CARDIFF UNIVERSITY

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Cardiff University School of Medicine

ENGINEERING AN IMPROVEMENT IN CHEST COMPRESSION QUALITY DURING SIMULATED INFANT CARDIOPULMONARY RESUSCITATION

A Thesis submitted to Cardiff University
for the Degree of Doctor of Philosophy

By

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THESIS SUMMARY

Cardiac arrests in the infant population result in undesirable rates of both mortality and morbidity. Cardiopulmonary resuscitation (CPR) is a potentially life-saving emergency procedure, performed during cardiac arrest, which aims to promote blood flow to vital organs through the provision of external chest compressions. To improve cardiac arrest outcomes, current international resuscitation guidelines emphasise the provision of high quality chest compressions during infant CPR.

The principle goal of this research was to monitor, assess and engineer an improvement in the quality of chest compressions performed during simulated infant CPR. This was investigated in three experimental stages that evaluated: (i) the current quality of chest compressions performed on a commercially available manikin, (ii) the effects of a more 'physiological' infant CPR training manikin design on chest compression quality and thoracic over-compression and (iii) the effects of a real-time performance feedback program, developed to aid resuscitators in achieving high quality chest compressions. Performance was benchmarked against infant specific evidence based quality targets, with highly trained resuscitators achieving these targets in <9% of chest compressions during unassisted simulated infant CPR. The potential for thoracic over-compression in clinical practice was also highlighted when investigating the effects of the more 'physiological' infant CPR manikin design. The provision of real-time performance feedback considerably improved chest compression quality, with resuscitators achieving quality targets in >70% of all chest compressions.

This research indicates that unassisted chest compressions rarely comply with evidence based quality targets during simulated infant CPR. Real-time performance feedback, in combination with a more 'physiological' infant CPR manikin, can considerably improve the quality of chest compressions performed by resuscitators. Importantly, these findings provide an excellent foundation for translation into clinical practice, particularly for assisting resuscitators in providing high quality chest compressions during infant CPR, which may contribute to improving the future outcomes of infant cardiac arrest.

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LIST OF THESIS PUBLICATIONS

The original research articles published as part of this research are presented in the following articles, which may be accessed in Appendix B of this Thesis:

I P.S. Martin*, A.M. Kemp, P.S. Theobald, S.A. Maguire, M.D. Jones. Do chest compressions during simulated infant CPR comply with international recommendations? Archives of Disease in Childhood, 2013;98(8):576-81.

II P.S. Martin*, A.M. Kemp, P.S. Theobald, S.A. Maguire, M.D. Jones. Does a more "physiological" infant -manikin design effect chest compression quality and create a potential for thoracic over-compression during simulated infant CPR? Resuscitation, 2013;84(5):666-671.

III P.S. Martin*, P.S. Theobald, A.M. Kemp, S.A. Maguire, I.K. Maconochie, M.D. Jones. Real-time feedback can improve manikin cardiopulmonary resuscitation by up to 79%. Resuscitation, 2013;84(8):1125-1130.

The conference proceedings published as part of this research are presented in the following articles, which may be accessed in Appendix B of this Thesis:

IV P.S. Martin*, P.S. Theobald, A.M. Kemp, S. O'Brien, S.A. Maguire, M.D. Jones. Chest compression performance during infant CPR. Archives of Disease in Childhood, 2011;96(Suppl 1):A86.

V P.S. Martin*, P.S. Theobald, A.M. Kemp, S.A. Maguire, I.K. Maconochie, M.D. Jones. P11 Can Real-Time Performance Feedback Improve Chest Compression Quality During Simulated Infant CPR? A Randomised Controlled Trial. Archives of Disease in Childhood, 2013;98(Suppl 1):A5-A6.

The letter to the editor published as part of this research is presented in the following article, which may be accessed in in Appendix B of this Thesis:

VI P.S. Martin*, M.D. Jones, S.A. Maguire, P.S. Theobald, A.M. Kemp. Letter to the Editor: Increased incidence of CPR-related rib fractures in infants - Is it related to changes in CPR technique? Resuscitation, 2012;83:e 109.

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LIST OF ABBREVIATIONS

CPR	Cardiopulmonary resuscitation
CDmax	Maximum achievable chest compression depth
IHCA	In-hospital cardiac arrest
OHCA	Out-of-hospital cardiac arrest
PEA	Pulseless electrical activity
VF	Ventricular fibrillation
VT	Ventricular tachycardia
SIDS	Sudden infant death syndrome
AEDs	Automated external defibrillators
EMS	Emergency medical service
ED	Emergency department
ICU	Intensive care unit
ECMO	Extracorporeal membrane oxygenation
AHA	American Heart Association
PALS	Paediatric Advanced Life Support
RCUK	Resuscitation Council UK
APLS	Advanced Paediatric Life Support
ALSG	Advanced Life Support Group
ERC	European Resuscitation Council
EPLS	European Paediatric Life Support
ILCOR	International Liaison Committee on Resuscitation
HSFC	Heart and Stroke Foundation of Canada
ANZCOR	Australian and New Zealand Committee on Resuscitation
RCSA	Resuscitation Councils of Southern Africa
IAHF	Inter-American Heart Foundation

RCA	Resuscitation Councils of Asia
ECC	Emergency cardiovascular care
METs	Medical emergency teams
ROSC	Return of spontaneous circulation
CV	Compression-ventilation ratio
TT	Two-thumb infant chest compression technique
TF	Two-finger infant chest compression technique
AP	Anterior-posterior
CRD	Centre for Reviews and Dissemination
PICO	Population, intervention, comparator, outcome
BNI	British Nursing Index
CINAHL	Cumulative Index to Nursing and Allied Health Literature
MeSH	Medical subject heading
CADE	Critical appraisal and data extraction form
LOE	Level of evidence
QOE	Methodological quality of evidence
CASP	Critical appraisal skills programme
ETP	Endotracheal pressures
PET_{CO2}	End-tidal carbon dioxide pressures
NHS	National Health Service
CT	Computed tomography
ID	Internal anterior-posterior chest depth
$CDmax_{40}$	Maximum achievable chest compression depth of 40mm
$CDmax_{40}$	Maximum achievable chest compression depth of 56mm
VAM	Voice advisory manikin
BLS	Basic Life Support

DEFINITION OF CHEST COMPRESSION QUALITY MEASURES

Chest Compression Cycle	Chest compression cycles defined between consecutive chest release forces
Chest Compression Depth	The maximum chest deflection achieved during the chest compression phase of each chest compression cycle
Chest Release Force	The minimum chest compression force achieved during the chest release phase of each chest compression cycle
Chest Compression Rate	The inverse of the time taken for each chest compression cycle and quantified as the number of compressions per minute
Compression Duty Cycle	The proportion of each chest compression cycle with the active compression of the chest, which is often described as the compression-to-release ratio. Calculated for each chest compression cycle by dividing the area under the chest deflection curve by the product of the chest compression depth and chest compression cycle time

Figure 1-1 (overleaf) illustrates the above definitions for the chest compression quality measures.

