Resuscitation Plus 20 (2024) 100786

Contents lists available at ScienceDirect

Resuscitation Plus

journal homepage: www.elsevier.com/locate/resuscitation-plus

Clinical paper

Complication frequency of mechanical chest compression devices: A single-center, blinded study using retrospective data☆

Takumi Tsuchida [a,*], Takashi Kamiishi [b], Hiroaki Usubuchi [b], Akiko Semba [c], Masaki Takahashi [a], Asumi Mizugaki [a], Mariko Hayamizu [a], Mineji Hayakawa [a], Takeshi Wada [a]

[a] Division of Acute and Critical Care Medicine, Department of Anesthesiology and Critical Care Medicine, Hokkaido University Faculty of Medicine, Sapporo, Japan
[b] Department of Radiology, Sapporo City General Hospital, Sapporo, Japan
[c] Department of Emergency and Critical Care Medicine, Sapporo City General Hospital, Sapporo, Japan

ARTICLE INFO

Keywords:
Cardiac arrest
Mechanical chest compression
Cardiopulmonary resuscitation
Complication
LUCAS

ABSTRACT

Aim: Use of mechanical chest compression devices for patients with cardiac arrest is increasing. As cardiopulmonary resuscitation (CPR) guidelines and LUCAS are updated, the evidence requires updating.

Methods: This single-center, retrospective study observed adult patients with out-of-hospital cardiac arrest receiving CPR from emergency services. Patients were assigned to LUCAS or manual CPR groups, matched by propensity score, and evaluated through computed tomography images by a radiologist blinded to their data. The primary outcome was complications from chest compressions, and logistic regression was used to analyze their risk factors.

Results: Overall, 261 patients were selected and divided into manual and LUCAS groups (n = 69 each). The manual CPR group exhibited higher witnessed cardiac arrest percentages (p = 0.023) and shorter times from scene to emergency department (p = 0.001) and total CPR duration (p = 0.002), versus the LUCAS group. Complication rates showed no significant intergroup differences in overall CPR complications (p = 0.462); however, the LUCAS group reported more hemothorax incidents (p = 0.028), versus the manual group. Logistic regression indicated that female sex (odds ratio [OR] 3.743, 95 % confidence interval [CI] 1.333–10.506), older age (OR 1.089, 95 % CI 1.048–1.132), and longer CPR durations (OR 1.045, 95 % CI 1.006–1.085) significantly correlated with compression complications, whereas LUCAS use did not (OR 0.713, 95 % CI 0.304–1.673).

Conclusion: No association was observed between LUCAS use and the overall incidence of chest compression complications in adults with OHCA. LUCAS is associated with more hemothorax cases and longer transport time, versus manual CPR. Evaluating LUCAS's benefits necessitates multiple perspectives and further research.

Introduction

Cardiopulmonary resuscitation (CPR) has been recognized as an emergency intervention for cardiac arrest since the 1960 s [1,2]. Subsequently, researchers have continued to determine the optimal depth and frequency of chest compressions. This has resulted in the American Heart Association recommending in its 2020 guidelines that chest compressions should be performed at a depth of 5–6 cm and a frequency of 100–120/min [3].

The LUCAS is a piston-type device with a suction cup placed at the center of the chest for compression and active decompression. Since its launch in 2002, it has been used worldwide. The LUCAS has been improved with updated guidelines and is now available in version 3 (LUCAS-3). Manual compressions were found to have several disadvantages, such as inappropriate depth and frequency, and notably, frequent and prolonged interruptions [4–6]. Therefore, it was anticipated that LUCAS could enhance the prognosis of patients with cardiac arrest by addressing these issues.

Several randomized controlled trials have examined the effects of mechanical chest compression devices [7–9]; however, none has shown

☆ CI, confidence interval; CPR, cardiopulmonary resuscitation; CT, computed tomography;; ED, emergency department; EMS, emergency medical services; OHCA, out-of-hospital cardiac arrest; OR, odds ratio; ROSC, return of spontaneous circulation

* Corresponding author at: Division of Acute and Critical Care Medicine, Department of Anesthesiology and Critical Care Medicine, Hokkaido University Faculty of Medicine, N15W7, Kita-ku, Sapporo 060-8638, Japan.

