

**School of Nursing, Midwifery and Paramedicine
Prehospital, Resuscitation and Emergency Care Research Unit
(PRECRU)**

**The relationship between the quality of cardiopulmonary
resuscitation (CPR) performed by paramedics and survival
outcomes from out-of-hospital cardiac arrest (OHCA)**

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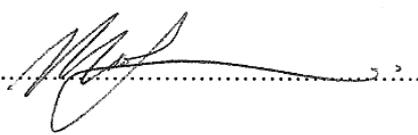
**This thesis is presented for the Degree of
Doctor of Philosophy
of
Curtin University**

June 2017

Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature: 

Date: 16/08/17

Abstract

Background: International resuscitation guidelines specify parameters for the provision of high quality cardiopulmonary resuscitation (CPR) to persons in cardiac arrest. High quality CPR primarily consists of chest compressions that are of adequate depth, delivered at an adequate rate and with minimal interruptions. In addition, rescuers should avoid leaning on the patient's chest and avoid excessive ventilation. Although it has previously been associated with patient outcome, the quality of CPR provided by rescuers, including healthcare professionals, is often suboptimal.

Aim: To determine the relationship between the quality of CPR provided by St John Ambulance Western Australia (SJA-WA) paramedics and out-of-hospital cardiac arrest (OHCA) patient survival outcomes.

Methods:

Systematic review

Firstly a systematic review of the research literature was undertaken to determine the relationship between CPR quality metrics (the individual elements comprising CPR quality) and OHCA patient survival outcomes. The key metrics considered were chest compression depth, compression rate and compression fraction (defined as the proportion of resuscitation time without spontaneous circulation during which chest compressions were administered). Duty cycle, incomplete chest release, peri-shock pause and ventilation rate were also considered. The association of CPR quality with three cardiac arrest survival outcomes was examined: return of spontaneous circulation (ROSC), survival to hospital discharge (STHD) and good neurological outcome at hospital discharge. Five electronic databases were searched (MEDLINE, Embase, CINAHL, Scopus and Cochrane) as well as the grey literature (MedNar) to identify studies that reported human cases of in- or out-of-hospital cardiac arrest where CPR quality had been recorded using an automated device; and where the relationship with survival outcomes had been examined. Where the statistical heterogeneity was acceptable ($I^2 < 75\%$), the results of individual studies were included in a meta-analysis. This systematic review and meta-analysis formed my first published paper: *Talikowska M, Tohira H, Finn J. Cardiopulmonary resuscitation quality and patient survival outcome in cardiac arrest: A systematic review and meta-analysis. Resuscitation. 2015;96:66-77.*

Review of data intervals used for analysis within the literature

Next I compared the methods used to measure CPR quality and examine its relationship with survival among existing published studies. Specifically, the length and characteristics of the data intervals used for analysis were examined; including whether CPR quality was measured over the entire resuscitation episode or part thereof. The findings were reported in my second published paper: *Talikowska M, Tohira H, Bailey P, Finn J. Cardiopulmonary resuscitation quality: Widespread variation in data intervals used for analysis. Resuscitation. 2016;102:25-8.*

Retrospective cohort study

My primary doctoral research project comprised a retrospective cohort study to assess CPR quality among SJA-WA paramedics and determine whether it was associated with OHCA patient survival outcomes. I examined OHCA cases (aged 8 years or older) in which resuscitation had been attempted by SJA-WA paramedics between July 2014 and June 2016 in the Perth metropolitan area. CPR quality was measured using the Q-CPR feedback device (Philips Healthcare and Laerdal Medical). I compared the mean and median for each CPR quality metric with the values recommended by international guidelines and with those reported in other studies. I then employed multivariable logistic regression analysis to determine the relationship between CPR quality and survival outcomes in the cohort, adjusted for known confounders. Subsequently I sought to determine whether the relationship between chest compression fraction (CCF) and ROSC varied based on the 'downtime' from onset of arrest to the provision of CPR by paramedics. The results of these analyses comprised my third published paper: *Talikowska M, Tohira H, Inoue M, Bailey P, Brink D, Finn J. Lower chest compression fraction associated with ROSC in OHCA patients with longer downtimes. Resuscitation. 2017;116:60-5.*

I further examined the relationship between the seemingly counterintuitive inverse association between CCF and ROSC with respect to peri-shock pause, resulting in the submission of a follow-up letter to the Editor of *Resuscitation*: *Talikowska M, Tohira H, Inoue M, Bailey P, Brink D, Finn J. Letter to the Editor: Lower chest compression fraction among patients with longer downtime and ROSC was not due to peri-shock pause. Resuscitation. (Accepted 2 Aug 2017).*

Survey

Finally, a survey of the SJA-WA workforce was conducted to determine the paramedic-reported barriers towards the use of the Q-CPR in clinical practice. The findings were reported in my final published paper: *Talikowska M, Tohira H, Brink D, Bailey P, Finn PJ.*

Paramedic-reported barriers towards use of CPR feedback devices in Perth, Western Australia. Journal of Paramedic Practice. 2016;8(12):597-606.

Results and Discussion:

Systematic review

Database searching yielded 8,842 unique citations resulting in the inclusion of 22 relevant articles. Thirteen were included in the meta-analysis. I found that those patients who achieved ROSC received significantly deeper chest compressions compared to those who did not (mean difference (MD): 0.99 mm, 95% CI: 0.04, 1.93), and survivors to hospital discharge received deeper compressions than non-survivors (MD: 2.59 mm, 95% CI: 0.71, 4.47). Within the range of approximately 100–120 compressions per minute (cpm), compression rate was significantly associated with STHD; survivors were characterised by a lower mean compression rate than non-survivors (MD -1.17 cpm, 95% CI: -2.21 , -0.14). Chest compression fraction could not be included in a meta-analysis due to high statistical heterogeneity, however a higher fraction appeared to be associated with survival in cases with a shockable first monitored rhythm. These findings highlight the well-documented link between high quality CPR and survival outcomes.

Review of data intervals used for analysis within the literature

Among 21 studies that reported the association between CPR quality and cardiac arrest patient survival, two thirds utilised data from the start of the resuscitation episode for analysis; most commonly the first 5 minutes. Variation was observed in the event that marked the commencement of the analysis interval, ranging from the placement of ECG pads on the patient, to the first chest compression. Nine studies specified a minimum duration of data that had to have been collected for the individual case to be included in the analysed cohort; most commonly one minute of data. These findings were used to inform the methodology for my retrospective cohort study.

Retrospective cohort study

The intention of this study was to report the CPR quality provided by SJA-WA paramedics and to determine whether there was a relationship with OHCA patient survival outcomes. From among 1,882 OHCA cases with resuscitation attempted during the study period, it was identified that the Q-CPR was used in 356, of which 341 met the study inclusion criteria. While chest compression rate was within the range recommended by the European Resuscitation Council's (ERC) and American Heart Association's (AHA) resuscitation guidelines, compression depth was below the recommended minimum value (mean \pm SD: 41.8 \pm 9.17mm vs. recommended 50 - 60 mm). Furthermore compression depth did not significantly improve over resuscitation time, despite the provision of real-time feedback.

The mean chest compression fraction (CCF) was greater than the minimum 60% recommended by guidelines. A significant, inverse relationship between CCF and return of spontaneous circulation (ROSC) was noted; CCF>80% was significantly associated with decreased odds of ROSC compared to CCF≤80% (adjusted Odds Ratio (aOR): 0.49, 95% CI: 0.28, 0.87). Furthermore, the relationship appeared to vary depending on patient downtime; the adjusted odds of ROSC were significantly less with CCF>80% compared to CCF≤80% in the group with a downtime of greater than 15 minutes (aOR: 0.06 [95% CI: 0.01, 0.38]), while non-significant among those with downtime ≤ 15 minutes. The lower compression fraction among those who achieved ROSC in the group with a downtime > 15 minutes was not due to more time spent administering shocks. This study was the first to explore the potential influence of downtime on the relationship between CCF and survival outcomes in OHCA.

Survey

A survey was conducted to gain an understanding of the SJA-WA paramedic-reported barriers towards the use of the Q-CPR device in clinical practice. Of the 264 SJA-WA paramedics who participated in the survey, 41% reported having used the Q-CPR during their last attempted resuscitation. Of those who had not used it, the most commonly cited reason (37%) was that a mechanical chest compression device arrived on scene prior to the Q-CPR being deployed. Secondly, other interventions such as intubation, setting up an intravenous line or drug administration were prioritised over the use of the Q-CPR (20%). Thirdly, hand and wrist pain associated with use of the Q-CPR prevented its utilisation in 17% of cases. Other reasons were less frequently reported.

Conclusions: The international literature clearly supports an association between CPR quality metrics (in particular chest compression depth) and OHCA patient survival. While the CPR quality recorded among SJA-WA paramedics complied with guideline requirements with respect to some of the CPR quality metrics, the mean value for compression depth was notably lower than that recommended by guidelines. Furthermore it did not improve with real-time feedback. Within the SJA-WA data I did not find a significant association between compression depth and survival outcomes, nor compression rate and survival outcomes. I did however identify that CCF was significantly but inversely associated with ROSC; this counter-intuitive finding has likewise recently been reported by other authors. A more detailed analysis of the cohort revealed an effect of downtime on this association. This finding provides justification for further investigation into whether a single CCF recommendation is appropriate for all OHCA patients. Overall, it was noted that SJA-WA paramedics were not routinely using the Q-CPR device despite its use being considered

mandatory. The survey results indicated several reasons for this; but given the current widespread distribution of Q-CPR equipment within the ambulance service in Perth, there is potential for increased use. This could be in part achieved by emphasising the importance of high quality CPR as well as the potential role of feedback devices in helping to optimise performance. However, in the case of SJA-WA, the provision of real-time feedback by the Q-CPR device was not associated with improved CPR performance. The reasons for why this was the case require further investigation. Overall, devices like the Q-CPR should be used within a comprehensive system of care that emphasises the importance of high quality CPR and works to promote maximum patient survival.

Acknowledgements

I would like to thank my supervisors Dr Hideo Tohira, Professor Judith Finn, Dr Paul Bailey and the late Professor Ian Jacobs for the mentorship and guidance provided to me during the undertaking of this thesis. In particular it was Professor Ian Jacobs who inspired me to pursue this doctoral degree after attending a presentation by him on survival outcomes from cardiac arrest. At the time I was a volunteer with St John Ambulance and it was Professor Jacobs' dedication to improving patient outcomes that inspired me to change from working as an engineer to enrolling in a postgraduate degree in prehospital research. I hope that this PhD can make at least a small contribution to the area of research that Professor Jacobs pursued with such great enthusiasm and devotion.

I would also like to make a special acknowledgment of Dr Tohira, my primary supervisor, for the very helpful guidance and timely feedback that he provided to me throughout the course of my PhD. He is an exceptional individual who I regard very highly, and it was an honour to be able to have the opportunity to learn from his expertise.

I would also like to thank Dr Madoka Inoue, Research Fellow at the Prehospital, Resuscitation and Emergency Care Research Unit (PRECRU) at Curtin University and the Manager of the SJA-WA cardiac arrest database from which my patient characteristic and survival data was sourced. Dr Inoue works tirelessly to maintain the database to the highest standard and I would like to acknowledge her generous assistance and support, not only with the provision of data but also with giving guidance on the PhD journey as a whole. Dr Inoue together with Dr Tohira provided a great degree of wisdom and advice throughout the PhD process.

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Communications Room staff who permitted me to listen in on emergency calls to gain an understanding of the emergency response system as a whole.

I would like to thank the Australian Resuscitation Outcomes Consortium (Aus-ROC), a National Health and Medical Research Council (NHMRC) Centre of Research Excellence (CRE #1029983) for providing scholarship funding towards this PhD. I also would like to particularly thank Professor Judith Finn, the Director of Aus-ROC, for providing me with valuable guidance and many opportunities to meet fellow researchers and present the results of my PhD at international conferences. This project was likewise funded by an Australian Postgraduate Award (APA) with top-up contributions via a Curtin University Postgraduate Scholarship (CUPS). Curtin University also provided additional funding for consumables and fieldwork and conference attendance.

I would like to say a sincere thank you to all my colleagues at the Prehospital, Resuscitation and Emergency Care Research Unit for their support and companionship throughout the course of my PhD; they made the experience enjoyable and rewarding.

Finally I would especially like to thank my family and my fiancé Paris Christoforou for their wonderful and positive influence throughout this period.

Publications, Presentations and Scholarships

Publications

1. **Talikowska M**, Tohira H, Finn J. Cardiopulmonary resuscitation quality and patient survival outcome in cardiac arrest: A systematic review and meta-analysis. *Resuscitation*. 2015;96:66-77.
2. **Talikowska M**, Tohira H, Bailey P, Finn J. Cardiopulmonary resuscitation quality: Widespread variation in data intervals used for analysis. *Resuscitation*. 2016;102:25-8.
3. **Talikowska M**, Tohira H, Inoue M, Bailey P, Brink D, Finn J. Lower chest compression fraction associated with ROSC in OHCA patients with longer downtimes. *Resuscitation*. 2017;116:60-5.
4. **Talikowska M**, Tohira H, Inoue M, Bailey P, Brink D, Finn J. Letter to the Editor: Lower chest compression fraction among patients with longer downtime and ROSC was not due to peri-shock pause. *Resuscitation*. (Accepted 2 Aug 2017).
5. **Talikowska M**, Tohira H, Brink D, Bailey P, Finn PJ. Paramedic-reported barriers towards use of CPR feedback devices in Perth, Western Australia. *Journal of Paramedic Practice*. 2016;8(12):597-606.

Presentations

Conference presentations

- Poster presentation at Spark of Life Conference, Melbourne, Australia, 2015
Cardiopulmonary resuscitation quality and patient survival outcome in cardiac arrest: A systematic review and meta-analysis.
- Poster presentation at European Resuscitation Council Congress, Prague, Czech Republic, 2015
A systematic review of the association between cardiopulmonary resuscitation quality and survival.

- Oral presentation at Resuscitation in Motion Conference, Toronto, Canada, 2016
Paramedic-reported barriers towards use of CPR quality feedback devices in Perth, Western Australia.
- Poster presentation at the Spark of Life conference, Adelaide, Australia, 2017.
Chest compression fraction inversely associated with return of spontaneous circulation (ROSC) in prolonged out-of-hospital cardiac arrest (OHCA).

Other presentations

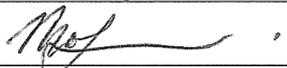
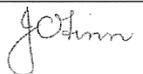
- Presentation for Candidacy, School of Nursing, Midwifery and Paramedicine, Curtin University, Perth, Australia, 2014
- Poster Presentation at Mark Liveris Seminar, Faculty of Health Sciences, Curtin University, Perth, Australia, 2014
- Presentation at Australian Resuscitation Outcomes Consortium Annual Face-to-Face Meeting, Monash University, Melbourne, Australia, 2014/5/6/7
- Presentation at Mark Liveris Seminar, Faculty of Health Sciences, Curtin University, Perth, Australia, 2016 (**Best Paper Award** for School of Nursing, Midwifery and Paramedicine)
- Presentation at the Australian Resuscitation Outcomes Consortium (Aus-ROC) Seminar, Melbourne, Australia, 2016

Scholarships

- Curtin University - Australian Resuscitation Outcomes Consortium (Aus-ROC) PhD Scholarship
- Australian Postgraduate Award (APA)
- Curtin University Postgraduate Scholarship (CUPS)

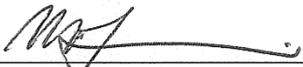
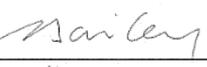
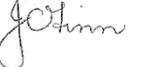
Statement of Author Contributions to Published Papers

1. **Talikowska M, Tohira H, Finn J.** *Cardiopulmonary resuscitation quality and patient survival outcome in cardiac arrest: A systematic review and meta-analysis. Resuscitation. 2015;96:66-77.*

Author	Contribution	Signature
<i>Ms Milena Talikowska</i>	70%	
<i>Dr Hideo Tohira</i>	20%	
<i>Prof Judith Finn</i>	10%	

I, Milena Talikowska, was the primary author of this paper. The extent of my contribution was 70%. I searched the literature and selected potentially relevant papers. Together with my supervisor, Dr Hideo Tohira, we independently screened these papers to identify relevant articles for inclusion. I then performed the meta-analyses. Dr Hideo Tohira confirmed the results. I drafted the article for publication. All three authors were involved in conceiving this study and contributed to the analysis plan, interpretation of results and revision of the article.

2. **Talikowska M, Tohira H, Bailey P, Finn J.** *Cardiopulmonary resuscitation quality: Widespread variation in data intervals used for analysis. Resuscitation. 2016;102:25-8.*

Author	Contribution	Signature
<i>Ms Milena Talikowska</i>	75%	
<i>Dr Hideo Tohira</i>	10%	
<i>Dr Paul Bailey</i>	5%	
<i>Prof Judith Finn</i>	10%	

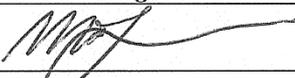
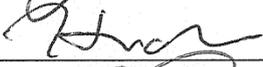
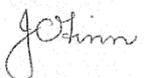
I, Milena Talikowska, was the primary author of this paper. I and my supervisors Dr Hideo Tohira and Prof Judith Finn conceived and designed the study. I extracted data from relevant studies and prepared the associated tables; these were checked by Dr Hideo Tohira for accuracy of content. I prepared the manuscript; all other authors were involved in the revision of the article critically for important intellectual content, and final approval of the version to be submitted.

3. **Talikowska M, Tohira H, Inoue M, Bailey P, Brink D, Finn J.** Lower chest compression fraction associated with ROSC in OHCA patients with longer downtimes. *Resuscitation*. 2017;116:60-5.

Author	Contribution	Signature
<i>Ms Milena Talikowska</i>	75%	
<i>Dr Hideo Tohira</i>	5%	
<i>Dr Madoka Inoue</i>	5%	
<i>Dr Paul Bailey</i>	5%	
<i>Mr Deon Brink</i>	5%	
<i>Prof Judith Finn</i>	5%	

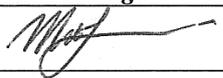
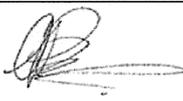
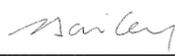
I, Milena Talikowska, was the primary author of this paper. My contribution was 75%. Data for the study was sourced from St. John Ambulance Western Australia (SJA-WA) records in consultation with Mr Deon Brink and Dr Paul Bailey. A proportion of the study dataset was extracted from the SJA-WA OHCA database by Dr Madoka Inoue, the database manager, and provided to me for merging with data collected from the Q-CPR audio-visual feedback device. With the assistance of my supervisor Dr Hideo Tohira, I conducted all data cleaning and analysis. I prepared the manuscript, which was reviewed by Dr Hideo Tohira in the first instance. All other authors were involved in the subsequent revision of the article critically for important intellectual content, and final approval of the version to be submitted.

4. **Talikowska M, Tohira H, Inoue M, Bailey P, Brink D, Finn J.** Letter to the Editor: Lower chest compression fraction among patients with longer downtime and ROSC was not due to peri-shock pause. *Resuscitation*. (Accepted 2 Aug 2017).

Author	Contribution	Signature
<i>Ms Milena Talikowska</i>	75%	
<i>Dr Hideo Tohira</i>	5%	
<i>Dr Madoka Inoue</i>	5%	
<i>Dr Paul Bailey</i>	5%	
<i>Mr Deon Brink</i>	5%	
<i>Prof Judith Finn</i>	5%	

I, Milena Talikowska, was the primary author of this letter. My contribution was 75%. I undertook the additional analysis described in the letter. The results were checked by Dr Hideo Tohira. The original idea for preparing this letter originated from Prof Judith Finn. All other authors were involved in the subsequent revision of the letter critically for important intellectual content, and final approval of the version to be submitted.

5. *Talikowska M, Tohira H, Brink D, Bailey P, Finn J. Paramedic-reported barriers towards use of CPR feedback devices in Perth, Western Australia. Journal of Paramedic Practice. 2016;8:597-606.*

Author	Contribution	Signature
<i>Ms Milena Talikowska</i>	80%	
<i>Dr Hideo Tohira</i>	5%	
<i>Mr Deon Brink</i>	5%	
<i>Dr Paul Bailey</i>	5%	
<i>Prof Judith Finn</i>	5%	

I, Milena Talikowska, was the primary author of this paper. My contribution was 80%. The survey that was the subject of this paper was distributed to paramedics by St John Ambulance Western Australia (under the direction of Mr Deon Brink and Dr Paul Bailey). I analysed the results and prepared the manuscript; all other authors were involved in the revision of the article critically for important intellectual content, and final approval of the version to be submitted.

I warrant that I have obtained, where necessary, permission from the copyright owners to use any third party copyright material reproduced in this thesis or to use any of my own published work in which the copyright is held by another party. Copies of license agreements granting permission for me to include my published journal articles in this thesis are included in the appendices.

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Ethics Approval

The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Number HR 128/2013 and RDHS-209-15.

My name was added to the list of investigators for HR 128/2013: “Western Australian Pre-hospital Care Record Linkage Project” to enable data access and analysis. A copy of this approval is provided in Appendix 1.

A separate approval (RDHS-209-15) was obtained for the analysis of St John Ambulance Western Australia survey results. A copy of this approval is provided in Appendix 2.

Additional approvals to access St John Ambulance Patient Care Records, Patient Medical Records and Death Records were gained from the St John Ambulance Research Advisory Group, the individual hospitals in Perth and the Western Australian Death Registry respectively.

List of Abbreviations

AED	Automated External Defibrillator
AHA	American Heart Association
AM	Area Manager
ANZCOR	Australian and New Zealand Committee on Resuscitation
CCF	Chest Compression Fraction
CoSTR	International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science with Treatment Recommendations
CPC	Cerebral Performance Category
CPG	Clinical Practice Guideline
cpm	Compressions per minute
CPR	Cardiopulmonary Resuscitation
CSP	Clinical Support Paramedic
ECG	Electrocardiograph
ED	Emergency Department
EMS	Emergency Medical Service
ePCR	Electronic Patient Care Record
ERC	European Resuscitation Council
IHCA	In-hospital Cardiac Arrest
ILCOR	International Liaison Committee on Resuscitation
IV	Intravenous
LUCAS	Lund University Cardiopulmonary Assist System
OHCA	Out-of-hospital Cardiac Arrest
PEA	Pulseless Electrical Activity
pVT	Pulseless Ventricular Tachycardia
Q-CPR™	<i>CPR feedback device (Laerdal Medical, Philips Healthcare)</i>
ROC	Resuscitation Outcomes Consortium
ROSC	Return of Spontaneous Circulation
SJA-WA	St John Ambulance Western Australia
STHD	Survival to Hospital Discharge
VF	Ventricular Fibrillation
vpm	Ventilations per minute
VT	Ventricular Tachycardia
WA	Western Australia

Chapter 1 Introduction

1.1 Background and rationale

Out-of-hospital cardiac arrest (OHCA) is an issue that affects an estimated 30,000 Australians¹ (and over 350,000 Americans) annually.² It is a condition in which the heart ceases to pump blood around the body, leading to immediate loss of consciousness and either a total lack of breathing or the presence of occasional, agonal gasping. In the majority of cases it results in patient death. Even within many modern Emergency Medical Service (EMS) systems globally, survival from this condition is around 10% for those patients in whom resuscitation was attempted.¹ However, there is increasing understanding of the potential ways to improve survival outcomes for OHCA patients. One method involves the provision of high quality cardiopulmonary resuscitation (CPR). Although CPR, together with defibrillation, comprises the standard Basic Life Support (BLS) treatment for OHCA, the quality of CPR administered can vary between rescuers. Past studies have shown that often the quality provided has been suboptimal, including among trained medical professionals.³⁻⁶ CPR quality can be described in terms of a number of discrete metrics. These include:⁷

- **compression depth:** for a single compression the maximum depth to which the sternum is compressed prior to chest recoil;
- **compression rate:** the rate at which chest compressions are delivered, measured only during the time that compressions are being provided and not over the time that there are breaks in compressions;
- **compression fraction:** the proportion of time spent delivering chest compressions during the resuscitation effort, excluding periods of restored spontaneous circulation;
- **shock pause:** the duration of time for which compressions are paused to deliver an electrical shock to the chest; defined in terms of pre-shock pause: the time interval between chest compression cessation and shock delivery, post-shock pause: the time between shock delivery and chest compression resumption, and peri-shock pause: the sum of pre-shock and post-shock pause;
- **duty cycle:** during a single compression, the proportion of time that is assigned to the downward stroke of the compression, or, the proportion of time during which pressure is applied to the chest of the patient;

- **chest wall recoil:** the proportion of compressions in which the chest is allowed to return to its resting position prior to the administration of the subsequent compression, or, the proportion of compressions where pressure is completely released from the chest prior to the administration of the next compression. The inverse is often measured: the proportion of compressions with **leaning**; and
- **ventilation rate:** the number of ventilations delivered per minute of CPR.

Recommendations pertaining to each of these CPR quality metrics have been issued by the International Liaison Committee on Resuscitation (ILCOR)⁸ and subsequently translated into regional CPR guidelines. These include guidelines issued by the American Heart Association (AHA),⁹ the European Resuscitation Council (ERC)¹⁰ and the Australian and New Zealand Committee on Resuscitation (ANZCOR).^{11, 12} These guidelines represent the current consensus on the definition of high quality CPR and are intended to guide optimised clinical practice.

High quality CPR has been associated with improved OHCA patient survival across a number of studies. For example, deeper compressions have been linked to improved OHCA patient survival to hospital discharge,^{13, 14} while a compression rate in the range of 100-120 cpm has also been associated with improved survival.¹⁵ I sought to commence my research by synthesising the reported evidence regarding the relationship between the individual CPR quality metrics and OHCA patient survival outcomes. I then aimed to specifically investigate the relationship between the quality of CPR performed by paramedics and survival outcomes from OHCA in Perth, Western Australia (W.A.).

I conducted a retrospective cohort study using data sourced from St John Ambulance Western Australia (SJA-WA), the single provider of road ambulance services in the state of W.A. I analysed data that had been collected using the Q-CPRTM feedback device to ascertain the quality of CPR provided by SJA-WA paramedics. I then compared this to OHCA patient survival outcomes. The outcomes of interest were: prehospital return of spontaneous circulation (ROSC), survival to hospital discharge (STHD) and good neurological outcome at discharge, as defined by a Cerebral Performance Category (CPC)¹⁶ score of 1 or 2. I also sought to investigate paramedics' attitudes towards using the Q-CPR device through the undertaking of a survey. My ultimate goal was to provide a set of recommendations to SJA-WA to allow for optimised performance in order to maximise the chances of OHCA patient survival. The broad aims of my research project are summarised in Table 1.

Table 1 Summary of broad research aims

1	To synthesise the reported evidence regarding the association between CPR quality and cardiac arrest patient survival outcomes.
2	To measure the quality of CPR performed by SJA-WA paramedics.
3	To analyse the link between CPR quality and OHCA patient survival outcomes in the study cohort.
4	To explore the attitudes of SJA-WA paramedics towards the use of the Q-CPR device in clinical practice.
5	To provide a set of recommendations to SJA-WA on the basis of my research findings.

1.2 Specific research objectives

In order to address the research aims outlined in Table 1, I set a number of specific research objectives. These are outlined in Table 2.

Table 2 Research objectives linked to each of the research aims

Aim 1: To synthesise the reported evidence regarding the association between CPR quality and cardiac arrest patient survival outcomes.
<ol style="list-style-type: none">i. to conduct a systematic review and a meta-analysis to document the reported association between CPR quality and survival outcomes in the literature.ii. to review the methods used by other studies to analyse the relationship between CPR quality and survival outcomes. More specifically, to determine the details of the intervals that were used for analysis, for example, whether data from the start of the resuscitation episode was used or all available episode data was used.
Aim 2: To measure the quality of CPR performed by SJA-WA paramedics.
<ol style="list-style-type: none">iii. to undertake a retrospective cohort study in which CPR quality is measured using the Q-CPR feedback device.iv. to describe the mean and median values for each of six CPR quality metrics (compression depth, compression rate, compression fraction, duty cycle, chest recoil and ventilation rate) and to plot their distributions.v. to compare the CPR quality recorded for the study cohort against the recommendations provided by international resuscitation guidelines.^{9,10}vi. to compare the performance recorded for the study cohort against that recorded in the literature for other EMS agencies or trained CPR providers.vii. to analyse trends in CPR performance over resuscitation time among the study cohort.
Aim 3: To analyse the link between CPR quality and OHCA patient survival outcomes in the study cohort.
<ol style="list-style-type: none">viii. to use multivariable logistic regression analysis to determine the link between CPR quality and survival outcomes (ROSC, STHD and good neurological outcome upon discharge).ix. Additional: to explore the relationship between chest compression fraction and ROSC in greater detail by:<ul style="list-style-type: none">• using a variety of alternative measurement intervals for analysis, including using data exclusively from the first few minutes of the resuscitation episode compared to data from

the entire episode;

- adjusting for factors linked to compression fraction and/or survival that have been previously shown to change the nature of the relationship between chest compression fraction and OHCA survival;¹⁷ and
- analysing the relationship between chest compression fraction and ROSC using alternative analysis techniques: artificial neural network (ANN) analysis¹⁸ and classification and regression tree (CART) analysis.¹⁹

Aim 4: To explore the attitudes of SJA-WA paramedics towards the use of the Q-CPR device in clinical practice.

- x. to analyse the results of a survey on the topic of the Q-CPR device that was distributed to a sample of SJA-WA paramedics and to report the findings.

Aim 5: To provide a set of recommendations to SJA-WA on the basis of my research findings.

- xi. to synthesise the reported findings into a set of practical recommendations.

Details of the approach taken in this thesis to address each of the above mentioned research aims and objectives is outlined in Section 1.3.

1.3 Thesis approach

This thesis comprises a ‘hybrid model’ that incorporates both published research papers and a written description of the work undertaken. An overview of each chapter is provided in Table 3 below.

Table 3 Overview of thesis chapters

Chapter	Description	Aim	Objective
Chapter 1	<i>Introduction</i>		
Chapter 2	<i>Background</i> A brief overview of cardiac arrest, including incidence and survival rates. A description of the metrics by which CPR quality is defined and of the Q-CPR device that is used to provide feedback on CPR quality. A summary of findings from the literature on the potential role of feedback devices in optimising CPR quality.		
Chapter 3	<i>Systematic review: CPR quality and patient survival in cardiac arrest</i> Paper published - Talikowska M, Tohira H, Finn J. <i>Cardiopulmonary resuscitation quality and patient survival outcome in cardiac arrest: A systematic review and meta-analysis. Resuscitation. 2015;96:66-77.</i>	(1)	(i)

Chapter	Description	Aim	Objective
Chapter 4	<p><i>Methodologies used by other studies</i></p> <p>Paper published - <i>Talikowska M, Tohira H, Bailey P, Finn J. Cardiopulmonary resuscitation quality: Widespread variation in data intervals used for analysis. Resuscitation. 2016; 102:25-8.</i></p> <p>A review of the methodologies used by other studies to explore the relationship between CPR quality and survival, in particular, the characteristics of the data intervals used for analysis.</p>	(1)	(ii)
Chapter 5	<p><i>Methods</i></p> <p>A detailed description of the methods used in my retrospective cohort study to estimate the relationship between CPR quality and OHCA patient survival, including the statistical analysis techniques used.</p>	(2)	(iii)
Chapter 6	<p><i>Quality of CPR performed by SJA-WA paramedics</i></p> <p>Description of the results from my retrospective cohort study of the CPR quality measured among SJA-WA paramedics. Includes a comparison of results against the international resuscitation guidelines and against the performance recorded for other EMS agencies and for trained rescuers, as reported in the published literature. Also includes a description of trends in CPR performance over resuscitation time.</p>	(2)	(iv-vii)
Chapter 7	<p><i>The relationship between CPR quality and OHCA patient survival outcomes</i></p> <p>Paper published - <i>Talikowska M, Tohira H, Inoue M, Bailey P, Brink D, Finn J. Lower chest compression fraction associated with ROSC in OHCA patients with longer downtimes. Resuscitation. 2017; 116:60-5.</i></p> <p>This manuscript describes the results of the retrospective cohort study in relation to the association between the quality of CPR provided by SJA-WA paramedics and OHCA patient survival outcomes.</p> <p>Particular emphasis was placed on the link between chest compression fraction and ROSC, with a number of sensitivity analyses undertaken to explore this relationship in detail.</p> <p>Furthermore, a letter was submitted to the Editor of Resuscitation describing the effect of peri-shock pause on compression fraction. This letter was accepted for publication on 2 August 2017 - <i>Talikowska M, Tohira H, Inoue M, Bailey P, Brink D, Finn J. Letter to the Editor: Lower chest compression fraction among patients with longer downtime and ROSC was not due to peri-shock pause. Resuscitation. (Accepted 2 Aug 2017).</i></p>	(3)	(viii-ix)

Chapter 8 ***Paramedic-reported barriers towards the use of the Q-CPR*** (4) (x)

Paper published - *Talikowska M, Tohira H, Bailey P, Finn J. Cardiopulmonary resuscitation quality: Widespread variation in data intervals used for analysis. Resuscitation. 2016; 102:25-8.*

A manuscript describing the results of a survey undertaken among a sample of SJA-WA paramedics to determine the possible reasons for the low usage of Q-CPR observed in clinical practice.

Chapter 9 ***Discussion and Conclusions*** (5) (xi)

A detailed discussion of my findings, the limitations of my research and suggestions for future work. The provision of a final set of recommendations based on the research findings.

Chapter 2 Background

2.1 Introduction

This chapter is intended to provide a brief background about cardiac arrest and its management. In particular, it outlines the metrics that define high quality CPR and the tools used to measure CPR quality. This information sets the scene for the subsequent literature review, that explores the relationship between CPR quality and patient survival from cardiac arrest (Chapter 3).

2.2 Cardiac arrest

As defined by the American Heart Association (AHA), the term cardiac arrest refers to an abrupt loss of heart function in a person who may or may not have underlying heart disease.²⁰ More specifically, it is defined as the cessation of cardiac mechanical activity as confirmed by the absence of signs of circulation.²¹ It is characterised by patient unresponsiveness together with an absence of breathing or alternatively the presence of abnormal breathing that is most commonly manifested as occasional, agonal gasping.²² The majority of cardiac arrests are attributed to a cardiac aetiology.²²⁻²⁴ Additional causes of arrest may include, but are not limited to, trauma, drug overdoses, drownings, electrocution and asphyxia.^{24, 25} Although the terms ‘cardiac arrest’ and ‘heart attack’ are often used interchangeably by the lay public, they represent discrete conditions.²⁶ A cardiac arrest may be precipitated by a heart attack (myocardial infarction), but as explained above, a cardiac arrest does not always have a cardiac-related cause. Irrespective of cause, mortality from cardiac arrest is high;²⁷ on average less than 10% of patients survive from an arrest that occurs in the out-of-hospital setting from among those who have resuscitation attempted by emergency medical services (EMS).²⁸

2.3 Incidence rate

According to the American Heart Association (AHA), in the U.S. there are in excess of 350,000 cardiac arrests that occur outside of the hospital and are attended to by Emergency Medical Services (EMS) annually.²⁰ This equates to just under 1,000 out-of-hospital cardiac arrests (OHCAs) per day. With the U.S. population exceeding 323 million in 2016,²⁹ this corresponds to an incidence rate of 110.8 events per 100,000 population (95% CI, 108.9, 112.6).³⁰ In Australia the incidence of cardiac arrest is considered to be comparable. A 2010 systematic review by Berdowski et al. estimated that the median incidence of EMS-attended

out-of-hospital cardiac arrest (OHCA) in Australia was 112.9 events per 100,000 person years. This equates to just under 30,000 OHCA's annually. In Perth, Western Australia, where my doctoral research took place, data from St John Ambulance Western Australia (SJA-WA) revealed that the age-standardised incidence rate of OHCA of presumed cardiac aetiology was 70.6 events per 100,000 population in 2010. Standardisation was undertaken with reference to the 2011 Australian population. OHCA of a presumed cardiac aetiology comprised approximately three quarters of all OHCA.³¹ By contrast, the age-standardised incidence of other high-profile diseases such as breast cancer and lung cancer across Australia were 64 cases per 100,000 persons³² and 43 cases per 100,000 persons³³ respectively in 2013. These figures highlight that cardiac arrest is a major public health issue²⁸ and furthermore, with a survival rate of typically less than 10%,³⁴ a significant contributor to national mortality.

2.4 Survival rate

Globally the average rate of survival to hospital discharge following adult OHCA was estimated to be 7% by a 2010 systematic review, although significant variation was found based on geographical location.¹ Similarly a 2008 prospective observational study by Nichol et al. demonstrated that among ten study sites across the U.S. and Canada, the rate of survival to hospital discharge (STHD) following EMS-treated OHCA ranged from 3.0% in Alabama to 16.3% in Seattle.³⁵ Seattle is regarded as the gold standard globally for survival from OHCA. The observed differences in survival rates had been attributed to several factors including the efficiency of the local emergency medical service (EMS), the level of implementation of a public access defibrillation (PAD) program in the community, the frequency of bystander CPR as well as differences in ambulance case recording and reporting practices.^{1, 35} Nevertheless recent data from across the United States and Canada from sites comprising the Resuscitation Outcomes Consortium (ROC) suggested that in 2015 the mean rate of STHD was 11.4% among all cases that had been treated by emergency medical services.² By contrast in the city of Perth, Western Australia, where my study took place, the rate of STHD was 8.7% among patients who suffered an OHCA of a medical cause between 1997 and 2014 and had resuscitation attempted by paramedics.³⁶ Regardless of the inherent variability across different jurisdictions, overall survival is low, and efforts to improve survival are of critical importance. My research project sought to explore the link between the quality of CPR delivered by paramedics and OHCA patient survival outcomes.

2.5 The chain of survival

The Chain of Survival concept (as depicted in Figure 1) provides a useful framework for considering strategies to improve OHCA outcomes. Each of the links in the chain should be optimised in order to maximise a patient's chances of survival. These links are:

- Early recognition and call for help
- Early CPR
- Early defibrillation
- Early advanced life support and standardised post resuscitation care.¹⁰

The focus of my research was on CPR, in particular, high quality CPR. I therefore describe CPR in detail below.



Figure 1 The chain of survival as illustrated in the European Resuscitation Council Guidelines for Resuscitation 2015¹⁰

2.5.1 Cardiopulmonary resuscitation (CPR)

CPR is an attempt to restore circulation by administering compressions to the chest of the cardiac arrest victim. In some instances, but not always, the compressions are accompanied by ventilations.^{21, 22} Closed chest cardiac massage was first described in 1960.³⁷ The current process entails the rescuer placing the heel of their hand in the centre of the victim's chest, with the other hand on top, and pressing down over the lower half of victim's sternum in a rhythmic manner.³⁸ There are two proposed theories on how this procedure leads to the circulation of blood.³⁹ The first is the cardiac pump theory, first described by Kouwenhoven et al. in 1960.³⁷ In this theory compression of the heart between the sternum and the spine causes blood to be expelled from the heart, while release of the sternum causes blood to re-enter the heart. In this way blood is circulated with each subsequent compression. The second proposition is the thoracic pump theory;⁴⁰ in this theory CPR is believed to lead to the circulation of blood primarily via phasic changes in intrathoracic pressure. Intrathoracic

pressure, as the name suggests, refers to the pressure within the chest cavity (thorax). Compression of the thorax generates a decrease in volume, corresponding to an increase in intrathoracic pressure. When this occurs, blood travels from the area of high pressure towards areas of low pressure, therefore being transported away from the heart and into blood vessels. Release of the compression results in a decrease in intrathoracic pressure which permits the movement of a new unit of blood into the heart, ready for the cycle to begin again. Backflow is prevented by one-way valves. Intrathoracic pressure is also believed to influence air exchange in the lungs.⁴¹

For trained rescuers, manual CPR consists of 30 chest compressions alternated with two ventilations in adult victims of cardiac arrest.⁹⁻¹² However in many jurisdictions, hands-only CPR is encouraged for lay rescuers.³⁸ Several studies have found that the exclusion of ventilations during CPR did not have a detrimental effect on patient survival in adult OHCA.⁴²⁻⁵¹

2.5.2 High quality CPR

There is a large degree of variation among rescuers in terms of the ‘quality’ of CPR delivered to victims of cardiac arrest. Furthermore CPR quality has often been shown to be suboptimal, even among trained medical professionals.³⁻⁶ CPR quality can be defined in terms of seven key metrics:

1. Chest compression depth
2. Chest compression rate
3. Chest compression fraction (inverse: hands-off fraction)
4. Shock pause duration (pre-, post- and peri-shock pause)
5. Duty cycle
6. Chest wall recoil (inverse: incomplete release)
7. Ventilation rate.

These metrics are described in further detail in Sections 2.5.3 - 2.5.9. The 2015 International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science with Treatment Recommendations (CoSTR)³⁸ issued by the International Liaison Committee on Resuscitation (ILCOR)⁸ provides recommendations pertaining to each of the metrics, including, in some cases, the provision of specific target values or ranges. These recommendations have been translated into regional resuscitation guidelines, including the European Resuscitation Council (ERC) Guidelines for Resuscitation 2015¹⁰ and the 2015 American Heart Association (AHA) Guidelines Update for CPR and Emergency

Cardiovascular Care (ECC).⁹ These guidelines are collectively referred to in this thesis as the ‘international guidelines’. In addition the Australian and New Zealand Committee on Resuscitation (ANZCOR) also published resuscitation guidelines in 2016,^{11, 12} although the recommendations provided therein were not as detailed as those contained in the ERC and AHA guidelines. Nevertheless all recommendations for high quality CPR are discussed below.

2.5.3 Compressions depth

Compression depth is defined as the “...maximum posterior deflection of the sternum prior to chest recoil.”⁷ This is pictorially illustrated in Figure 2. The 2015 CoSTR provides a strong recommendation for a compression depth of approximately 50mm in average adult patients.³⁸ This recommendation was based on the finding of several observational studies that showed an association between chest compression depth and patient survival.^{6, 14, 52-55} The CoSTR also provides a weak recommendation discouraging excessive compressions depths exceeding 60mm.³⁸ This upper limit is derived from one study that demonstrated an increased rate of injury when compression depth exceeded 60mm.⁵⁶ Unlike the resuscitation guidelines issued by the ERC¹⁰ and AHA,⁹ those issued by ANZCOR do not specify an upper limit for compression depth.¹²

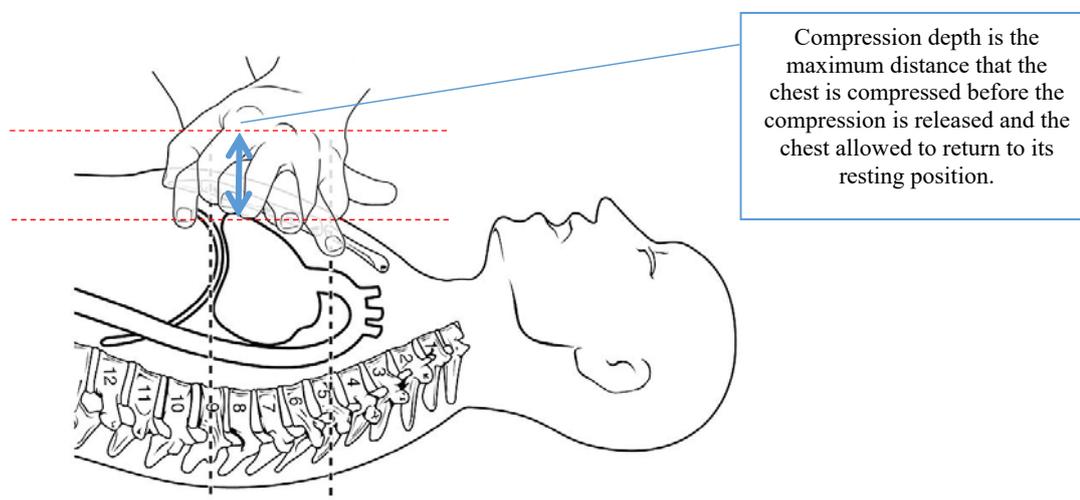


Figure 2 Pictorial illustration of compression depth

Original image⁵⁷ modified as permitted under Copyright Licence.

Several studies have found that when compressions are performed on a non-rigid surface such as on an ambulance stretcher or hospital bed, the recorded depth measurement can be inaccurate.¹⁰ This is pictorially illustrated in Figure 3. Some device manufacturers have attempted to overcome this challenge by independently measuring the movement of the non-

rigid surface beneath the patient and then factoring this into the depth calculation. Alternative approaches to minimise this measurement error include the placement of a rigid backboard beneath the patient.

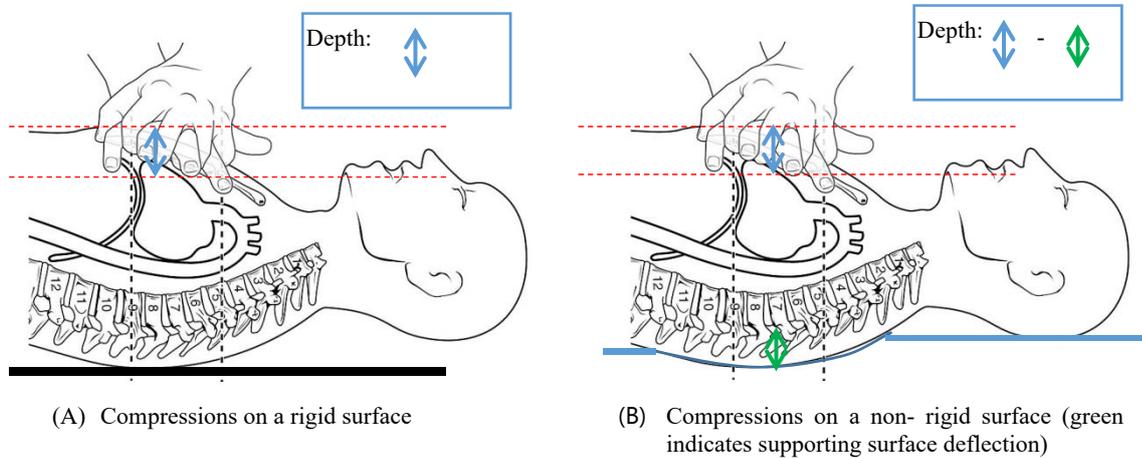


Figure 3 Illustration of the effect on compression depth of mattress deflection/compression on a non-rigid surface

Original image⁵⁷ modified as permitted under Copyright Licence.

2.5.4 Compression rate

The term “compression rate” refers to the frequency (in compressions per minute or cpm) at which chest compressions are delivered to the chest of the patient by the rescuer.⁷ The rate is only measured during uninterrupted periods of chest compressions. For example, if the rescuer pauses to deliver ventilations or allow for cardiac rhythm analysis, the time taken for the pause is not counted when calculating the compression rate. This concept is illustrated in Figure 4. The CoSTR recommends a compression rate in the range 100-120 cpm.³⁸ The upper limit of 120 cpm was imposed primarily due to the results of a large observational study suggesting that compression depth was compromised when compression rates were greater than 120 cpm.^{9, 15} The ERC,¹⁰ AHA⁹ and ANZCOR^{11, 12} guidelines all recommend a compression rate in the range 100-120 cpm.

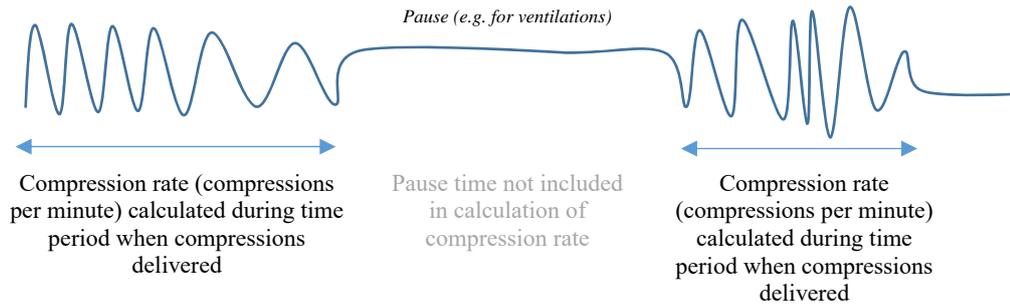


Figure 4 Calculation of chest compression rate

2.5.5 Compression fraction

Chest compression fraction (CCF) is defined as the proportion of time during the resuscitation effort that is spent delivering compressions to the patient (Figure 5). Rescuers may pause compressions for many reasons including, but not limited to, providing ventilations, intubating the patient, allowing for cardiac rhythm analysis, delivering a shock, changing rescuers or moving a patient, for example, from a mattress to the floor. Periods of ROSC are subtracted from the compression fraction calculation.⁷

The CoSTR recommendation for compression fraction is that it should be as high as possible, but at least 60%.³⁸ This is reflected within the ERC¹⁰ and AHA⁹ guidelines. In addition the AHA guidelines state that the general consensus of experts was that a minimum compression fraction of 80% should be achievable in a variety of rescue scenarios.⁹ Both sets of guidelines recommend that during manual CPR without an advanced airway, compressions should not be paused for greater than 10 seconds to deliver 2 rescuer breaths. Likewise both sets of guidelines state that the time period without chest compressions before and after the delivery of a shock should be minimised; this is discussed in further detail in Section 2.5.6. The ANZCOR guidelines, which are not as prescriptive, provide a general recommendation for the minimisation of pauses in chest compressions.^{11, 12}

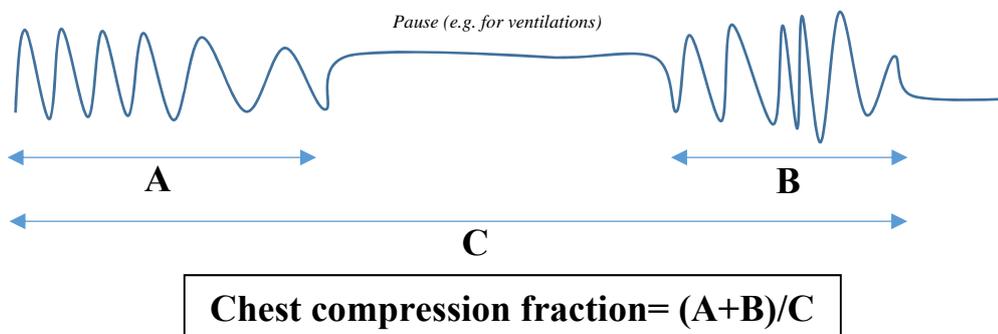


Figure 5 Calculation of chest compression fraction

2.5.6 Shock pause duration

If a cardiac arrest patient has a shock delivered using a defibrillator, rescuers should aim to minimise the pause in compressions both before and after the shock. Shock pause can be defined in terms of three separate elements:

1. **pre-shock pause:** the time interval between chest compression cessation and shock delivery;
2. **post-shock pause:** the time interval between shock delivery and chest compression resumption; and
3. **peri-shock pause:** the sum of pre-shock and post-shock pause.