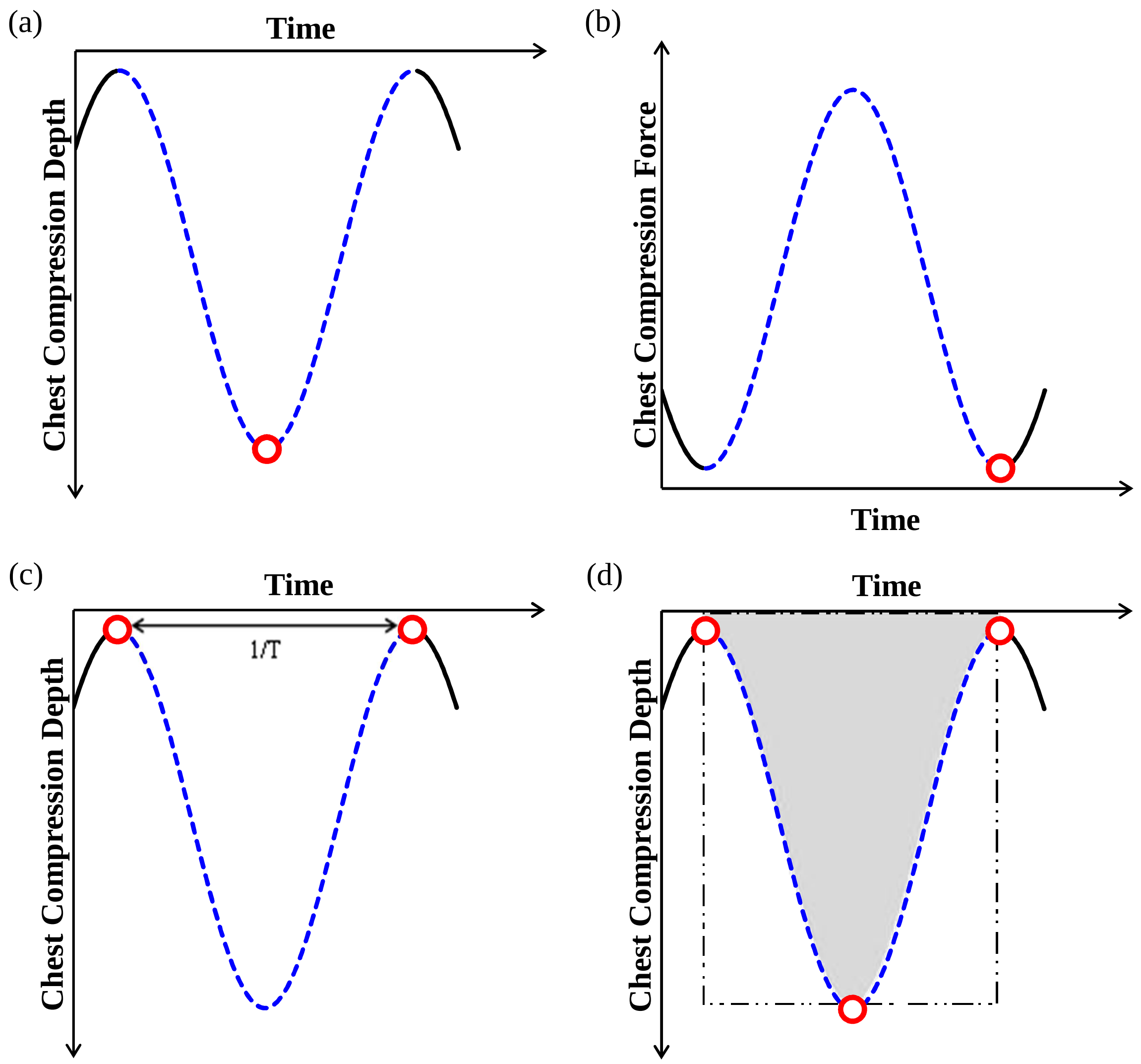

Figure 1-1: Example chest deflection curves defining (a) chest compression depths, (b) chest release forces, (c) chest compression rates and (d) compression duty cycles.

Each chest compression cycle is represented by a dashed line, the circular markers represent the points recorded for each quality measure, the shaded region represents the area under the chest deflection curve and the dashed-dotted box represents the product of the compression depth and the chest compression cycle time.

1 INTRODUCTION

1.1 Research Rationale

One of the most critical and dramatic of emergency situations is a cardiac arrest and the subsequent administration of cardiopulmonary resuscitation (CPR). The provision of CPR, a potentially life-saving procedure performed during cardiac arrest, focuses on a series of interventions that aim to restore and sustain the viability of vital organs. The immediate goal of CPR is to re-establish and maintain blood flow to fulfil the metabolic demands of the myocardium, brain and other vital organs. The overall goal of CPR is to reverse the effects of the underlying cause and to discharge the patient without physiological or neurological sequelae [1-3].

Infant cardiac arrests are considered to be rare events that result in undesirable rates of mortality and morbidity [4, 5]. In the United Kingdom, approximately 6,000 children experience a cardiac arrest each year [6]. Younger patients, specifically infants aged less than 1 year old, comprise the majority of these cardiac arrests (~62%) [6]. Despite more than five decades of research, survival rates remain poor, and outcomes vary considerably with the location, underlying pathophysiology and duration of each cardiac arrest [4, 5]. The years of potential life lost due to premature mortality are therefore substantial [7], whilst the long-term healthcare implications associated with morbidity in survivors are often expensive [8, 9]. Consequently, cardiac arrests in the infant population remain a substantial public health problem [1-3].

Cardiac arrests in the infant population vary considerably from those experienced in the adult and paediatric populations, principally due to the fundamental differences in the aetiology and physiology of infant cardiac arrest [4, 5, 10-12]. In contrast to adults, the causes of infant cardiac arrests are typically secondary to tissue hypoxia and acidosis caused by respiratory failure or circulatory shock. Consequently, current international resuscitation guidelines recommend treatment and educational strategies that specifically target the requirements of the infant population [1-3].

Infant CPR is currently performed according to the international guidelines for paediatric CPR [1-3]. To improve outcomes, these guidelines emphasise the provision of high quality chest compressions during infant CPR [1-3]. Fundamental to this is the optimum performance of four internationally recommended quality measures; chest compression depths, chest release forces, chest compression rates and compression duty cycles (i.e. the compression-to-release ratio) [13]. Recent research, however, reports the provision of poor quality chest compressions during simulated infant CPR [14-21]; caused principally by inadequate compression depths and a large variation in compression rates.

Although little is known about infant CPR quality in clinical practice, the disadvantages of poor quality CPR are well documented in other populations. Pauses during adult CPR are common [22-24], with interruptions in chest compressions affecting coronary perfusion pressures [25, 26] and impairing both the short and long term outcomes of cardiac arrest [27-29]. Shallow chest compressions correlate with a reduction in the haemodynamic [30, 31] and short term outcomes of cardiac arrest [32, 33], whilst the incomplete release of the chest limits the return of venous blood to the heart to reduce myocardial perfusion and ventricular preload [34, 35]. Prolonged duty cycles and excessive chest compression rates can further reduce cerebral blood flow, myocardial blood flow and cardiac output [36, 37], decreasing the likelihood of short-term survival [38, 39].

Real-time performance feedback systems may be valuable for monitoring and assisting resuscitators providing chest compressions during infant CPR. The benefits of feedback systems during adult CPR are well reported, with chest compression depth, chest release force and chest compression rate quality all improved through the provision of feedback [32, 40-42]. The effects of performance feedback on the quality of chest compressions provided during infant CPR have, however, never been quantified. Fundamental to this is a previous paucity of scientific evidence with which to establish chest compression quality targets for the optimisation of infant CPR quality. Recent advances in paediatric resuscitation research may now present sufficient scientific evidence to pave the way for the development of real-time performance feedback systems for infant CPR.

1.2 Research Aims and Objectives

The primary focus of this research was to monitor, assess and engineer an improvement in the quality of chest compressions provided during simulated infant CPR. To achieve these aims, the following objectives were identified:

1. Establish a technique to benchmark resuscitator performance against evidence based infant CPR chest compression quality targets.
2. Investigate the quality of chest compressions provided by trained healthcare resuscitators during simulated infant CPR on a commercially available manikin.
3. Design an instrumented infant CPR training manikin able to monitor both chest compression quality and thoracic over-compression during simulated infant CPR.
4. Assess chest compression quality and the presence of thoracic over-compression using this novel infant CPR manikin.
5. Develop a performance feedback system to assist resuscitators in achieving high quality chest compression during simulated infant CPR.
6. Evaluate the effects of the performance feedback system on chest compression quality and thoracic over-compression during simulated infant CPR.

1.3 Thesis Overview

Chapter 2: Literature review

Chapter 2 describes the current epidemiology, aetiology and pathophysiology of infant cardiac arrest, whilst also summarising the current practices of infant CPR. This Chapter further presents a systematic review of the literature to develop evidence based chest compression quality targets for infant CPR. These quality targets were based on current international recommendations to report chest compression depths, chest release forces, chest compression rates and compression duty cycles achieved during CPR.

Chapter 3: Establishing chest compression quality during simulated infant CPR

Chapter 3 presents a technique for benchmarking resuscitator performance against these evidence based chest compression quality targets and a study investigating the current quality of chest compressions provided by trained healthcare providers. A commercially available infant CPR manikin was instrumented to monitor chest deflections and chest compression forces during simulated infant CPR. The chest compression depths, chest release forces, chest compression rates and compression duty cycles achieved using the two-thumb and two-finger infant chest compression techniques were described. These were assessed against the evidence based chest compression quality targets to compare the differences in quality between techniques.

Chapter 4: Chest compression quality using a more 'physiological' manikin design

Chapter 4 describes the design of a more 'physiological' infant CPR training manikin, able to both monitor chest compression quality and simulate thoracic over-compression, to evaluate the chest compressions performed by highly trained healthcare resuscitators during simulated infant CPR. This more 'physiological' manikin allowed for a switch between a physiologically representative maximum achievable chest compression depth (CDmax) and a CDmax replicating that of the commercially available infant CPR training manikin. Two-thumb and two-finger technique chest compressions were simulated by trained healthcare providers using both infant CPR manikin designs. Differences in chest compression quality between manikin designs and chest compression techniques were compared, whilst the proportion of chest compressions that over-compressed the thorax using the more 'physiological' manikin design were also analysed.

