

ORIGINAL ARTICLE

Prehospital cardiopulmonary resuscitation with manual or mechanical chest compression: A study of compression-induced injuries

Louise Milling¹ | Birgitte Schmidt Astrup^{1,2} | Søren Mikkelsen^{1,3,4} 

¹Department of Clinical Research, University of Southern Denmark, Odense, Denmark

²Department of Forensic Medicine, University of Southern Denmark, Odense, Denmark

³The Mobile Emergency Care Unit, Department of Anaesthesiology and Intensive Care Medicine, Odense University Hospital, Odense, Denmark

⁴Institute of Regional Health Research, University of Southern Denmark, Odense, Denmark

Correspondence

Søren Mikkelsen, Mobile Emergency Care Unit, Department of Anaesthesiology and Intensive Care Medicine V, Odense University Hospital, Odense, Denmark.
Email: soeren.mikkelsen@rsyd.dk

Objective: Concerns for iatrogenic injuries associated with cardiopulmonary resuscitation led us to investigate the extent and the pattern of chest compression-related injuries in patients subjected to either mechanical and/or manual cardiac compression.

Method: In a retrospective study, we performed a manual review of all prehospital discharge reports, in-hospital records, and autopsy reports for evidence of injuries related to chest compression. We included all patients receiving physician-administered treatment for out-of-hospital cardiac arrest in the Region of Southern Denmark from 2015 to 2017.

Results: Eighty four patients undergoing manual and mechanical chest compression and 353 patients with manual chest compression only were included. Unadjusted, mechanical chest compression as an adjunct was associated with a higher risk of injuries than manual chest compression ($P < 0.001$, odds ratio, OR 3.10). Adjusted for the duration of compression, this difference waned. Visceral injuries were more frequent in patients receiving mechanical chest compression even when adjusted for the duration of compression, age, sex, body mass index and anticoagulant therapy ($P < 0.001$, OR 29.84). We found a higher incidence of potentially life-threatening injuries in patients receiving mechanical chest compression. The occurrence of injuries overall was associated with the duration of chest compression ($P = 0.02$, OR 1.02).

Conclusion: Mechanical chest compression as an adjunct to manual chest compression was strongly associated with potentially life-threatening visceral injuries. The duration of chest compression was associated with injury. Our results suggest that mechanical chest compression should only be applied in situations where manual chest compression is unfeasible.

1 | INTRODUCTION

Since its introduction more than 50 years ago,¹⁻³ external chest compression has remained the most vital component of cardiopulmonary resuscitation. In recent years, mechanical devices automatically performing

chest compression (mech-CPR) have been introduced in both prehospital and in-hospital medicine. Guidelines for resuscitation suggest that these devices should not be applied routinely but may be considered under circumstances where sustained high-quality manual chest compression (manual-CPR) is impractical or may compromise provider safety.⁴

Mechanical chest compression devices work by rhythmically tightening and loosening a load-distributing band placed around the patient's chest or by rhythmically applying pressure on the sternum with a piston-type device.⁵ Manual-CPR may lead to visceral injuries possibly contributing to fatal outcomes.⁶⁻⁸ A similar concern has now been raised in relation to mech-CPR.⁹⁻¹¹

The aim of this pragmatic study was to investigate whether the extent of injuries and the injury pattern caused by chest compression differs between patients receiving manual-CPR and patients receiving mech-CPR as an adjunct to manual CPR.

2 | MATERIALS AND METHODS

2.1 | Study setting

This retrospective cohort study was performed in the Region of Southern Denmark, one of Denmark's five health regions. The emergency medical service in the region is comprised of 70 ambulances, three paramedic manned rapid response vehicles, and six anaesthesiologist-manned Mobile Emergency Care Units (MECUs). All medical emergency calls are directed to the emergency medical dispatch centre assessing the urgency of the task.¹² The dispatched resource may be an ambulance, an ambulance and a rapid response vehicle, or an ambulance and a MECU, the latter being dispatched in 26.2% of all emergency runs in the Region of Southern Denmark.¹³ In cases of suspected cardiac arrest, a MECU always accompanies the ambulance.