These pauses are illustrated in Figure 6. The pre-shock pause generally includes the time required for cardiac rhythm analysis as well as the time associated with preparing the electrical charge that will be delivered.⁵⁸ The CoSTR recommendation is that the pre-shock pause should not exceed 10 seconds for manual defibrillation.³⁸ More generally, CoSTR recommends the minimisation of all pauses in compressions associated with the delivery of a shock.³⁸ This is reflected in the ERC¹⁰ and AHA⁹ guidelines, but not the ANZCOR guidelines^{11,12} which are less prescriptive.

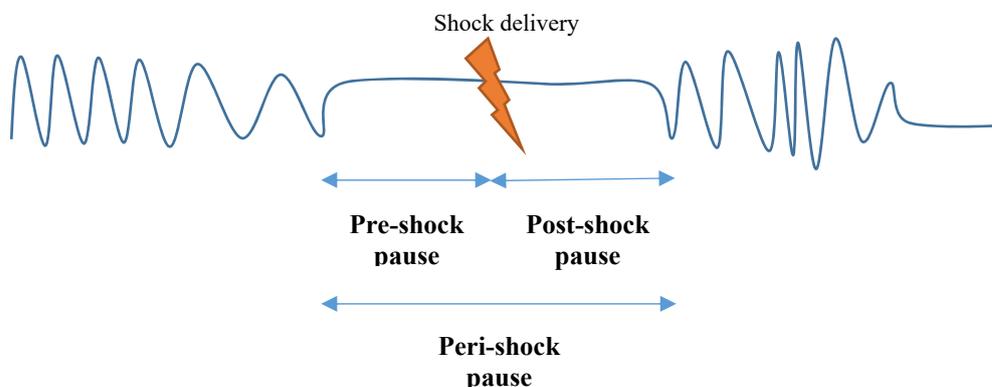


Figure 6 Illustration of pre, post and peri-shock pause

2.5.7 Chest wall recoil

When a rescuer provides chest compression to a cardiac arrest victim, they should allow for full chest wall recoil, in other words, allow for the chest to return to its resting position prior to the delivery of the subsequent chest compression. Rescuers should avoid leaning on the chest of the cardiac arrest victim.⁷ This concept is pictorially illustrated in Figure 7. Chest wall recoil is usually documented as the percentage of compressions per episode that had

incomplete chest release. The CoSTR recommends that leaning is minimised during CPR, although no specific target value is provided.³⁸ Correspondingly the ERC¹⁰ and AHA⁹ guidelines likewise instruct rescuers to avoid leaning, however the ANZCOR guidelines^{11, 12} provide no specific recommendation of this nature.

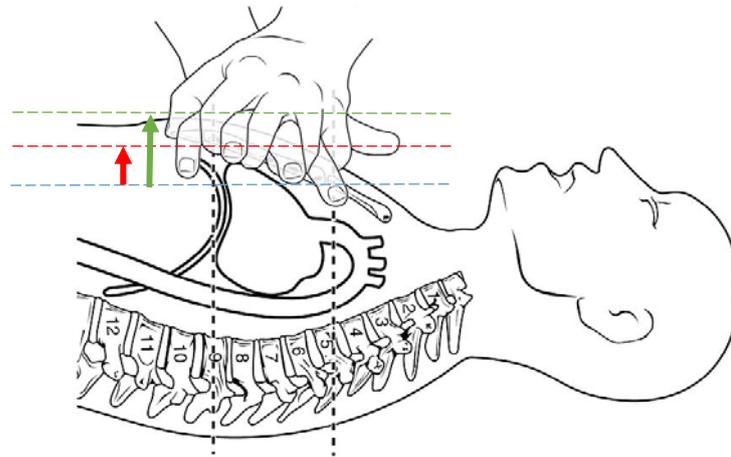


Figure 7 Full chest recoil versus incomplete chest release (leaning)

Allowing for full chest recoil (green arrow) means allowing for the chest to return to its resting position prior to administering the next chest compression; not doing so corresponds to leaning on the chest (red).

Original image⁵⁷ modified as permitted under Copyright Licence.

2.5.8 Duty cycle

The term ‘duty cycle’ refers to “...the fraction of time with active mechanical or hand pressure on the chest”.⁷ More simply, it describes the percentage of time during a compression that the rescuer is pushing down on the chest as opposed to releasing the applied pressure to allow the chest to return to its resting position (Figure 8). A duty cycle of 50% is recommended by the AHA⁹ and ERC¹⁰ guidelines, although the authors of the latter publication acknowledge that there is very little evidence to recommend any specific duty cycle.¹⁰

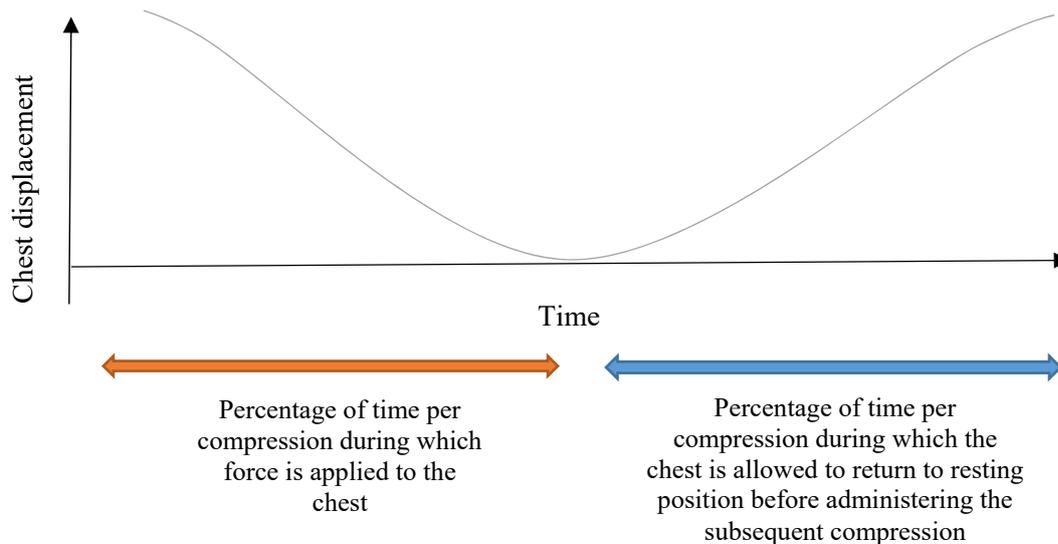


Figure 8 Illustration of duty cycle - the percentage of time per compression that force is applied to the chest of the patient

2.5.9 Ventilation rate

The term ‘ventilation rate’ refers to the number of ventilations delivered per minute of CPR. Although there is no specific recommendation for ventilation rate made by CoSTR,³⁸ a compression to ventilation ratio of 30:2 is recommended among trained rescuers willing to provide rescue breaths. This is reflected in the ERC,¹⁰ AHA⁹ and ANZCOR^{11, 12} guidelines. For untrained rescuers, continuous chest compressions without ventilations are recommended. Following the insertion of an advanced airway, the ERC and AHA guidelines recommend a ventilation rate of 10 ventilations per minute (vpm),⁵⁸ corresponding to one breath administered every 6 seconds.⁹

The ERC and AHA guidelines also recommend that during the delivery of mouth-to-mouth ventilations, each rescue breath is provided over a period of approximately one second and such that it generates a visible rise in the chest of the patient.^{9, 10} I did not have the means to measure compliance with this recommendation in my study.

2.6 CPR quality in practice

As alluded to previously, CPR quality is often suboptimal, even among trained medical professionals. Two landmark studies were published in 2005 on this topic; by Wik et al.⁵ on OHCA and by Abella et al.⁴ on in-hospital cardiac arrest (IHCA). Wik et al. examined 176 cases of OHCA across three European cities (Stockholm in Sweden, London in the UK and Akershus in Norway). Patients were resuscitated either by paramedics or nurse anaesthetists.

Mean chest compression fraction was 52%, indicating that chest compressions were not delivered during approximately half (48%; 95% CI: 45%, 51%) of the time. When the authors subtracted the time required for electrocardiographic (ECG) analysis and shock delivery, it was found that compressions were not given 38% of the time (95% CI: 36%, 41%). The mean compression depth was too low in the majority of cases; only 28% of compressions met the minimum depth recommended by guidelines. Similarly, the study of 67 IHCA patients by Abella et al. found that during 37% of the time, compression depth was less than the minimum recommended value. Compression rate failed to comply with minimum requirements 28% of the time. In addition excessive ventilation was common; in 61% of data segments, ventilation rate exceeded 20 vpm. Other studies likewise demonstrated suboptimal performance, both among trained medical professionals⁵⁹⁻⁶¹ and laypersons.^{62,63}

Among trained rescuers, poor CPR performance has often been linked to poor retention of skills after the completion of training. One early study of simulated cardiac arrest found that among 21 doctors (MDs), 17 registered nurses (RNs) and 21 laypersons, all had difficulty with achieving adequate compression depth and compression rate and with the delivery of ventilations four to twelve months post training. The authors of the study noted that despite having more training and experience, the CPR performance of MDs and RNs was comparable with that of laypersons, which was in general poor.⁶⁴ Numerous other studies have likewise reported poor knowledge retention several months post training.⁶⁵⁻⁶⁸

2.7 CPR feedback devices

One approach intended to support consistent, high quality CPR is through the utilisation of CPR feedback devices. These devices collect data on CPR performance during the resuscitation effort and provide real-time feedback to allow rescuers to optimise their performance. The feedback provided is in most cases visual, with optional audio feedback. In addition some devices feature a metronome that provides auditory prompts to guide optimal compression rate. There are a number of CPR feedback devices commercially available on the market; popular models include ZOLL Medical Corporation's Real CPR Help® feedback tool that can be used with the AED Plus®, AED Pro®, R Series® and X Series® defibrillators, Physio Control's TrueCPR coaching device that can be used in conjunction with the LIFEPAK series of defibrillators, and Philips Medical/Laerdal Medical's Q-CPR feedback tool that can be used with Philips' HeartStart defibrillators. The latter is the technology option selected for implementation by St John Ambulance Western Australia (SJA-WA) in the city of Perth, where my study took place. As a result, the features of the Q-CPR feedback device are described in detail below.

2.7.1 The Q-CPR feedback device

The Q-CPR feedback device includes an accelerometer that records chest acceleration during CPR. It is placed on the chest of the patient, underneath the hands of the rescuer, where it collects information about compression depth, compression rate, compression fraction (hands-off time), incomplete chest release (leaning) and duty cycle. The device model used by SJA-WA is connected to the Philips HeartStart MRx monitor/defibrillator via a cable. The assembly is shown in Figure 9. Ventilation rate is derived from the transthoracic impedance signal measured through the ECG pads.



Figure 9 The Q-CPR feedback device which plugs into the Philips HeartStart MRx Monitor/Defibrillator

Picture sourced from Laerdal Medical.⁶⁹

The Q-CPR device provides both visual and (optional) audio feedback in real time to the rescuer, enabling immediate performance correction during CPR. A simplified version of the visual feedback is displayed on the Q-CPR unit itself, such that the rescuer can observe their performance while they are facing the chest of the patient and delivering compressions. This visual feedback identifies whether compressions are of adequate depth, within the correct compression rate range and whether the rescuer is leaning on the chest of the patient (Figure 10). If voice prompts are enabled, the rescuer may be provided with auditory instructions such as to “compress faster” or “release pressure between compressions”. In addition, a more detailed waveform plot is depicted on the screen of the monitor/defibrillator and is updated in real time. This is accompanied by numerical values for various compression and ventilation parameters (Figure 11). All data collected is stored for retrospective review, thus enabling post-event performance debriefing / research.



Figure 10 Visual feedback displayed on the Q-CPR device

A) Incomplete release of chest notification (yellow arrow); B) compression rate outside of the recommended range; and C) inadequate compression depth notification (yellow arrow).

Pictures sourced from Philips.⁷⁰

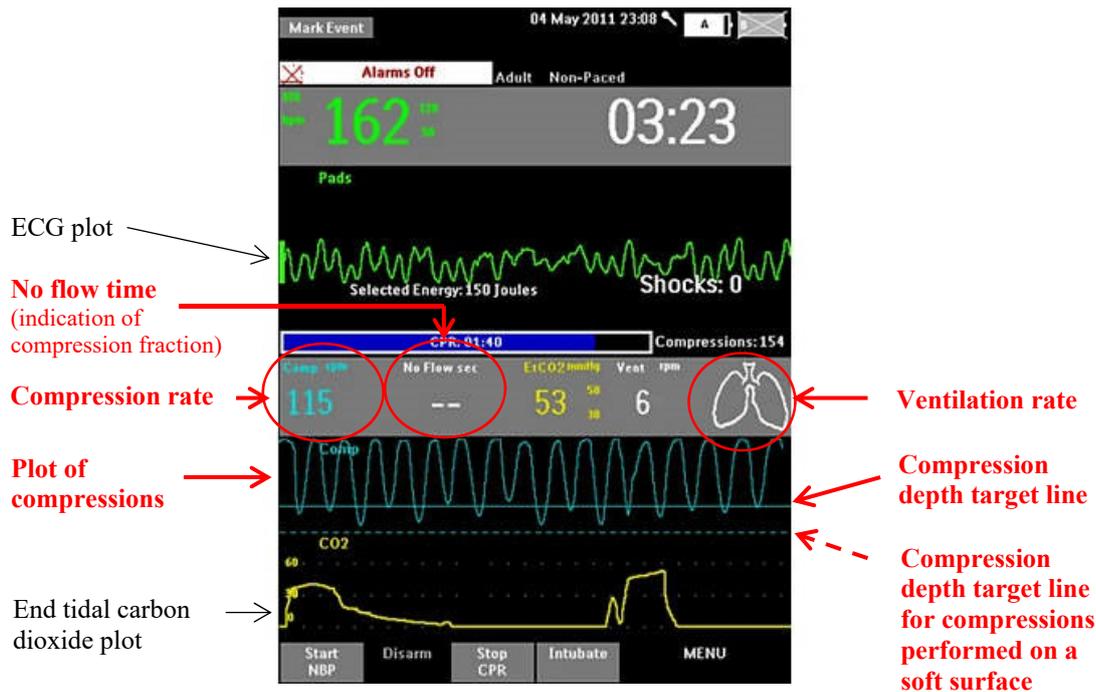


Figure 11 Visual feedback displayed on Philips HeartStart MRx Monitor/Defibrillator
CPR quality feedback shown in red.

Pictures sourced from Philips.⁷⁰

2.8 The effect of CPR feedback on CPR quality metrics

The use of CPR feedback devices has been linked to improved CPR quality by a number of studies in the literature. The effect of feedback on each of the individual CPR quality metrics is discussed below, with particular emphasis on chest compression depth, chest compression rate and chest compression fraction. Results from both simulation (manikin) and human studies are discussed.

2.8.1 Compression depth

As described in a 2013 systematic review,⁷¹ a number of manikin studies demonstrated a significant improvement in chest compression depth following the implementation of CPR feedback. One randomised controlled trial of 223 hospital staff by Noordergraaf et al.⁷² found that mean compression depth was significantly greater with the use of the CPREzy feedback tool compared to when it was not used (mean±SD: 45±4mm vs. 40±9 mm, p=0.0001). In another, cross-over study using the CPREzy tool,⁷³ compression depth again significantly increased when feedback was used, from 34.2±7.6mm to 42.9±4.4mm; p=0.001. Two other studies^{74, 75} demonstrated a non-significant improvement in compression

depth with the use of feedback; however in both of these cases the mean depth achieved prior to the provision of feedback was already close to or within the range recommended by international guidelines^{9, 10} (47.7mm without feedback in one study⁷⁴ and 59.0mm without feedback in the other⁷⁵). The link between CPR feedback and compression depth in human patients is discussed below.

One North American cluster-randomised trial of 1,586 OHCA cases by Hostler et al. reported a significant increase in compression depth with the use of CPR feedback (mean difference: 1.6mm [95% CI: 0.5, 2.7]).⁷⁶ A second randomised trial by Bohn et al. in Muenster, Germany, comprising 312 OHCA patients, found a non-significant improvement in mean compression depth from 47.4mm to 48.4mm with the use of feedback, $p=0.31$.⁵³ In a prospective interventional study by Kramer-Johansen et al. of 284 OHCA patients from Akershus (Norway), Stockholm (Sweden), and London (England), the average compression depth increased from 34 ± 9 mm to 38 ± 6 mm during the period that feedback was used, $p<0.001$. Likewise the median percentage of compressions with adequate depth (defined as 38-51mm according to guidelines that were applicable at the time) increased from 24% to 53% ($p<0.001$).⁵⁹ Again in a before-after study of 484 cases of OHCA by Bobrow et al., (USA) compression depth significantly increased following the introduction of CPR feedback and scenario-based training, from 45.2 mm to 54.6 mm, representing a mean difference of 9.65 mm (95% CI: 7.11, 11.9mm).⁷⁷ There are many studies, both in manikins and patients, that provide evidence of deeper compressions following the introduction of CPR feedback.

2.8.2 Compression rate

As reported in a 2013 systematic review,⁷¹ CPR feedback devices have been shown to decrease chest compression rate among manikin studies, aligning it closer to the lower recommended value of 100 cpm.^{9, 10} In a randomised cross-over study of 186 participants,⁷⁴ compression rate was found to be significantly lower when feedback was provided compared to when it was not (107.0 ± 9.9 cpm with feedback vs. 113.9 ± 17.3 cpm without feedback, $p=0.001$). Similarly in a study that compared three types of feedback devices (CPREzy, Q-CPR and a metronome), all three devices were linked to a reduction in compression rate, two of them significantly.⁷⁸ In another study of 66 pairs of flight attendants, randomised to perform 12 minutes of CPR either with or without CPR feedback from the ZOLL AED Pro®, compression rate was significantly lower with feedback; 101 ± 9 cpm compared to 109 ± 15 cpm without feedback, $p=0.009$.⁷⁹ Other studies did not report a significant difference in compression rate with the use of feedback.^{72, 73, 75}

A number of human studies have observed a significant decrease in compression rate after CPR feedback was enabled. This included the large, North American cluster-randomised trial of 1,586 OHCA patients by Hostler et al. that reported a compression rate of 108 cpm prior to the implementation of feedback, followed by 103 cpm after its implementation, $p < 0.001$.⁷⁶ In the prospective interventional study of 284 OHCA patients in Akershus (Norway), Stockholm (Sweden), and London (England) by Kramer-Johansen et al., compression rate decreased from a mean of 121 cpm without feedback to 109 cpm with feedback ($p < 0.001$).⁵⁹ Bobrow et al. (USA) also demonstrated a significant decrease in mean compression rate from 128 cpm to 106 cpm in 484 OHCA patients following the introduction of feedback combined with a scenario-based training intervention.⁷⁷ These findings led the 2015 CoSTR to conclude that "...the use of CPR feedback devices may be effective in limiting rates that are too fast".³⁸

2.8.3 Compression fraction

In the 2013 systematic review⁷¹ on the link between CPR feedback device use and CPR quality among health care professionals, only one manikin study reported on compression fraction. This study found that there was no significant difference in compression fraction regardless of whether feedback was used or not.⁷⁹ The same systematic review⁷¹ also explored the relationship between feedback device use and compression fraction in human studies. Based on a meta-analysis comprising three studies,^{59, 76, 80} the authors concluded that feedback use was associated with a 1.9% (95% CI: 1.8, 2.0%) increase in chest compression fraction.⁷¹ This result was predominantly derived from the large, North American randomised trial⁷⁶ in 1,586 OHCA patients that reported that with the use of feedback, mean compression fraction significantly increased from 64.0% to 65.9% (mean difference 1.9%, (95% CI: 0.4, 3.4), $p = 0.016$).⁷⁶ Although this difference was statistically significant, clinically its magnitude was not large.³⁸ However a before-and-after study conducted in 484 OHCA patients in Mesa, Arizona, that was published after the compilation of the systematic review, reported a larger increase in median compression fraction (from 66.2% to 83.7%) following the implementation of CPR feedback (provided by the ZOLL E-series monitor/defibrillator) combined with a targeted training intervention. This corresponded to a mean difference of 17.6% (95% CI: 15.0, 20.1).⁷⁷ Therefore, the use of CPR feedback devices has been linked to a higher compression fraction in OHCA patients in some studies.

2.8.4 Shock pause, duty cycle, chest recoil and ventilation rate

Few studies reported on the relationship between shock pause, duty cycle, chest recoil or ventilation rate and the use of CPR feedback devices. Firstly, in regards to shock pause, the audio-visual feedback provided in relation to this quality metric does not generally differ in nature to that provided for all other pauses in compressions. Therefore the potential impact of feedback on shock pause duration was not independently explored but rather it was considered to be part of compression fraction.

To my knowledge, although commercially available feedback devices collect data on duty cycle, they do not provide corrective feedback for this metric. As mentioned previously, there is little evidence to support any specific duty cycle.¹⁰ Furthermore the potential for its manipulation may be limited during manual CPR. As such I could not identify any studies that compared duty cycle with and without feedback.

In regards to leaning, one randomised controlled trial of 132 flight attendants found that during a simulation scenario, leaning occurred far less frequently when feedback was used compared to when it was not; a mean±SD of 21±31% of compressions were characterised by leaning when feedback was used compared to 77±33% when it was not used; $p < 0.001$.⁷⁹ Another North American cluster-randomised trial of 1,586 OHCA patients found that there was a significantly lower proportion of compressions with leaning when feedback was activated compared to when it was not (mean difference: -3.4%, 95% CI: -5.2, -1.5%).⁷⁶

Regarding ventilation rate, two human observational studies^{59, 80} found that it did not significantly differ after the introduction of CPR feedback. By contrast a third paper found a significant decrease in ventilation rate with the implementation of CPR feedback combined with a scenario-based training intervention.⁷⁷

2.9 Conclusion

This chapter provides a background into cardiac arrest and CPR, particularly the elements that comprise high quality CPR. The tools used to measure CPR quality and provide feedback have also been discussed. Although the use of CPR feedback devices has been associated with the closer compliance of some of the CPR quality metrics with international resuscitation guidelines, it is important to determine whether a relationship has been observed between high quality CPR and patient survival outcomes. This was the subject of the systematic review presented in the following chapter.

Chapter 3 Systematic review: CPR quality and patient survival in cardiac arrest

3.1 Overview

I undertook a systematic review of the literature in order to investigate and synthesise the reported evidence regarding the association between CPR quality and cardiac arrest patient survival outcomes. I searched across five databases and the grey literature to identify studies that documented human cases of IHCA or OHCA where CPR quality had been recorded using a CPR feedback/measurement device and where the relationship with patient survival outcomes had been assessed. Prior to doing so I registered my protocol with PROSPERO, the international prospective register of systematic reviews.⁸¹ A copy of the registration document is contained in Appendix 4. I completed my review in accordance with the PRISMA checklist for the transparent reporting of systematic reviews and meta-analyses.⁸² A copy of this checklist and other supplementary material is provided in Appendix 5. My findings are reported in the following manuscript that was published in *Resuscitation* in 2015.

Talikowska M, Tohira H, Finn J. Cardiopulmonary resuscitation quality and patient survival outcome in cardiac arrest: A systematic review and meta-analysis. Resuscitation. 2015; 96:66-77.

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Resuscitation

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Review article

Cardiopulmonary resuscitation quality and patient survival outcome in cardiac arrest: A systematic review and meta-analysis[☆]Milena Talikowska^{a,*}, Hideo Tohira^a, Judith Finn^{a,b,c}^a Prehospital, Resuscitation and Emergency Care Research Unit (PRECRU), School of Nursing, Midwifery and Paramedicine, Curtin University, Bentley, WA, Australia^b St. John Ambulance, Western Australia, Belmont, WA, Australia^c School of Public Health and Preventive Medicine, Monash University, Melbourne, VIC, Australia

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ABSTRACT

Aim: To conduct a systematic review and meta-analysis to determine whether cardiopulmonary resuscitation (CPR) quality, as indicated by parameters such as chest compression depth, compression rate and compression fraction, is associated with patient survival from cardiac arrest.

Methods: Five databases were searched (MEDLINE, Embase, CINAHL, Scopus and Cochrane) as well as the grey literature (MedNar). To satisfy inclusion criteria, studies had to document human cases of in- or out-of-hospital cardiac arrest where CPR quality had been recorded using an automated device and linked to patient survival. Where indicated ($I^2 < 75\%$), meta-analysis was undertaken to examine the relationship between individual CPR quality parameters and either survival to hospital discharge (STHD) or return of spontaneous circulation (ROSC).

Results: Database searching yielded 8,842 unique citations, resulting in the inclusion of 22 relevant articles. Thirteen were included in the meta-analysis. Chest compression depth was significantly associated with STHD (mean difference (MD) between survivors and non-survivors 2.59 mm, 95% CI: 0.71, 4.47); and with ROSC (MD 0.99 mm, 95% CI: 0.04, 1.93). Within the range of approximately 100–120 compressions per minute (cpm), compression rate was significantly associated with STHD; survivors demonstrated a lower mean compression rate than non-survivors (MD -1.17 cpm, 95% CI: -2.21 , -0.14). Compression fraction could not be examined by meta-analysis due to high heterogeneity, however a higher fraction appeared to be associated with survival in cases with a shockable initial rhythm.

Conclusions: Chest compression depth and rate were associated with survival outcomes. More studies with consistent reporting of data are required for other quality parameters.

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1. Introduction

Several studies have investigated the link between the quality of cardiopulmonary resuscitation (CPR) provided to persons experiencing cardiac arrest and subsequent survival outcomes. Quality is commonly defined in terms of parameters such as chest compression depth, compression rate and compression fraction, along with others including ventilation rate, ventilation pause duration, peri-shock pause, duty cycle and incomplete chest release.

Compression depth, rate and fraction are most extensively described in the literature. A number of papers have reported a statistically significant relationship between compression depth and various survival outcomes, for example survival to emergency department (ED),¹ survival to hospital admission,² survival to hospital discharge (STHD)^{3,4} and STHD with favourable functional outcome.³ European Resuscitation Council (ERC) Guidelines for Resuscitation 2010 recommended pushing to a depth of between 50 and 60 mm.⁵ Compression rate has likewise been linked to survival.^{6,7} ERC Guidelines 2010 recommended a compression rate in the range of 100–120 compressions per minute (cpm).⁵ Papers^{3,8} have also linked compression fraction (the proportion of time spent delivering chest compressions during CPR)⁸ to survival outcomes. ERC 2010 Guidelines advise that rescuers minimise interruptions to chest compressions.⁵

A systematic review investigating the effect of CPR quality on cardiac arrest outcome was previously undertaken by Wallace

[☆] A Spanish translated version of the abstract of this article appears as Appendix in the final online version at <http://dx.doi.org/10.1016/j.resuscitation.2015.07.036>.

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et al.⁹ Since the time of that review, a number of papers^{3,4,6,7,10–15} have been published, including several large studies^{4,6,7,10,12,14} from the North American Resuscitation Outcomes Consortium (ROC).¹⁶ By incorporating the most recent literature, the present review sought to answer the question of whether a relationship exists between individual CPR quality parameters and patient outcomes from cardiac arrest.

2. Methods

The protocol for this systematic review was registered with PROSPERO (CRD42014010125).¹⁷

2.1. Eligibility criteria

To be eligible for inclusion: (1) papers had to be original articles with a comparative design; (2) papers had to have been published within the last 20 years; (3) papers had to document human cases of either in-hospital or out-of-hospital cardiac arrest (IHCA or OHCA); (4) the quality of CPR has to have been recorded using a dedicated, automated CPR quality measurement device (for example the Philips HeartStart Monitor/Defibrillator with Q-CPR (Laerdal Medical AS) or the ZOLL AED Plus with Real CPR Help®); and (5) papers had to report on the association between at least one CPR quality parameter with at least one survival outcome or provide data that enabled reviewers to compute the relationship. The primary outcome of interest was return of spontaneous circulation (ROSC). Secondary outcomes were STHD and STHD with good neurological outcome (as defined by either a Cerebral Performance Category (CPC) score 1–2 or Modified Rankin Score ≤ 3). (Note – with reference to the outcomes listed on PROSPERO, the primary outcome was extended to cover all definitions of ROSC, not just ROSC at any time prior to hospital admission, to accommodate IHCA cases). Both adult and paediatric studies and all cardiac arrest aetiologies were considered. Database searches were restricted to articles published from January 1994 onwards. This was due to the fact that automated CPR quality measurement devices were not widely available prior to this time. No language restrictions were set.

The following studies were excluded: (1) editorials, commentaries, letters, case studies/case reports and conference abstracts; (2) animal and manikin studies; (3) studies where CPR quality was measured subjectively e.g. by an observer; (4) studies that featured a device that provided real-time guidance or feedback but did not store data for retrospective analysis (e.g. metronome); (5) studies that reported surrogate or physiological outcomes as a proxy for the abovementioned survival outcomes, for example, first shock success or failure¹⁸; and (6) studies that provided CPR quality data but did not relate it directly to survival outcome, e.g. they provided only the overall survival outcome for the entire patient cohort and did not stratify by CPR quality parameter.¹⁹

2.2. Information sources

Ovid MEDLINE, Ovid Embase, EBSCO CINAHL, Scopus and the Cochrane Library were searched up to 11 April 2015. MedNar was also used to search the grey literature. Reviewers consulted the reference lists of relevant papers to determine whether there were any additional relevant articles. Reviewers also examined other publications of the first authors of included papers.

2.3. Search

Our search strategy incorporated several key concepts and analogous terms: cardiac arrest, CPR and quality, including the

individual parameters of CPR quality, and analogous terms of these keywords. A number of limits were placed upon the search in order to comply with the pre-specified eligibility criteria. A full electronic search strategy for MEDLINE is provided in Appendix A.

2.4. Study selection

One reviewer (MT) performed the database searching and selected potentially relevant papers based upon review of titles and abstracts. Two reviewers (MT, HT) then independently reviewed the full text versions of potentially relevant papers against the inclusion criteria to select relevant papers. Any uncertainties or disagreements amongst reviewers were referred to a third reviewer (JF) for resolution.

2.5. Data collection process

Data were collected from the relevant papers and entered into a pre-piloted form by MT. The form was developed with reference to the Cochrane Handbook.²⁰ Data extracted included: author(s), publication year, title, study location, number of cases, period over which cases were collected, study design, reported CPR quality parameters, devices used to collect data, reported survival outcomes and whether the study focused on OHCA, IHCA or both. In addition the reviewers noted the definition of ROSC used in the paper (where applicable), the time period over which CPR quality was measured during the resuscitation episode and the distribution of initial cardiac rhythms. This information was later used to facilitate subgroup analyses. All data used for meta-analyses were collated by one reviewer (MT) and independently checked by a second reviewer (HT).

2.6. Risk of bias in individual studies

The Newcastle-Ottawa Scale²¹ was used by two reviewers (MT, HT) to assess bias in individual papers. Papers were considered of poor quality if they attained a score of 1–3, of intermediate quality with a score of 4–6 and of high quality with a score of 7–9.²² Poor quality papers were not included in meta-analysis.

2.7. Studies with overlapping cohorts

Several papers featured overlapping cohorts. In these cases, for each individual quality parameter, the reviewers chose to preferentially include those papers that (1) were primarily designed to examine the relationship between the parameter of interest and survival, otherwise (2) contained data in a format that could be used in meta-analysis, otherwise (3) featured the largest sample size.

2.8. Summary measures

The summary measure used in the meta-analysis examining the relationship between individual CPR quality parameters and survival outcome was mean difference (MD). Where data were not available as mean (standard deviation (SD)) authors were contacted to request further information. Some articles included other measures such as Odds Ratio (OR). Although not used in meta-analysis, these alternative measures are described in tables that feature in the Results section of this review.

2.9. Synthesis of results

Compression depth, rate and fraction were the most frequently studied parameters in the literature; a table summarising the relationship of each with survival outcome is provided. *p*-Values were

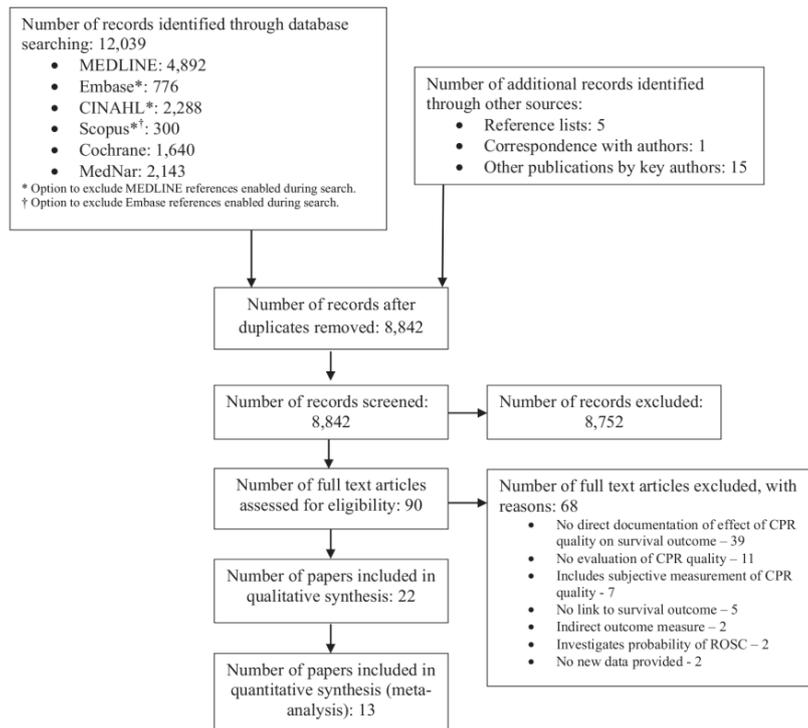


Fig. 1. PRISMA flowchart.

either obtained directly from the article or calculated by the reviewers using STATA v13.1 using a Student's *t*-test.

In addition to the above summary tables, meta-analysis was performed for the individual CPR quality parameters against discrete outcome measures (ROSC or STHD). A meta-analysis was only undertaken if, in total, there were two or more papers reporting on the same CPR quality parameter using mean (SD) and where heterogeneity was acceptable. The heterogeneity across studies was assessed using the I^2 statistic.²³ Where $I^2 \leq 75\%$, meta-analysis was performed in RevMan version 5.3 using an inverse-variance random effects model.²⁴ Subgroup analyses were performed based on initial cardiac rhythm, the time period over which CPR quality data was collected, whether the paper described OHCA or IHCA and the specific definition of ROSC used within a paper (where applicable).

3. Results

3.1. Study selection

Database searching yielded a total of 12,039 citations. After the removal of duplicates 8,842 remained. Ninety potentially relevant papers were selected based upon review of titles and abstracts against the inclusion/exclusion criteria. Twenty two relevant papers^{1-4,6-8,10-15,25-33} were then selected based upon review of the full text articles of potentially relevant papers. These results are summarised in the PRISMA flow diagram in Fig. 1.³⁴ This diagram also documents the reasons for exclusion of articles; the majority (39 of 68) were excluded because they did not directly document the relationship between at least one CPR quality parameter

and at least one survival outcome or allow the direct calculation of such a relationship.

3.2. Study characteristics

Characteristics of included papers are summarised in Table 1. There were 16 papers from the USA and/or Canada^{3,4,6-8,10,12,14,15,25-28,31-33}; ten of those from centres participating in the ROC.^{4,6-8,10,12,14,26-28} Additionally there were six studies from Europe.^{1,2,11,13,29,30} The majority of papers featured a cohort design.^{3,4,6,8,11-14,25-28} Six studies were observational.^{15,29-33} Four^{1,2,7,10} represented a post hoc analysis of data from a trial. The number of patients enrolled varied from $n=9$ ³⁰ to $n=10,371$.⁷ Five papers exclusively examined IHCA,^{15,30-33} 16 papers examined OHCA^{1-4,6-8,10-13,25-29} and one paper examined both IHCA and OHCA cases.¹⁴

3.3. Risk of bias within studies

Using the Newcastle Ottawa Scale, the quality scores assigned to papers ranged between four and nine out of a possible nine (Appendix A). Seventeen papers were considered of high quality,^{2-4,6-8,10-13,15,26-29,32} and five were considered of intermediate quality.^{14,25,30,31,33}

3.4. Results of individual studies

Of the 22 relevant papers, 13 contained data suitable for meta-analysis.^{1-4,6-8,13,26,27,29,30,32} In nine cases additional data were provided by the authors upon request.^{2,6-8,10,13,26-28}

Table 1
Characteristics of included studies.

No.	Study ID	Country	Cases	Enrolment	Study design	CPR quality parameters linked to survival	Device used	Reported survival outcomes	I/OHCA
1	Abella 2005 ³²	USA	60	11 Dec 2002–5 April 2004	Observational study	Compression depth Compression rate No-flow fraction	Prototype defibrillator (IDE G020121, CE mark 2002-OSL-MDD-0009)	ROSC	IHCA
2	Babbs 2008 ²⁵	USA	695	Records obtained from ZOLL Medical Corporation in early 2007.	Cohort	Ventilation rate Compression depth	ZOLL AED Pro or ZOLL AED Plus	ROSC	OHCA
3	Beesems 2013 ¹¹	Netherlands	199	Sept 2010–March 2011	Cohort	Ventilation pause duration	ZOLL AED Plus or PhysioControl LP500, LP1000 or LPCR+	STHD	OHCA
4	Bohn 2011 ¹	Germany	300	April 2007–April 2009	Post hoc analysis of prospective, randomized trial	Compression depth Compression rate Hands-off fraction	ZOLL AED Pro with CPR-D Padz	ROSC to ED	OHCA
5	Camacho Leis 2013 ¹³	Spain	108	Nov 2007–Dec 2010	Cohort	Compression depth Compression rate Incomplete chest release	Defibrillator with Q-CPR	ROSC to hospital arrival	OHCA
6	Cheskes 2011 ²⁸	USA & Canada	815	Dec 2005–June 2007	Cohort	Compression depth Compression rate Pre-shock pause Post-shock pause	PhysioControl, Phillips, ZOLL and other defibrillators.	ROSC to ED STHD	OHCA
7	Cheskes 2014 ¹⁰	USA & Canada	2006	June 2007–Nov 2009	Post hoc analysis of RCT	Compression fraction Pre-shock pause Post-shock pause Compression rate Compression fraction	ZOLL, Philips, Medtronic and other defibrillators	STHD Neurologically intact STHD (Modified Rankin Score ≤ 3)	OHCA
8	Christenson 2009 ⁸	USA & Canada	506	Dec 2005–March 2007	Cohort	Pre-shock pause Post-shock pause Compression rate Compression fraction	ZOLL, Philips and Medtronic defibrillators	STHD	OHCA
9	Idris 2012 ⁶	USA & Canada	3098	Dec 2005–May 2007	Cohort	Compression rate	ZOLL, Philips, Medtronic and Laerdal defibrillators	ROSC STHD	OHCA
10	Idris 2015 ⁷	USA & Canada	10371	June 2007–Nov 2009	Post hoc analysis of RCT	Compression rate Compression fraction ^a	ZOLL, Philips, Medtronic and other defibrillators	ROSC STHD Functionally favourable STHD (Modified Rankin Score ≤ 3)	OHCA

Table 1 (Continued)

No.	Study ID	Country	Cases	Enrolment	Study design	CPR quality parameters linked to survival	Device used	Reported survival outcomes	I/OHCA
11	Kamarainen 2012 ³⁰	Finland	9	Nov 2008–Jan 2010	Observational study	Compression depth Compression rate No flow fraction Ventilation rate Incomplete chest release Duty cycle	Philips HeartStart MRx with Q-CPR (Laerdal)	ROSC Survival to 6 months	IHCA
12	Kramer-Johansen 2006 ²	Norway, UK, Sweden	284	March 2002–Sept 2004	Post hoc analysis of non-randomised trial	Compression depth Compression rate No flow ratio Ventilation rate	Prototype defibrillator (IDE G020121, CE mark 2002–OSL–MDD–0009)	Hospital admission with ROSC STHD	OHCA
13	McInnes 2011 ³³	USA	24	Oct 2006–June 2009	Observational study	Ventilation rate	Philips HeartStart MRx with Q-CPR (Laerdal)	ROSC	IHCA
14	Niles 2012 ³¹	USA	35	Oct 2006–Dec 2009	Observational study	Compression depth	Philips HeartStart MRx with Q-CPR (Laerdal)	ROSC STHD	IHCA
15	Sheak 2015 ¹⁴	USA	583	April 2006–May 2013	Cohort	Compression depth Compression rate	Philips HeartStart MRx with Q-CPR (Laerdal)	ROSC STHD	IHCA OHCA
16	Stiell 2012 ^{4,26}	USA & Canada	1029	May 2006–June 2009	Cohort	Compression depth Compression rate Compression fraction	Philips & Zoll defibrillators	ROSC Survival to day after arrest STHD	OHCA OHCA
17	Stiell 2014 ⁴	USA & Canada	9136	June 2007–Dec 2010	Cohort	Compression depth Compression rate Compression fraction	Philips & Zoll defibrillators	ROSC Survival to day after arrest STHD	OHCA
18	Sutton 2014 ¹⁵	USA	87	Oct 2006–Sept 2013	Observational study	Compression depth	Philips HeartStart MRx with Q-CPR (Laerdal)	ROSC 24-hour survival STHD	IHCA
19	Sutton 2015 ¹²	USA & Canada	390	Dec 2005–Dec 2012	Cohort	Compression depth Compression rate Compression fraction	Physio-Control, Philips, Zoll and other defibrillators ZOLL E-series	ROSC 24-hour survival STHD STHD with good neurological outcome (PCPC 1–2 or no change compared to admission PCPC status)	OHCA
20	Vadeboncoeur 2014 ³	USA	592	7 Oct 2008–30 Sept 2011	Cohort	Compression depth Compression rate Compression fraction	Physio-Control, Philips, Zoll and other defibrillators ZOLL E-series	ROSC 24-hour survival STHD STHD with favourable functional outcome (CPC Score = 1 or 2)	OHCA
21	Vaillancourt 2011 ²⁷	USA & Canada	2103	Dec 2005–June 2007	Cohort	Compression rate Compression fraction	Physio-Control, Zoll, Philips & Laerdal defibrillators	ROSC STHD	OHCA
22	Wik 2005 ²⁹	Sweden, UK, Norway	75	March 2002–Oct 2003	Observational study	Compression depth No-flow ratio Ventilation rate	Prototype defibrillator based on Philips HeartStart 4000	STHD	OHCA

CPC: Cerebral Performance Category; ED: emergency department; IHCA: in-hospital cardiac arrest; OHCA: out-of-hospital cardiac arrest; PCPC: Paediatric Cerebral Performance Category; RCT: randomised controlled trial; ROSC: return of spontaneous circulation; STHD: survival to hospital discharge.

^a Based exclusively upon additional information supplied by authors.

3.4.1. Compression depth

Sixteen papers contained data about compression depth in relation to survival outcome.^{1–4,10,12–15,25,26,28–32} Eleven papers reported 'ROSC',^{1,2,4,12,13,15,25,26,30–32} nine 'STHD',^{2–4,10,15,26,28,29,31} and two 'STHD with favourable functional status'.^{3,15} Several papers featured overlapping cohorts,^{4,10,12,14,26,28} therefore only the summary data for the most relevant papers^{4,12,26} are shown in Table 2. Three papers reported a statistically significant relationship with ROSC^{2,15,25}; two with STHD^{3,4} and one with STHD with favourable functional outcome.³

Meta-analyses were performed where appropriate. Five studies^{1,13,26,30,32} were included in a meta-analysis of compression depth vs ROSC (Fig. 2a). Four studies^{2–4,29} were considered in terms of compression depth vs STHD (Fig. 2b). Both meta-analyses yielded an overall significant result. It was found that those who achieved ROSC had deeper compression by 0.99 mm (95% CI: 0.04, 1.93) than those who did not achieve ROSC. Similarly, survivors received deeper compressions than non-survivors (MD 2.59 mm, 95% CI: 0.71, 4.47). In terms of STHD, subgroup analyses did not change the statistical significance of the result (Appendix A).

3.4.2. Compression rate

Sixteen papers contained data about compression rate in relation to survival outcome.^{1–4,6–8,10,12–14,26–28,30,32} Ten used ROSC as an outcome measure,^{1,2,6–8,12,26,27,30,32} ten investigated STHD^{3,4,6–8,10,12,26–28} and one investigated STHD with favourable functional outcome.³ Among the papers that featured overlapping cohorts^{4,6–8,10,12,14,26–28} only the summary data for the most relevant papers^{6,7,12} are shown in Table 3. Overall one paper⁷ found a significant relationship between compression rate and ROSC using univariate analysis, however upon conducting multivariate analysis this result was not replicated. The same paper did however find a significant relationship between compression rate and STHD; rates in the range of 80–99 cpm and 120–139 cpm were 27% and 37% less likely to survive to hospital discharge than a rate of 100–119 cpm after adjusting for compression depth and fraction. The paper also noted that an increase in compression rate was generally associated with a decrease in compression depth ($p < 0.0001$). This inverse relationship between rate and depth was also been described in other papers.^{3,4,6,7,12,26}

Meta-analysis revealed that compression rate was not significantly associated with ROSC (−0.37 cpm, 95% CI: −1.47, 0.73) (Fig. 3a). However, within a compression range of approximately 100–120 cpm, a lower compression rate was significantly associated with STHD (−1.17 cpm 95% CI: −2.21, −0.14) (Fig. 3b). Results remained non-significant for ROSC and significant for STHD in subgroup analyses (Appendix A).

3.4.3. Compression fraction

There were 14 papers that provided data on compression fraction in relation to survival outcomes.^{1–4,7,8,10,12,26–30,32} Eight used ROSC as an outcome,^{1,7,8,12,26,27,30,32} eleven used STHD^{2–4,7,8,10,12,26–29} and one used STHD with favourable functional outcome.³ From those papers that featured overlapping cohorts,^{4,7,8,10,12,26–28} only data from the most relevant papers^{7,8,12,27} are shown in Table 4. Although some papers^{8,27} found a significant difference in compression fraction between those who did and did not achieve ROSC, in the one paper²⁷ where subsequent multivariate analysis was undertaken, a significant relationship was not reported. However, a significant relationship between compression fraction and STHD was noted by Vaillancourt et al.⁸ using multivariate analysis (adjusted OR 1.11 for every 10% increase in compression fraction, 95% CI: 1.01, 1.21). Another study³ reported a significant relationship with STHD with favourable functional outcome however the nature of this relationship was in the opposite direction, where increased fraction was associated with

decreased odds of survival (adjusted OR 0.48, 95% CI: 0.28, 0.82 for each 10% increase in compression fraction).

Meta-analysis was not possible due to high heterogeneity ($I^2 > 75%$) (Fig. 4a and b).

3.4.4. Ventilation rate

Four papers^{2,29,32,33} contained data regarding ventilation rate in relation to survival outcomes. One study³² reported a non-significant difference in ventilation rate between those who achieved ROSC and those who did not ($p = 0.17$). A small paediatric study³³ of $n = 24$ cases also found a non-significant association between ventilation rate and ROSC ($p = 0.92$). Another study²⁹ reported no significant association between ventilation rate and STHD ($p = 0.94$). A larger study² of $n = 261$ cases reported a non-significant unadjusted OR of 0.7, 95% CI: 0.33, 1.5 for hospital admission when the average number of ventilations was between 6 and 16 ventilations per minute. The variation in describing how ventilation rate affects survival outcomes prevented the undertaking of a meta-analysis.

3.4.5. Ventilation pause

The pause in providing chest compressions to deliver ventilations was investigated by Beesems et al.¹¹ Across $n = 199$ cases it was found that ventilation pauses of ≥ 6 s were not significantly associated with decreased odds of neurologically intact STHD compared to the reference category of 3–5 s.

3.4.6. Peri-shock pause

Two papers^{10,28} found that pre-shock and peri-shock pause were significantly associated with STHD, however post-shock pause was not. One paper²⁸ reported that the chance of STHD was approximately halved for longer pre-shock and peri-shock pauses (adjusted OR 0.47, 95% CI: 0.27, 0.82 for a pre-shock pause of ≥ 20 s compared to < 10 s and adjusted OR 0.54, 95% CI: 0.31, 0.97 for a peri-shock pause of ≥ 40 s compared to < 20 s). Another paper¹⁰ demonstrated 50% and 80% greater chance of STHD for those who had shorter pre-shock (< 10 s) and peri-shock (< 20 s) pauses compared to those who had longer pre-shock (≥ 20 s) and peri-shock (≥ 40 s) pauses (adj OR 1.52, 95% CI: 1.09, 2.11 and adj OR 1.82, 95% CI: 1.17, 2.85 respectively).

3.4.7. Duty cycle and incomplete chest release

A limited number of studies^{13,30} provided data on the relationship between duty cycle or incomplete chest release and survival. Given the limited number of papers, the authors were unable to draw strong conclusions about these CPR quality parameters.

3.5. Risk of bias across studies

Funnel plots (not shown here) were constructed for all studies included in meta-analysis. However, in each case there were too few studies to draw meaningful conclusions about the potential for publication bias.

4. Discussion

4.1. Summary of evidence

Several large studies examining the relationship between CPR quality and survival have emerged since the publication of the previous systematic review by Wallace et al.⁹ The inclusion of these studies has increased the cohort of patients included in meta-analysis by a factor of six or more, to exceed 11,000 patients per CPR quality parameter. In addition, the increase in relevant studies has allowed us to examine the link between individual CPR quality parameters and ROSC separately from the link between

Table 2
Summary of results from individual studies for compression depth.

