Optimal Position for External Chest Compression During Cardiopulmonary Resuscitation

An Analysis Based on Chest CT in Patients Resuscitated From Cardiac Arrest

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Abstract and Introduction

Abstract

Objectives This study was conducted to determine the proper hand position on the sternum for external chest compression to generate a maximal haemodynamic effect during cardiopulmonary resuscitation (CPR).

Methods 114 patients with cardiac arrest who underwent chest CT after successful resuscitation from January 2006 to August 2009 were included in the study. To evaluate the area of the cardiac chambers subjected to external chest compression, the area of each cardiac chamber under the sternum was measured using cross-sectional CT at three different locations: the internipple line on the sternum (point A), halfway between point A and the sternoxiphoid junction (point B) and at the sternoxiphoid junction (point C).

Results The widest total heart area, total ventricular area and left ventricular area (LVA) were observed most frequently at point C (58%, 85% and 78% of all cases, respectively). Few cases (six in total heart area, one in total ventricular area and one in LVA) were observed as the widest at point A. Predicted compressed areas of the right and left ventricle were wider at point C than at points A or B (right ventricular area: 366 ± 536 mm^2 at point A, 961 ± 653 mm^2 at point B and 1383 ± 689 mm^2 at point C, p<0.001; LVA: 65 ± 236 mm^2 at point A, 365 ± 506 mm^2 at point B and 1099 ± 817 mm^2 at point C, p<0.001).

Conclusions Only a small proportion of the ventricle is subjected to external chest compression when CPR is performed according to the current guidelines. Compression of the sternum at the sternoxiphoid junction might be more effective to compress the ventricles.

Introduction

Cardiopulmonary resuscitation (CPR) is an emergency technique performed by artificial ventilation and external chest compression to support tissue perfusion, which has been recognised as a standard method for resuscitation since its introduction in the 1960s.[1] In cardiac arrest, tissue perfusion critically depends on CPR until spontaneous circulation returns. Therefore, chest compression is the essential factor in supplying blood to the vital organs during CPR. Although the cardiac output generated by chest compression is within 17–27% of the normal cardiac output, it has been proved that the survival rate for cardiac arrest patients on whom CPR was performed was increased two to threefold than that in patients who did not receive CPR.[2–5] There have been a number of studies to increase cardiac output generated by chest compression during CPR; however, most dealt with compression rate and depth rather than compression location.[6] According to the guideline for CPR announced by the International Liaison Committee on Resuscitation, the American Heart Association and the European Resuscitation Council in 2005, it was suggested that the rescuer should compress at the point where the sternum and internipple line meet.[7–9] However, there is insufficient evidence for the proper hand position for chest compression, and it was changed more ambiguously to the lower half of the sternum in the 2010 guidelines.[10–12]

The cardiac pump theory and the thoracic pump theory have been suggested as artificial circulatory mechanisms during CPR. The cardiac pump theory suggests that increased intraventricular pressure, generated as the ventricles are compressed between the sternum and the thoracic vertebrae during CPR, leads to the closure of the mitral and tricuspid valves and opening of the aortic and pulmonary valves, which generates systemic and pulmonary circulation.[1, 13, 14] On the other hand, the thoracic pump theory suggests that the circulation is generated by the difference between the external and internal thoracic pressure when the chest is compressed, with the heart simply serving as a pathway for blood flow.[15–17] Several recent studies using transoesophageal echocardiography have provided evidence that artificial circulation during CPR can be attributed to the direct compression of the heart, which supports the cardiac pump theory as the main circulatory mechanism during CPR.[13, 14,

[18, 19]According to the cardiac pump theory, it is speculated that the left ventricle should be compressed as much as possible for most effective circulation. However, there have been few studies to investigate the effective method for compressing the left ventricle during CPR.

In this chest CT-based study, the structures below each chest compression point and the area of the left ventricle actually compressed were analysed in each patient who received CPR, to study the efficiency and validity of the currently recommended chest compression location.

Patients and Methods

Study Design and Participants

A retrospective cohort study was conducted to evaluate the chest CT in out-of-hospital cardiac arrest patients older than 18 years who had been admitted to the emergency department in cardiac arrest and resuscitated after CPR. The study was approved by the Institutional Review Board. Chest CT were evaluated within a day after resuscitation when patients were stabilised. From 1 January 2006 to 30 August 2009, 180 patients were resuscitated from cardiac arrest in our emergency department. Among them, 127 patients had a chest CT scan within a day after resuscitation. Thirteen patients with pectus excavatum or any kind of deformity in their thoracic structure, autopneumonectomy status due to a chronic pulmonary disease, or dislocation of the heart due to emphysema were excluded. Finally, a total of 114 patients was enrolled in the study.