E-mail address: t.tsuchida@pop.med.hokudai.ac.jp (T. Tsuchida).

https://doi.org/10.1016/j.resplu.2024.100786
Received 9 July 2024; Received in revised form 14 September 2024; Accepted 17 September 2024

superiority of mechanical chest compression devices over manual CPR. Notably, the use of mechanical chest compression devices increases the frequency of complications [10–13]. Given this background, the recommendation for mechanical chest compression devices in the latest guidelines is limited to cases where prolonged transport is necessary or the terrain is difficult [14].

However, studies that provided evidence for the guidelines were conducted when mechanical chest compression devices were first introduced. In addition, they do not reflect the updated guidelines and improvements in mechanical chest compression devices that have been made to date. No studies involving actual patients have been conducted since the LUCAS-3 generation. Furthermore, the mechanical chest compression devices used were not uniform, and some study designs were not well-refined [13,15].

Recently, there have been reports that LUCAS does not increase the incidence of traumatic injuries, making the situation increasingly confusing [16]. Meanwhile, we frequently encounter severe chest compression complications in clinical practice, as depicted in Fig. 1, and recent reports continue to affirm these findings [17,18].

Therefore, the aim of this study was to investigate the frequency of complications and characteristics of injuries in a population in which the latest LUCAS was used according to the latest resuscitation guidelines, compared with a population in which manual CPR was performed. The potential risk factors for chest compression complications were also assessed with the use of LUCAS.

Methods

Setting

The study was conducted using data from Sapporo City General Hospital, which receives more than 1,000 emergency patients per year, including 500 critically ill patients. In this facility, patients who are transported for out-of-hospital cardiac arrest always undergo computed tomography (CT) to determine the cause of cardiac arrest or postmortem CT, except in case of special reasons, such as lack of consent.

In Japan, a domestic guideline, that the use of mechanical chest compression devices should be managed by local medical control, was established in 2015. Since then, the use of mechanical chest compression devices has been gradually implemented in the emergency medical services (EMS) in each region.

In Sapporo EMS, where the research was carried out, the introduction of chest compression devices commenced in March 2021. The Sapporo EMS comprised 35 units during the study period. Of these units, 13 were equipped with chest compression devices from March 15, 2021, to January 31, 2023, and 26 units from April 2022 to January 31, 2023. The specific device utilized was the LUCAS-3 (version 3.1). Prior to implementing the LUCAS-3, a 2-week training session was conducted to ensure that all EMS personnel were adept at using the device. The use of LUCAS-3 was governed by the protocol outlined in Supplementary file 1.

All Japanese EMS personnel are trained to perform CPR according to the Japanese resuscitation guidelines, which adhere to the recommendations set forth by the International Liaison Committee on Resuscitation. Furthermore, EMS personnel are legally required to continue resuscitation efforts at the scene; patients experiencing out-of-hospital cardiac arrest (OHCA) are invariably transported to the hospital unless death is unmistakably confirmed. Specifically, patients with OHCA are unconditionally conveyed to the closest critical care center, as mandated by the regional protocol where the study was conducted.

Patient selection and data collection

Consecutive patients for whom data were collected were patients with OHCA transported to Sapporo City General Hospital between March 1, 2021, and January 31, 2023. Data were extracted from the Sapporo Fire Bureau database, which contains records of all emergency transportations in Sapporo.

The patients with OHCA were adults aged 18 years or older who did not receive bystander CPR. This is attributed to the often inaccurate record of chest compressions by bystanders, alongside variations in their intensity and location. The exclusion criteria included: return of spontaneous circulation (ROSC) upon EMS arrival, CPR duration less than 5 min, cardiac arrest due to trauma (including suspected cases), absence of postmortem CT, and terminal stages of malignancy.

Data collected from the Sapporo Fire Bureau encompassed basic information such as age, sex, witnessed cardiac arrest, and initial electrocardiogram, in addition to detailed time lapses concerning EMS activities. These included the time of contact with the patient, initiation of chest compressions, application of LUCAS-3, achievement of ROSC, and arrival at the hospital. These data were correlated with medical records from Sapporo City General Hospital to gather CT data and prognostic information, including survival and hospitalization rates.