Compression depth vs ROSC				
Study	n	ROSC mean (SD)	No ROSC mean (SD)	p-Value
Abella 2005 ³²	60	42 (13)	41 (12)	0.82
Bohn 2011 ¹	300	48.9 (8.2)	47.0 (8.7)	0.054
Camacho Leis 2013 ¹³	108	41 (5)	41 (5)	≥0.05
Kamarainen 2012 ³⁰	9	55 (13)	50 (8.5)	0.21
Stiell 2012 ²⁶	1029	38.6 (9.7)	37.6 (10.0)	0.16
Compression depth vs ROSC				
Study	n	Odds ratio (95%CI)	Reference category	p-Value
Babbs 2008 ²⁵ *	202	2.35 (1.46, 3.24) ^u	Compared to <47.8 mm	0.028 ^u
Kramer-Johansen 2006 ²	284	1.05 (1.01, 1.09) ^u	Per 1 mm increase	0.011 ^a
Stiell 2012 ^{4,26}	1029	1.05 (0.98, 1.14) ^u	Per 5 mm increase	≥0.05
Sutton 2015 ¹² †	153	1.99 (0.90, 4.42) ^a	Compared to <38 mm	0.09 ^a
Compression depth vs ROSC				
Study	n	ROSC (%) in events with depth <X mm	ROSC (%) in events with depth ≥ X mm	p-Value
Niles 2012 ³¹ †	35	26% for <38 mm	25% for ≥38 mm	1.0
Sutton 2014 ¹⁵ †	24	31% for <51 mm	74% for ≥51 mm	0.014
Compression depth vs STHD				
Study	n	Survivors mean (SD)	Non-survivors mean (SD)	p-Value
Kramer-Johansen 2006 ²	284	40 (12)	35 (8)	0.22
Stiell 2014 ^{4,10,26,28}	9136	43.5 (10.7)	41.8 (11.8)	<0.001
Vadeboncoeur 2014 ³	592	53.6 (50.5–56.7) [†]	48.8 (47.6–50.0) [†]	<0.001
Wik 2005 ²⁹	75	38 (25–52) [†]	38 (35–41) [†]	0.89
Compression depth vs STHD				
Study	n	Odds ratio (95%CI)	Reference category	p-Value
Stiell 2014 ^{4,26}	9136	1.04 (1.00, 1.08) ^a	Per 5 mm increase	0.045 ^a
Vadeboncoeur 2014 ³	592	1.29 (1.00, 1.65)	Per 5 mm increase	<0.05
Compression depth vs STHD				
Study	n	STHD (%) in events with depth <X mm	STHD (%) in events with depth ≥ X mm	p-Value
Niles 2012 ³¹ †	35	4% for <38 mm	8% for ≥38 mm	1.0
Sutton 2014 ¹⁵ †	24	7% for <51 mm	23% for ≥51 mm	0.11 ^u
Compression depth vs STHD with favourable functional outcome				
Study	n	Odds ratio (95%CI)	Reference category	p-Value
Vadeboncoeur 2014 ³	592	1.30 (1.00, 1.70)	Per 5 mm increase	<0.05
Compression depth vs STHD with favourable functional outcome				
Study	n	STHD (%) in events with depth <X mm	STHD (%) in events with depth ≥ X mm	p-Value
Sutton 2014 ¹⁵ †	24	5% for <51 mm	18% for ≥51 mm	0.094 ^u

* For patients who required multiple shocks (similar results obtained for shocks delivered >3 min after pad application).

^a Adjusted.

^u Unadjusted.

[†] Paediatric cases only.

[‡] 95% Confidence interval.

ROSC: return of spontaneous circulation; STHD: survival to hospital discharge.

CPR quality parameters and STHD; whereas Wallace et al.⁹ examined survival collectively (i.e. ROSC and STHD combined in a single meta-analysis).

In our review compression depth was significantly associated with survival outcomes across a number of studies.^{2–4,15,25} Several of the studies^{1,3,15} provided support for a compression depth greater than the minimum 50 mm recommended by the ERC; however one recent, large North American study⁴ reported that survival peaked at a compression depth of 45.6 mm. In meta-analysis, compression depth was found to be significantly associated with both ROSC and STHD. This was consistent with the results of the previous review by Wallace et al.⁹

Clinical heterogeneity was present among those studies included in meta-analysis. Variations existed in the definitions of ROSC utilized; two studies^{30,32} described in-hospital ROSC, one study⁶ reported prehospital ROSC meaning the presence of a palpable pulse for any duration of time prior to arrival at hospital, whilst two studies^{1,13} documented ROSC to ED. Variations also existed in terms of the time interval over which CPR quality measurements were collected, which ranged from the first few minutes^{4,26,29,32} of resuscitation to the entire episode.^{3,30} The guidelines for the uniform reporting of measured CPR quality developed by Kramer-Johansen et al. in 2007³⁵ recommend collection of data over the entire resuscitation episode. Where it was not explicitly stated in

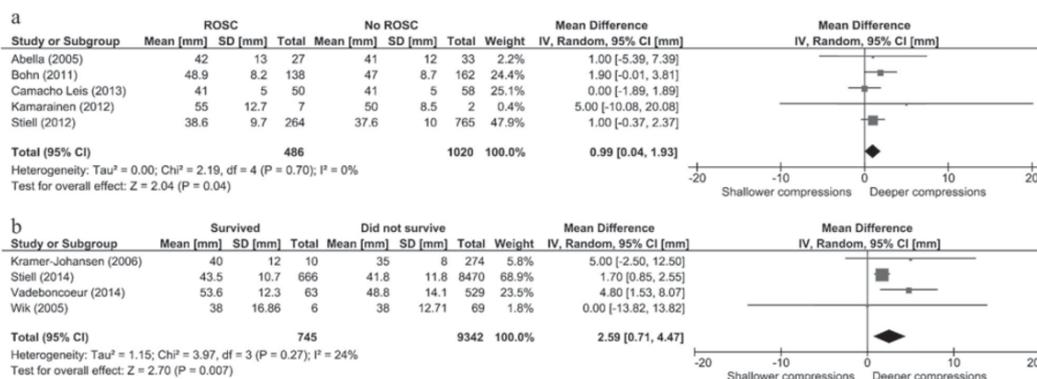


Fig. 2. Forest plots for (a) compression depth vs ROSC and (b) compression depth vs STHD.

Table 3
Summary of results from individual studies for compression rate.

Compression rate vs ROSC				
Study	n	ROSC mean (SD)	No ROSC mean (SD)	p-Value
Abella 2005	60	98 (18)	107 (18)	0.07
Bohn 2011 ¹	300	103.25 (5.76)	103.45 (7.05)	0.79
Camacho Leis 2013 ¹³	108	105 (8)	106 (8)	≥0.05
Idris 2012 ^{6,8,26,27}	3098	112.4 (17.6)	111.5 (19.4)	0.19
Idris 2015 ⁷	10,371	109.9 (18.0)	110.9 (19.2)	0.009
Kamarainen 2012 ³⁰	9	99 (10.8)	98 (0.7)	0.93

Compression rate vs ROSC				
Study	n	Odds ratio (95%CI)	Reference category	p-Value
Idris 2012 ^{6,26,27}	3098	1.18 (0.78, 1.79) ^a	For 0–80 cpm (ref: 80–140 cpm)	0.79 ^a
		1.01 (0.72, 1.41) ^a	For >140 cpm (ref: 80–140 cpm)	0.96 ^a
Idris 2015 ⁷	6399	0.97 (0.74, 1.27) ^b	For <80 cpm (ref: 100–119 cpm)	0.811 ^b
		0.99 (0.86, 1.13) ^b	For 80–99 cpm (ref: 100–119 cpm)	0.841 ^b
		0.98 (0.82, 1.16) ^b	For 120–139 cpm (ref: 100–119 cpm)	0.781 ^b
		1.08 (0.79, 1.47) ^b	For ≥140 cpm (ref: 100–119 cpm)	0.640 ^b
			Global test for ROSC	0.98 ^b
Kramer-Johansen 2006 ²	284	1.1 (0.58, 1.9) ^a	For average rate 90–120 cpm (yes/no)	0.84
Sutton 2015 ¹² †	153	1.13 (0.52, 2.54) ^b	For 100–120 cpm (compared to outside this range)	0.75 ^b

Compression rate vs STHD				
Study	n	Survivors mean (SD)	Non-survivors mean (SD)	p-Value
Idris 2012 ^{4,6,8,10,26–28}	3098	111.1 (16.8)	111.9 (19.0)	0.46
Idris 2015 ⁷	10,371	109.3 (17.9)	110.7 (18.9)	0.024
Vadeboncoeur 2014 ³	592	113.5 (108.5, 118.6) [†]	112.7 (110.9, 114.4) [†]	0.02

Compression rate vs STHD				
Study	n	Odds ratio (95%CI)	Reference category	p-Value
Idris 2012 ^{6,8,26}	3098	1.32 (0.67, 2.62) ^a	For 0–80 cpm (ref: 80–140 cpm)	0.42 ^a
		0.61 (0.29, 1.25) ^a	For >140 cpm (ref: 80–140 cpm)	0.18 ^a
Idris 2015 ⁷	6399	0.89 (0.53, 1.50) ^b	For <80 cpm (ref: 100–119 cpm)	0.65 ^b
		0.73 (0.57, 0.93) ^b	For 80–99 cpm (ref: 100–119 cpm)	0.011 ^b
		0.63 (0.45, 0.88) ^b	For 120–139 cpm (ref: 100–119 cpm)	0.007 ^b
		0.95 (0.53, 1.70) ^b	For ≥140 cpm (ref: 100–119 cpm)	0.864 ^b
			Global test for ROSC	0.02 ^b
Sutton 2015 ¹² †	383	1.14 (0.51, 2.53) ^a	For 100–120 cpm (compared to outside this range)	0.76 ^a
Vadeboncoeur 2014 ³	592	0.97 (0.71, 1.32) ^a	Per 10 cpm increase	≥0.05

Compression rate vs STHD with favourable functional outcome				
Study	n	Odds ratio (95%CI)	Reference category	p-Value
Vadeboncoeur 2014 ³	592	0.88 (0.62, 1.26) ^a	Per 10 cpm increase	≥0.05

^a Adjusted.
^b Additional adjustment for compression fraction and depth.
[†] Paediatric cases only.
[†] 95% Confidence interval.
 cpm: compressions per minute; ROSC: return of spontaneous circulation; STHD: survival to hospital discharge.

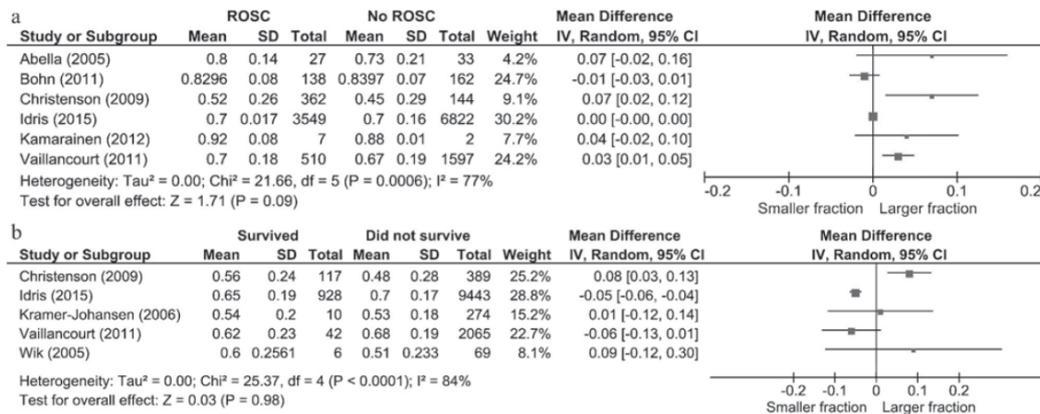


Fig. 4. Forest plots for (a) compression fraction vs ROSC and (b) compression fraction vs STHD.

the relevant articles, the reviewers assumed collection over the entire episode.^{1,2,13} The effect of all of the abovementioned variations was explored in subgroup analyses (Appendix A).

Our meta-analyses revealed that whilst compression rate was not significantly associated with ROSC, it was associated with STHD. This was primarily due to the inclusion of a large, recent study⁷ which reported lower odds of survival for compression rates immediately outside of the range 100–119 cpm, after adjusting for compression depth and compression rate in addition to the traditional Utstein¹⁷ variables. The systematic review by Wallace et al.⁹ found no significant association between compression rate and survival outcomes, although the authors suggested that a rate in the range of 85–100 cpm appeared to be beneficial. The authors determined this range by calculating the absolute difference between rates recorded by the survivor and non-survivor groups and a series of compression rate set points in the range 80–120 cpm; meta-analyses were then performed at each set point. In our meta-analyses, the majority of papers^{1,3,6,7,13} reported a mean compression rate above 100 cpm and in all cases^{1,3,6,7,13,30,32} below the 120 cpm recommended by the ERC. Within this compression range of approximately 100–120 cpm, our meta-analysis revealed that a lower compression rate was significantly associated with survival to hospital discharge. This may be linked to the fact that across various studies higher compression rates have been associated with lower compressions depths.^{3,4,6,7,12,26,36} Clinically, this means that rescuers should aim to provide compressions closer to 100 cpm than 120 cpm, in order to maintain adequate compression depth.

The previous meta-analysis by Wallace et al.⁹ found no significant association between compression fraction and survival outcome. Our review noted that while some papers had associated compression fraction with survival outcomes,^{3,8} many had found no significant relationship.^{1,2,27,29,30,32} Of those that did find a significant relationship,^{3,8} one paper⁸ reported that a higher compression fraction was associated with increased odds of STHD whilst the other³ noted that a higher fraction was linked to lower rates of STHD with favourable functional outcome. This could possibly be attributable to the fact that in the latter study³ compression fraction was recorded across the entire resuscitation episode, whereas in the former study⁸ it was measured only in the minutes before the first attempted defibrillation. In addition, the distribution of compression fraction values varied across studies, with one study³ being largely characterised by high compression fraction values (median (IQR) 79.2% (67.5–86.8%)) whilst

the other⁸ featured a more dispersed distribution. Although the total number of cases was similar in both studies, one study⁸ included only shockable initial arrest rhythms. In our review, unacceptably high heterogeneity prohibited meta-analysis, however studies that included a greater proportion of patients with a shockable rhythm^{2,8,29} reported an association between a greater compression fraction and survival to discharge. This observation suggests that minimising interruptions to chest compressions is most critical for those patient cases with a shockable initial rhythm.

In terms of other CPR quality parameters, information regarding their potential associations with survival was derived from a limited number of studies. Pre-shock pause and peri-shock pause were found to be significantly associated with improved patient survival outcomes in two individual papers.^{10,28} There was no significant association found between ventilation rate or ventilation pause duration and survival. An insufficient number of cases were available to draw strong conclusions about duty cycle or incomplete chest release.^{13,30} Larger studies that report these CPR quality parameters in a uniform manner are required for future determination of their effect on survival.

4.2. Limitations

Against our original intention, we could not examine the effect of 'good quality' CPR vs 'poor quality' CPR on survival due to the limited range of data available within included studies. This was because all data were obtained from CPR quality measurement devices that provide feedback to enable rescuers to deliver high quality CPR within the range recommended by guidelines. Furthermore, it would not have been considered ethical in human resuscitation to intentionally provide CPR outside of the recommended range. Animal studies³⁷ however have demonstrated that rates outside of the recommended range are detrimental to survival.

The retrospective nature of the relevant studies meant that the reviewers could not exclude confounding associated with individual patient characteristics. Another limitation lies in the fact that a small number (between three and six) of studies were included per meta-analysis. This was in part because many of the relevant papers^{4,6–8,10,12,14,26–28} were compiled based upon data collected by one group (ROC)¹⁶ and therefore featured overlapping cohorts.

5. Conclusions

Compression depth is an important component of high quality CPR and has consistently been associated with patient survival. Within the range of approximately 100–120 cpm, a lower compression rate was significantly associated with survival to hospital discharge. Minimising interruptions to chest compressions appeared to be most critical for cases where patients had a shockable initial rhythm. In order to examine the effect of other CPR quality on survival, more studies with consistent reporting of data are required.

Authors' contribution

MT performed the literature searches. MT and HT selected relevant articles. MT performed meta-analysis and HT confirmed results. MT drafted the article and takes responsibility for this paper as a whole. MT, HT and JF were involved in conceiving this study and contributed to the analysis plan, interpretation of results and revision of the article. All have given approval to submit this article.

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Conflict of interest statement

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.resuscitation.2015.07.036>

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3.3 Summary

This systematic review and meta-analysis found that deeper compressions were significantly associated with both return of spontaneous circulation (ROSC) and survival to hospital discharge (STHD). The mean difference in depth between those with and without ROSC was 0.99 mm (95% CI: 0.04, 1.93). It was 2.59 mm (95% CI: 0.71, 4.47) between those who did and did not survive to hospital discharge. Within the range of approximately 100-120 cpm, compression rate was found to be significantly associated with STHD. Compression fraction could not be examined by meta-analysis due to high statistical heterogeneity ($I^2 \geq 75\%$) between the studies. However a higher compression fraction appeared to be associated with survival in cases with a shockable initial rhythm. Two studies^{83, 84} found that a shorter pre-shock and peri-shock pause was associated with improved survival outcomes. I could not reliably comment on the link between duty cycle, chest recoil or ventilation rate with survival outcomes because there were few studies that investigated these relationships in a consistent manner. However since the publication of my review, one North American study of duty cycle in paediatric and adolescent in-hospital cardiac arrest (IHCA) found no association with survival.⁸⁵

This review provided an understanding of the relationships between individual CPR quality metrics and patient survival outcomes, as reported by others in the literature. Following this I sought to measure the quality of CPR performed by St John Ambulance WA paramedics responding to OHCA cases in the Perth metropolitan area. I then sought to explore the link between CPR quality and OHCA patient survival outcomes in this cohort. While undertaking the abovementioned review however, I noticed that there was notable variation between studies in the characteristics of the data intervals that were used for analysis. I therefore prepared a paper highlighting these observed differences, prior to finalising the methodology for my own retrospective cohort study.

Chapter 4 Methodologies used by other studies

4.1 Overview

For this paper, I investigated the characteristics of the data intervals that were used for analysis by other studies; specifically those that met the inclusion criteria for the systematic review⁸⁶ described in the previous chapter. My motivation was to analyse the work of other authors before finalising the methods for my retrospective cohort study. I specifically looked at the length of the data interval used for analysis, the event that marked the start of the analysis interval and the minimum amount of data that was required for an individual case to be included in the analysed cohort. My findings are summarised in the following manuscript that was published in *Resuscitation* in 2016.

Talikowska M, Tohira H, Bailey P, Finn J. Cardiopulmonary resuscitation quality: Widespread variation in data intervals used for analysis. Resuscitation. 2016; 102:25-8.

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Short communication

Cardiopulmonary resuscitation quality: Widespread variation in data intervals used for analysis[☆]Milena Talikowska^{a,*}, Hideo Tohira^a, Paul Bailey^{a,b,c}, Judith Finn^{a,b,d}^a Prehospital, Resuscitation and Emergency Care Research Unit (PRECRU), School of Nursing, Midwifery and Paramedicine, Curtin University, Bentley, WA, Australia^b St. John Ambulance, Western Australia, Belmont, WA, Australia^c Emergency Department, St. John of God Murdoch Hospital, Murdoch, WA, Australia^d School of Public Health and Preventive Medicine, Monash University, Melbourne, VIC, Australia

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ABSTRACT

Aim: There is a growing body of evidence for the relationship between CPR quality and survival in cardiac arrest patients. We sought to describe the characteristics of the analysis intervals used across studies.**Methods:** Relevant papers were selected as described in our recent systematic review. From these papers we collected information about (1) the time interval used for analysis; (2) the event that marked the beginning of the analysis interval; and (3) the minimum amount of CPR quality data required for a case to be included in the analysed cohort. We then compared this data across papers.**Results:** Twenty-one studies reported on the association between CPR quality and cardiac arrest patient survival. In two thirds of studies data from the start of the resuscitation episode was analysed, in particular the first 5 min. Commencement of the analysis interval was marked by various events including ECG pad placement and first chest compression. Nine studies specified a minimum amount of data that had to have been collected for the individual case to be included in the analysis; most commonly 1 min of data. The use of shorter intervals allowed for inclusion of more cases as it included cases that did not have a complete dataset.**Conclusion:** To facilitate comparisons across studies, a standardised definition of the data analysis interval should be developed; one that maximises the amount of cases available without compromising the data's representability of the resuscitation effort.

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Introduction

Recently, increased emphasis has been placed on providing high quality cardiopulmonary resuscitation (CPR) to patients in cardiac arrest. Several studies have indicated a significant relationship between survival outcomes and CPR quality parameters such as chest compression depth,^{1–5} rate⁶ and fraction.^{3,7} However, among studies, heterogeneity exists in how CPR quality parameters are reported for individual patients and then used in analysis. In 2007, Kramer-Johansen et al.⁸ authored recommendations for uniform reporting of measured quality of CPR. These recommendations

proposed that CPR quality data be collected over the entire resuscitation episode. The start of an episode should coincide with the first therapeutic event after arrival at a cardiac arrest patient, including first recorded chest compression, first defibrillator rhythm analysis, or first defibrillation.⁸ For studies that investigate CPR quality and survival, it was recommended that researchers use discrete measurement windows of 30 s or less for parameters such as compression depth to detect haemodynamic changes associated with compressions.⁸ In terms of undertaking analysis in these types of studies, no recommendations were made in regards to the length of the interval that should be used for analysis, nor the minimum interval length required for inclusion.

In practice, CPR quality is recorded using devices such as the Q-CPR™ (Philips Medical) or the Real CPR Help® (ZOLL Medical Corporation). Such devices provide CPR quality summary data for an entire resuscitation episode as well as on an interval-by-interval basis; however there is variation in the proportion of episode data that is used by researchers for statistical analysis. When considering the relationship between CPR quality and survival across existing

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Table 1
Summary of how CPR quality data was analysed across studies.

No.	Study ID	Cases	Interval used for analysis of CPR quality vs. survival	Event to signify the start of the interval	Minimum amount of data required for inclusion in analysis
1	Abella (2005) ¹⁰	60	First 5 min	Not specified	Not specified
2	Babbs (2008) ¹	695	All available episode data ^a	Device activation	Not specified
3	Beesems (2013) ¹⁹	199	The first and when available the last complete cycle of CPR	Prompt to "Start CPR" or, if compressions occurred before this, at the first compression	1 cycle
4	Bohn (2011) ²¹	300	All available episode data ^a	Not specified	1 min
5	Camacho Leis (2013) ²²	108	All available episode data ^a	Not specified	Not specified
6	Cheskes (2011) ¹¹	815	Data from the first 3 shocks	ECG pad placement	Data for at least 1 shock
7	Cheskes (2014) ²⁰	2006	Data from the first 3 shocks	Not specified	Data for at least 1 shock
8	Christenson (2009) ⁷	506	Minute interval during which first analysis performed and all recorded minute intervals before first analysis	Not specified	1 min
9	Idris (2012) ¹⁴	3098	First 5 min	Not specified	Not specified
10	Idris (2015) ⁵	10371	First 5 min	First monitored compression	Not specified
11	Kramer-Johansen (2006) ⁴	284	All available episode data ^a	Not specified	Not specified
12	McInnes (2011) ²³	24	All available episode data ^a	Not specified	Not specified ^a
13	Niles (2012) ¹⁷	35	First 500 chest compressions ^b	Not specified	Not specified
14	Sheak (2015) ²⁴	583	All available episode data ^a	Not specified	Only cardiac arrest events that contained ≥ 2 min of time-synchronised CPR quality and ETCO ₂ data were included
15	Stiell (2012) ¹⁸	1029	Minute interval during which first analysis performed and all recorded minute intervals before first analysis	Not specified	1 min ^c
16	Stiell (2014) ²	9136	First 10 min	ECG pad placement	1 min ^c
17	Sutton (2014) ⁵	87	First 5 min	Not specified	Not specified
18	Sutton (2015) ¹⁶	390	First 10 min	Not specified	1 min
19	Vadeboncoeur (2014) ³	592	Whole resuscitation episode	Not specified	Not specified
20	Vaillancourt (2011) ⁹	2103	First 5 min	Not specified	1 min
21	Wik (2005) ¹⁵	75	First 5 min	Start of first recorded chest compression	Not specified

CPR: cardiopulmonary resuscitation; ECG: electrocardiogram; ETCO₂: end-tidal carbon dioxide.

^a Assumed from other information provided within the paper.

Further restrictions: ^a All CPR epochs lasting less than 30 s were excluded from analysis. ^b The initial 5 chest compressions were excluded from analysis. ^c Cases with >5 min of EMS CPR prior to application of AED pads were excluded.

studies, some studies analysed data collected over the entire resuscitation episode³ whereas others only included the first 5 min.^{9,10} Furthermore, there were variations in when the analysis interval began; in some cases it was from when CPR pads were placed on the patient's chest,¹¹ whereas in others it was from the first monitored compression.⁶ There were also variations between studies in the minimum interval length required for analysis.

We aimed to describe the characteristics of the data analysis intervals used by papers that examined the relationship between CPR quality and survival, noting sources of heterogeneity, so as to encourage a uniform approach to data description.

Methods

We reviewed papers that reported the association between CPR quality and cardiac arrest patient survival. The protocol for locating and selecting these papers was documented in our previous systematic review.¹² In all identified papers, CPR quality was recorded using an automated CPR quality measurement device.

From relevant papers we collected information about (1) the time interval used for analysis; (2) the event that marked the beginning of the analysis interval; and (3) the minimum amount of CPR quality data required for a case to be included in the analysed cohort. We then compared this data across papers.

Results

Twenty-one studies reported on the association between CPR quality and cardiac arrest patient survival (see Table 1). In contrast

to our systematic review,¹² we excluded one paper¹³ that did not directly examine this association statistically.

Length of analysis interval

The majority of studies analysed data from the start of the resuscitation period, including six studies^{5,6,9,10,14,15} that analysed data over the first 5 min and two studies^{2,16} that analysed data over the first 10 min. Alternative analysis intervals included: up to the first 500 compressions (not including the first 5 compressions),¹⁷ the minute interval during which the first analysis was performed in addition to all recorded minute intervals before the first analysis,^{7,18} and the first, and where available, the last complete cycle of CPR.¹⁹ Two studies used data from the first three shocks.^{11,20} In six studies,^{1,4,21–24} it was assumed, based on other descriptions in the paper, that the authors analysed all available episode data. In one study³ it was explicitly stated that analysis occurred over the entire episode.

Start of interval

In two studies,^{6,15} the measurement interval commenced from the first recorded compression, in two cases^{2,11} from ECG pad placement, in one study¹ from device activation and in another study¹⁹ either from the prompt to commence CPR or, if compressions were initiated prior to this prompt, from the first compression. In the remaining cases the starting point was not explicitly specified.

Minimum duration of interval

Nine out of twenty-one studies specified a minimum amount of data that had to be collected for the individual case to be included in analysis; in five studies it was at least 1 min of data^{7,9,16,18,21} while in one study¹⁹ it was data from at least one compression cycle. Two studies required data from at least one shock^{11,20} whilst one study required at least 2 min of time synchronised CPR quality and end tidal carbon dioxide (ETCO₂) data.²⁴ In two studies,^{2,18} if there was more than 5 min of CPR provided by Emergency Medical Service (EMS) personnel prior to placement of ECG pads, the case was excluded.

Discussion

Overall there was heterogeneity in how CPR quality data was collected and analysed across various studies that examined the association between CPR quality and cardiac arrest patient survival. Two thirds of studies considered data from the early portion of resuscitation; the majority using data from the first 5 min. One of the earliest studies¹⁰ to do so argued that the first 5 min was thought to represent the best rescuer effort in terms of fatigue and also was considered the most important clinically. At the same time however this study¹⁰ demonstrated that CPR performance, as defined by individual parameters including chest compression rate and depth, did not differ significantly throughout the episode. Several other studies demonstrated that the first 5 min of data were comparable to that for the entire episode,^{15,23,25,26} albeit with limited sample sizes ranging from $n=20$ to $n=176$. The use of shorter intervals in analysis allows for inclusion of more cases because it allows for inclusion of cases that do not have a complete dataset representing the entire resuscitation effort.

Kramer-Johansen et al.⁸ defined the start of an episode as being "...the first therapeutic event after arrival at a patient in cardiac arrest, including first recorded chest compression, first defibrillator rhythm analysis, or first defibrillation". In the studies that we examined, both first recorded compression and placement of ECG pads were the most common events to signify commencement of the analysis interval. We assume that in many EMS-attended resuscitations these events would occur seconds apart as most EMS protocols prioritise CPR and defibrillation above other interventions. In fifteen out of twenty-one cases however, the event signifying the start of an analysis interval was not explicitly defined.

In terms of the minimum amount of data required for analysis, the most frequently applied limit was for 1 min of data. Again, by specifying such a limit, researchers can increase the number of cases available for analysis by including those that contain CPR quality measurement for only a proportion of the episode. For example, in a large study of compression depth by the Resuscitation Outcomes Consortium (ROC),² the authors analysed data from within the first 10 min of resuscitation, specifying a minimum requirement for 1 min of data. However care should be taken when calculating parameters such as compression fraction to ensure that the short segment of data is truly representative of the remainder of the interval of interest, particularly if other interventions were carried out during the rescue effort that resulted in extended breaks that are not accurately captured by the short segment of data chosen for analysis. It is therefore recommended that researchers note the percentage of the total cohort made up of such short intervals, and, if indicated, perform sensitivity analyses based on their inclusion or removal.

In addition to variation observed in the intervals used for analysis, variation was also observed in the methods of analysis employed by studies, including whether CPR quality parameters

were examined as continuous variables or categorically, and if so, how such categories were defined. Although there was notable heterogeneity in analysis techniques among studies, their description is beyond the scope of this short paper.

Conclusion

Across studies that explored the relationship between CPR quality and survival, we observed heterogeneity in the interval over which CPR quality data was analysed, the event that marked commencement of the analysis interval and the minimum amount of data required for inclusion. In order to more reliably make comparisons between studies, particularly for the purpose of answering clinical questions or formulating guideline recommendations, a standardised definition for the data analysis interval is recommended; one that maximises the amount of cases available for analysis without compromising the data's representability of the resuscitation effort.

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Conflict of interest statement

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Author contributions

JF, HT and MT were involved in the conception and design of the study. MT extracted data from relevant studies and prepared the associated table; this was checked by HT for accuracy of content. MT prepared the manuscript; all authors including PB were involved in the revision of the article critically for important intellectual content. All have given approval to submit this article.

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Appendix A. Supplementary data

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4.3 Summary

In this manuscript I observed that there was notable variation among those studies that investigated the relationship between CPR quality and cardiac arrest patient survival, with respect to the characteristics of the data intervals used for analysis of the relationship between CPR quality and survival outcomes. Fourteen of 21 studies used data only from the first few minutes of the resuscitation episode for analysis, for example the first five or ten minutes. The remainder used either all available data within the entire resuscitation episode or did not specify the data period used. For this reason, in planning the retrospective cohort study that I would undertake, I chose to measure CPR quality data from four discrete time intervals. Three of those were from the start of the resuscitation episode:

- a) The first 3 minutes from placement of ECG pads on the patient;
- b) The first 5 minutes from placement of ECG pads on the patient;
- c) The first 10 minutes from placement of ECG pads on the patient; and
- d) All available episode data.

Similarly to two of the studies,^{13, 84} I considered the start of the analysis interval to be marked by the placement of the ECG pads on the patient. I likewise adopted the requirement for at least one minute of CPR quality data to have to have been captured for the case to be included in the analysed cohort. Comprehensive details of the methods used for my retrospective cohort study are described within the following chapter.

Chapter 5 Methods

5.1 Overview of study

The key aim of this PhD research was to investigate the relationship between the quality of CPR performed by paramedics and survival outcomes from OHCA. This was to be done specifically in the context of SJA-WA. In order to address this aims I conducted a retrospective cohort study utilising prospectively collected data obtained from OHCA cases in which resuscitation had been attempted by SJA-WA paramedics. The arrests had to have occurred within the Perth metropolitan area between 1st July 2014 and 30th June 2016 (2 years). CPR quality data was collected using the Q-CPR feedback device; the start of the study period coincided with the introduction of this device into routine clinical practice among metropolitan ambulance personnel. The device collected information about individual CPR quality metrics including chest compression depth, compression rate, compressions fraction, duty cycle, chest wall recoil and ventilation rate. I extracted and cleaned this data and then used it to estimate CPR performance. I subsequently examined the link between CPR quality and survival outcomes in OHCA patients using multivariable logistic regression analysis. Further details of each of the aspects of my methods are provided within the subsequent sections of this chapter.

5.2 Setting

SJA-WA is the sole provider of emergency road ambulance services within the state of Western Australia (W.A.). With an area of over 2.5 million square kilometres,⁸⁷ W.A. is the largest land mass globally to be covered by a single ambulance service.⁸⁸ Perth, the capital city of W.A., is inhabited by approximately 2 million people.⁸⁹ Within its metropolitan area there are 29 ambulance depots (stations). In 2014/15, the SJA-WA combined on-road capability ranged from 26 day vehicles operating between 7am and midnight to 36 ambulances operating 24 hours a day.⁸⁸ Emergency medical services dispatch for all of W.A., including Perth, are managed out of the State Operations Centre located in Belmont (Perth).

For every OHCA call, the Operations Centre dispatches two ambulance vehicles, each staffed by two paramedics. SJA-WA employs university-educated paramedics to deliver prehospital care within the metropolitan area. On-road teams often comprise one student paramedic who is undertaking undergraduate study and one qualified paramedic who provides guidance and supervision. In addition, a senior Clinical Support Paramedic (CSP)

or Area Manager (AM) is dispatched to each OHCA to provide additional support and equipment. The CSP's and AM's transport the Lund University Cardiac Arrest System (LUCAS) mechanical chest compression device to the scene of the arrest.

All of the vehicles are dispatched on Priority 1. Priority 1 is assigned to high acuity cases such as cardiac arrest or chest pain; the responding crew should aim to arrive on scene within 15 minutes of receiving dispatch instruction from the State Operations Centre (Table 4). Timely response is enabled by the use of lights and sirens. Priority 2 is assigned to urgent but non-emergency conditions, for example, a peripheral wound resulting from a penetrating trauma; such incidents should be responded to within 25 minutes (Table 4). Additionally there is also a third dispatch priority ('Priority 3') however this is assigned to non-urgent, low acuity cases such as a minor haemorrhage; these should be attended within 60 minutes (Table 4).

Once paramedics arrive on scene, the cardiac arrest is managed in accordance with the SJA-WA Clinical Practice Guideline (CPG) for Cardiac Arrest;⁹⁰ a copy of the guideline is provided in Appendix 3. This guideline prioritises early chest compressions and defibrillation and promotes the use of the Q-CPR feedback device. Each metropolitan ambulance crew carries a Q-CPR device together with a Philips HeartStart MRx monitor/defibrillator. The Q-CPR should be promptly applied to the chest of the patient once paramedics arrive on scene. If a decision is then made to apply the LUCAS mechanical compression device, the Q-CPR should be removed as the two devices are incompatible.

Table 4 SJA-WA ambulance dispatch priorities and targeted response times

Priority	Urgency	Maximum response time	Performance* 2014/5
1	Emergency	15 minutes	92.6%
2	Urgent	25 minutes	91.6%
3	Non-urgent	60 minutes	96.0%

*Percentage of calls that were attended to within the maximum allocated response time.⁸⁸

Patients transported by paramedics are taken to one of the public or private emergency departments (EDs) listed in Table 5. In general Australia has a universal health care system comprising publicly funded hospitals supplemented by private facilities. Patients are taken to the closest hospital that has the capacity to receive them, however patients with ST segment elevation myocardial infarction (STEMI) can be transported directly to a hospital that has percutaneous coronary intervention (PCI) services.

Table 5 List of public and private hospitals with an emergency department in Perth⁹¹

Hospital	Percutaneous Coronary Intervention (PCI) Service
Armadale/Kelmscott District Memorial Hospital	
Fiona Stanley Hospital ¹	✓
Fremantle Hospital ²	
Joondalup Health Campus	✓ ³
King Edward Memorial Hospital For Women ⁴	
Peel Health Campus	
Princess Margaret Hospital For Children	
Rockingham General Hospital	
Royal Perth Hospital	✓
Sir Charles Gairdner Hospital	✓
St John of God Midland Public Hospital ⁵	
St John of God Murdoch Private Hospital*	✓
Swan District Public Hospital ⁶	

*Private Hospital

Additional notes:

1. The Emergency Department at Fiona Stanley Hospital opened in February 2015, during the study period.
2. The Emergency Department at Fremantle Hospital closed in February 2015, during the study period.
3. 24 hour PCI services commenced at Joondalup Health Campus in 2016, during the study period. Prior to this PCI services were during day time hours only.
4. This is primarily a maternity hospital therefore a very limited number of cardiac arrest patients are transported there.
5. St John of God Midland Public Hospital opened in November 2015, during the study period.
6. Swan District Public Hospital closed in November 2015, during the study period.

5.3 Population

Collection of study data was restricted to OHCA cases in the Perth metropolitan area, the boundaries of which were defined by the Australian Bureau of Statistics (ABS).⁸⁹ The study cohort was comprised of patients aged eight years or older since the Q-CPR device is only approved for use in this age group. I included arrests of all aetiologies, but excluded patients who had been successfully resuscitated prior to the arrival of paramedics as I could not then accurately confirm the suspected diagnosis of cardiac arrest (and the Q-CPR device would not have been used). Finally I excluded cases that had resuscitation commenced but then terminated due to a “do not resuscitate” (DNR) order being identified.

5.4 Patient characteristics and outcomes

Patient data was sourced from SJA-WA electronic patient care records (ePCRs); these are completed by treating paramedics for each attended case. They detail any relevant reports from bystanders, any prehospital interventions administered by paramedics and any recorded patient measurements such as body temperature and cardiac rhythms. Additionally they document the occurrence of short-term outcomes such as return of spontaneous circulation (ROSC) or whether resuscitation was terminated at the scene.

The three patient outcomes relevant to my study were:

- (i) ROSC at any time during prehospital treatment by paramedics, up to the patient's arrival at the emergency department (ED);
- (ii) survival to hospital discharge (STHD); and
- (iii) good neurological outcome at hospital discharge.

For patients admitted to hospital, survival status was sourced from in-patient hospital records, cross-checked against the Western Australian Death Registry. The patient's neurological outcome was determined by hospital medical chart review, undertaken by a research nurse after the patient had been discharged from hospital. Neurological status was scored using the Cerebral Performance Category (CPC) scale.^{16, 92} This comprises five categories ranging from 1 ('good cerebral performance') to 5 ('brain death') (Table 6). A CPC score of 1 or 2 was considered to be a good neurological outcome in my study.

Table 6 Cerebral performance category (CPC) scale of patient neurological status⁹²

CPC score	Representation
1	Good cerebral performance: Conscious, alert, able to work and lead a normal life. May have minor psychological or neurologic deficits (mild dysphasia, nonincapacitating hemiparesis, or minor cranial nerve abnormalities).
2	Moderate cerebral disability: Conscious. Sufficient cerebral function for part-time work in sheltered environment or independent activities of daily life (dress, travel by public transportation, food preparation). May have hemiplegia, seizures, ataxia, dysarthria, dysphasia, or permanent memory or mental changes.
3	Severe cerebral disability: Conscious; dependent on others for daily support (in an institution or at home with exceptional family effort). Has at least limited cognition. This category includes a wide range of cerebral abnormalities, from patients who are ambulatory but have severe memory disturbances or dementia precluding independent existence to those who are paralysed and can communicate only with their eyes, as in the locked-in syndrome.
4	Coma or vegetative state: Unconscious, unaware of surroundings, no cognition. No verbal or psychologic interaction with environment.
5	Brain death: Certified brain dead or dead by traditional criteria.

Extraction and collation of OHCA patient data (from the SJA-WA e-PCR and computer aided dispatch data) is routinely undertaken by Dr Madoka Inoue, the OHCA Database Manager at the Prehospital, Resuscitation and Emergency Care Research Unit (PRECRU) at Curtin University. For the purposes of my study, Dr Inoue provided me with a de-identified dataset containing all OHCA cases that had resuscitation attempted by paramedics during the study period, excluding those aged less than eight years, those with AED use prior to ambulance arrival or those who had already been successfully resuscitated from apparent arrest at the time of ambulance arrival on scene. I then identified which of these cases had valid CPR quality data recorded. More information about how this was done is described in the following sections. I also compared baseline characteristics and survival outcomes between those OHCA patients meeting the study inclusion criteria and those excluded; using t-tests or chi² tests with a 5% level of significance.

5.5 Obtaining CPR quality data

5.5.1 Collection of data

The Q-CPR device was used to collect data on the following six CPR quality metrics:

- Chest compression depth
- Chest compression rate
- Chest compression fraction
- Duty cycle
- Chest wall recoil (proportion of compressions with leaning)
- Ventilation rate.

The device did not automatically collect data on shock pauses, therefore the measurement of this metric was considered beyond the scope of my study, with the exception of some manual calculations carried out in Chapter 7. All pauses in compressions, regardless of the reason for the pause, were generically captured under the compression fraction metric.

All Q-CPR data that was collected was securely uploaded to the SJA-WA server following a resuscitation episode. To then access the data for a given case, the SJA-WA case number was entered into the search field of the SJA-WA secure intranet website. I obtained the case numbers for all OHCA cases that had had resuscitation attempted by paramedics during the study period from within the dataset provided to me by the Database Manager. I did not know in advance which cases would contain CPR quality data, therefore I individually entered all case numbers into the search field. I then individually reviewed the results for each case to see whether a downloadable CPR quality file was included. If there was a file present, I downloaded it to the secure project drive accessible from the PRECRU office at Curtin University. This drive has restricted access and is backed up regularly by PRECRU staff.

5.5.2 Reviewing cases

I reviewed all downloaded files using Philips' proprietary HeartStart Event Review Pro software package (version 4.2, EMS edition). This program produces waveform plots for a number of discrete input channels. The plots include a compression waveform plot (Figure 12), an ECG plot (Figure 13) and a ventilation waveform plot, among others. I firstly reviewed the compression waveform plot for each case. Where there was at least one minute of compression data depicted, the case was retained for inclusion in the analysed cohort,

otherwise it was excluded. The cut-off point of one minute of data was selected based on observations from my second paper⁹³ that found that several studies in the literature required at least one minute of CPR quality data for cases to be included in the analysed cohort.⁹³

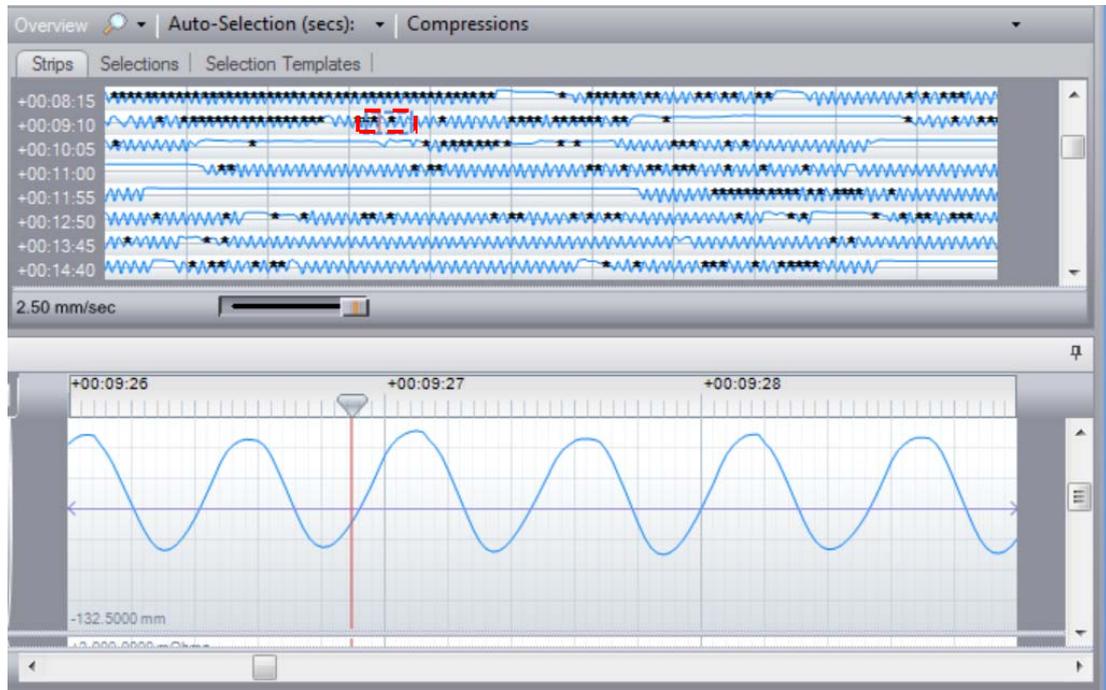


Figure 12 Screenshot from Philips' Event Review Pro program showing compression waveform plots

Overview [above] and detailed segment [below].



Figure 13 Screenshot from Philips' Event Review Pro program showing ECG plot *Overview [above] and detailed segment [below].*

In addition to providing waveform plots, the Event Review Pro program also automatically generates summary reports for individual resuscitation episodes. These contain the average values for each of the CPR quality metrics. As a third alternative the program provides summary data on a 30 second-by-30 second basis over the duration of the resuscitation episode. This is contained within a downloadable Microsoft Excel file; a sample is shown in Figure 14 albeit with a smaller number of variables than exist in the real file. To increase the accuracy of my estimates for each of the CPR quality metrics, I chose to manually calculate them from the data contained within the Microsoft Excel files, instead of extracting the average values from the automatically generated summary reports. Utilisation of the Microsoft Excel files also allowed me to make manual adjustments where required, such as for the exclusion of periods of ROSC from calculations. Details of these adjustments are described in Section 5.7.

Type	Start	Length	NFT	NFT %	FT	FT %	Comp	Correct	D
Episode	851887	328016	41049	12.51	286967	87.49	590	70	1
Period	851887	328016	41049	12.51	286967	87.49	590		
Interval	851887	30000			8991	96.64	56		
Interval	881887	30000			7640	58.8	35		
Interval	911887	30000			5311	84.37	51		
Interval	941887	30000			7800	92.67	56	5	0
Interval	971887	30000	0	0	30000	100	60	18	0
Interval	1001887	30000	16720	55.73	13280	44.27	27	0	0
Interval	1031887	30000	1920	6.4	28080	93.6	58	2	0
Interval	1061887	30000	1940	6.47	28060	93.53	60	2	0
Interval	1091887	30000	0	0	30000	100	65	0	0
Interval	1121887	30000	0	0	30000	100	64	7	0
Interval	1151887	28016	0	0	28016	100	57	7	0

Figure 14 Example of a Microsoft Excel file containing 30 second-by-30 second summary data for a resuscitation episode

5.6 Calculation of average CPR quality for each resuscitation episode

My supervisor (HT) and I created unique syntax in the SPSS software package (Version 21.0, IBM, Armonk, NY) to calculate the mean of each CPR quality metric within a given resuscitation episode. We used the following formulae for our calculations:

$$\text{Mean compression depth for episode} = \frac{\sum_{\text{All 30s intervals}} (\text{mean compression depth for 30s interval} \times \text{number of compressions in interval})}{\text{Total number of compressions in episode}}$$

$$\text{Mean compression rate for episode} = \frac{\text{Total number of compressions in episode}}{\text{Total flow time (mins)*}}$$

$$\text{Mean compression fraction for episode} = \frac{\sum_{\text{All 30s intervals}} (\text{flow time* per 30s interval})}{\text{Total episode duration}}$$

$$\text{Mean duty cycle for episode} = \frac{\sum_{\text{All 30s intervals}} (\text{mean duty cycle for 30s interval} \times \text{number of compressions in 30s interval})}{\text{Total number of compressions in episode}}$$

$$\text{Proportion of compressions with incomplete release in episode} = \frac{\sum_{\text{All 30s intervals}} (\text{compressions with incomplete release per 30s interval})}{\text{Total number of compressions in episode}}$$

$$\text{Mean ventilation rate per episode} = \frac{\sum_{\text{All 30s intervals}} (\text{ventilations per 30s interval})}{\text{Total episode duration}}$$

*Flow time = time during which compressions were delivered.

The syntax was run across all cases in the dataset and the results were input into a single file. To confirm that the syntax was functioning as expected, for a number of randomly selected cases I checked the results generated against manual calculations. I then sorted all results from highest to lowest to confirm that there were no unexpected outliers.

5.7 Manual adjustments

I made a number of manual adjustments to the data to increase the accuracy of the estimates, in particular with regard to the compression fraction metric. I did this by:

- (i) Excluding all breaks corresponding to ROSC;
- (ii) Reviewing all breaks that were greater than 30 seconds in duration to confirm that they were real breaks in compressions and not breaks in the use of the Q-CPR device; and
- (iii) Reviewing the end of the resuscitation episode to confirm that the final segment of data recorded was representative of compressions and not of artefact from moving the Q-CPR device or the patient.

Each of these corrections is described in more detail in the following sections.

5.7.1 Correction for ROSC

Firstly I identified which cases had had prehospital ROSC by reviewing the corresponding variable in the dataset that had been provided to me by the Database Manager; all cases with ROSC were coded as “1”. I then sought to ascertain the timing of ROSC by manually reviewing the corresponding electronic Patient Care Record (ePCR). If the timing of ROSC was clearly documented in the ePCR, I then examined the corresponding time point on the compression waveform plot to see whether a concurrent break in compressions was present. If so, I assumed that the break corresponded to ROSC and I excluded it from my calculations. Where the timing of ROSC was not clearly documented in the ePCR, I looked for other information such as the timing of delivered shocks to provide guidance on the possible timing of ROSC. I then examined the compression waveform plot for corresponding breaks in compressions. I looked at the ECG plot at the time of the breaks to see if the rhythm depicted could potentially be representative of a perfusing rhythm (alternatively it could be representative of PEA). If the ECG plot did resemble a perfusing rhythm/PEA, I re-examined the ePCR to see whether PEA was documented to have occurred around this time. If not, in most cases where the break was of an extended length I assumed that the corresponding ECG plot represented a perfusing rhythm and therefore excluded the break from calculations. In the situation where there were no specific details regarding the timing of ROSC in the ePCR and it could not be deduced based on other information, I simply examined all episode data to identify any extended breaks. I then reviewed the ECG plot during each of these breaks. If a potentially perfusing rhythm was present, I looked at the duration of this rhythm. If its duration was long (several minutes) and there was evidence of compressions and breaks throughout, I assumed it may have been PEA. Therefore I did not exclude any of this data from my calculations. However if the rhythm persisted for some time without concurrent compressions, I assumed that it may have been a perfusing rhythm. In this case I excluded the associated breaks from my calculations. Where available, I confirmed my findings using end-tidal carbon dioxide (ETCO₂) readings.

5.7.2 Correction for periods when Q-CPR was not utilised

I manually reviewed all breaks in compressions of duration greater than 30 seconds. I used the syntax to aid me in identifying which cases had such breaks. Where such a break occurred, I examined the ECG waveform at the time of the break to identify whether compressions were concurrently visible on the ECG (see Figure 15). If they were, I concluded that compressions were being administered by the rescuer but the Q-CPR was not being used to the record compression data. Therefore, given that there was no CPR quality data available for analysis, I excluded this period from calculations. However, if there were no compressions visible on the ECG, I assumed that this was a genuine break in compressions and I included it in calculations.

