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Experimental paper

Comparing sternal versus left-sided chest compressions for thoracoabdonimal injuries and compression biomechanics: A clinical-grade cadaver study

J. Gould[a], R.A. Marshall[b], D. French[c], M. Dyer-Heynen[d], P. Olszynski[e,*]

Abstract

Background: The lower half of the sternum is currently recommended as the area of compression (AOC) in CPR. Compressions over this area often result in outflow obstruction and inadequate compression of the left ventricle. Alternative left-sided chest compressions that target the left ventricle may improve cardiac arrest outcomes. However, little is known about the risks of thoracoabdominal injuries or the biomechanics of left-sided compressions.

Methods: The objective of this study was to examine the thoracoabdominal injury patterns and compression biomechanics during standard (control) and left-sided (experimental; off sternum, patient left, 6th rib) chest compressions. N = 6 clinical-grade cadavers (control n = 2; experimental n = 4) underwent six 2-minute rounds of chest compressions with intermittent fluoroscopy. Chest compression depth, recoil, and rate were standardized using compression feedback devices. Post-CPR dissection was used to examine for thoracoabdominal injuries.

Results: Standard compressions resulted in rib fractures (n = 1 [50%]). Left-sided compressions resulted in rib fractures (n = 4 [100%]), flail chest segments (n = 3 [75%]), and internal thoracic artery injury (n = 1 [25%]). No abdominal organ injuries were identified in either group (N = 6 [0%]). During compression, each condition yielded a different pattern of chest wall deformity (standard – regular trapezoid [midline, comparable left–right sides, flat top, and bottom]; left-sided – irregular trapezium [left-sided, unequal sides, leftward sloped top]).

Conclusion: Experimental left-sided compressions consistently produced rib fractures and flail chest segments. Findings should be interpreted with caution due to the limited sample size. Further studies investigating the biomechanics and outcomes of left sided chest compressions are warranted.

Keywords: Cardiac arrest, Cardiopulmonary Resuscitation (CPR), Basic Life Support (BLS), Advanced Cardiac Life Support (ACLS), Chest compressions, Area of Compression, Biomechanics, Injuries, Cadavers, Landmarks

Introduction

Despite advances in defibrillation and compression-focused resuscitation, current out-of-hospital-cardiac-arrest (OHCA) survival rates remain poor (∼10%).[1–3] According to the American Heart Association, external chest compressions should be performed over the lower half of the sternum.[3] Evidence suggests that during CPR, forward blood flow is the result of combined effects on the thoracic cavity and heart, generating flow through what are respectively known as the thoracic and cardiac pumps.[4–6] Emerging research suggests that chest compressions over the standard area of compression (AOC) often result in outflow obstruction and inadequate compression of the left ventricle,[7–11] raising questions about the universality of the current AOC.

Porcine models of CPR demonstrated gains when compressions were performed directly over the left ventricle, including an increase in return of spontaneous circulation.[12,13] Clinically, transesophageal echocardiography (TEE) and transthoracic echocardiography (TTE) have been deployed to bolster chest compressions by guiding the AOC off the standard position according to alleviation of outflow obstruction and improved left ventricular compression.[14–19]

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* Corresponding author at: 107 Wiggins Rd, Saskatoon, SK, S7N 5E5, Canada.
E-mail address: p.olszynski@usask.ca (P. Olszynski).

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However, these studies do not report on the location (on the chest) of these alternate AOCs. A recent survey of healthcare providers who have participated in TEE-guided resuscitation reported a leftward and/or caudal shift to the AOC following TEE guidance.[20] Concordantly, experience from TTE suggests that the left ventricle lies to the left of the sternum, between the 5th and 7th intercostal spaces (ICS) in the majority (77%) of patients.[21]

When performing chest compressions over the standard AOC, the most common injuries are rib fractures, reported at a rate of 27–90% for a single fracture and 30–42% for multiple fractures.[22–26] Sternal fractures are also common (4–38% of patients).[22–26] These injuries are associated with reduced chance of survival.[22] Injuries to the heart and pericardium may happen independently of chest wall injury. Coronary artery rupture occurs in up to 38% of CPR recipients,[22] mediastinal bleeding in 10%[22] and cardiac hematoma in 10%.[24] Hemopericardium occurs in 8% with reports of pericardial tamponade.[22] Upper airway injury varies widely from 20-75% while lung contusion has been detected in 41% of CPR survivors.[22] Hemothorax has also been observed but its frequency is unknown.[24] Injury to abdominal viscera may be present in up to 31% of people subjected to CPR. Liver and spleen injury are troubling as they have been identified as a cause for cardiovascular collapse after initial resuscitation. Liver injury occurs in 0.8–3% of CPR recipients. Gastric perforation and splenic rupture have also been reported.[22]