Chapter 5: Effects of performance feedback on chest compression quality

Chapter 5 presents a real-time performance feedback program designed to assist trained healthcare providers in performing high quality chest compressions during simulated infant CPR. This real-time performance feedback program provided resuscitators with audio-visual feedback that aimed to assist them in achieving the evidence based chest compression quality targets for infant CPR. Using the more 'physiological' infant CPR manikin, the differences were compared between the quality of chest compressions provided by both infant chest compression techniques during both unassisted and feedback assisted simulated infant CPR.

Chapter 6: General Discussion

Chapter 6 discusses the principle findings of this research, comparing these findings against relevant literature, whilst also analysing the potential impact of this research on both the clinical and educational aspects of infant CPR.

Chapter 7: Conclusions

This final Chapter summarises the principle research conclusions, whilst also discussing potential directions for future research.

2 LITERATURE REVIEW

2.1 Research Background

2.1.1 Epidemiology of Infant Cardiac Arrest

In the United Kingdom, approximately 6,000 children experience a cardiac arrest each year [6]. Younger patients, specifically infants aged less than 1 year old, comprise of the majority of paediatric cardiac arrests (~62%), with males also affected in a higher proportion (~56%) [6]. A collective review of paediatric cardiac arrest cases, published over a decade ago, reported a survival to hospital discharge rate of 13%, with favourable neurologic outcomes in 62% of these patients [4]. This early study in paediatric cardiac arrest epidemiology identified that patients who sustain cardiac arrests in the in-hospital setting have much better survival rates, particularly when compared with patients that suffer cardiac arrests in the out-of-hospital environment (24 vs. 8.4%, respectively) [4].

Since this seminal epidemiological review, two further cohort studies have confirmed this observed difference in survival, concluding that paediatric patients experiencing in-hospital cardiac arrest (IHCA) and out-of-hospital cardiac arrests (OHCA) should be treated as two distinctive populations [43, 44]. Given the current advances in paediatric research and the recent collaborative efforts amongst medical centres, significant data now exist to comprehensively define the epidemiology of paediatric cardiac arrest [4]. Much less is understood, however, of the epidemiology of cardiac arrests in the infant population.

The purpose of this section, therefore, is to review the contemporary epidemiological aspects of cardiac arrests in the infant population. The epidemiological aspects of both out-of-hospital and in-hospital cardiac arrests, such as the incidence, aetiology and outcome, are all evaluated, in addition to the unique event characteristics of infant CPR. A full systematic epidemiological review for infant OHCA and IHCA is provided in the Electronic Appendices, whilst collated data tables are presented in Appendix A.1.

2.1.1.1 Out-of-Hospital Infant Cardiac Arrest

The annual incidence of infant OHCA lies between 33.8 and 72.7 (median: 65.9) cases per 100,000 infant persons [45-49]. A North American prospective multi-centre study determined that the incidence of cardiac arrest in infants is far greater than in children and adolescents (72.7 vs. 3.7 vs. 6.3 annual cases per 100,000 persons) [45]. This same study found that survival to hospital discharge was lower in infants than in children and adolescents (3.3% vs. 9.1% vs. 8.9%), but similar to that in adults (4.5%) [45]. Overall, survival to hospital discharge was achieved in 7% of all reported infant OHCA cases, ranging between 3% and 12% throughout the literature [45-53], with only a quarter of all survivors achieving a favourable neurological outcome [46, 48, 49, 51].

Initial cardiac arrest rhythms were documented during infant OHCA by a total of five articles and acquired in 98% of all cases [45, 47-49, 53]. The most common initial cardiac rhythms documented during infant OHCA were non-shockable pulseless rhythms (86%) [45, 47-49], with 89% of these cases experiencing asystole and 11% experiencing pulseless electrical activity (PEA) [49]. Shockable pulseless rhythms, such as ventricular fibrillation or ventricular tachycardia (VF/VT), occurred in just 3% of cases [45, 47-49, 53], but were associated with an improved likelihood of survival (9% vs. 3%) [53].

The aetiology of infant OHCA was reported for 919 patients across three studies [45, 47, 49]. Cardiac failure (44%), primarily diagnosed through excluding non-cardiac and non-natural arrests, and acute respiratory compromise (23%) were the most prevalent aetiologies, alongside patients that presented with the sudden infant death syndrome (SIDS). The prevalence of SIDS was reported across eight studies [45, 50, 51, 54-57], with 37% of infants categorised in these studies as having experienced a SIDS event. A further 30% of infant OHCA cases remained unspecified [45, 47, 49], indicating the current difficulties in determining the causes of infant OHCA [58].

With 93% of all infant cardiac arrests occurring in private locations, such as the home [45, 47, 49], the majority (77.5%) of infant cardiac arrests remained unwitnessed [45, 47-49, 53]. Bystander CPR was initiated in just 44% of cases [45-48, 53], whilst the use of automated external defibrillators (AEDs) by bystanders was rarely documented [45, 48, 53]. Average (weighted by number of cases) emergency medical service (EMS) response time (defined between the first emergency call and EMS arrival or EMS CPR provision) was 6.7 mins [47-49, 53], whilst average emergency department (ED) arrival time (defined between the first emergency call and ED arrival) was 27.6 mins [47, 53]. EMS interventions implemented during CPR include mechanical ventilation (21%), the provision of resuscitation drugs (3%) and AED use (2%) [45, 47, 53].

Only one article included by this review was observed to determine outcome predictors for cardiac arrests in the infant population [53]. This study identified four factors that were significantly associated with outcome following OHCA in infants: a witness to the OHCA, bystander rescue breathing, ED arrival time and EMS response time. Through categorising the study population into five subgroups based upon these factors, survival was found to range between 6% and 45% [53]. Amongst these subgroups, infant OHCA cases that were witnessed and ventilated by a bystander and that arrived at an ED within 17 mins had the greatest likelihood of survival (45%), whilst infant OHCA cases that were not witnessed had the lowest likelihood of survival (6%) [53].

2.1.1.2 In-Hospital Infant Cardiac Arrests

The incidence of infant IHCA remained unreported by all articles included for review, principally due to the difficulties in obtaining hospital admission data for this specific population. Assuming a relative proportion of patients admitted to those that experience a cardiac arrest, paediatric IHCA incidences may be used as a surrogate measure. These range from 0.1% to 2.9% (median: 1.3%) of all hospital admissions [59-61] and from 1.9% to 26% (median: 5.5%) of all intensive care unit (ICU) admissions [59-62]. Overall survival was achieved in 35% of all infant IHCA patients, ranging from 11% to 54% throughout the literature [59, 60, 62-71], whilst at least two-thirds of survivors achieved a favourable neurological outcome [60, 64, 67].

Initial cardiac arrest rhythms were reported by just two articles and documented in 93% of infant IHCA patients [64, 72]. Non-shockable pulseless cardiac rhythms presented in 49% of patients, with 48% of these diagnosed as asystolic and 52% diagnosed with PEA [64]. Shockable pulseless cardiac rhythms, however, were observed to present in 19% of infant IHCA patients [64, 72]. Pulsatile cardiac arrest rhythms were further reported in 38% of infant patients, with the majority (88%) of these patients primarily diagnosed with bradycardia [64].

Only one study was found to report the pre-existing pathological conditions diagnosed prior to infant IHCA and the aetiology of the precipitating event preceding infant IHCA [64]. Cardiac complications were the most prevalent pre-existing condition, with cardiac diseases (81%), circulatory shock (43%) and arrhythmias (24%) frequently reported. This was reflected in the aetiology of the precipitating event, as both circulatory shock (62%) and arrhythmias (40%) were commonly observed. Other pre-existing conditions included respiratory compromise (63%), infection or septicaemia (19%) and metabolic or electrolytic imbalances (20%). Acute respiratory compromise was perhaps the most common aetiology for the precipitating event, with acute respiratory diseases (46%) and airway obstructions (8%) frequently observed. Other documented aetiologies include metabolic or electrolytic imbalances (11%) and toxicological mechanisms (1%).

The majority of infant IHCA cases were observed to arrest primarily in the ICU (86%), with the remainder arresting in other wards [61]. Pre-arrest interventions were reported for 167 infant IHCA patients in one study only [64]. These reported the extensive use of patient monitoring systems prior to infant IHCA, with patients monitored via electrocardiograms (97%), pulse oximeters (96%) and arterial catheters (47%). Mechanical ventilations were also common (74%), as was the provision of vasoactive drugs (53%). The interventions implemented during infant CPR were fully reported in one study only [64]. Common interventions included open chest CPR (15%), extracorporeal membrane oxygenation (ECMO) (13%) and resuscitation drug therapies. The most common drugs administered during infant CPR included multiple epinephrine doses (79%), atropine (29%), sodium bicarbonate (72%) and calcium (47%) [64].

