	0.3%	0.1%	0.1%	0.1%	0.0%	0.0%		0.1%	0.1%
	Pause Time (median [IQR])	11 [8-15]	15 [12-24]	12 [10-21]	9 [7-22]	5 [4-12]	13 [9-17]	3 [3-5]	7		13 [8-17]	10 [5-18]

Table S2. Pauses for Endotracheal Intubation.

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Overall
Total Patients	322	357	351	324	325	379	388	381	390	384	3,601
N (%) Patients with Pause for Intubation	108 (33.5%)	64 (17.9%)	60 (17.1%)	69 (21.3%)	69 (21.2%)	81 (21.4%)	65 (16.8%)	80 (21.0%)	60 (15.4%)	64 (16.7%)	720 (20.0%)
N Pauses	148	96	81	100	103	115	92	122	90	89	1,036
Total Pause Duration (seconds)	5,058	2,923	2,980	3,177	3,837	3,399	2,786	3,115	2,990	3,455	33,720
Median (IQR) Pause Time (seconds)	24 [15-44]	21 [14-36]	23 [13-47]	22 [11-46]	25 [12-48]	21 [12-36]	24 [12-40]	20 [11-33]	21 [11-35]	31 [21-54]	23 [13-41]

IQR = Interquartile Range

There was a statistically significant association between time and the percent of patients with pauses for intubation ($p<0.0001$ by Chi-square for trend statistic). Since this was a patient level analysis, the Chi-square for trend statistic was used.

Table S3. Details of Pauses for Endotracheal Intubation.

		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Overall
Intubation	N Pauses	52	81	68	85	81	86	68	90	71	60	742
	Total Pause Duration (seconds)	1,386	2,061	1,987	2,447	2,613	1,985	1,930	2,234	1,785	2,222	20,650
	% of Total Pause Time	27.4%	70.5%	66.7%	77.0%	68.1%	58.4%	69.3%	71.7%	59.7%	64.3%	61.2%
	Pause Time (median [IQR])	16 [11-24]	19 [13-31]	22 [13-39]	18 [9-42]	20 [10-40]	15 [9-32]	20 [10-34]	19 [10-33]	17 [10-32]	29 [16-50]	19 [11-35]
Intubation & Manual Rhythm Analysis & Pulse Check	N Pauses	80	13	11	14	20	27	24	29	18	27	263
	Total Pause Duration (seconds)	3,012	729	609	671	1,108	1,300	856	737	682	1,131	10,835
	% of Total Pause Time	59.5%	24.9%	20.4%	21.1%	28.9%	38.2%	30.7%	23.7%	22.8%	32.7%	32.1%
	Pause Time (median [IQR])	31 [17-50]	43 [34-71]	39 [29-74]	41 [31-57]	40 [31-50]	33 [23-70]	32 [20-42]	21 [16-31]	26 [18-53]	34 [26-58]	34 [20-54]
Intubation & AED Analysis	N Pauses	8	1	1	1				1			12
	Total Pause Duration (seconds)	320	105	27	59				85			596
	% of Total Pause Time	6.3%	3.6%	0.9%	1.9%				2.7%			1.8%
	Pause Time (median [IQR])	36 [25-46]	105	27 [27-27]	59 [59-59]				85			43 [27-66]
Intubation & Surgical Cricothyrotomy	N Pauses									1		1
	Total Pause Duration (seconds)									523		523
	% of Total Pause Time									17.5%		1.6%
	Pause Time (median [IQR])									523		523
Manual Rhythm Analysis & Pulse Check & Insert Central Line & Intubation	N Pauses			1								1
	Total Pause Duration (seconds)			357								357
	% of Total Pause Time			12.0%								1.1%
	Pause Time (median [IQR])			357								357