To date, the effects of a leftward AOC on chest compression biomechanics (flexion, recoil, chest wall deformity) and associated patterns of injury have not been well described. The primary objective of this study was to investigate the differences between standard and left-sided chest compressions in terms of thoracoabdominal injury and compression biomechanics.

Methods

Ethics

This study used a clinical grade cadaver (CGC) model of CPR to examine standard and left-sided chest compressions, respectfully. This study was designed, reviewed, approved, and conducted under the guidance of the University of Saskatchewan Research Ethics Board (Bio-3396), and the Nova Scotia Health Authority Research Ethics Board (1028114).

CGCs provide a model of training, education and research that mimics living tissue. The preservation techniques used allow for chest wall movement and injury patterns similar to that of a cardiac arrest patient. As such, CGCs provide an excellent model to examine compression dynamics and compression-related patterns of injury. Consent is required for body donation to the clinical grade cadaver program that includes cadaver use for education and research purposes. The Human Donation consent form, signed by the donor (or next of kin and/or legal executor) states that the donor authorized the faculty of medicine to use the remains for medical education and research purposes. As such, further consent was not required for this project. Although minimal risk to research members and assistants was anticipated (radiation exposure, surgical instruments), consent forms were offered and signed by all personnel involved in the lab aspects of the study.

In 2020, a pilot study using one cadaver was conducted to test if procedures and interventions were feasible and would provide accurate information. Results of that pilot study demonstrated changes to chest wall compression dynamics and injuries. Positioning the fluoroscopy device while doing compressions proved challenging but adjustments to the original compressions and fluoroscopy procedures (i.e., location of compressor and c-arm relative to the cadaver) were subsequently integrated into the revised protocol of this study.

Protocol

The Dalhousie Division of Anatomy's Clinical Cadaver program uses an embalming technique, the Dalhousie Preparation, to produce CGCs that retain the natural compliance and texture of human tissues. Six CGCs were secured for the study, balancing the financial and resource limitations of the project with the ability to meet the objectives. Up until exposure to the respective experimental conditions, all preparation for each CGC followed consistent institutional protocols. CGCs were placed supine on a clinical grade surgical table. Cadavers were separated by sex (three female, three male) and then assigned to either the standard chest compression (control) or left-sided chest compression (experimental) group in a one (control) to two (experimental) ratio (control n = 1 female, n = 1 male; experimental n = 2 female, n = 2 male), representing a stratified convenience sample.

Baseline characteristics collection

Prior to experimentation, to assist in determining chest wall biomechanics and deformity, several measurements were recorded including supine height (i.e., standing height; cm), chest level (degrees), left chest height (table to anterior left sternal border; cm), right chest height (table to anterior right sternal border cm), manubrium length (superior margin to angle of louis; cm), sternal length (angle of louis to inferior margin; cm), and sternal width (left sternal boarder to right sternal border; cm) were all recorded. No additional CGC details (weight, age, comorbidities) were available.

During compression data collection

Chest compressions were performed by two experienced members of the study team. Manual compressions were chosen for this study since commercially available mechanical compression devices cannot accommodate lateral displacement of the plunger for a leftward AOC. Given the variability found in our cadavers, repeated alterations to such a device might inadvertently alter compressions (not solely the AOC, but also directional force of compression), The two CGCs in the control group received chest compressions at the standard AOC (lower half of sternum). The four CGCs in the experimental group received chest compressions at a left-sided location (off sternum to the left of the standard AOC). The experimental AOC was selected based on previous AOC mapping of the left ventricle to surface anatomy[19] and a recent survey of healthcare providers who had performed chest compressions under guidance of TEE.[20] Accordingly, in the experimental arm, the decision was made to landmark completely left of the lower half of sternum (i.e., no overlap onto the sternum) to examine the potential differences of a substantial leftward shift in the AOC. To maintain the exact chest compression location, the adhesive semi-rigid compression pad of the chest compression feedback device (Zoll X Series Monitor/Defibrillator with Compression Feedback, Mississauga, ON, Canada) was applied to either the standard or left-sided AOC site. Except for AOC differences, chest compressions were performed and standardized to the American Heart Association guidelines.[3] A metronome (110 beats per minute) was used to guide chest compression rate. The chest compression feedback device was used to provide real-time feedback on rate, depth, and recoil to ensure compressions were performed consistent with the American Heart Association standards. Cadavers were not ventilated.