2.1.1.3 Epidemiological Literature Limitations

A lack of uniformity in case definitions, study designs, patient selection criteria and data abstraction methods across all studies impedes the epidemiological evaluation of infant cardiac arrest. Case definitions of cardiac arrest remain inconsistent across the literature, with several studies combining respiratory arrests with cardiac arrests, whilst further including aetiologies associated with increased risks of mortality such as septic shock, traumatic arrests and sudden infant death syndrome (SIDS) cases. Study sizes, designs, geographical location and length all varied extensively between studies, whilst inconsistencies in data abstraction and quality were widespread. Perhaps most importantly, the majority of infant cardiac arrest studies focussed primarily on the epidemiological characteristics of paediatric cardiac arrests, thus resulting in a paucity of detailed infant specific data.

2.1.2 A Brief History of Cardiopulmonary Resuscitation Guidelines

The first apparent attempts at resuscitation were recorded over two millennia ago, with written accounts of efforts to revive people found both in Ancient Egyptian texts and the Bible [73]. The 1950s and early 1960s, however, marked the birth of modern CPR as we know it today. The fundamental elements of CPR were developed after a series of pioneering experimental studies during this period, with CPR recognised as having the potential to save lives. Elam, Safar and Gordon published a series of seminal studies demonstrating the importance of positioning the airway to eliminate its occlusion by the tongue [74], the ability to maintain adequate oxygenation with expired air ventilations [75] and the superiority of mouth-to-mouth ventilations over previous strategies [76]. The concept of external chest compressions was introduced by Kouwenhoven, Jude and Knickerbocker, who established sufficient cardiac output during chest compressions to revive the heart or temporarily support the patient until they could be defibrillated [77].

Despite records of external chest compressions and artificial ventilations reported before these pioneering publications, it was these scientists that convinced mainstream medical communities to implement CPR in patients experiencing cardiac arrests. The translation of these findings from the bench to bedside has been essential in increasing the number of lives saved through the implementation of CPR. In 1966, the first conference on CPR was organised by the National Research Council of the National Academy of Sciences. They met with the American Heart Association during 1973 and published the standards for cardiopulmonary resuscitation and emergency cardiac care in 1974 [78]. In 1983, the

American Heart Association and American Academy of Pediatrics first developed the guidelines for paediatric and neonatal patients [79]. Since this seminal publication, these guidelines have been regularly updated with increasing detail and scientific evidence.

Advances in paediatric CPR have since escalated, evolving from a technique performed exclusively by highly trained healthcare practitioners to a lifesaving skill simple enough for everyone to learn. Since 1988, several organisations have developed courses to train healthcare providers and laypersons in how to treat infant cardiac arrests. The American Heart Association (AHA) first developed the Pediatric Advanced Life Support (PALS) course, educating physicians in how to treat infants that experience cardiac arrest [80]. In the United Kingdom, the Resuscitation Council UK (RCUK) was founded in 1981 [81], publishing the first national recommendations for resuscitation of children in 1986 [82]. The Advanced Paediatric Life Support (APLS) training course was developed by the Advanced Life Support Group (ALSG) during the early 1990s. This training course was unique in offering training in the management of cardiac arrest, the seriously ill and the injured child [83]. Finally, the European Resuscitation Council (ERC) was founded by 1990 [84], publishing the first European Paediatric Life Support (EPLS) guidelines in 1994 [85] and introducing the EPLS course in 2002 [86].

Since 1992, resuscitation experts from around the World have formed an international collaborative forum to rigorously review resuscitation science and develop evidence-based resuscitation guidelines. The International Liaison Committee on Resuscitation (ILCOR) is a council currently comprising of representatives from the AHA, the ERC, the Heart and Stroke Foundation of Canada (HSFC), the Australian and New Zealand Committee on Resuscitation (ANZCOR), the Resuscitation Councils of Southern Africa (RCSA), the Inter American Heart Foundation (IAHF) and the Resuscitation Councils of Asia (RCA) [87, 88]. Its mission is to identify and review the international scientific evidence base relevant to cardiopulmonary resuscitation (CPR) and emergency cardiovascular care (ECC) and, if consensus is achieved, offer recommendations on treatment [87, 88].

In 1995, ILCOR representatives published the paediatric "Utstein" guidelines, the first international consensus statement for the uniform reporting of outcomes from paediatric cardiac arrest [89], whilst in 1997 they published an advisory statement summarising the international recommendations for paediatric resuscitation [90]. In 2000, the first evidence-based guidelines on paediatric CPR and ECC were published simultaneously in Circulation and Resuscitation [91-94]. These protocols were revised by the 2005 International Consensus on CPR and ECC Science with Treatment Recommendations [95, 96]; the summary report from an international review of the resuscitation science and treatment recommendations that achieved international consensus. Several resuscitation councils, including the ERC and RCUK, supplemented this report further by publishing localised paediatric resuscitation guidelines and training materials [97-99]. Current ERC and RCUK paediatric CPR guidelines [2, 3] are established based upon the 2010 International Consensus on CPR and ECC Science with Treatment Recommendations [1, 100], whilst the evidence evaluation process is already underway in preparation for the publication of the 2015 report [101].

2.1.3 The Four Phases of Infant Cardiac Arrest

The physiology of infant cardiac arrest shares several common features across both the paediatric and adult populations. Four distinct phases of cardiac arrest can be identified: pre-arrest, no-flow (untreated cardiac arrests), low flow (CPR) and post-resuscitation. To maximise infant cardiac arrest outcomes, interventions should target the optimisation of therapies according to the aetiology, timing and phase of each individual cardiac arrest (Table 2-1).

The pre-arrest phase consists of the events preceding infant cardiac arrest and represents an important opportunity to impact survival rates. These preceding events include both the pre-existing pathological conditions and developmental status of the patient and the aetiology of the precipitating event. This phase experiences a period of abnormal blood flow, with infants primarily suffering progressive tissue hypoxia and acidosis secondary to respiratory arrest or circulatory shock. Pre-arrest interventions, therefore, focus on the prevention, anticipation and recognition of cardiac arrest in the infant population. In the in-hospital environment, this has driven interest in the implementation of rapid response medical emergency teams (METs) that are trained to identify and treat the precipitating factors of infant cardiac arrest prior to its onset [102, 103]. In the out-of-hospital setting, a number of paediatric caregiver education schemes (i.e. the 'Back to Sleep' campaign

Table 2-1: The four phases of infant cardiac arrest with interventions [10]

Cardiac Arrest Phase	*Key Interventions*
Pre-Arrest Phase	• Optimise community education regarding child safety • Optimise patient monitoring • Prompt recognition and implementation of interventions to avoid progression of respiratory compromise and shock
No-Flow Phase	• Minimise interval to initiation of BLS/APLS protocols • Rapid emergency response systems • Minimise interval to defibrillation, when indicated
Low-Flow Phase	• Effective CPR to optimise myocardial blood flow and cardiac output • Consider adjuncts to improve vital organ perfusion • Consider extracorporeal CPR if standard CPR unsuccessful
Post-Resuscitation Phase	• Optimise cardiac output and cerebral perfusion • Treat arrhythmias, if indicated • Avoid hyperglycaemia, hyperthermia and hyperventilation • Consider mild post-resuscitation systemic hypothermia • Debrief to improve future emergency responses • Early intervention with occupational and physical therapy • Bioengineering and technology interface • Possible future role for stem cell transplantation

BLS: basic life support; APLS: advanced paediatric life support; CPR: cardiopulmonary resuscitation

[104, 105]) and accident prevention strategies (i.e. vehicle booster seat legislation [106]) have been successfully implemented to reduce the incidences of infant cardiac arrests.

The no-flow phase represents the untreated cardiac arrest period, prior to its recognition by bystanders in the out-of-hospital setting or healthcare providers in the in-hospital setting. No-flow time is particularly detrimental, with the absence of cardiac activity resulting in a rapid decrease in both coronary and cerebral perfusion pressures until the initiation of CPR. The primary focus of any no-flow phase intervention is, therefore, the early recognition of pulseless cardiac arrests and the prompt initiation of paediatric life support protocols. To ensure prompt diagnoses within the in-hospital setting, high-risk infants are closely maintained in monitored units with immediate healthcare provider availability [4]. In the out-of-hospital setting, however, the majority of infant OHCA cases are unwitnessed, whilst bystander CPR can often be delayed or not provided at all [4, 5]. This considerably increases the no-flow periods experienced during infant OHCA and substantially reduces the chances of survival.

The low-flow phase commences at the initiation of CPR. The primary goal of effective CPR is to optimise coronary and cerebral perfusion pressures and cardiac output to the critical organs to support the viability of vital organs during the low-flow phase. During this essential phase, the only source of coronary and cerebral perfusion comes from the blood pressures generated by high-quality chest compressions provided during CPR. The provision of high-quality chest compressions that generate adequate coronary and cerebral perfusion pressures are critical to a successful resuscitation, whilst interruptions to perform procedures, check for pulses or change resuscitator are potentially harmful. With infant cardiac arrest patients principally suffering progressive tissue hypoxia and acidosis secondary to respiratory arrest or circulatory shock, the provision of adequate myocardial perfusion and oxygen delivery with ventilations is of vital importance. If presenting in ventricular fibrillation (VF) or ventricular tachycardia (VT), however, the prompt recognition of a shockable rhythm and its subsequent defibrillation is most vital.

