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Use of Transthoracic Impedance Data to Evaluate Intra-Arrest Chest Compression Quality

Jonathan W Kamrud[1], Lori L Boland[1,2]*, Carol L Frazee[1], Tyler G Kinzy[2], Paul A Satterlee[1,3], Charles J Lick[1]

[1]Allina Health Emergency Medical Services, USA

[2]Division of Applied Research, Allina Health, USA

[3]Department of Emergency Medicine, Abbott Northwestern Hospital, USA

*Corresponding author: Lori L Boland, Managing Scientist, Division of Applied Research, Allina Health, 2925 Chicago Avenue, Minneapolis, MN 55407, USA, Tel: 612-262-6022, Email: lori.boland@allina.com

Abstract

Objective: Mechanical compression devices purportedly improve the quality of chest compressions by minimizing interruptions and maintaining optimal rate and depth, but this claim has not been objectively substantiated using transthoracic impedance (TTI) recordings from applied setting cardiac arrests. In this study, we use TTI data to compare chest compression quality metrics from the manual versus mechanical compression phases of out-of-hospital cardiac arrests (OHCA) treated with the LUCAS™ mechanical compression device.

Methods: A retrospective analysis was conducted among all LUCAS™-aided OHCA worked by a single ambulance service in Minnesota in 2013. Events were excluded from analysis if the TTI recording was unavailable or of inadequate quality, or if duration of recorded compressions was < 5 minutes. Two paramedics independently annotated and reviewed TTI tracings using CodeStat™ software, isolated the manual and mechanical compression phases of the arrest, and recorded total CPR time, compression rate (per min) and compression fraction for each distinct phase. The main pause for LUCAS™ application was not included in either phase. Time of first mechanical compression and duration of main pause for compression device application were also determined.

Results: A total of 202 events met inclusion criteria. The median (range) duration of the manual and mechanical phases were 3:13 min (0:05-19:51) and 23:24 min (0:13-65:30), respectively. Median compression fraction was lower during manual versus mechanical compressions (77% vs. 89%; p < 0.001). Median compression rates were 121/min during manual compressions and 102/min with the mechanical device (p < 0.001). On average, device placement occurred approximately 4 minutes after the start of TTI recording, with a median application pause of 26 sec (IQR = 17-44).

Conclusion: These data demonstrate that use of a mechanical chest compression device can improve compression fraction and increase compliance with compression rate guidelines, but further study is needed to determine whether the observed improvement in compression quality after device placement is solely related to the mode of compression. Based on these findings, our system will emphasize earlier device placement with minimal pauses for application.

Introduction

An estimated 350,000 people suffer out-of-hospital cardiac arrests (OHCA) annually in the United States. In 2013, only 9.5% of OHCA victims survived to hospital discharge [1], and it is well known that a key determinant of survival is the rapid delivery of high quality cardiopulmonary resuscitation (CPR) [2]. According to the most recent CPR guidelines from the American Heart Association (AHA), an essential component of high quality CPR is the delivery of chest compressions at the proper rate and depth with minimal interruption [2], and transthoracic impedance (TTI) data captured by electrocardiogram (EKG) defibrillator/monitors can be used to retrospectively assess certain aspects of chest compression quality [3]. With the use of specialized software, TTI tracings can be used to examine the rate of chest compressions and the frequency and duration of compression pauses that occurred during a resuscitation attempt. In late 2012, we acquired the necessary tools and training to institute a cardiac arrest post-event TTI review process in our ambulance service.

