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ORIGINAL ARTICLE

Frequency and influencing factors of cardiopulmonary resuscitation-related injuries during implementation of the American Heart Association 2010 Guidelines: a retrospective study based on autopsy and postmortem computed tomography

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Abstract
Aim To determine the frequency of cardiopulmonary resuscitation (CPR)-related injuries and factors involved in their occurrence, data based on forensic autopsy and postmortem computed tomography (PMCT) during implementation of the 2010 American Heart Association Guidelines for CPR were studied.
Methods We retrospectively evaluated data on adult patients with non-traumatic deaths who had undergone manual CPR and autopsy from January 2012 to December 2014. CPR-related injuries were analyzed on autopsy records and PMCT images and compared with results of previous studies.
Results In total, 180 consecutive cases were analyzed. Rib fractures and sternal fractures were most frequent (overall frequency, 66.1 and 52.8%, respectively), followed by heart injuries (12.8%) and abdominal visceral injuries (2.2%). Urgently life-threatening injuries were rare (2.8%). Older age was an independent risk factor for rib fracture [adjusted odds ratio (AOR), 1.06; 95% confidence interval (CI), 1.04–1.08; $p < 0.001$], ≥ 3 rib fractures (AOR, 1.06; 95% CI, 1.02–1.09; $p = 0.002$), and sternal fracture (AOR, 1.03; 95% CI, 1.01–1.05; $p < 0.001$). Female sex was significantly associated with sternal fracture (AOR, 2.08; 95% CI, 1.02–4.25; $p = 0.04$). Chest compression only by laypersons was inversely associated with rib and sternal fractures. Body mass index and in-hospital cardiac arrest were not significantly associated with any complications. The frequency of thoracic skeletal injuries was similar to that in recent autopsy-based studies.
Conclusions Implementation of the 2010 Guidelines had little impact on the frequency of CPR-related thoracic skeletal injuries or urgently life-threatening complications. Older age was the only independent factor related to thoracic skeletal injuries.

Keywords Cardiopulmonary resuscitation (CPR) · Chest compression · Traumatic injuries · Forensic pathology · Autopsy · Postmortem computed tomography

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Introduction

The American Heart Association (AHA) 2010 Guidelines for cardiopulmonary resuscitation (CPR) suggested increases in the target chest compression depth and frequency to ≥ 5.0 cm and ≥ 100/min, respectively, with no upper limit [1]. These guidelines were based on accumulated evidence that quicker and deeper uninterrupted chest compression increased survival in patients undergoing cardiac arrest [2–4]. However, recent reports have indicated that a chest compression depth of 4.56 cm yields maximum survival [5] and that compression of > 6 cm results in more complications [6]. These findings suggest that the target compression depth in the AHA 2010 Guidelines might be too high. As a result, the 2015 Guidelines set the upper compression depth and frequency limits to 6 cm and 120/min, respectively [7, 8].

Many studies have investigated complications of CPR [9–13]. Principal studies found that rib fracture is the most frequent complication (13–97%), followed by sternal fracture (1–43%) [10]. A recent review showed that the overall frequencies of CPR-related rib and sternal fractures were 31.2 and 15.1%, respectively [11]. The results ranged widely because they were derived from pooled analyses of studies conducted from the 1960s to early 2010s. Thus, these studies included different guideline periods, CPR methods (manual or mechanical), diagnostic methods with highly variable sensitivity [autopsy, computed tomography (CT), radiography], and study populations (patients who survived or did not survive), making direct comparisons difficult. The impact of implementation of the AHA 2010 Guidelines has therefore never been assessed by comparison of studies conducted during a specific period, particularly after the AHA 2000 Guidelines were released, when the use of automated external defibrillators and the depth of chest compression were emphasized, as in the current guidelines.

Accurate autopsy-based epidemiological data on CPR-related injuries in Japan have never been compiled, although previous CT-based studies have reported that the frequencies of CPR-related rib and sternal fractures were around 70 and 10%, respectively. They also addressed causative factors of CPR-related injuries but did not perform autopsies in all cases as a reference standard [14, 15]. One forensic autopsy-based study reported that the frequencies of CPR-related rib and sternal fractures were 52 and 39%, respectively; however, the study period, patient demographics, and inclusion and exclusion criteria were not described [16]. No study using institutional consecutive data for CPR-related injuries based on both autopsy and postmortem CT (PMCT) has yet been performed in Japan.