The post-resuscitation phase begins with the return of spontaneous circulation (ROSC). This period is a particularly high-risk period for the progression of brain injuries and myocardial dysfunction and the extension of reperfusion trauma. Cells injured during the no-flow and low-flow phases of cardiac arrest can hibernate, die or either partially or fully recover physiological function. Reperfusion trauma can occur immediately after the reestablishment of circulation after a period of ischemia. The reintroduction of blood flow can cause both systemic inflammation and oxidative stress, increasing coagulation, impairing vasoregulation, suppressing adrenal release and lowering the immune system.

Myocardial dysfunction and severe hypotensive shock are common among survivors of cardiac arrest and are reversible phenomenon in the majority of infant cases. These are marked by global myocardial hypokinesis and low cardiac outputs and can manifest as hypotension, dysrhythmias and cardiovascular collapse. The primary objective of post-resuscitation rehabilitation, therefore, is to salvage injured cells, recruit hibernating cells and reduce neuronal losses. Critical interventions in this final phase, including the careful management of temperature, glucose, blood pressure, coagulation and ventilation, carry the potential for innovative advances.

The specific phase of infant cardiac arrest should determine the focus of care, with the timing, intensity and duration of interventions optimised to improve the outcomes of each phase. Special care should be taken to ensure that interventions, which improve the outcomes of one phase, are withheld if deleterious in another. Current understanding of the physiology of infant cardiac arrest, resuscitation and recovery has enabled the crude titration of blood pressure, global oxygen delivery and consumption, body temperature, inflammation, coagulation and other pathophysiological parameters to optimise survival outcomes. Future strategies will likely benefit from emerging discoveries, technologies and knowledge to focus on optimising the outcomes of all four phases of cardiac arrest.

2.1.4 Background on Infant Cardiopulmonary Resuscitation

The prompt initiation of high-quality cardiopulmonary resuscitation (CPR), in the low-flow phase of cardiac arrest, can considerably impact survival in the infant population. The goal of effective CPR is to optimise coronary and cerebral perfusion pressures and cardiac output to support the viability of vital organs. Recent research has provided important insights into basic life support during infant CPR, advocating the importance of a better understanding of these processes to optimise outcomes. The emphasis of the following sections is, therefore, to provide information pertinent to the current status of infant CPR, with a focus on its physiology and associated interventional therapies.

2.1.4.1 Airway and Breathing

The most common precipitating event for cardiac arrests in the infant population is respiratory compromise [4]. The provision of adequate ventilation and oxygenation must, therefore, remain a priority during cardiopulmonary resuscitation. Airway patency must be assessed to ensure it is free from obstruction, whilst the airway must be manoeuvred to lift the mandibular block of tissue from the posterior pharyngeal wall (Figure 2-1). If there is an absence of spontaneous breathing, the effort of breathing must be assumed by the provider through either mouth-to-mouth ventilations or advanced paediatric life support technologies, if available.

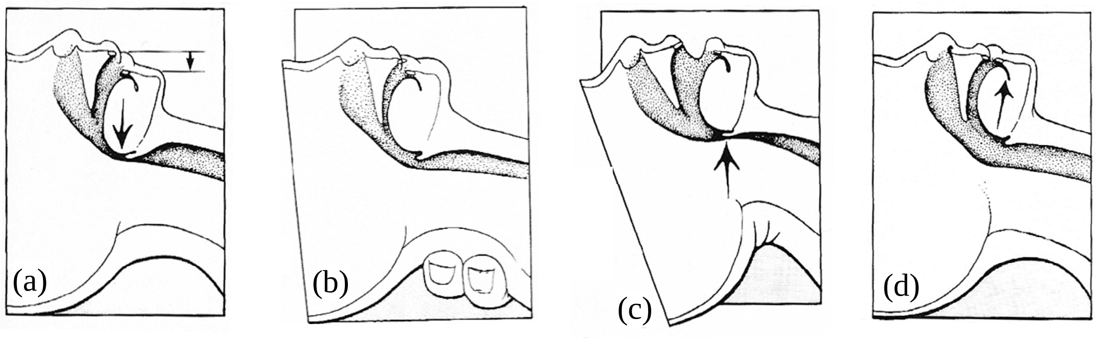

Figure 2-1: Upper airway obstruction management [107].
(a) Mandibular block obstructs upper airway due to onset of hypertonia; (b) Partial relief of airway obstruction by means of the head tilt technique (should not be performed if danger of cervical spine trauma); (c) Avoid extreme hyperextension causing airway obstruction; (d) Fully open airway through the jaw thrust or jaw lift technique.

The provision of adequate oxygen delivery, to meet metabolic demands and the removal of carbon dioxide, is the primary goal of initial assisted breathing. During CPR, cardiac output and pulmonary blood flow are reduced to between 10% and 25% of the levels experienced during a normal sinus rhythm [31, 108, 109]. Subsequently, less ventilation is required for the adequate exchange of oxygen, due to a reduction in blood traversing the pulmonary circulation [110]. Consequently, unintentional hyperventilation is common during paediatric CPR [111], resulting in adverse haemodynamics and aggravating the outcomes of cardiac arrest. Furthermore, as chest compressions maintain adequate aortic and coronary pressures during CPR, the interruption of these to provide rescue breaths results in a rapid decrease in both aortic and coronary perfusion pressure [25].

Ideal compression-ventilation (CV) ratios and tidal volumes for infant patients, therefore, remain unknown and are principally based on rational conjecture, tradition and educational retention theory. Optimal CV ratios depend on many factors, including tidal volumes, compression rates, the volume of blood flow generated by chest compressions and the period of time that chest compressions are interrupted to provide ventilations. Current infant CPR guidelines recommend CV ratios of 15 chest compressions to two ventilations (15:2), for trained healthcare providers, and 30:2 for lay rescuers and lone responders [1-3]. A CV ratio of 15:2 is the most effective CV ratio observed in infant animal and manikin studies, whilst ratios of 30:2 minimise the additional information needed to learn for lay rescuers and reduces interruptions during lone responder CPR to improve coronary blood flow. Consequently, optimum CV ratios for infant CPR remain an area of great research interest.

2.1.4.2 Chest Compressions

In the absence of signs of life, the provider must maintain adequate circulatory support during cardiac arrest through the provision of external chest compressions. The goal of effective chest compressions during infant CPR is to optimise coronary and cerebral perfusion pressures and cardiac output to support vital organs, as this is associated with improved outcomes [1-3]. The haemodynamic mechanisms of blood flow that results from chest compressions performed during CPR, however, remains the subject of continuous research.

External chest compressions circulate blood during CPR through several haemodynamic mechanisms (Figure 2-2) [10]. According to the ‘direct cardiac compression’ model, the left and right ventricles are compressed between the sternum and vertebral column during CPR [77, 112]. This generates a pressure gradient between the ventricles and the aorta and pulmonary arteries, closing the mitral and tricuspid valves and ejecting blood from the ventricles to generate the forward blood flow. During the release of the chest, negative pressure gradients across the heart promote retrograde blood flow to refill the heart and myocardium prior to the next compression [113]. The ‘thoracic pump’ model regards the heart as a passive conduit without any pumping mechanism [114]. This is instead provided by the thoracic circulation, where global rises in intrathoracic pressures during chest compressions force blood to flow from the thorax, through the heart and into the systemic circulation. During the chest recoil, negative intrathoracic pressures promote the return of venous blood to the thorax and heart in preparation for the next compression. In practice, a hybrid of these mechanisms probably contributes to the haemodynamics of chest compressions [10, 115]. Due to the increased compliance of the infant ribs and intrathoracic structures, however, the 'direct cardiac compression' mechanism may play a greater role during infant CPR [116].