		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Overall
Intubation & Manual Rhythm Analysis & Shock	N Pauses	1	1			2	1				1	6
	Total Pause Duration (seconds)	21	28			116	31				39	235
	% of Total Pause Time	0.4%	1.0%			3.0%	0.9%				1.1%	0.7%
	Pause Time (median [IQR])	21	28			58 [57-60]	31				39	35 [29-51]
Intubation & AED Analysis & AED Shock	N Pauses	5										5
	Total Pause Duration (seconds)	183										183
	% of Total Pause Time	3.6%										0.5%
	Pause Time (median [IQR])	37 [29-38]										37 [29-38]
Move Patient & Intubation	N Pauses	1							2			3
	Total Pause Duration (seconds)	42							59			101
	% of Total Pause Time	0.8%							1.9%			0.3%
	Pause Time (median [IQR])	42							30 [23-36]			42 [30-42]
Move Patient & Intubation & AED Analysis	N Pauses	1										1
	Total Pause Duration (seconds)	94										94
	% of Total Pause Time	1.9%										0.3%
	Pause Time (median [IQR])	94										94
Other Vascular Access & Intubation & Manual Rhythm Analysis & Pulse Check	N Pauses						1					1
	Total Pause Duration (seconds)						83					83
	% of Total Pause Time						2.4%					0.2%
	Pause Time (median [IQR])						83					83
Pulse Check & Intubation	N Pauses										1	1
	Total Pause Duration (seconds)										63	63

		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Overall
	% of Total Pause Time										1.8%	0.2%
	Pause Time (median [IQR])										63	63
Grand Total	N Pauses	148	96	81	100	103	115	92	122	90	89	1,036
	Total Pause Duration (seconds)	5,058	2,923	2,980	3,177	3,837	3,399	2,786	3,115	2,990	3,455	33,720
	% of Total Pause Time	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	Pause Time (median [IQR])	24 [15-44]	21 [14-36]	23 [13-47]	22 [11-46]	25 [12-48]	21 [12-36]	24 [12-40]	20 [11-33]	21 [11-35]	31 [21-54]	23 [13-41]

IQR = Interquartile range

Figure S1. Example CPR Grid.

CARDIAC ARREST - QA FOLLOW UP

DATE	XX/XX/XX				**Incident ID**	**XXXXX**
						E32/L11/M32
WHO	**START CPR**	**STOP CPR**	**CPR DONE**	**CPR NOT DONE**	**REASON TO STOP CPR**	
		GOAL	**2 mins**	**< 10 secs**		
EMTS	9:39:44	9:41:40	0:01:56	0:00:13	to analyze with LP500	
EMTS	9:41:53	9:42:09	0:00:16	0:00:07	to SHOCK x 1	
EMTS	9:42:16	9:44:35	0:02:19	0:00:22	to analyze with LP500	
EMTS	9:44:57	9:46:53	0:01:56	0:00:20	to analyze with LP500	
MEDICS	9:47:13	9:49:40	0:02:27	0:00:06	to ck rhythm/pulse	
MEDICS	9:49:46	9:50:18	0:00:32	0:00:20	to intubate	
MEDICS	9:50:38	9:51:50	0:01:12	0:00:03	to ck rhythm/pulse	
MEDICS					**PULSE**	**9:51:53**
MEDICS				0:00:00	**LOST PULSE**	**9:56:04**
MEDICS	9:56:04	9:58:24	0:02:20	0:00:01	to ck rhythm/pulse	
MEDICS					**PULSE**	**9:58:25**
MEDICS				0:00:00	**LOST PULSE**	**10:22:58**
MEDICS	10:22:58	10:25:04	0:02:06	0:00:06	to ck rhythm/pulse	
MEDICS	10:25:10	10:25:29	0:00:19	0:00:04	to SHOCK x 1	
MEDICS	10:25:33	10:26:56	0:01:23	0:00:01	to ck rhythm/pulse	
MEDICS					**PULSE**	**10:26:57**
TOTAL		**CPR needed**	**CPR done**	**CPR not done**		
		0:18:29	0:16:46	0:01:43		
			91%	**9%**		
arrival at patient to IV		2mins/50secs				
arrival at patient to ETT		3mins/15secs				

Figure S2. Common pause etiologies (% of total pause time per year).