Mechanical compression devices purportedly improve the quality of chest compressions by minimizing interruptions and maintaining optimal rate and depth. Since 2008, our ambulance service has used a mechanical compression device as standard equipment in the prehospital treatment of OHCA [4]. Briefly, prehospital clinicians use the mechanical device in all instances of nontraumatic OHCA in nonpregnant patients 12 years of age or older where manual compressions would otherwise be used. Manual compressions are delivered initially, with providers instructed to place the mechanical device at the first clinically appropriate opportunity thereafter. Routine use of a mechanical compression device, coupled with the practice of conducting post-arrest TTI data reviews in our system provides a unique opportunity to explore CPR quality under

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manual versus mechanical compression within a resuscitation attempt and to better understand the device placement practices of our providers. The specific objectives of the current study were therefore to use TTI data to

(1) Describe intra-arrest differences in indicators of chest compression quality during the manual versus mechanical phases of resuscitation attempts, and

(2) To examine the timing of device placement and the duration of the pause required for device application.

Methods

Setting and study design

Allina Health EMS (AH-EMS) is the prehospital emergency services provider of Allina Health, a not-for-profit system of hospitals, clinics, and other health care services providing care throughout Minnesota. The agency employs approximately 425 dispatchers, emergency medical technicians (EMTs) and paramedics to provide 911 dispatch service, advanced life support, and scheduled medical transport in 100 communities in and around Minneapolis-St Paul, Minnesota. The service area covers 3100 km^2 and includes about 1 million residents. In these communities, first response is provided by a variety of full-time, part-time, and volunteer services as determined by the municipality. With a 70-ambulance fleet, AH-EMS responds to approximately 80,000 emergency calls annually, using both paramedic/paramedic and paramedic/EMT configurations. An electronic prehospital patient care record (ePCR; Imagetrend) was fully implemented in early 2008. In January 2008, AH-EMS instituted use of the LUCAS™ mechanical chest compression system (Lund University Cardiopulmonary Assist System, Physio-Control Inc., Redmond, WA) as standard equipment in the treatment of OHCA [4].

We conducted a retrospective analysis of all mechanical device-assisted OHCA resuscitations performed by our ambulance service in 2013. Eligible events were cases of non-traumatic OHCA in patients ≥ 18 years of age where the LUCAS™ device was used. Events were excluded if no TTI data were retrievable for the event, TTI data were of insufficient quality for analysis, if the patient received fewer than 5 minutes of total compressions from ambulance personnel, or if there was no manual phase evident on the TTI tracing (i.e. a mechanical device was placed by first responders and operational upon arrival of the ambulance crew). Standard protocol for use of mechanical compression was as follows: when the device is not contraindicated, placement is to occur as soon as possible, manual compressions are not to be delayed for the purpose of application, and pauses for application should be less than 10 seconds. The study protocol was approved by Allina Health's appointed external institutional review board with a waiver of informed consent.

Transthoracic impedance data

AH-EMS uses LIFEPAK®12 and LIFEPAK®15 cardiac monitor/defibrillators (Physio-Control, Inc., Redmond, WA). TTI data are captured by these devices via a low amplitude carrier signal that continually travels between the defibrillation electrodes and can be used reliably to determine the timing of chest compressions and identify pauses in compressions [3]. As part of an on-going quality improvement initiative in the current setting, all resuscitation attempts are reviewed and annotated by a trained paramedic (CLF) using CPR analytic software (CODE-STAT™ 9.0 Advanced CPR Analytic Software, Physio-Control, Inc., Redmond, WA), and all EMTs and paramedics (hereafter paramedics) involved in the resuscitation attempt receive an electronic summary report of CPR quality metrics within 24 hours of the incident.

Data collection

For the purposes of this study an independent data collection tool was created to capture specific metrics from the TTI recording for each event. Two paramedics (JWK, CLF) each independently reviewed approximately 6 months of annotated cases, collaborating on the review of approximately 30 cases at the beginning of data collection to ensure a uniform approach to interpretation and data collection. Upon review of TTI tracings, three ordered phases of the resuscitation attempt were recognized and labeled:

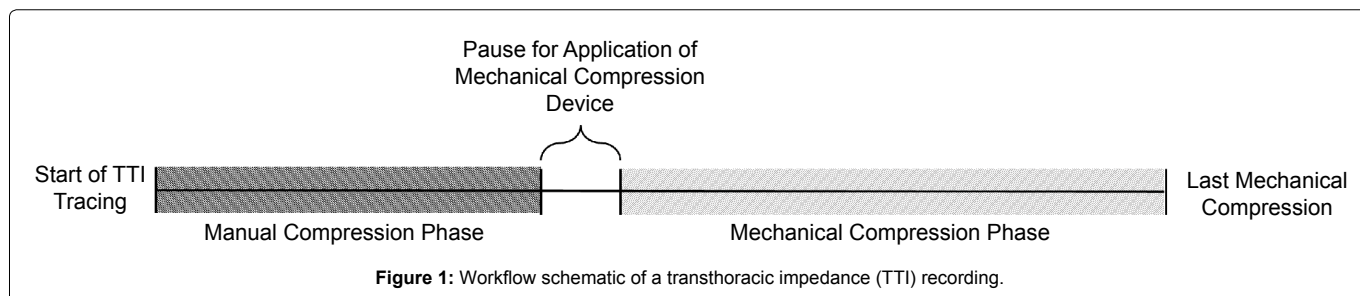(1) An initial phase of manual compressions,

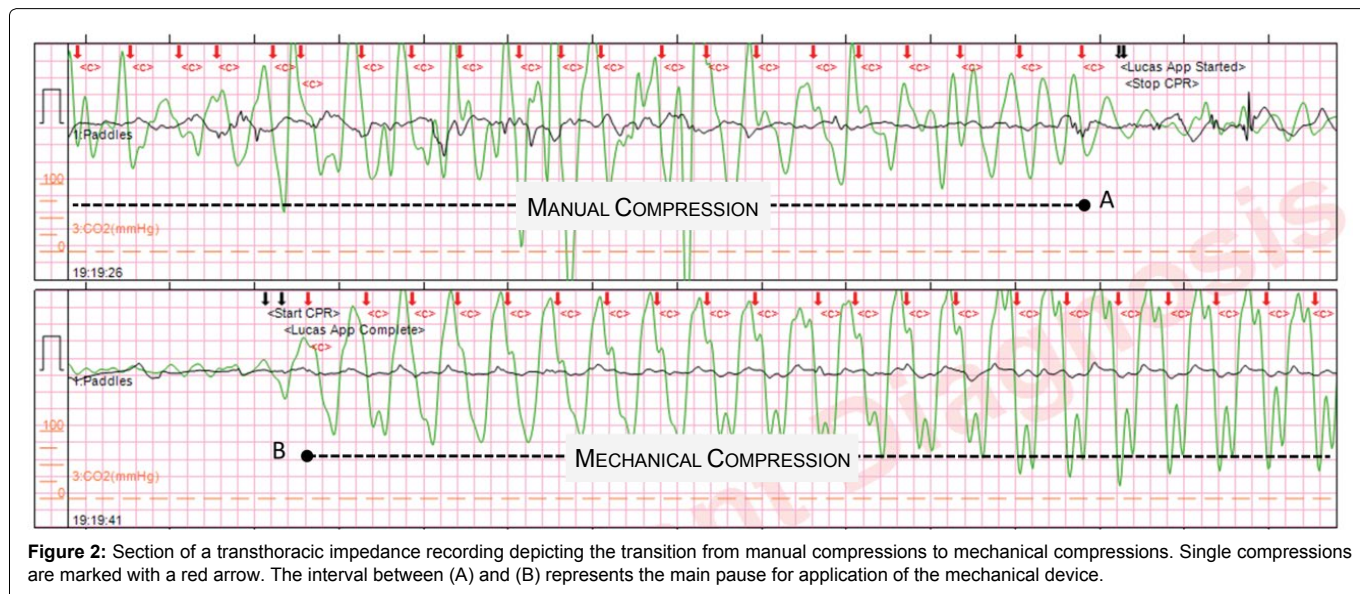**Figure 1:** Workflow schematic of a transthoracic impedance (TTI) recording.

