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A Systematic Review and Pooled Analysis of CPR-Associated Cardiovascular and Thoracic Injuries

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Abstract

OBJECTIVE—The incidence of thoracic injuries resulting from cardiopulmonary resuscitation (CPR) is not well characterized. We describe a case in which a CPR-associated atrial rupture was identified with ultrasound and successfully managed in the intensive care unit with a bedside thoracotomy and atrial repair. We then describe a systematic review with pooled data analysis of CPR-associated cardiovascular, pulmonary, pleural, and thoracic wall injuries.

DATA SOURCES—PubMed, Scopus, EMBASE, and Web of Science were searched to identify relevant published studies. Unpublished studies were identified by searching the Australian and New Zealand Clinical Trials Registry, World Health Organization International Clinical Trials Registry Platform, Cochrane Library, ClinicalTrials.gov, Current Controlled Trials, and Google.

STUDY SELECTION—Inclusion criteria for the pooled analysis were any clinical or autopsy study in which a) patients underwent cardiopulmonary resuscitation, b) chest compressions were administered either manually or with the assistance of active compression-decompression devices, and c) autopsy or dedicated imaging assessments were conducted to identify complications. Exclusion criteria for the pooled analysis were pre-clinical studies, case reports and abstracts.

DATA EXTRACTION—Nine-hundred twenty-eight potentially relevant references were identified. Twenty-seven references met inclusion criteria.

DATA SYNTHESIS—A systematic review of the literature is provided with pooled data analysis.

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CONCLUSIONS—The incidence of reported CPR-associated cardiovascular and thoracic wall injuries varies widely. CPR with active compression-decompression devices has a higher reported incidence of cardiopulmonary injuries. Bedside ultrasound may be a useful adjunct to assess and risk-stratify patients to identify serious or life-threatening CPR-associated injuries.

Keywords

CPR; cardiopulmonary resuscitation; automated compression devices; vascular injury; cardiac injury; thoracic injury

INTRODUCTION

Effective chest compression remains the cornerstone of successful cardiopulmonary resuscitation (CPR). International guidelines note the critical importance of the quality of manual chest compression components including hand position, rescuer and victim position, and the depth and rate of compression and decompression.^{1, 2} In attempts to improve outcomes with CPR, several devices have been developed to improve the consistency and quality of chest compression and CPR. While none of these circulatory adjuncts are currently recommended because of insufficient data, some are being used routinely in resuscitation as alternatives to standard manual chest compressions.^{3, 4} These include active compression-decompression (ACD) devices based on suction-cup technology and automated devices using either piston technology or a load-distributing band.

The incidence of CPR-associated thoracic injuries in the setting of manual chest compressions or with circulatory adjuncts using active compression-decompression technology is not well characterized. Injuries to the thoracic wall, pulmonary and cardiovascular systems may cause significant morbidity and mortality and may represent potentially reversible causes of resuscitation failure. We describe a case in which an atrial rupture associated with standard manual CPR was identified with ultrasound and successfully managed in the intensive care unit with a bedside thoracotomy and atrial repair. This case was the impetus for us to perform a systematic review with pooled data analysis of CPR-associated cardiovascular, pulmonary, pleural, and thoracic wall injuries.

CASE

A 44-year-old woman with a 16-year history of synovial cell sarcoma and a recent asymptomatic pulmonary embolism underwent a right thoracotomy with parietal pleurectomy, extra-pericardial resection of a large inferior mediastinal mass extending from the carina to the diaphragmatic hiatus, and excision of several right pulmonary metastases by parenchyma sparing techniques. The patient's sarcoma had originated in the right thigh, and had been definitively treated with surgery and adjuvant radiation without local recurrence. She subsequently developed isolated metachronous right pulmonary metastases, which were treated by resection, each time rendering her with no evidence of disease. On routine imaging approximately six months prior to her most recent surgery, she was noted to have a large mass in the inferior mediastinum with several pulmonary nodules ranging in size from 1–3cm in diameter. Due to the volumes and locations of disease, she underwent Adriamycin and ifosfamide therapy with partial response, and was referred to the NCI for