Chest compressions were delivered for a total of 12 min (six 2-minute rounds of continuous compressions). This protocol length was selected to recreate a practical situation similar to clinical practice. Fluoroscopy (BV Pulsera, Phillips, Netherlands) was used to record the final 10 s of compressions (cross table lateral) at the end of each 2-minute round of compressions (six sections of 10 s of imaging). All those present during the data collection portion of experimentation wore personal protective equipment to mitigate radiation exposure (e.g., lead aprons, etc.) in accordance with best practices as outlined by Dalhousie University and Nova Scotia Health.

Post-compression data collection

Following compressions, chest level (degrees), left chest height (cm), and right chest height (cm) were recorded. A single static chest compression was delivered and held at full depth (5 cm) while chest level (degrees), left chest height (cm), right chest height (cm), width of compression-caused cavity (left anterior margin to right anterior margin (cm), and left anterior cavity width (distance from the centre of the plunger to the left anterior margin).

To examine for and describe thoracoabdominal injury patterns, a blinded practicing thoracic surgeon performed a sternotomy and laparotomy to dissect each CGC. A midline sternotomy was performed. Prior to inserting a retractor, the anterior and posterior tables of the sternum were palpated. Next, the pericardium and pleura were opened. The internal thoracic artery on both sides was identified and examined. Rib fractures close to the artery were noted. Ribs 1–9 were systematically palpated on the right and the left to identify posterior, lateral, and anterior fractures.

A retractor was then inserted to expose the thorax. The surface of each lobe of both lungs were inspected for lacerations. The heart was rotated out of the pericardium and examined for injury. The incision was extended into an upper midline laparotomy. The peritoneal cavity was entered, and the anterior surface of the stomach was inspected for injury. The spleen was medialized by releasing the lateral attachments to allow thorough inspection of the organ. The left diaphragmatic surface was inspected from both the abdomen and thorax. The falciform ligament was divided to allow access to the liver. The right hemi-diaphragm was inspected, then divided anteriorly to facilitate exposure to the dome of the liver.

Of *a priori* and particular interest were 1) the number and location of rib fractures; 2) lung and vascular injury (penetrating or blunt); 3) cardiac injury (penetrating or blunt); 4) diaphragmatic injury; 5) abdominal injury of the liver, stomach and spleen (penetrating or blunt), and 6) internal thoracic artery injury. Findings were recorded and injuries were photographed.

Data analysis and statistics

To characterize the differences between standard and left-sided chest compressions in terms of thoracoabdominal injury, injury data from the surgical dissection was tabulated and presented as n/N (%). Owing to insufficient sample size to conduct valid and reliable statistical comparisons, strictly descriptive statistics were calculated.

To characterize the differences between standard and left-sided chest compressions in terms of chest wall deformity and biomechanics, fluoroscopy images were reviewed to determine downward displacement of the sternum and left chest wall. During an initial pilot study performed in 2020, it was observed that during left-sided compressions, the left chest wall was displaced more posteriorly than the

Table 1 – Injuries during standard and left sided chest compressions, identified in order of dissection in each of the cadavers.