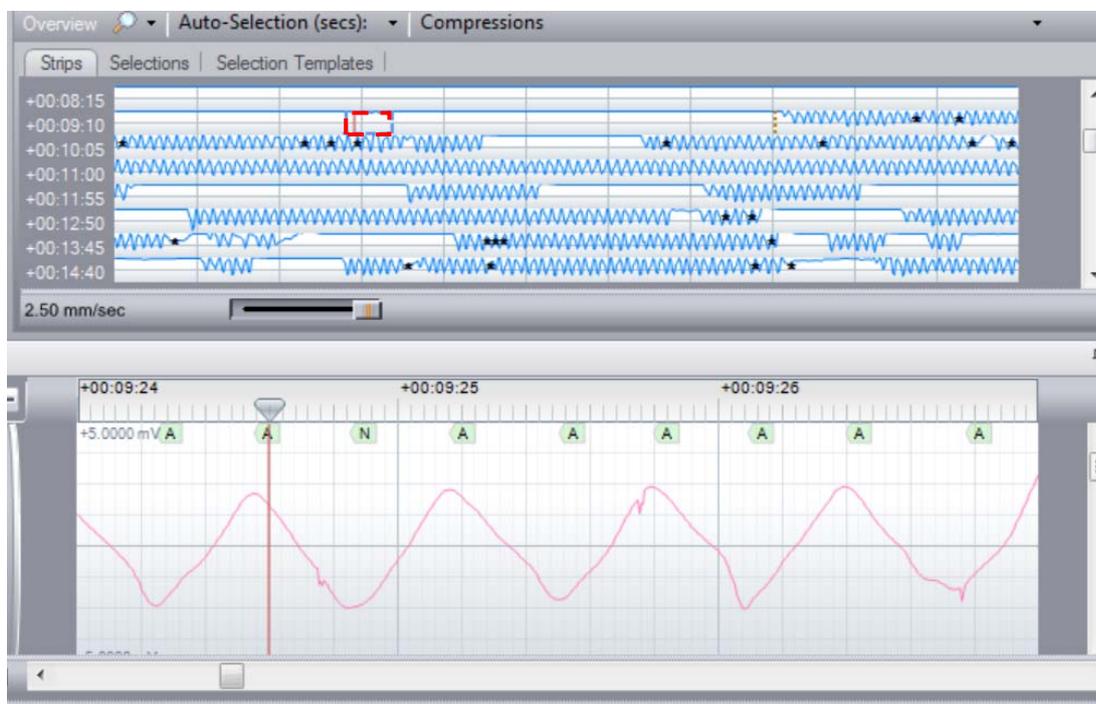


Figure 15 Screenshot from Philips' Event Review Pro program showing a lack of recorded compression data

A lack of recorded compression data is indicated by a flat line on the compression waveform [above] while compressions are visible on the corresponding ECG [below].

5.7.3 Correction for artefact at the end of the data collection window

After reviewing the compression waveforms of a number of cases in the study cohort I observed that in some instances there was a short and irregular piece of ‘compression data’ visible at the end of the data collection period (Figure 16) that were included in the calculations made by the syntax. Such aberrations were often preceded by a pause in compressions of up to several minutes duration. Given the irregular amplitude and short duration of these data I concluded that in most cases they represented artefact from moving or unplugging the Q-CPR device or from moving the patient. Given that they did not represent compressions, I excluded them from calculations, together with the preceding break if relevant.

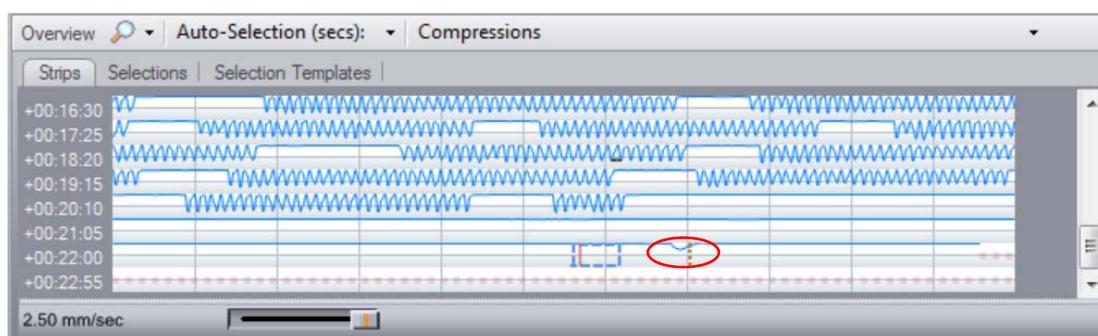


Figure 16 Artefact visible towards the end of the data collection period

5.7.4 Adjustment for ventilation rate

In addition to performing the manual adjustments described above, I also found that in a small proportion of cases the ventilation rate values returned by the syntax were an order of magnitude higher than expected. I manually reviewed their corresponding Microsoft Excel files and waveform plots to determine the number ventilations recorded. I hypothesised that in some cases compressions were being registered as ventilations or, if the patient achieved ROSC, potentially their own respirations were being recorded as administered ventilations. Therefore for the small proportion of cases with excessively high ventilations rates I manually adjusted these to include only those ventilations that were clearly distinguishable on the ventilation waveform and did not appear during periods of ROSC.

5.8 Calculation of group CPR performance

Following implementation of the manual adjustments described above, I sought to calculate the group mean and standard deviation (SD) and median and interquartile range (IQR) across

all cases within the study cohort using widely accepted formulae. I then plotted the distribution for each CPR quality metric across all cases in the cohort. I tested the distributions for normality based on skewness and kurtosis, using the 5% level of significance. I then compared the mean and median values against the target values recommended by the ERC and AHA resuscitation guidelines.^{9, 10} Although the study was based in Perth, Australia, I did not compare performance against the Guidelines issued by the Australian and New Zealand Committee on Resuscitation (ANZCOR).^{11, 12} This was because the latter guidelines were not as comprehensive as the AHA⁹ and ERC guidelines¹⁰ in providing recommendations for CPR quality. I also compared the performance of the study cohort to that reported by other studies in the literature; specifically I focused on those examined in my systematic review.⁸⁶ The results are outlined in Chapter 6.

5.9 The use of various data interval durations for calculations

I initially performed all of the calculations described above using all of the data that was available for each case. However, given the variability in the length of data interval used for analysis by other papers,⁹³ I also performed the calculations using the first 3, 5 and 10 minutes of CPR quality data. I assumed that the start of the episode was signified by the placement of ECG pads on the patient.⁹³ I then sought to determine whether the group mean for each of the CPR quality metrics differed depending on which data interval was used for calculations. I did this by first matching cases across the four time intervals and the comparing their means using paired t-tests with a 5% level of significance. Specifically I compared the means of each of the shorter measurement durations to that for the entire resuscitation episode. All comparisons were done in Stata (Version SE13, StataCorp LP, College Station, TX).

5.10 Investigating the relationship between CPR quality and survival outcomes

As mentioned previously a key aim of my study was to investigate the relationship between CPR quality and OHCA patient survival outcomes in the study cohort. I sought to do this by using multivariable logistic regression analysis. I used the dataset containing all available episode data and merged it with the earlier dataset containing details of patient characteristics and survival outcomes. As described previously, the survival outcomes of interest were ROSC, STHD and good neurological outcome at hospital discharge. All modelling was performed in Stata SE13. Details are provided below.

5.10.1 Multivariable logistic regression analysis

I employed multivariable logistic regression analysis with robust estimates of variance to explore the relationship between CPR quality and survival outcomes. This methodology was chosen because it was the standard used among other papers.^{13, 15 94} As had been done in other studies, I adjusted for the Utstein predictors of survival (Table 7) in my models; these are factors known to modulate cardiac arrest survival outcome.^{25, 95} I elected to include all of these variables into my model even if they were not found to be significant in univariate analysis. Two of the variables were continuous - that representing patient age and the time from the emergency call to EMS arrival on scene. The rest were binary variables. Where data was coded as missing or unknown, it was assigned to the “no” category for the variables representing bystander-witnessed arrest and bystander CPR. For all other variables, if an individual case had missing data for any one of these variables, the case was excluded from the analysed cohort. While a number of studies in the literature also adjusted for in-hospital treatments like the provision of therapeutic hypothermia, I lacked the data to be able to adjust for such in-hospital parameters in my model.

Table 7 Utstein predictors for survival that were adjusted for in the multivariable logistic regression analysis

Utstein predictors of survival	Format
Age (years)	Continuous
Gender	Binary
Bystander-witnessed arrest	Binary
EMS-witnessed arrest	Binary
Arrest location = public	Binary
Bystander response = CPR	Binary
First monitored rhythm = shockable	Binary
Pathogenesis = presumed cardiac	Binary
Time from emergency call to EMS arrival on scene (s)	Continuous

Given that my systematic review⁸⁶ found that compression depth and compression rate (within a given range) were associated with improved patient survival, I chose to focus on the relationship between these metrics and patient survival in the study cohort. I also prioritised my attention on compression fraction given that many studies in the literature^{96, 97} had explored its relationship with survival outcomes. Therefore, I commenced my investigation by examining whether having all three of these CPR quality metrics in compliance with international resuscitation guideline^{9, 10} requirements was associated with improved survival outcomes. I defined compression depth as being compliant with guideline

requirements if it was in the range of 50-60mm; compression rate if it was in the range 100-120 cpm and compression fraction if it was greater than or equal to 80%. I chose the cut-off of 80% for compression fraction because although both sets of international resuscitation guidelines^{9, 10} recommend a minimum compression fraction of 60%, the AHA expert consensus was that a compression fraction of 80% or above should be achievable in a variety of settings.⁹

I created three separate logistic regression models for each of the three survival outcomes of interest. In each model the dependent variable was the dichotomous survival outcome, while the CPR quality metrics were independent variables. I reported unadjusted odds ratios (OR) with 95% confidence intervals (95% CIs). The 95% CIs indicate that we are 95% confident that the true OR lies within this range. In this case the ORs represented the odds of achieving the survival outcome with all three CPR quality metrics in compliance with guideline requirements. I then reported adjusted odds ratios (aOR) following adjustment for the so-called Utstein predictors of survival. After this I reported aOR's following adjustment for the Utstein predictors and for the remaining CPR quality metrics: duty cycle, chest wall recoil and ventilation rate.

Next I investigated whether having compression depth, compression rate or compression fraction individually compliant with resuscitation guidelines was associated with improved patient survival outcome in the study cohort. Again I created a separate model for each of the three survival outcomes. I derived unadjusted odds ratios representing the odds of achieving the survival outcome if one of the given CPR quality metrics complied with guideline requirements, for example, the odds of ROSC if compression depth was in the range 50-60mm. I then adjusted for the Utstein predictors of survival plus the other two key CPR quality metrics. Following this, I adjusted for the Utstein predictors plus all of the CPR quality metrics.

Finally I created a logistic regression model that incorporated all of the CPR quality metrics, this time expressed as continuous variables, together with all of the Utstein predictors. I investigated whether any of the CPR quality metrics were significantly associated with a survival outcome while adjusting for the other confounders. I also tested for interactions between individual variables, where it was deemed that such an interaction would make sense; for example, between compression rate and compression depth. Again I created a separate model for each of the three survival outcomes. The results are described in Chapter 7.

5.11 Extension of PhD work: A detailed investigation of compression fraction

After examining the relationship between CPR quality and OHCA patient survival outcomes in my study cohort, I further investigated the relationship between chest compression fraction and survival outcomes. As seen in my systematic review,⁸⁶ a number of studies reported mixed findings pertaining to the association between chest compression fraction and survival outcomes. While a 2009 study by Christenson et al.⁹⁶ found that a higher compression fraction was independently predictive of better survival in OHCA patients with a shockable initial rhythm, several of the papers cited in my review,^{14, 15} in addition to other recently published studies,^{14, 98} have reported an inverse association between compression fraction and survival outcomes. I therefore chose to investigate the relationship between compression fraction and survival outcomes in detail in the SJA-WA cohort. I chose ROSC as the outcome of interest because it was expected to have the greatest number of patients who achieved a positive result. I performed three separate sensitivity analyses that are described in detail below.

5.11.1 Analysis utilising alternative measurement durations

Firstly, I conducted logistic regression analyses using three alternative durations of measurement interval (3, 5 and 10 minutes). In my earlier paper⁹³ I had observed that there was a large degree of heterogeneity in the length of data interval used for analysis among studies that investigated the relationship between CPR quality and survival. Indeed among those studies that included compression fraction I found that the length of data interval used ranged from a mean (IQR) of 1.6 (1.1) minutes⁹⁶ to all episode data.⁹⁸ I hypothesised that compression fraction would be one of the CPR quality metrics that would be most influenced by the duration of the measurement interval used for analysis. This is because of the variety of interventions that could be administered during the resuscitation effort (for example, intubation); whether these were captured within the analysis window could notably influence the overall compression fraction calculated. Also, very short durations of CPR quality measurement comprising only a few minutes of data may be much more vulnerable to inaccuracies compared to larger segments of CPR quality data. Therefore I repeated the logistic regression analysis using the three alternative measurement durations to examine whether the relationship between chest compression fraction and ROSC differed to that found using all available data from the resuscitation episode.

5.11.2 Adjustment for known confounders

In a study by Wik et al.,¹⁷ the authors found an inverse relationship between chest compression fraction and survival prior to statistical adjustment for confounders that were significantly associated with either chest compression fraction or survival. However, following the adjustment, the relationship was in the expected direction. I sought to investigate whether adjusting for the same variables as Wik et al. would change the direction of the relationship observed between chest compression fraction and ROSC in the SJA-WA cohort. I therefore created a logistic regression model using all available episode data that examined compression fraction as a continuous variable and adjusted for the same factors as Wik et al. (with the exception of site location which was not relevant to my study and median duration of treatment which was not accurately captured).¹⁷ My results are reported in Chapter 7.

5.11.3 Use of alternative modelling techniques

Thirdly, under the direction of my supervisor Dr Hideo Tohira, I employed alternative modelling techniques to investigate the relationship between CPR quality and ROSC. The intent was to further investigate whether chest compression fraction was a predictor of ROSC using these techniques. I derived a classification tree using Classification and Regression Tree (CART) modelling and likewise applied artificial neural network (ANN) analysis to the study data. Both analyses were carried out in IBM SPSS version 21.0 (IBM, Armonk, NY). I then compared the level of predictability of these models to that of logistic regression modelling.

A classification tree is a flowchart-like model that illustrates the key factors predictive of outcome and the cut-off points at which branching occurs. The tree commences from a root node that contains all of the study cohort data and branches out in a recursive manner until all nodes contain data with the same outcome (or, alternatively, until stopping criteria are met, however none were assigned in my study). The cut-off points are determined based on the Gini impurity index; when this is minimised, it indicates that the heterogeneity of the outcomes at each of the subsequent downstream nodes is minimised.¹⁹ The predictors used for building the decision tree for my cohort were: age (years), gender, witnessed arrest, arrest location, bystander CPR, first monitored rhythm = shockable, pathogenesis = presumed cardiac, EMS response time in seconds, mean compression depth, mean compression rate and mean compression fraction. The outcome studied was ROSC.

Artificial neural network analysis was also applied to my data. This is a non-linear statistical modelling tool used for complex pattern-recognition tasks. It likewise reports the key factors predictive of outcome. It attempts to simulate the learning behaviour of human beings; this is done by starting off with a collection of interconnected nodes with pre-specified computational rules. The nodes then interact with each other, passing information between each other, and while doing so modify their structure to provide a predictive model for system output based on the input data. In this way the system learns to make predictions based on the observations that it encounters.⁹⁹ The ANN used in my study was the most common type of ANN referred to as the multilayer perceptron (MLP). This was made up of three layers of nodes arranged in series: an input layer, a hidden layer and an output layer. The input layer comprised the variables age (years), gender, witnessed arrest, arrest location, bystander CPR, first monitored rhythm = shockable, pathogenesis = presumed cardiac, EMS response time in seconds, mean compression depth, mean compression rate, mean compression fraction mean duty cycle, the mean proportion of compressions with leaning and mean ventilation rate. The output was ROSC. OHCA cases were grouped by a 7:3 ratio to create training samples and testing samples. Repeated training cycles were then run based on trial-and-error until the prediction process was optimised and the network could be used to reliably deliver an answer for output based on a new set of input variables.

I then compared the results generated from ANN and CART analyses to those produced by logistic regression modelling. I was interested to know whether the same variables were considered key predictors of outcome across all three modelling techniques. I then compared the area under the receiver operating characteristic (AUROC) curve for each of the techniques to determine their relative degrees of predictability; a higher AUROC is indicative of a higher degree of predictability. The AUROC can range from 0.5 which indicates that the predictability of the model is not better than guessing to 1 which indicates perfect predictability. For determining the AUROC (95% CI) for the ANN model only, I used a bootstrapping technique because SPSS does not provide a 95% CI for the AUROC for ANN. Following training of the neural network as described in the paragraph above, I input the test data into the network and calculated an AUROC, then I repeated this process 1000 times in order to obtain 95% confidence intervals. My results are presented in the appendix to the manuscript in Chapter 7.

5.11.4 Time-dependent nature of the relationship between compression fraction and survival outcomes

In a further exploratory analysis, I investigated the potential time-dependency of the relationship between compression fraction and survival outcomes. Other authors had proposed that this relationship may vary depending on the duration of the resuscitation effort provided by EMS personnel or depending on the timing of ROSC.^{98, 100} I sought to examine an alternative model of time-dependency based on results from animal data. Recent porcine studies had suggested that the deliberate introduction of breaks in compressions during the initial minutes of CPR had been associated with survival benefit in cases where resuscitation efforts were delayed by 15-17 minutes from onset of arrest.¹⁰¹⁻¹⁰⁴ Referred to as ‘post conditioning (PC), the proposed mechanism is that, following an extended period with no circulation, the deliberate introduction of pauses in compressions may help to prevent reperfusion injury to the myocardium and brain.^{105, 106} In light of this, and given that no similar observational study had been carried out in humans, I sought to investigate whether a similar phenomenon was observed in the study cohort. Specifically I examined whether the relationship between compression fraction and ROSC varied depending on the ‘downtime’ from onset of arrest to delivery of CPR by emergency medical services (EMS-CPR).

The onset of arrest was estimated from bystanders’ and paramedics’ descriptions on the ePCR. Downtime was measured up to the time of EMS arrival on scene. I used the time of EMS arrival because in the majority of cases the time from arrival to commencement of CPR was assumed to be short unless otherwise documented in the ePCR. In general I attempted to place downtime into one of two categories, namely: less than or equal to 15 minutes or greater than 15 minutes. The cut-off of 15 minutes was selected based on animal studies.¹⁰¹⁻¹⁰³ Because estimation of downtime was done retrospectively, to minimise potential error I used a conservative approach and coded the downtime variable as “unknown” if it was not possible to reliably estimate it. I also consulted the first recording of patient temperature to justify my downtime estimates. I considered that downtime was longer than 15 minutes if the first recording of body temperature was below 35°C.¹⁰⁷ I did not assume the inverse; that a first recorded body temperature of above 35°C was indicative of a downtime of less than 15 minutes. I was also conservative with geriatric patients who may have had a lower body temperature prior to arrest. The estimation of downtime was conducted by me and my supervisor HT, and consensus was to be sought from my other supervisor, Professor Judith Finn, in case of disagreement.

I then conducted univariate analyses within each of the three downtime groups (≤ 15 minutes, > 15 minutes and unknown) separately. I compared the mean \pm SD compression fraction for cases with and without ROSC in each group. I estimated compression fraction using data from the first three minutes of the episode because in animal studies ‘post conditioning’ was administered only during the first three minutes of CPR. I also compared the means and standard deviations for cases with and without ROSC for the Utstein predictors of survival and for the other CPR quality metrics.

I subsequently conducted multivariable logistic regression analyses in each downtime group separately. ROSC was the dependent variable while compression fraction was the independent variable. Again I utilised ROSC as the outcome of interest because I expected that a greater number of patients would achieve ROSC than STHD; if I had used STHD I would run the risk of having very few or no survivors in one or more of the downtime categories, which would be prohibitive for conducting logistic regression analysis. Compression fraction was dichotomised to $\leq 80\%$ versus $> 80\%$ as per initial analyses and per AHA consensus.⁹ I sought to adjust for those variables that were significant in univariate analysis. If none were found to be significant, I would adjust for age and two key predictors of survival: bystander CPR and shockable first monitored rhythm,⁹⁵ as well as adjusting for compression depth and compression rate. Bystander CPR and shockable rhythm were chosen because they were often linked to improved survival outcomes, while compression depth and rate had also been linked to survival. I was restricted in the number of covariates that I could include in my model because my sample size was substantially reduced by the fact that the regression analyses were conducted separately within each of the three downtime groups instead of in the cohort as a whole. The results are outlined in Chapter 7.

5.12 Conclusion

This chapter outlined the methods used to derive the results presented in the two subsequent chapters (Chapter 6 and Chapter 7). Chapter 6 reports the quality of CPR measured among SJA-WA paramedics while Chapter 7 investigates its relationship with survival outcomes, with a specific focus on the relationship between chest compression fraction and ROSC.

Chapter 6 Quality of CPR performed by SJA-WA paramedics

6.1 Background

The quality of CPR delivered by rescuers, including trained medical professionals, is often suboptimal. Landmark studies from 2005 reported this finding in both OHCA⁵ and IHCA.⁴ Wik et al. found that most of the compressions delivered by paramedics and nurse anaesthetists to 176 adult OHCA patients were too shallow (mean depth: 34mm, 95% CI: 33, 35mm). Furthermore compressions were only delivered during half of the resuscitation time (mean CCF: 52%, 95% CI: 49, 55%).⁵ Abella et al. found that among 67 cases of IHCA treated by hospital staff, compression depth was too low in 37.4% of the compressions, while ventilation rates were frequently too high.⁴ Almost a decade later, Kampmeier et al. demonstrated that over half (50.9%) of compressions performed by emergency physicians and ambulance personnel on 149 OHCA patients in Muenster, Germany, failed to meet the minimum depth recommended by guidelines.¹⁰⁸ Steps to improve CPR performance have included the provision of targeted training programs, performance debriefing and the introduction of CPR feedback devices into clinical practice.¹⁰⁹ Such devices provide audio and/or visual feedback allowing rescuers to improve performance in real time. For example, Bobrow et al. demonstrated that training combined with the use of feedback devices was associated with significant improvements not only in CPR quality (compression depth, rate, fraction, pre-shock pause and ventilation rate) but also in survival and neurological outcome in 484 OHCA patients in Mesa, Arizona.⁷⁷ In Perth, W.A., St John Ambulance Western Australia (SJA-WA) in July 2014 introduced the Q-CPR feedback device (Laerdal Medical and Philips Healthcare) into all metropolitan ambulance vehicles. My PhD research centred upon the processing and analysis of the data collected by this device.

6.2 Aim

The aim of this Chapter was to describe the quality of CPR performed by SJA-WA paramedics and to compare it against recommendations from international resuscitation guidelines. Furthermore I aimed to compare it against the performance reported for trained rescuers within other publications. In addition I sought to compare the CPR quality calculated across different lengths of measurement interval, ranging from the first three minutes of CPR to the entire resuscitation episode.

6.3 Methods

I conducted a retrospective cohort study examining OHCA cases where resuscitation was attempted by SJA-WA paramedics between July 2014 and June 2016 (2 years). I only included cases from the Perth metropolitan area where at least one minute of CPR quality data had been collected using the Q-CPR device. The value of one minute was chosen based on observations from my second paper regarding the minimum limit set by other authors.⁹³ Because the Q-CPR device is indicated for use in patients aged 8 years or older, the study cohort was limited to this age group. I included all arrest aetiologies. I excluded the data of patients who had had resuscitation commenced by paramedics but were subsequently discovered to have a ‘do not resuscitate’ order in place. I also excluded patients who had been successfully resuscitated from cardiac arrest prior to ambulance arrival. Further details about the methods used are contained in Chapter 5.

6.3.1 Characteristics of the study cohort

I collected data on the baseline characteristics and survival outcomes of the cases included in the study cohort and of those cases excluded. I used t-tests or chi-square tests to compare the two groups and employed a 5% level of significance.

6.3.2 CPR quality among SJA-WA paramedics

I downloaded data for each individual resuscitation episode and examined it using Philips’ proprietary Event Review Pro software package, in addition to Microsoft Excel. Specific details of how this was done are provided in Chapter 5. For each episode I calculated the mean \pm SD for each CPR quality metric. The metrics examined were: chest compression depth, compression rate, compression fraction, duty cycle, the proportion of compressions with leaning and ventilation rate. I used all available episode data for this calculation and excluded periods of ROSC. I also performed the adjustments described in Section 5.7. I then used the individual episode information to calculate the collective mean \pm SD and median (IQR) across all cases in the study cohort. I plotted the resultant frequency distributions for each of the six CPR quality metrics. I tested the distributions for normality based on skewness and kurtosis, using the 5% level of significance. I then compared the calculated averages to the recommendations contained in the European Resuscitation Council (ERC) Guidelines for Resuscitation 2015¹⁰ (“2015 ERC guidelines”) and the 2015 American Heart Association (AHA) Guidelines for Cardiopulmonary Resuscitation and Emergency Care⁹ (“2015 AHA guidelines”). Although the study was based in Perth, Western Australia, I did not compare performance against the Guidelines issued by the Australian and New Zealand

Committee on Resuscitation (ANZCOR)^{11, 12} This was because they were less specific and detailed than the ERC and AHA guidelines. Furthermore, the ANZCOR guidelines do not specify an upper limit for compression depth.¹²

6.3.3 Comparison to other studies

I compared the CPR quality calculated for SJA-WA paramedics to that reported in the literature for other EMS agencies and hospital staff. My comparison was not exhaustive but rather reflects a convenience sample of major published works selected from among those analysed in my systematic review,⁸⁶ including from the multi-centre North American Resuscitation Outcomes Consortium (ROC).^{110, 111} I calculated 95% confidence intervals in Stata SE13 for the mean values reported by each of the studies. Calculations were made based on the reported mean, standard deviation and sample size provided for each study. This approach assumes that the data are normally distributed, however I lacked this information for the majority of studies. However given that most authors chose to report mean \pm SD, I assumed that this indicated that the distributions were approximately normal and justified use of this approach. Where median (IQR) was provided, I still calculated 95% CIs however these should be interpreted with caution. For compression depth, rate, fraction, duty cycle and ventilation rate I plotted the mean (95% CI) for the SJA-WA data versus other studies to provide a visual comparison.

6.3.4 CPR quality calculated using different time intervals

While the CPR quality referred to thus far was calculated using all available episode data, I also calculated CPR quality using data from the first 3, 5 and 10 minutes of the resuscitation episode. My earlier paper revealed that there was variation among published studies in terms of the duration of the data interval that was used to derive CPR performance.⁹³ For example, of 21 studies included in my systematic review, six used data from the first 5 minutes of the resuscitation episode,^{4, 5, 15, 97, 112, 113} and two used data from the first 10 minutes.^{13, 94} As a result, my cohort study utilised a range of data intervals to derive CPR quality, namely the first 3, 5 and 10 minutes of measured Q-CPR data, as well as all available episode data. I matched cases from each of the four measurement intervals and, using paired t-tests with a 5% level of significance, compared CPR quality between each one of these shorter data measurement intervals and all available episode data.

6.4 Results

Resuscitation was attempted by SJA-WA paramedics in 1,882 patients aged 8 years or older in the Perth metropolitan area between June 2014 and July 2016. The Q-CPR device was used in 356 (19%) of cases. The usage rate was lower than had been initially anticipated; potential reasons for this are explored in Chapter 8. Twelve cases were excluded due to there being less than one minute of CPR quality data recorded. A further three cases were subsequently excluded after the patient was discovered to have been 'not for resuscitation' (NFR) following the commencement of CPR. This resulted in 341 cases that were eligible for inclusion.

6.4.1 Characteristics of the study cohort

The baseline characteristics and survival rates for the study cohort are shown in Table 8. The mean±SD age among patients was 62±20 years. The majority (70%) were male. One fifth (20%) had a shockable initial rhythm. A quarter of patients (25%) achieved ROSC at some point during the resuscitation effort prior to ED arrival, however only 3.5% survived to hospital discharge and 2.9% had good neurological outcome at discharge as defined by a Cerebral Performance Category (CPC) score of 1 or 2.

Table 8 also provides baseline characteristics and survival rates for the excluded cohort. There were significant differences between the two cohorts with respect to: the proportion of witnessed arrests, the location of the arrests, STHD and good neurological outcome at discharge. The proportion of EMS-witnessed arrests was significantly lower among the analysed cohort compared to the excluded cohort (5.0% vs. 13%, $p<0.001$) and the proportion of unwitnessed arrests was significantly higher (66% vs. 59%, $p=0.02$). Among the analysed cohort, there were more arrests that occurred in a residential premise (79% vs. 73%, $p=0.02$). There was also a significantly lower rate of STHD among the analysed cohort compared to the excluded patients (3.5% vs. 11.6%, $p<0.001$), as well as a significantly lower proportion overall of good neurological outcome at hospital discharge (2.9% vs. 9.0%, $p<0.001$). However, if only those cases that had STHD were considered then the difference in good neurological outcomes was similar i.e. 10/12 (83%) versus 137/178 (77%).

Table 8 Baseline characteristics and survival rates among the analysed cohort and excluded cases (July 2014 – June 2016)

Characteristic	Analysed cohort (n=341)	Excluded cases (n=1,541)	p-value
Age, mean (SD)	62.21 (20.19)	61.82 (20.18)	0.74
Male (%)	69.79	67.21	0.36
Witnessed arrest (%)			
EMS witnessed	4.99	12.46	<0.001
Bystander witnessed	29.32	28.49	0.76
Unwitnessed	65.69	59.05	0.02
Bystander CPR (%)	60.12	54.71	0.07
Arrest location (%)			
Public	13.49	18.17	0.04
Residential	79.47	73.20	0.02
Other	7.04	8.63	0.34
Presenting initial rhythm (%)			
VF/VT	20.23	20.65	0.86
PEA	20.23	24.23	0.12
Asystole	59.53	55.11	0.14
Unknown	0	0.39	0.25
Medical cause of arrest (%)	83.87	80.86	0.20
Response time (minutes), mean (SD) ¹	8.04 (6.94)	8.22 (5.13)	0.58
ROSC (Any), n(%)	85 (24.93)	448 (29.07)	0.12
STHD, n(%)	12 (3.52)	178 (11.57)	<0.001
Good neurological outcome at hospital discharge ² , n(%)	10 (2.93)	137 (9.04) ³	<0.001

EMS: emergency medical service; ROSC: return of spontaneous circulation; STHD: survival to hospital discharge; VF: ventricular fibrillation; VT: ventricular tachycardia.

1. Time interval from emergency call to the arrival of the first EMS vehicle on scene.
2. Good neurological outcome was defined by a Cerebral Performance Category (CPC) score of 1 or 2.
3. There were 26 cases with missing CPC data in this group.

6.4.2 CPR quality among SJA-WA paramedics

Table 9 lists the mean±SD and median (IQR) for each of the six CPR quality metrics, calculated across the 341 cases that comprised the study cohort. As mentioned previously, this was calculated using data from across the whole resuscitation episode. These values are contrasted against the recommendations in the 2015 ERC guidelines¹⁰ and 2015 AHA guidelines.⁹ The frequency distribution for each CPR quality metric is depicted in Figure 17 – Figure 22. Table 10 presents the results of the test for the normality of each distribution based on skewness and kurtosis.

Table 9 Quality of CPR performed by SJA-WA paramedics, compared against the 2015 AHA and ERC resuscitation guidelines (based on n=341 cases of OHCA)

CPR quality metric	Mean	(SD)	Median	IQR	Guideline recommendation	Complies
Compression depth (mm)	41.8	(9.17)	41.9	(35.0, 48.2)	50 – 60	x
Compression rate (cpm)	114	(10.9)	113	(106, 121)	100 – 120	✓
Compression fraction (%)	77.8	(9.23)	78.4	(71.6, 84.7)	Pauses in chest compressions should be minimised; compression fraction should be at least 60%; do not interrupt compressions for >10s to deliver 2 rescue breaths; minimise pre-shock and post-shock pauses.	✓ ²
Duty cycle (%)	43.0	(3.21)	43.3	(43.3, 45.2)	50	- ³
Compressions with leaning (%)	13.2	(17.0)	5.11	(1.73, 18.4)	Avoid leaning after each compression	- ⁴
Ventilation rate (vpm) (adjusted) ¹	3.98	(2.75)	3.71	(1.99, 5.35)	30 compressions: 2 ventilations	- ⁵

AHA: American Heart Association; cpm: compressions per minute; CPR: cardiopulmonary resuscitation; ERC: European Resuscitation Council; IQR: interquartile range; SD: standard deviation; vpm: ventilations per minute.

1. Ventilations rates higher than 10 vpm were manually inspected and then adjusted if required (see Section 5.7.4).
2. Compression fraction was considered compliant based on the fact that the mean and median values were greater than 60%. Pauses for rescue breaths were not specifically measured in my study.
3. Although international resuscitation guidelines recommend a duty cycle of 50%, this is a weak recommendation based on limited evidence. Other studies have shown that in practice duty cycle is often less than this value. Refer to Sections 6.4.2.5 and 6.5.4.
4. Although ERC guidelines recommend that rescuers avoid leaning, no acceptable target value is specified. Refer to Section 6.5.5.
5. No specific target value for ventilation rate is documented within the ERC and AHA guidelines; however a compression to ventilation ratio of 30 to 2 is recommended. Refer to Sections 6.4.2.6 and 6.5.6.

6.4.2.1 Frequency distribution for compression depth

The mean±SD and median (IQR) values for compression depth were 41.8±9.17 mm and 41.9 (35.0, 48.2) mm respectively. Only a minor proportion of cases (16%) fell within the 50-60mm range recommended by ERC and AHA guidelines. More than four fifths (82%) of cases had a mean compression depth that was below the minimum recommended value, while two percent had a mean compression depth that was greater than the upper limit of 60mm.

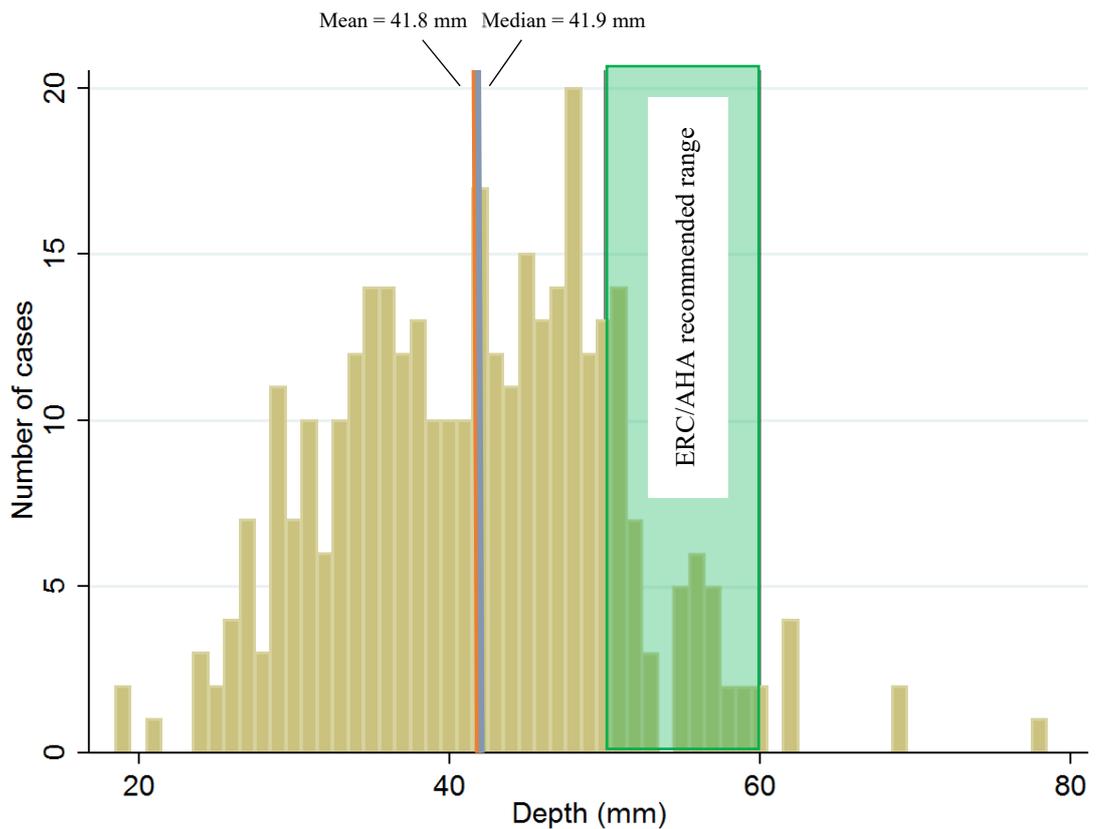


Figure 17 Frequency distribution for compression depth across the cohort (n=341)

6.4.2.2 Frequency distribution for compression rate

Both the mean and the median values for compression rate were within the 100-120 cpm range recommended by ERC¹⁰ and AHA⁹ guidelines (mean±SD: 114±10.9, median [IQR]: 113 [106, 121]). Nevertheless over a quarter of cases (28%) had a compression rate that was greater than the 120 cpm upper limit, while nine percent of cases had a compression rate less than the 100 cpm minimum value.

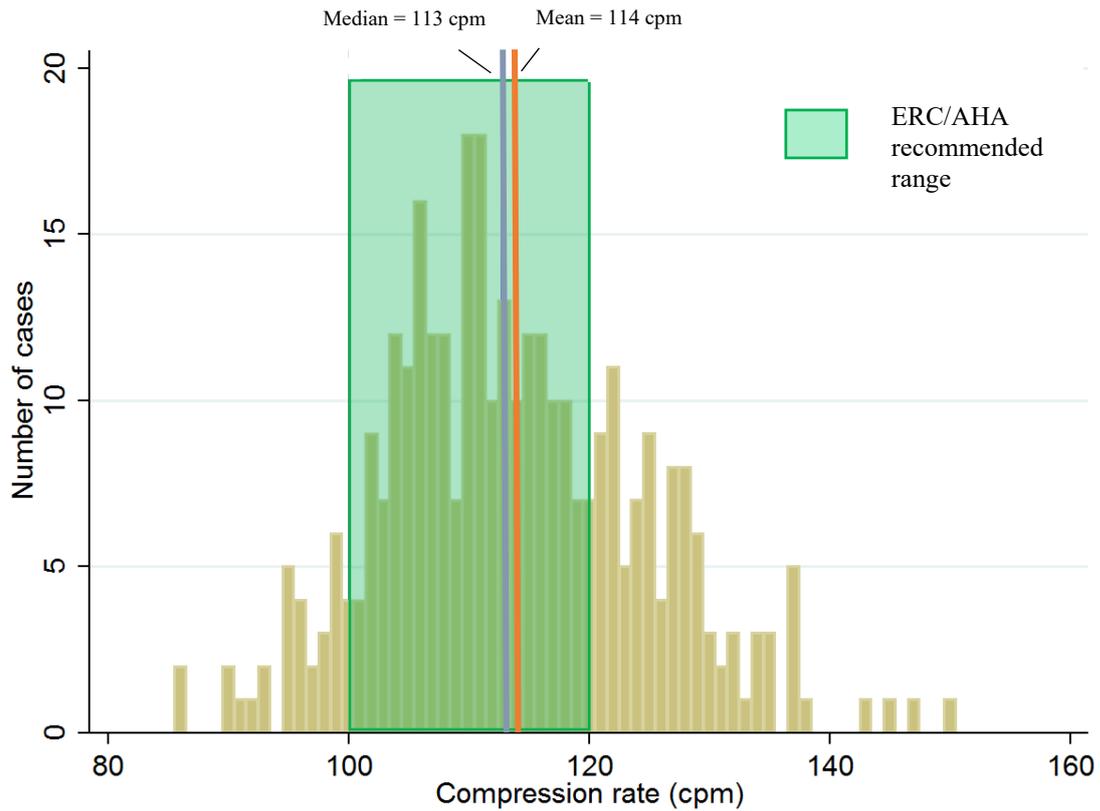


Figure 18 Frequency distribution for compression rate across the cohort (n=341)

6.4.2.3 Frequency distribution for compression fraction

Both the mean \pm SD and median [IQR] values for compression fraction exceeded the 60% minimum recommended by guidelines (77.8 \pm 9.23% and 78.4 [71.6, 84.7]% respectively). Only 4% of cases failed to achieve this minimum value. Forty five percent of cases had an average compression fraction greater than 80%; this was the fraction considered by AHA expert consensus to be achievable in a variety of settings.

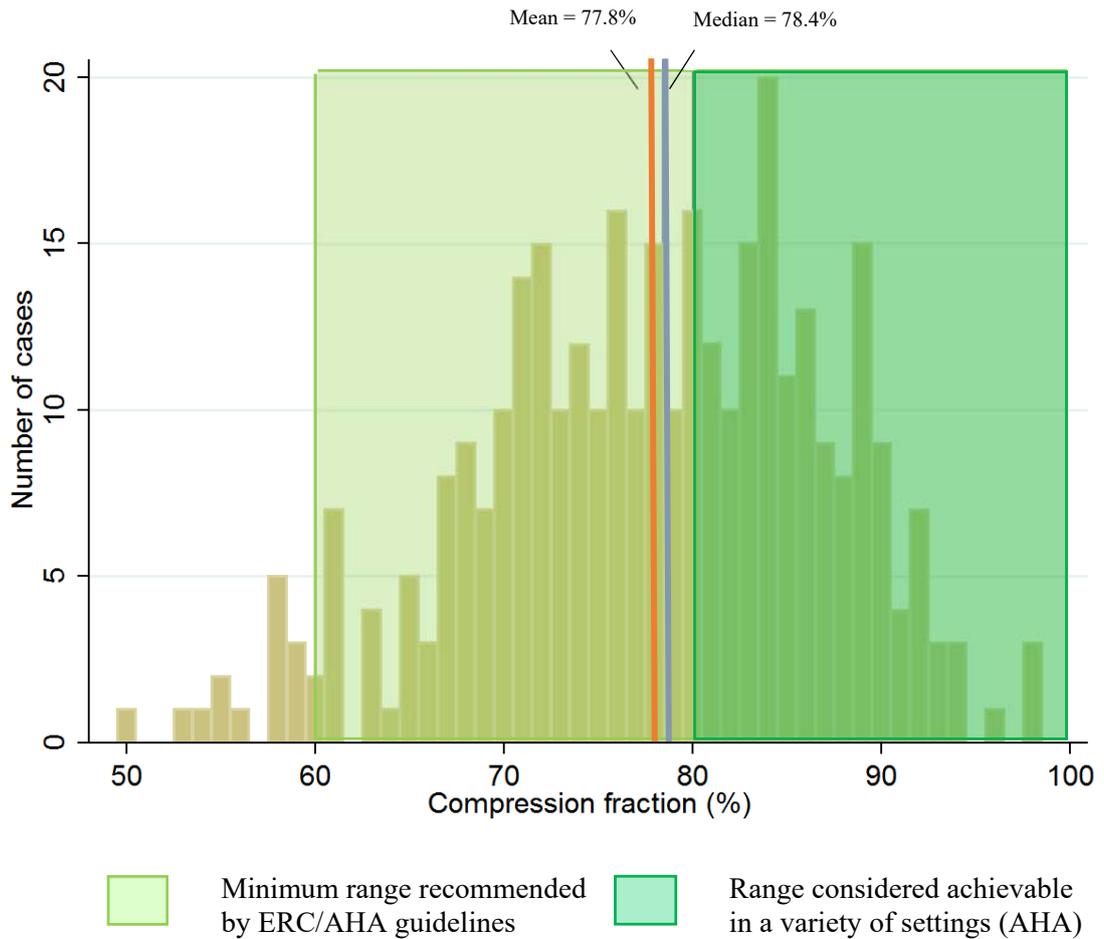


Figure 19 Frequency distribution for compression fraction across the cohort (n=341)

6.4.2.4 Frequency distribution for duty cycle

The mean±SD duty cycle was 43.0±3.21% while the median (IQR) was 43.3 (41.2, 45.2)%. Although both values fell below the 50% recommended by resuscitation guidelines, this recommendation was based on very limited evidence from the literature.¹⁰ Duty cycle is further discussed in Section 6.5.4.

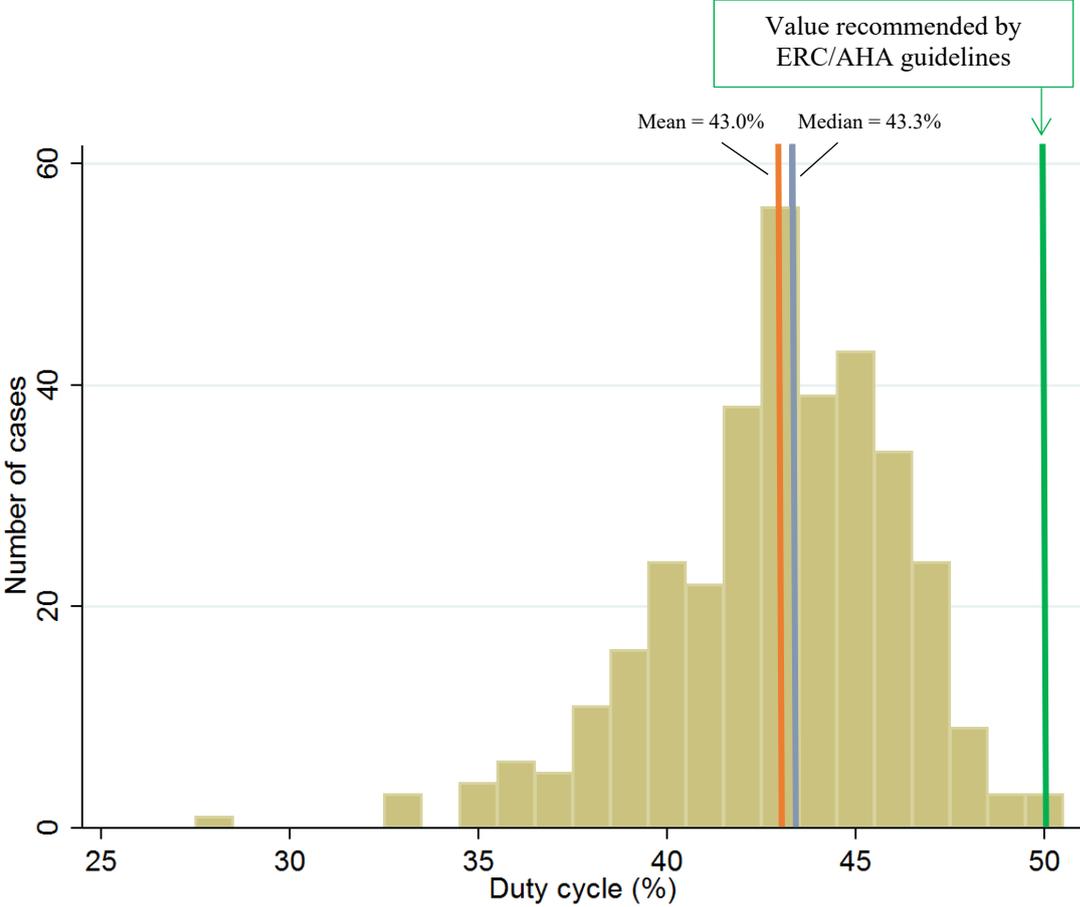


Figure 20 Frequency distribution for duty cycle across the cohort (n=341)

6.4.2.5 Frequency distribution for leaning

The frequency distribution for the proportion of compressions with leaning was highly skewed to the right; the distribution had a mean±SD of 13.2±17.0% and a median (IQR) of 5.11 (1.73, 18.4)%. Sixty two percent of cases had less than 10% leaning while six percent had greater than 20% leaning. International resuscitation guidelines recommend that rescuers minimise the occurrence of leaning, however they do not indicate a threshold value that is considered acceptable. I therefore could not make any specific conclusion about whether the levels of leaning observed among my study cohort were in compliance with the guideline recommendations.

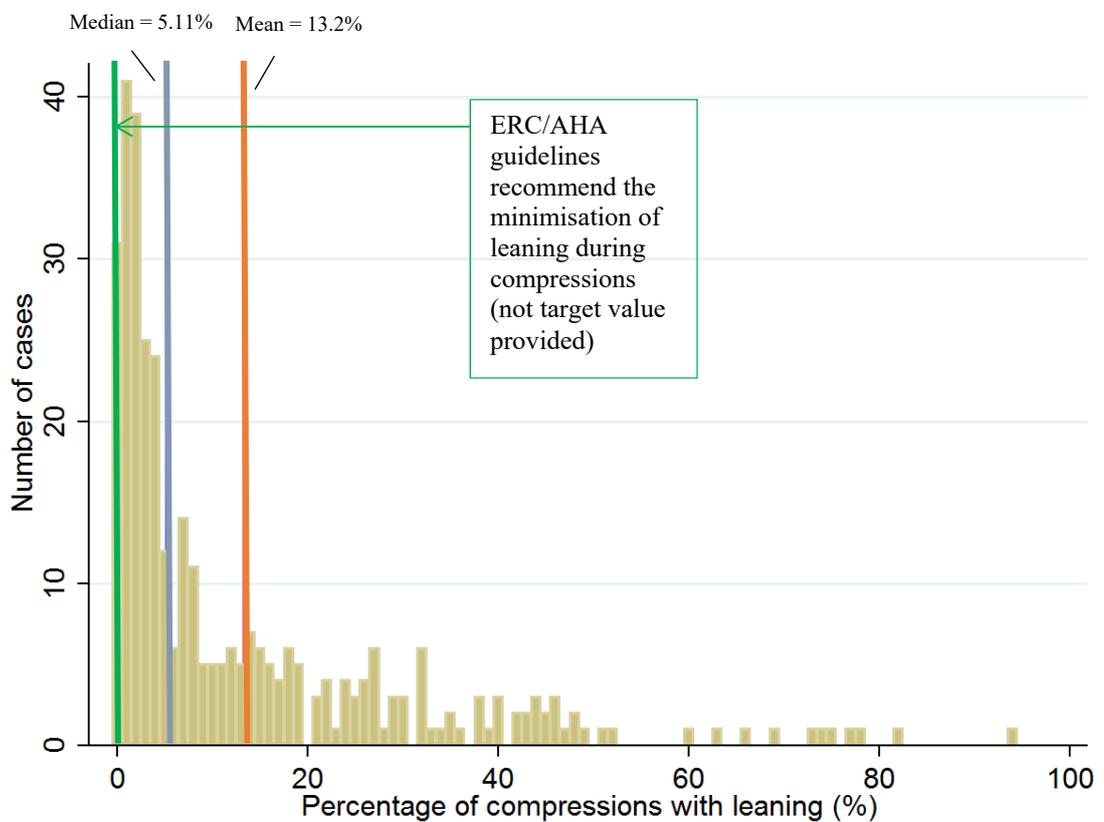


Figure 21 Frequency distribution for the percentage of compressions with leaning across the cohort (n=341)

6.4.2.6 Frequency distribution for ventilation rate

The mean±SD ventilation rate was 3.98±2.75 vpm while the median (IQR) was 3.71 (1.99, 5.35) vpm. Both the ERC¹⁰ and the AHA⁹ guidelines do not stipulate a target value for ventilation rate. However they recommend a 30:2 compression to ventilation ratio, which equates to a ventilation rate of approximately 4 vpm based on the following assumptions: a compression rate of 100 cpm, a break of 10 seconds for the delivery of every two rescue breaths, a break of 8 seconds every 2 minutes for rhythm analysis and no other interruptions. The mean ventilation rate reported among SJA-WA paramedics was proximal to this value.