The primary aim of this retrospective observational study was to determine the frequency and severity of CPR-related injuries based on forensic autopsy data during implementation of the AHA 2010 Guidelines with reference to data from studies conducted during implementation of the AHA Guidelines from 2000 to 2010. The secondary aim was to investigate factors associated with these complications. Both aims could provide useful references for comparing results of previous studies and improving future guidelines.

Methods

Subjects

Patients autopsied in our institution from January 2012 (assuming that the AHA 2010 Guidelines had been implemented and prevailed among citizens) to December 2014 were considered for inclusion in the study. Information on CPR-related injuries was collected, including the sites, frequency, and severity of such injuries, from the autopsy records and PMCT image interpretations. The following factors considered to be associated or inversely associated with CPR-related injuries with reference to previous studies were also extracted from autopsy and medical records: sex, age (as a continuous variable; per year from 18 years of age onward), body mass index (BMI) of < 18.5 kg/m^2, in-hospital cardiac arrest (IHCA), and chest compression only by laypersons [chest compression only by bystander layperson (including witnessed or not witnessed cardiac arrest), no professional rescuers attempts]. Most patients underwent manual CPR because mechanical chest compression devices are not in widespread use in our district. We retrospectively analyzed the association between the above-mentioned factors and injuries. The relevant institutional review board approved this study [approval reference number 1195].

Autopsy technique

Four board-certified forensic pathologists with seven trainee forensic pathologists in our department systematically performed the autopsies immediately after the PMCT examination. Sites of injuries and whether the injuries were associated with chest compression were recorded. The final diagnosis was made by consensus of the autopsy diagnosis and PMCT interpretation. The severity of injuries was coded according to the Abbreviated Injury Scale (AIS) (AIS 2005 Update 2008; Association for the Advancement of Automotive Medicine, Chicago, IL, USA). Injuries with a score of ≥ 3 were designated severe (injuries with AIS scores of 3−6 were designated serious to maximum).

Image protocol and interpretation

All PMCT examinations were performed using a 16-row multidetector CT system (ECLOS; Hitachi Medical Corporation, Tokyo, Japan) with the following parameters and protocol: collimation, 1.25 mm; reconstructive interval, 1.25 mm; tube voltage, 120 kV; tube current, 200 mA; and rotation time, 1/s. All subjects were imaged from the head to the lower extremities in the supine position. Contrast medium was not administered.

One board-certified radiologist with 8 years of experience in forensic imaging and forensic pathology and one board-certified emergency physician with 10 years of experience in clinical diagnostic imaging and 4 years of experience in forensic pathology interpreted the whole-body PMCT images. Final interpretations were reached by consensus. The images were processed on a workstation (Synapse Vincent; Fujifilm Medical, Tokyo, Japan) to obtain two-dimensional transverse, coronal, and sagittal datasets and three-dimensional images. Rib fractures were also evaluated by CT oblique axial multiplanar reconstruction: "rib view" production for accurate detection of each complete and incomplete type of fracture, including so-called buckle rib fractures (compressive fracture disruption leading to kinking or bending of the inner cortex that is often observed following CPR, as detected on PMCT), according to the method introduced by Yang et al. [17]. Total rib and sternal fractures detected by autopsy and PMCT were then respectively counted.

Statistical analysis

Statistical analysis was performed for complete data using SPSS version 21 software (IBM, Chicago, IL, USA) and R software (The R Foundation for Statistical Computing, 2014, Vienna, Austria, version 3.1.2; available at http://www.R-project.org). Fisher's exact test or the χ^2 test were used for univariate analysis of rib fractures, sternal fractures, and heart and pericardial sac injuries and their association with selected categorical variables: sex, BMI of < 18.5 kg/m^2 (defined as underweight) or ≥ 18.5 kg/m^2, site of CPR [IHCA or out-of-hospital cardiac arrest (OHCA)], and chest compression only by laypersons. The association between heart injuries and thoracic skeletal injuries was also tested. The association between each complication and age (as a continuous variable) was evaluated by univariate logistic regression analysis.