Study design

This single-center retrospective study used data from patients previously transferred to Sapporo City General Hospital. The design was specific to the evaluation of complications by limiting patients to a population without history of trauma, in whom only the EMS performed chest compressions, thus eliminating bias as much as possible. The present study was performed as a complete-case analysis, eliminating cases with missing values. The patients for whom data were collected were divided into the LUCAS and manual CPR groups and matched using propensity scores. After matching, patients were evaluated for chest compression complications by a single diagnostic radiologist (Dr. Takashi Kamiishi), who was blinded to patient information.

Outcomes and definitions

The primary outcome of this study was complications due to chest

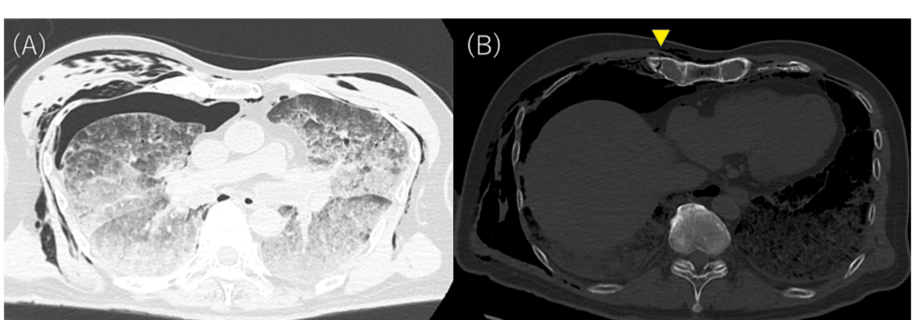

Fig. 1. Example of chest compression complication during prolonged mechanical cardiopulmonary resuscitation (A) Computed tomography (CT) of lung window at the level of the pulmonary arteries, showing pneumothorax, mediastinal emphysema, and subcutaneous emphysema. (B) CT of soft tissue window at the level of the liver showing pneumothorax, mediastinal emphysema, subcutaneous emphysema, as well as costal cartilage fracture (yellow annotation).

compressions. Specifically, rib fractures, sternal fractures, pneumothorax, hemothorax, anterior mediastinal hematoma, dorsal sternal hematoma, and bloody pericardial fluid were investigated. In the current study, a patient was considered “complicated” if any of these injuries were observed.

The incidence of rib fractures, including cases of multiple rib fractures, was assessed as a secondary outcome. In our study, multiple rib fractures were specifically defined as ten or more rib fractures, to focus on the occurrence of severe complications. The CT slice thickness specified at Sapporo City General Hospital was 3 mm for the soft tissue windows and 2 mm for the lung and bone windows. Rib fractures of indeterminate age were not classified as rib fractures, and pericardial fluid present in cases of aortic dissection was not considered a complication related to chest compression. Radiological assessments were conducted using non-enhanced CT.

Statistical analysis

The patient groups were propensity score-matched, with LUCAS use as the dependent variable, and age, sex, and chest compression duration as independent variables. Calipers were set at 0.2 times the standard deviation of the propensity score. Outcomes assessed by a blinded diagnostic radiologist were compared between the two matched groups. In addition, to verify the robustness of the results of the main analysis, logistic regression analysis was performed on the matched cases. The response variable was the presence of chest compression complications, as in the main analysis outcome. For the explanatory variables, one-tenth of those in the events category were selected. Specifically, four risk factors for chest compression complications were selected upon clinical consideration: age, sex, implementation of mechanical CPR, and CPR duration. Age and CPR duration were used as continuous variables.

As the numerical variables in the data set used in this study were non-normally distributed, they are presented as medians and interquartile ranges, and the Mann–Whitney *U* test was used for analysis. Patient characteristics and outcomes were compared between the two groups using the Mann–Whitney *U* test (for numerical variables), Fisher’s exact test (for categorical variables), and the chi-square test (for categorical variables). All analyses were performed using IBM SPSS software version 25 (IBM Japan, Tokyo, Japan). All reported p-values were two-tailed, and differences with $p < 0.05$ were considered statistically significant.