Figure 2: Section of a transthoracic impedance recording depicting the transition from manual compressions to mechanical compressions. Single compressions are marked with a red arrow. The interval between (A) and (B) represents the main pause for application of the mechanical device.

(2) A pause in compressions attributable to application of the mechanical compression device, and

(3) A subsequent phase of mechanical compressions (Figure 1).

Clear identification of the transition from manual to mechanical compression is made possible by a noticeable change in the uniformity, consistent rate, and distinct rectangular morphology of the signal that is created when the mechanical device is providing compressions, as illustrated in Figure 2

Definition of manual and mechanical compression phases

The manual phase was defined as the start of the impedance signal to the last manual compression prior to the start of the main pause for device application. The mechanical phase was defined as the interval between the first mechanical compression and the trailing edge of the last mechanical compression. Figure 1 provides a schematic of the two phases and the application pause. It should be noted that the interval in the TTI tracing corresponding to the main device application pause was not initially included in either the manual or the mechanical phase when computing CPR quality metrics for the two phases, but a sensitivity analysis in which the device application pause was included in the mechanical phase was conducted.

Definition of pause for mechanical device application

As described previously [5,6], application of this particular mechanical device is completed in two steps. The two steps can be and are often performed within a single compression interruption, and in the interest of consistency, we defined the main pause for device application as the interval of time from the trailing edge of the last manual compression to the leading edge of the first mechanical compression. This is depicted as the interval between A and B in Figure 2, and this approach results in the exclusion of the back plate pause in instances where the two steps occurred with separate compression interruptions. The main pause for device application was considered indeterminate and set to missing when a defibrillatory shock or AED analysis occurred concurrent with device application, as these actions would artificially lengthen the pause. To examine how long into the resuscitation attempt the mechanical compression device is typically placed, time to first mechanical compression was defined as the interval between the start of the impedance signal to the leading edge of the first mechanical compression (labeled B in Figure 2).

Compression quality metrics

CPR time, compression fraction, and compression rate were evaluated separately for the manual and mechanical compression phases of each arrest. CPR time is defined as the total amount of TTI tracing time where no spontaneous circulation is present and the patient would have required chest compressions. Compression fraction is defined as the proportion of CPR time during which compressions were being delivered (i.e. the proportion of elapsed tracing time that compressions were being performed when no spontaneous circulation was present). Compression rate is the average number of compressions per minute across all periods of active compression. CPR time, compression fraction and compression rate are calculated and displayed by the analytical software.

Compression pauses

The TTI data analysis software allows the end user to designate a threshold for identifying pauses in CPR. For this analysis, the threshold was set at 2 seconds, so that each interval on the TTI tracing greater than 2 seconds during which no compressions were performed constituted a compression pause. Details about each pause, including the duration and a categorization of the pause as peri-shock or non-shock related, are automatically generated and displayed by the software. Information about all pauses in both the manual and mechanical phases was transcribed by reviewers into the study database for use in analysis.

Other variables

The EKG defibrillator/monitor mode used during the arrest is evident on the TTI recording and was categorized as manual mode

only, AED (semi-automated) mode only, or a combination (i.e. the clinician used both modes during the course of the resuscitation attempt). During the study time frame, a preference for AED mode was expressed by medical direction, but monitor mode was not mandated by protocol and was ultimately the decision of the paramedics. Patient demographic information and event characteristics such as initial rhythm, bystander CPR, and witnessed arrest were obtained from the Cardiac Arrest Registry for Enhanced Survival database [7].

Analysis

Means and proportions were used to describe patient and event characteristics. Interval data were analyzed in seconds, but where appropriate, results are presented in the more intuitive format min:sec. Differences in the means or medians of CPR time, compression rate, compression fraction, and the frequency and duration of pauses in the manual and mechanical compression phases of arrests were assessed using t-tests or Wilcoxon sign-rank tests, respectively. Analyses of compression pauses that occurred in arrests worked in AED versus manual monitor mode included a comparison of the median duration of all pauses, peri-shock pauses, and non-shock pauses under each mode. To investigate the occurrence of "extended" pauses, we computed a variable that reflected the number of pauses > 10 seconds in duration adjusted for the length of the resuscitation attempt (specifically, the number of pauses > 10 sec in duration per 5 minutes of total CPR time). All statistical analyses were conducted using Stata 12.1 (StataCorp, College Station, TX).