Cadaver	**1**		**2**		**3**		**4**		**5**		**6**	
Compression Location	**Standard (control)**		**Standard (control)**		**Left-Sided (experimental)**		**Left-Sided (experimental)**		**Left-Sided (experimental)**		**Left-Sided (experimental)**	
Hemithorax	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
Sternal Fracture	Not Present		Not Present		Present (subtle)		Not Present		Not Present		Not Present	
Number of Rib Fractures	0	0	7	6	2	10	4	12	3	12	0	10
Anterior Rib Number(s)	0	0	2–8	2–7	2, 6	3–7	3–6	2–8	3–5	2–7	0	3–8
Lateral Rib Number(s)	0	0	0	0	0	3–5	0	3–7	0	2–7	0	4, 6
Flail Segments	Not Present	Not Present	Not Present	Not Present	Not Present	Present	Not Present	Present	Not Present	Present	Not Present	Not Present
Internal thoracic artery injury	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present	Present	Not Present	Not Present	Unable to determine*	Not Present
Lung Injury	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present
Diaphragm Injury	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present	Not Present
Cardiac Injury	Not Present		Not Present		Not Present		Not Present		Not Present		Not Present	
Liver Injury	Not Present		Not Present		Not Present		Not Present		Not Present		Not Present	
Spleen Injury	Not Present		Not Present**		Not Present		Not Present		Not Present		Not Present	
Gastric Injury	Not Present		Not Present		Not Present		Not Present		Not Present		Not Present	

*Unable to determine due to adipose tissue. ** This cadaver had evidence of gastric cancer with local invasion, limiting dissection accuracy.

sternum during downward compression. Cross-table lateral fluoroscopy was used to first confirm location of the Zoll compression feedback device and then track its displacement through both standard and left-sided compression.

Results

Thoracoabdominal injuries

A full list of thoracoabdominal injuries can be found in Table 1. Compressions over the standard AOC resulted in rib fractures (n = 1 [50%]). Compressions over the experimental AOC resulted in rib fractures (n = 4 [100%]), flail chest segments (n = 3 [75%]), and internal thoracic artery injury (n = 1 [25%]) (see Fig. 1). No abdominal organ (liver, spleen, stomach) injuries were identified (N = 6 [0%]).

Compression biomechanics – Fluoroscopy

Fluoroscopic images (cross table lateral) showed downward displacement of the AOC (identified by the Zoll compression feedback device) beyond the sternum during left-sided compressions (see Fig. 2). These images also showed marked loss of decompression (chest recoil) as demonstrated by persisting downward displacement of the Zoll compression device from before compressions (anterior to sternum) to level of sternum after the first round of compressions (as seen on cross-table lateral imaging).

Compression biomechanics – Chest wall deformity

Differences in chest wall compression deformity were observed. During standard compressions, the thoracic cavity deformity took the form of a nearly symmetrical, regular trapezoid (midline, comparable left–right sides, flat top, and bottom). During left sided compressions, the thoracic cavity deformity demonstrated an asymmetrical, irregular trapezium (left-sided, unequal sides, leftward sloped top) (Table 2; Fig. 3).

Discussion

To our knowledge, this is the first study describing injuries and changes to thoracic biomechanics during left-sided compressions. No thoracic (heart, lung) or abdominal organ (liver, spleen, stomach) injuries were identified following either condition (see Supplemental Fig. 1). During left sided compressions, irregular trapezium (left-sided, unequal sides, leftward sloped top) shaped deformities were observed as compared to regular trapezoid (midline, comparable left–right sides, flat top, and bottom) during standard compressions. This was associated with an increased number of rib fractures during left sided compressions, including flail chest segments. Fluoroscopic images also showed an increased downward (posterior) displacement of the AOC (as evidence by the position of the Zoll compression feedback device) during experimental left-sided compressions (see Fig. 2). Accordingly, there was a substantial reduction in decompression (recoil) following the first round of left-sided compressions, with the device being visualized several centimeters anterior to the sternum before any compressions to at the level of the sternum after compressions.

The chest wall findings suggest that compression over the left chest location could contribute to an increased number of rib fractures, with subsequent injury to major internal vessels and lung parenchyma. Of note, cadavers were not ventilated during this study, possibly contributing to the lack of lung injury observed. While standard chest compression can also cause rib fractures, left-sided compressions caused a pattern of lateral rib fractures not mirrored in the standard group, resulting in flail segments in three of four specimens