In the Region of Southern Denmark, the Lund University Cardiopulmonary Assist System (LUCAS, Physio-Control Inc., Lund, Sweden), a piston-type device, has been used in two regional MECUs since January 2014. From September 1st 2015, a piston type mech-CPR device was available in all MECUs in the region and has been used at the discretion of the attending anaesthesiologists when treating prehospital patients in cardiac arrests.

2.2 | Study population

During the study period from January 2015 to March 2017, all patients with out-of-hospital cardiac arrest (OHCA) treated with mech-CPR and/or manual-CPR were assessed for inclusion.

2.3 | Data sources

The information sources consisted of the MECU discharge summaries, the prehospital and in-hospital medical records, and the autopsy reports. All autopsies were performed at the Department of Clinical Pathology at Odense University Hospital or at the Institute of Forensic Medicine at The University of Southern Denmark, Odense.

2.4 | Inclusion criteria

- Prehospital cardiopulmonary resuscitation initiated by or maintained by the MECU.

Editorial Comment

This article confirms that manual as well as mechanical chest compressions are associated with skeletal and visceral injuries. Mechanical compressions and duration of CPR are associated with more injuries. So far, no studies have shown better general survival with mechanical chest compressions. This article is accompanied by an editorial.

- Patient 18 years or older.

2.5 | Exclusion criteria

- Patients declared dead by the MECU physician at the scene without any physician-directed resuscitation attempts.
- Cardiac arrest caused by trauma.
- Age less than 18 years.
- Unavailable or incomplete medical data.

2.6 | Data collection

The following information was collected:

- Age, sex, type of chest compression (manual-CPR or mech-CPR), duration of chest compression, patient's medication including anticoagulant therapy at the time of the OHCA, Body Mass Index (BMI), and survival to discharge.
- All clinically registered injuries were recorded. This included all injuries described in the medical records and/or the autopsy records. The injuries were registered according to the anatomical location of injury and the perceived severity of the injury.

2.7 | Injury assessment

Injuries were registered by manual review of all medical files and available autopsy records. All written entries or perioperative findings describing injuries that could be attributed to the preceding chest compression were recorded. Furthermore, all descriptions following diagnostic imaging procedures were reviewed for indications of injuries related to the chest compression. These imaging diagnostics included findings from plain radiologic examinations, computerized tomographic imaging, magnetic resonance imaging, and ultra-sonographic findings.

According to the practice in Denmark, autopsies were performed in cases requested by the hospital or the patient's relatives and in cases where medicolegal investigations led the police to order a forensic autopsy. Injuries were subcategorized into visceral injuries and skeletal injuries.

To determine the severity of the registered injuries, a pre-study definition of potentially life-threatening injuries was established

by a forensic pathologist (Author BSA) as: Contusions of the heart, liver, spleen, and/or pancreas, lacerations of the lung, haemopericardium, rupture of the spleen or the gastric ventricle, and haemoperitoneum.

2.8 | Considerations regarding data quality and data completeness

Dual data entry was applied to minimize the risk of data-input errors.

Patients declared dead at the scene who did not have an autopsy performed and whose medical records did not contain any descriptions of injuries or diagnostic imaging were considered lost to follow-up.

2.9 | Statistical analysis

Statistical analyses were performed using STATA 15, College Station, TX. For descriptive analyses, percentages were used for categorical data. Median and quartiles were used for continuous data. Fishers exact test was applied for categorical values. Wilcoxon rank sum test was applied for continuous variables. A two-sided $P < 0.05$ was considered significant.

Logistic regression analysis was applied to investigate the association between manual-CPR and mech-CPR and sex, age, duration of compressions, BMI and current anticoagulant therapy. The total numbers of all injuries are presented with the odds ratio (OR) estimate and 95% confidence limits.

Data are presented according to the STROBE initiative.¹⁴

2.10 | Ethical issues

This study was approved by the Danish Patient Safety Authority (ref. no. 3-3013-786/1) and the Danish Data Protection Agency (ref. no. 17 /9159).

3 | RESULTS

3.1 | Baseline data

The screened population consisted of 1440 patients. Following exclusion according to the predefined criteria, the study population consisted of 84 patients receiving mech-CPR and 353 patients receiving manual-CPR. A flowchart of the study population is shown in Figure 1.