Study Theory

Cardiac output is calculated by multiplying stroke volume and heart rate. To increase cardiac output therefore either stroke volume or heart rate has to increase. However, because during cardiac arrest heart rate is usually fixed within the range of 100–120 beats per minute, stroke volume would have to be increased at each chest compression during CPR to increase cardiac output. We hypothesised that the larger area of the left ventricle that is compressed, the higher the cardiac output. We therefore planned to measure the cross-sectional area of each cardiac structure beneath the sternum at different levels in the chest CT.

Measurement

CT Scan and Measuring Programme A 64-slice multidetector CT scanner (Brilliance CT; Philips Healthcare Systems, Cleveland, Ohio, USA) was used. The following imaging parameters were used: tube voltage 120 kV, tube current 150 mA, detector collimation 64×0.625 mm, pitch 0.891, gantry rotation time 0.5 s, slice thickness 5 mm, slice overlap 0 and matrix 512×512. All studies were performed using breath-hold with full inspiration. CT images were displayed at the window width of 400 HU and a window level of 40 HU.

The cross-sectional area of the heart was analysed by the Centricity Work Station RA 1000 program by the General Electric Company (GE Healthcare Integrated IT Solution, Barrington, Illinois, USA).

Measurement and Definition of Parameters The areas were calculated independently by two emergency physicians. During chest compression, the midway portion width between the costochondral junction and the sternum, and that between the sternum and costochondral junction (SCM) had been designated as the compressed areas; we measured the cross-sectional area of the heart below SCM. The SCM and cross-sectional area of the heart were measured from three different levels: the internipple line (A), sternoxiphoid junction (C), and the halfway between the two points (B). We used the maximum SCM within three levels (SCM_{max}) as the standard width to measure the cross-sectional area of the heart below each level.

We set landmarks that divide each structure—a point where the bicuspid valve meets the left ventricle and left atrium; a point where the tricuspid valve meets the right ventricle and the right atrium; and a point where the aortic valve meets the left ventricle and the aorta—and measured the area of each structure. The left ventricular area (LVA) was measured including the wall of the left ventricle and the interventricular septum.

Below SCM_{max}, the predicted compressed areas were defined as the total area of compression (TAC). TAC was defined as the sum of each of the predicted compressed areas such as the right atrium area compressed (RAA_{cmp}), the right ventricle area compressed (RVA_{cmp}), the left atrium area compressed (LAA_{cmp}), the left ventricle area compressed (LVA_{cmp}) and the great vascular area compressed (GVA_{cmp}). The total heart area (THA) was defined as the sum of the predicted compressed areas