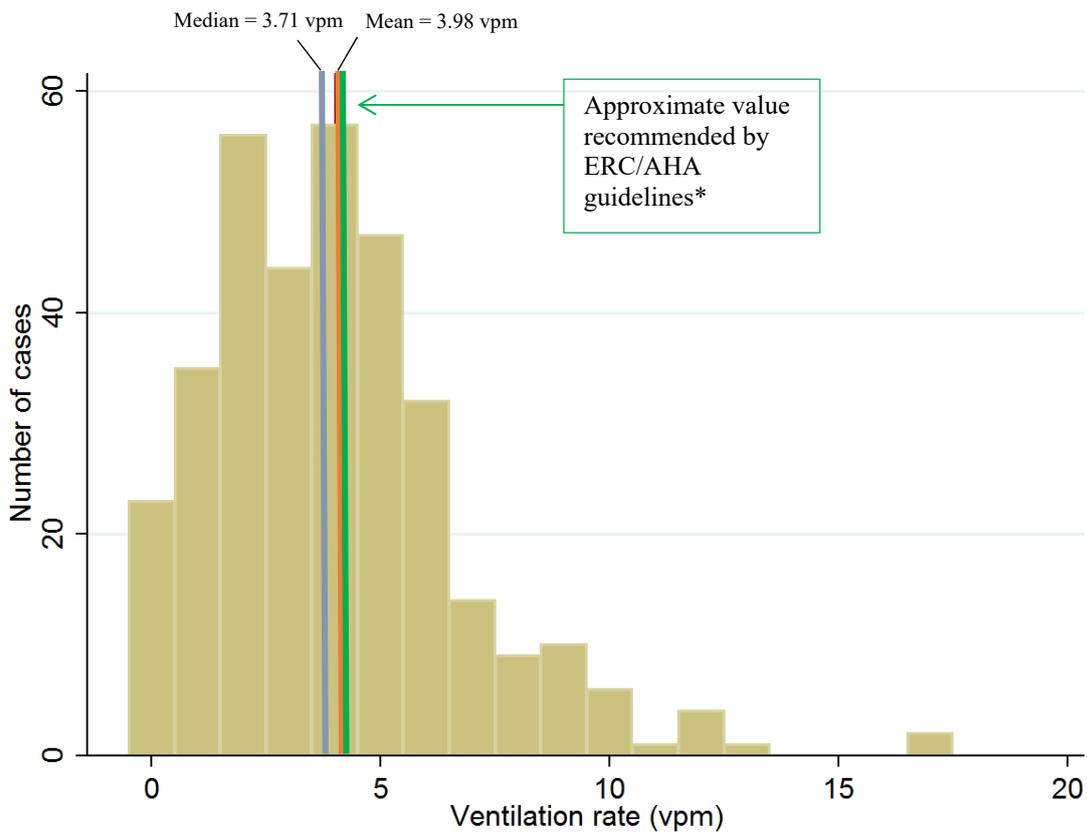


Figure 22 Frequency distribution for ventilation rate across the cohort (n=341)

* Approximate value calculated based on a compression rate of 100 cpm, a compression to ventilation ratio of 30:2, a break of 10 seconds for delivery of two rescue breaths, a break of 8 seconds for rhythm analysis every 2 minutes and no other interruptions to compressions.

6.4.2.7 Results of test for normality of distributions

I tested each of the six frequency distributions for normality based on skewness and kurtosis. From Table 10 it can be seen that compression depth was the only CPR quality metric with a normal distribution; for all other CPR quality metrics there was a statistically significant lack of normality.

Table 10 Test for normality of distributions based on skewness and kurtosis

CPR quality metric	P(skewness)	P(kurtosis)	Normal
Compression depth	0.09	0.3	Yes
Compression rate	0.02	0.6	No
Fraction	0.004	0.4	No
Duty cycle	p<0.001	p<0.001	No
Leaning	p<0.001	p<0.001	No
Ventilation rate	p<0.001	p<0.001	No

6.4.3 Comparison of CPR quality to other papers

I compared my results to those of seven studies^{4, 5, 14, 15, 53, 59, 110} published over a ten year period between 2005 and 2015, including two^{15, 110} that utilised data from the ROC group. Table 11 reports the mean±SD for the SJA-WA cohort alongside the mean±SD or median (IQR) reported by the other studies. Figure 23 – Figure 27 provide a visual representation of the mean [95% CI] calculated for each study, enabling a statistical comparison between studies.

I found that the mean [95% CI] compression depth recorded for SJA-WA (41.8 [40.8, 42.8]mm) was not significantly different from that reported by Abella et al.⁴ (43 [39, 47]mm), Idris et al.¹⁵ (42 [41.8, 42.2]mm) and Sheak et al.¹¹⁰ (40.7 [38.0, 41.4]mm). It was notably lower than that recorded by Bohn et al.⁵³ (47.4 [46.5, 48.4]mm) and Vadeboncoeur et al.¹⁴ (49.8 [48.9, 50.7]mm). Only the latter study had a mean value that potentially met the 50mm value recommended by the 2015 ERC¹⁰ and AHA⁹ resuscitation guidelines.

The mean [95% CI] compression rate recorded for the SJA-WA cohort (114 [113, 115] cpm) was not significantly different from that reported for Vadeboncoeur et al.¹⁴ (114 [112, 115] cpm). The mean compression rate for the majority of studies^{4, 14, 15, 53, 59, 110} including mine was within the 100-120 cpm range recommended by 2015 guidelines.^{9, 10}

The mean [95% CI] compression fraction recorded for the SJA-WA cohort (77.8 [76.9, 78.8]%) was not significantly different to that reported by Abella et al.⁴ (76 [71, 81]%) and

Vadeboncoeur et al.¹⁴ (79.2 [78.1, 80.4]%). It was lower than that reported by Bohn et al.⁵³ (83.8 [83.0, 84.6]%) but markedly higher than that reported by Wik et al.⁵ (52 [48, 56]%) and Kramer-Johansen et al.⁵⁹ (56 [54, 58]%).

The mean [95% CI] duty cycle recorded for the SJA-WA cohort (43.0 [42.6, 43.3]%) was not significantly different to that reported by Wik et al.⁵ (42 [41, 43]%). In all cases the mean duty cycle was below the 50% target recommended by guidelines.^{9, 10}

Data on the proportion of compression with leaning was only reported for two studies,^{5, 59} they both indicated a median rate of leaning that was less than one percent. By contrast the median (IQR) rate of leaning for the SJA-WA cohort was 5.11 (1.73, 18.4)%.

The adjusted ventilation rate (mean [95% CI]) recorded for the SJA-WA cohort was significantly lower than that reported by other studies.^{3, 5, 59, 110}

The above mentioned findings are further discussed in Section 6.5, including consideration of the version of the guidelines that was relevant at the time of data collection for each study.

Table 11 Quality of CPR performed by SJA-WA paramedics compared to that reported in the literature for other EMS agencies and hospital staff

	SJA-WA	Abella 2005 ^a	Wik 2005 ^a	Kramer-Johansen 2006	Bohn 2011 ^b	Vadeboncoeur 2014	Idris 2015	Sheak 2015
CPR quality parameter	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean SD	Mean SD	Median IQR
Compression depth (mm)	41.8 (9.17)	43 (14)	34 (9)	38 (6)	47.44 (8.6)	49.8 (11.0)	42 (12)	40.7 ^c (34.7, 46.8) ^c
Compression rate (cpm)	114 (10.9)	105 (21)	121 (18)	109 (12)	103.67 (7.53)	113.9 (18.1)	111 (19)	110.4 ^c (102.4, 118.6) ^c
Compression fraction (%)	77.8 (9.23)	76 (18)	52 (18)	56 (17)	83.84 (7)	79.2 ^c (67.5, 86.8) ^c	70 (17)	* *
Duty cycle (%)	43.0 (3.21)	* *	42 (4)	41 (4)	* *	* *	* *	* *
Leaning (%)	13.2 (17.0)	* *	0 (0, 2) ^c	0 ^c (0, 1) ^c	* *	* *	* *	* *
Ventilation (vpm)	3.98 (2.75)	20 (13)	11 (4.7)	11 (4)	* *	* *	* *	8.0 ^c (4.0, 12.0) ^c

* Information not available

- a. Mean (SD) calculated using data from the whole resuscitation episode.
- b. Results listed are for the group with extended feedback.
- c. Median (IQR). All other performance metrics are shown as mean (SD).

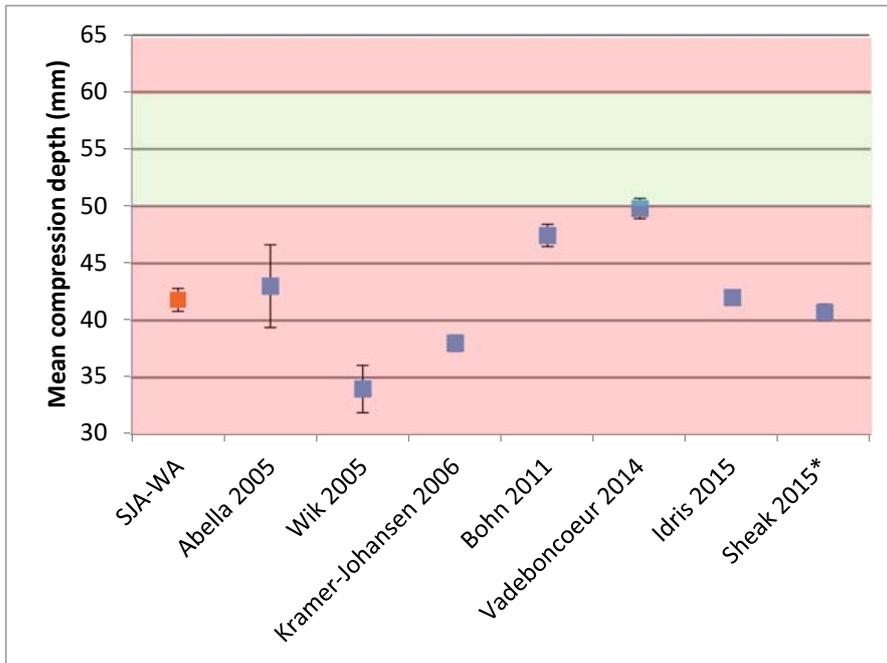


Figure 23 Compression depth: A comparison of mean (95% CI) across studies

(*) Indicates that mean (95% CI) was calculated from the median (IQR) and should be interpreted with caution. The green shading indicates the compression depth range (50-60mm) that is recommended by the 2015 AHA and ERC guidelines, while the red shading indicates values that are outside of this range.

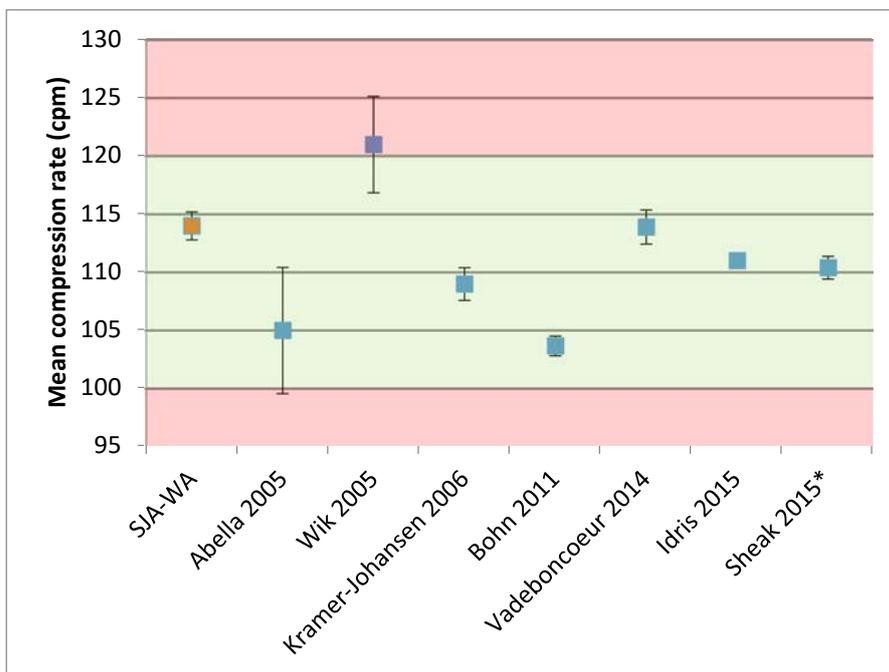


Figure 24 Compression rate: A comparison of mean (95% CI) across studies

(*) Indicates that mean (95% CI) was calculated from the median (IQR) and should be interpreted with caution. The green shading indicates the compression rate range (100-120 cpm) that is recommended by the 2015 AHA and ERC guidelines, while the red shading indicates values that are outside of this range.

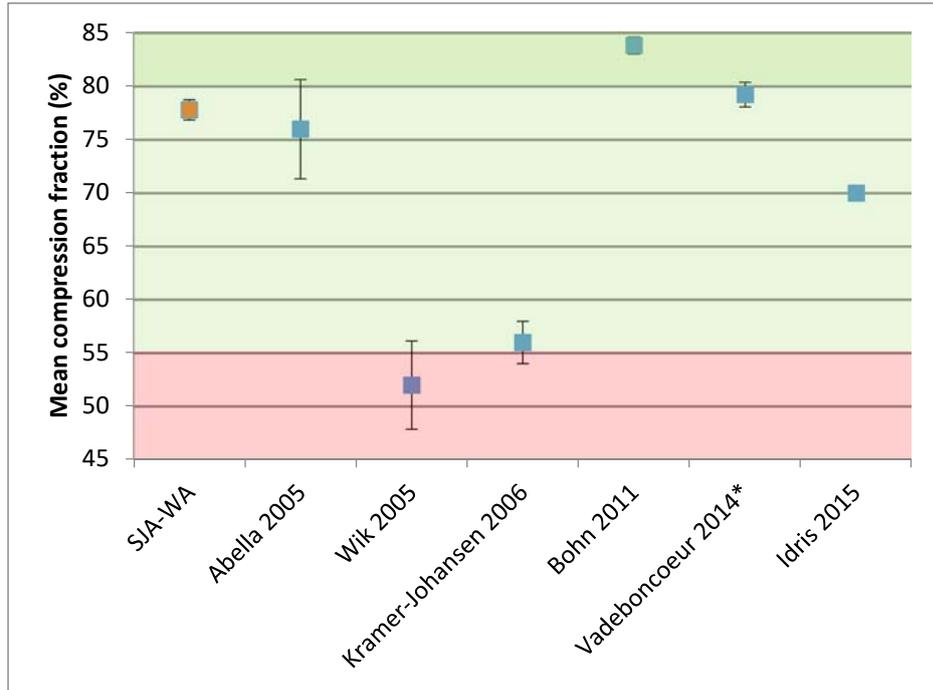


Figure 25 Compression fraction: A comparison of mean (95% CI) across studies

(*) Indicates that mean (95% CI) was calculated from the median (IQR) and should be interpreted with caution. The green shading indicates the compression fraction range (>60%) that is recommended by the 2015 AHA and ERC guidelines, while the red shading indicates values that are outside of this range. The darker green shading indicates the range (>80%) considered by AHA expert consensus to be achievable in a variety of settings.

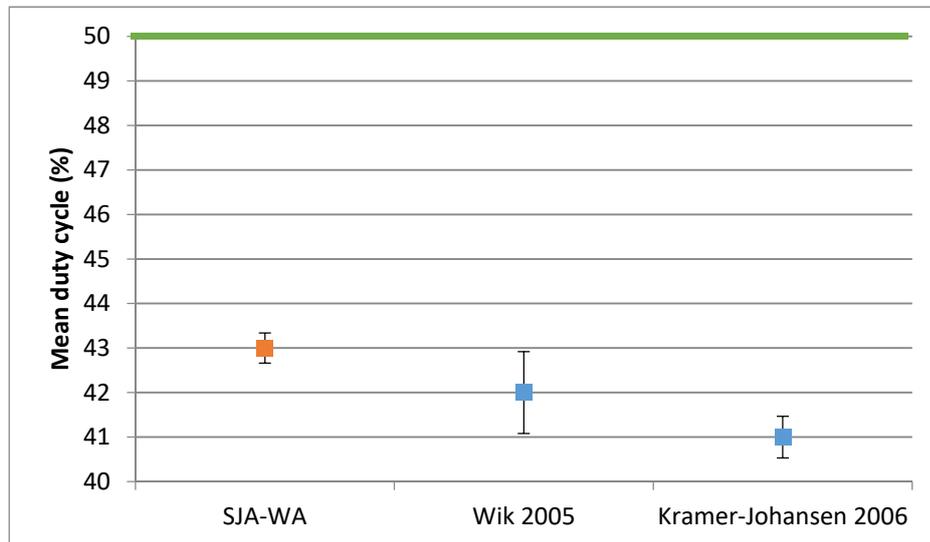


Figure 26 Duty cycle: A comparison of mean (95% CI) across studies

The green line indicates the duty cycle value (50%) recommended by the 2015 AHA and ERC guidelines.

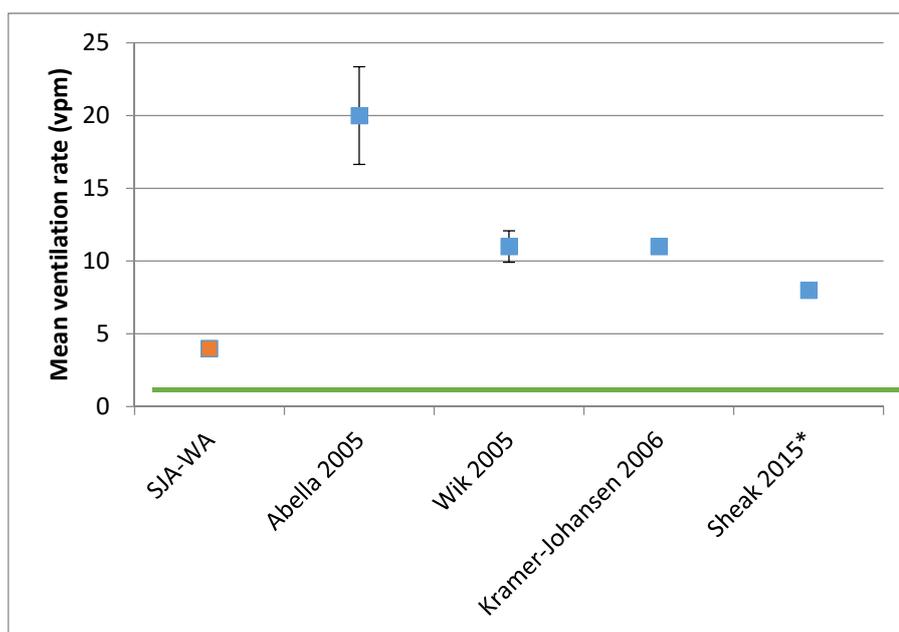


Figure 27 Ventilation rate: A comparison of mean (95% CI) across studies

(*) Indicates that mean (95% CI) was calculated from the median (IQR) and should be interpreted with caution. The green line indicates the recommended ventilation rate that was inferred from the 2015 ERC and AHA guidelines. This inferred value was calculated based on a compression rate of 100 cpm, a compression to ventilation ratio of 30:2, a break of 10 seconds for delivery of two rescue breaths, a break of 8 seconds for rhythm analysis every 2 minutes and no other interruptions to compressions.

6.4.4 CPR quality calculated using different time intervals

For each CPR quality metric I compared the mean that was calculated using all available episode data to that calculated using the first 3, 5 and 10 minutes of episode data (Table 12). I used 202 cases in my analysis; I was restricted to this value because it was the number of cases contained within my smallest (3 minute) dataset which was matched to corresponding cases in the remaining three datasets. The comparisons revealed that for compression depth, rate, duty cycle and leaning there were no significant differences in the mean calculated using data from the start of the resuscitation episode compared to from the whole of the resuscitation episode (Table 12). For compression fraction however, the mean calculated during the initial 3 minutes of resuscitation was significantly higher than that calculated using all available episode data (mean±SD: 79.4±11.3 vs. 77.3±8.98, p<0.001). Otherwise it appeared to remain relatively steady over time. Mean ventilation rate on the other hand increased significantly across each subsequent time interval compared to that calculated using all available episode data (p<0.001). For reference, the mean±SD length of the data in the group comprising ‘all available episode data’ was 14.3±11.2 minutes.

Table 12 Comparison of CPR quality measured across four time intervals (n=202)

CPR quality parameter	3 minutes		p	5 minutes		p	10 minutes		p	All available episode data	
	Mean	(SD)		Mean	(SD)		Mean	(SD)		Mean	(SD)
Compression depth (mm)	41.68	(9.26)	0.26	41.38	8.93	0.72	41.13	8.67	0.33	41.28	(8.24)
Compression rate (cpm)	115.17	(14.45)	0.51	115.17	13.69	0.42	114.56	12.13	0.50	114.75	(11.23)
Compression fraction (%)	79.41	(11.29)	p<0.001	77.84	10.24	0.16	77.25	9.57	0.99	77.25	(8.98)
Duty cycle (%)	42.75	(3.61)	0.61	42.95	3.47	0.36	43.00	3.37	0.07	42.83	(3.19)
Compressions with leaning (%)	13.99	(20.70)	0.48	13.34	18.47	0.88	13.22	17.32	1.00	13.22	(16.82)
Ventilation (vpm)	2.73	(3.12)	p<0.001	3.01	3.12	p<0.001	3.31	2.71	p<0.001	3.87	(2.68)

cpm: compressions per minute; vpm: ventilations per minute.

6.5 Discussion

This retrospective cohort study allowed me to measure CPR quality across a subset of OHCA cases in which resuscitation was attempted by SJA-WA paramedics using the Q-CPR device. I observed that while mean compression rate and fraction were compliant with international resuscitation guidelines,^{9, 10} mean compression depth was notably below the recommended range of 50-60mm. Given that my systematic review⁸⁶ had found that compression depth was significantly associated with survival outcomes, this underperformance should be investigated by SJA-WA. I also observed neither a significant improvement nor significant deterioration in CPR quality over resuscitation time, with the exception of a marginal initial decrease in compression fraction and significant upward trend in ventilation rate. This suggests that my data lacked evidence for a significant correction of CPR performance with the use of real-time. Below I discuss the findings for each CPR quality metric individually.

6.5.1 Compression depth

6.5.1.1 Compliance with guidelines

A large majority of the 341 cases comprising the study cohort had a mean compression depth that was outside of the range recommended by international resuscitation guidelines.^{9, 10} Importantly 82% had a depth that was below the 50mm minimum recommended value. Since my earlier systematic review⁸⁶ revealed that survivors had significantly deeper compressions than non-survivors (mean difference: 2.59 mm, 95% CI: 0.71, 4.47), my recommendation is that SJA-WA promptly investigate this issue.

6.5.1.2 Comparison to other papers

The mean compression depth of 41.8mm recorded among SJA-WA paramedics was similar to that published by Abella et al.⁴ for trained medical staff responding to in-hospital cardiac arrest (IHCA). However data for the latter study was collected between December 2002 and April 2004, when resuscitation guidelines recommended a depth in the range of 1.5-2 inches (38-51mm). Therefore the mean depth of 43mm was compliant with guidelines relevant at the time. Similarly, the mean depth of 42mm described in the 2015 publication by Idris et al.¹⁵ was calculated based on data collected between June 2007 and November 2009 and was likewise acceptable according to the guidelines applicable during data collection. The requirement for a depth in the range of 50-60mm emerged with the publication of the 2010 guidelines.¹¹⁴ Other studies in Table 11 published after 2010, including that by Vadeboncoeur et al.¹⁴ and Sheak et al.¹¹⁰ included data collected both before and after the 2010 guidelines change. Therefore, although their mean depths fall below the 50-60mm

range, they include data collected during the period when a lower compression depth was regarded as acceptable. The data for my study however was collected between July 2014 and June 2016, when the minimum target of 50mm was applicable. The mean compression depth recorded for my study cohort (41.8mm) was significantly and markedly less than this value. A similar phenomenon was seen by Wik et al.⁵ when the authors examined CPR quality among ambulance personnel responding to OHCA during 2002 and 2003; the mean compression depth of 34mm was significantly below the minimum of 38mm recommended by resuscitation guidelines at the time. The authors of that study provided recommendations for targeted CPR training aimed at promoting high quality CPR and at avoiding mistakes commonly made in the field, the use of online tools that prompt improved performance, and finally the use of real-time audio-visual feedback both during training and in the field. For SJA-WA I also suggest more training emphasising the importance of high quality CPR and the increased use of CPR feedback in clinical practice.

For a more current comparison I contrasted the mean compression depth measured among the study cohort to that reported in the 2017 Update of the Heart Disease and Stroke Statistics issued by the American Heart Association.² The latter publication reported a mean±SD of 49.3±10.2mm for OHCAs captured within the ROC Epistry between 1 January 2015 and 30 June 2015. I derived the associated 95% confidence interval and I found that compression depth among the SJA-WA cohort (mean [95% CI]: 41.8 [40.8, 42.8]mm) was significantly lower than that reported for the ROC Epistry (49.3 [49.2, 49.4]mm). Temporal trends in compression depth reported for the ROC Epistry are shown in Figure 28.

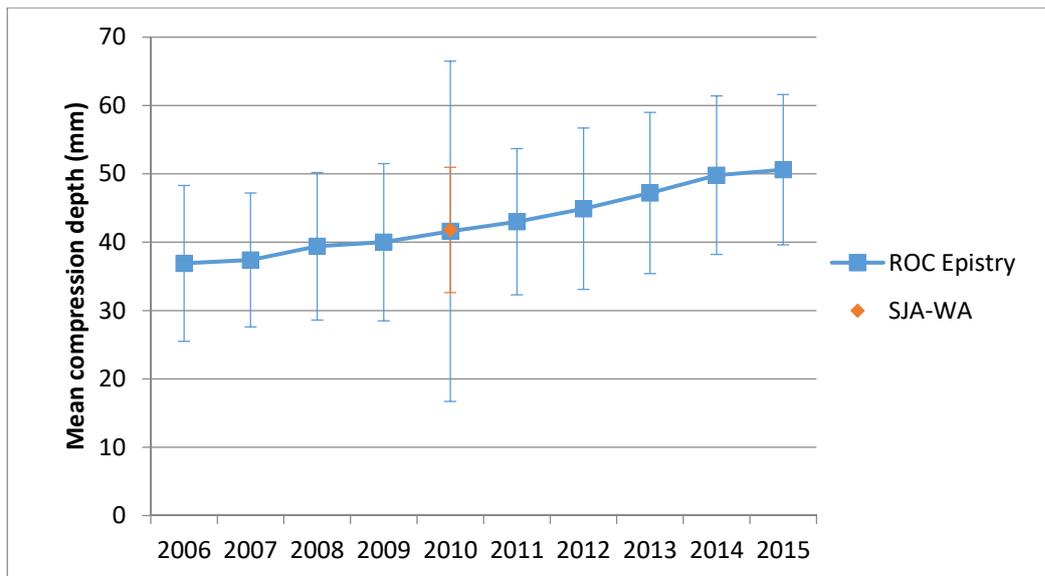


Figure 28 Temporal trend in mean compression depth reported by the ROC Epistry² compared to the mean compression depth reported for the SJA-WA study cohort

Error bars indicate standard deviation.

6.5.1.3 Compression depth calculated using different time intervals

There was no significant difference in the mean compression depth calculated using the first 3, 5 and 10 minutes of data compared to that calculated using all available episode data. It appeared that there was no significant improvement in the mean compression depth over resuscitation time despite the provision of feedback by the Q-CPR. While the audio feedback can be disabled by the user, the visual feedback is always available, both on the sensor unit that is positioned over the chest of the patient and on the Philips HeartStart MRx monitor/defibrillator (Section 2.7.1). This observation prompted me to consider whether the correct target depth range (50-60mm) had been programmed into the Q-CPR devices that are used by the metropolitan ambulance service. SJA-WA was alerted to the study’s findings and it was subsequently confirmed that the correct compression depth range had been set.

I likewise observed no deterioration in performance over resuscitation time. Some deterioration in performance may be expected as a result of rescuer fatigue.¹¹⁵ It is possible that my sample size was too small to detect a significant difference. Alternatively the compressions delivered were already relatively shallow making it perhaps less likely to observe a variation in compression depth due to fatigue. Fatigue may have also been made less likely by the fact that SJA-WA dispatches two crews (and a further single rescuer) to each cardiac arrest, resulting in five paramedics in attendance allowing for more frequent changeover of rescuers.

6.5.1.4 Conclusion

The mean compression depth recorded for the majority of examined cases was substantially lower than the 50mm minimum value recommended by international guidelines. Furthermore no improvement was observed in compression depth over resuscitation time. This underperformance should be further investigated by SJA-WA since compression depth has been previously linked to patient survival.

6.5.2 Compression rate

6.5.2.1 Compliance with guidelines

The mean compression rate measured among the study cohort (mean±SD: 114±10.9) fell within the range of 100-120 cpm recommended by international guidelines.^{9, 10} My systematic review⁸⁶ found that survivors tended to have a lower compression rate within this range than non-survivors (mean difference: -1.17 cpm, 95% CI: -2.21, -0.14). Within other studies higher compression rates have also been associated with lower compression depths.^{6, 13-15, 113} Therefore although the mean compression rate was within the recommended range, there was potential for further optimisation by achieving an even lower rate within this range.

6.5.2.2 Comparison to other papers

Like in most of the studies listed in Table 11,^{4, 14, 15, 53, 59, 110} the mean compression rate observed among the SJA-WA study cohort was compliant with ERC¹⁰ and AHA⁹ guidelines. Only one study⁵ reported a mean compression rate that exceeded the upper limit of 120 cpm; the authors recorded a mean rate of 121 cpm. However during the time that data was collected for that study (2002-2003) there was no recommendation for an upper limit in place; this was introduced in 2010.¹¹⁴ Therefore, all studies, including mine, complied with the guideline requirements that were relevant at the time of data collection.

6.5.2.3 Compression rate calculated using different time intervals

There was no significant difference in mean compression rate observed between the first 3, 5 and 10 minutes of CPR versus all available episode data. The mean compression rate recorded did not differ by more than one compression per minute.

6.5.2.4 Conclusion

The mean compression rate recorded among the SJA-WA study cohort was compliant with guideline requirements, but could be reduced even further to bring it closer to the value of 100 cpm. It remained consistent throughout the resuscitation effort.

6.5.3 Compression fraction

6.5.3.1 Compliance with guidelines

The mean \pm SD compression fraction calculated for the SJA-WA cohort was 77.8 \pm 9.23%. ERC¹⁰ and AHA guidelines⁹ state that rescuers should target a minimum fraction of 60% in adult cardiac arrest with an unprotected airway. Ninety six percent of the SJA-WA cohort met this requirement, while forty five percent exceeded the value of 80% that is considered by AHA expert consensus to be achievable in a variety of settings.⁹ The international resuscitation guidelines also recommend the minimisation of breaks for delivering rescue breaths;^{9, 10} however I did not specifically measure this in the study.

6.5.3.2 Comparison to other papers

The mean compression fraction recorded among the SJA-WA cohort (77.8%) was similar to that reported by Abella et al.⁴ in 2005 (76%) and to the median reported by Vadeboncoeur et al.¹⁴ in 2014 (79.2%). In general however compression fraction was lower among earlier studies (52% and 56% respectively for Wik et al.⁵ and Kramer-Johansen et al.⁵⁹). Due to the large variation in compression fraction observed between studies I hypothesised that there may have been methodological differences in how compression fraction was calculated. Therefore in my study I strove to be as accurate as possible by manually reviewing data from individual OHCA cases and, where required, performing the adjustments described in Chapter 5 (Section 5.7).

I also compared the performance of SJA-WA paramedics during the first 5 minutes of CPR against that reported for OHCA cases in the ROC Epistry between 1 January and 30 June 2015. The mean [95% CI] compression fraction reported for SJA-WA (77.8 [76.9, 78.8]%) was significantly less than that reported for the ROC Epistry (86 [85.9, 86.1]%).

6.5.3.3 Compression fraction calculated using different time intervals

A marginally but significantly higher mean compression fraction was noted during the first three minutes of resuscitation compared to all available episode data. I hypothesised that this may have been because crews prioritised CPR and defibrillation during the initial minutes of the rescue effort in preference to the implementation of other interventions such as intubation

that may have led to additional breaks. The first crew on scene may have also waited for a back-up crew to arrive prior to carrying out other interventions. Following the first three minutes of resuscitation, mean compression fraction marginally decreased and then remained steady for the rest of the resuscitation episode.

6.5.3.4 Conclusion

Almost all of the analysed cases (96%) had a mean compression fraction that complied with or exceeded the minimum 60% recommended by guidelines, while just under half (45%) met or exceeded the recommended value of 80%. Mean compression fraction was marginally higher during the first three minutes of resuscitation then decreased and remained steady over time.

6.5.4 Duty cycle

6.5.4.1 Compliance with guidelines

The mean±SD duty cycle recorded among the SJA-WA study cohort was 43.0±3.21%. Although the 2015 ERC guidelines¹⁰ recommend a duty cycle of 50%, the authors of these guidelines state that there is very little evidence to recommend any specific duty cycle.

6.5.4.2 Comparison to other papers

The mean duty cycle observed among the study cohort (43%) was similar to that reported by Wik et al.⁵ (42%). Apart from Kramer-Johansen et al. (41%),⁵⁹ no other studies in Table 11 provided duty cycle data. A recent human observational study by Johnson et al.¹¹⁶ found that the median duty cycle recorded among 164 OHCA ranged between 32.2% (SD:4.3%) and 38.8% (SD: 5.5%) depending on which methodology was used to derive it. A paediatric study of 87 IHCA cases reported a mean±SD duty cycle of 40±2.8%.⁸⁵ The authors concluded that duty cycle recommendations were only met in 5% of events.

6.5.4.3 Duty cycle calculated using different time intervals

Mean duty cycle did not differ significantly when comparing results from the first 3, 5 and 10 minutes of CPR to that derived from all available episode data.

6.5.4.4 Conclusion

The mean duty cycle recorded among the SJA-WA study cohort was below the value of 50% recommended by guidelines, but similar to that reported by other studies.

6.5.5 Leaning

6.5.5.1 Compliance with guidelines

The frequency distribution for leaning was highly skewed to the right, indicating that there were many cases with a low occurrence of leaning and few cases with a high occurrence of leaning. Although both sets of guidelines state that rescuers should minimise leaning, no acceptable value is documented within the guidelines.^{9,10}

6.5.5.2 Comparison to other papers

There were few studies in Table 11 that reported the degree of leaning among trained responders. Only Kramer-Johansen et al.⁵⁹ and Wik et al.⁵ provided this information. Kramer-Johansen et al.⁵⁹ recorded leaning among 3% of chest compressions which corresponded to an episode median of less than 1%. Wik et al.⁵ also reported a median of less than 1%. Given the limited data for leaning available in Table 11, I searched the literature for additional studies for comparison. Fried et al.¹¹⁷ found that leaning was common during resuscitation in IHCA; 12% of all of the compressions delivered to 108 patients were characterised by leaning. Forty one of the 108 cases (38%) had less than 5% leaning. By comparison in the SJA-WA cohort 170 cases (50%) had less than 5% leaning.

6.5.5.3 Leaning calculated using different time intervals

There was no significant difference in the mean percentage of leaning calculated using data from the initial 3, 5 and 10 minutes of CPR compared to that derived from all available episode data. The mean value may have been expected to decrease over time with the provision of feedback.

6.5.5.4 Conclusion

The frequency of leaning during CPR observed among SJA-WA paramedics was both less than and greater than that seen among other studies in the literature.^{5, 59, 117} It remained relatively constant over resuscitation time.

6.5.6 Ventilation rate

6.5.6.1 Compliance with guidelines

The mean±SD ventilation rate performed by SJA-WA paramedics was 3.98±2.75 vpm. Both ERC¹⁰ and AHA⁹ guidelines recommend a 30:2 compression to ventilation ratio. With a compression rate of 100 cpm, a break of 10 seconds for delivery of two rescue breaths, a break of 8 seconds for rhythm analysis every 2 minutes and no other interruptions, this would be equivalent to a ventilation rate of 4 vpm. With a faster compression rate (as seen

among the study cohort) and/or with shorter interruptions to compressions, the ventilation rate would be higher. For example with a compression rate of 115 cpm, a pause of 6 seconds to deliver two rescue breaths and a break of 10 seconds for rhythm analysis every two minutes, the corresponding ventilation rate would be 5 vpm.

The mean±SD of 3.98±2.75 vpm was calculated following manual adjustment of excessively high ventilation rates. I recorded ventilation rates as high as 85.7 vpm; these are likely to reflect a calculation error rather than a realistic ventilation rate. Therefore I manually reviewed any cases with a ventilation rate above 10 vpm and, if required, adjusted them as described in Chapter 1 (Section 5.7.4). Had I not performed any adjustment, and simply excluded the 4% of cases with a ventilation rate above 20 vpm from calculations (because I did not consider 20 vpm to be clinically likely to occur in the study cohort), the corresponding ventilation rate would have been 4.44 vpm. Both this and the former rate are approximately consistent with the ventilation rate inferred from the 2015 AHA and ERC guidelines.^{9, 10}

6.5.6.2 Comparison to other papers

The mean ventilation rate performed by SJA-WA paramedics (3.98 vpm) was lower than that reported by other studies (Abella et al.,¹¹⁸ Wik et al.⁵ and Kramer-Johansen et al.⁵⁹). However at the time that data was collected for the latter three studies, the recommended compression to ventilation ratio was 15:2 instead of 30:2, therefore justifying a higher ventilation rate. The mean ventilation rate among the SJA-WA cohort was also lower than the median reported by Sheak et al.¹¹⁰ (8 vpm) who collected data during the time when a 30:2 compression to ventilation ratio was prescribed; data collection occurred between April 2006 and May 2013. It is possible that the higher ventilation rate observed was reflective of a higher rate of intubation. However analysis of intubation was beyond the scope of my research.

6.5.6.3 Ventilation rate calculated using different time intervals

I observed an increase in mean ventilation rate with increasing resuscitation time. This may have corresponded to increasing numbers of patients being intubated over the course of the rescue effort. Alternatively, I hypothesised that in some cases the Q-CPR feedback device may have recorded the patient's own respirations as 'administered ventilations' following ROSC but prior to ROSC being confirmed with a pulse check (therefore while compressions were still being performed). This phenomenon however is unlikely to have been the biggest contributor to the upward trend in ventilation rate. Because ventilation rate is detected by the ECG pads as changes in transthoracic impedance, I hypothesised that in some cases compressions, which also generate a change in transthoracic impedance, could have been

registered as ventilations. However, if this were the case, it still did not explain the upward trend in ventilation rate over resuscitation time. Furthermore I did not observe a significant increase in other CPR quality metrics over time that could have accompanied an increase in transthoracic impedance, for example, increased compression depth or increased leaning.

6.5.6.4 Conclusion

The mean ventilation rate seen among the SJA-WA cohort was compliant with the ventilation rate of 4-5 vpm that was extrapolated from guidelines, but was lower than that observed among a selection of studies from the literature. There was an upward trend in ventilation rate observed over resuscitation time.

6.5.7 Data interval used for analysis

The lack of a significant difference in the mean compression depth, compression rate and leaning calculated using the first 3, 5 and 10 minutes of CPR compared to all available episode data is reflective of earlier findings by other authors.^{5, 60, 61, 119} These showed that CPR quality metrics calculated using the first 5 minutes of CPR data were comparable to those calculated using data from the whole resuscitation episode.

6.5.8 Representativeness of study cohort

The CPR quality calculated for my study cohort was based on 341 OHCA cases in which the Q-CPR device had been used. This represents less than a fifth of all cases that had resuscitation attempted by SJA-WA paramedics during the study period. To determine whether my findings could be considered representative of all cases, I compared Utstein characteristics^{25, 95} between the included and excluded cases (Table 8). In particular I sought to determine whether the circumstances under which paramedics used the Q-CPR were similar in both groups.

As mentioned in Section 6.4.1, there was a significantly lower proportion of EMS-witnessed arrests ($p < 0.001$) among the study cohort compared to the excluded cohort and a significantly higher proportion of unwitnessed arrests ($p = 0.02$) and of those occurring in a residential premise ($p = 0.02$). These characteristics are traditionally associated with lower odds of survival.⁹⁵ Indeed I observed a significantly lower rate of STHD among the study cohort compared to the excluded cohort (3.5% vs. 11.6%, $p < 0.001$) as well as a significantly lower rate of good neurological outcome at hospital discharge (2.9% vs. 9.0%, $p < 0.001$). The proportion of survivors with good neurological outcome however was similar in both groups (83% and 78% respectively). For both STHD and good neurological outcome at discharge, the significant difference remained after I completed a sensitivity analysis excluding EMS-

witnessed cases from each group. A possible contributor to the difference could have been that, for patients who responded to treatment early and reverted to a perfusing cardiac rhythm shortly after having resuscitation commenced by paramedics, there may not have been adequate time to apply the Q-CPR and collect sufficient data for the case to be included in the analysed cohort. This may have contributed to a higher survival rate among the excluded cohort.

Whether the observed difference in survival rate could have indicated that paramedics selectively used the Q-CPR in those cases that they perceived to inherently have lower chances of survival is unclear. Paramedics' attitudes towards the use of the Q-CPR device are discussed in Chapter 8. Lower perceived chances of survival could have corresponded to lower CPR quality. However this is not necessarily the most likely explanation for the shallow compressions observed among the SJA-WA study cohort.

Another possibility is that use of the Q-CPR device itself may have been associated with shallower compressions among the study cohort. For example, hand and wrist pain linked to Q-CPR use was frequently reported by paramedics anecdotally. Pain was formally investigated as part of the paramedic survey discussed in Chapter 8. It is possible that pain or the expectation of pain may have led to shallower compressions. Furthermore shallower compressions may have precipitated lower survival rates in the study cohort. However, this phenomenon does not seem to have been reported by other studies in which the Q-CPR was used.^{112, 149}

In the absence of CPR quality data from all paramedics, I assumed that my study cohort was representative of an approximately 'random' sample of SJA-WA paramedics. I considered ways in which I could determine whether the CPR quality recorded was truly reflective of that of all SJA-WA paramedics. I thought of reviewing records of paramedics' CPR performance during training and comparing them to my results. However it has been well documented in the literature that knowledge acquired during training deteriorates rapidly over time if not reinforced by further training,^{64, 120-125} therefore training records may not be an accurate representation of CPR quality in practice. Nevertheless with these considerations in mind, I assumed that the results collected for my cohort were representative of the performance of SJA-WA paramedics at large.

6.5.9 Recommendations for SJA-WA

Based on the findings of my research I make several recommendations for SJA-WA. Given the low mean compression depth observed, it is advised that SJA-WA implement initiatives that prioritise the optimisation of compression depth among rescuers. Compression rate could also be reduced to bring it closer to the value of 100cpm. Potential reasons for the ineffectiveness of the Q-CPR device to correct suboptimal compression depth in the study cohort should likewise be investigated. SJA-WA should continue to monitor CPR quality as well as the effect of any introduced quality improvement initiatives.

6.6 Conclusion

Data was collected for over 341 OHCA cases in Perth, W.A., in which resuscitation was attempted by SJA-WA paramedics using the Q-CPR feedback device over a two year period. While the average values for compression rate and compression fraction were compliant with the 2015 AHA and ERC guidelines,^{9, 10} importantly, compression depth was too shallow in a large majority of cases. Since my previous systematic review⁸⁶ demonstrated that deeper compressions were associated with higher rates of patient survival, I recommend that SJA-WA work to address this issue. In the next chapter I examine whether the CPR quality described in this chapter was associated with OHCA patient survival outcomes in the SJA-WA study cohort.

Chapter 7 The relationship between CPR quality and OHCA patient survival outcomes

7.1 Overview

In the previous chapter I described the quality of CPR performed by SJA-WA paramedics who used the Q-CPR device during the study period. In this chapter I investigated whether CPR quality was associated with OHCA patient survival outcomes. Specifically the outcomes examined were return of spontaneous circulation (ROSC), survival to hospital discharge (STHD) and good neurological outcome at hospital discharge, as defined by a Cerebral Performance Category (CPC) score of 1 or 2. I used multivariable logistic regression analysis to firstly examine whether collectively having compression depth, compression rate and compression fraction in compliance with ERC¹⁰ and AHA⁹ guidelines was associated with greater odds of ROSC, STHD or good neurological outcome at hospital discharge. I then examined whether having any one of the CPR quality metrics individually in compliance with guidelines was associated with OHCA survival outcomes. The results are described in the following manuscript.¹²⁶ I also carried out logistic regression analyses investigating the association of duty cycle, leaning and ventilation rate with survival outcomes. My findings are presented below in Section 7.4 due to the restrictions that were imposed on the word count of the manuscript.

The primary focus of my manuscript¹²⁶ was on determining the relationship between chest compression fraction (CCF) and survival outcomes. Several authors^{14, 98} have previously reported a significant, inverse relationship between CCF and either ROSC or STHD. Furthermore it has been proposed by some studies that this relationship may be time-dependent rather than constant.^{98, 100} I sought to investigate the potentially time-dependent nature of the relationship between CCF and ROSC in the SJA-WA cohort. Prompted by findings from animal studies,¹⁰¹⁻¹⁰⁴ I analysed whether this relationship varied based on 'downtime'. Downtime was defined as the time between onset of arrest to the provision of CPR by paramedics. I divided the cohort into three groups: those with a downtime of less than or equal to 15 minutes, greater than 15 minutes and those with an unknown downtime. I selected the value of 15 minutes as the cut-off for downtime based on porcine studies that had found that the deliberate introduction of breaks in compressions during the initial minutes of CPR following a downtime of 15-17 minutes was associated with survival benefit.¹⁰¹⁻¹⁰⁴ The proposed mechanism for this effect was the prevention of reperfusion

injury via ischemic post-conditioning.^{105, 106} I sought to detect whether there was any indication of such an effect in the SJA-WA study cohort. I performed univariate and multivariable logistic regression analyses in each of the three downtime groups separately. Specifically I looked at whether a lower chest compression fraction, signifying more pauses in compressions, during the initial minutes of CPR was associated with higher likelihood of ROSC. The results are discussed in detail in the following manuscript.

Talikowska M, Tohira H, Inoue M, Bailey P, Brink D, Finn J. Lower chest compression fraction associated with ROSC in OHCA patients with longer downtimes. Resuscitation. 2017; 116:60-5.

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Clinical paper

Lower chest compression fraction associated with ROSC in OHCA patients with longer downtimes[☆]Milena Talikowska^{a,*}, Hideo Tohira^{a,e}, Madoka Inoue^{a,b}, Paul Bailey^{a,b,c}, Deon Brink^{a,b}, Judith Finn^{a,b,d,e}^a Prehospital, Resuscitation and Emergency Care Research Unit (PRECRU), School of Nursing, Midwifery and Paramedicine, Curtin University, Bentley, WA, Australia^b St John Ambulance, Western Australia, Belmont, WA, Australia^c Emergency Department, St John of God Murdoch Hospital, Perth, WA, Australia^d School of Public Health and Preventive Medicine, Monash University, Melbourne, VIC, Australia^e Discipline of Emergency Medicine, University of Western Australia, Crawley, WA, Australia

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ABSTRACT

Aim: To investigate the relationship between chest compression fraction (CCF) and survival outcomes in OHCA, including whether the relationship varied based upon downtime from onset of arrest to provision of cardiopulmonary resuscitation (CPR) by emergency medical services (EMS).

Methods: Data from resuscitations performed by St John Ambulance Western Australia (SJA-WA) paramedics between July 2014 and June 2016 was captured using the Q-CPR feedback device. Logistic regression analysis was used to study the relationship between CCF and return of spontaneous circulation (ROSC). Various lengths of Q-CPR data were used ranging from the first 3 min to all available episode data. Cases were subsequently divided into groups based upon downtime; ≤ 15 min, > 15 min and unknown. Univariate and multivariable logistic regression analyses were performed in each group.

Results: There were 341 cases eligible for inclusion. CCF $> 80\%$ was significantly associated with decreased odds of ROSC compared to CCF $\leq 80\%$ (aOR: 0.49, 95%CI: 0.28–0.87). This relationship remained significant whether the first 3 min of data was used, the first 5 min or all available episode data. Among the group with a downtime > 15 min, CCF was significantly lower for those who achieved ROSC compared to those who did not (mean (SD): 73.01 (12.99)% vs. 83.05 (9.38)% $p = 0.002$). The adjusted odds ratio for achieving ROSC in this group was significantly less with CCF $> 80\%$ compared to CCF $\leq 80\%$ (aOR: 0.06, 95%CI: 0.01–0.38). **Conclusion:** We demonstrated an inverse relationship between CCF and ROSC that varied depending upon the time from arrest to provision of EMS-CPR.

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Introduction

The 2015 international guidelines for adult basic life support (BLS) recommend a compression rate of 100–120 compressions per minute (cpm) and a chest compression depth of 50–60 mm during cardiopulmonary resuscitation (CPR) [1,2]. Both compression rate and depth have been linked to patient survival outcomes [3]. For chest compression fraction (CCF) however, although guide-

lines [1,2] state that rescuers should maximise the CCF delivered, its relationship with survival has not been as clear. Whilst a 2009 paper [4] found that increased CCF was independently predictive of better survival in out-of-hospital cardiac arrest (OHCA) patients with a shockable initial rhythm, a number of recent studies have reported an inverse association between CCF and return of spontaneous circulation (ROSC), survival to hospital discharge (STHD) and neurologically intact survival in OHCA [5,6]. Several hypotheses have been proposed to attempt to explain this seemingly counter-intuitive observation. Wik et al. reported that there was an inverse relationship between CCF and survival, but after statistical adjustment for possible confounders, the relationship was in the expected direction [7]. Another study [5] however found that the relationship remained inverse despite adjustment for so-called Utstein predictors [8,9] and for several CPR quality metrics. The authors proposed

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that the relationship between CCF and survival outcomes may be time-dependent. Rea et al. also noted that the relationship between CCF and ROSC, survival to hospital discharge (STHD) and survival with favourable neurological outcome was linked to the duration of CPR delivered by emergency medical services (EMS) [10].