resection of residual disease. Heparin-based therapy was briefly interrupted, and enoxaparin was re-started on post-operative day 2. On post-operative day 12, she developed an acute alteration in mental status followed by hypotension and hypoxemia that progressed to cardiac arrest with pulseless electrical activity (PEA) (time 0). Advanced cardiac life support was initiated and reversible causes of PEA evaluated. A bedside transthoracic echocardiogram revealed a dilated right atrium and ventricle with no wall motion and no pericardial effusion. Return of spontaneous circulation (ROSC) occurred and a massive pulmonary embolism was considered to be the most likely cause of the cardiac arrest. At 18 minutes she again developed PEA and was treated with 100 mg (IV) of tissue plasminogen activator. Within minutes, ROSC occurred and supportive care continued. Bleeding began from her pre-existing thoracotomy tubes and progressed to hemorrhagic shock with 8 liters of blood loss after 135 min. Despite aggressive volume and vasopressor therapy, she remained pre-load dependent with a narrow pulse pressure. A repeat transthoracic echocardiogram at 205 minutes demonstrated the new development of an intrapericardial echodense mass that completely compressed the right ventricle throughout the cardiac cycle (Figure 1). At 230 minutes the patient again developed PEA that deteriorated to asystole by 243 minutes. Uninterrupted CPR was continued and a bedside thoracotomy was performed with release and evacuation of intrapericardial clot under tension. The patient experienced persistent hemorrhage from an identified right atrial tear that was closed. Intrathoracic cardiac massage was performed, and resuscitation continued with ROSC. Surgical closure was performed at 335 minutes. The patient recovered without significant neurological sequelae.

METHODS

A systematic search was performed to capture published and unpublished pre-clinical and clinical studies of CPR-associated cardiac, vascular and thoracic injuries. PubMed, Scopus, EMBASE, and Web of Science were searched to identify relevant published studies. The search strategies were adapted to accommodate the unique searching features of each database, including database-specific MESH and Emtree controlled vocabulary terms. Searches were not limited by date, language or publication status. (Detailed search strategies are summarized in Appendix 1). The cited and citing references of selected studies were also searched for additional relevant material. To minimize publication bias, relevant unpublished studies were identified by searching the Australian and New Zealand Clinical Trials Registry, World Health Organization International Clinical Trials Registry Platform, Cochrane Library, ClinicalTrials.gov, Current Controlled Trials, and Google.

Inclusion criteria were any clinical or autopsy study in which a) patients underwent cardiopulmonary resuscitation, b) chest compressions were administered either manually (standard) or with the assistance of active compression-decompression devices, and c) assessments were made to specifically identify CPR-associated cardiopulmonary complications either by autopsy or dedicated imaging. Exclusion criteria for the pooled analysis were pre-clinical studies, and case reports. Clinical and methodological diversity precluded combining these studies in a meta-analysis.

RESULTS and DISCUSSION

Our search strategy identified 928 potentially relevant studies. Additional references were identified from bibliography assessments. Twenty-seven references met inclusion criteria. For resuscitation non-survivors, injuries were detected post-mortem by autopsy assessments. For resuscitation survivors, injuries were detected by plain radiographs, CT scan, ultrasound assessment, or combinations of these modalities. The data from the pooled analysis is summarized in Tables 1 – 4.

The reported cardiovascular and thoracic injuries associated with CPR vary widely. Several reports describe high rates of injury depending on whether patients are treated with standard CPR (32–45%), active compression decompression (ACD) CPR (58–75%), or standard CPR followed by ACD-CPR (up to 100%).^{5–11} Up to 11% of patients may have multiple CPR-associated injuries⁵ and major injuries occur in up to 3% and 7% of CPR-treated pediatric and adult patients respectively.^{5–9}

CARDIAC AND VASCULAR INJURIES

Major cardiac and large vessel injuries may occur following standard CPR (Figure 2). Cardiac and pericardial injury may occur in the absence of associated thoracic wall injury.^{12, 13} In a pooled analysis, pericardial injury occurs in 8.9% and hemopericardium occurs in 7.5% of CPR-treated patients (Table 1) following standard or ACD-CPR.^{5, 6, 8, 11, 13–22} Resultant cardiac tamponade has been described as well^{17, 23–26} either with or without associated pericardial laceration.

A broad spectrum of cardiac injuries have been observed including both contusions of the epi-, myo-, or endocardium (4.4%, 1.7%, and 3% respectively)^{5–7, 9–11, 18, 26–31} and lacerations or chamber ruptures (0.6%) involving the right atrium,^{13, 15, 23, 24} right ventricle,^{13, 28, 32–34} left ventricle,^{5, 12, 18, 25, 28} or locations not specified.^{5, 14, 17} Cardiac rupture has been associated with thoracic wall injuries or myocardium weakened by ischemia. However, there are cases in which cardiac rupture has been observed independent of these conditions.^{12, 13} Similar to the case described above, right atrial and ventricular rupture following closed-chest standard CPR associated with pulmonary embolism has occurred in the absence of chest wall injury.¹³ It is exceedingly unlikely that the cardiac rupture observed in our case was directly related to the patient's recent surgery since the mediastinal mass was resected in an extra-pericardial manner without technical complications. When rapidly identified, such injuries may be successfully managed with thoracotomy and cardiac repair.¹² Other significant cardiac complications of CPR including intracavitary hematoma,³⁵ prosthetic valve dehiscence,³⁰ papillary muscle rupture,³⁶ and conduction system injuries that occurred in up to 10% of patients in one report.³⁷