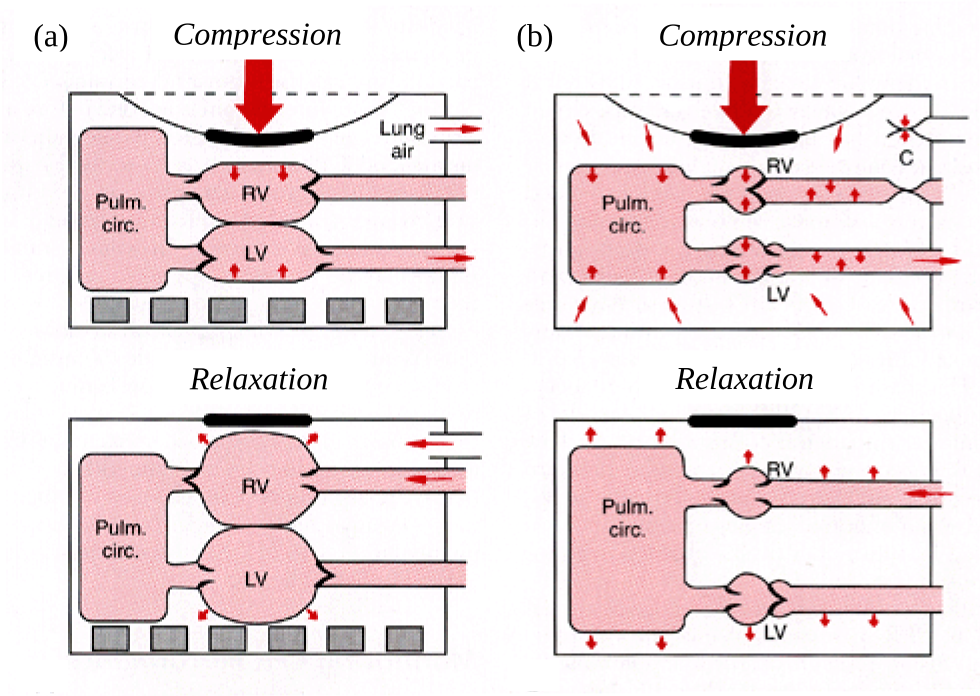

Figure 2-2: Haemodynamic mechanisms of blood flow during infant CPR for (a) the direct cardiac compression and (b) the thoracic pump chest compression models [10].
RV, right ventricle; LV, left ventricle; C, inspiratory impedance threshold device; Pulm. circ., pulmonary circulation; CPR, cardiopulmonary resuscitation.

The scientific evidence currently informing the quality of infant chest compressions was recently reviewed by the International Liaison Committee on Resuscitation (ILCOR) [1]. This has since formed the basis of both the European Resuscitation Council (ERC) and Resuscitation Council UK (RCUK) guideline recommendations for infant CPR [2, 3]. These propose that chest compressions be performed using either the two-thumb

(TT) hand encircling or two-finger (TF) technique (Figure 2-3), to chest compression depths of at least one-third the external anterior-posterior (AP) thoracic diameter (~4cm in infants), at compression rates of 100-120 min^{-1} and allowing the complete recoil of the chest [1-3]. TT technique chest compressions are favoured by the guidelines if two or more rescuers are present. The TF technique typically provides chest compressions with the infant in the supine position and using two fingers placed over the lower third of the sternum, whilst the TT technique provides chest compressions by squeezing the thorax between the thumbs and fingers with both hands encircling the lower third of the thorax [1-3].

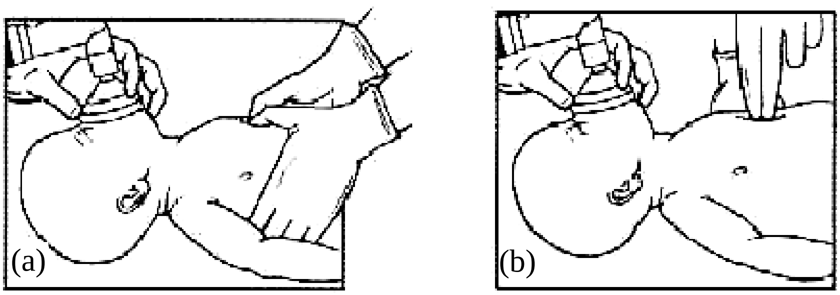

Figure 2-3: Hand positions for (a) the two-thumb (TT) hand encircling and (b) the two-finger (TF) chest compression techniques [107].

Finally, it is imperative that the provider continually assesses the efficacy of CPR. This can be simply evaluated through monitoring brachial/femoral pulse strength or through more innovative solutions, such as the use of capnography to continuously monitor end-tidal carbon dioxide concentrations and the use of displacement transducers to monitor and assist the chest compression rates and depths provided by the rescuer. Over the past decade, however, several studies have demonstrated the delivery of suboptimal CPR [22, 23]. To ensure high-quality chest compressions during infant CPR, current international guidelines recommend providers "push hard, push fast, ensure full chest recoil and minimise chest compression interruptions and hyperventilation" [1-3]. Automated feedback systems aim to provide objective real-time feedback on rescuer performance. This has been observed to improve chest compression depths and chest compression rates and reduce residual leaning and interruptions; all of which can lead to improved survival outcomes [32].

2.1.4.3 Resuscitation Medications

Resuscitation medications commonly administered in infants during CPR include vasopressors, antiarrhythmics, sodium bicarbonate, calcium and glucose [107]. The delivery of vasopressors (i.e. epinephrine or vasopressin) features prominently in the treatment of infant cardiac arrest; whilst the use of antiarrhythmics (i.e. amiodarone or lidocaine), sodium bicarbonate, calcium and glucose are of benefit in specific resuscitation circumstances (ventricular fibrillation, prolonged cardiac arrests, hyperkalaemia and hypoglycaemia, respectively). Intravenous fluids can also be administered, particularly when a patient exhibits signs of circulatory failure in the absence of volume overload. Although epinephrine and vasopressin improve haemodynamics and ROSC in animal surrogate models of cardiac arrest [117, 118], no single resuscitation medication has been shown to consistently improve survival outcomes after infant or paediatric cardiac arrest. The non-selective administration of these medications has, however, been associated with an increased likelihood of mortality and morbidity [62, 66, 119].

2.1.4.4 Defibrillation

Prompt defibrillation is vital to the successful resuscitation of ventricular fibrillation (VF) and ventricular tachycardia (VT) cardiac arrests across all ages. As infant cardiac arrests are primarily caused by respiratory compromise and circulatory shock, shockable cardiac arrest rhythms are rarely experienced in the out-of-hospital setting [5]. In the in-hospital environment, shockable cardiac arrest rhythms carry a much greater incidence, primarily due to the majority of infant IHCA cases being either cardiac surgery patients or patients with congenital cardiac diseases [4].

Although the requirement to defibrillate shockable rhythms is uncommon in infants, it should always be considered, particularly within the in-hospital environment. To use automated external defibrillators (AEDs) on infants, a shockable rhythm must be identifiable, appropriately sized paddles must be available and the AED must be attenuated to allow the delivery of a single $4Jkg^{-1}$ biphasic shock [1-3]. A paucity of evidence exists, however, to support these recommendations in the infant population.

2.2 Infant Chest Compression Quality Recommendations

Cardiac arrests require the prompt provision of cardiopulmonary resuscitation (CPR), with chest compressions remaining an essential component of CPR. The goal of chest compressions is to establish and maintain the perfusion of the vital bodily organs by mechanically generating sufficient cardiac output during the low-flow phase of cardiac arrest. To optimise haemodynamics, current international resuscitation guidelines recommend the provision of high quality chest compressions during infant CPR [1-3].

Infant chest compression guidelines have previously been developed and scaled using a combination of animal, paediatric and adult literature, in addition to consensus based expert opinions. The unique anatomy and physiology of infants and neonates, however, differs appreciably from these more readily available surrogates. The heart occupies a larger proportion of the intrathoracic cavity in infants, the size and shape of the thorax varies with both age and species and the infant rib cage exhibits a greater compliance than that of older children and adults [120]. Furthermore, infants experience faster heart rates, smaller stroke volumes and lower blood pressures [121].

The infrequent nature of infant cardiac arrest has impeded the rigorous investigation of the most effective chest compression technique during infant CPR. In fact, very little scientific evidence specifically exists to inform current infant CPR recommendations. Systematic literature reviews are a means to identify, evaluate and interpret all available research relevant to a specific research question, topic or phenomenon of interest [122]. The practice of systematically performing literature reviews has become an essential aspect of evidence-based medicine, with such reviews commonly used to summarise existing evidence for developing treatment strategies, to provide recommendations for the practice of future research and to identify opportunities in current research [122]. To date, however, no single review has systematically identified and critically appraised the scientific evidence currently informing the quality targets for chest compressions during infant CPR.

This aspect of the literature review therefore intends to systematically identify, interpret and appraise all research relevant to performing the most effective chest compressions during infant CPR. It is hoped that the results of this review will help inform current infant chest compression guidelines, improving the current understanding of this critical aspect of infant CPR, whilst also forming the basis of a system to benchmark the quality of chest compressions provided during simulated infant CPR across this research.

2.2.1 Chest Compression Quality Measures

Prior to performing this systematic review it is important to standardise the reporting of chest compression quality with the international resuscitation guidelines. The principal determinants of CPR quality have been previously formalised in a series of international collaborative conferences staged by the leading researchers in CPR quality [13]. These recommended a uniform reporting system to monitor and report the measured quality of chest compressions provided during CPR [13]. Specific quality measures recommended by these guidelines included chest compression depths, compressions with incomplete chest release, chest compression rates and compression duty cycles, all performed using the most effective technique at the most appropriate anatomical location [13].