Animal studies [11–14] have similarly shown time-dependency; the deliberate introduction of breaks in compressions during the initial minutes of CPR was associated with survival benefit for cases where resuscitation efforts had been delayed by 15–17 min from onset of arrest. Referred to as ‘post conditioning’ (PC), the proposed mechanism is that, following an extended period with no circulation, the deliberate introduction of pauses during CPR may help to prevent reperfusion injury in the myocardium and brain [15,16]. Collectively, there is a growing body of evidence suggesting the potentially time-dependent nature of the relationship between CCF and survival. We therefore sought to investigate this relationship further and determine whether it varied depending on the time between onset of arrest and delivery of EMS-CPR.

Methods

Study design

We conducted a retrospective observational study of OHCA cases that had had resuscitation attempted by St. John Ambulance Western Australia (SJA-WA) paramedics in the Perth metropolitan area between July 2014–June 2016. We considered arrests of all causes in patients aged eight years or older. Specifically we sought cases that had a record of CPR quality and we explored its relationship with survival outcomes.

Setting

SJA-WA is the sole provider of road EMS in the state of Western Australia (WA). The capital city, Perth, has a population of approximately 2.0 million within a land area encompassing 6418 square kilometres [17]. Information about all EMS-attended cardiac arrests is captured within the OHCA database that is maintained at the Prehospital, Resuscitation and Emergency Care Research Unit (PRECRU) at Curtin University on behalf of SJA-WA. The database contains information sourced from the SJA-WA paramedic-completed electronic patient care records (ePCRs) supplemented with patient outcome data from in-patient hospital records and the WA Death Registry.

CPR quality data

We identified cases that had CPR quality data captured using the Q-CPR™ feedback device [18]. We only included cases with at least one minute of CPR quality data. The Q-CPR device is meant to be used by SJA-WA paramedics during all attempted resuscitations of patients aged 8 years and above where a mechanical compression device is not in use. The Q-CPR collects data on compression rate, depth, fraction, chest recoil, duty cycle and ventilation rate. For each case we imported individual Microsoft Excel files containing 30s summary data for each CPR quality metric. We utilised a bespoke algorithm to find the mean for each metric over the measurement interval. We excluded from calculations any periods of ROSC documented in the ePCR. To increase the integrity of our data, we also manually reviewed apparent breaks in compressions of greater than 30s to determine, by comparison against electrocardiography (ECG) data, whether these were true breaks in compressions or a break in the use of Q-CPR. We likewise excluded the end of the recorded data interval if the data was contaminated by artefact from moving or unplugging the Q-CPR device.

Relationship between CPR quality and outcome

We used multivariable logistic regression analysis with robust estimates of variance to investigate the relationship between CPR quality metrics and survival outcomes. The survival outcomes examined were: ROSC present at any time during the resuscitation, STHD and good neurological outcome at hospital discharge. The patient’s neurological status was determined by medical chart review; a cerebral performance category (CPC) score [19] of 1 or 2 was defined as ‘good’ neurological outcome. We assessed whether having compression rate, depth and CCF in compliance with current ERC and/or AHA guidelines was associated with improved patient outcomes. Although current AHA and ERC guidelines [1,2] recommend a CCF above 60%, the AHA expert consensus is that a CCF of 80% is achievable in a variety of settings [1]. Therefore we considered a CCF cut-off of 80% in our regression models. We calculated unadjusted odds ratios (OR) and 95% confidence intervals (95% CI) and then adjusted for compression rate, depth and CCF and the Utstein predictors of survival [8,9]. We used all available data within the resuscitation episode for this analysis.

Time-dependent relationship between CCF and survival outcomes

We investigated whether the relationship between CCF and survival outcomes varied depending upon the time from onset of arrest to the provision of EMS-CPR (‘downtime’). Specifically we defined downtime as the interval between time of arrest (as estimated from bystanders’ and paramedics’ descriptions in the ePCR) and the recorded EMS arrival time on scene. We used the time of EMS arrival because in the majority of cases the time from EMS arrival to commencement of CPR was very short unless otherwise documented in the ePCR. Because estimation of downtime was done retrospectively, to minimise potential error we used a conservative approach recording the maximum reasonable downtime based upon descriptions, and where it was not possible to estimate, we coded the downtime variable as “unknown” and analysed it separately. We also used the first recording of patient temperature to justify our estimates. We considered that the downtime was longer than 15 min if the first recording of body temperature was below 35 °C but did not assume the inverse [20]. This retrospective estimation of downtime was conducted by two authors (MT and HT). Consensus was sought in case of disagreement between the two. We divided cases into downtime ≤ 15 min versus >15 min based upon the definition of ‘prolonged’ downtime used within the majority of animal studies [11–13].

We compared the mean (SD) CCF for cases with and without ROSC within each of the two downtime categories and for the unknown cases. CCF was calculated using recordings from the first three minutes of CPR only because in animal studies ‘post conditioning’ was administered during the first three minutes. We subsequently computed unadjusted and adjusted OR for achieving ROSC with CCF $> 80\%$ compared to CCF $\leq 80\%$ for cases with downtime ≤ 15 min, downtime >15 min and for cases with an unknown downtime. We adjusted for age and two key predictors of survival: bystander CPR and shockable initial rhythm [8]. We also adjusted for compression depth and compression rate.

Statistical analysis

We conducted univariate analysis using *t*-tests or Mann-Whitney *U* tests for comparison of continuous variables and chi-squared tests or Fisher’s exact tests for categorical variables, assessed at the 5% level of significance. We used IBM SPSS version 22.0 (IBM, Armonk, NY) for decision tree and neural network anal-

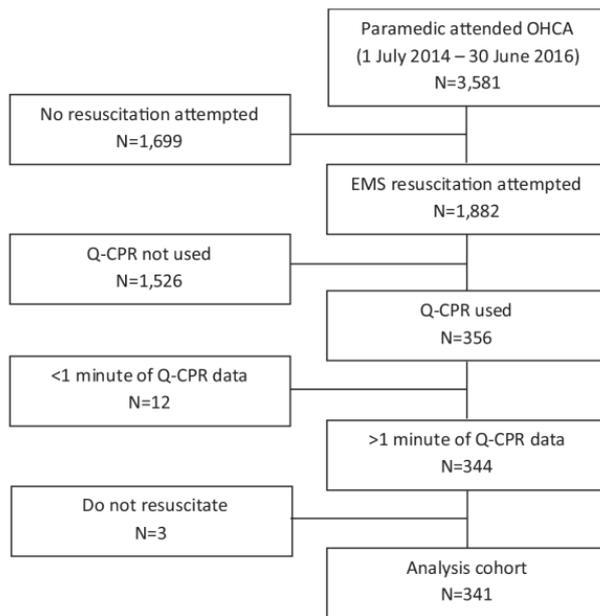


Fig. 1. Patient flow diagram of analysed cohort and exclusions.

Table 1
Baseline characteristics of analysed cohort (July 2014–June 2016).

Characteristic	Analysed cohort ^a (n = 341)
Age, mean (SD)	62.21 (20.19)
Male (%)	69.79
Witnessed arrest (%)	
EMS witnessed	4.99
Bystander witnessed	29.32
Unwitnessed	65.69
Bystander CPR (%)	60.12
Arrest location (%)	
Public	13.49
Residential	79.47
Other	7.04
Presenting initial rhythm (%)	
VF/VT	20.23
PEA	20.23
Asystole	59.53
Medical cause of arrest (%)	83.87
Response time (minutes), mean (SD) ^b	8.04 (6.94)
ROSC (Any), n (%)	85 (24.93)
STHD, n (%)	12 (3.52)
Good neurological outcome at hospital discharge, n (%)	110 (29.3)

EMS: emergency medical service; ROSC: return of spontaneous circulation; STHD: survival to hospital discharge; VF: ventricular fibrillation; VT: ventricular tachycardia.

^a OHCA cases that had resuscitation attempted by paramedics, had at least 1 min of CPR quality data recorded using the Q-CPR device and did not have a 'do not resuscitate' (DNR) advance directive.

^b Time interval from emergency call to the arrival of the first EMS vehicle on scene.

yses (see below) and StataSE13.1 for all other analyses (StataCorp LP, College Station, TX).

Sensitivity analyses

We conducted three sensitivity analyses to further explore the relationship between CCF and ROSC. Firstly, we repeated initial logistic regression analyses using three different durations (3, 5 and 10 min) of CPR quality measurement to investigate whether the duration affected our results. In our previous paper we described

Table 2
Odds ratios for survival outcomes by compliance of compression depth, rate and fraction with AHA and ERC guidelines; calculated using all available episode data.

Compliance of CPR quality metrics with ERC/AHA guidelines	Number compliant (n)	ROSC (Any)		STHD		Good neurological outcome at hospital discharge	
		Unadjusted OR (95% CI)	Adjusted ^a OR (95% CI)	Unadjusted OR (95% CI)	Adjusted ^a OR (95% CI)	Unadjusted OR (95% CI)	Adjusted ^a OR (95% CI)
Depth 50–60mm, Rate 100–120cpm and Fraction >80%	15	1.10 (0.34, 3.55)	1.09 (0.36, 3.26)				
Depth 50–60mm, Rate 100–120cpm and Fraction >80%	54	0.84 (0.42, 1.68)	0.74 (0.35, 1.55)	1.82 (0.48, 6.94)	1.22 (0.36, 4.17)	1.34 (0.28, 6.50)	1.02 (0.27, 3.85)
Depth 50–60mm, Rate 100–120cpm and Fraction >80%	216	0.88 (0.53, 1.47)	0.85 (0.50, 1.46)	0.80 (0.25, 2.59)	0.65 (0.17, 2.57)	0.86 (0.24, 3.12)	0.83 (0.20, 3.38)
Depth 50–60mm, Rate 100–120cpm and Fraction >80%	154	0.47 (0.28, 0.79)	0.49 (0.28, 0.87)	0.39 (0.10, 1.48)	0.61 (0.17, 2.24)	0.51 (0.13, 2.01)	0.86 (0.20, 3.68)

AHA: American Heart Association; CI: confidence interval; CPR: cardiopulmonary resuscitation; ERC: European Resuscitation Council; OR: odds ratio; ROSC: return of spontaneous circulation; STHD: survival to hospital discharge.

^a Adjusted for Utstein characteristics and compression depth, rate and fraction as required.

^b There were no survivors in the group with mean compression depth, rate and fraction within the ranges recommended by AHA/ERC guidelines.

the high degree of heterogeneity within the published literature in the length of data interval used when investigating the link between CPR quality and survival outcomes [21]. Secondly, we sought to investigate whether adjusting for the same variables as Wik et al. [7] changed the direction of the relationship observed between CCF and ROSC in our cohort; we derived logistic regression models examining CCF as a continuous variable while adjusting for the same factors as Wik et al. with the exception of site location (not applicable to our study) and median duration of treatment [7]. Thirdly, we derived a classification tree with Classification and Regression Tree (CART) modelling and likewise employed artificial neural network (ANN) analysis to examine whether the inverse relationship between CCF and survival outcomes was consistent regardless of the method of statistical modelling used. A decision tree is a flowchart-like model that illustrates the key factors predictive of outcome and their corresponding cut-off points. ANN is used for complex pattern-recognition tasks and likewise reports the key factors predictive of outcome. These techniques have been applied previously in prehospital [22] and cardiac research [23]. In our study we compared results derived using these two methodologies to those from logistic regression, while also comparing the degree of predictability of the models through comparison of the respective areas under the receiver operating characteristic (AUROC) curves.

Ethics approval

Ethics approval for this study was granted by the Human Research Ethics Committee of Curtin University (HR128/2013).

Results

There were 3581 OHCA cases that occurred in Perth during the study period. Over half of the cases (1882) had resuscitation attempted by paramedics. Q-CPR was utilised in 356 cases. Twelve cases were excluded due to there being less than one minute of Q-CPR data recorded. A further three cases were excluded due to resuscitation being started but subsequently terminated when the cases were discovered to have a 'do not resuscitate' advance directive in place. This resulted in 341 cases being included in the analysed cohort (Fig. 1). The Utstein characteristics and survival rates for this cohort are described in Table 1.

Relationship between CPR quality and outcome

There was no significant association with ROSC (aOR: 1.09, 95%CI: 0.36–3.26) when all three metrics (compression depth, rate and CCF) met ERC and AHA guidelines (Table 2). There were only 15 patients in this group and none of them survived to hospital discharge. Compression depth and rate were not significantly associated with any survival outcomes (Table 2). However, CCF was significantly associated with ROSC (Table 2); a CCF of >80% was associated with decreased odds of ROSC (aOR: 0.49, 95%CI: 0.28–0.87). The relationship was not significant for STHD nor for the outcome of good neurological outcome at hospital discharge (Table 2).

Time-dependent relationship between CCF and survival outcomes

For arrests with a downtime of ≤ 15 min, there was no significant difference in CCF between those who did and did not achieve ROSC (mean (SD): 75.59 (12.14)% vs. 76.69 (11.35)%; $p=0.69$) (Table 3), nor for those who did and did not STHD (mean (SD): 76.55 (14.59)% vs. 76.23 (11.44)% $p=0.58$). However, among those with a downtime >15 min, those with ROSC had a significantly lower CCF compared to those without (mean (SD): 73.01 (12.99)% vs. 83.05

(9.38)% $p=0.002$) (Table 3). Among cases with an unknown downtime, there was no significant difference in CCF between those with and without ROSC (mean (SD): 80.75 (8.09)% vs. 80.32 (12.72)%; $p=0.96$) (Table 3). We likewise found no significant differences in other CPR quality metrics and Utstein variables between those with and without ROSC in each of the three downtime categories (Table 3).

Among patients with downtime >15 min, the odds of those with CCF >80% achieving ROSC were 93% lower than for those with CCF $\leq 80%$ (OR: 0.07, 95%CI: 0.01–0.33) (Table 4). After adjusting for age, bystander CPR, shockable initial rhythm, compression depth and compression rate, the odds remained significant (aOR: 0.06, 95%CI: 0.01–0.38) (Table 4). In the group with a downtime ≤ 15 min, the odds of ROSC were not significantly different with a CCF >80% compared to $\leq 80%$ (aOR: 0.63, 95%CI: 0.23–1.71) (Table 4). Other CPR quality metrics were not significant predictors of ROSC.

Sensitivity analyses

We found that higher CCF was significantly associated with lower odds of ROSC when using the 3 and 5 min dataset, but not significant when using the 10 min dataset (aOR: 0.64, 95%CI: 0.35–1.15). We found that in a logistic regression model adjusting for the same variables as Wik et al. [7] CCF remained significantly and inversely associated with ROSC (aOR for ROSC: 0.96 (95%CI: 0.93, 0.98)). Using ANN we found that CCF was a key predictor of ROSC (Appendix A of Supplementary material). Using CART we found that lower CCF was always associated with a higher rate of ROSC in our derived decision tree (Appendix A of Supplementary material). We also found that CCF was not a predictor for ROSC if response time was less than or equal to 4.3 min (Appendix A of Supplementary material). The predictabilities (as represented by AUROC) of these two methodologies were similar to that of logistic regression analysis (0.69 (95%CI: 0.62–0.75) for the logistic regression model vs. 0.72 (95%CI: 0.66–0.78) for the decision tree and 0.687 (95%CI: 0.685–0.689) for ANN).

Discussion

Our results show that CCF was inversely and significantly associated with ROSC. This was true across three of the four time durations examined; the first 3 and 5 min of EMS-CPR and all available episode data. Furthermore, the relationship between CCF and ROSC appeared to vary depending on the timing from onset of arrest to provision of EMS-CPR.

Our results are consistent with other recently published studies that show that a higher CCF was associated with lower odds of ROSC [5,6]. These studies used all available episode data in their analyses. Their approach differed to earlier work by Christenson et al. [4] that utilised data only until the first analysis check, a mean (IQR) of 1.6 (1.1) minutes [5], to demonstrate a positive relationship between CCF and survival. In our present work we demonstrated an inverse relationship both during the initial minutes of resuscitation as well as across all available episode data. We also compared our findings to those of Wik et al. [7] who reported that the relationship between CCF and survival changed from inverse to positive following adjustment for variables associated with CCF and/or survival. We adjusted for the same predictors as Wik et al. (with the exception of median duration of treatment) however found that the relationship remained inverse. We also utilised alternative methods of analysis to test our findings. Using decision tree analysis we found that depending on EMS response time a lower CCF was associated with higher rates of ROSC.

Other authors have proposed that the relationship between CCF and survival outcome is time-dependent [5,10]. We sought

Table 3

Univariate comparison of Utstein OHCA characteristics and CPR quality metrics between cases with and without ROSC (Any), grouped by downtime from onset of arrest to EMS arrival on scene, calculated using data from the first 3 min of CPR.

Characteristic	Downtime ≤ 15 minutes			Downtime > 15 minutes			Unknown downtime		
	ROSC	No ROSC	P – value	ROSC	No ROSC	P – value	ROSC	No ROSC	P – value
N	30	45		15	83		9	20	
Age (years)	65.77 (17.70)	64.09 (17.71)	0.69	53.73 (24.71)	60.81 (19.83)	0.28 ^b	52.22 (20.60)	60.65 (22.16)	0.35 ^b
Male (%)	76.67	77.78	0.91	53.33	71.08	0.17	77.78	75.00	1.00 ^a
Bystander-witnessed arrest (%)	46.67	53.33	0.57	13.33	15.66	1.00 ^a	0	0	N/A
Paramedic-witnessed arrest (%)	6.67	11.11	0.70 ^a	0	0	N/A	0	0	N/A
Bystander-CPR (%)	60.00	60.00	1.00	46.67	69.88	0.08	88.89	50.00	0.10 ^a
Public location of arrest (%)	23.33	20.00	0.73	13.33	6.02	0.29 ^a	22.22	20.00	1.00 ^a
Shockable initial rhythm (%)	43.33	24.44	0.09	6.67	9.64	1.00 ^a	0	10.00	1.00 ^a
Medical cause of arrest (%) ^c	86.67	93.33	0.43 ^b	73.33	79.52	0.73	88.89	80.00	1.00 ^a
Response time (min) ^d	5.91 (2.01)	6.87 (2.88)	0.12	6.73 (3.08)	8.50 (4.01)	0.17 ^b	8.16 (5.12)	5.57 (2.26)	0.09 ^b
Compression depth (mm)	41.82 (7.99)	39.32 (8.91)	0.22	41.50 (9.26)	42.53 (9.15)	0.65 ^b	40.69 (12.26)	43.80 (10.83)	0.45 ^b
Compression rate (cpm)	113.81 (15.77)	115.91 (15.28)	0.57	116.25 (14.77)	114.69 (13.64)	0.76 ^b	115.89 (14.95)	116.38 (14.95)	0.85 ^b
Compression fraction (%)	75.59 (12.14)	76.69 (11.35)	0.69	73.01 (12.99)	83.05 (9.38)	0.002 ^b	80.75 (8.09)	80.32 (12.72)	0.96 ^b
Duty cycle (%)	42.33 (4.69)	42.50 (4.11)	0.86	43.54 (3.43)	42.89 (3.09)	0.31 ^b	41.01 (3.74)	43.50 (2.54)	0.06 ^b
Leaning (%)	15.69 (21.86)	16.52 (25.80)	0.88	12.89 (18.27)	13.92 (20.20)	0.89 ^b	8.55 (13.23)	9.27 (11.15)	0.74 ^b
Ventilation rate (vpm)	4.00 (4.81)	2.68 (2.96)	0.14	2.53 (2.08)	2.27 (2.71)	0.39 ^a	3.08 (2.42)	2.88 (2.61)	0.74 ^b

EMS: emergency medical service; ROSC: return of spontaneous circulation.

Results listed as mean (SD) or percentage as relevant.

^a P-value calculated using non-parametric methods (Fisher's Exact Test).

^b P-value calculated using non-parametric methods (Mann-Whitney U Test).

^c Previously referred to as 'presumed cardiac cause'.

^d Time interval from emergency call to the arrival of the first EMS vehicle on scene.

Table 4

Odds of ROSC (Any) for CCF >80% compared to CCF ≤ 80%, categorised by downtime from onset of arrest to arrival of the first EMS on scene; calculated using data from the first 3 min of CPR.

Downtime	N	Unadjusted OR	95%CI	Adjusted ^a OR	95%CI	Adjusted ^b OR	95%CI
≤15 min	75	0.63	(0.24, 1.63)	0.61	(0.23, 1.63)	0.63	(0.23, 1.71)
>15 min	98	0.07	(0.01, 0.33)	0.07	(0.01, 0.38)	0.06	(0.01, 0.38)
Unknown	29	1.63	(0.32, 8.45)	1.33	(0.15, 11.82)	1.26	(0.15, 10.75)

CCF: chest compression fraction; CI: confidence interval; EMS: emergency medical service; OR: odds ratio; ROSC: return of spontaneous circulation.

^a Adjusted for patient age, shockable rhythm and bystander CPR.

^b Adjusted for patient age, shockable rhythm, bystander CPR, compression depth and compression rate.

to investigate whether it varied depending upon downtime from onset of arrest to delivery of EMS-CPR, prompted by positive findings from animal studies [11–13]. We found that for arrests with a 'prolonged' downtime of greater than 15 min, a higher CCF during the first 3 min of CPR was significantly associated with lower odds of ROSC. This was not the case with downtime ≤15 min or for the cases with unknown downtime. This finding suggests that there may be survival advantages associated with the deliberate introduction of breaks in compressions during the first minutes of CPR where patients have been without circulation for an extended period. While in animal models the use of PC, either alone [13] or bundled with other therapies [11,12], was linked to increased survival, we could not demonstrate this in our dataset. The downtime used in animal studies was 15–17 min, however our cohort contained many cases with a substantially longer downtime, up to several hours. Neurological recovery may be less likely despite the use of PC in such cases. We had too few survivors to conduct logistic regression analyses in each of the downtime groups. However, given that ROSC is a necessary precursor for survival [8], the fact that we observed an association between CCF and ROSC provides an optimistic outlook for an association with survival in those patients with a downtime marginally, but not substantially, greater than, 15 min. We therefore recommend that a retrospective analysis similar to the one described herein be conducted by others using a larger dataset. Our preliminary results also provide reason for further investigation into whether a single CCF recommendation is appropriate for all patients.

Limitations

Our analysed cohort represented less than one fifth (18.1%) of all OHCA cases with resuscitation attempted. However, we found that cases with Q-CPR data did not differ significantly on Utstein characteristics compared to all cases with resuscitation attempted (Appendix B of Supplementary material) with the exception of significantly lower proportions of paramedic-witnessed arrests ($p < 0.001$) and arrests occurring in a public location ($p = 0.04$) in our study cohort. These differences may help to explain why STHD was significantly lower in our cohort (3.5% vs 11.6%; $p < 0.001$) but also may signify a higher proportion of patients with a prolonged downtime thus allowing us to more easily identify an inverse relationship between CCF and ROSC in our cohort.

We encountered difficulty with recruitment due to low usage rates of the Q-CPR device; the reasons for this were outlined in our previous paper [24]. Given the sample size available, we may have lacked the power to detect a significant difference in some variables using univariate analysis and to perform meaningful regression analyses in some instances where the distribution of patients was highly polarised. Nevertheless, we had sufficient power to demonstrate a significant relationship between CCF and ROSC, including in the group with downtime >15 min.

Conclusions

We demonstrated an inverse relationship between CCF and ROSC, regardless of whether we analysed data from the first few minutes of CPR or all available episode data. Furthermore, a lower

CCF during the initial minutes of CPR appeared to be more important in cases with a prolonged downtime of greater than 15 min. Further research is required to understand the growing evidence for this counter-intuitive finding.

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Potential conflict of interest

Prof. Judith Finn is the Director of the Australian Resuscitation Outcomes Consortium (Aus-ROC), a NHMRC Centre of Research Excellence (CRE #1029983), and receives partial salary support from St John Ambulance Western Australia (SJA-WA). A/Prof. Paul Bailey is Clinical Services Director at SJA-WA. Mr. Deon Brink is the Executive Manager Clinical Governance at SJA-WA. Dr. Madoka Inoue maintains the SJA-WA OHCA database and receives partial salary support from SJA-WA and Aus-ROC. Ms. Milena Talikowska is a PhD student funded by Aus-ROC. There are no other potential conflicts of interest to declare. The authors alone are responsible for the content and writing of the paper.

Author contribution

MT, HT and JF were involved in the conception and design of the study. Data was sourced from St. John Ambulance Western Australia (SJA-WA) in consultation with DB and PB. The study dataset was extracted from the SJA-WA OHCA database with the important assistance of MI, the database manager. MT and HT conducted all data cleaning and analysis. MT and HT prepared the manuscript; all other authors were involved in the revision of the article critically for important intellectual content, and final approval of the version to be submitted.

All have given approval to submit this article.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.resuscitation.2017.05.005>.

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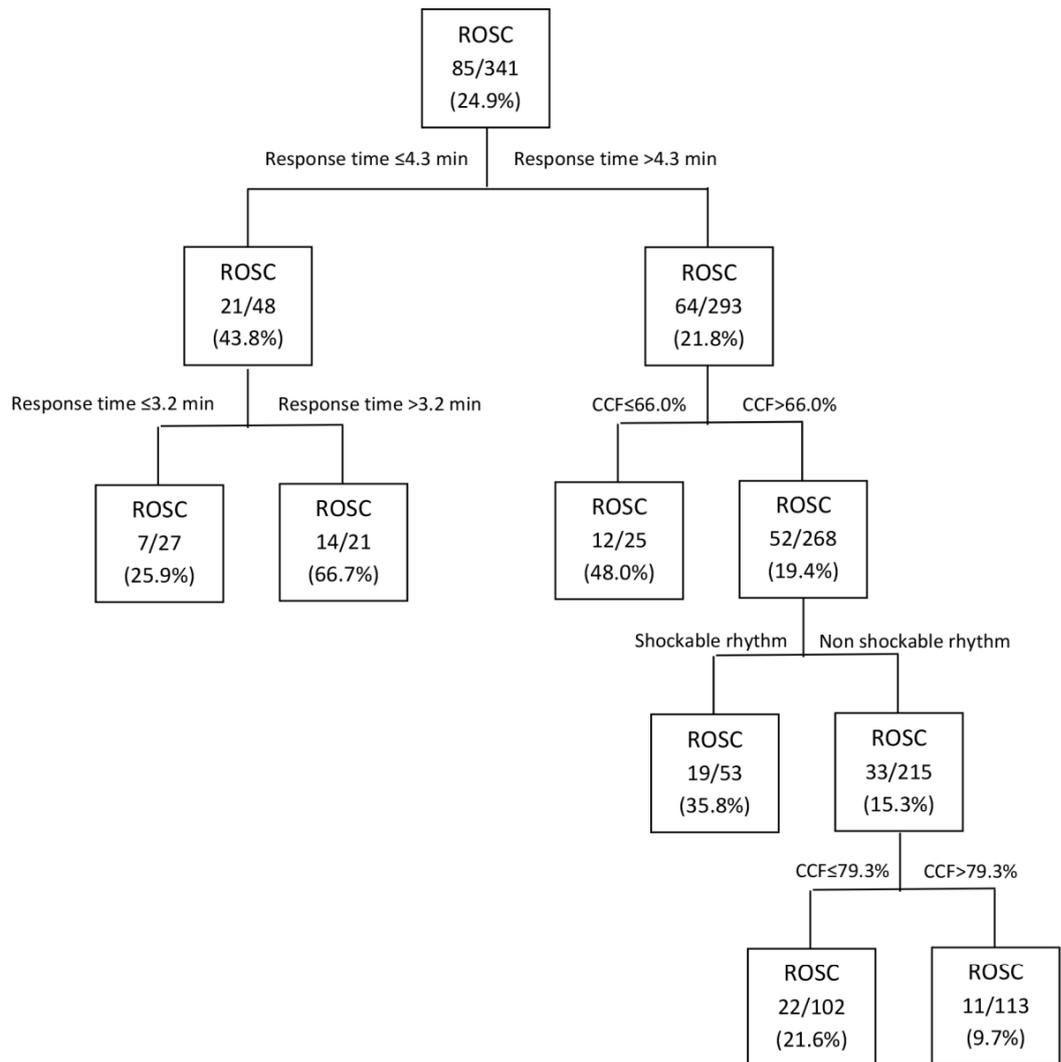


Figure A1: Decision tree derived using Classification and Regression Tree (CART) analysis. Results show that a response time > 4.3 minutes was a primary predictor. CCF was not devisor when a response time was equal to or shorter than 4.3 minutes, while CCF was devisors when a response time was longer than 4.3 minutes. Lower chest compression fraction (CCF) was always associated with higher rate of return of spontaneous circulation (ROSC). CCF≤66.0% was associated with higher chances of ROSC compared to CCF>66.0% (48.0% vs. 19.4%). Among those with CCF>66.0%, shockable initial rhythm was a subsequent predictor of ROSC. For those with a non-shockable initial rhythm, CCF≤79.3% was associated with higher rates of ROSC. The area under the receiver operating characteristic curve for this model was 0.72 (95% CI: 0.66, 0.78) corresponding to a similar level of predictability as with the logistic regression model (0.69, 95% CI: 0.62, 0.75).

Table A1: Relative role of Utstein OHCA elements and CPR quality variables in predicting ROSC in the dataset containing all available episode data, derived using artificial neural network (ANN) analysis. Results indicate that the key predictive variable was chest compression fraction (CCF) with a mean normalised importance of 82.5% (95% CI: 81.1%, 83.8%). The area under the receiver operating characteristic (ROC) curve was 0.687 (95% CI: 0.685, 0.689) corresponding to a similar level of predictability as with the regression model (0.69, 95% CI: 0.62, 0.75).

Variable	Normalised importance (%)	
	Mean	95% CI
Compression fraction	82.5	(81.1, 83.8)
Response time	79.2	(77.8, 80.6)
Compression depth	56.8	(55.3, 58.4)
Duty cycle	51.1	(49.6, 52.5)
Leaning	46.1	(44.8, 47.4)
Compression rate	43.0	(41.7, 44.2)
Age	34.2	(33.1, 35.2)
Shockable initial rhythm	26.9	(26.0, 27.7)
Bystander witnessed arrest	20.3	(19.6, 21.0)
Public location of arrest	19.4	(18.6, 20.1)
Paramedic witnessed arrest	15.7	(15.1, 16.3)
Medical cause of arrest	13.8	(13.2, 14.3)
Sex	13.4	(12.9, 13.9)
Bystander CPR	12.4	(11.9, 12.8)

Table B1: Baseline characteristics of analysed cohort versus excluded cases (July 2014 – June 2016)

Characteristic	Analysed cohort ¹ (n=341)	Excluded cases ² (n=1,541)	p-value
Age, mean (SD)	62.21 (20.19)	61.82 (20.18)	0.74
Male (%)	69.79	67.21	0.36
Witnessed arrest (%)			
EMS witnessed	4.99	12.46	<0.001
Bystander witnessed	29.32	28.49	0.76
Unwitnessed	65.69	59.05	0.02
Bystander CPR (%)	60.12	54.71	0.07
Arrest location (%)			
Public	13.49	18.17	0.04
Residential	79.47	73.20	0.02
Other	7.04	8.63	0.34
Presenting initial rhythm (%)			
VF/VT	20.23	20.65	0.86
PEA	20.23	24.23	0.12
Asystole	59.53	55.11	0.14
Unknown	0	0.39	0.25
Medical cause of arrest (%)	83.87	80.86	0.20
Response time (minutes), mean (SD) ³	8.04 (6.94)	8.22 (5.13)	0.58
ROSC (Any), n(%)	85 (24.93)	448 (29.07)	0.12
STHD, n(%)	12 (3.52)	178 (11.57)	<0.001
Good neurological outcome at hospital discharge, n(%)	10 (2.93)	137 (9.04) ⁴	<0.001

EMS: emergency medical service; ROSC: return of spontaneous circulation; STHD: survival to hospital discharge; VF: ventricular fibrillation; VT: ventricular tachycardia.

1. OHCA cases that had resuscitation attempted by paramedics, had at least 1 minute of CPR quality data recorded using the Q-CPR device and did not have a 'Not For Resuscitation' (NFR) directive.
2. OHCA cases that had resuscitation attempted by paramedics but where the Q-CPR device was not used or, if used, the patient was subsequently found to have a NFR directive or the data captured by the Q-CPR device was of less than 1 minute duration.
3. Time interval from emergency call to the arrival of the first EMS vehicle on scene.
4. There were 26 cases with missing CPC data in this group.

7.3 CCF and ROSC

This manuscript¹²⁶ documents the finding of a significant, inverse relationship between CCF and ROSC. Furthermore, the relationship appeared to vary based on downtime. In the group with a downtime of greater than 15 minutes, a lower compression fraction during the first three minutes of CPR was significantly associated with ROSC. However, I hypothesised that the patients who achieved ROSC in this group may have been characterised by a lower compression fraction because more of the resuscitation time was spent administering defibrillations; which could have precipitated ROSC. Therefore, I reviewed all cases in the study cohort that were coded as having received one or more shocks during the resuscitation. I identified which cases had at least one shock within the first three minutes of CPR quality data capture and I measured the length of the shock pause intervals (pre-, post-, and peri-shock pause). The shock had to have occurred during the time that CPR quality data was collected because I was interested in the effect of the shock pause on the compression fraction calculated. Where there was more than one shock that occurred during the first three minutes of CPR quality data capture, I combined the data from all shocks to obtain an indication of the total time spent delivering shocks during that time. The results are presented in Table 13 grouped by downtime.

Table 13 Total time spent delivering shocks in cases that had at least one shock delivered during the first three minutes of CPR (results grouped by downtime)

	Downtime ≤15 min		Downtime >15 min		Unknown downtime	
	ROSC	No ROSC	ROSC	No ROSC	ROSC	No ROSC
Total number of cases	30	45	15	83	9	20
Number of cases with a shock delivered during the first 3 min of CPR quality data capture	9	6	0	4	0	3
Mean number of shocks during first 3 min of CPR quality data capture	1.2	1.2	0	1	0	1
Total pre-shock pause duration (seconds, mean±SD) ^a	7.2± 4.9	9.0±4.3	-	7.0± 1.4	-	8.3± 7.1
p-value	0.48		- ^b		- ^b	
Total post-shock pause duration (seconds, mean±SD) ^a	5.6±6.0	3.0± 2.2	-	2.8± 2.4	-	8.0± 8.7
p-value	0.34		- ^b		- ^b	
Total peri-shock pause duration (seconds, mean±SD) ^a	13± 10	12± 6.1	-	9.8± 2.6	-	16± 10
p-value	0.87		- ^b		- ^b	

- a) If there was more than one shock delivered during the first three minutes of CPR, we combined the time from all shocks to obtain an estimate of the total time spent on delivering shocks.
- b) It was not possible to derive a p-value for these two groups.

From this table we see that none of the patients in the group with a downtime of greater than 15 minutes who achieved ROSC received a shock during the first three minutes of CPR quality data capture. Importantly, we confirm that the lower compression fraction seen among those who achieved ROSC in the group with a downtime of greater than 15 minutes was not due to the fact that more time was spent delivering defibrillations. These results are summarised in a Letter to the Editor (Appendix 6) that was accepted for publication in *Resuscitation*.

I also derived mean pre-, post-, and peri-shock pause using data from up to the first three shocks,⁸⁴ regardless of whether the shocks occurred within the first three minutes of resuscitation or after. I then sought to determine whether a significant difference was observed between patients with and without ROSC in each downtime group, and, if so, I sought to adjust for shock pause duration in the subsequent multivariable logistic regression analyses (after checking for collinearity). Similarly to Cheskes et al.⁸⁴ I selected the pause with the longest duration to include in the univariate analyses. My results are shown in Table

14. I did not find a significant difference in shock pause duration between those with and without ROSC in any of the downtime categories. Therefore I did not modify my logistic regression models to adjust for this metric.

Table 14 Comparison of the longest pre-, post- and peri-shock pause between patients with and without ROSC in each of the downtime categories. Includes data from up to the first three shocks

	≤15 min		>15 min		Unknown	
	ROSC	No ROSC	ROSC	No ROSC	ROSC	No ROSC
Total number of cases	27 ^a	42 ^a	15	81 ^a	7 ^a	19 ^a
Number of cases with a shock delivered ^b	17	13	4	10	2	8
Mean±SD (longest) pre-shock pause ^c	9.76± 1.15	9.85± 1.66	10.0± 0.91	13.0± 1.76	10.0± 4.00	11.4± 3.07
p-value	0.97		0.32		0.84	
Mean±SD (longest) post-shock pause ^c	4.76± 1.32	4.00± 0.41	4.00± 0.71	3.10± 0.69	2.50± 0.50	3.25± 0.75
p-value	0.63		0.47		0.65	
Mean±SD (longest) peri-shock pause ^c	14.5± 1.78	13.7± 1.57	14.0± 1.58	15.7± 2.00	12.0± 4.00	14.1± 3.23
p-value	0.74		0.62		0.77	

- a) Where shock pause duration could not reliably be determined from the compression waveform or ECG plot, or where a shock was documented on the patient record but did not appear on the ECG, the case was excluded from the total number of cases.
- b) Number of cases that had at least one shock delivered during the resuscitation effort, and the length of the pre-, post- and peri-shock pause could be derived from the compression waveform or the ECG plot.
- c) The duration of the longest shock delivered, measured from up to the first three shocks.

In the above mentioned analysis, in some cases it was difficult to accurately derive the length of shock pauses because no compression data was collected adjacent to the time that a shock was delivered. Sometimes however, pre-, post- and peri-shock pause could be estimated from the ECG plot if compressions were clearly distinguishable on the ECG. In other cases however it was not possible to determine when compressions started and stopped from the ECG. In this scenario, the case was excluded from the study cohort. In Table 14 there were eight cases that were excluded for this reason, in addition to three cases that were excluded because a shock was documented on the patient care record but no shock was visible on the ECG.

7.4 Summary

This study sought to investigate whether CPR quality was associated with OHCA patient survival outcomes in the cohort of patients who had resuscitation commenced by SJA-WA paramedics using the Q-CPR device. I found that concurrently having compression depth, compression rate and compression fraction in compliance with international resuscitation guidelines was not significantly associated with survival outcomes. While my sample size only comprised 341 cases, a much larger study by Cheskes et al. of 19,568 defibrillator records revealed similar findings.¹²⁷ Neither compression depth nor compression rate were individually associated with survival outcomes in my study. Chest compression fraction however was significantly and inversely associated with ROSC. Sensitivity analyses using the first 3 and 5 minutes of resuscitation episode data generated similar results.

I likewise investigated the relationship between the three other CPR quality metrics (duty cycle, leaning and ventilation rate) and survival outcomes. Due to word limitations imposed on the manuscript I did not publish my findings but instead describe them here. Using multivariable logistic regression analysis, the CPR quality metrics were entered into the model as continuous variables. After adjusting for the so-called Utstein covariates^{25, 95} and other CPR quality metrics, I found no significant relationship between duty cycle and either ROSC or STHD (aOR: 1.00, 95% CI: 0.91, 1.09 and aOR: 0.87, 95% CI: 0.67, 1.12 respectively). I also found no significant relationship between the proportion of compressions with leaning and either ROSC or STHD (aOR: 0.99, 95% CI: 0.97, 1.003) and aOR: 0.96, 96% CI: 0.91, 1.003 respectively). I did however find a significant relationship between ventilation rate and both ROSC and STHD (aOR: 1.11, 95% CI: 1.02, 1.22 and aOR: 1.58, 95% CI: 1.19, 2.09 respectively). However I lacked confidence in the accuracy of the ventilation rate readings and suspected that perhaps patient respirations following ROSC were being registered as administered ventilations leading to the erroneous detection of a relationship (see Section 6.5.6). As seen in my previous systematic review,⁸⁶ other studies did not report a significant relationship between ventilation rate and survival in OHCA. Furthermore hands-only CPR has been encouraged among lay rescuers, as a lack of administered ventilations has not been linked to detrimental effects on survival in adults. I repeated the previously-described logistic regression analyses investigating the relationship of compression depth, compression rate and/or compression fraction with survival outcomes, while adjusting for duty cycle, leaning and ventilation rate, and found that this did not change the significance of the results reported in the manuscript.

I also further investigated the significant relationship detected between CCF and ROSC. As described in Section 7.3, I found that this appeared to vary with downtime and was not

linked to the early administration of defibrillations. Overall these findings provide justification for further research into whether a uniform CCF recommendation is appropriate for all patients, or whether a more personalised approach is required. I also recommend that similar research be undertaken using a larger cohort of patients. In my study the usage of the Q-CPR device among SJA-WA paramedics was lower than initially anticipated; the potential reasons for this are explored in Chapter 8.

Chapter 8 Paramedic-reported barriers towards the use of the Q-CPR

8.1 Overview

In July 2014, SJA-WA introduced the Q-CPR feedback device into all metropolitan emergency ambulance vehicles. It was prescribed for use in all attempted resuscitations of patients aged eight years or older where the LUCAS mechanical chest compression device had not already been applied to the patient. Initial usage rates were as high as 43% during the first month of its introduction, however they gradually dropped, reaching as low as 11% in April 2015 (Figure 29).

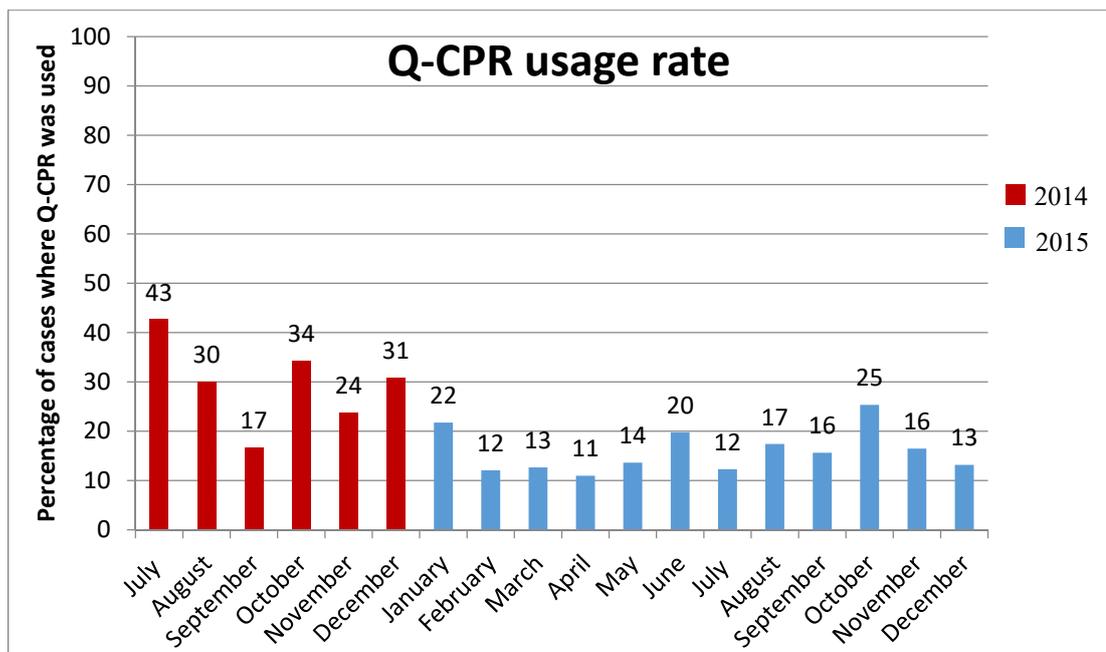


Figure 29 Percentage of cases where Q-CPR was used from among those where resuscitation was attempted by paramedics in the Perth metropolitan area (July 2014 to December 2015)

To ascertain why Q-CPR use was much lower than expected, I worked with SJA-WA to develop a survey for completion by paramedics. The survey was distributed as an anonymous and voluntary hard copy document to a convenience sample of SJA-WA paramedics who were participating in clinical refresher and research training courses between September and December 2015. The survey comprised 11 questions (see Appendix 7) and sought to identify potential barriers preventing widespread use of the Q-CPR device

within the ambulance service. I conducted the data analysis for all survey responses. The results are discussed in the following manuscript that was published in the Journal of Paramedic Practice in 2016.

Talikowska M, Tohira H, Brink D, Bailey P, Finn J. Paramedic-reported barriers towards use of CPR feedback devices in Perth, Western Australia. Journal of Paramedic Practice. 2016; 8:597-606.

The journal's copyright policy allows for only the unformatted version of the final accepted manuscript to be included in this thesis. Additional supplementary material associated with this article is included in Appendix 7.

8.2 Manuscript

TITLE: PARAMEDIC-REPORTED BARRIERS TOWARDS USE OF CPR FEEDBACK DEVICES IN PERTH, WESTERN AUSTRALIA

ABSTRACT

Feedback devices for cardiopulmonary resuscitation (CPR) have been introduced across a number of emergency medical services (EMS) worldwide with the intention of increasing the provision of high quality CPR. In July 2014, St. John Ambulance Western Australia (SJA-WA) introduced the Q-CPR™ device into mandatory clinical practice; however usage rates were lower than expected.

Methods: A voluntary, anonymous survey was issued to a convenience sample of SJA-WA paramedics from September to December 2015 to determine the paramedic-reported barriers towards the use of Q-CPR.

Results: Of the 264 paramedics who participated in the survey, 41% reported having used Q-CPR during their last attempted resuscitation. Among those who had not used it, the reason most commonly cited (37%) was that a mechanical chest compression device arrived on scene prior to the Q-CPR being deployed. Secondly, other interventions were prioritized above the use of Q-CPR (20%). Thirdly, pain associated with use of the Q-CPR prevented its utilization in 17% of cases. Other reasons were less frequently reported.

Conclusion: Lower usage rates appeared to be primarily linked to the utilization of other equipment and interventions in preference to the Q-CPR and to a lesser extent due to pain associated with the use of such devices.

KEYWORDS: cardiopulmonary resuscitation; emergency medical services; heart arrest; quality improvement; feedback.

1 INTRODUCTION

2 High quality cardiopulmonary resuscitation (CPR) has been linked to improved survival
3 outcomes for cardiac arrest patients (Babbs et al., 2008, Christenson et al., 2009, Idris et al.,
4 2015, Kramer-Johansen et al., 2006, Stiell et al., 2014, Sutton et al., 2014, Vadeboncoeur et
5 al., 2014, Perkins et al., 2015b, Perkins et al., 2015a, Talikowska et al., 2015). To promote
6 the delivery of high quality CPR by healthcare professionals, a number of Emergency
7 Medical Services (EMS) worldwide have introduced CPR feedback devices into routine
8 clinical use. An example of one such device is the Q-CPR™ developed by Laerdal Medical
9 and Philips Healthcare. It comprises a force sensor and an accelerometer, and, placed
10 underneath the hands of the rescuer, it delivers both visual and (optional) auditory feedback
11 to the user in real-time about their CPR performance. Specifically it provides feedback on
12 parameters such as compression depth, compression rate, adequate chest recoil and time
13 without compressions ('hands-off time'). In addition, information about ventilation rate is
14 captured by measuring transthoracic impedance using the multifunction defibrillation pads
15 (Laerdal Medical Corporation, 2016, Philips Healthcare, 2011).

16 In July 2014, St. John Ambulance Western Australia (SJA-WA) introduced Q-CPR as a
17 mandatory tool for all metropolitan ambulance crews to use when attempting to resuscitate
18 victims of out-of-hospital cardiac arrest (OHCA). Initial usage rates were as high as 43% of
19 attempted resuscitations within the first month, however they gradually declined, dropping
20 to 13% in December 2015. The reasons for this were not clear. In the literature there are
21 limited reports that shed light on the possible reservations of clinical staff towards using
22 such devices. One study of a helicopter EMS (HEMS) in Turku, Finland, found that among the
23 eight physician respondents, the most common reason cited for not having used CPR

24 feedback was that the Q-CPR device had not been transported to the scene (Sainio et al.,
25 2013). In another study by Perkins et al. (2005) hand and wrist pain was frequently reported
26 by participants using the CPREzy™ feedback device during simulated cardiac arrest. Similarly
27 van Berkomp et al. (2008) stated that CPR feedback had been associated with rescuer
28 complaints such as of “stiff wrists”. To investigate why Q-CPR implementation rates were
29 low and declining over time, and to identify specific, paramedic-reported barriers towards
30 the usage of CPR feedback devices, SJA-WA issued survey to a sample of the metropolitan
31 ambulance workforce.

32 **METHODS**

33 A voluntary, anonymous survey was distributed to SJA-WA paramedics participating in
34 clinical refresher and research training courses from September 2015 to December 2015.
35 The survey consisted of 11 questions that required participants to either select a binary or
36 multiple choice answer or provide a rating on a five point Likert scale ranging from “strongly
37 agree” to “strongly disagree”. For three questions, free text answers were permitted. A copy
38 of the survey form is available in Appendix A.

39 SJA-WA paramedics of all levels of experience were given an opportunity to participate in
40 the survey, ranging from ‘on-road’ undergraduate paramedic students to senior positions
41 such as that of Clinical Support Paramedic and Area Manager. The survey did not request
42 information that would allow the participant to be identified, such as name, date of birth or
43 staff ID. While hard copies of the survey were distributed and collected by SJA-WA on their
44 premises, data analysis was performed by researchers at the Prehospital, Resuscitation and
45 Emergency Care Research Unit (PRECRU) at Curtin University. Ethical approval was obtained
46 from the Human Research Ethics Office at Curtin University (RDHS-209-15).

47 ***St. John Ambulance WA***

48 SJA-WA is the sole provider of road EMS in Perth, Western Australia. Perth has a population
49 of approximately 2.0 million within a land area encompassing approximately 6418 square
50 kilometers (Australian Bureau of Statistics). At the time of the survey, SJA-WA employed 769
51 paramedics to service this area. Use of the Q-CPR device is mandated in OHCA resuscitations
52 of patients 8 years of age or older, with the exception of those cases where the LUCAS (Lund
53 University Cardiopulmonary Assist System) mechanical compression device is in use (St John
54 Ambulance Western Australia, 2016). Q-CPR devices are carried by all metropolitan
55 ambulance vehicles, whilst the LUCAS device is carried by two on-duty Clinical Support
56 Paramedics and three Area Managers who transport it to the resuscitation scene using a
57 designated support vehicle. Two ambulance vehicles, staffed by two paramedics per vehicle,
58 are dispatched on Priority 1 (lights and sirens) to every OHCA. A Clinical Support Paramedic
59 or Area Manager also attends all attempted resuscitations.

60 ***Data analysis***

61 Sample size calculations showed that 257 responses were required in order to produce an
62 error margin of 5% (Australian Bureau of Statistics - National Statistical Service, 2015).
63 Descriptive tables and figures were generated in Stata SE13.1 (StataCorp LP, College Station,
64 Texas USA) or Microsoft Excel Version 14.0.7166.5000 (Microsoft Corporation, Redmond,
65 Washington, USA). Stata was used to perform chi-squared tests where comparisons were
66 made between groups of respondents. All statistical tests were assessed at the 5% level of
67 significance.