Ethics

All procedures were performed in accordance with the World Medical Association Declaration of Helsinki, and the manuscript was prepared in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement. A completed STROBE checklist is presented as Supplementary file 2. This was a retrospective study with no invasions or interventions performed for research purposes on the patients. Therefore, consent was obtained via an opt-out method, which provides patients the opportunity to refuse to participate in the study by information disclosed about the study, rather than by obtaining their individual consent. Information regarding the conduct of the study, including its purpose, is published on the website. The website clearly states the contact information of the principal researcher to be contacted if a research participant and their relatives wants to refuse participation in the study. Written informed consent was obtained from the patient for publication of the accompanying images. Ethical approval was obtained from the Ethics Committee of Sapporo City General Hospital (approval number: r4-063–1007).

Results

A flowchart of the patients included in this study is shown in Fig. 2. Patients with OHCA who were transported to Sapporo City General Hospital were selected from the database, and those who met the

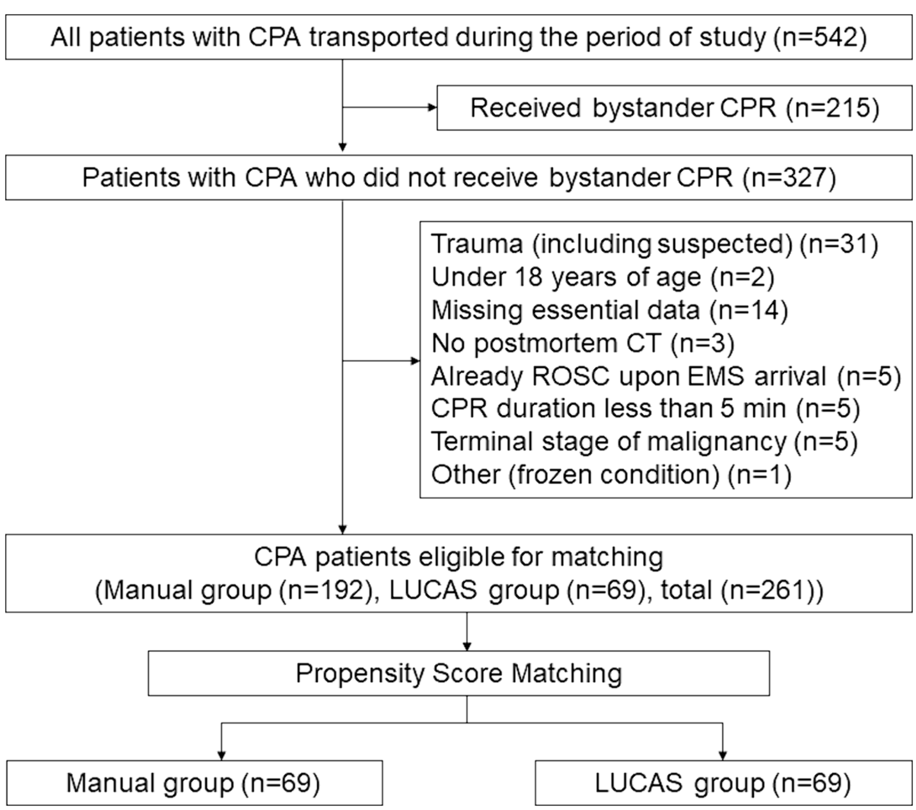

Fig. 2. Flow chart of patient enrollment in this study The odds ratios for age and CPR duration were per year and per minute, respectively. CPA, cardiopulmonary arrest; CPR, cardiopulmonary resuscitation; CT, computed tomography; EMS, emergency medical services; ROSC, return of spontaneous circulation.

exclusion criteria were excluded. This resulted in 261 eligible individuals. The background characteristics of the 261 patients are shown in Table 1. The manual group exhibited a lower percentage of witnessed cardiac arrests, compared with the LUCAS group ($p = 0.023$). Furthermore, the time from calling the EMS to arrival at the scene was not significantly different between the two groups ($p = 0.294$); however, the time from arrival at the scene to arrival at the Emergency Department (ED) and the total CPR duration were significantly shorter in the manual group ($p = 0.001$ and $p = 0.002$, respectively) than in the LUCAS group.