Multivariate logistic regression analyses were used to obtain an odds ratio (OR) and 95% confidence interval (CI) for the aforementioned variables regarding the most frequent complications: rib fracture, ≥ 3 rib fractures, and sternal fracture. Notably, unilateral or bilateral rib fractures and/or flail chest are given an AIS score of ≥ 3. In the AIS code, flail chest includes not only anatomical injury but also mechanical (clinical assessment of paradoxical respiration). Because this is difficult to detect by autopsy and PMCT, we focused on the sum of the fractured ribs in the present study, not the clinical severity (AIS score). When choosing these complications for the multivariate analysis, we followed standard methods to estimate the sample size for multiple logistic regression, with at least 10 outcomes needed for each independent variable. A value of $p < 0.05$ was considered to indicate statistical significance.

Results

Patient demographics and overall frequency of CPR-related injuries

Among 1032 consecutive autopsied patients, 343 who had undergone chest compression were eligible for the study. After excluding 28 patients < 18 years of age and 135 with trauma-induced death, we identified 180 cases for final inclusion in the analysis (Fig. 1). Female patients were significantly older than male patients ($p < 0.001$). However, there were no significant differences between the two sexes in the proportions of a BMI of < 18.5 kg/m^2, occurrence of IHCA, or performance of chest compression by laypersons (Table 1).

Table 2 shows the causes of death among all 180 eligible patients. Cardiogenic death was the most frequent ($n = 39$), followed by asphyxia ($n = 25$) and drowning ($n = 19$).

Table 3 shows all complications detected. Rib fractures ($n = 119$, 66.1%) were the most frequent, followed by sternal fractures ($n = 95$, 52.8%) and heart and great vessel injuries ($n = 23$, 12.8%). Most of the rib fractures ($n = 101/119$, 84.9%) were multiple (≥ 3). The frequency of abdominal visceral injuries was about 2.2%, and the liver and spleen were the organs most commonly injured ($n = 3$, 1.6%); these injuries mostly comprised simple capsular tears with a parenchymal depth of ≤ 3 cm or superficial hematomas (AIS score of 2). Among them, two patients with right atrial and ventricular laceration with perforation and three with tension or bilateral pneumothorax that would have required immediate life-saving interventions were considered to have had urgent life-threatening injuries. Figure 2 presents representative autopsy and PMCT findings in those cases. Their overall frequency was 2.8%.

Table 4 shows number of patients with rib and sternal fractures identified only on autopsy, only on PMCT, and on both autopsy and PMCT. Among all rib and sternal fractures, fewer were identified only on PMCT than only on autopsy.

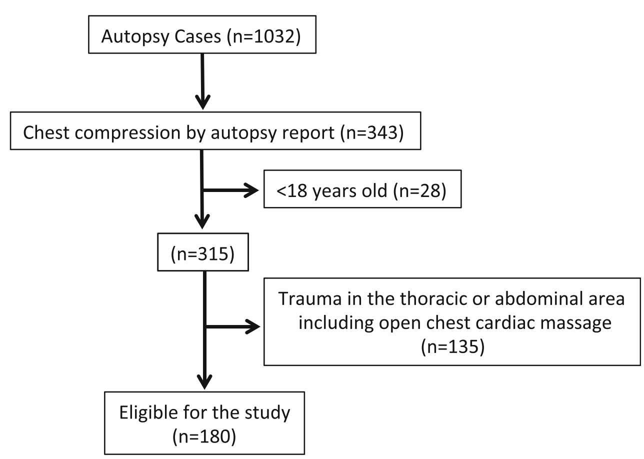

Fig. 1 Flowchart of the study objectives

Table 1 Patient demographics

Parameter	Total (n = 180)	Male (n = 119)	Female (n = 61)	p
Age, median (IQR)	62 (43, 73)	54 (41, 69)	69 (53, 80)	< 0.001
BMI < 18.5 kg/m^2, % (n/total)	22.2 (40/180)	19.3 (23/119)	27.9 (17/61)	0.26
IHCA % (n/total)	20.0 (26/180)	14.3 (17/119)	14.8 (9/61)	1.00
Chest compression only by laypersons, % (n/total)	9.4 (17/180)	9.2 (11/119)	9.8 (6/61)	1.00

IQR interquartile range, *BMI* body mass index, *IHCA* in-hospital cardiac arrest

Representative autopsy findings and PMCT images from these cases are shown in Fig. 3.