and non-compressed areas, and was composed of the right atrial area (RAA), the right ventricular area (RVA), the left atrial area (LAA), the LVA and the great vascular area (figure 1). An area fraction of the predicted compressed cardiac structures was calculated by dividing THA into the predicted compressed cardiac structure area.
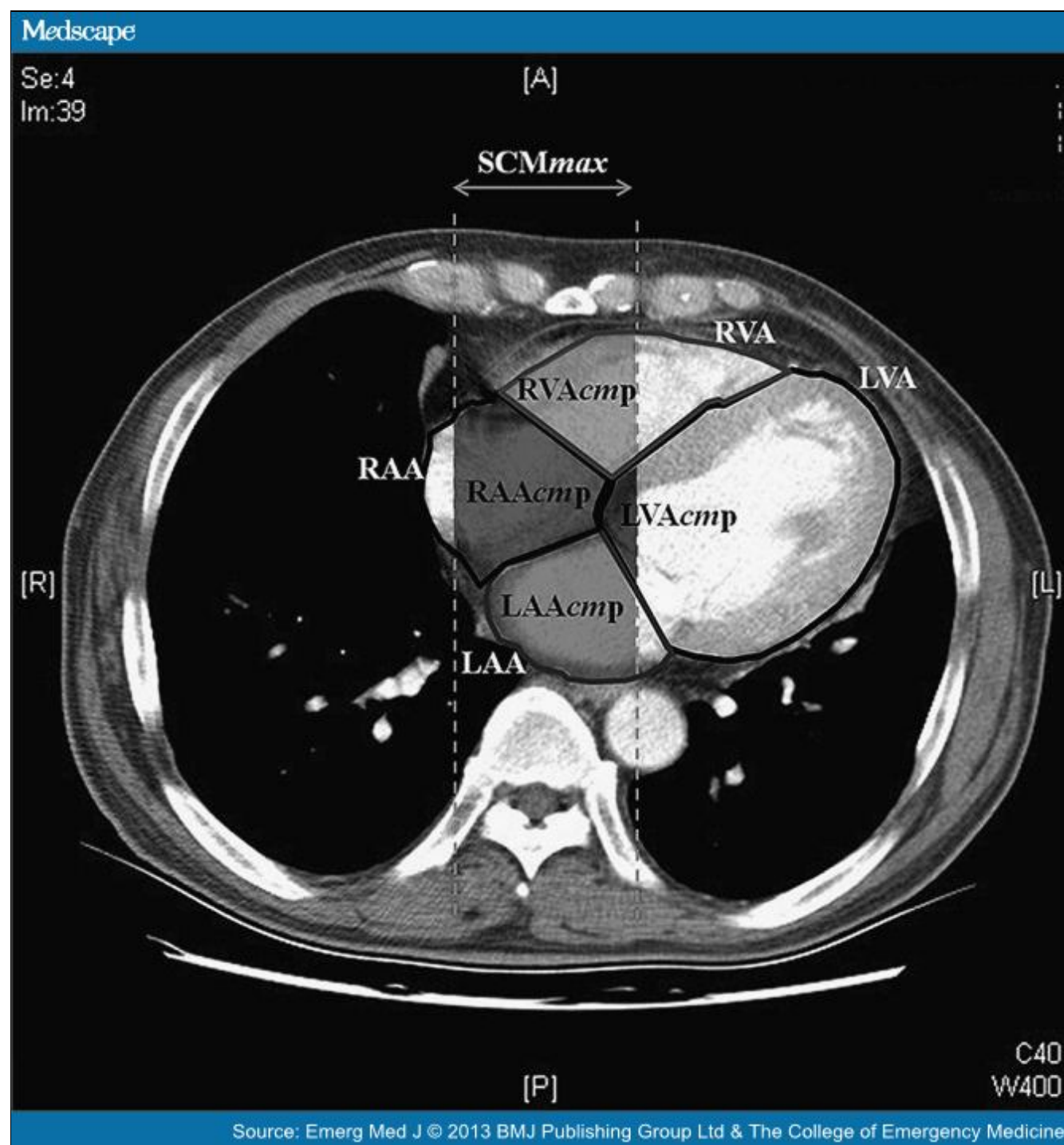

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Figure 1.

Measurement of areas on chest CT images (SCM_{max}, the maximal width of the midway portion between the costochondral junction and the sternum; red line area, left ventricular area (LVA); blue line area, right ventricular area (RVA); pink line area, left atrial area (LAA); purple line area, right atrial area (RAA); red colour area, predicted left ventricular area compressed (LVA_{cmp}); blue colour area, predicted right ventricular area compressed (RVA_{cmp}); pink colour area, predicted left atrial area compressed (LAA_{cmp}); purple colour area, predicted right atrial area compressed (RAA_{cmp}). This figure is produced in colour in the online journal–please visit the website to view the colour figure.

Statistical Analysis

Data were analysed using an averaged value of the area calculated by each assessor. Interobserver agreement for the measurement of the area was assessed by Cronbach's α. Continuous data were presented as means with standard deviations and compared with the independent sample t test or Mann–Whitney U test as appropriate. Nominal data were presented as the percentage frequency of occurrence and compared with a χ^2 or Fischer's exact test as appropriate. The cross-sectional areas of the heart at points A, B and C were compared by analysis of variance test. Any differences were regarded as significant if p values were less than 0.05. Statistical analysis was performed using a statistical software package (SPSS V.12.0 for Windows).

Results

General Characteristics and Interobserver Agreement for Measurement

Men accounted for 73 cases (64%) and the mean age was 56 years. Fifty-five (48%) of the cardiac arrest cases were of cardiac aetiology, while 44 (39%) were of non-cardiac aetiology and 15 (13%) were secondary to trauma. The mean SCM_{max} was 7.85±0.63 cm. The level of interobserver agreement for measurement of the area was excellent (Cronbach's α 0.90).