Major vascular complications (Table 2) including aneurysm, pseudoaneurysm, dissection, laceration or rupture to the coronary vasculature,^{37–42} coronary bypass grafts,⁴³ aorta,^{8, 10, 11, 17, 32, 44–47} subclavian artery and vein, and the vena cava⁶ may also occur following both manual and ACD-CPR (Figure 2). Notably, among patients that fail to recover from cardiac arrest after CPR, fractures of the coronary arteries, often at multiple sites have been described.³⁹ These injuries may also be associated with hemorrhage into the

region of the bundle of HIS^{37, 38, 40} or the sinoatrial node³⁷ further compromising cardiac conduction.

Differing injury patterns and incidence have begun to emerge when comparing types of CPR (i.e. standard, ACD, or standard followed by ACD). In our pooled analysis, the incidence of post-resuscitation rib fractures was 31.2%, with a higher incidence noted for both suction cup based ACD-CPR devices and standard CPR followed by ACD-CPR compared to standard CPR alone (Table 3).^{5-8, 10, 15, 16, 19-22, 25, 28, 33, 46, 48-56} Multiple rib fractures (29.2%),^{8, 11, 16, 19, 51, 54} bilateral fractures,⁵⁴ and flail chest^{21, 46, 51, 57} occurred frequently as well. Although the overall pooled incidence of flail chest was 1.7%, flail chest has been reported to occur at a rate of 5.6 per 100 survivors of CPR.⁵⁷ Despite the common nature of these injuries, their detection is challenging. The majority of rib fractures (86%) found during autopsies of patients after CPR were not detected with antero-posterior chest radiographs.⁵⁸ Standard chest radiograph views with an additional oblique rib view, detected only 10% (8 of 83) of rib fractures found by chest wall ultrasound and after 3 weeks were positive in only 6 of 39 patients (15%) who had fractures detected by repeat chest wall ultrasound.⁵⁹ Other common chest wall injuries include separation of costochondral junction (0.5%),⁸ clavicle fracture (0.3%),⁸ lung herniation,^{50, 60, 61} mediastinal (10.2%)^{5, 6, 8, 28, 51} or subcostal bleeding (17.6%),⁶² and hemothorax.^{19, 20, 22, 50, 51, 56}

Despite a pooled incidence of 15.1%, sternal fractures are also commonly missed on plain chest radiographs. In one study, 33% of the sternal fractures found at autopsy were not detected with antero-posterior chest radiographs.⁵⁸ This suggests that the detection of sternal fractures in survivors of CPR may be even higher given the limitations of portable chest radiograph. The highest incidence of sternal fractures has been reported with ACD-CPR devices utilizing suction-cup based technology (80.6%).^{10, 63} ACD-CPR using piston-based devices has been associated with significantly more sternal fractures (28.9%) than standard CPR^{10, 11, 54} and may have a higher incidence in women.^{64, 65} The rate of thoracic complications (i.e. sternal and rib fractures) may be less with ACD-CPR utilizing load-distributing band technology compared to standard CPR (45% vs. 14% respectively). However, the latter has been associated with an increase in vertebral fractures (0% vs. 4.5%).⁶⁶

PULMONARY

The most commonly clinically recognized pulmonary complications (Table 4) associated with CPR include aspiration of gastric contents (10.9%), pneumothorax (2.5%), pneumomediastinum (1.4%), pleural effusion / hemothorax (2.1%), pulmonary laceration, and pulmonary contusion or hemorrhage (1.2%).^{5, 6, 8, 10, 11, 16, 18-20, 33, 55} A common yet often unrecognized complication is pulmonary bone marrow or fat emboli which has a pooled incidence of 19.2% in autopsy series of CPR non-survivors.^{5, 7, 16, 19, 21, 28, 46, 63} The clinical significance of this type of injury as well as the incidence amongst CPR survivors has not been clearly described.