Propensity score matching yielded two groups with 69 patients each (Fig. 2), and statistical adjustments were made (Table 2). The two groups were adjusted via propensity score matching to eliminate significant differences. The frequencies of complications in the matched cohorts are detailed in Table 3. No significant differences were observed between the groups regarding the incidence of complications related to CPR ($p = 0.462$). All patients experiencing complications consistently had rib fractures. Research into the characteristics of rib fractures indicated that the LUCAS group was more likely to suffer from multiple rib fractures, compared with the manual group, although this difference was not significant. Notably, the incidence of hemothorax was significantly higher in the LUCAS group than in the manual group ($p = 0.028$).

Logistic regression analysis showed that female sex (odds ratio [OR] 3.743, 95 % confidence interval [CI] 1.333–10.506), older age (OR 1.089, 95 % CI 1.048–1.132), and longer CPR duration (OR 1.045, 95 % CI 1.006–1.085) were associated with the development of chest compression complications (Fig. 3). However, the use of LUCAS was not a risk factor for chest compression complications (OR 0.713, 95 % CI 0.304–1.673).

Discussion

A blinded radiologist evaluated the frequency of chest compression complications in both the LUCAS and manual CPR groups. In the unadjusted patient population not evaluated for complications, the time from arrival at the scene to arrival in the ED was significantly longer in the LUCAS group than in the manual group. A comparison of the matched patients evaluated for complications showed no significant difference between the two groups in terms of overall complication rates. Additionally logistic regression analysis demonstrated no relationship between the incidence of complications and CPR by LUCAS. Meanwhile, hemothorax was significantly more frequent in the LUCAS group than in the manual group.

The main outcome of this study was the occurrence of chest compression-related complications. Rib fractures are the most common complications of chest compressions during CPR. [19,20] In this study, rib fractures were the most frequent complications, at 68.8 % (95 of 138) overall, 60.2 % (53 of 88) in men, and 84.0 % (42 of 50) in women (data not shown). These frequencies were comparable to those in previous studies of the epidemiology of rib fractures as a chest compression complication (approximately 70 % in male patients and 80 % in female patients) [21].

LUCAS is a device capable of active decompression; therefore, it cannot be said that the occurrence of rib fractures diminished the quality of chest compressions [22,23]. However, the presence of six or more rib fractures or displaced rib fractures due to CPR is associated with longer hospitalization and intensive care unit stays [24]. Currently, the influence of CPR-induced rib fractures on the overall prognosis of patients with OHCA is unclear, as rib fractures often accompany adequate chest compressions.

In contrast, existing studies have shown no difference in the frequency of life-threatening complications between manual and

Table 1
Background in the eligible patient population.

	Manual group (n = 192)	LUCAS group (n = 69)	p value
Sex (male, %)	105 (54.7)	43 (62.3)	0.261
Age (years)	80.0 (68.0–88.0)	79.0 (74.0–87.0)	0.660
Cardiac arrest witnesses (Yes, %)	68 (35.4)	35 (50.7)	0.023
Intrinsic CPA (n, %)	160 (83.3)	60 (87.0)	0.565
CPA after EMS contact (n, %)	27 (14.1)	6 (8.7)	0.295
Initial ECG waveform (n, %)			0.459
VF	12 (6.3)	6 (8.7)	
VT	0 (0.0)	0 (0.0)	
PEA	27 (14.1)	18 (26.1)	
Asystole	128 (66.7)	38 (55.1)	
Other	25 (13.0)	7 (10.1)	
Time from calling EMS to arrival at the scene (min)	9.0 (8.0–11.0)	8.0 (7.0–10.0)	0.294
Time from arrival at the scene to arrival at the ED (min)	26.0 (21.0–32.0)	30.0 (27.0–36.0)	0.001
Total CPR duration (min)	33.0 (27.0–40.0)	40.0 (33.0–46.0)	0.002
Deaths in the ED (n, %)	177 (92.2)	62 (89.9)	0.459

Data is presented as median (25th–75th percentile), percentage, or numbers. CPA, cardiopulmonary arrest; CPR, cardiopulmonary resuscitation; ECG, electrocardiography; ED, emergency department; EMS, emergency medical services; PEA, pulseless electrical activity; VF, ventricular fibrillation; VT, ventricular tachycardia.

Table 2
Patient background after propensity score matching.