Cross-sectional Areas of the Cardiac Structures at Levels A, B and C

THA and RAA was wider at points B and C than at point A (THA: 5202±2228 mm^2 at point A, 7510±2216 mm^2 at point B and 7615±3016 mm^2 at point C, p<0.001; RAA: 451±624 mm^2 at point A, 1134±787 mm^2 at point B and 1215±850 mm^2 at point C, p<0.001). LAA was widest at point B (945±1032 mm^2 at point A, 1626±828 mm^2 at point B and 808±860 mm^2 at point C, p<0.001). LVA and RVA were widest at point C (RVA: 481±694 mm^2 at point A, 1228±768 mm^2 at point B and 1633±783 mm^2 at point C, p<0.001; LVA: 501±1054 mm^2 at point A, 2023±1566 mm^2 at point B and 3671±1477 mm^2 at point C, p<0.001). The great vascular area was widest at point A (2821±1347 mm^2 at point A, 1487±1281 mm^2 at point B and 296±569 mm^2 at point C, p<0.001) ().

Table 1. Comparison of areas for each estimation point

	Estimation point			p Value*
	A	**B**	**C**	
	n=114	**n=114**	**n=114**	
THA (mm^2)	5202±2228	7510±2216	7615±3016	<0.001
T†	A	b	B	
RAA (mm^2)	451±624	1134±787	1215±850	<0.001
T†	A	b	B	
LAA (mm^2)	945±1032	1626±828	808±860	<0.001
T†	A	b	A	
RVA (mm^2)	481±694	1228±768	1633±783	<0.001
T†	A	b	C	
LVA (mm^2)	501±1054	2023±1566	3671±1477	<0.001
T†	A	b	C	
GVA (mm^2)	2821±1347	1487±1281	296±569	<0.001
T†	A	b	C	

*Statistical significance was tested by one-way analysis of variances among groups.
†The same letters indicate non-significant difference groups based on Tukey's multiple comparison test.
Estimation point A, internipple line; estimation point B, halfway point A and C; estimation point C, sternoxiphoid junction; GVA, area of the great vessel; LAA, area of the left atrium; LVA, area of the left ventricle; RAA, area of the right atrium; RVA, area of

the right ventricle; THA, total heart area.

The widest THA, total ventricular area and LVA were observed most frequently at point C (58%, 85% and 78%, respectively). Few cases (six in THA, one in total ventricular area and one in LVA, respectively) were observed as the widest at point A (figure 2). This result suggests that point A is located on the great vessel area rather than the ventricles in most cases.
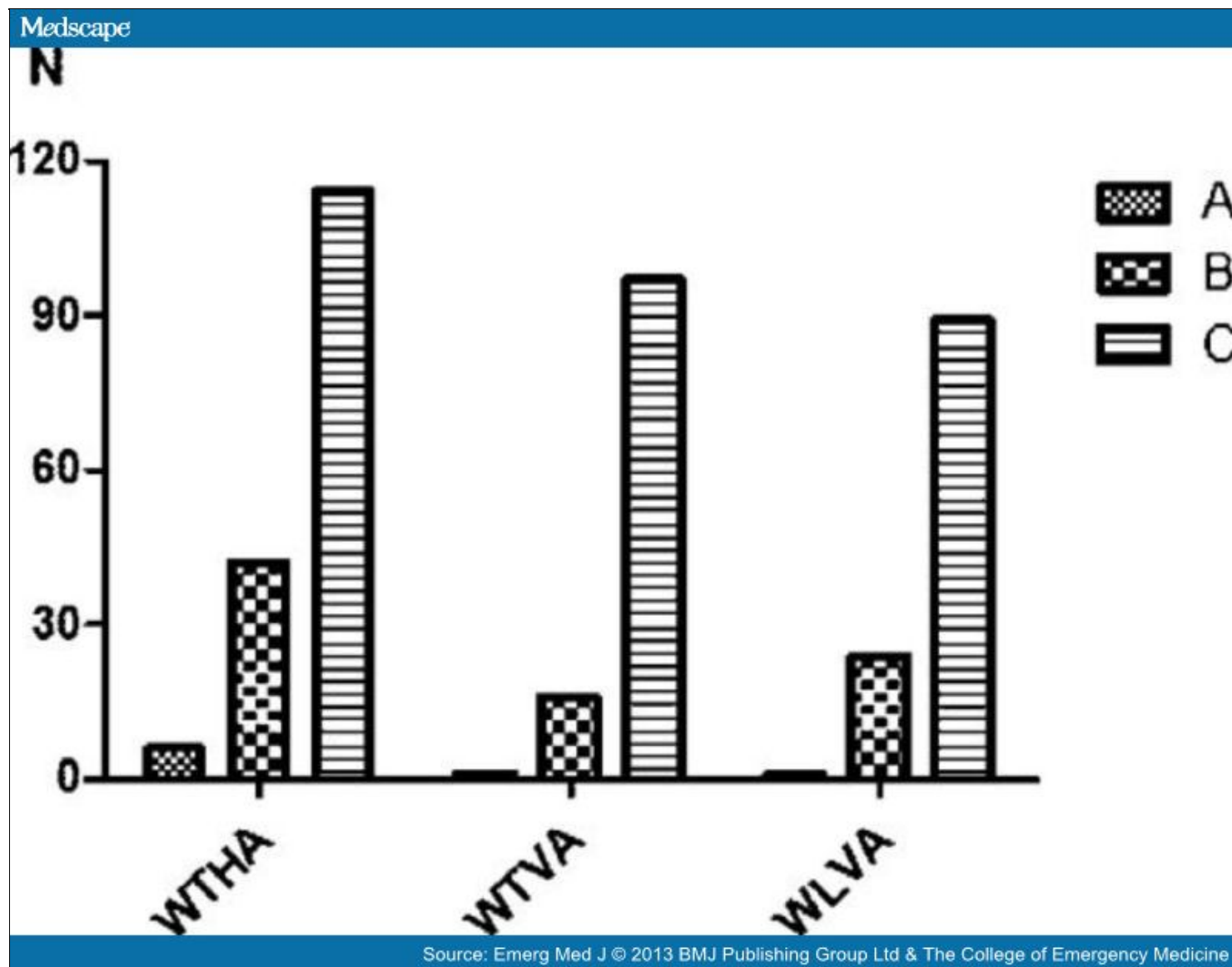