Results

In 2013, 351 patients with nontraumatic OHCA were treated with mechanical compression by AH-EMS paramedics. Of these, 149 incidents were excluded from analysis because the mechanical compression device was not actually used (n = 4) or was placed prior to ambulance arrival (n = 65), TTI data were of poor quality (n = 25) or unavailable (n = 36), or the patient received < 5 minutes of compressions in the presence of ambulance personnel (n = 19). TTI data are only captured and available for analysis when the cardiac monitor is viewing the paddles lead, so cases where TTI data were unavailable reflect events during which the cardiac monitor was set to view an alternative lead. TTI recordings categorized as poor quality included those which reflected use of multiple lead views across the duration of the event or tracings found to have copious amounts of impedance signal interference. A total of 202 OHCA resuscitation events with both a manual and mechanical compression phase contributed to analysis. Patient and event characteristics are presented in Table 1. Return of spontaneous circulation (ROSC)

Table 1: Patient and event characteristics in 202 arrests with mechanical compression.

Variable	N = 202[a]
Age, y	67 (16)
Male	67% (136)
Witnessed Arrest	55% (111)
Bystander CPR	32% (65)
Initial rhythm	
PEA/Asystole	79% (160)
VF/VT	21% (42)
Monitor mode during arrest	
Manual Mode	23% (46)
AED (Semi-automated) Mode	66% (134)
Combination	11% (22)
EMS Response Time, min[b]	7 (5-9)
Any return of spontaneous circulation	28% (57)
Survival to hospital discharge	
All Rhythms	7% (14)
PEA/Asystole	3% (4)
VF/VT	24% (10)

[a]Results are expressed as mean (SD) or percent (n) unless otherwise noted;
[b]Median (IQR)

CPR = cardiopulmonary resuscitation; PEA = pulseless electrical activity; VF = ventricular fibrillation; VT = ventricular tachycardia; AED = automated external defibrillator; EMS = emergency medical services

occurred in 28% of patients, and 24% of those with shockable initial rhythms survived to hospital discharge [8]. The primary focus of this study was not to associate the metrics found in either phase to outcomes. Outcomes are provided to give a general sense of the patient population included in this study.

As expected, the manual compression phase of resuscitations was significantly shorter than the mechanical phase (Table 2). Manual compressions were delivered for 3 min 13 sec (IQR = 1:40-4:53), while mechanical compressions were delivered for 23 min 24 sec (IQR = 13:22-33:22; p < 0.001). The median compression rate was significantly higher during manual compression phases (121/min, IQR = 109-131) versus mechanical phases (102/min, IQR = 102-102; p < 0.001), and the median compression fraction was only 77% (IQR = 68-85) under manual compression as compared to 89% (IQR = 86-92) during phases of mechanical compression (p < 0.001). In a sensitivity analysis in which the device application pause was considered part of the mechanical phase, results did not differ. Among the 184 cases for which mechanical device application could be clearly ascertained on the TTI tracing, the mechanical device was placed an average of 4 min 7 sec after the start of the TTI tracing, with a median application pause of 26 sec (IQR = 17-44; Table 3).

To examine whether monitor mode is associated with duration of compression pauses, pause data from the manual and mechanical phases of each arrest were combined. Median peri-shock pauses were approximately 6.4 sec longer with the monitor in AED versus manual mode, but due to the small number of patients with a shockable rhythm, this difference did not reach statistical significance (Table 4). Resuscitation attempts conducted with the monitor in AED mode also resulted in a higher frequency of pauses > 10 sec per each 5 minutes of CPR.