THROMBOLYSIS

Systemic thrombolysis may be indicated for a number of clinical conditions including myocardial infarction (MI), pulmonary embolism (PE), and cerebrovascular accident (CVA).^{67–69} Cardiac rupture has been described after both systemic thrombolysis administration for myocardial infarction^{70–72} and following percutaneous coronary intervention (PCI) with intracoronary thrombolysis.⁷¹ The relationship of the development of cardiac rupture to the presence of the underlying infarct and to the effects of systemic thrombolysis however remains controversial.^{73–75}

Hemopericardium with cardiac tamponade may occur in the setting of systemic thrombolysis for MI and may be associated with either cardiac rupture,^{72, 76} PCI-associated coronary artery injury,⁷⁷ or may develop in the absence of either of these conditions.^{78–89} In the setting of MI, hemodynamic instability may not always improve following pericardiocentesis due to difficulty in aspirating thrombus, and thoracotomy may be unavoidable.^{80, 85, 88, 89} In one study of 43 patients, no increase in bleeding complications was observed in patients given thrombolysis during CPR.⁹⁰

Thrombolytic therapy may also be used to treat acute massive pulmonary embolism (PE) manifested by hemodynamic instability or right ventricular failure.^{68, 91} In an analysis of 66 patients with cardiac arrest due to massive PE, no significant difference in major bleeding events was observed⁹² and CPR duration greater than 10 minutes did not increase the incidence of major bleeding complications.⁹² In our literature review, we found only 1 case of hemopericardium with cardiac tamponade after systemic thrombolytic (streptokinase) administration to treat PE,⁹³ and no reports of cardiac rupture following thrombolytic administration for PE were identified.

BEDSIDE ULTRASOUND DURING RESUSCIATION

The traumatic complications of CPR are well known but typically difficult to assess in real time. Ultrasound is a readily available non-invasive assessment tool that may be utilized to further assess the patients' clinical status and potentially identify CPR-associated complications, thereby allowing prompt recognition and intervention without interrupting the resuscitation or transporting the patient.^{94, 95} In one prospective analysis of 21 emergency department patients who underwent focused ultrasound assessment following CPR, 29% were noted to have findings that could have resulted from CPR associated injuries.⁹⁶ Similarly, inpatient assessment of cardiac ultrasound during in-hospital arrest with CPR has been reported to be both feasible and prognostic in identifying potentially reversible causes of cardiac arrest.⁹⁷

CONCLUSION

The incidence of reported CPR-associated cardiovascular and thoracic wall injuries varies widely. This may reflect several factors including the quality of the chest compressions and CPR, the diligence in defining these complications in survivors and non-survivors and the varying sensitivity of different diagnostic modalities to detect these injuries. Patients who undergo CPR with circulatory adjuncts using automated or active compression-

decompression devices have a higher reported incidence of cardiothoracic injuries. Bedside ultrasound may be a useful adjunct to assess and risk-stratify patients requiring CPR and to identify serious or life-threatening CPR-associated injuries.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. Bedside transthoracic echocardiogram following initial resuscitation showing interval development of an echodense pericardial collection with collapse of the right ventricle during diastole.

Figure 2.
Schematic of CPR-associated cardiac, vascular, and thoracic wall injuries.

TABLE 1

Pooled analysis of CPR-associated cardiac injuries based on CPR type.

Injury*	Reference	Mixed Series or Unspecified % (n)	Standard CPR % (n)	ACD-CPR Piston % (n)	Standard Followed by ACD-CPR (Suction) % (n)	Total % (n)
Pericardial injury	10,11		8.5 (4/47)	7.9 (3/38)	12.5 (2/16)	8.9 (9/101)
Hemopericardium	5,6,10,11, 16,18-21,55	7.9 (117/1486)	8.5 (23/372)	7.9 (3/38)	6.3 (1/16)	7.5 (144/1912)
Epicardial contusion / hematoma	6,7,11,28	3.6 (26/732)	8.2 (8/97)	10.5 (4/38)		4.4 (38/867)
Myocardial contusion / hematoma	6,7,10,18, 28	1.5 (21/1443)	8 (4/50)		6.3 (1/16)	1.7 (26/1509)
Endocardial contusion / hematoma	7,10		2 (1/50)		6.3 (1/16)	3 (2/66)
Myocardial rupture or laceration	5,6,10,28	0.5 (4/802)			6.3 (1/16)	0.6 (5/818)
Conduction system injury	37	10 (8/80)				10 (8/80)

Active compression-decompression cardiopulmonary resuscitation (ACD-CPR)

* Cardiac tamponade was reported only in case reports and series, but in clinical studies.

** There were no studies identified that reported data for ACD-CPR utilizing suction cup or load distributing band technology, or standard CPR followed by ACD-CPR using either piston or load distributing band technology.