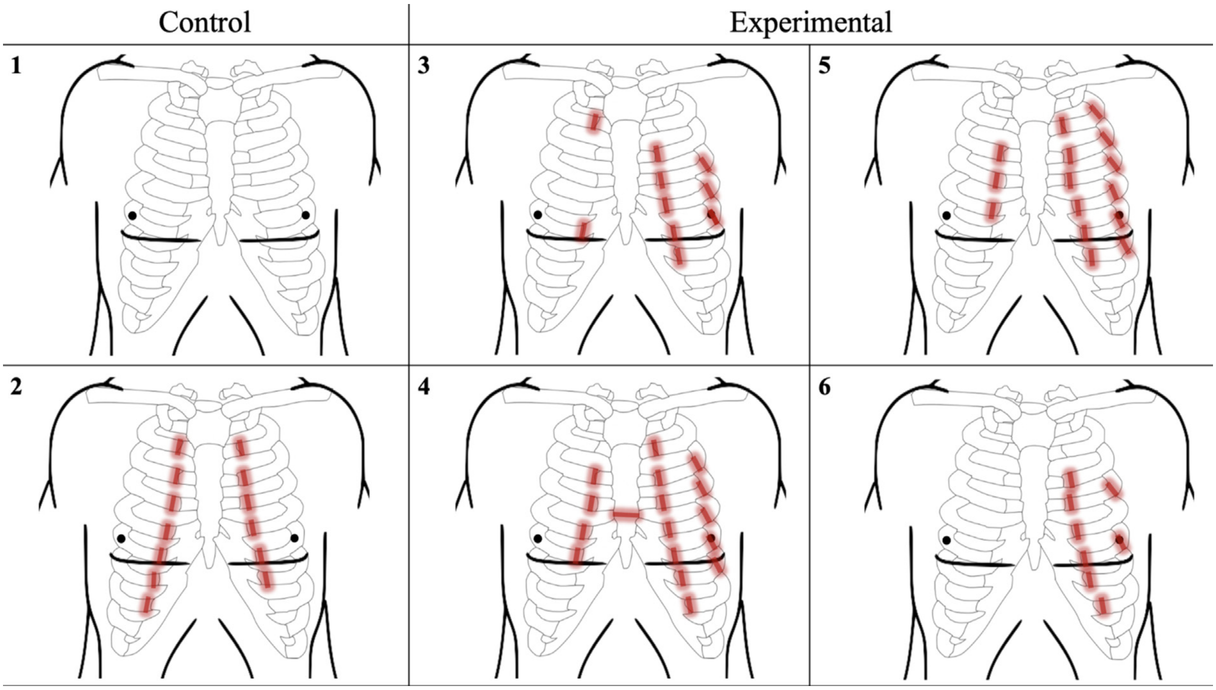


Fig. 1 – Rib Fractures during standard and left sided chest compressions in each of the cadavers. In the experimental left-sided compressions, cadavers 3–5 were found to have flail chest segments.

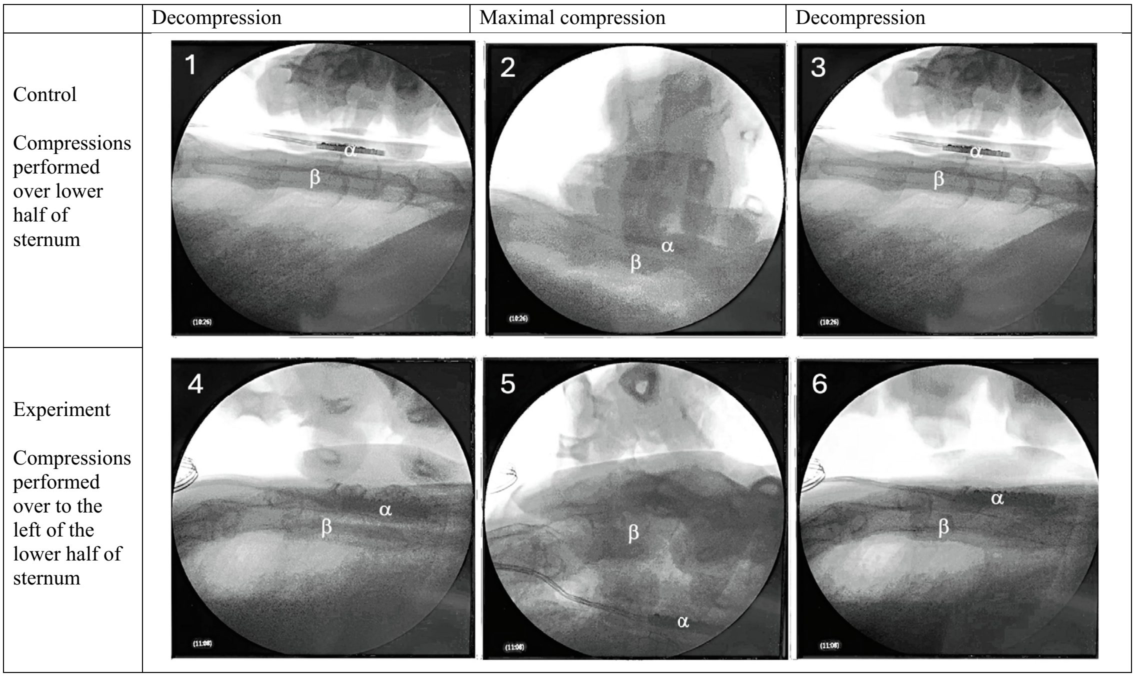
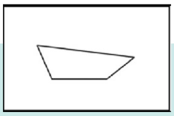
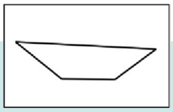
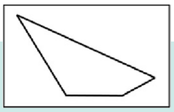
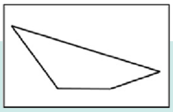
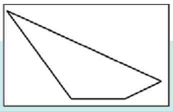
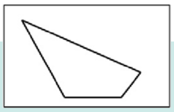