Figure 2.

The frequencies of the widest total heart area (WTHA), total ventricular area (WTVA) and left ventricular area (WLVA) at points A, B and C. The WTHA, WTVA and WLVA are most frequently observed at point C.

Cross-sectional Areas of the Predicted Compressed Cardiac Structures at Levels A, B and C

TAC was wider at point B than at points A or C (4313 ± 1528 mm^2 at point A, 5284 ± 1443 mm^2 at point B and 4683 ± 1976 mm^2 at point C, $p<0.001$). RAA$_{cmp}$ was wider at points B and C than at point A (438 ± 615 mm^2 at point A, 1094 ± 780 mm^2 at point B and 1133 ± 823 mm^2 at point C, $p<0.001$). LAA$_{cmp}$ was wider at point B than at points A or C (815 ± 936 mm^2 at point A, 1499 ± 785 mm^2 at point B and 765 ± 814 mm^2 at point C, $p<0.001$). RVA$_{cmp}$ and LVA$_{cmp}$ were widest at point C than at points A or B (RVA$_{cmp}$: 366 ± 536 mm^2 at point A, 961 ± 653 mm^2 at point B and 1383 ± 689 mm^2 at point C, $p<0.001$; LVA$_{cmp}$: 65 ± 236 mm^2 at point A, 365 ± 506 mm^2 at point B and 1099 ± 817 mm^2 at point C, $p<0.001$). GVA$_{cmp}$ was wider at point A than at points B or C (2671 ± 1286 mm^2 at point A, 1368 ± 1174 mm^2 at point B and 294 ± 566 mm^2 at point C, $p<0.001$) (; figure 3). This result

suggests that the wider area of the ventricles will be subjected to chest compression at point C than chest compression at points B or C.

Table 2. Comparison of predicted compressed areas for each estimation point

	Estimation point			p Value*
	A	**B**	**C**	
	n=114	**N=114**	**n=114**	
TAC (mm^2)	4313±1528	5284±1443	4683±1976	<0.001
T†	A	B	a	
RAA$_{cmp}$ (mm^2)	438±615	1094±780	1133±823	<0.001
T†	A	B	b	
LAA$_{cmp}$ (mm^2)	815±936	1499±785	765±814	<0.001
T†	A	B	a	
RVA$_{cmp}$ (mm^2)	366±536	961±653	1383±689	<0.001
T†	A	B	c	
LVA$_{cmp}$ (mm^2)	65±236	365±506	1099±817	<0.001
T†	A	B	c	
GVA$_{cmp}$ (mm^2)	2671±1286	1368±1174	294±566	<0.001
T†	A	B	c	

*Statistical significance was tested by one-way analysis of variances among groups.
†The same letters indicate non-significant difference groups based on Tukey's multiple comparison test.
Estimation point A, internipple line; estimation point B, halfway point A and C; estimation point C, sternoxiphoid junction; GVA$_{cmp}$, predicted compressed area of the great vessel; LAA$_{cmp}$, predicted compressed area of the left atrium; LVA$_{cmp}$, predicted compressed area of the left ventricle; RAA$_{cmp}$, predicted compressed area of the right atrium; RVA$_{cmp}$, predicted compressed area of the right ventricle; TAC, total area of compression.