Discussion

TTI data recorded during cardiac arrests has been used to examine a variety of CPR quality metrics in the setting of both manual [3,9-13] and mechanical prehospital chest compression [5,6], but there are no previous reports comparing intra-arrest TTI-assessed CPR quality metrics across the manual versus mechanical compression segments in OHCAs where both were delivered by the same team of paramedics. Standard use of mechanical compression and universal post-arrest TTI review in our system facilitated a systematic quantitative study of how the introduction of a mechanical compression device during the course of a resuscitation attempt impacts CPR quality.

Mechanical chest compression devices ostensibly can reduce if not remove some of the inherently human challenges to achieving high quality CPR by ensuring uniform compressions are delivered at an optimal rate, and by minimizing compression pauses. Our data demonstrate that within prehospital resuscitation attempts made by our paramedics, the quality of CPR prior to the application of a mechanical compression device was suboptimal to that performed after device application with regard to compression rate and compression fraction. The median compression rate of 121/min we observed during phases of manual compression is higher than the 112/min average reported by the Resuscitation Outcomes Consortium (ROC) investigators [14], lower than average rates reported by others [9,12,15], and notably higher than the 100/min minimum recommended by the AHA [16]. In contrast, and by design, the mechanical device reliably maintained a more ideal compression rate of 102 compressions per minute with virtually no detectable variability. And although not measured in this study, the mechanical device also maintains a consistent and optimal depth for each compression delivered [17].

Compression fraction also improved from 77% to 89% with the introduction of the mechanical device. Theoretically, this reflects one of the much heralded benefits of mechanical compression devices - that they afford the constant delivery of compressions during provider activities which often render manual compressions difficult if not impossible to perform continuously, e.g. moving of the patient, airway placement, ambulance transport, and transfer into the care of emergency department staff. But in the current study, the manual phase of compressions always occurred at the outset of resuscitation, a period of high intensity and critical multitasking that may compromise the ability of paramedics to delivery optimal compressions. Two studies of all-manual CPR have addressed this "early flurry" hypothesis by comparing compression quality in the first five minutes of prehospital resuscitation attempts with quality during the remainder of the attempt [3,9], but only one [3] documented poorer CPR quality during the first five minute segment. So although the manual phases in our arrests were more vulnerable to compression interruptions, it is impossible to determine whether the lower compression fraction observed with manual compressions was wholly attributable to the compression mode, or whether it partly reflects early assessments and interventions, initial challenges

Table 2: Comparison of chest compression quality and characteristics of pauses[a] in the manual and mechanical phases of 202 device-assisted arrests.

Variable	Manual Phase[b]	Mechanical Phase[b]	p-value[c]
CPR Time[d] (min:sec)	3:13 (1:40-4:53)	23:24 (13:22-33:22)	< 0.001
Compression rate (per min)	121 (109-131)	102 (102-102)	< 0.001
Compression fraction[d] (%)	77 (68-85)	89 (86-92)	< 0.001
Pauses			
Duration (sec)			
All Pauses	9.9 (7.5-15.0)	13.7 (10.8-18.0)	< 0.001
Peri-Shock Pauses	22.0 (18.0-28.0)	24.0 (19.5-30.0)	0.72
Non-Shock Pauses	9.1 (6.8-13.0)	13.0 (10.4-16.8)	< 0.001

[a]The main pause for application of the mechanical device was excluded from analysis;

[b]Results are expressed as median (IQR);

[c]p-value for Wilcoxon signed -rank test;

[d]See Methods for definition;

CPR = cardiopulmonary resuscitation

Table 3: Mechanical compression device application timing for 184 arrests where application time of device could be determined.

Time from start of impedance signal to first mechanical compression (min:sec)	
Mean (SD)	4:07 (2:26)
Median (IQR)	4:02 (2:10-5:25)
Compression interruption for application of mechanical device[a] (sec)	
Mean (SD)	34 (27)
Median (IQR)	26 (17-44)

[a]See Methods. Includes only main application and activation and not placement of back plate when the steps are performed separately

Table 4: Comparison of characteristics of pauses by monitor mode.