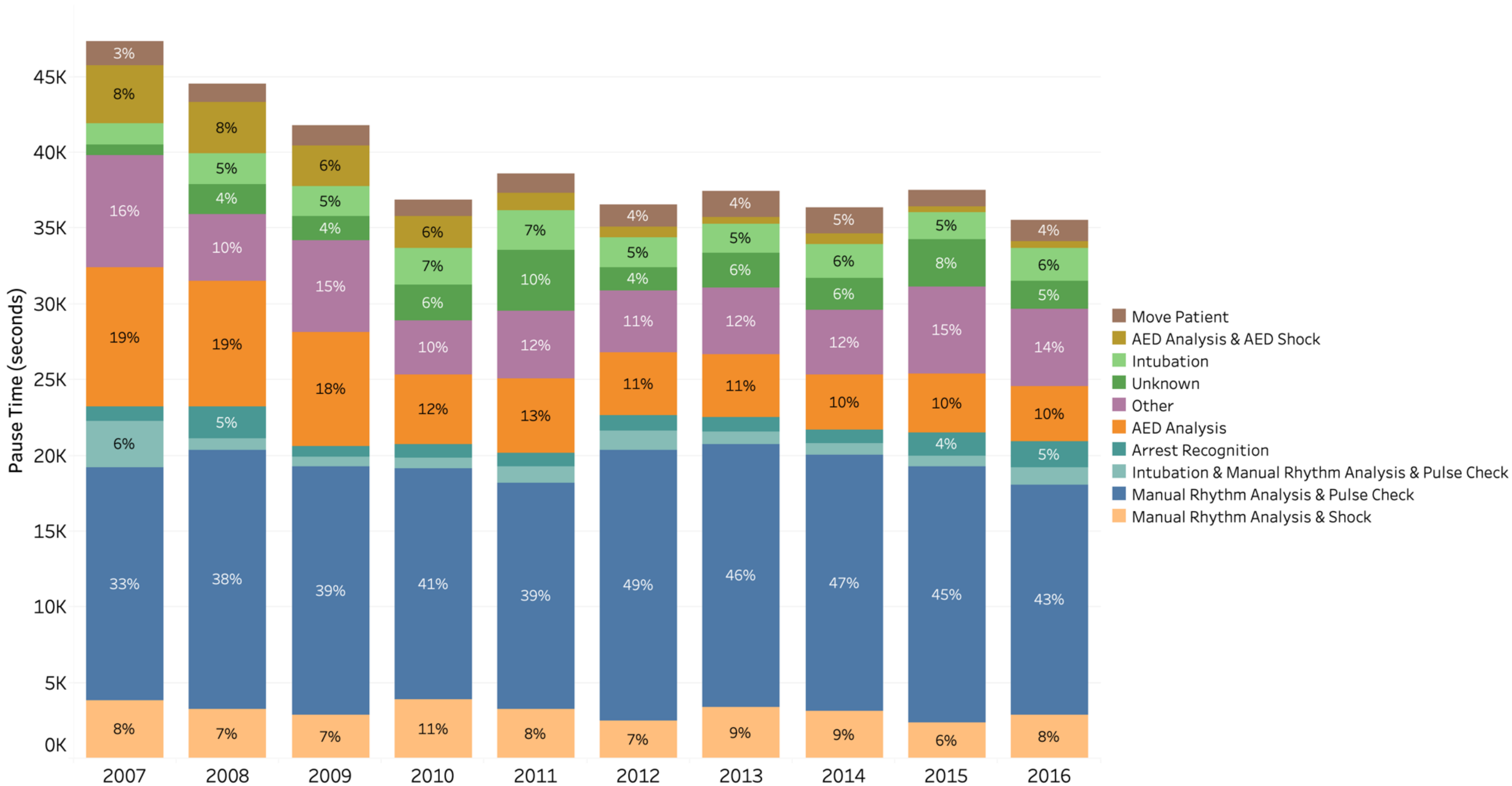
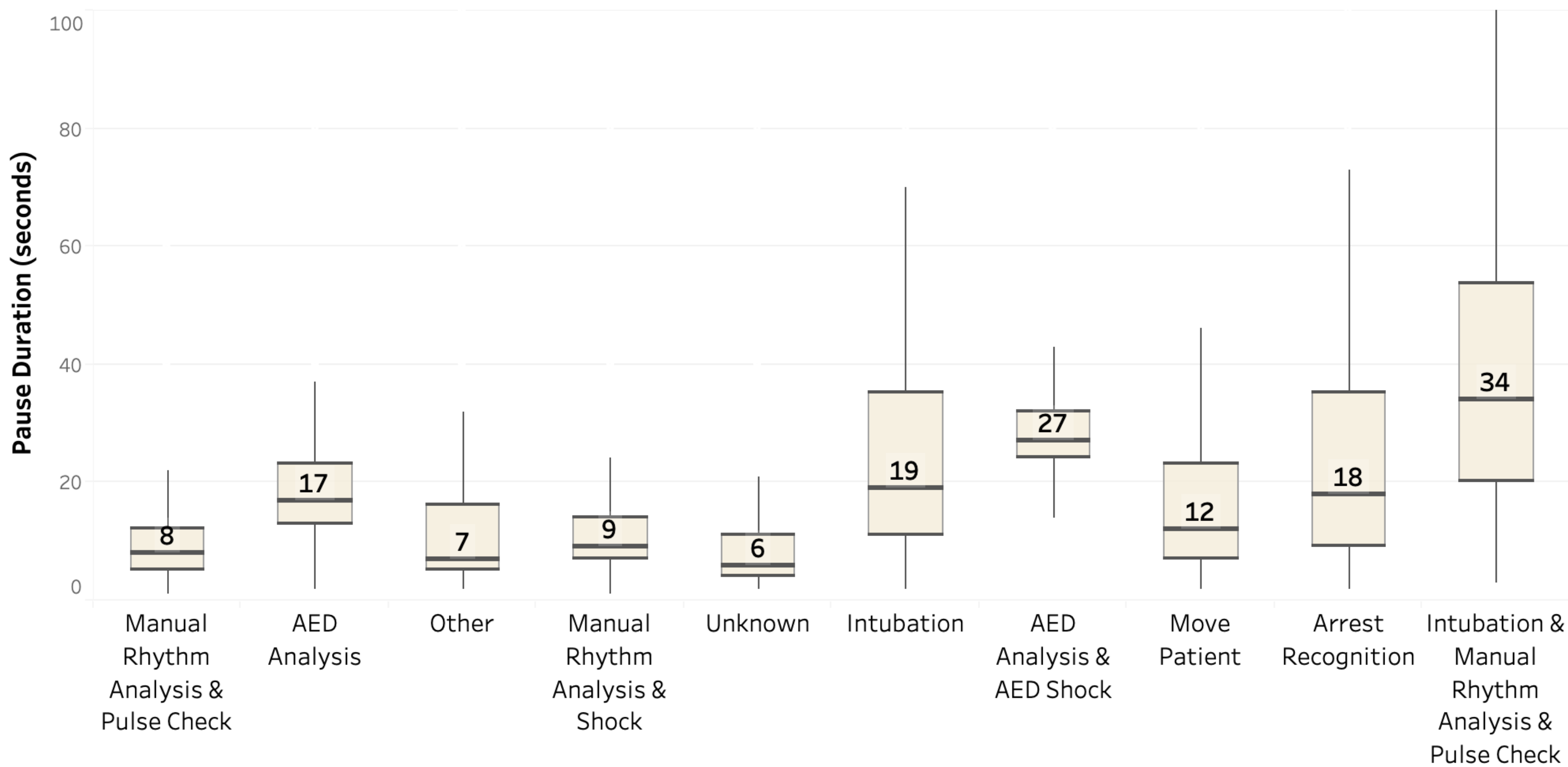


Figure S3. Variation in Top 10 Reasons for Pauses.



	Manual Rhythm Analysis & Pulse Check	AED Analysis	Other	Manual Rhythm Analysis & Shock	Unknown	Intubation	AED Analysis & AED Shock	Move Patient	Arrest Recognition	Intubation & Manual Rhythm Analysis & Pulse Check
N Pauses	16,749	2,779	3,120	2,565	2,248	742	548	650	340	263
% of Total Pause Time	41.6%	13.7%	12.8%	8.0%	5.5%	5.3%	4.0%	3.5%	3.0%	2.8%