TABLE 2

Pooled analysis of CPR-associated vascular injuries based on CPR type.

Injury*	Reference	Mixed Series or Unspecified % (n)	Standard CPR % (n)	ACD-CPR (Piston) % (n)	Standard Followed by ACD-CPR (Suction) % (n)	Total % (n)
Coronary air Embolism	6	1.3 (9/705)				1.3 (9/705)
Coronary artery rupture or laceration	10,38	43.6 (35/80)			6.3 (1/16)	37.5 (36/96)
Aortic rupture or laceration	8,10,11,46	5 (1/20)	0.9 (3/324)	2.6 (1/38)	6.3 (1/16)	1.5 (6/398)
Aortic dissection	11		0 (0/47)	2.6 (1/38)		1.2 (1/85)
Vena cava injury	6	0.9 (6/705)				0.9 (6/705)

Active compression-decompression cardiopulmonary resuscitation (ACD-CPR)

* The following variables are reported only in case reports and series, but not reported in clinical studies: coronary artery aneurysm, pseudo-aneurysm or dissection, aortic aneurysm or pseudo-aneurysm, and subclavian artery or vein injury.

** There were no studies identified that reported data for ACD-CPR utilizing suction cup or load distributing band technology, or standard CPR followed by ACD-CPR using either piston or load distributing band technology.

TABLE 3

Pooled analysis of CPR-associated thoracic wall injuries based on CPR type.

Injury	Reference	Mixed Series or Unspecified %(n)	Standard CPR %(n)	ACD-CPR (Suction) %(n)	ACD- CPR (Piston) %(n)	ACD-CPR (Load- Distributing Band) %(n)	Standard Followed by ACD-CPR (Suction) %(n)	Total %(n)
Sternum fracture	5-8,10,11,18,20-22,28,51,53-56,58,63,66,98,99	16.8 (350/2086)	8.5 (87/1019)	80.6 (25/31)	16.9 (12/71)	13.6 (12/88)	93.8 (15/16)	15.1 (501/3311)
Rib fracture	5-8,10,11,16,18-22,28,46,51,53-56,58,63,65,98,99	33.0 (695/2106)	25.9 (242/933)	47.2 (17/36)	25.4 (18/71)		93.8 (15/16)	31.2 (987/3162)
Multiple rib fractures	7,19		29.2 (28/96)					29.2 (28/96)
Flail chest	6,21,46,51	1.9 (15/788)	1.7 (4/241)					1.7 (19/1129)
Clavicle fracture	8		0.3 (1/377)					0.3 (1/377)
Costochondral junction separation	8		0.5 (2/377)					0.5 (2/377)
Mediastinal bleeding	5,6,8,28,51	15.3 (123/802)	0.5 (2/418)					10.2 (125/1220)
Vertebral fracture	6,51,66	0.1 (1/705)	0.4 (1/228)			4.5 (4/88)		0.6 (6/1021)

Active compression-decompression cardiopulmonary resuscitation (ACD-CPR)

* There were no studies identified that reported data for either standard CPR followed by ACD-CPR using either piston or load distributing band technology.

TABLE 4

Pooled analysis of CPR-associated pulmonary injuries based on CPR type.

Injury*	Reference	Mixed Series or Unspecified % (n)	Standard CPR % (n)	ACD-CPR (Suction) % (n)	ACD-CPR (Piston) % (n)	Standard Followed by ACD-CPR (Suction) % (n)	Total % (n)
Aspiration	6,18	10.9 (155/1426)					10.9 (155/1426)
Pneumothorax	6,8,11	2.7 (19/705)	2.1 (9/424)		2.6 (1/38)		2.5 (29/1167)
Pneumomediastinum	5	1.4 (1/70)					1.4 (1/70)
Pleural effusion / hemothorax	6,8,10,19,20,55	0.7 (5/705)	3.9 (19/490)			6.3 (1/16)	2.1 (25/1211)
Lung contusion / hemorrhage	11,99		0 (0/47)		2.8 (2/71)		1.7 (2/118)
Pulmonary bone marrow / fat emboli	5,7,16,19,21,28,46	15.4 (18/117)	21 (52/248)				19.2 (70/365)

Active compression-decompression cardiopulmonary resuscitation (ACD-CPR)

* Lung laceration was reported only in case reports, but not in clinical studies.

**

There were no studies identified that reported data for ACD-CPR utilizing suction cup or load distributing band technology, or standard CPR followed by ACD-CPR using either piston or load distributing band technology