Factors influencing CPR-related injuries

Univariate analysis of the association between considerably influential variables and frequent (n > 10) complications showed that rib fracture was associated with female sex (p = 0.03) and higher age (OR, 1.06; 95% CI, 1.04–1.08; p < 0.001). A BMI of < 18.5 kg/m^2 (p = 0.19), IHCA (p = 0.51), and chest compression by laypersons (p = 0.28) were not significantly associated with rib fracture. Sternal fractures were also significantly associated with female sex (p = 0.01) and higher age (OR, 1.03; 95% CI, 1.02–1.05; p < 0.001). They were inversely associated with chest compression only by laypersons (p = 0.004) but were not associated with a BMI of < 18.5 kg/m^2 (p = 0.59) or IHCA (p = 0.83). There was no significant association between any variables and heart and great vessel injury (Supplementary Table 1). Heart and great vessel injuries were associated with sternal fractures (p = 0.01) but not with rib fractures (p = 0.1) (Supplementary Table 2).

Multivariate logistic regression analysis revealed that higher age was an independent risk factor for rib fractures [adjusted OR (AOR), 1.06; 95% CI, 1.04–1.08; p < 0.001], ≥ 3 rib fractures (AOR, 1.06; 95% CI, 1.02–1.09; p = 0.002), and sternal fractures (AOR, 1.03; 95% CI, 1.02–1.05; p < 0.001). Female sex was significantly and independently associated with sternal fractures (AOR, 2.08; 95% CI, 1.02–4.25; p = 0.04). IHCA was less frequently observed in patients with ≥ 3 rib fractures and sternal fractures, however not significant (AOR, 0.54; 95% CI, 0.14–2.10; p = 0.37 and AOR, 0.68; 95% CI, 0.28–1.66; p = 0.40, respectively). Chest compression only by laypersons was inversely associated with rib

Table 2 Causes of death in 180 eligible cases

Causes of death		% (n)
Cardiogenic	Total	21.7 (39)
	Myocardial infarction	15.0 (27)
	Heart failure/cardiomyopathy	3.9 (7)
	Myocarditis	1.7 (3)
	Lethal arrhythmia	1.1 (2)
Asphyxia	Total	13.9 (25)
	Strangulation/hanging	6.1 (11)
	Choking	5.0 (9)
	Gaseous suffocation (CO, N_2)	2.8 (5)
Drowning		10.6 (19)
Digestive organ disorder		9.4 (17)
Respiratory system disorder		7.2 (13)
Poisoning		6.1 (11)
Burn/death by fire		5.0 (9)
Aortic dissection/aortic rupture		3.3 (6)
Hyper and hypothermia		3.3 (6)
Pulmonary embolism		2.8 (5)
Intracranial hemorrhage		2.8 (5)
Endocrine disorder		1.7 (3)
Other/unknown		12.2 (22)

Table 3 Complications associated with cardiopulmonary resuscitation in 180 eligible cases

Complication	% (n)
Thorax	75.0 (135)
Rib fracture	66.1(119)
Rib fracture ≥ 3	56.1 (101)
Sternal fracture	52.8 (95)
Pneumothorax	2.2 (4)
Haemothorax	2.2 (4)
Vertebral fracture	0.6 (1)
Lung contusion	1.7 (3)
Heart and great vessels	12.8 (23)
Pericardial sac injury	6.7 (12)
Epicardial contusion/subepicardial haematoma	4.4 (8)
Hemopericardium	3.3 (6)
Great vessel injury	1.1 (2)
Myocardial contusion/intramural haematoma	1.1 (2)
Myocardial rupture or laceration	1.1 (2)
Abdomen	2.2 (4)
Liver injury	1.1 (2)
Splenic injury	0.6 (1)
Mesenteric injury	0.6 (1)