The baseline characteristics are shown in Table 1. Patients that received mech-CPR as adjunct to manual-CPR were younger (median 55 years vs 63 years) and received chest compressions of longer duration than the patients receiving only manual-CPR (median 53 minutes vs 19 minutes). There was no difference in sex, BMI, or anticoagulant therapy between the two groups, nor did the proportion of patients that had received bystander CPR prior to arrival of the ambulance differ between the two groups. In the mech-CPR group, 35.9% underwent autopsy while 39.1% underwent autopsy in the manual-CPR group ($P = 0.36$). A significant larger number of injuries were found in the group where an autopsy was performed (53.9%) compared to the group that did not undergo autopsy (46.2%) ($P < 0.001$).

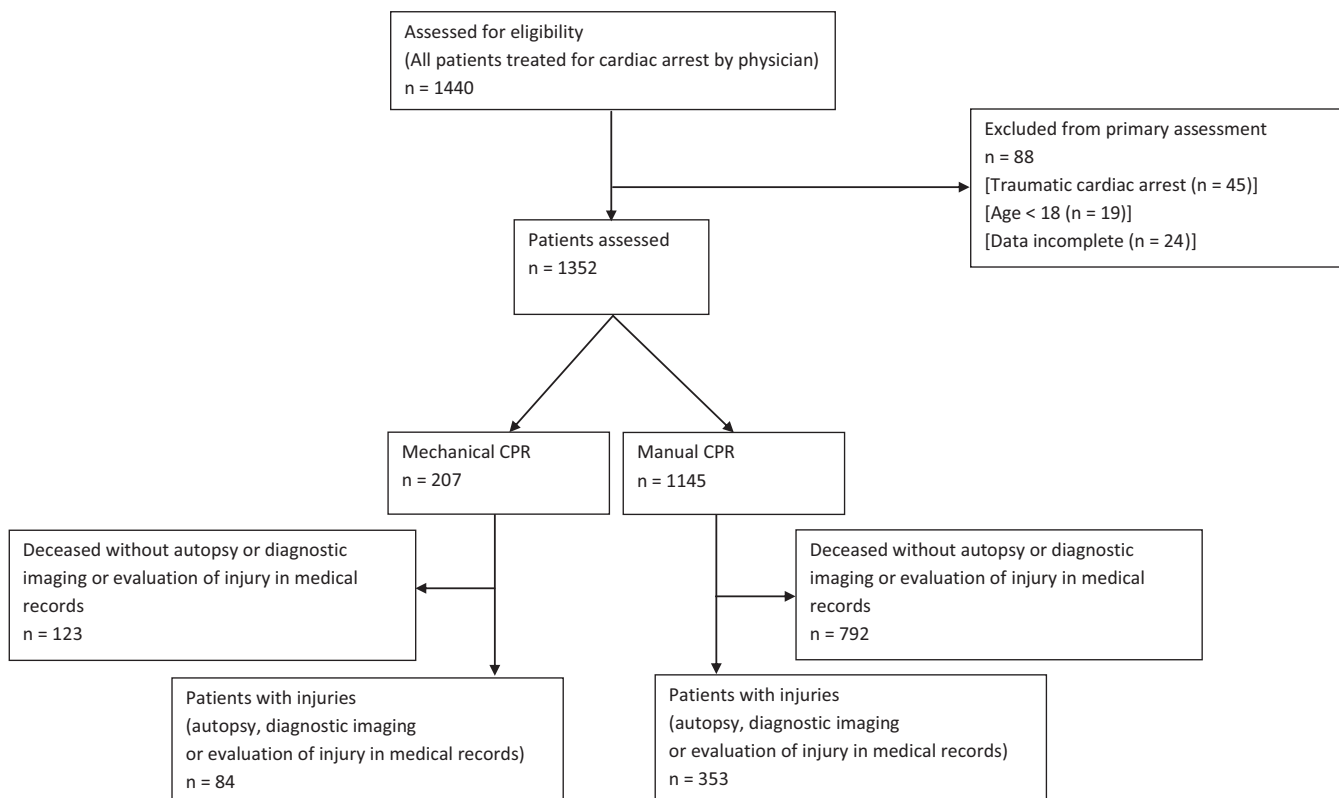


FIGURE 1 Flowchart over study population

Variable	Manual (n = 353)	Mechanical (n = 84)	P-value
Age (y), median (IQR)	63 (53-73)	55 (46.5-65.5)	<0.001
Sex, n (%)			
Male	260 (73.7)	62 (73.8)	0.55
Female	93 (26.4)	22 (26.2)	
CPR duration (min), median (quartiles)	19 (9-24)	53 (25-80)	<0.001
Bystander CPR, n (%)			
Yes	162 (45.9)	45 (53.6)	0.36
No	184 (52.1)	37 (44.1)	
N/A	7 (3.0)	3 (4.0)	
Anticoagulant therapy, n (%)			
Yes	114 (32.3)	21 (25.0)	0.24
No	232 (65.7)	61 (72.6)	
N/A	7 (2.0)	2 (2.4)	
Body mass index (kg/m ²), median (quartiles)	27.7 (23.75-30.44)	26.9 (23.85-30.83)	0.24

TABLE 1 Demographics: Overview of the study population consisting of patients receiving manual chest compression and patients receiving mechanical chest compression

Injury	Manual-CPR (N = 353)	Mech-CPR (N = 84)	P-value
<i>Skeletal injuries</i>			
Rib fractures			
≥3	53 (15.0)	27 (32.1)	<0.001
<3	12 (3.4)	0 (0.0)	0.07 (NS*)
Flail chest	2 (0.6)	5 (6.0)	0.004
Sternal fractures, n (%)	20 (8.5)	17 (20.2)	0.005
Vertebral fracture, n (%)	1 (0.3)	0 (0.0)	1.00 (NS*)
<i>Visceral injuries</i>			
Intra-thoracic injuries, n (%)			
Lung contusion	11 (3.1)	18 (21.4)	<0.001
Skin, fat, or muscle contusion	0 (0.0)	11 (13.1)	<0.001
Heart contusion	0 (0.0)	5 (6.0)	<0.001
Lung laceration	0 (0.0)	1 (1.2)	0.19 (NS*)
Hemopericardium	0 (0.0)	1 (1.2)	0.19 (NS*)