Fig. 2 – Fluoroscopy demonstrating standard compressions (top row) where the compression feedback device (a) remains anterior to sternum (b) during maximal compression (image 2) and decompression (image 3). During experimental left-sided compressions (bottom row), the compression feedback device is pushed more posteriorly, beyond the sternum during maximal compression (image 5) and then returns to sternal height at decompression (image 6).

Table 2 – Chest wall deformity during standard and experimental (leftsided) compressions. Standard compressions generated trapezoids whereas left sided compressions resulted in irregular trapeziums with leftward slopes (measurements in cms).

Cadaver	**1**	**2**	**3**	**4**	**5**	**6**
Compression Location	**Standard (control)**	**Standard (control)**	**Left-Sided (experimental)**	**Left-Sided (experimental)**	**Left-Sided (experimental)**	**Left-Sided (experimental)**
Top	11.4	16.5	17.2	18.6	19.7	14.6
Patient Left Side	4.0	6.0	4.2	6.6	4.6	3.6
Bottom	6.4	6.4	6.4	6.4	6.4	6.4
Patient Right Side	4.2	6.9	10.6	9.2	12.5	9.9
Quadrilateral						

(see Fig. 1). Correspondingly, a recent computer-simulated model also demonstrated that compression over the left costal cartilage would likely result in higher risk of rib fractures.[30] Reductions in chest wall recoil appear to be related to the pattern of these rib fractures. These injuries may have significant implications given the postulated role decompression via chest recoil plays in supporting venous return during CPR.[31] Conversely, deteriorated chest wall structure could permit greater cardiac compression. In the available pre-clinical and clinical data, hemodynamics were improved with AOCs chosen to target the left ventricle.[10,13,19,20] Even in the presence of additional injuries, preservation of the heart and brain remain paramount during cardiac arrest care. Further investigation in the clinical setting is needed to examine the relationship between standard outcomes (e.g., $ETCO_2$, blood pressure, return of spontaneous circulation, neurologically intact survival), compression-caused injuries, and chest compression biomechanics.

TEE-CPR has been implicated as a useful tool to help guide potential AOC adjustments. Given the relative novelty of TEE-CPR, there is a paucity of data on the effects of moving the AOC, by adjusting the hands of compressors or by moving the compres-

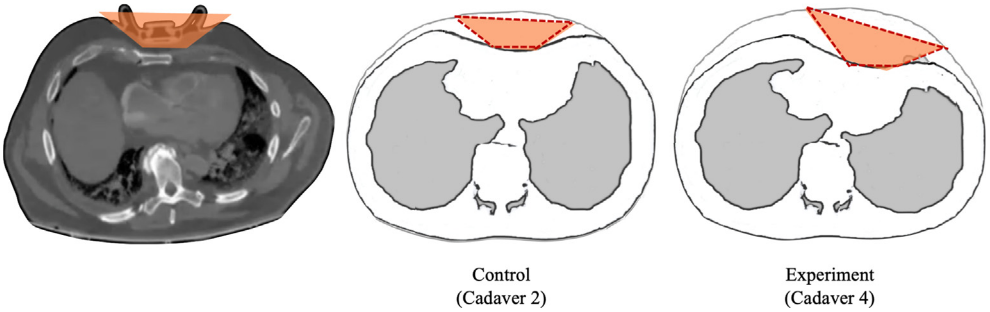


Fig. 3 – Cross-sectional imaging of the chest during compression demonstrating typical chest wall deformity adapted from Hansen et al. 2020 (left)[29], integrated with illustrations of compression-associated chest wall deformity during standard mid-line compressions (middle, trapezoid) versus left-sided compression (right, irregular trapezium) from cadavers 2 and 4 respectively.