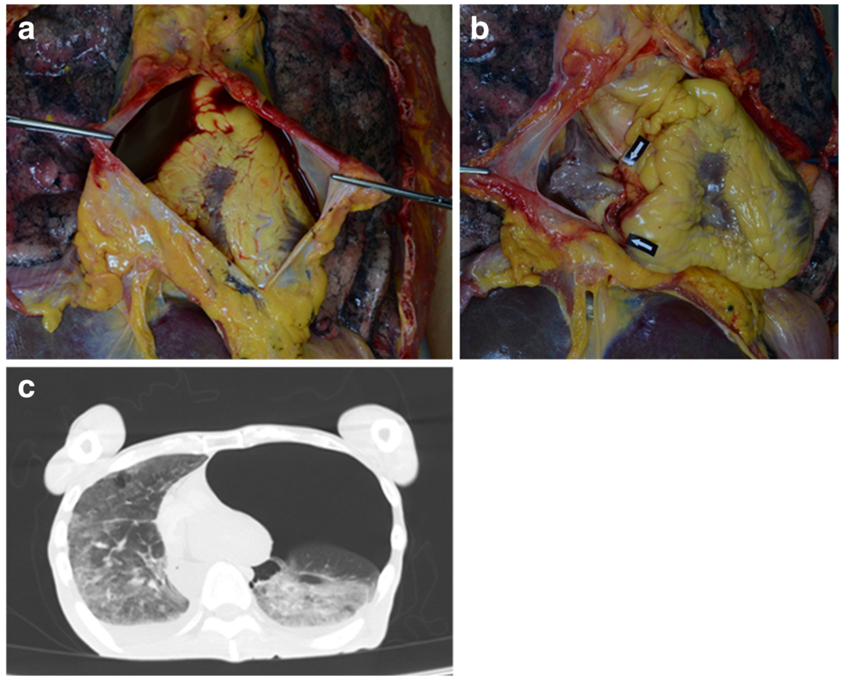

Fig. 2 Life-threatening CPR-related injuries observed in the study population. **a**, **b** A 79-year-old man (BMI, 17.3 kg/m^2; CPR by emergency medical services) who died of gastrointestinal hemorrhage showed pericardial hemorrhage and right atrial wall rupture. **c** A 42-year-old man (BMI, 12.1 kg/m^2; CPR only by laypersons) who died of hemorrhage from a gastric ulcer showed left tension pneumothorax

fractures (AOR, 0.27; 95% CI, 0.08–0.90; $p = 0.03$), ≥ 3 rib fractures (AOR, 0.16; 95% CI, 0.03–0.87; $p = 0.03$), and sternal fracture (AOR, 0.12; 95% CI, 0.03–0.46; $p = 0.002$). BMI had no significant association with these complications (Table 5).

Discussion

Overall injury frequency

Implementation of the AHA 2010 Guidelines, in which no upper limits of the recommended frequency and depth of chest compression were prescribed, increased the incidence of CPR-related injuries in some studies [6, 18]. However, the results of the present study do not concur with the results of these previous studies.

When assessing the impact of implementation of the AHA 2010 Guidelines, we emphasized comparison between the recent Guidelines (2000 and 2005) and focused on comparing the incidences of rib and sternal fractures, which were also the most frequent injuries in previous studies. For each period, we attempted to clarify the number of study subjects and injury incidences, differences among the study subjects, diagnostic methods, and CPR methods described in the literature (Table 6). Our results mostly agree with those of the autopsy-based studies of which the study period and subjects were included during implementation of the AHA 2000 and 2005 Guidelines [18–20] (the frequency ranges for rib and sternal fractures were 64.6–89.0% and 45.0–65.3%, respectively). However, the frequency of sternal fractures was higher than that of CT-based studies [13–15, 21, 22] and only partially autopsy-based studies [6] (the frequency ranges for rib and sternal fractures were 26.8–77.7% and 4.2–38.9%, respectively).

CT-based studies depend on the capability and quality of the image reconstruction method (i.e., multiplanar reconstruction) and the reviewers' experience, especially in the field of forensic radiology. This might have contributed to the lower frequency of sternal fractures in CT-based studies, as the authors inferred [18]. Although we used multiplanar reconstruction to detect fractures, many more sternal fractures were overlooked on PMCT than on autopsy. Schulze et al. [23] reported that the general sensitivity of PMCT for detecting partial rib fractures was relatively low (63%), although superior to that of autopsy. One small series demonstrated that CT failed to detect CPR-related minor and undisclosed rib and sternal fractures that were detected by autopsy [24]. The frequency of rib fractures in CT-based studies might depend on whether the degree of dislocation and type of fracture is diagnosable by CT. In the present study, several incomplete and "buckle" rib or sternal fractures, such as those without cortical

Table 4 Cases of rib and sternal fractures identified on autopsy and PMCT

	Rib fracture (n = 119) % (n)	Sternal fracture (n = 95)% (n)
Autopsy	18.5 (22)	41.1 (39)
PMCT	67.2(8)	52.6 (5)
Autopsy and PMCT	74.8 (89)	53.7 (51)