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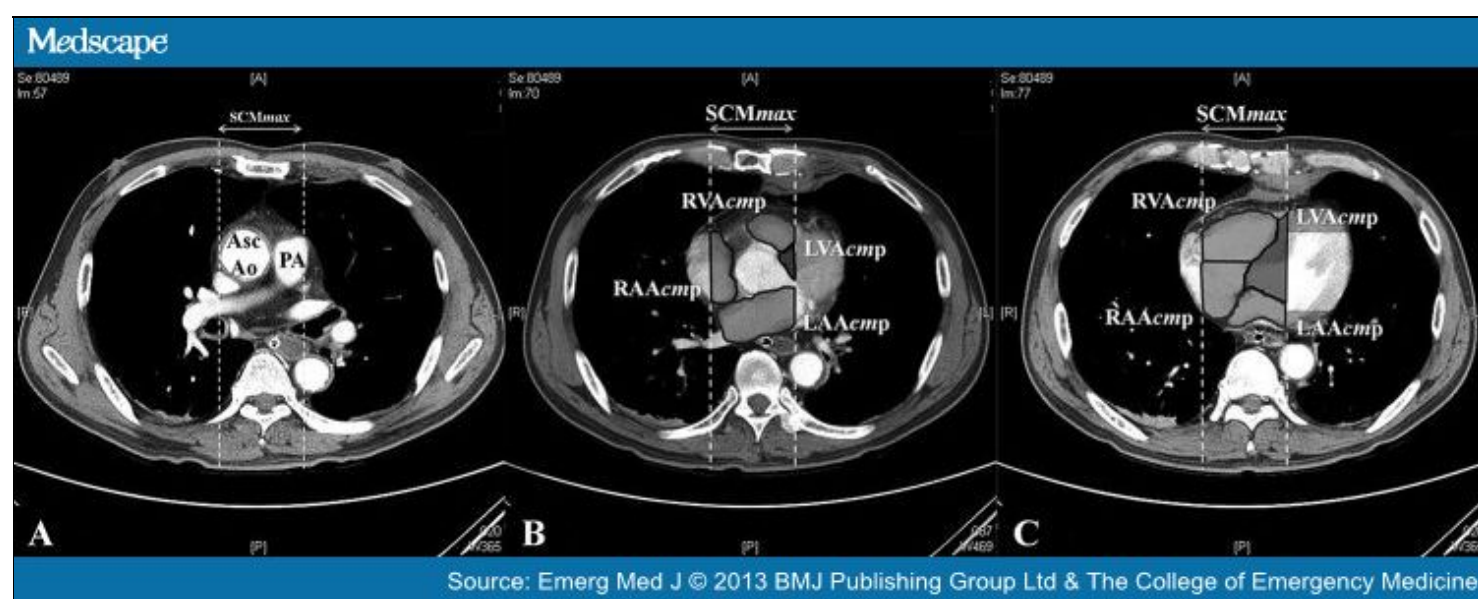
Figure 3.

An illustrated case of the predicted compressed area of each structure of the heart at the internipple line (A), halfway between A and C (B) and the sternoxiphoid junction (C). The predicted compressed area is occupied with the great vessels at point A while it is occupied with cardiac chambers at points B and C. Asc Ao, ascending aorta; PA, pulmonary artery; RAA_{cmp}, predicted right atrial area compressed; LAA_{cmp}, predicted left atrial area compressed; RVA_{cmp}, predicted right ventricular area compressed; LVA_{cmp}, predicted left ventricular area compressed.