68 **RESULTS**

69 ***Description of respondents***

70 There were 264 survey responses received, representing an estimated response rate of over
71 80% of those paramedics who were given the opportunity to participate. Respondents' level
72 of experience ranged from 'Student' to 'Level 3' Paramedic. In total 255 respondents
73 (96.6%) were qualified career paramedics, six respondents were undergraduate students
74 (2.3%) and two were Community Paramedics (0.8%) who provide training, clinical and
75 operational support to volunteer ambulance sub centres. One respondent did not provide
76 identifying information. All respondents are governed by the same requirement for
77 mandatory use of Q-CPR. 'Level 3' paramedic is the highest qualification attainable for SJA-
78 WA paramedics; this group represented 45% of all respondents (n=119). Almost three
79 quarters of respondents (n=190) were male.

80 ***Usage of Q-CPR***

81 Ninety three percent of all respondents (n=246) indicated that they had attended a cardiac
82 arrest within the past year, in other words, within the timeframe during which use of the Q-
83 CPR was compulsory. However, of those, 41% (n=100) reported having used the Q-CPR
84 during their last attempted resuscitation.

85 ***Reasons reported for not having used Q-CPR***

86 The primary reason reported for not having used the Q-CPR was that the LUCAS mechanical
87 compression device had arrived on scene; this was reported in 40 cases (37% of 109 valid
88 responses) (Table 1). The second most commonly reported reason, cited in 22 cases (20%),
89 was that respondents prioritized other interventions such as securing the airway, setting up

90 an intravenous (IV) line or administering therapeutic drugs over use of the Q-CPR. The third
91 most commonly reported reason, cited in 19 cases (17%) was that use of the Q-CPR was
92 associated with pain experienced by the person doing chest compressions. Other reasons
93 were less frequently reported. Valid responses were considered to be those that featured
94 only a single response to question seven instead of having multiple responses selected;
95 nevertheless had multiple responses been permitted, this did not change the distribution of
96 the top three reasons for not having used Q-CPR.

97 ***Anticipating the arrival of the LUCAS device***

98 As stated previously, the arrival of the LUCAS device was the most commonly cited reason
99 for not having used the Q-CPR. In another section of the survey that required respondents
100 to rate their answers on a scale ranging from “strongly agree” to “strongly disagree”, 43
101 respondents (18%) from among the 234 who provided a valid response, agreed or strongly
102 agreed that they would intentionally delay initiating use of the Q-CPR in anticipation of the
103 arrival of the LUCAS device on scene.

104 ***Prioritization of other procedures above use of the Q-CPR***

105 Approximately 60% of respondents agreed or strongly agreed that they would prioritize
106 other interventions over use of the Q-CPR (Figure 1). This does not mean that they would
107 prioritize other interventions over performing chest compressions in general; 235 (96%) of
108 those who provided a valid response rated chest compressions as the first or second most
109 important intervention when managing a confirmed cardiac arrest patient. However the
110 majority would postpone using the Q-CPR device in favor of securing the airway,
111 establishing IV access or administering therapeutic drugs.

112 ***Pain experienced while using the Q-CPR***

113 Over three quarters of respondents (n=190) either agreed or strongly agreed that using the
114 Q-CPR on a manikin during training caused pain (Figure 2). Significantly more women
115 reported pain than men ($\chi^2(2, N=247)=9.7135, p=0.008$). In regards to using the Q-CPR on a
116 patient, 141 (62%) either agreed or strongly agreed that it caused pain. Again significantly
117 more women agreed or strongly agreed than men ($\chi^2(2, N=227)=6.3625, p=0.042$). A
118 sensitivity analysis was performed to compare responses between those who had reported
119 using the Q-CPR during their last attempted resuscitation versus those who had not.
120 Significantly fewer of those who had used the Q-CPR reported experiencing pain compared
121 to those who had not used it ($\chi^2(1, N=221)=5.0503, p=0.025$). Nevertheless 55% (n=53) of
122 respondents who had recently used Q-CPR reported pain.

123 The Q-CPR appeared to cause pain during short as well as long resuscitations; only 49
124 respondents (22%) agreed or strongly agreed that the Q-CPR is only painful during long
125 resuscitations (Figure 2). Approximately half (n=112) either disagreed or strongly disagreed
126 with this statement. In a sensitivity analysis that compared responses between those who
127 had reported having used the Q-CPR during their last attempted resuscitation and those
128 who had not, significantly more of those respondents who had recently used the device
129 agreed or strongly agreed that pain results only from extended use of the Q-CPR ($\chi^2(1,$
130 $N=214)=5.1355, p=0.023$).

131 Of the free text comments that were received at the end of the survey, the largest number
132 were complaints about the current design of the Q-CPR (n=22), together with complaints
133 about pain associated with use of the Q-CPR (n=20) (Appendix B).

134 ***Opinions of quality of own CPR and usefulness of Q-CPR***

135 Over half of respondents (n=142) agreed or strongly agreed that their CPR was already of
136 “good quality” while only 25 respondents (10%) either disagreed or strongly disagreed with
137 this statement (Figure 3). At the same time, 165 respondents (65%) either agreed or
138 strongly agreed that using Q-CPR would help them to ensure that their CPR was of good
139 quality. A total of 123 respondents (49%) found the visual feedback from Q-CPR useful. Only
140 16 respondents (6%) either agreed or strongly agreed that they did not want anybody
141 analyzing the quality of their chest compressions.

142 ***Practical considerations associated with use of Q-CPR***

143 Twenty six percent of respondents (n=60) either agreed or strongly agreed that the Q-CPR
144 slides off the patient’s chest when in use (Figure 4). Twenty eight percent (n=68) either
145 agreed or strongly agreed that their hand easily slips off the Q-CPR when doing chest
146 compressions. Thirty six percent (n=89) agreed or strongly agreed that an additional
147 reminder on the Philips HeartStart MRx defibrillator would prompt them to use the Q-CPR.

148 **DISCUSSION**

149 Although 65% of respondents agreed or strongly agreed that using Q-CPR would help them
150 ensure that their CPR is of good quality, implementation rates fell notably short of this
151 number. Rates were comparable to those reported by Sainio et al. (2013) for the helicopter
152 EMS in Finland, where, over a period of 18 months, Q-CPR was used in 28% of attempted
153 resuscitations. In the case of SJA-WA, survey results revealed that the most frequently
154 reported reason for its non-use was its lower prioritization in the OHCA response algorithm
155 by respondents compared to other equipment and other interventions.

156 Specifically, the primary reason reported for not having used the Q-CPR during respondents'
157 last attempted resuscitation was that the LUCAS device arrived on scene. The SJA-WA
158 dispatch model for OHCA in Perth recommends that two ambulance vehicles are dispatched
159 on Priority 1 to the scene, subsequently joined by one of two on-duty Clinical Support
160 Paramedics or one of three Area Managers who arrive on Priority 1 with the LUCAS device.
161 There can therefore be a delay between the arrival of the first dispatched crew, who will
162 likely have been the closest available crew, and the Clinical Support Paramedic or Area
163 Manager (carrying the LUCAS device) who could have been located anywhere within either
164 the northern or the southern metropolitan area. Since all metropolitan ambulance vehicles
165 carry the Q-CPR, in many cases an opportunity exists for crews to initiate use of the Q-CPR
166 prior to the arrival of the LUCAS. In addition, SJA-WA records indicate that the LUCAS device
167 was deployed in less than half (approximately 40%) of attempted resuscitations; it is
168 primarily indicated for use by SJA-WA during the transportation of patients. Therefore it
169 appears that some respondents may be missing an opportunity to apply the Q-CPR early in
170 the resuscitation, prior to the arrival of the LUCAS.

171 The second reason most commonly reported for not having used the Q-CPR was that
172 respondents prioritized other interventions, such as the administration of therapeutic drugs,
173 setting up an IV line or securing the airway, over use of the Q-CPR. In fact approximately
174 60% of respondents agreed or strongly agreed that they would prioritize such interventions
175 over use of the Q-CPR. While there is evidence that high quality CPR, in particular
176 compressions of adequate depth and rate improves survival (Idris et al., 2015, Stiell et al.,
177 2014, Vadeboncoeur et al., 2014), there is limited clinical evidence that other interventions
178 such as the administration of adrenaline or the application of an advanced airway increase

179 patient survival (Soar et al., 2015). Therefore earlier use of CPR feedback devices in the
180 resuscitation effort should be promoted.

181 While approximately two thirds of respondents reported that the Q-CPR would help them to
182 ensure that their CPR was of good quality, over half already considered their CPR to be of
183 good quality. Without the automated measurement of CPR quality during resuscitation it is
184 difficult to confirm whether this is true. Reports in the literature demonstrate that CPR
185 quality is often suboptimal, even among trained rescuers (Wik et al., 2005, Abella et al.,
186 2005). In regards to the measurement of CPR quality, only 6% of respondents expressed
187 concern with having their CPR quality analysed. Nevertheless, if respondents already
188 considered their CPR to be of good quality, this may have influenced the priority placed on
189 using the Q-CPR.

190 Over three quarters of respondents reported experiencing pain while using Q-CPR during
191 training and over 60% while using Q-CPR on a patient. The latter figure was reduced when
192 considering only those respondents who explicitly reported having used the Q-CPR during
193 their last attempted resuscitation, suggesting that Q-CPR may not be as painful in real
194 arrests as paramedics would extrapolate from training. Nevertheless over half of those who
195 had recently used the Q-CPR on a patient reported pain (55%). In an evaluation of the
196 CPREzy™ feedback device during simulated cardiac arrest, Perkins et al. (2005) found that
197 95% of participants reported discomfort in the heels of their hands and wrists. In addition,
198 one participant sustained a soft tissue injury as a result of using the device. Similarly in a
199 study by Zapletal et al. (2014) one participant sustained an injury when using the CPR
200 meter™. In another study, van Berkomp et al. (2008) sought to determine whether using the
201 CPREzy™ required any additional force compared to standard chest compressions
202 performed without a feedback device. The investigation was carried out as a result of

203 rescuer complaints of stiff wrists, as well as the perceived requirements for more force and
204 increased rescuer fatigue. Results indicated that no additional force was required to achieve
205 a given depth when using CPREzy™ however 21-26.5% more work was required to
206 compress the CPREzy in addition to compressing the chest wall. In the SJA-WA survey, while
207 a notable number of respondents reported experiencing pain when using the Q-CPR, less
208 than one fifth reported this as the primary reason for not having used Q-CPR in their last
209 attempted resuscitation. This suggests that most respondents would still consider using Q-
210 CPR despite the discomfort that might be associated with its use.

211 One common feature of the above-mentioned CPR feedback devices that potentially could
212 have contributed to the reporting of pain is a bulky and rigid design. In the free text
213 comment section of the SJA-WA survey, there were several instances of paramedics calling
214 for a flatter, wider or more flexible design. A change in design could potentially improve the
215 comfort profile of the device, as well as minimizing the occurrence of other usability issues
216 such as the feedback device sliding off the patient's chest or the rescuer's hand sliding off
217 the device. Ideally such a design should be achieved without compromising on data
218 accuracy or ease of recording.

219 Finally, although high quality CPR has been shown to be associated with improved patient
220 survival (Idris et al., 2015, Stiell et al., 2014, Vadeboncoeur et al., 2014, Christenson et al.,
221 2009, Perkins et al., 2015a, Perkins et al., 2015b) the link between the use of CPR feedback
222 devices specifically and improved patient survival has not been well established (Perkins et
223 al., 2015a, Perkins et al., 2015b). Therefore the European Resuscitation Council Guidelines
224 for Resuscitation 2015 call for CPR feedback or prompt devices during CPR to only be
225 considered as part of a broader system of care that should include comprehensive CPR

226 quality improvement initiatives rather than as an isolated intervention (Perkins et al.,
227 2015a).

228 **Limitations**

229 The survey represented approximately one third of the SJA-WA paramedic workforce. In
230 addition, only those who participated in refresher or research training programs were given
231 the opportunity to partake in the survey. However, all paramedics are required to attend
232 these training programs and therefore there is minimal risk of selection bias. While the
233 responses of undergraduate paramedic students were included in the results, they
234 represent 2.3% of all respondents and are governed by the same requirement to use Q-CPR
235 during a resuscitation as qualified paramedics. This survey represents the personal opinions
236 and experiences of paramedics; there has been no quantitative measurement of pain scores
237 nor any form of objective measurement in relation to the use of the Q-CPR in this study
238 apart from the tracking of usage rates. Only SJA-WA paramedics were surveyed, and as such
239 the results may not be transferrable to other EMS in other locations.

240 **CONCLUSION**

241 Lower usage rates of the Q-CPR feedback device by SJA-WA paramedics within the Perth
242 metropolitan area appeared to be primarily attributable to respondents assigning Q-CPR a
243 lower prioritization within the OHCA response algorithm relative to other devices and
244 interventions; and secondly due to pain experienced by paramedics when using the device.
245 Pain was a frequent complaint among respondents both during training and when Q-CPR
246 was used on a patient, however it did not appear to be the primary driver of paramedics'
247 reservations towards using the device. While CPR feedback devices have the potential to

248 improve CPR quality, their widespread uptake may be limited by the above-mentioned
249 factors.

250 **DECLARATION OF INTEREST**

251 Deon Brink is the Executive Manager Clinical Governance at SJA-WA. Paul Bailey is the
252 Clinical Services Director at SJA-WA. Judith Finn receives research funding from SJA-WA.

253 The authors alone are responsible for the content and writing of the paper.

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259 **KEY POINTS**

260 CPR feedback devices, while having the potential to improve CPR quality among trained
261 responders, may encounter hurdles to their clinical implementation. In the case of SJA-WA
262 survey respondents, high usage rates were limited by a lower prioritization of CPR feedback
263 devices by rescuers compared to other equipment and interventions. To a lesser extent,
264 usage rates were also hindered by concern over hand and wrist pain that was frequently
265 reported by the respondents. If used, CPR feedback devices should be employed early in the
266 resuscitation and as part of a comprehensive system of care for cardiac arrest.

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Table 1: Reasons reported for not having used the Q-CPR during last attempted resuscitation, distributed as per question 7 of the survey (n=109)

Reason reported	Number of responses	Percentage of responses
Clinical Support Paramedic or Area Manager arrived with the LUCAS device	40	37%
We saw other procedures as a priority	22	20%
Q-CPR causes pain to the person doing chest compressions	19	17%
Worried about damage to the patient's chest	2	2%
"Other"(variety of other reasons)	26	24%

FIGURES

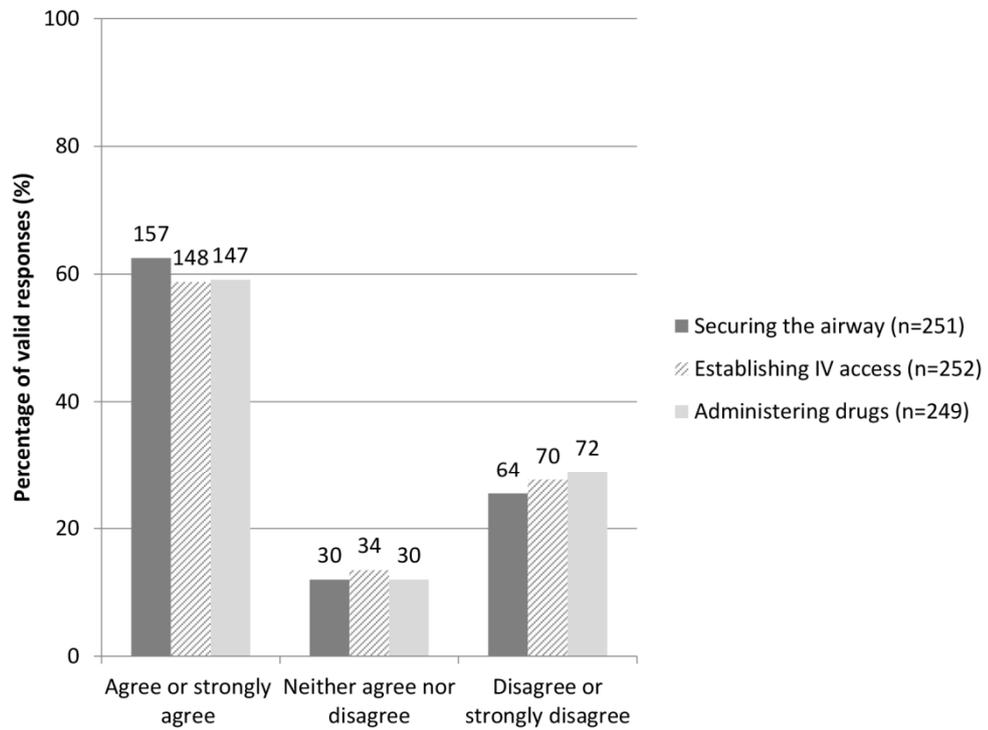


Figure 1: Respondents' opinions on the prioritization of other interventions above use of the Q-CPR feedback device in the OHCA response algorithm. Numbers above the column represent the number of valid responses for the category described on the x-axis. Numbers shown in brackets on the right represent the total number of valid responses.

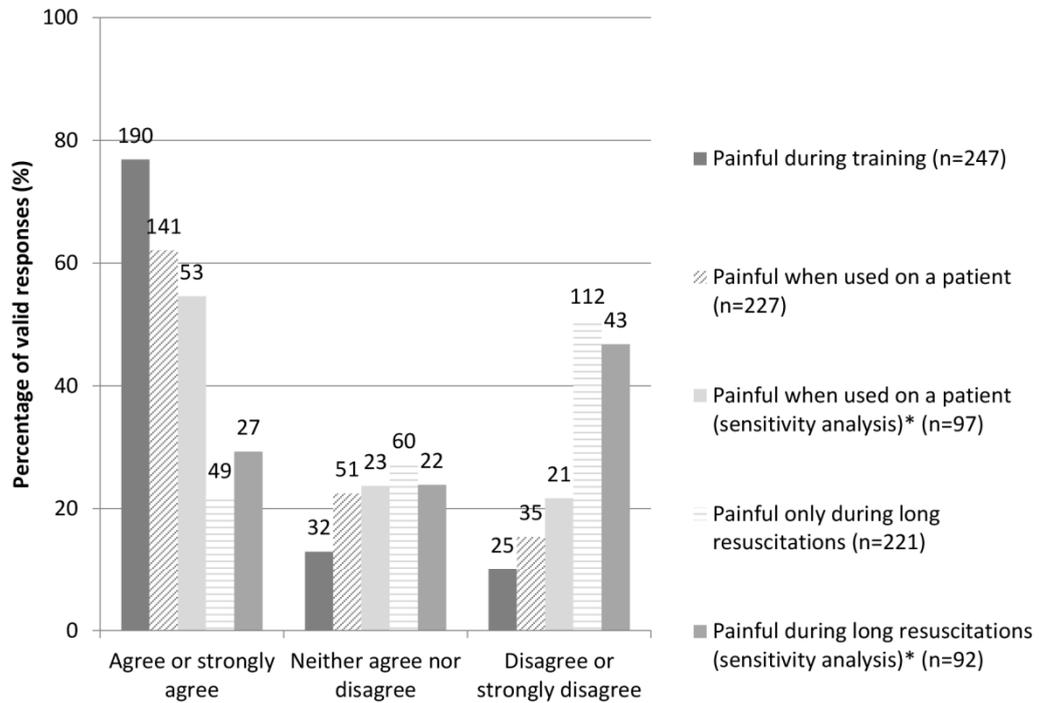


Figure 2: Reports of pain associated with the use of the Q-CPR feedback device. A sensitivity analysis was performed (*) that included only those respondents who had reported having used the Q-CPR during their last attended resuscitation. Numbers above the column represent the number of valid responses for the category described on the x-axis. Numbers shown in brackets on the right represent the total number of valid responses.

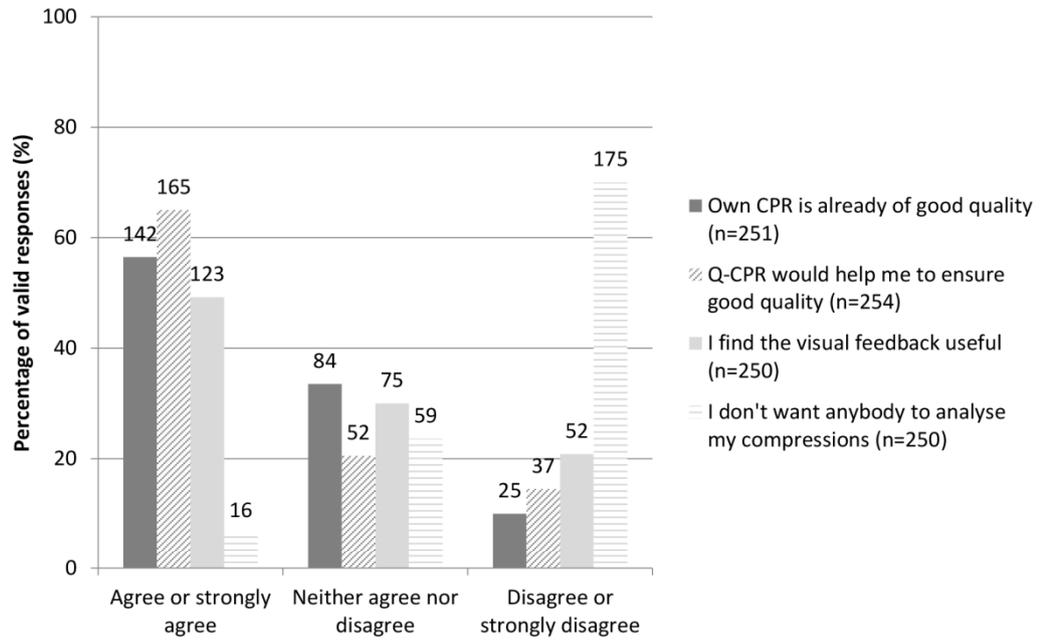


Figure 3: Respondents' opinions of the quality of their own CPR and the usefulness of Q-CPR feedback device. Numbers above the column represent the number of valid responses for the category described on the x-axis. Numbers shown in brackets on the right represent the total number of valid responses.

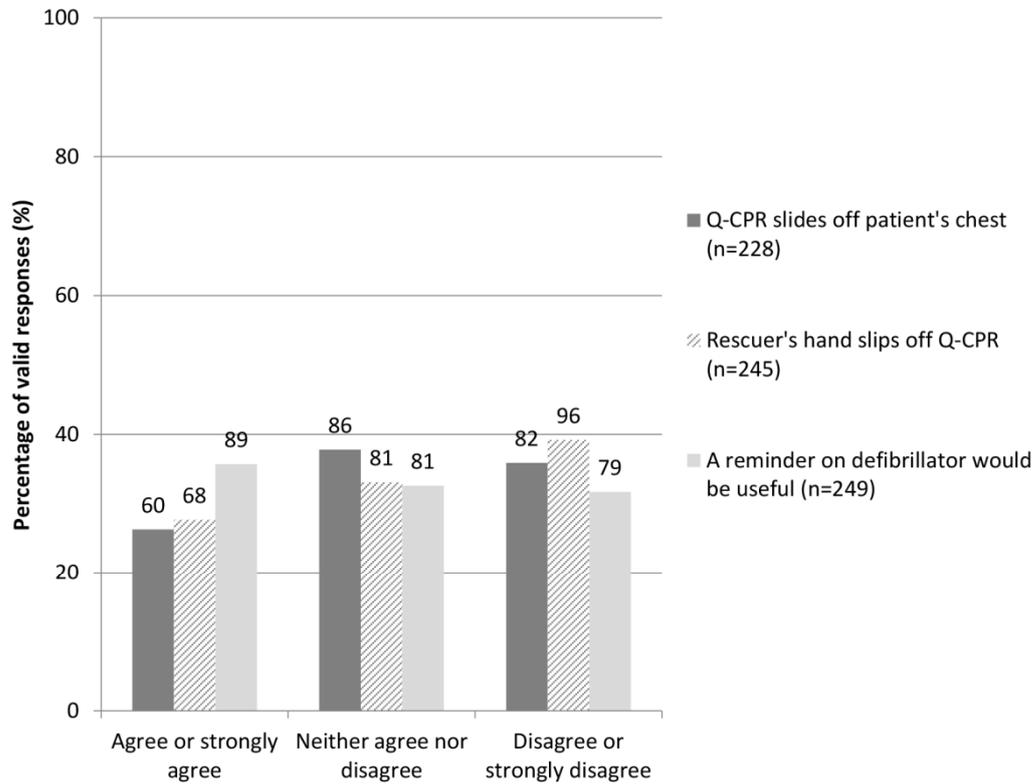


Figure 4: Summary of responses relating to practical considerations associated with the use of the Q-CPR feedback device. Numbers above the column represent the number of valid responses for the category described on the x-axis. Numbers shown in brackets on the right represent the total number of valid responses.

8.3 Summary

This survey of SJA-WA paramedics revealed that the most frequently reported reason for the lower-than-expected usage rate of the Q-CPR device was that paramedics did not see this device as a key component of the OHCA response algorithm; and instead prioritised other procedures and interventions over its use. Many respondents reported that the LUCAS device arrived on scene prior to the Q-CPR being deployed; the LUCAS device is a contraindication to the use of the Q-CPR device. Approximately 60% of respondents agreed or strongly agreed that they would prioritise interventions such as intubation, IV insertion and the administration of drugs over the use of the Q-CPR. Hand and wrist pain, which had been hypothesised to be a major contributor accounting for the device's limited use, was cited in only 17% of cases as the primary reason for non-use. The results of the survey were detailed into a comprehensive report that was prepared for SJA-WA, as well as being published in the Journal of Paramedic Practice. The findings of this survey have contributed to the final set of recommendations outlined in Chapter 9.

Chapter 9 Discussion and Conclusions

The primary purpose of this research was to examine the relationship between the quality of CPR performed by paramedics and survival outcomes from OHCA. Specifically this was done in the context of Perth, Western Australia, where St John Ambulance WA is the sole provider of road ambulance services. I begin my Discussion with a summary of the key work undertaken. I then discuss the interpretation of my findings, within a context of recent literature. I discuss the limitations of my research and propose a direction for future research. Finally I use the insights from my research to provide a set of recommendations for SJA-WA.

9.1 Summary of key work undertaken

9.1.1 Systematic review

Aim 1: To synthesise the reported evidence regarding the association between CPR quality and cardiac arrest patient survival outcomes

A systematic review of the literature was undertaken to determine whether individual CPR quality metrics were associated with cardiac arrest survival outcomes (ROSC, STHD and neurologically intact survival). I searched across five databases and the grey literature to identify 8,842 unique citations, of which 22 were found to be relevant. Sixteen papers exclusively related to OHCA, five to IHCA and one to both OHCA and IHCA cases. Where statistical heterogeneity permitted ($I^2 \leq 75\%$) I conducted meta-analyses for each individual CPR quality metric. I found that deeper chest compressions were significantly associated with both ROSC and STHD; the mean difference (MD) in those patients with and without ROSC was 0.99 mm, 95% CI: 0.04, 1.93, while the MD between those who did and did not survive to hospital discharge was 2.59 mm, 95% CI: 0.71, 4.47. Within the range of 100-120 cpm, a lower compression rate appeared to favour survival: MD -1.17 cpm, 95% CI: -2.21, -0.14. Results for compression fraction varied largely between studies, however a higher compression fraction appeared to be associated with survival in cases with a shockable initial rhythm. Pre- and post-shock pause was also found to be associated with survival in two studies.^{83, 84} I could not draw strong conclusions about the association of other CPR quality metrics with survival outcomes because there were too few studies that included these analyses, and among those that did, there was heterogeneity between studies in the reporting of results.

9.1.2 Review of methods

After reviewing the relationship between CPR quality (as measured using various devices) and survival outcomes reported in the literature, I sought to examine specific the methods used by these studies that were included in my systematic review⁸⁶ to explore this relationship. In particular I was interested in the length of the data interval used for analysis, the event that marked the start of the analysis interval (for example, the first chest compression or the placement of ECG pads) and the minimum amount of data required for the case to be included in the analysed cohort. I wanted to ensure that the methods used in my subsequent retrospective cohort study would be consistent with those used by other published papers. Among twenty-one studies I found that two thirds analysed data from the start of the resuscitation interval, most commonly the first 5 minutes. The start of the analysis interval was marked by various events including the first recorded compression, the placement of ECG pads on the patient, device activation and the prompt to commence compressions. Two fifths of studies specified a minimum amount of data that had to have been captured for the case to be included in the analysed cohort; most commonly this was one minute of data. I used these findings to inform the methodology for my subsequent study; I chose to analyse data over four different intervals during the resuscitation episode; the first 3, 5 and 10 minutes of CPR as well as all available episode data. I defined the start of the analysis interval as being marked by the placement of ECG pads on the patient. Finally, I required at least one minute of data to have been recorded for the case to be included in the analysed cohort. Further details pertaining to the cohort study are summarised below.

9.1.3 CPR quality among SJA-WA paramedics

Aim 2: To measure the quality of CPR performed by SJA-WA paramedics

I conducted a prospectively collected, retrospectively analysed cohort study of CPR quality data from OHCA cases managed by St John Ambulance Western Australia (SJA-WA) paramedics within the Perth metropolitan area. I included patients aged eight years or older who had had resuscitation attempted by SJA-WA paramedics using the Q-CPR feedback device⁶⁹ during the study period (July 2014-June 2016). From among 341 cases eligible for inclusion, I found that the mean compression rate (114 cpm) was within the 100-120 cpm range recommended by the ERC and AHA resuscitation guidelines.^{9, 10} Mean compression fraction (77.8%) was greater than the minimum 60% specified by guidelines^{9, 10} while 45% of cases had a compression fraction greater than 80%.⁹ Although mean duty cycle (43.0%) was lower than the value of 50% recommended by guidelines,^{9, 10} a number of other studies

also reported a lower duty cycle. The median proportion of compressions that were characterised by leaning was 5.11%; although guidelines advise that leaning should be minimised, they do not specify a value or range of values that would be considered acceptable. Finally mean ventilation rate was 3.98 vpm; this was compliant with the recommended value that was inferred from the guidelines.^{9, 10} Most notably however, mean compression depth (41.8mm) was substantially below the minimum 50mm value recommended by guidelines; 82% of cases had a compression depth that was too shallow. This result is problematic given the abovementioned findings from my systematic review⁸⁶ that deeper compressions were significantly associated with both ROSC and STHD.

9.1.4 CPR quality calculated using various time intervals

The above calculations were carried out using all available episode data. I also compared the CPR quality calculated using the first 3, 5 and 10 minutes of CPR to that calculated using all available data. I did not find a significant difference in the mean compression depth, compression rate, duty cycle or proportion of compressions with leaning. I did however find a significantly higher compression fraction during the first 3 minutes of CPR compared to all available episode data ($p < 0.001$). I also observed a steady increase in ventilation rate over time ($p < 0.001$). However, I suspected that this may have reflected an increase in the number of patients being intubated or that the Q-CPR may have erroneously captured the patient's own respirations as administered ventilations. A surprising finding was the failure to observe an improvement in compression depth over time given that the Q-CPR provides real-time audio-visual feedback aimed at guiding rescuers towards a guideline-compliant range.

9.1.5 The relationship between CPR quality and survival outcomes

Aim 3: To analyse the link between CPR quality and OHCA patient survival outcomes in the study cohort

I used multivariable logistic regression analysis to explore the relationship between CPR quality and survival outcomes in my study cohort. I found that having compression depth, compression rate and compression fraction simultaneously in compliance with international resuscitation guidelines was not associated with improved survival outcome. Assessed alone, only compression fraction was associated with patient outcome; a compression fraction of greater than 80% was significantly associated with decreased odds of ROSC compared to a compression fraction of less than or equal to 80% (aOR: 0.49, 95% CI: 0.28, 0.87). Neither

duty cycle nor leaning were associated with survival outcomes. Although ventilation rate was significantly associated with both ROSC and STHD (aOR: 1.11, 95% CI: 1.02, 1.22 and aOR: 1.58, 95% CI: 1.19, 2.09 respectively), I was cautious to make any interpretations from these findings given that I hypothesised that in some cases the patient's own respirations may have been registered as administered ventilations. My systematic review of the literature also failed to demonstrate a significant association between ventilation rate and survival in human studies.⁸⁶ Furthermore several large observational studies had found that the use of an advanced airway, which facilitates a higher ventilation rate, compared to a bag-mask device was not associated with improved outcomes;^{128, 129} on the contrary, in some cases it was associated with worse outcomes.¹³⁰⁻¹³⁵ Overall however, the significant, inverse relationship between compression fraction and ROSC in my study cohort was a major finding; this was explored in detail in an additional analysis.

9.1.6 Time variation in the relationship between CCF and ROSC

I investigated the significant, inverse relationship between chest compression fraction (CCF) and ROSC in a subsequent analysis. Specifically I observed whether this relationship varied depending on 'downtime' from onset of arrest to delivery of CPR by paramedics. This was prompted by suggestions from other studies that the relationship between CCF and survival outcomes may vary with time;^{98, 136} supported by findings from porcine studies that showed that the deliberate introduction of breaks in compressions during the initial minutes of CPR, either alone or combined with other interventions, was associated with survival benefit.¹⁰¹⁻¹⁰⁴ In the SJA-WA cohort I found that among those patients with a downtime > 15 minutes, those who achieved ROSC has a significantly lower chest compression fraction than those who did not (mean±SD: 73.0±13.0% vs. 83.1±9.38% p=0.002). Furthermore, for patients in this downtime category, the odds of those with CCF>80% achieving ROSC were 93% lower than for those with CCF≤80% (OR: 0.07, 95% CI: 0.01, 0.33). A significant, inverse relationship was not present in those patients who had a downtime of less than or equal to 15 minutes, or for those with an unknown downtime; in these categories all results were non-significant. I investigated whether the lower CCF was linked to more time having been spent on defibrillation, and found that it was not. These findings provide the impetus for further investigation into whether one uniform chest compression fraction recommendation is appropriate for all OHCA patients or, alternatively, whether CCF should be tailored to the individual depending on the characteristics of their arrest, for example, the time between the onset of arrest and receipt of CPR by trained providers.

9.1.7 Barriers towards the use of Q-CPR reported by paramedics

Aim 4: To explore the attitudes of SJA-WA paramedics towards the use of the Q-CPR device in clinical practice

The SJA-WA study cohort comprised 341 cases from among 1,882 that had resuscitation attempted by paramedics during the study period. This reflects an average Q-CPR usage rate of less than 20%. This rate was much lower than anticipated, particularly since the Q-CPR device is carried by all metropolitan ambulance vehicles and it is considered mandatory for use for the majority of resuscitations. To investigate potential reasons for this low usage rate, I worked with SJA-WA to develop a survey which they administered to a convenience sample of its paramedic workforce who were undertaking clinical refresher and research training. I analysed the results of the survey. There were 264 respondents, representing an estimated response rate of over 80% from among the paramedics who were given the opportunity to participate. I found that the primary reason reported for not having used the Q-CPR device was that paramedics prioritised other procedures and interventions over use of the Q-CPR. In particular, 37% reported that the LUCAS mechanical chest compression device arrived on scene prior to the Q-CPR being deployed (these two devices are not compatible). There is generally a delay however between the first paramedics arriving on scene with the Q-CPR and the Clinical Support Paramedic or Area Manager subsequently arriving with the LUCAS device, therefore allowing for the Q-CPR device to be deployed before the LUCAS. Others (20%) prioritised procedures such as setting up an intravenous line, securing the airway or administering therapeutic drugs. This does not indicate that these procedures were prioritised over compressions in general; rather it signifies that the Q-CPR was considered an adjunct that was assigned a lower priority compared to other equipment and interventions. Although hand and wrist pain was frequently reported by survey respondents (ranging from 55% among those who had recently used the Q-CPR on a patient to 77% among those who had used it on a manikin), it was not the primary reason reported for not having used the Q-CPR. It accounted for only 17% of the reported non-use. Other reasons were less frequently reported.

9.1.8 Recommendations

Aim 5: To provide a set of recommendations to SJA-WA on the basis of my research findings

Collectively the abovementioned findings helped to inform the final recommendations outlined at the end of this chapter.

9.2 Suboptimal compression depth

A major finding of the retrospective cohort study was that mean compression depth was too shallow among 82% of cases. Furthermore, the degree by which it was too shallow was notable; the mean for the cohort was 8mm (or 16%) below the minimum recommended value of 50mm. Additionally no improvement in mean depth was observed over time. This prompted consideration of whether or not rescuers were being provided with corrective feedback according to the revised depth target range of 50-60mm. It was hypothesised that the Philips HeartStart MRx monitor/defibrillators with Q-CPR procured by SJA-WA may have been set to a target depth range of 40-50mm as per software version F.01/R.01 and superseded guidelines.¹³⁷ Subsequent software versions (F.02/R.02 and later) feature a minimum depth target of 50mm on a rigid surface and 70mm on a soft surface.¹³⁸ Since being alerted to these findings however, SJA-WA has confirmed that the correct compression depth is programmed into existing devices.

This raises the question of why the Q-CPR device has not been effective in correcting compression depths that are too low. It is possible that even though a visual indicator of compression depth is displayed on the device itself as well as on the HeartStart MRx monitor/defibrillator, paramedics were not actively checking it, and rather were focusing on other aspects of the resuscitation. Generally the device is used in the visual-only mode by SJA-WA paramedics, with the audio prompts disabled. Alternatively it is possible that paramedics were seeing the visual feedback but not responding to the corrective prompts provided – the reason for this is unclear. It is also possible that the design of the device itself may have prohibited adequate compression depth in this cohort. The paramedic survey¹³⁹ revealed that hand and wrist pain associated with the use of the Q-CPR was reported as the third most common reason for not having initiated use of the device. Over three quarters (77%) of respondents reported that the device was painful to use during training and, of those who had used the Q-CPR during their last attempted resuscitation, 55% reported that it was painful to use on a patient. It is possible that either experienced pain or the expectation of pain may have prevented paramedics from achieving adequate compression depth when

using the Q-CPR. Overall the reasons for the failure of the Q-CPR device to correct compression depth underperformance among the SJA-WA cohort is unclear and requires further research. In order to facilitate quality improvement, SJA-WA has recently appointed a senior paramedic to coordinate strategies to improve OHCA outcomes.

9.3 Paramedics' perceptions of CPR quality versus measured CPR quality

The paramedic survey¹³⁹ also demonstrated that over half of respondents (57%) agreed or strongly agreed that their CPR performance was already of "good quality". However, as noted above, measurement of CPR quality using the Q-CPR device revealed that compression depth was too shallow in over 80% of cases. Although we cannot be certain that the compression depth measured using the Q-CPR device is accurately representative of the compression depth routinely provided by all SJA-WA paramedics, it is important that paramedics are made aware of the difference between the perceived quality of CPR and that measured.

9.4 Comparison of the findings from the SJA-WA cohort study to other studies

Below I compare the findings from the SJA-WA retrospective cohort study¹²⁶ in regards to the association between CPR quality and survival to those reported in the systematic review that I previously conducted.⁸⁶ This is done individually for compression depth, compression rate and compression fraction as these were the key CPR quality metrics focused on in both studies.

9.4.1 Compression depth

The systematic review that I conducted⁸⁶ found a significant association between deeper chest compressions and both ROSC and STHD, however analysis of CPR performance among SJA-WA paramedics failed to demonstrate this association. The sample size (n=341) of the SJA-WA cohort study was relatively small compared to some of the studies in the systematic review that reported a significant association (n=9136¹³ and n=592¹⁴). However others with a smaller sample size (n=202,⁵² n=284⁵⁹ and n=24¹¹²) also reported a significant result. I considered whether the low mean compression depth recorded among the SJA-WA cohort could have partially accounted for the lack of significance, however my systematic review⁸⁶ revealed that the mean compression depth among many of the studies that had reported a significant result was comparable to that among SJA-WA paramedics (mean±SD:

41.8±9.17mm for the SJA-WA cohort compared to 41.9±11.7mm reported by Stiell et al.¹³ and 38±6mm by Kramer-Johansen et al.⁵⁹). Finally, I observed that the rate of STHD observed among the SJA-WA cohort (3.5%) was significantly lower than among other studies that found a significant relationship with compression depth (for example, 7.3% noted by Stiell et al.¹³ and 10.6% by Vadeboncoeur et al.¹⁴). I therefore hypothesised that the lower survival rate may have made it more difficult to detect a significant association between STHD and compression depth in the SJA-WA cohort. This does not however explain the lack of significance for the relationship between compression depth and ROSC in the SJA-WA cohort.

9.4.2 Compression rate

The meta-analysis undertaken in my systematic review⁸⁶ revealed a significant association between compression rate and STHD. Within the range of approximately 100-120 cpm survivors demonstrated a lower mean compression rate than non-survivors (MD -1.17 cpm, 95% CI: -2.21, -0.14). I did not however observe the same relationship in the SJA-WA cohort. The sample size of the SJA-WA cohort however (n=341) was notably lower than that among other studies that reported a significant relationship between compression rate and cardiac arrest survival outcomes (n=10,371¹⁵ and n=592¹⁴) which may have explained the reason for my lack of a significant result. The mean±SD compression rate calculated for my study cohort was comparable to that of other studies; 114±10.9 cpm for the SJA-WA cohort vs. 111±19 cpm¹⁵ and 113.9±18.1 cpm¹⁴ among other studies. Again I noted that the rate of STHD was notably lower in the SJA-WA cohort (3.5%) compared to other studies (9.0%¹⁵ and 10.6%¹⁴) which may have contributed to the lack of a significant result.

9.4.3 Compression fraction

In my systematic review⁸⁶ the relationship between compression fraction and survival outcomes could not be examined by meta-analysis due to high statistical heterogeneity between studies ($I^2 > 75\%$). However, individual studies demonstrated marked variability in their reported relationship with survival outcomes. Some papers noted a significant relationship in the positive direction (i.e. that a higher compression fraction was associated with improved odds of survival),⁹⁶ while others found that the inverse was true, namely that survivors had a significantly lower compression fraction than non-survivors prior to^{15, 97} or after adjustment for confounders.¹⁴ These mixed findings prompted me to consider whether compression fraction was uniformly and accurately measured across studies.

9.4.3.1 Length of data interval used for analysis

I hypothesised that compression fraction was the one CPR quality metric that would be most sensitive to variations in measurement interval. The average compression fraction calculated for any case could be notably influenced by whether potentially time consuming interventions such as intubation were included in the measurement window or not, particularly if the measurement window was of a short duration. Similarly it would be difficult to use data from only one to two minutes of the resuscitation episode to extrapolate the compression fraction representative of the whole episode. My second paper⁹³ found that the length of data interval used by studies to explore the relationship between chest compression fraction and survival outcomes varied between a mean of 1.6 minutes to all available episode data. This could perhaps account for some of the variability in the results observed. Therefore in my study, the relationship between ROSC and CCF was calculated using four alternative time intervals, the first 3, 5 and 10 minutes of CPR, as well as all available episode data. It was found that in three out of the four scenarios compression fraction was significantly and inversely linked to ROSC, with the exception of the 10 minute data scenario, where the relationship was not significant. Earlier comparison of 202 cases from the 10 minute dataset matched to 202 cases from the dataset containing all available episode data however revealed no significant difference in mean compression fraction between the two groups.

9.4.3.2 Manual adjustment of data to increase accuracy

Given the varied nature of the results from the literature, I sought to be as accurate as possible in estimating compression fraction in my study. I had suspected that there may have been minor methodological differences between other studies that could have led to differing results. For this reason, I manually reviewed all breaks in compressions of duration 30 seconds or greater to ensure that these were real breaks and not simply breaks in the use of Q-CPR while compressions continued to be delivered. My methodology involved checking the compression waveform against the ECG plot to observe whether compressions were visible on the ECG; further details are provided in Chapter 5. I also checked cases for the inclusion of interference that could have represented moving or unplugging the Q-CPR device or moving the patient at the end of the data collection interval. If I found that it had been included, I removed it from my calculations, along with the preceding break in compressions if appropriate. According to standard practice I also excluded breaks due to ROSC from calculations. In this way I sought to increase the accuracy of my data, in particular the compression fraction metric. Despite my adjustments however, the counter-intuitive, inverse relationship between chest compression fraction and ROSC remained.

9.4.3.3 Review of first monitored rhythm

Given the mixed results of my systematic review⁸⁶ regarding the relationship between chest compression fraction and cardiac arrest survival outcomes, I reviewed the first monitored rhythm among included studies to determine if it could have been associated with the relationship between compression fraction and survival. One study featuring exclusively cases with a shockable initial rhythm found that survivors had a significantly higher compression fraction compared to non-survivors (mean±SD: 56±24% vs. 48±28%; p=0.003). This translated into an adjusted odds ratio of 1.11 (95% CI: 1.01, 1.21) per 10% increase in compression fraction.⁹⁶ Another study of 10,371 patients with varied first monitored rhythms found that survivors had a lower mean±SD compression fraction compared to non-survivors (65±19% vs. 70±17%, p<0.001).¹⁵ A further study of 593 OHCA patients with both shockable and non-shockable first monitored rhythms also found a significant, inverse relationship between CCF and survival with good neurological outcome (aOR: 0.48, 95% CI, 0.28, 0.82).¹⁴ Finally a study by Vaillancourt et al. of exclusively patients with a non-shockable first monitored rhythm found that survivors had a significantly lower compression fraction than non-survivors prior to adjustment for confounders (mean±SD: 62±23% among survivors vs. 68±19% among non-survivors, p=0.04).⁹⁷ From these findings I made the crude observation that chest compression fraction appeared to be positively associated with cardiac arrest survival where there was a high proportion of cases with a shockable first monitored rhythm.⁹⁶ On the contrary when the proportion of cases with a shockable rhythm was lower (0-28.7%),^{14, 15, 97} the relationship between CCF and survival appeared to be inverse (i.e. lower CCF associated with higher survival rates). This prompted me to consider whether compression fraction may be a time-dependent variable modulated by the downtime from onset of arrest to delivery of CPR by paramedics, since the likelihood of encountering a shockable first monitored rhythm is greater with a shorter downtime. However, a North American study by Cheskes et al. published after the publication of my systematic review⁸⁶ reported an inverse relationship among OHCA cases that exclusively had a shockable first monitored rhythm.⁹⁸

9.5 The counter-intuitive relationship between chest compression fraction and ROSC

Similar to that reported in other studies,^{14 98} a significant, inverse relationship between compression fraction and ROSC was identified in the SJA-WA cohort study. This remained after adjusting for covariates, including those that had been shown in another study¹⁷ to convert the inverse relationship to a positive direction. Furthermore, this inverse relationship between CCF and ROSC in the SJA-WA cohort study was observed regardless of whether

the first three or five minutes of CPR or all available episode data was used. Furthermore ANN and CART analyses confirmed that compression fraction was a key predictor of ROSC in the study cohort. The inverse manner of this relationship appears counterintuitive and contrary to the current guidelines for CPR issued by the American Heart Association⁹ and European Resuscitation Council.¹⁰

Interestingly other authors have reported similar findings.^{14, 98} In addition, although it was not explicitly designed to examine the relationship between chest compression fraction and survival, a large, cluster-randomised, crossover trial from the Resuscitation Outcomes Consortium (ROC) investigators of 23,711 OHCA patients found that continuous chest compressions (with positive pressure ventilation) were not associated with a survival benefit compared to compressions that were interrupted for ventilations at a ratio of 30:2.¹⁴⁰ Survival to discharge in the two groups was 9.0% and 9.7% respectively, representing a difference of -0.7 percentage points (95% CI: -1.5, 0.1; $p=0.07$).¹⁴⁰ Clearly the group with continuous compressions should have been characterised by a higher compression fraction compared to the group in which compressions were interrupted to deliver ventilations. Results were similar for survival to discharge with favourable neurological function (7.0% in the group with continuous compressions versus 7.7% in the group with interruptions for ventilations; difference -0.6 percentage points; 95% CI, -1.4, 0.1).¹⁴⁰ Apart from differing significantly on compression fraction (mean \pm SD: 83 \pm 14% versus 77 \pm 14%, $p<0.001$), the groups were otherwise matched on compression depth, rate, pre-shock and post-shock pause, as well as Utstein variables and pre-hospital and hospital treatment factors. In light of these counterintuitive observations, I examined whether there could be a third factor modulating the relationship between compression fraction and survival outcomes.

9.6 Time variation in the relationship between chest compression fraction and ROSC

In an attempt to understand the seemingly counterintuitive relationship between chest compression fraction and OHCA survival, I investigated whether the relationship between CCF and ROSC was time-dependent. While other authors had analysed whether the relationship was influenced by the timing of ROSC⁹⁸ or the duration of EMS-CPR,¹⁰⁰ I focused on whether it showed variation based on the ‘downtime’ from onset of arrest to the provision of CPR by paramedics (as approximated by arrival time on scene). As described in Chapter 5 and Chapter 7, I adopted this approach because a number of animal studies¹⁰¹⁻¹⁰⁴ had shown that the deliberate introduction of breaks in compressions during the initial minutes of CPR in pigs with induced VF arrest and without intervention for 15-17 minutes

was associated with improved outcomes, either individually or in combination with other therapies. I sought to determine whether a similar effect was observed in humans by further analysing the SJA-WA cohort data.

I found that in the group with a downtime greater than 15 minutes, those with ROSC indeed had a significantly lower compression fraction during the first 3 minutes of CPR (corresponding to more breaks in compressions) compared to those without ROSC. This was not true for those patients who received ambulance care within 15 minutes post arrest, or for the unknown cases. Similarly, among those in the group with a downtime of greater than 15 minutes, those with a compression fraction $> 80\%$ had significantly lower odds of achieving ROSC compared to those with a downtime $\leq 80\%$. Common sense would suggest that those with longer breaks may have seen greater rates of ROSC because the patient was in a shockable rhythm and therefore more time was spent defibrillating the patient. However I did not find this to be the case.

A recent study published by Matsuura et al.¹⁴¹ proposed the potential mechanism for the survival benefit observed with post conditioning in pigs. Based on an analysis of mitochondria extracted from the hearts and brains of pigs subject to prolonged (15 minute) cardiac arrest, the deliberate introduction of breaks in compressions during the early minutes of CPR attenuated the cardiac mitochondrial dysfunction caused by cardiac arrest, however had limited effect on mitochondria in the brain.¹⁴¹ This effect on the heart mitochondria could perhaps explain the improvement in ROSC observed among the SJA-WA cohort. The lack of an improvement in brain mitochondria could perhaps have contributed to the failure to see an improvement in STHD among the SJA-WA cohort. The authors of the porcine study¹⁴¹ however noted that in their study the follow-up post-arrest was short and the potentially neuroprotective effects of post conditioning could take effect after several hours.