	Manual group (n = 69)	LUCAS group (n = 69)	p value
Sex (male, %)	45 (65.2)	43 (62.3)	0.860
Age (years)	80.0 (74.0–86.0)	79.0 (74.0–87.0)	0.992
Cardiac arrest witnesses (Yes, %)	31 (44.9)	35 (50.7)	0.609
Intrinsic CPA (n, %)	59 (85.5)	60 (87.0)	1.000
CPA after EMS contact (n, %)	8 (11.4)	6 (8.7)	0.779
Initial ECG waveform (n, %)			0.935
VF	7 (10.0)	6 (8.7)	
VT	0 (0.0)	0 (0.0)	
PEA	18 (25.7)	18 (26.1)	
Asystole	39 (52.2)	38 (55.1)	
Other	5 (7.1)	7 (10.1)	
Time from calling EMS to arrival at the scene (min)	8.0 (7.0–10.0)	8.0 (7.0–10.0)	0.529
Time from arrival at the scene to arrival at the ED (min)	28.0 (22.0–36.0)	30.0 (27.0–36.0)	0.098
Total CPR duration (min)	38.0 (30.0–50.0)	40.0 (33.0–46.0)	0.811
Deaths in the ED (n, %)	67 (95.7)	62 (89.9)	0.325

Data is presented as median (25th–75th percentile), percentage, or numbers. CPA, cardiopulmonary arrest; CPR, cardiopulmonary resuscitation; ECG, electrocardiography; ED, emergency department; EMS, emergency medical services; PEA, pulseless electrical activity; VF, ventricular fibrillation; VT, ventricular tachycardia.

Table 3
Complication frequency of chest compression in each group.

	Manual group (n = 69)	LUCAS group (n = 69)	p value
Injury likely caused by CPR (%)	**45 (65.2)**	**50 (72.5)**	**0.462**
Rib fracture (%)	45 (65.2)	50 (72.5)	0.462
Sternum fracture (%)	9 (13.0)	10 (14.5)	1.000
Pneumothorax (%)	3 (4.3)	3 (4.3)	1.000
Hemothorax (%)	0 (0.0)	6 (8.7)	0.028
Anterior mediastinal hematoma (%)	8 (11.6)	6 (8.7)	0.779
Dorsal sternal hematoma (%)	1 (1.4)	3 (4.3)	0.619
Bloody pericardial fluid (%)	0 (0.0)	3 (4.3)	0.245
Characteristics of rib fracture			
Total number of rib fractures	5.0 (0.0–8.0)	6.0 (0.0–9.0)	0.080
Total number of rib fractures≧10 (%)	9 (12.9)	16 (23.9)	0.184

Data is presented as median (25th–75th percentile), percentage, or numbers. CPR, cardiopulmonary resuscitation

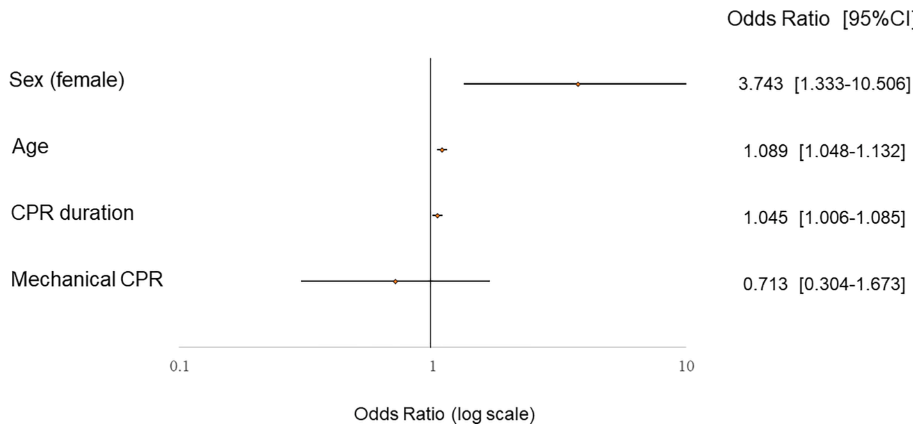

Fig. 3. Results of logistic regression analysis CPR, cardiopulmonary resuscitation.

mechanical compressions [13]. However, this study found that the incidence of hemothorax, which is considered a relatively serious complication, was significantly higher in the LUCAS group than in the manual group (Table 3). Moreover, bloody pericardial fluid was found only in the LUCAS group, although the difference was not significant. Thus, there was no change in the trend toward a higher complication frequency in the mechanical chest compression group in this study or in existing studies [11–13].