sion device, on chest wall biomechanics and associated patterns of injury.[15,22,27,28] How injury patterns may differ when the AOC is altered during TEE-CPR remains to be elucidated. Prospective TEE-CPR studies should also include attention to potential changes in injury patterns. Studies of standard (conventional) compressions using 4D computed tomography have provided additional insights into compression biomechanics (chest wall deformity and cardiac chamber compression)[29,32] and could be modified to study left-sided chest compressions. Such research could help inform which novel AOCs should be investigated in future clinical trials, either as alternates in certain patient groups/populations or as a next best AOC when standard compressions fail to return spontaneous circulation in out of hospital cardiac arrests.

Despite the clinical utility, there is little data describing exactly how TEE-CPR is being used to alter and bolster chest compressions.[15,27,28] TEE-CPR has been described as being used to guide both the area and directional force of chest compression.[28] However, changes in these variables in the context of adjusting the AOC have not been well-described. In this study, compression vectors were performed as uniformly as possible with consistent force perpendicular to the body over standard or experimental AOC. Given the compression-caused change in chest wall structure, additional changes in vectors could bolster the efficacy of LV targeted CPR. Future studies should explore the force and magnitude of compression vectors in relation to alternate areas of compression. Thorough descriptions of the AOC and vector factors could yield important information to guide the future of CPR. If consistent and preferential improvements can be identified, then widespread clinical implications for out-of-hospital CPR may exist.

Limitations

This study had several limitations. Most importantly, this was a stratified convenience sample with only four specimens in the experimental arm, markedly limiting generalizability. Furthermore, the use of frozen-thawed clinical grade cadavers results in uninflated lungs and no forward flow of blood. As such, to what extent the thoracic injuries identified would have compromised the lungs could not be determined. Similarly, while suspected transections of the internal thoracic artery could have serious hemodynamic consequences they could not be further investigated in this pre-clinical model. Such injuries are well described in the literature and do not always necessitate intervention.[23,24] Furthermore, compressions directly leftward from the lower half of the sternum, immediately lateral to the sternal border may not be indicative of more subtle AOC adjustments clinically made to target the left ventricle. Left-sided compressions that include the sternum in the compression site (e.g., left sternal border) could emerge as a utilitarian hybrid location between the standard and experimental conditions used herein. A prospective clinical trial comparing the standard AOC to left-sided AOC compressions should be pursued to generate new knowledge in this area. Before such a trial, data to ensure patient safety is of upmost importance. This study provides some insights regarding changes in compression dynamics and potential associated injuries that were necessary to advance this line of investigation.

Conclusion

In this study of 6 clinical grade cadavers, experimental left-sided compressions yielded rib fracture patterns and flail chest segments that were not observed following chest compressions at the standard AOC. No difference in thoracoabdominal organ injuries were observed. Reported chest compression biomechanics suggest a marked change in chest wall deformity, consistent with the observed thoracic wall injury pattern. Findings should be interpreted with caution due to the limited sample size. Future studies investigating the biomechanics and outcomes of left sided chest compressions are warranted.

CRediT authorship contribution statement

J. Gould: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **R.A. Marshall:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **D. French:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **M. Dyer-Heynen:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **P. Olszynski:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, 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.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resplu.2025.100865.

Author details

[a]Department of Emergency Medicine, Dalhousie University, Halifax, NS, Canada [b]Faculty of Health and Social Development, University of British Columbia Okanagan, Kelowna, BC, Canada [c]Department of Surgery, Dalhousie University, Halifax, NS, Canada [d]Department of Internal Medicine, University of Saskatchewan, Saskatoon, SK, Canada [e]Department of Emergency Medicine, University of Saskatchewan, Saskatoon, SK, Canada

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