Hemothorax	2 (0.6)	2 (2.4)	0.17 (NS*)
Pneumothorax	10 (2.8)	2 (2.4)	0.57 (NS*)
Intra-abdominal injuries, n (%)			
Liver contusion	1 (0.3)	4 (4.8)	0.005
Spleen contusion	2 (0.6)	1 (1.2)	0.47 (NS*)
Kidney contusion	0 (0.0)	2 (2.4)	0.04
Pancreas contusion	0 (0.0)	1 (1.2)	0.19 (NS*)
Spleen rupture	0 (0.0)	2 (2.4)	0.04
Hemoperitoneum	0 (0.0)	1 (1.2)	0.19 (NS*)
Gastric ventricle rupture	0 (0.0)	1 (1.2)	0.19 (NS*)

TABLE 2 Injury characteristics: Prevalence of skeletal and visceral injuries found in each of the groups: Patients receiving manual chest compression and patients receiving mechanical chest compression (N = total number of injuries in each group; % denotes the percentage of patients with the specific injury in each group.)

3.2 | Injury characteristics

All injuries were grouped in two subcategories: Skeletal injuries and visceral injuries (see Table 2). Skeletal injuries were found in 20.2% of patients with mech-CPR and in 7.9% of patients with manual-CPR ($P = 0.002$). Visceral injuries were found in 14.3% of patients receiving mech-CPR as adjunct and in 1.1% of patients receiving only manual-CPR ($P < 0.001$). In 16 cases, visceral injuries in the form of contusions of the heart, skin, fat, or muscle were observed in the mech-CPR group. No injuries of this kind were found in the manual-CPR group. This difference was significant ($P < 0.001$).

No other individual injuries were significantly associated with either type of chest compression. In the group of patients receiving mech-CPR group as adjunct, however, both skeletal and visceral injuries lesions tended to be more extensive.

See Table 2 for a detailed overview of individual injuries.

Table 3 shows crude and adjusted ORs for injuries overall. The crude analysis showed that receiving mech-CPR as adjunct was associated with a significantly higher incidence of injuries than manual-CPR ($P < 0.001$, OR 3.16, CI 1.82-5.48). When adjusted for the total duration of CPR, this difference proved insignificant ($P = 0.18$). Additional adjustments for age, gender, anticoagulant therapy, bystander CPR, and BMI had no impact on the result.