Variable	AED Mode	Manual Mode	p-value[a]
N	134	46	
Median Duration in sec (IQR)			
All Pauses	13.6 (10.9-16.9)	10.6 (7.0-16.4)	0.003
Peri-Shock Pauses	25.7 (21.7-31.0)	19.3 (10.3-30.5)	0.13
Non-Shock Pauses	13.2 (10.4-15.5)	10.7 (6.8-15.5)	0.006
Mean number of pauses > 10 sec per 5 min of CPR (SD)	2.11 (0.61)	1.16 (0.74)	< 0.001

[a]p-value for independent samples t-test or Mann-Whitney U test;

AED = automated external defibrillator; CPR = cardiopulmonary resuscitation

with environment, and the general "settling in" of the crew that characteristically occurs in the first minutes of resuscitation.

Among 184 arrests for which the pause in compressions required for transition to LUCAS™ could be unambiguously determined with TTI data, we observed a median pause of 26 sec (IQR = 17-44). We are aware of only two other reports that have objectively quantified the interruption in prehospital compressions required for LUCAS™ application in applied settings [5,6]. In an analysis of TTI data from 32 OHCAs that occurred in 2008-2010, Yost *et al.*[5] observed a median compression pause for application of the LUCAS™ device of 32.5 sec (IQR = 25-61). More recently, a 2013 quality improvement initiative conducted by the Anchorage Fire Department targeted the technique for LUCAS™ application and successfully yielded a significant reduction in the median main application pause, which dropped from 21 sec (IQR = 15-31) to 7 sec (IQR = 4-12) [6]. The compression interruptions for device application in our system are notably longer. Efforts to retrain clinicians with an emphasis on rapid deployment have been implemented, and interruptions for device application are now a focus of quality monitoring and clinician feedback.

With a monitor/defibrillator in AED mode, the duration of the "hands-off" interval required for automated rhythm analysis is voice-prompted and standardized, while in manual mode, the rhythm recognition speed and discretion of the provider dictates the duration of this interval and thus it can be shorter. Consistent with this technological design, we found that peri-shock pauses were 6.4 sec longer with monitors in AED mode and that arrests worked in AED mode produced almost twice as many compression interruptions longer than 10 sec in duration per each 5 min of CPR. In a prospective analysis of 44 OHCAs, Tomkins *et al.* [13] similarly concluded that manual mode was preferable to AED mode with regard to implications for duration of compression interruptions. In high-performance EMS systems where paramedics achieve a high level of accuracy and competency in EKG interpretation, the use of monitors in manual mode may improve overall compression fraction, and our protocol has been modified to reflect this preference.

Limitations

In this retrospective study, the inability to randomize the order of the manual and mechanical compression phases of arrests precluded analysis of whether the timing of the phase may be associated with compression quality independent of compression mode. A sizeable number of cases were excluded from analysis due to poor quality or missing TTI data, but this is most often caused by technical issues and is unlikely to be systematic or related to clinician performance. Another limitation is the presumption that the main pause identified just prior to the start of mechanical compressions was entirely the result device application. Given the retrospective nature of this study and the lack of direct observation of the event, we cannot conclude that this particular interruption contained only activities related to device placement. And because TTI cannot be used to measure depth of compressions, we were unable to examine the ability of clinicians to consistently achieve compressions of the recommended depth. And finally, we did not examine whether the CPR quality metrics included in our analysis were associated with outcomes in this population.

Conclusion

Data from our EMS system demonstrate that compression fraction and rate were improved with the introduction of a mechanical compression device during the course of a resuscitation attempt, but further study is needed to determine whether the observed improvement in compression quality after device placement is solely related to the mode of compression. Compression pauses for device application are frequently longer than necessary and should be targeted for reduction. Irrespective of whether manual or mechanical compression is the standard of care, EMS agencies should aim to employ routine, objective post-arrest analysis of CPR process data to identify deficiencies in quality.

Ethical Statement

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