PMCT postmortem computed tomography

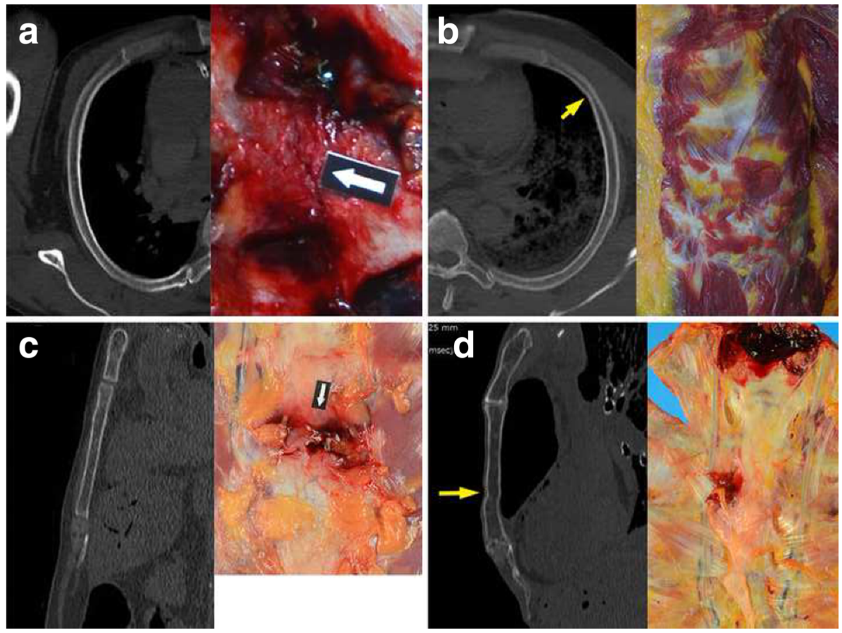

Fig. 3 Examples of rib fractures and sternal fractures identified only on autopsy or PMCT. **a** Incomplete rib fracture: slight crack of the outer cortex of the anterior part of the right fourth rib identified on autopsy (arrow), but not on PMCT (the corresponding rib is presented on the "rib view"). **b** "Buckle" rib fracture: bending of the inner cortex of the left fourth rib identified on the "rib view" PMCT (arrow), but not on autopsy. **c** Sternal fracture: crack of the inner cortex and hemorrhage identified only on autopsy (arrow), not on PMCT. **d** Sternal fracture: bending of the inner and outer cortex identified on PMCT (arrow). On autopsy, this fracture was not identified; only slight hemorrhage was present around the affected region

plate separation, were identified only on CT; however, fewer fractures were diagnosable only by CT and not by autopsy. Therefore, the dual method (CT + autopsy) is needed for precise detection of injuries, and the present results are therefore some of the most reliable data for describing the real frequency of CPR-related injuries during the AHA 2010 Guidelines implementation period.

The overall frequencies of heart and great vessel injuries and abdominal visceral injuries were similar to those in previous representative autopsy-based studies involving the AHA 2005 Guidelines (or earlier) implementation periods [9, 11].

Clinical importance of CPR-related injuries in the AHA 2010 Guidelines implementation period

Life-threatening CPR-related injuries are reportedly uncommon and rarely cause death [9]. Consistent with this, urgently life-threatening injuries (AIS score of ≥ 5) were rare (2.8%).

Most of the rib fractures were multiple (≥ 3) and might have affected the outcome and length of hospital stay by constricting respiratory chest motion, leading to difficult sputum expectoration, atelectasis, and pneumonia even after successful resuscitation. Such observed thoracic skeletal injuries—i.e., abdominal visceral injuries with solid organ laceration at ≤ 3 cm (AIS score of ≤ 3), minor hematomas of the mesentery (AIS score of 2), and vertebral fractures—would have required repair and prolonged hospitalization if the patients had survived. However, if they had been successfully resuscitated, most patients would have been intubated and under positive airway pressure ventilation. Therefore, the influence of severe thoracic skeletal injuries would not emerge as a problem until ventilator weaning and the extubation phase. Assessment and treatment of injuries is required until that time. Abdominal visceral injuries might be minor to moderate, but hemorrhage after return of the circulation could be fatal, especially if the patient had a coagulopathy and had been

Table 5 Multivariate logistic regression analysis of odds ratios for fracture types, with selected variables