Logistic regression analysis showed more chest compression complications in female patients, older patients, and patients with longer CPR duration (Fig. 3). The benefits of LUCAS include a reduced burden on EMS [25], its usefulness in confined environments [23,26], and stable chest compression [22,27]. Furthermore, this study showed that the use of LUCAS may increase transport time, although the exact causal relationship remains unknown (Table 1). This may have been due to the time required to apply LUCAS. Moreover, previous studies have reported a prolonged time to first defibrillation with LUCAS [23]. Thus, the evaluation of the benefits of LUCAS requires a multifaceted perspective. This study evaluated only complications and not prognosis, therefore, further studies are required.

Limitations

This study was designed to eliminate the influence of confounding factors as much as possible; however, it has some limitations. First, this was a single-center retrospective study, and patient selection bias by region or hospital may have been present, interfering with the generalizability of the results. Second, the information available from the patients was limited, and characteristics such as blood pressure, alcohol intake, and smoking habits possibly confounded the results. Although results were adjusted for sex and age, there was no specific information regarding patient height or weight. Finally, because radiological interpretations were not performed for all postmortem CT scans owing to human and time constraints, the complication frequencies in the unadjusted subset could not be assessed. In addition, as the images were evaluated by a single radiologist, no interobserver variation was present in the evaluation, but the interpretation of the results might have been biased.

Conclusions

No association was observed between LUCAS use and the overall incidence of chest compression complications in adults with OHCA. However, the incidence of relatively severe complications, such as hemothorax, may be high. Transport time is longer in the LUCAS group than in the manual group. Future multifaceted evaluations of the influence of LUCAS are required to accumulate evidence for improving the prognosis of patients with cardiac arrest.

Funding.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Takumi Tsuchida: Project administration, Methodology, Formal analysis, Conceptualization. **Takashi Kamiishi:** Data curation. **Hiroaki Usubuchi:** Writing – review & editing, Supervision. **Akiko Semba:** Data curation. **Masaki Takahashi:** Writing – original draft, Data curation. **Asumi Mizugaki:** Data curation. **Mariko Hayamizu:** Writing – original draft, Conceptualization. **Mineji Hayakawa:** Writing – original draft, Formal analysis. **Takeshi Wada:** Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank Mikiyoshi Taniuchi and Masaaki Onishi, employees of the Sapporo Fire Bureau, for their efforts in data collection. We would also like to thank Editage (https://online.editage.jp/) for the English language editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resplu.2024.100786.

References

1. Jude JR, Kouwenhoven WB, Knickerbocker GG. Cardiac arrest: Report of application of external cardiac massage on 118 patients. *JAMA*. 1961;178:1063–1070.
2. Kouwenhoven WB, Jude JR, Knickerbocker GG. Closed-chest cardiac massage. *JAMA*. 1960;173:1064–1067.
3. Panchal AR, Bartos JA, Cabañas JG, et al. Part 3: adult basic and advanced life support: 2020 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. *Circulation*. 2020;142:S366–S468.
4. Wik L, Kramer-Johansen J, Myklebust H, et al. Quality of cardiopulmonary resuscitation during out-of-hospital cardiac arrest. *JAMA*. 2005;293:299–304.
5. Berg RA, Hemphill R, Abella BS, et al. Part 5: Adult basic life support: 2010 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. *Circulation*. 2010;122(Supplement 3):S685–S705.
6. Sugerman NT, Edelson DP, Leary M, et al. Rescuer fatigue during actual in-hospital cardiopulmonary resuscitation with audiovisual feedback: A prospective multicenter study. *Resuscitation*. 2009;80:981–984.