Chest compression depths are defined as the maximum posterior deflection of the sternum prior to chest recoil. The incomplete release of the chest is described as a “leaning” phenomenon where the compression force is not completely removed from the chest between chest compressions. This can be reported either as a binary measure (whether the compression force is released beyond a target or not) or as a quantitative metric (the chest release force). Chest compression rates are calculated from the reciprocal of the time between two successive chest compressions and are conventionally quantified as compressions per minute. Finally, compression duty cycles (the compression-to-release ratio) describe the fraction of time with the active compression of the chest, evaluating this by calculating the area under the chest compression curve divided by the product of the chest compression depth and cycle time [13].

2.2.2 Search Strategy and Article Selection Criteria

This review of the literature was conducted following the core principles and methods for systematic reviews, as defined by the Centre for Reviews and Dissemination (CRD) [123] and the ILCOR evidence evaluation process [124]. Subsequently, this literature review sought to systematically address the six key PICO (Population, Intervention, Comparator and Outcome) questions overleaf:

1. *In infants receiving CPR* [P], *does any specific chest compression technique* [I], *as opposed to standard care* [C], *improve outcomes* [O]?
2. *In infants receiving CPR* [P], *do chest compressions performed at any specific location* [I], *as opposed to standard care* [C], *improve outcomes* [O]?
3. *In infants receiving CPR* [P], *does any specific chest compression depth or force* [I], *as opposed to standard care* [C], *improve outcomes* [O]?
4. *In infants receiving CPR* [P], *does any specific chest release depth or force* [I], *as opposed to standard care* [C], *improve outcomes* [O]?
5. *In infants receiving CPR* [P], *does any specific chest compression rate* [I], *as opposed to standard care* [C], *improve outcomes* [O]?
6. *In infants receiving CPR* [P], *does any specific compression duty cycle* [I], *as opposed to standard care* [C], *improve outcomes* [O]?

Seven online databases (Medline, Embase, ISI Web of Science, Scopus, Cochrane, BNI, and CINAHL) were searched for relevant literature through utilising the search strategy described in Table 2-2 (search strategies for each database are provided in Appendix A.2). This review attempted to identify all English language articles published prior to the 31st December 2012, which evaluated the most effective technique for providing chest compressions during infant CPR. All duplicate articles, conference abstracts, editorial letters, review articles and statements of expert opinion were excluded. Article titles and abstracts were screened for relevance, with identified articles included for the detailed review of the full manuscript. Finally, alongside specific searches of appropriate journal archives and grey literature for further relevant articles, the bibliographies of all studies selected for full text review were recursively searched.

Table 2-2: Medline database search strategy using MeSH terms and keywords

1	exp Infant/ *(896169)*
2	exp Infant, Newborn/ *(475786)*
3	(Infant* or Newborn* or Neonat* or Baby or Babies).tw. *(506997)*
4	exp Animals/ *(16529234)*
5	exp Models, Animal/ *(389512)*
6	exp Animal Experimentation/ *(5768)*
7	(Animal* or Animal Model* or Animal Experiment*).tw. *(769709)*
8	(Swine* or Porcine* or Pig* or Dog* or Pupp* or Canin*).tw. *(543765)*
9	exp Manikins/ *(2773)*
10	(Manikin* or Mannequin*).tw. *(2278)*
11	exp Cardiopulmonary Resuscitation/ *(10506)*
12	exp Resuscitation/ *(69363)*
13	exp Heart Massage/ *(2469)*
14	(Cardiopulmonary Resus* or CPR or Resus*).tw. *(47212)*
15	(Heart Massage or Cardi* Massage).tw. *(1206)*
16	((Chest or Thora* or Stern* or Abdom* or Cardi*) adj5 Compress*).tw. *(5328)*
17	(Two-finger or Two Finger).tw. *(174)*
18	(Two-thumb or Two Thumb or Hand Encircl* or (Chest adj5 Encircl*)).tw. *(28)*
19	(Compress* adj5 (Method* or Techni* or Maneuv* or Manoeuv*)).tw. *(4375)*
20	((Compress* or Heart) adj5 (Position* or Locat* or Site*)).tw. *(5095)*
21	(Compress* adj5 (Depth* or Force*)).tw. *(3679)*
22	((Release or Leaning) adj5 (Depth* or Force*)).tw. *(757)*
23	((Recoil or Decompression) adj5 (Depth* or Force*)).tw. *(200)*
24	(Compress* adj5 (Rate* or Frequenc*)).tw. *(2095)*
25	(Duty Cycle).tw. *(1635)*
26	(Compression adj5 (Ratio* or Fraction* or High Impulse or Duration))).tw. *(1491)*
27	or/1-10 *(16729199)*
28	or/11-16 *(97114)*
29	or/17-26 *(17998)*
30	and/27-29 *(1277)*

Number of articles retrieved by each line of the search strategy code is shown in *(italics)*. MeSH, medical subject heading; exp, exploded MeSH search term; tw, keyword search in title and abstract only; * keyword truncation; adj5, retrieves articles where two keywords appear, in no specific order, within 5 words of each other.

All articles were selected that evaluated the effectiveness of infant chest compression techniques during infant CPR. These included all clinical studies involving post-mortem or live infants (aged <1 year old), all radiological studies involving post-mortem or live infants with the subject in the supine position only, all laboratory studies involving live animals weighing 12kg or less (based on a 98th percentile 1 year old male), all laboratory studies involving manikins designed to represent infants and all mathematical models designed to represent infants and validated against age or weight appropriate human or animal experimental data. Articles were excluded if the study involved: data from adults or children (aged >1 year old); radiological data from subjects that were not lying in the supine position; data from animal surrogates weighing >12kg; data from post-mortem animal surrogates; data from manikins or mathematical models that represent adults or children; and data from mathematical models that were not appropriately validated.

Data extraction and critical appraisal procedures were performed using a standardised critical appraisal and data extraction (CADE) form, adapted from the CASP tools of the Public Health Resource Unit (Appendix A.3) [125]. Studies were classified by level of evidence (LOE) according to ILCOR definitions (Table 2-3) [124]. All infant manikin, animal, radiological and mathematical/computational model studies were classified as level of evidence 5 (LOE5) studies, irrespective of study design. Studies were further classified by methodological quality of evidence (QOE) according to ILCOR definitions [124]. Studies that failed to report potential confounders (i.e. chest compression quality)

Table 2-3: ILCOR levels of evidence (LOE) hierarchy for therapeutic interventions

LOE1:	Randomised controlled trials (or meta-analyses of randomised controlled trials)
LOE2:	Studies using concurrent controls without true randomisation (e.g. “pseudo” randomised)
LOE3:	Studies using retrospective controls
LOE4:	Studies without a control group (e.g. case series or reports)
LOE5:	Studies not directly related to the specific population (e.g. different populations, radiological studies, animal models, mechanical models, mathematical models etc.)

Table 2-4: ILCOR methodological quality of evidence (QOE) hierarchy for level of evidence (LOE) 4 and 5 studies

LOE4 Studies:	
Good:	Outcomes measured objectively, known confounders identified and controlled and patients adequately followed up
Fair:	Any two of the above
Poor:	Only one of the above
LOE5 Studies:	
Good:	Randomised controlled or crossed-over studies (equivalent of LOE1)
Fair:	Studies without randomised controls (equivalent of LOE2 or LOE3)
Poor:	Studies without any controls and studies with inadequate control of potential confounders

were classified with a poor QOE, whilst studies that failed to adequately control potential confounders were also reduced by one classification. All radiological studies were initially classified with a fair QOE, but this was reduced if appropriate selection criteria were not reported. Finally, all studies with missing data were also reduced by a classification. Illustrated in Table 2-4 are the ILCOR defined QOE hierarchies for both LOE4 and LOE5 classified studies (accounting for 97% (37/38) of all studies included in this literature review).

2.2.3 Included Articles

The flow of articles through the review selection process is illustrated by the PRISMA flow diagram in Figure 2-4 [126]. There were 3,842 citations retrieved from the original search, of which 3,789 were excluded based upon the *a priori* criteria. Of the 53 articles selected for full review, a total of 38 met the selection criteria and were fully evaluated. Of these 38 articles, fifteen reported on chest compression technique [14-20, 127-134], eight reported on chest compression location [128, 135-141], seven reported on chest compression depth [116, 140, 142-146], three reported on chest release force [147-149], seven reported on chest compression rate [150-156] and three reported on compression duty cycle [150, 153, 154]. One article reported on both chest compression technique and location [128], one on both chest compression location and depth [140] and three on both chest compression rate and duty cycle [150, 153, 154].