Factor	Overall rib fractures		Rib fractures ≥ 3		Sternal fractures	
	Adjusted OR (95% CI)	*p*	Adjusted OR (95% CI)	*p*	Adjusted OR (95% CI)	*p*
Female sex	1.33 (0.6–2.95)	0.48	0.59 (0.19–1.8)	0.35	2.08 (1.02–4.25)	0.04
Age[a]	1.06 (1.04–1.08)	< 0.001	1.06 (1.02–1.09)	0.002	1.03 (1.01–1.05)	< 0.001
BMI < 18.5 kg/m^2	1.14 (0.44–2.95)	0.79	0.85 (0.21–1.14)	0.82	1.02 (0.44–2.34)	0.97
IHCA	1.3 (0.46–3.68)	0.62	0.54 (0.14–2.1)	0.37	0.68 (0.28–1.66)	0.4
Chest compression only by laypersons	0.27 (0.08–0.9)	0.03	0.16 (0.03–0.87)	0.03	0.12 (0.03–0.46)	0.002

OR odds ratio, *CI* confidence interval, *BMI* body mass index, *IHCA* in-hospital cardiac arrest

[a] For linear trend by raw age (year)

Table 6 Overview of recent studies

Study (year)	Number of cases during guideline periods 2000	2005	2010	Diagnostic method	Subjects	CPR method	Incidence of rib fractures (%)	Incidence of sternal fractures (%)
Pinto[20] (2013)	175 (2000 + 2005 total)		–	Autopsy	Forensic autopsy cases	M/A	NR (M > A)	45
Hellevuo[6] (2013)	–	115	55	Autopsy, CT, radiography[a]	IHCA survivors/ non-survivors	M	26.8	10.5
Smekal[19] (2014)	–	222	–	Autopsy	OHCA non-survivors	M/A	64.6 (M)/78.8 (A)	54.2(M)/58.3 (A)
Kralj[18](2015)	353	1072	723	Autopsy	Forensic autopsy cases	M/A	81 (2000)[b] 88 (2005)[b] 89 (2010)[b]	65.3
Kim[21] (2011)	–	40	–	CT	Survivors	NR	65	30
Kim[13] (2013)	–	–	71	CT	IHCA/OHCA survivors	NR	31	4.2
Kashiwagi[14] (2015)	–	84	139	CT	OHCA survivors/ non-survivors	M	72.6 (2005)[c] 68.3 (2010)[c]	11.9 (2005)[c] 5.8 (2010)[c]
Koga[15] (2015)	–	61	262	CT	OHCA non-survivors	M/A	72(M)/76 (A)	13 (M)/9 (A)
Seung[22] (2016)	–	36	112	CT	OHCA/IHCA survivors	M	66.7 (2005)[c] 77.7 (2010)[c]	38.9 (2005)[c] 33.9 (2010)[c]
Our study (2017)	–	–	180	Autopsy + CT	Forensic autopsy cases	M	66.1	52.8

CPR cardiopulmonary resuscitation, *M* manual-only CPR, *A* mechanical active compression–decompression CPR, *NR* not reported, *CT* computed tomography, *IHCA* in-hospital cardiac arrest, *OHCA* out-of-hospital cardiac arrest

[a] Autopsy 71%; CT 9%; radiography 21%

[b] Total incidence of skeletal chest injuries, including rib fracture, sternal fracture, and sternocostal separation

[c] Numbers in parentheses indicate guideline periods

given anticoagulation therapy [25]. Notably, plain CT-based assessment alone would underestimate these important complications. Detection of solid organ injuries is a shortcoming of PMCT investigation [26–28]. Enhanced CT or repeated bedside ultrasonography for survived patients in the clinical setting and autopsy for postmortem investigations are required for diagnosis of such injuries.

One study of the results of implementation of the AHA 2010 Guidelines revealed that the mean compression depth was significantly different between patients with and without CPR-related injury (56 and 52 mm, respectively) only among patients treated after 2011 [6]. Although the results of the study yielded statistical significance, the degree of clinical importance and the severity of the injuries were not clarified.

The results of the present study cannot be considered supporting evidence for attempting to regulate the compression depth within a narrow range, such as ≥ 5 but < 6 cm, as is recommended in the AHA 2015 Guidelines.