7. Perkins GD, Lall R, Quinn T, et al. Mechanical versus manual chest compression for out-of-hospital cardiac arrest (PARAMEDIC): A pragmatic, cluster randomized controlled trial. *Lancet*. 2015;385:947–955.
8. Wik L, Olsen J-A, Persse D, et al. Manual vs. integrated automatic load-distributing band CPR with equal survival after out of hospital cardiac arrest. The randomized CIRC trial. *Resuscitation*. 2014;85:741–748.
9. Smekal D, Johansson J, Huzevka T, Rubertsson S. A pilot study of mechanical chest compressions with the LUCAS™ device in cardiopulmonary resuscitation. *Resuscitation*. 2011;82:702–706.
10. Wik L. Automatic and manual mechanical external chest compression devices for cardiopulmonary resuscitation. *Resuscitation*. 2000;47:7–25.
11. Baubin M, Sumann G, Rabl W, Eibl G, Wenzel V, Mair P. Increased frequency of thorax injuries with ACD-CPR. *Resuscitation*. 1999;41:33–38.
12. Harrison-Paul R, Resuscitation great. A history of mechanical devices for providing external chest compressions. *Resuscitation*. 2007;73:330–336.
13. Gao Y, Sun T, Yuan D, et al. Safety of mechanical and manual chest compressions in cardiac arrest patients: A systematic review and meta-analysis. *Resuscitation*. 2021; 169:124–135.
14. Lott C, Truhlář A, Alfonzo A, et al. European Resuscitation Council Guidelines 2021: Cardiac arrest in special circumstances. *Resuscitation*. 2021;161:152–219.
15. Primi R, Bendotti S, Currao A, et al. Use of mechanical chest compression for resuscitation in out-of-hospital cardiac arrest-device matters: A propensity-score-based match analysis. *J Clin Med*. 2023:12.
16. Saleem S, Sonkin R, Sagy I, et al. Traumatic Injuries Following Mechanical versus Manual Chest Compression. *Open Access Emerg Med*. 2022;14:557–562.
17. Yamada T, Nakao S, Fukuma H, Matsuoka T. Delayed massive bleeding from minor splenic injury due to mechanical chest compression for cardiopulmonary resuscitation. *Acute Med Surg*. 2023;10:e845.
18. Waqar A, Rajput F, Rachwan RJ, Abi-Saab T, Gimelli G. LUCAS compression device-related severe injuries in a series of patients presenting with outside hospital cardiac arrest. *J Cardiol Cases*. 2022;26:432–435.
19. Krischer JP, Fine EG, Davis JH, Nagel EL. Complications of cardiac resuscitation. *Chest*. 1987;92:287–291.
20. Friberg N, Schmidbauer S, Walther C, Englund E. Skeletal and soft tissue injuries after manual and mechanical chest compressions. *Eur Heart J Qual Care Clin Outcomes*. 2019;5:259–265.
21. Kralj E, Podbregar M, Kejžar N, Balažic J. Frequency and number of resuscitation related rib and sternum fractures are higher than generally considered. *Resuscitation*. 2015;93:136–141.
22. Gyory RA, Buchle SE, Rodgers D, Lubin JS. The efficacy of LUCAS in prehospital cardiac arrest scenarios: A crossover mannequin study. *West J Emerg Med*. 2017;18: 437–445.
23. Putzer G, Braun P, Zimmermann A, et al. LUCAS compared to manual cardiopulmonary resuscitation is more effective during helicopter rescue-a prospective, randomized, cross-over manikin study. *Am J Emerg Med*. 2013;31: 384–389.
24. Prins JTH, Van Lieshout EMM, Van Wijck SFM, et al. Chest wall injuries due to cardiopulmonary resuscitation and the effect on in-hospital outcomes in survivors of out-of-hospital cardiac arrest. *J Trauma Acute Care Surg*. 2021;91:966–975.
25. Rehatschek G, Muench M, Schenk I, et al. Mechanical LUCAS resuscitation is effective, reduces physical workload and improves mental performance of helicopter teams. *Minerva Anestesiol*. 2016;82:429–437.
26. Chen CB, Chen KF, Chien CY, et al. Shoulder strap fixation of LUCAS-2 to facilitate continuous CPR during non-supine (stair) stretcher transport of OHCAs patients. *Sci Rep*. 2021;11:9858.
27. Şan İ, Bekgöz B, Ergin M, Usul E. Manual cardiopulmonary resuscitation versus mechanical cardiopulmonary resuscitation: Which one is more effective during ambulance transport? *Turk J Emerg Med*. 2021;21:69–74.