Area Fraction of Predicted Compressed Cardiac Structures

RAA_{cmp} fraction was 7±8% at point A, 14±8% at point B and 13±8% at point C; and LAA_{cmp} fraction was 13±14% at point A, 20±10% at point B and 8±8% at point C. RVA_{cmp} fraction was 5±8% at point A, 13±8% at point B and 18±10% at point C, and LVA_{cmp} fraction was 1±3% at point A, 5±7% at point B and 15±12% at point C. GVA_{cmp} fraction was 62±34% at point A, 21±20% at point B and 3±7% at point C (figure 4).
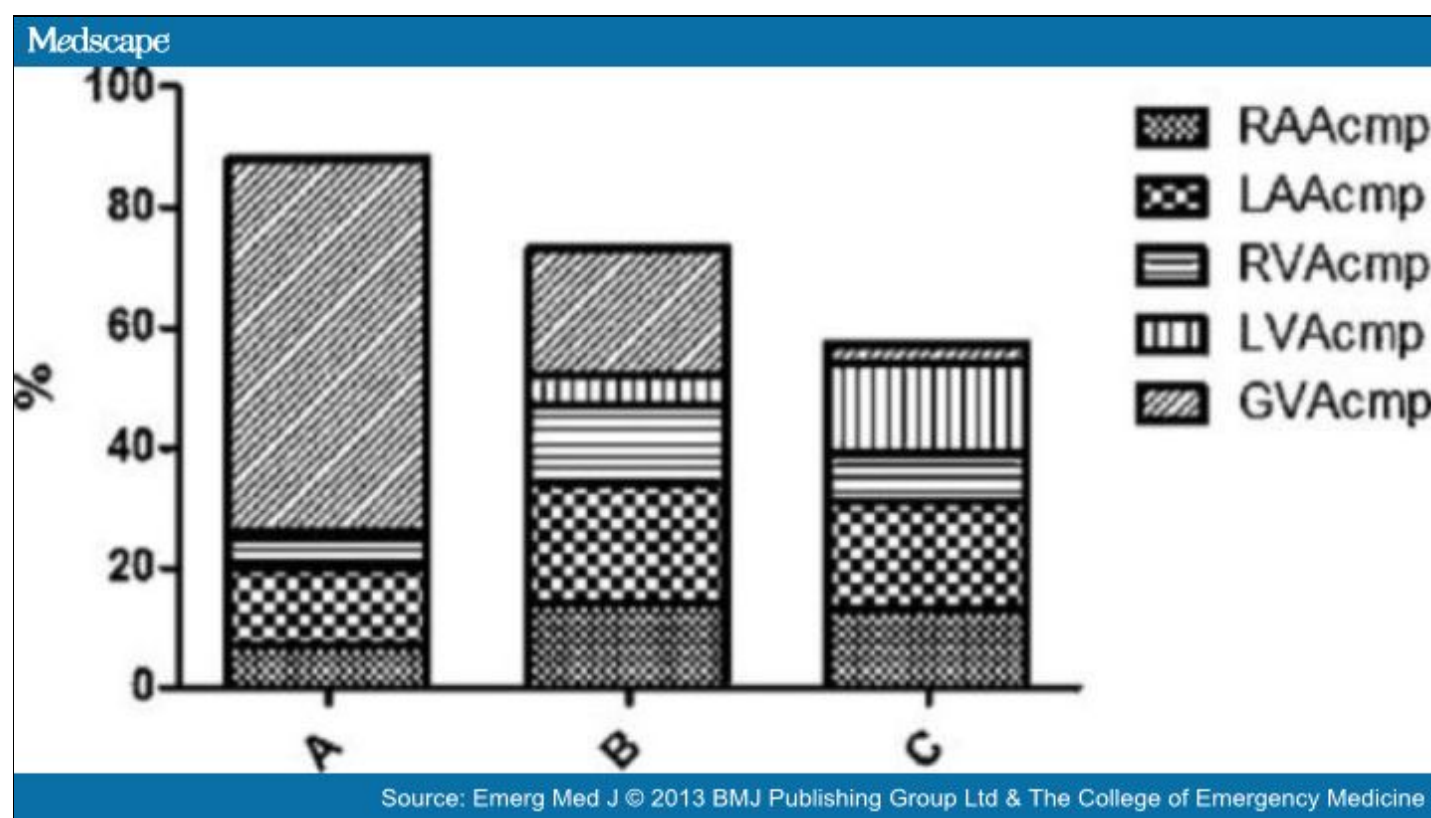

Figure 4.

Area fraction of predicted compressed cardiac structures. Area fraction of the cardiac chamber areas increases and that of the great vessel area (GVA) decreases as the compression point move from point A to points B and C. Point A, inter-nipple line; point B, halfway between A and C; point C, sternoxiphoid junction; RAA_{cmp}, predicted right atrial area compressed; LAA_{cmp}, predicted left atrial area compressed; RVA_{cmp}, predicted right ventricular area compressed; LVA_{cmp}, predicted left ventricular area compressed.

Discussion

We observed that the areas of the ventricles subjected to chest compression become wider as the compression point shifts from the internipple line to the sternoxiphoid junction. The results of our analysis suggest that the shift of the compression point towards the sternoxiphoid junction might produce a higher degree of ventricular compression than chest compression at the standard points does.

As Kouwenhoven and colleagues[1] suggested 'closed-chest cardiac massage' at the level of the head of the xiphoid process for cardiac resuscitation, a few studies have attempted to find the proper location for chest compression. In 1963, Thaler and Stobie[20] suggested that CPR should be performed near the middle of the sternum instead of below the sternum because many cases of liver injury were reported during infant CPR. In 1986, Orlowski[21] reported that CPR performed at the level of the lower one-third of the sternum was safe and effective in infants and young children.