The duration of CPR was associated with increased ORs for injuries in both groups ($P = 0.02$).

In the mech-CPR group, 10.7% of the injuries were considered potentially life threatening, while none of the injuries in the manual-CPR group fell into this category ($P < 0.001$). Patients treated with mech-CPR as adjunct had higher ORs for lung contusions ($P < 0.001$, OR 25.13, CI 6.93-118.87) and for flail chest ($P = 0.02$, OR 21.24, CI 1.57-287.62).

The presence of skeletal injuries was associated with the occurrence of visceral injuries in all patients ($P = 0.04$, OR 2.33, CI 1.03-5.28). Patients subjected to mech-CPR as adjunct had an increased OR for visceral injuries (crude analysis: $P < 0.0001$, OR 14.54, CI 4.56-46.37; adjusted analysis: $P < 0.001$, OR 29.84, CI 5.96-105.90). (See Table 4 for details).

4 | DISCUSSION

4.1 | Principal findings

In the present study, we have found a considerable risk of skeletal as well as visceral injuries when performing chest compressions. The risk of injuries seems to increase with the duration of CPR. Overall, we found that when adjusted for the duration of chest compression, the occurrence of injuries did not differ between patients receiving manual-CPR only and patients receiving mech-CPR as adjunct. However, regardless of adjusting for confounding factors, mech-CPR as adjunct to manual-CPR was associated with both a higher number of injuries per patient and a significantly higher number of visceral injuries.

There is uniform agreement that external chest compression per se may result in intrathoracic and intraabdominal injuries.¹⁵⁻²³

Several studies concerning manual-CPR alone report no association between the duration of chest compression and injuries.^{7,15,16,24,25} A proposed theory is that the injuries occur within the first minutes of CPR due to peak of energy at first compression.^{15,25} This theory has recently been challenged by three research groups all reporting an association between the duration of chest compression and injuries.^{20,22,26} The findings in these three studies are supported in our study, where we have found an association between

TABLE 3 Injuries associated with chest compression: Crude and adjusted odds ratios for injuries overall in the two groups: Patients receiving manual chest compression and patients receiving mechanical chest compression

Variable	Crude		Adjusted ^a	
	OR (95% CI)	P-value	OR (95% CI)	P-value
Type of CPR				
Manual	1 [Reference]		1 [Reference]	
Mechanical	3.16 (1.82-5.48)	<0.001	1.87 (0.75-4.64)	0.18 (*NS)
Age 1-y increase	0.99 (0.97-1.01)	0.23 (*NS)	0.99 (0.97-1.02)	0.61 (*NS)
Sex				
Male	1 [Reference]		1 [Reference]	
Female	0.89 (0.51-1.57)	0.50 (*NS)	1.07 (0.51-2.24)	0.87 (*NS)
Duration of CPR 1-min increase	1.03 (1.01-1.04)	<0.001	1.02 (1.01-1.04)	0.01
Anticoagulant therapy				
No	1 [Reference]		1 [Reference]	
Yes	1.14 (0.93-1.41)	0.21 (*NS)	2.02 (0.90-5.41)	0.09 (*NS)
Body mass index	1.00 (0.95-1.04)	0.89 (*NS)	1.01 (0.94-1.07)	0.86 (*NS)

Odds ratio adjusted for type of chest compression, duration of chest compression, age, sex, bystander chest compression, body mass index and anticoagulant therapy.

^aAdjusted for: Type of CPR, duration of CPR, age, sex, anticoagulant therapy and BMI.

Variable	Crude		Adjusted ^a	
	OR (95% CI)	P-value	OR (95% CI)	P-value
Skeletal injuries	2.95 (1.53-5.68)	<0.001	3.34 (0.86-6.40)	0.1 (NS*)
Soft tissue injuries	14.54 (4.56-46.37)	<0.001	29.84 (5.12-173.97)	<0.001

Odds ratio adjusted for type of chest compression, duration of chest compression, age, sex, bystander chest compression, body mass index and anticoagulant therapy.

^aAdjusted for: Type of CPR, duration of CPR, age, sex, anticoagulant therapy and BMI.

duration of compression and the occurrence of injuries regardless of the type of chest compression.