Factors influencing CPR-related injuries

Older age was the only independent risk factor for rib fracture occurrence and severity (≥ 3 rib fractures), and sternal fracture. Sternal fractures were observed more frequently in female patients. This association was similar to the conclusions of some previous studies [9, 12, 18]. However, the influence of sex on CPR-related injuries remains controversial and unclear [10]. A previous study suggested that compared with the male sternum, the female sternum exhibits a lower mineral density, is more subject to osteoporosis, and has a lower tolerable deflection level affected by material changes with aging [29]. Additionally, the female population tends to be older than the male population when resuscitation is required [30]. Attention to sternal fractures is important because although such fractures themselves are not fatal, they suggest the presence of serious complications such as heart injuries. Severe and fatal heart injuries such as laceration have been reported to result from rib fractures, and the right ventricle is the part most susceptible to rupture when increased pressure is present in the right side of the heart (i.e., outflow obstruction by pulmonary embolism) [31]. The present study revealed no significant relationship between rib fractures and heart injuries. Nonetheless, no conditions that increase right ventricular rupture were observed in the two patients with myocardial rupture or laceration. This might have been because the number of such cases was too small to detect such a trend.

As pointed out in a previous Japanese study [14], a smaller physical size is more likely to be associated with CPR-related injuries in the Japanese population than in European and US populations. However, the influence of a low BMI has not been reported as a significant risk factor for complications in the present study or previous studies [9, 20]. The total injury frequency in the present study was not much higher than those in recent studies worldwide. Based on the present results, application of the CPR maneuver should not necessarily be revised for populations of patients with a smaller physique.

Chest compression only by laypersons was significantly associated with fewer thoracic skeletal complications. The reason for this could be that chest compression by citizens tends to be timid and not sufficiently deep or frequent because such individuals are not familiar with the appropriate techniques and fear that they may harm the patient. These patients did not achieve return of spontaneous circulation and were declared dead on the scene. Although trained with the AHA 2010 Guidelines, lay bystanders' CPR performance did not fulfill the Guidelines' recommendations because of hesitation and rescue fatigue [32, 33].

IHCA tended to be associated with fewer multiple rib fractures (≥ 3) and sternal fractures than OHCA. This suggests that CPR performed by medical professionals would, at least, not increase the frequency of complications. However, OHCA was reportedly associated with more frequent and serious complications [22]. One study revealed that during ambulance transport, changes in acceleration and jerky transport exceeding a critical off-balance threshold frequently occurred and had the potential to directly affect CPR quality [34]. An unstable hand position and such off-balance forces on CPR during transport could lead to irrelevant chest compression maneuvers, resulting in more CPR-related injuries.

The total CPR duration in each case—which is reportedly associated with thoracic skeletal injuries [6, 9, 14, 22] and so could have non-negligible effects on the results—was not evaluated in this study. CPR only by laypersons and on IHCA cases might have lasted for a shorter duration based on the estimation of autopsy records (data not shown).

Limitations

This study has several limitations. First, the sample was too small to fulfill statistical power, and it was from a single institution. Second, because the sample comprised forensic autopsy cases, there was a lack of data for successfully resuscitated survivors. There seemed to be certain difference in crucial information between non-survivors and survivors, such as the duration of CPR and quality (force and depth) of chest compressions, which are factors that might influence the occurrence of CPR-related injuries. Third, our data were limited to cases after October 2010. Hence, we could not directly measure the impact of implementing the AHA 2010 Guidelines. Prospective data collection is ongoing for future assessment of the AHA 2015 Guidelines. Finally, because of our national system in which the police judge a death unnatural and to thereby require autopsy, uncontrollable selection bias is present when applying medicolegal autopsy cases to an epidemiological study. For example, exogenous causes of death accounted for a large proportion of deaths in the study population. However, our institution covers a population of more than 6 million, and we perform all autopsies for investigation of unnatural deaths in our district. Therefore, this study is highly important as the first report in Japan with a representative population.

Conclusion

This study has provided the first autopsy-based report complemented by PMCT data on the frequency and influencing factors of CPR-related injuries during implementation of the AHA 2010 Guidelines. The frequency of thoracic skeletal injuries in the present study was not much different from that in previous studies conducted during implementation of the AHA 2000 and 2005 Guidelines. Urgently life-threatening and irrecoverable complications were still rare. Therefore, the upper limit and narrow range of the chest compression depth recommended in the AHA 2015 Guidelines could be considered questionable. In particular, older patients who undergo CPR need special attention for CPR-related injuries after successful resuscitation.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval For this type of study, formal consent is not required.

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