In the recent CPR guideline from International Liaison Committee on Resuscitation, American Heart Association and European Resuscitation Council, the lower half of the sternum was recommended as the site for proper hand positioning during chest compression.[10–12] However, the lower half of the sternum is not a clear compression point to be found by rescuers, and it was recommended not because there was evidence that it was associated with effective generation of cardiac output but because it is easily applicable for rescuers.

There have recently been several studies suggesting the hand position for chest compression, ie, against the recent CPR guideline. In a study based on chest CT images from 189 patients, the root of the aorta, the ascending aorta and the left ventricular outflow tract (LVOT) were located right below the midpoint of the internipple line in 80% of patients. Furthermore, only 20% of the left ventricle was located below the midpoint of the internipple line, which suggested that it is more efficient to perform chest compression at the very end of the sternum instead of at the midpoint of the internipple line.[22] Another study revealed that the commonest anatomical structures that would be compressed are the ascending aorta and the top of the left atrium.[23] It was also identified that the internipple line is not an optimal chest compression point in the paediatric population in another study.[24] Furthermore, we had found that chest compression on the internipple line with a depth of 4–5 cm results in compression of LVOT or of the proximal descending aorta, and cardiac output increased as the area of maximal compression moved far away in the direction to the left ventricle from the LVOT in a previous study using transoesophageal echocardiography.[25]

In this study, THA and the area fraction of predicted compressed left ventricle increased and the area fraction of predicted compressed great vessel area decreased as the point of compression descended to the sternoxiphoid junction from the internipple line. The results imply that effective compressions of the ventricles are expected when chest compression is performed at the sternoxiphoid junction and would be an important basis for a more effective chest compression method during CPR.

Previous studies using chest CT images, which reported that the lower half of the sternum is not an optimal compression point during CPR, just verified the anatomical position of the heart below the sternum. We compared predicted compressed areas and the fraction of each structure of the heart and suggested an alternative chest compression point to generate effective cardiac output on the basis of these results. It would be more realistic to determine the optimal chest compression point during CPR than previous studies.

A concern regarding the safety aspect can be raised when chest compression is performed at the sternoxiphoid junction. Compression of the abdomen increases the risk of blunt upper abdominal trauma including injuries of the liver.[26] Therefore, the safety issue should be resolved before chest compression at the sternoxiphoid junction is implemented in clinical practice.

This study had several limitations. First, relocation of the structures within the thoracic cavity after intubation and artificial ventilation might be possible because chest CT images were not obtained during CPR. In addition, because chest CT is performed with the arms raised, there might be some discrepancy in the position of the nipples with that during CPR. A study revealed that the sternal notch moved up an average of 8.4 mm when a chest CT scan was taken in the arms-raised position.[27] It is not likely that this minor movement of the sternum causes a significant change in study results. Second, the uncertainty as to whether the heart is in systole or diastole might introduce bias in the measurement of the areas of cardiac structures. The LVA was measured including the wall of the left ventricle and the interventricular septum. The compressed portion of the heart during CPR is only the left ventricular chamber not the wall itself, so that it might be more realistic to measure only the contrast enhanced area of the left ventricle. However, we chose to include the wall of the left ventricle and the interventricular septum in the LVA because the left ventricular cavity area in a beating heart will be subject to a specific phase of cardiac cycles. Third, there might be a difference between areas of predicted compressed and actual compressed structures because the rectangular structure of the sternum might confer a similar haemodynamic effect to compressing part or a broad area of it. Further study evaluating haemodynamic effect by compression point could address this unsolved question. Fourth, this study assumed that the cardiac pump theory is the major mechanism in the generation of cardiac output during CPR. Therefore, it is not considered in this study that intrathoracic pressure could generate an additional haemodynamic effect.

Finally, with the analysis of chest CT images, we only measured a cross-sectional area, and did not perform a volumetric analysis. Therefore, measuring the volume of various structures in the thoracic cavity would allow this study to correlate better with real CPR situations.

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Conclusions
Only a small proportion of the ventricle is subjected to external chest compression when CPR is performed according to the current guidelines. Compression of the sternum at the sternoxiphoid junction might be more effective to compress the ventricles.

Ethics approval
Ethics approval was provided by the Institutional Review Board of Wonju Christian Hospital.

Provenance and peer review
Not commissioned; externally peer reviewed.