We found an overall association between injuries and the supplemental use of mech-CPR, although this association waned when adjusted for duration of CPR. However, when the injuries were subcategorized in skeletal and visceral injuries and adjusted for duration of chest compression, our data showed a strong association between mech-CPR and visceral injuries. Furthermore we observed an increasing risk of visceral injuries with an increasing number of skeletal injuries. This is in concordance with previous studies concerning injuries as a result of manual-CPR.^{7,27}

In an in-hospital setting, mechanical chest compression has been shown not to cause more visceral injury than manual chest compression.¹⁹ However, in prehospital use, taking all prehospital events into consideration, including the initial manual-CPR, the application of the LUCAS device, and the transportation of the patient with ongoing mech-CPR, we found that mech-CPR performed with a piston-type device apparently caused more severe injury than manual-CPR alone.

The duration of CPR was significantly different between the mech-CPR group and the manual-CPR group. This can be explained by application of the LUCAS device primarily when transporting patients over long distances. This is in concordance with ERC guidelines suggesting the use of mech-CPR in a moving ambulance where provider safety is at risk.⁴ It should however, be of some concern that the same measure that ensures safety for the provider, in our study, at least, seems to increase the risk for the patient.

As in three other studies, we found a strong association between injuries and duration of chest compression.^{20,22,26} This calls for measures to reduce the prehospital duration of chest compression. In high-volume centres, extracorporeal circulation has thus been considered.²⁸

4.2 | Strengths and limitations

One of the strengths of this study is that the study is a pragmatic study. Our study has investigated the injuries associated with the general utilisation of the mech-CPR as a supplemental treatment modality by examining a general prehospital application of the LUCAS-device as recommended in the European Resuscitation Council (ERC) guidelines⁴ within a regional emergency medical service.

Another strength of this study is the inclusion of both survivors and non-survivors and our combined review of both autopsy reports and medical records. This is a pragmatic method of securing as little

loss of information as possible. Furthermore, we excluded all patients with cardiac arrest following trauma. In this way, we have sought to eliminate potential bias caused by injuries of other external character.

This study had considerable limitations. While we believe that external validity is enhanced by our study being a pragmatic one, this approach is a weakness as well. We have thus lost a large number of patients to follow-up due to the decision of not performing autopsies. This may have induced selection bias. However, due to the decreasing number of autopsies in recent years in Denmark and other Scandinavian countries, this limitation cannot be overcome,²⁹ not even by performing a randomised controlled trial, as the decision to perform an autopsy may be overturned by the deceased patients' relatives.

A further weakness is that all patients with mech-CPR also received manual compressions prior to the application of the device. This is a potential limitation as it has been suggested, albeit contradictory to our findings, that injuries associated with chest compression occur within the first minutes.²⁵ One may, however, regard our study as simply a study on the effects of the application of mech-CPR upon routine OHCA treatment. As such, we believe that this limitation is minor.

One significant limitation was the difference between groups. Patients in the mech-CPR group were younger and received chest compression of a longer duration than patients receiving manual-CPR. This might have induced bias in the form of confounding by indication. We believe, however, that we have reduced some of this bias by adjusting for duration and age in our regression analysis.

5 | CONCLUSIONS

In this study, we have found that prolonged duration of chest compression of any kind is associated with an increasing prevalence of injuries of all types.

Furthermore, we have found that in the prehospital setting, the extent of visceral injuries and potentially life-threatening injuries is larger in patients receiving mech-CPR as an adjunct than in patients receiving manual-CPR alone.

AUTHORS' CONTRIBUTION

L. M.: Acquisition of data; drafting the article; analysis and interpretation of data; revising the manuscript critically for important intellectual

TABLE 4 Skeletal injuries and visceral injuries: Crude and adjusted odds ratios for skeletal and visceral injuries in the two groups: Patients receiving manual chest compression and patients receiving mechanical chest compression

content; final approval of the version to be submitted. B. S. A.: The conception and design of the study; analysis and interpretation of data; revising the manuscript critically for important intellectual content; final approval of the version to be submitted. S. M.: The conception and design of the study; acquisition of data; analysis and interpretation of data; drafting the article; revising the manuscript critically for important intellectual content; final approval of the version to be submitted.

CONFLICTS OF INTEREST

All authors report that there are no conflicts of interest.

ORCID

Søren Mikkelsen  <https://orcid.org/0000-0002-5187-7027>

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