Both the findings from the SJA-WA cohort study and those of the abovementioned animal studies¹⁰¹⁻¹⁰⁴ provide reason for further investigation into whether one uniform approach to resuscitation is appropriate for all victims of cardiac arrest. It is not unreasonable to hypothesise that the treatment of most benefit to patients may differ depending on where they are in the time-dependent cascade of ischemic injury. This cascade has previously been described in detail by other authors,^{142, 143} and initiates with a shortage in the supply of oxygen and glucose to cells, leading to a decrease in available adenosine triphosphate (ATP). ATP is used by cells to power specific pump proteins in the cell membrane (Na^+/K^+ - ATPases) that transport the sodium ion (Na^+) out of the cell against its concentration gradient. When this pump is de-activated, it allows for the influx of large amounts of Na^+ . This is accompanied by an influx of Ca^{2+} ions. This leads to cell swelling and necrotic cell

death. In a 2002 publication, Safar et al.¹⁴⁴ explained that in sudden cardiac arrest glucose and ATP stores are used up within five minutes. My interpretation of this, in the context of other literature that describes the benefits of ischaemic post conditioning,¹⁰¹⁻¹⁰³ is that the approach to resuscitating patients who have been without circulation for a shorter period of time (for example, less than five minutes) may differ to that used for those who have been without circulation for a longer period of time. For example, patients with a downtime of less than five minutes may benefit most from an immediate, continuous restoration of circulation because in these patients the ischemic injury cascade has not progressed as far. Associated with this, they may benefit from a higher chest compression fraction. On the other hand, for patients with a longer downtime, the cascade may have progressed further to the point where there are reactive oxygen species (ROS) being generated, leading to cell damage. Continuous reperfusion at this time may lead to increased cell death as a result of increased ROS production facilitated by increased oxygen supply. Reperfusion injury has been well documented during percutaneous coronary intervention (PCI), and ischaemic post conditioning has been proposed as one mechanism to reduce ischemic injury in that sphere.^{106, 145, 146} The same may be true in cardiac arrest. However it would be difficult to determine the time point when ischemic post conditioning (or a lower chest compression fraction) may become beneficial without knowing the specifics of the ischemic injury cascade in human cardiac arrest.

As far as I am aware, the research described in this thesis represents the first documented attempt to study effects analogous to ischemic post conditioning in human cardiac arrest, as all previous studies have been in animals. Despite this, my investigation of this issue was subject to several limitations.

9.7 Limitations

Some of the limitations of my doctoral research are discussed below.

Given the observational nature of my retrospective cohort study, it was inherently at risk of confounding. Furthermore I lacked sufficient information to adjust for in-hospital treatments such as targeted temperature management in the logistic regression analyses. Therefore I cannot prove causality for any of my findings, only posit an association.

My study was carried out using data collected from OHCA that occurred in the Perth metropolitan area during the study period, therefore it cannot be guaranteed that the associated findings would be transferrable to other locations and other EMS agencies. Differences in many factors such as the rate of bystander CPR, the comprehensiveness of

public access defibrillation programs and the baseline levels of CPR quality present among EMS rescuers in different geographical locations may result in different relationships being observed among variables and outcomes.

The rate of STHD seen among the SJA-WA study cohort was significantly less than that seen among OHCA cases that had resuscitation attempted without the use of the Q-CPR device during the study period (3.5% vs 11.6%; $p < 0.001$). A similar phenomenon was observed for good neurological outcome at discharge (although the percentage of those patients who survived to hospital discharge who had good neurological outcomes was similar in both groups). This may be attributable to a number of factors such as the significantly greater proportion of unwitnessed cases among the study cohort (66% vs. 59%, $p=0.02$) and the greater number of arrests that occurred in a residential premise (79% vs. 73%, $p=0.02$). These characteristics are traditionally associated with lower rates of survival. Additionally, the study cohort would not have included those patients who were shocked early and established a perfusing rhythm before any Q-CPR data was collected. The results of the SJA-WA paramedic survey¹³⁹ indicate that respondents generally placed a low priority on the use of the Q-CPR device in the resuscitation algorithm, preferring to prioritise other procedures and interventions. The marked difference in survival could also potentially be indicative of selection bias among paramedics. It is possible that paramedics selected to use the Q-CPR on patients that they perceived to have lower chances of survival and/or those that were treated in a private residence. However these suggestions are hypothetical. The included and excluded cohorts did not differ significantly on the other Utstein variables, such as age, sex, medical cause of arrest, first monitored rhythm and EMS response time.

Fewer paramedics used the Q-CPR than initially predicted. This resulted in a smaller sample size than anticipated. This was especially noticeable in the exploratory analysis that investigated downtime, as the cohort was further divided into three categories and univariate and multivariable logistic regression analyses were carried out in each. However, despite the small sample size, significant results for the relationship between chest compression fraction and ROSC were still obtained in the group with a downtime > 15 minutes. Nevertheless I recommend that in future such analyses be carried out using a larger sample size.

CPR quality data was collected for less than one fifth of OHCA cases that had resuscitation attempted by SJA-WA paramedics during the study period. This potentially limits the representativeness of the measurements collected; it is possible that CPR quality among those paramedics who used the Q-CPR differed to that among those paramedics who did not. Nevertheless I used the findings from the cohort study to prepare recommendations for SJA-WA. In future the increased use of the Q-CPR device in clinical practice should be

encouraged to obtain a more accurate representation of the quality of CPR provided by SJA-WA paramedics at large.

With respect to the investigation of the impact of downtime on the inverse relationship between CCF and OHCA survival, I utilised a cut-off point of 15 minutes to dichotomise downtime. This was based on the figure used in animal studies.¹⁰¹⁻¹⁰⁴ However this may not reliably translate to human data. Previous human studies have shown that survival decreases by approximately 10-12% per minute without defibrillation.¹⁰ This can be reduced to a 3-4% decrease if CPR is provided.¹⁰ However in the case of no CPR and no defibrillation, the chances of survival after 15 minutes are considered to be close to zero.⁹⁰ Current practice at SJA-WA dictates that if a patient has had an unwitnessed arrest, with no bystander CPR in place, asystole present in all three leads for 30 seconds or more, has fixed and dilated pupils, absent breath sounds on auscultation and absent heart sounds on auscultation or no palpable carotid pulses and absent corneal reflexes and is suspected to have been without circulation for greater than 15 minutes, paramedics can choose not to commence resuscitation efforts.⁹⁰ This directive however was not in place at the time of data collection for my study therefore resuscitation would still have been commenced in these patients. I found however that none of the patients in the group with a downtime > 15 minutes survived to discharge in my cohort. In summary, the progression of cardiac arrest may differ in humans compared to pigs, and the findings presented here are part of our exploratory analysis only, and as such are not intended to alter current clinical practice.

All of the animal studies¹⁰¹⁻¹⁰⁴ that explored the effects of post conditioning on survival outcomes featured pigs with induced VF arrest. These animals were studied under controlled conditions and treated at the 15-17 minute time point.¹⁰¹⁻¹⁰⁴ In the SJA-WA cohort study however I could not be sure of the patient's cardiac rhythm at the onset of arrest nor of their actual downtime. Patients were divided into three groups; ≤ 15 minutes, > 15 minutes and those patients with an unknown downtime. However the downtime in the > 15 minute group could have ranged anywhere from 15 minutes to several hours. It is perhaps therefore even less surprising that I did not see any survivors among this group.

Despite the limitations of this work, it generated a number of important findings that have translated into a set of final recommendations.

9.8 Recommendations

The following recommendations are provided on the basis of this research:

- Given that compression depth was below the minimum recommended value in the large majority of cases that used the Q-CPR, actions should be promptly taken to ensure optimal compression depth among rescuers.
- If not already done so, paramedics should be made aware of evidence from the literature that shows that deeper compressions have been associated with improved patient survival outcomes.
- In addition paramedics should be made aware of the difference between the perceived quality of CPR and that measured using the Q-CPR device.
- Given that overall the mean compression depth did not improve over the resuscitation time, despite the provision of visual feedback by the Q-CPR, further investigations should be undertaken to ascertain the possible reasons for why this was the case.
- Although the mean compression rate measured was within the range recommended by international resuscitation guidelines, since my systematic review found a significant association between lower compression rates within this range and survival, attempts could be made to further reduce the mean compression rate to bring it closer to 100 cpm. Furthermore, a lower compression rate may assist in achieving deeper compressions since an inverse relationship between compression rate and depth has previously been reported in the literature.
- In regards to the other CPR quality metrics, rescuers should continue to comply with current international resuscitation guideline recommendations. At this time no additional recommendations are made regarding chest compression fraction, despite the inverse nature of the relationship observed with ROSC.
- Given the low reported use of the Q-CPR device among paramedics, and its widespread availability in the metropolitan ambulance service, measures should be implemented to promote its increased use. However this should only be done following an investigation of its effectiveness at facilitating optimal compression depth.

- Since the results of the survey revealed that many respondents prioritised other equipment and interventions over use of the Q-CPR device, paramedics should be made aware of findings from the literature that suggest that some of these other interventions such as intubation and the administration of drugs like epinephrine may not be as effective at promoting survival as is the provision of high quality CPR.
- Regardless of how these recommendations are enacted, data should continue to be collected from the field to allow for ongoing monitoring of performance and to provide an indication on the effectiveness of any introduced quality improvement initiatives. In particular, trends in mean compression depth over time should continue to be monitored, as well as the Q-CPR usage rate.

The International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science with Treatment Recommendations (CoSTR) advises that CPR feedback devices like the Q-CPR should be used within a broader system of care that includes comprehensive CPR quality improvement initiatives.³⁸ Such a system of care should include tailored education and training programs and comprise a strategy to regularly monitor the performance of the system. In addition, the implementation of other initiatives such as personalised, post-event debriefing, while not discussed in this research, may increase the utility of feedback devices like the Q-CPR. SJA-WA is in the process of refining such a system and has recently employed a senior paramedic to coordinate strategies to improve OHCA outcomes in the organisation.

9.9 Recommendations for future research

Given the findings and inherent limitations of my research, I make several recommendations for future work. I recommend further investigation into the potential reasons for why devices like the Q-CPR may not always be effective at facilitating high quality CPR among rescuers in the field, as was widely observed among the study cohort of SJA-WA paramedics. I also recommend that others continue to explore the relationship between chest compression fraction and survival outcomes. Due to the variability in reported findings among studies, it is possible that a third factor or combination of factors are modulating this relationship and it would be useful to elucidate what this could be. In particular I recommend that others conduct further research to investigate the potential role of downtime in this relationship; however I propose that this be done using a larger sample size. I also recommend that others explore the potential for ‘personalised CPR’, in which CPR is customised on the basis of unique event characteristics such as downtime or titrated against patient physiological

measurements. The latter work is already being undertaken by others including Professor Robert Neumar and colleagues at the University of Michigan.¹⁴⁷ This may represent a future paradigm shift in the provision of CPR.

9.10 Concluding remarks

This thesis explored the relationship between the quality of cardiopulmonary resuscitation performed by SJA-WA paramedics and OHCA patient survival outcomes. Importantly, compression depth was found to be too shallow in the majority of cases. Furthermore, the provision of real-time feedback by the Q-CPR device did not improve compression depth over resuscitation time. There was capacity for the further optimisation of mean chest compression rate to bring it closer to the minimum value of 100 cpm recommended by international guidelines. While compression depth and rate were not significantly associated with survival outcomes in the study cohort, compression fraction was significantly and inversely associated with ROSC. Upon further exploration of this counter-intuitive finding, it was observed that a lower compression fraction was associated with greater odds of ROSC in OHCA patients who had been without circulation for at least 15 minutes. This finding proposes the need for further research into whether a uniform compression fraction recommendation is appropriate for all OHCA patients. It was likewise found that the Q-CPR device was seldom used by paramedics, despite being prescribed as a mandatory piece of equipment for resuscitation. Survey results revealed that it was generally not assigned a high priority by paramedics in the cardiac arrest response algorithm. Together these findings indicate that in the context of SJA-WA, the Q-CPR device did not represent a successfully implemented and effective tool for facilitating high quality CPR among paramedics. These findings also support the need for devices like the Q-CPR to be used within a comprehensive system of care.

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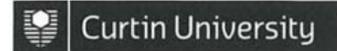
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Appendices

Appendix 1 Ethics approval for retrospective cohort study



Memorandum

To	Professor Ian Jacobs, CHIRI
From	Professor Peter O'Leary, Chair Human Research Ethics Committee
Subject	Protocol Amendment Approval HR 128/2013
Date	23 January 2014
By	Miss Milena Talikowska, Nursing and Midwifery

Office of Research and Development
Human Research Ethics Committee

TELEPHONE 9266 2784
FACSIMILE 9266 3793
EMAIL hrec@curtin.edu.au

Thank you for keeping us informed of the progress of your research. The Human Research Ethics Committee acknowledges receipt of your progress report, indicating modifications / changes, for the project "*Western Australian Pre-hospital Care Record Linkage Project*". Your application has been **approved**.

The Committee notes the following amendments have been approved:

1. In order to facilitate the undertaking of her PhD research into cardiopulmonary resuscitation, it is proposed that the name of Miss Milena Talikowska be added to the list of investigators on the WA Pre-hospital Care Record Linkage Project.

Approval for this project remains until **03-09-2017**.

Your approval number remains **HR 128/2013**, please quote this number in any further correspondence regarding this project.

Yours sincerely

Professor Peter O'Leary
Chair Human Research Ethics Committee

Appendix 2 Ethics approval for survey analysis

MEMORANDUM



To:	Prof Judith Finn PRECRU, School of Nursing, Midwifery & Paramedi
CC:	Ms Milena Talikowska
From:	Dr Catherine Gangell, Manager Research Integrity
Subject	Ethics approval Approval number: RDHS-209-15
Date:	22-Sep-15

Office of Research and
Development
Human Research Ethics Office

TELEPHONE 9266 2784
FACSIMILE 9266 3793
EMAIL hrec@curtin.edu.au

Thank you for your application submitted to the Human Research Ethics Office for the project: 6436
Use of the Q-CPR puck by St John Ambulance paramedics in Perth, Western Australia

Your application has been approved through the low risk ethics approvals process at Curtin University.

Please note the following conditions of approval:

1. Approval is granted for a period of four years from **22-Sep-15** to **22-Sep-19**
2. Research must be conducted as stated in the approved protocol.
3. Any amendments to the approved protocol must be approved by the Ethics Office.
4. An annual progress report must be submitted to the Ethics Office annually, on the anniversary of approval.
5. All adverse events must be reported to the Ethics Office.
6. A completion report must be submitted to the Ethics Office on completion of the project.
7. Data must be stored in accordance with WAUSDA and Curtin University policy.
8. The Ethics Office may conduct a randomly identified audit of a proportion of research projects approved by the HREC.

Should you have any queries about the consideration of your project please contact the Ethics Support Officer for your faculty, or the Ethics Office at hrec@curtin.edu.au or on 9266 2784. All human research ethics forms and guidelines are available on the ethics website.

Yours sincerely

Dr Catherine Gangell
Manager, Research Integrity

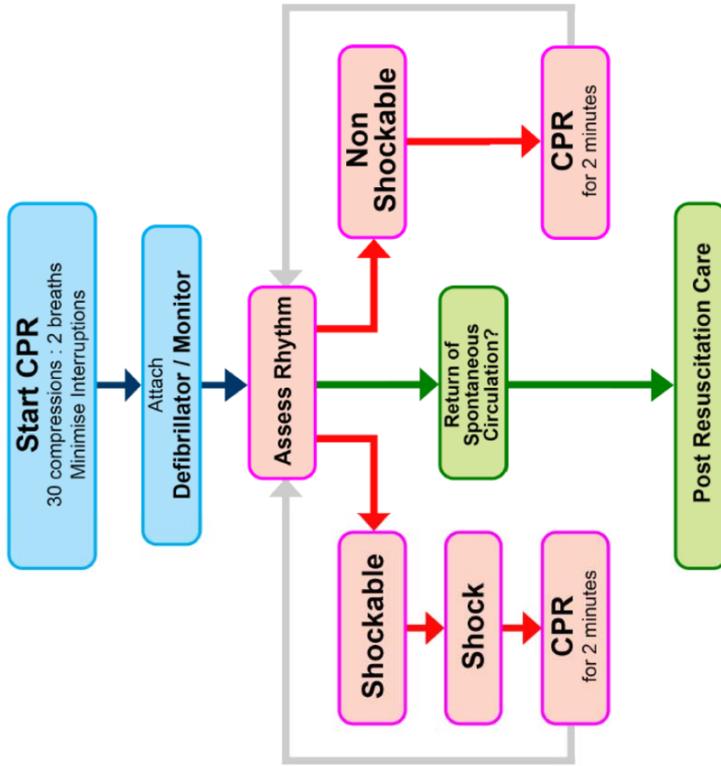
Appendix 3 St John Ambulance Clinical Practice Guideline for Cardiac Arrest

CIRCULATION 4.6A CARDIAC ARREST – ADULT (12 YEARS & OVER) July 2016

Introduction	
Cardiac arrest is a time critical condition requiring immediate intervention. The ALS algorithm allows for a systematic approach to cardiac arrest and assumes basic life support (BLS) measures have been initiated and remain ongoing.	
Assessment	Disposition
<ul style="list-style-type: none"> ▪ Following a primary survey, resuscitation must be commenced on all patients in suspected cardiac arrest not meeting the criteria set out in CPG 4.6D, in line with Australian Resuscitation Council (ARC) guidelines. ▪ If circulation is restored, please refer to CPG 4.6C – ROSC. 	<ul style="list-style-type: none"> ▪ If trauma is the cause, follow the Traumatic Cardiac Arrest CPG. ▪ Consider early transportation for non-asystolic patients as they will not meet the clinical criteria for termination of resuscitation efforts. ▪ If vascular access is unobtainable, continue resuscitative efforts without medications.
Management	Special Considerations
<p>Follow ARC Flowcharts.</p> <ul style="list-style-type: none"> ▪ Apply Q-CPR puck to monitor CPR performance quality. ▪ Minimise interruption to chest compressions. Good quality CPR is associated with improved clinical outcomes. ▪ Shockable Rhythms - VF, Pulseless VT (as per Skill 501). ▪ Non-Shockable Rhythms - PEA, Asystole. ▪ Status / rhythm check every 2 minutes. ▪ Once an advanced airway (ETT or LMA) is confirmed in position, compressions are continuous and ventilations asynchronous at 6-10 per minute. (N.B 4-6 per minute for asthmatic arrests). 	<p>Refer to CPG 4.6D for Termination Of Resuscitation and/or Recognition of Life Extinct. When in doubt regarding termination, please contact the State Operations Centre Clinical Support Paramedic for guidance and/or ASMA consultation.</p> <p>Pregnancy</p> <ul style="list-style-type: none"> ▪ In pregnant patients place padding, such as a towel, under the right hip to tilt the woman's hips approximately 15-30°. <p>Hypothermic Cardiac Arrest:</p> <ul style="list-style-type: none"> ▪ If the patient's core temperature is below 30°C, a maximum of 3 shocks should be delivered until patient is above 30°C. ▪ In the hypothermic patient, withhold cardioactive drugs until body temperature is above 30°C. ▪ Between 30 – 35°C, double the interval between the doses of cardioactive drug. ▪ If you suspect that the cardiac arrest was of hypothermic origin, resuscitation must be commenced and the patient must be transported to hospital.

Advanced Life Support for Adults

<p>During CPR</p> <ul style="list-style-type: none"> Airway adjuncts (LMA / ETT) Oxygen Waveform capnography IV / IO access <p>Plan actions before interrupting compressions (e.g. charge manual defibrillator)</p> <p>Drugs</p> <p>Shockable</p> <ul style="list-style-type: none"> * Adrenaline 1 mg after 2nd shock (then every 2nd loop) * Amiodarone 300mg after 3 shocks <p>Non Shockable</p> <ul style="list-style-type: none"> * Adrenaline 1 mg immediately (then every 2nd loop) <p>Consider and Correct</p> <ul style="list-style-type: none"> Hypoxia Hypovolaemia Hyper / hypokalaemia / metabolic disorders Hypothermia / hyperthermia Tension pneumothorax Tamponade Toxins Thrombosis (pulmonary / coronary) 	<p>Post Resuscitation Care</p> <ul style="list-style-type: none"> Re-evaluate ABCDE 12 lead ECG Treat precipitating causes Aim for: SpO2 94-98%, normocapnia and normoglycaemia Targeted temperature management
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January 2016

UNCONTROLLED WHEN PRINTED

Appendix 4 PROSPERO registration

PROSPERO International prospective register of systematic reviews

Cardiopulmonary resuscitation quality and patient survival outcome in cardiac arrest: a systematic review and meta-analysis

Milena Talikowska, Hideo Tohira, Judith Finn, Ian Jacobs

Citation

Milena Talikowska, Hideo Tohira, Judith Finn, Ian Jacobs. Cardiopulmonary resuscitation quality and patient survival outcome in cardiac arrest: a systematic review and meta-analysis. PROSPERO 2014:CRD42014010125 Available from http://www.crd.york.ac.uk/PROSPERO_REBRANDING/display_record.asp?ID=CRD42014010125

Review question(s)

In patients with in-hospital or out-of-hospital cardiac arrest, is there an association between cardiopulmonary resuscitation (CPR) quality and patient survival outcomes?

What CPR quality parameters are reported in the published literature and how are they defined?

Searches

The following sources will be searched:

MEDLINE (via Ovid)

EMBASE (via Ovid)

CINAHL (via EBSCO)

Scopus

Cochrane Library

Grey Literature (via Mednar)

All database searches will be restricted to only capture articles published within approximately the last 20 years (from January 1994 onwards). This is due to the fact that CPR quality measurement devices such as Laerdal's Q-CPR tool were not available prior to this time.

No language restrictions will be set. Grey literature articles will be considered. Review articles may be used to find other relevant articles. Reference lists from relevant articles will be used to identify additional relevant sources.

Types of study to be included

Only articles with a comparative study design will be considered.

Editorials, commentaries, letters and case studies/case reports will be excluded.

Studies which solely use a metronome device will be excluded, as will those that use any feedback devices which do not store CPR quality data for retrospective analysis. All forms of subjective CPR quality measurement will be excluded. Studies that use a feedback device without objective quality measurement will not be considered.

Condition or domain being studied

Cardiac arrest is a significant global health issue. In the U.S., there are approximately 360,000 out-of-hospital cardiac arrests (OHCA) occurring annually (Go et al., 2013). This equates to just under 1,000 cardiac arrests per day. Of these, 93.7% are fatal (Berdowski et al., 2010). Clearly, survival from OHCA is low; however there are opportunities

for improvement to be made. OHCA is managed in the first instance by cardiopulmonary resuscitation (CPR). It has long been argued that CPR 'buys time' in that it maintains some cardiac output until more definitive care can be instituted. In the last decade there has been an increased emphasis on the quality of the CPR performed (Hazinski et al., 2010). Quality is defined in terms of several parameters which include chest compression rate (compressions/minute), chest compression depth (mm), ventilation rate (ventilations/minute), among others. In the past it was difficult to accurately measure these parameters during a CPR event. However, with the introduction of automated CPR quality measurement devices, it is possible to log and process the quality data in real-time. This systematic review seeks to investigate the correlation between individual CPR quality parameters (as measured by such a device) and patient survival from cardiac arrest.

Participants/ population

Cardiac arrest patients on whom CPR has been performed and the quality of CPR has been measured using a CPR quality measurement device. Both in-hospital and out-of-hospital cardiac arrest; and adult and paediatric studies will be considered. All cardiac arrest aetiologies will be considered. Animal and manikin studies will be excluded.

Intervention(s), exposure(s)

The exposure of interest is the quality of CPR (as measured by a CPR quality measurement device) – where it is possible to categorise the exposure as 'good' or 'poor' quality CPR. Examples of CPR quality measurement devices include: Laerdal's Q-CPR and ZOLL's Real CPR Help.

Comparator(s)/ control

'Good' quality will be compared to 'poor' quality CPR. The definitions of 'good' and 'poor' quality will be gauged against the recommendations provided in the International Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care 2010.

Context

In-hospital and out-of-hospital cardiac arrest in which CPR quality has been measured using a CPR quality measurement device that records CPR performance in real-time during an arrest, and where the logged data is available for comparison with patient survival outcomes.

Outcome(s)

Primary outcomes

The review will examine studies in which CPR quality can be linked to patient survival outcome(s).

Primary outcome: Return of Spontaneous Circulation (ROSC) at any time during the resuscitation effort prior to hospital admission.

Secondary outcomes

Secondary outcomes:

- i) ROSC on arrival at ED;
- ii) ROSC on admission to hospital;
- iii) survival to hospital discharge;
- iv) survival to hospital discharge with good neurological outcome.

Surrogate or physiological outcomes will not be considered.

Data extraction, (selection and coding)

Two reviewers (MT and HT) will screen the titles and abstracts of all studies which have been identified through the database searching to extract potentially relevant studies. This will be followed by screening of the full papers of potentially relevant studies to identify relevant articles. Any disagreements in study eligibility will be resolved by consensus or, if unable to be resolved by consensus, by referral to a third party (JF). The results of each stage of the study selection process will be presented in a PRISMA flow chart.

Data will be extracted from relevant articles by one reviewer (MT) and entered into a pre-prepared Microsoft Excel spreadsheet. The same reviewer will then re-enter the data again into a separate case of the Microsoft Excel spreadsheet. The two spreadsheets will then be compared to ensure that there are no errors in data entry. A second reviewer (HT) will select a random sample of data and confirm that they have been entered correctly into the spreadsheet. Any discrepancy will be resolved by consensus or, if unable to be resolved by consensus, by referral to a third party (JF).

Extracted information will include:

Paper characteristics:

Author/s

Year of publication

Place (country) of study

Study characteristics:

Aim

Design

Sample size

OHCA, IHCA or both

Adult, paediatric or both

Who performed CPR (e.g. paramedics, nurses, etc.)

Name of CPR quality measurement device used

Name of CPR quality parameter/s considered in study

Details of how CPR quality parameters were defined (e.g. 'good' versus 'poor')

Outcome to which each CPR quality parameter was linked

Relationship between parameter and outcome.

Authors of original studies may be contacted to obtain missing or additional data where required.

Risk of bias (quality) assessment

The GRADE system will be used to assess bias in individual studies.

Strategy for data synthesis

The heterogeneity across studies will be assessed using the I-squared statistic. If a meta-analysis is indicated, a random effects model will be constructed.

Analysis of subgroups or subsets

Subgroup analysis will be performed for the following groups:

HCA/OHCA

Adult/paediatric

Initial rhythm

Aetiology

Trained or lay responder

Feedback on - Yes/No

Pre/post 2004 study

Dissemination plans

The intention is to publish the results in a peer-reviewed journal.

Contact details for further information

Milena Talikowska

Prehospital, Resuscitation & Emergency Care Research Unit (PRECRU)

School of Nursing & Midwifery

Curtin University

GPO Box U 1987

Perth 6845 Western Australia

milena.talikowska@postgrad.curtin.edu.au

Organisational affiliation of the review

Australian Resuscitation Outcomes Consortium (Aus-ROC), Prehospital, Resuscitation and Emergency Care Research Unit (PRECRU) - Curtin University

<https://www.ausroc.org.au/>, <http://healthsciences.curtin.edu.au/research/precru/index.cfm>

Review team

Ms Milena Talikowska, Curtin University

Dr Hideo Tohira, Curtin University

Professor Judith Finn, Curtin University, Monash University, St John Ambulance WA

Professor Ian Jacobs, Curtin University, St John Ambulance WA

Anticipated or actual start date

01 June 2014

Anticipated completion date

31 October 2014

Funding sources/sponsors

PhD scholarship (MT) funded by the Australian Resuscitation Outcomes Consortium (Aus-ROC) – a NHMRC Centre of Research Excellence #1029983

Conflicts of interest

Prof. Ian Jacobs is Clinical Services Director of St John Ambulance Western Australia where the quality of CPR is routinely measured.

Language

English

Country

Australia

Subject index terms status

Subject indexing assigned by CRD

Subject index terms

Cardiopulmonary Resuscitation; Heart Arrest; Humans

Stage of review

Ongoing

Date of registration in PROSPERO

09 June 2014

Date of publication of this revision

09 June 2014

Stage of review at time of this submission	Started	Completed
Preliminary searches	Yes	No
Piloting of the study selection process	No	No
Formal screening of search results against eligibility criteria	No	No
Data extraction	No	No
Risk of bias (quality) assessment	No	No
Data analysis	No	No

PROSPERO

International prospective register of systematic reviews

The information in this record has been provided by the named contact for this review. CRD has accepted this information in good faith and registered the review in PROSPERO. CRD bears no responsibility or liability for the content of this registration record, any associated files or external websites.

Appendix 5 Supplementary material for systematic review

Appendix A. Search strategy (Ovid MEDLINE)

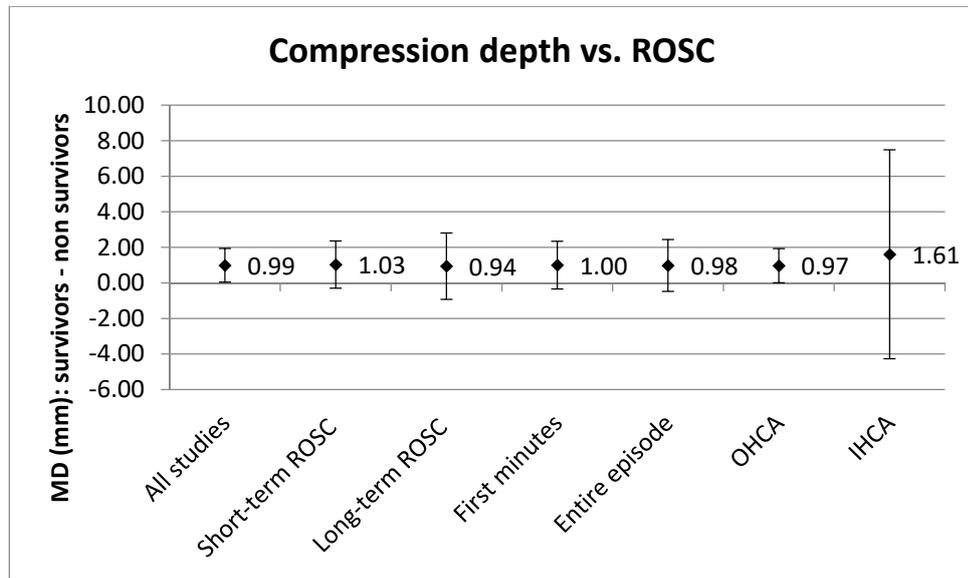
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2	CPR.mp.	
3	(heart adj massage\$).mp.	
4	(cardiac adj massage\$).mp.	
5	(cardiac adj arrest\$).mp.	
6	(heart adj arrest\$).mp.	Cardiac arrest/ resuscitation
7	(cardiopulmonary adj arrest\$).mp.	
8	(sudden adj cardiac adj death\$).mp.	
9	OHCA.mp.	
10	IHCA.mp.	
11	exp Heart Arrest/	
12	1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11	
13	quality.mp.	
14	(compression adj rate\$).mp.	
15	(compression adj depth\$).mp.	
16	(duty adj cycle\$).mp.	
17	(compression adj fraction\$).mp.	
18	(defibrillation adj timing\$).mp.	
19	(time adj2 first adj shock).mp.	
20	(chest adj recoil).mp.	
21	(hands-off adj time\$).mp.	
22	(Q-CPR or QCPR or CPR-meter or CPRmeter or CPR-Ezy or CPREzy).mp.	Quality of CPR
23	(real adj CPR adj Help).mp.	
24	(transthoracic adj impedance).mp.	
25	(peri-shock adj pause\$).mp.	
26	(peri-defibrillation adj pause\$).mp.	
27	(pre-shock adj pause\$).mp.	
28	(pre-defibrillation adj pause\$).mp.	
29	(post-shock adj pause\$).mp.	
30	(post-defibrillation adj pause\$).mp.	
31	13 or 14 or 15 or 16 or 17 or 18 or 19 or 20 or 21 or 22 or 23 or 24 or 25 or 26 or 27 or 28 or 29 or 30	
32	12 and 31	Quality of CPR during cardiac arrest
33	limit 32 to yr="1994 -Current"	
34	limit 33 to animals	
35	33 not 34	
36	letter.pt.	
37	comment.pt.	Limits
38	editorial.pt.	
39	35 not 36	
40	39 not 37	
41	40 not 38	

Appendix B. Risk of bias within studies (Newcastle Ottawa Scale)

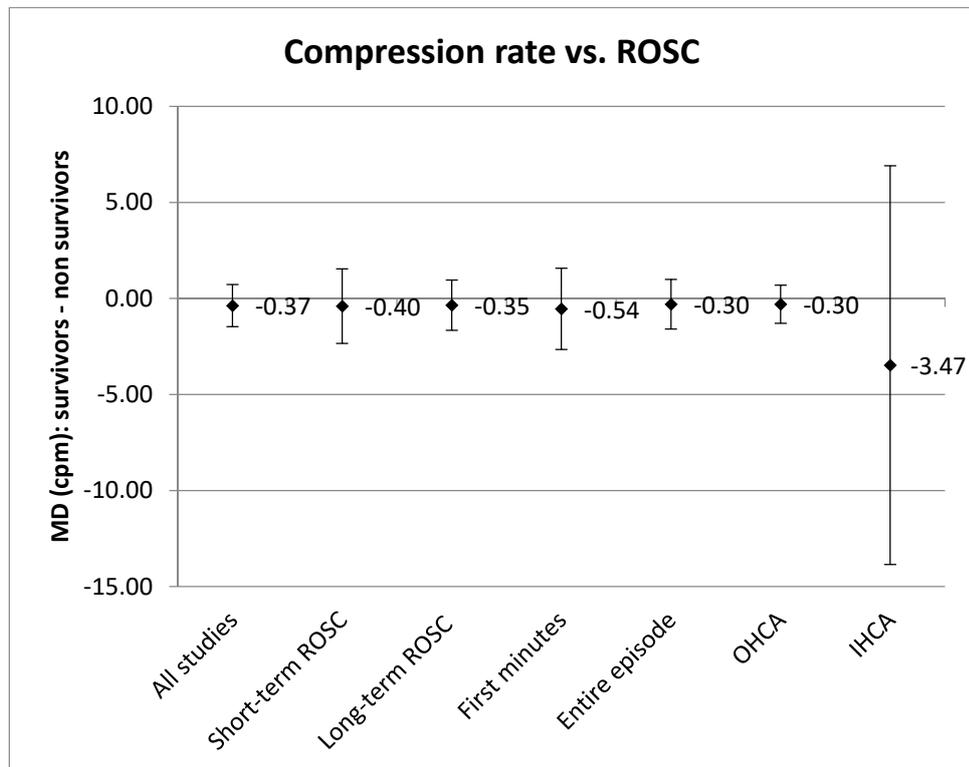
Author	SELECTION				COMPARABILITY Comparability of cohorts	OUTCOME			TOTAL SCORE	Corresponding quality rating
	Representativeness of exposed cohort	Selection of non-exposed cohort	Ascertainment of exposure	Outcome not present at start of study		Assessment of outcome	Follow-up time long enough	Adequacy of follow-up of cohorts		
Abella 2005 ⁴	★	★	★	★		★	★	★	7	Poor
Babbs 2008 ⁵²			★	★			★	★	4	Poor
Beesems 2013 ¹⁴⁸	★	★	★	★	★★	★	★	★	9	Good
Bohn 2011 ⁵³	★	★	★	★		★	★	★	7	Poor
Cheskes 2011 ⁸⁴	★	★	★	★	★★	★	★	★	9	Good
Cheskes 2014 ⁸³	★	★	★	★	★★	★	★	★	9	Good
Christenson 2009 ⁹⁶	★	★	★	★	★★	★	★	★	9	Good
Idris 2012 ¹¹³	★	★	★	★	★★	★	★	★	9	Good
Kamarainen 2012 ¹⁴⁹			★	★	★	★	★	★	6	Fair
Kramer-Johansen 2006 ⁵⁹	★	★	★	★	★★	★	★	★	9	Good
Niles 2012 ¹⁵⁰			★	★		★	★	★	5	Poor
Stiell 2012 ⁶	★	★	★	★	★	★	★	★	8	Fair
Stiell 2014 ¹⁵¹	★	★	★	★	★★	★	★	★	9	Good
Vadeboncoeur 2014 ¹⁴	★	★	★	★	★★	★	★	★	9	Good
Vaillancourt 2011 ⁹⁷	★	★	★	★	★★	★	★	★	9	Good
Wik 2005	★	★	★	★	★	★	★	★	8	Fair

Appendix C. Subgroup meta-analyses

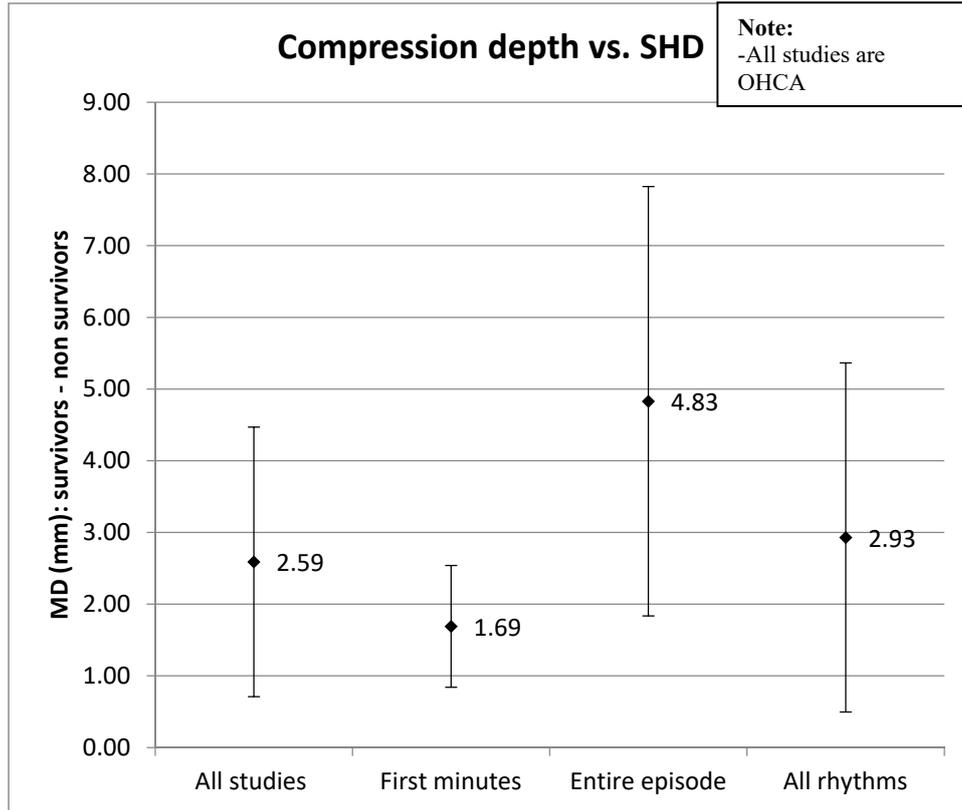
(a) compression depth vs. ROSC



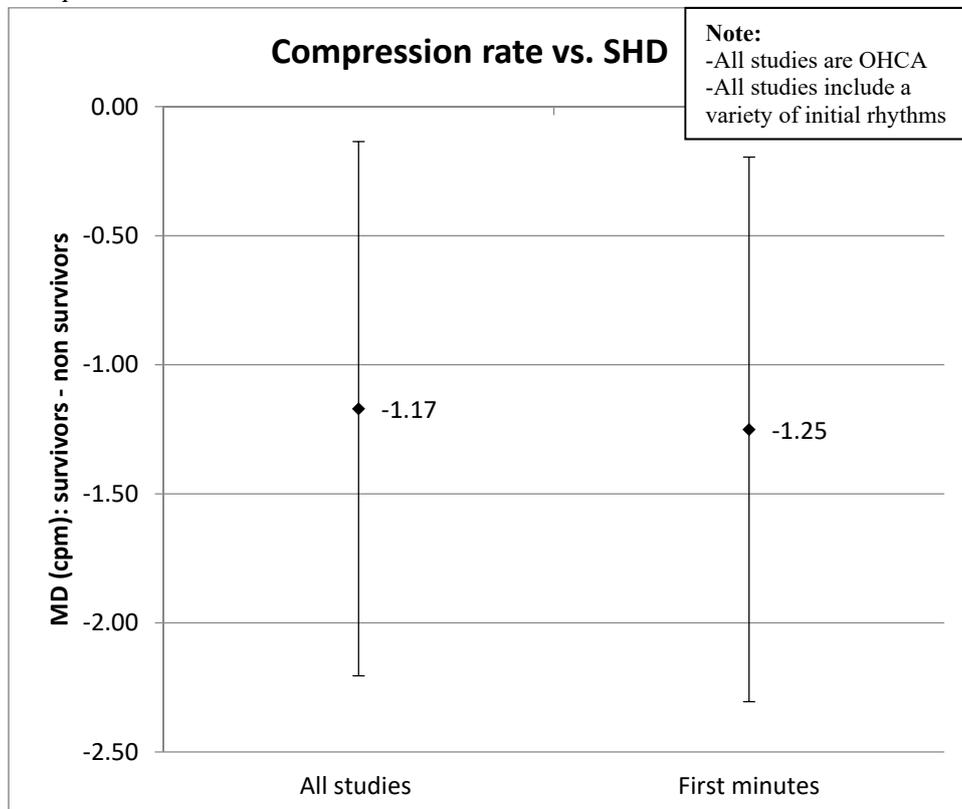
(b) compression rate vs. ROSC



(c) *Compression depth vs. STHD*



(d) *Compression rate vs. STHD*



Further notes: Where a subgroup analysis would include only one study, the results are not shown.

Appendix D. PRISMA Checklist

Section/topic	#	Checklist item	Reported on page #
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	2
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	3
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	3
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	3
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	3-4
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	4
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	4
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	4-5

Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	5
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	5
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	5
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	5
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	5-6
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	6
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	6
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	6
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	6
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	6
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	6-9
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	6-9
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	9
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	6-9

DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	9-10
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	10-11
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	11
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	11

Appendix 6 Letter to the Editor (accepted for publication in *Resuscitation*)

Letter to the Editor

Sir,

In our paper entitled “Lower chest compression fraction associated with ROSC in OHCA patients with longer downtimes”¹ we reported a significant, inverse relationship between chest compression fraction (CCF) and return of spontaneous circulation (ROSC); furthermore this relationship was shown to vary with downtime from onset of arrest to the provision of CPR by paramedics. We found specifically that in the group with a downtime of greater than 15 minutes, a lower CCF during the first three minutes of cardiopulmonary resuscitation (CPR) was significantly associated with ROSC. In this Letter to the Editor we present some additional data for pre-, post- and peri-shock pause² that was not included in our previously published work. The reason that it was not included was because there were few cases in our cohort that received a shock during the first three minutes of CPR quality data capture. However, we believe that presentation of this additional shock pause data aids in demonstrating that the significantly lower CCF observed among patients who achieved ROSC in the group with a downtime of greater than 15 minutes was not due to more time spent administering defibrillations.

We analysed shock pause duration for all cases in our study cohort that received at least one shock during the first three minutes of CPR. The shock had to have occurred during the time that CPR quality data was captured because we were interested in the effect of the shock pause on the compression fraction calculated. We reviewed the compression waveform for each case using the Event Review Pro software package (version 4.2, EMS edition, Philips Healthcare, Seattle, WA, USA). Pre-shock pause was measured from the time of the last administered compression to shock delivery, post-shock pause was measured from shock delivery to the next administered compression and peri-shock pause was the combination of these two measurements. Where more than one shock was provided during the first three minutes of data capture, we combined the data from both shocks to obtain an indication of the total time spent defibrillating the patient during this time. Our findings, grouped by downtime, are presented in Table 1.

Table 1 - Total time (seconds) spent delivering shocks in cases that had at least one shock delivered during the first three minutes of CPR. Results are grouped by downtime.

	Downtime ≤15 min		Downtime >15 min		Unknown downtime	
	ROSC	No ROSC	ROSC	No ROSC	ROSC	No ROSC
Total number of cases	30	45	15	83	9	20
Number of cases with a shock delivered during the first 3 min of CPR quality data capture	9	6	0	4	0	3
Mean number of shocks during first 3 min of CPR quality data capture	1.2	1.2	0	1	0	1
Total pre-shock pause duration (seconds, mean±SD) ^a	7.2± 4.9	9.0±4.3	-	7.0± 1.4	-	8.3± 7.1
p-value	0.48		- ^b		- ^b	
Total post-shock pause duration (seconds, mean±SD) ^a	5.6±6.0	3.0± 2.2	-	2.8± 2.4	-	8.0± 8.7
p-value	0.34		- ^b		- ^b	
Total peri-shock pause duration (seconds, mean±SD) ^a	13± 10	12± 6.1	-	9.8± 2.6	-	16± 10
p-value	0.87		- ^b		- ^b	

1. If there was more than one shock delivered during the first three minutes of CPR, we combined the time from all shocks to obtain an estimate of the total time spent on delivering shocks.
2. It was not possible to derive a p-value for these two groups.

None of the patients in the group with a downtime of greater than 15 minutes who achieved ROSC received a shock during the first three minutes of CPR quality data capture. Importantly, we confirm that the lower compression fraction seen among those who achieved ROSC in the group with a downtime of greater than 15 minutes was not due to the fact that more time was spent delivering defibrillations.

Conflict of interest statement

Prof. Judith Finn is the Director of the Australian Resuscitation Outcomes Consortium (Aus-ROC), a NHMRC Centre of Research Excellence (CRE #1029983), and receives partial salary support from St John Ambulance Western Australia (SJA-WA). A/Prof. Paul Bailey is Clinical Services Director at SJA-WA. Mr. Deon Brink is the General Manager - Clinical Services at SJA-WA. Dr. Madoka Inoue maintains the SJA-WA OHCA database and receives partial salary support from SJA-WA and Aus-ROC. Ms. Milena Talikowska is a PhD student funded by Aus-ROC. There are no other potential conflicts of interest to declare.

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1. Talikowska M, Tohira H, Inoue M, Bailey P, Brink D, Finn J. Lower chest compression fraction associated with ROSC in OHCA patients with longer downtimes. *Resuscitation*. 2017; 116:60-5.
2. Cheskes S, Schmicker RH, Christenson J, Salcido DD, Rea T, Powell J, et al. Perishock pause: an independent predictor of survival from out-of-hospital shockable cardiac arrest. *Circulation*. 2011; 124:58-66.

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Appendix 7 Supplementary material for survey paper

SJA-WA CLINICAL SURVEY

USE OF THE Q-CPR PUCK

Thank you for taking part in this survey on the use of the Q-CPR “puck”. The results of this survey will be used for continuous quality improvement and to optimise patient care.

This survey is anonymous.



1. Please indicate your professional level:
 - a. Student
 - b. Ambulance Officer
 - c. Paramedic Level 1
 - d. Paramedic Level 2
 - e. Paramedic Level 3
2. Gender:
 - a. Female
 - b. Male
3. Have you ever responded to a cardiac arrest while on shift? (*Note: only actual cardiac arrests – not those that were incorrectly dispatched*).
 - a. Yes
 - b. No (go to question 8)
4. Have you responded to a cardiac arrest in the last 12 months?
 - a. Yes
 - b. No (Go to question 8)
5. In the last arrest you attended, you were:
 - a. the first crew on scene
 - b. the back-up crew
 - c. Clinical Support (CSP) / Area Manager
6. If resuscitation was attempted:
 - a. We used the Q-CPR puck (go to question 8)
 - b. We **didn't** use Q-CPR
7. The main reason why we didn't use Q-CPR was:
 - a. We saw other procedures as a priority (securing airway, setting up IV line, administering drugs, etc.)
 - b. The CSP arrived with LUCAS
 - c. Q-CPR causes pain to the person doing chest compressions
 - d. We were worried about damage to the patient's chest
 - e. Other (please specify)

8. The use of Q-CPR is compulsory for all arrests where resuscitation is attempted:
 - a. Yes
 - b. No
 - c. There are exceptions (please specify)

9. Please indicate whether you agree or disagree with the following statements about the Q-CPR puck:

	Strongly Agree	Agree	Neither Agree nor disagree	Disagree	Strongly Disagree	Not applicable
Using the Q-CPR puck is painful during training on a manikin	1	2	3	4	5	N/A
Using the Q-CPR puck is painful when using it on a patient	1	2	3	4	5	N/A
Using the Q-CPR puck is ONLY painful during long resuscitations	1	2	3	4	5	N/A
The Q-CPR puck slides off the patient's chest	1	2	3	4	5	N/A
My hand easily slips off the Q-CPR puck when I'm doing compressions	1	2	3	4	5	N/A
I would prioritise securing the patient's airway over using the Q-CPR puck	1	2	3	4	5	N/A
I would prioritise setting up IV access over using the Q-CPR puck	1	2	3	4	5	N/A
I would prioritise administering therapeutic drugs (adrenaline, etc) over the use of the Q-CPR puck	1	2	3	4	5	N/A
I would hold off putting on the puck if I know that the CSP is coming with the LUCAS	1	2	3	4	5	N/A
I think that my CPR is already of good quality (i.e. meets the guidelines)	1	2	3	4	5	N/A
I think that the Q-CPR would help me to make sure that my CPR quality is good	1	2	3	4	5	N/A
I find the visual feedback from Q-CPR useful	1	2	3	4	5	N/A
I don't want anybody to analyse the quality of my chest compressions	1	2	3	4	5	N/A
It would help me if there was something in the MRx kit to remind me to use the Q-CPR puck	1	2	3	4	5	N/A

10. Please rate these interventions (1-6) from most to least important when managing a confirmed cardiac arrest patient (1 = most important, 6 = least important):

- Securing the airway
- Ventilation
- IV insertion

- Administration of adrenaline / other arrest drugs
- Defibrillation (where appropriate)
- Chest compressions

11. Please provide any additional feedback that you have about the Q-CPR puck:

Thank you for taking part in this survey.

Appendix B: Summary of additional comments about the Q-CPR

No.	Reported issue	Number of times reported
1	A redesign is required/complaints about current design of Q-CPR	22
2	Reports of pain associated with use of Q-CPR	20
3	Positive comments about Q-CPR	15
4	Device is forgotten/ a reminder would be useful	10
5	Messy/additional wire	4
6	Q-CPR slides off chest or does not sit correctly	4
7	Concern that Q-CPR causes damage to chest/ concern over use in elderly patients	3
8	Respondent has never used Q-CPR on patient	3
9	Useful for bystanders/volunteers	3
10	Confuses bystanders & volunteers/they complain	2
11	Embarrassing to use	2
12	Provides incorrect feedback	2
13	Fatigue associated with use of Q-CPR	1
14	Concerns data may be used to discipline paramedics	1
15	Would appreciate feedback to know what data is used for	1
16	Q-CPR use should be optional	1
17	Not suitable in traumatic arrest	1
18	Results in compressions that are not as deep	1
19	Feedback not useful	1

20	Difficult to see visual feedback	1
21	Should be discarded	1
22	General criticism regarding ambulance service	1
23	In an arrest with a reversible cause, would prioritise other interventions	1
24	Feedback from Q-CPR is useful in a controlled setting (training)	1
25	Have not seen any ambulance crews use it on road	1

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1

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