Of the 38 articles included in this review, 31 studies took place in the USA and Canada [14-20, 116, 127-132, 135-137, 142-150, 152-156], five took place in Asia [133, 134, 139-141] and two took place in Europe [138, 151]. Six articles were clinical studies of infant cardiac arrest [127, 129, 130, 137, 144, 155], two were anthropometrical studies in live infants [134, 145], one was an experimental study using live infants [148], two were infant cadaver studies [128, 135], 12 were radiological studies [128, 133, 135-141,

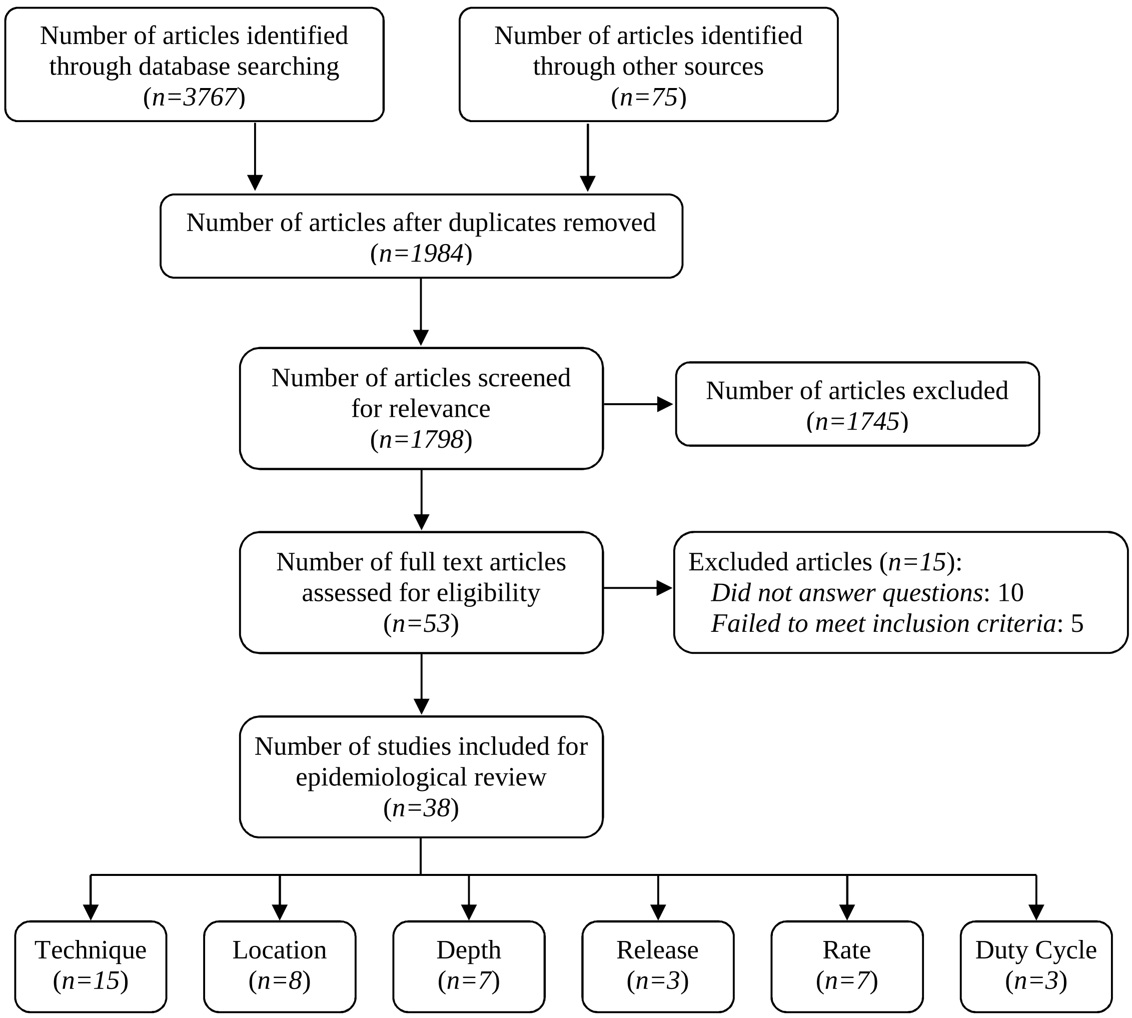

Figure 2-4: PRISMA flow diagram illustrating the flow of articles through the study selection process.
One article reported on both chest compression technique and location, one reported on both chest compression location and depth and three reported on both chest compression rate and duty cycle.

143, 146], eleven were animal surrogate studies [116, 131, 132, 142, 147, 149-154], seven were infant manikin studies [14-20] and one used a mathematical model [156]. Two articles were found to report on both infant radiological and cadaver case series [128, 135], whilst one article reported on infant radiological, cardiac arrest, surgery and autopsy cases [137]. Only one pseudo-randomised cross-over study using infant cardiac arrest subjects was identified by this systematic review [155]. Twelve articles were observational case series [127, 128, 133-141, 143, 145, 146], eight articles were experimental case reports or case series [116, 128-130, 135, 137, 144, 148], whilst the remaining articles were randomised controlled or cross-over laboratory studies that used manikins, animal surrogates or mathematical models.

2.2.4 Descriptive Analysis of Included Studies

2.2.4.1 Scientific evidence base establishing the most effective technique for chest compressions during infant CPR

Fifteen articles were identified by this review that investigated the most effective infant chest compression technique (Table 2-5). The earliest article reporting these effects was performed on a single neonate during cardiac arrest in a poor quality case series (LOE4) reported by Moya *et al*. in 1962 [127]. This study compared systolic and diastolic blood pressures generated by the TT and TF chest compression techniques, concluding that TF technique provided greater systolic blood pressures (70mmHg vs. 40mmHg) and similar diastolic blood pressures (20mmHg), when compared to the TT technique [127].

These conclusions were, however, challenged by a number of other early studies. Thaler and Stobie investigated the systolic blood pressures generated using early adaptations of the TT and TF techniques in a poor quality case series (LOE5) that used infant cadavers

Table 2-5: Articles included by this review that investigated the most effective chest compression technique during infant CPR

First Author	Year	Study Location	Study Type	Study Design	Study Population	Level of Evidence	Quality of Evidence	Primary Measure	Key Recommendation
Moya [127]	1962	USA	Experimental	Case Report	Infant Cardiac Arrest	LOE4	Poor	SBP, DBP	TF *better than* TT
Thaler [128]	1963	Canada	Experimental	Case Series	Infant Cadaver	LOE5	Poor	SBP	TT *better than* TF
Todres [129]	1975	USA	Experimental	Case Report	Infant Cardiac Arrest	LOE4	Poor	SBP	TT *better than* TF
David [130]	1988	USA	Experimental	Case Report	Infant Cardiac Arrest	LOE4	Poor	MAP, PP	TT *better than* TF
Menegazzi [131]	1993	USA	Experimental	Randomised Cross-Over Study	Animal Surrogate	LOE5	Poor	SBP, DBP, MAP, CPP	TT *better than* TF
Houri [132]	1997	USA	Experimental	Randomised Cross-Over Study	Animal Surrogate	LOE5	Fair	SBP, DBP	TT *better than* TF
Dorfsman [14]	2000	USA	Experimental	Randomised Cross-Over Study	Infant Manikin	LOE5	Fair	SBP, DBP, MAP, PP, F	TT *better than* TF
Whitelaw [15]	2000	USA	Experimental	Randomised Cross-Over Study	Infant Manikin	LOE5	Good	CD	TT *better than* TF
Haque [16]	2008	USA	Experimental	Randomised Control Study	Infant Manikin	LOE5	Good	CD, CP, CR, CC, F	TT *better than* TF
Udassi [17]	2009	USA	Experimental	Randomised Control Study	Infant Manikin	LOE5	Good	CD, CP, CR, CC, F	TT *better than* TF
Udassi [18]	2010	USA	Experimental	Randomised Cross-Over Study	Infant Manikin	LOE5	Good	CD, CP, CC, V	TT *better than* TF
Christman [19]	2011	USA	Experimental	Randomised Cross-Over Study	Infant Manikin	LOE5	Good	CD, CR, COV, T	TT *better than* TF
Lee [133]	2011	South Korea	Observational	Case Series	Infant Radiological	LOE5	Fair	LV, A	TT-S *better than* TT-A
Huynh [20]	2012	USA	Experimental	Randomised Cross-Over Study	Infant Manikin	LOE5	Fair	CD, CC, F	TT *better than* TF
Saini [134]	2012	India	Observational	Case Series	Live Neonatal Subjects	LOE5	Good	A	TT *better than* TF

LOE, level of evidence; SBP, systolic blood pressure; DBP, diastolic blood pressure; MAP, mean arterial pressure; PP, pulse pressure; CPP; coronary perfusion pressure; F, fatigue; CD, chest compression depth; CP, chest compression pressure; CR, chest compression rate; CC, total number of chest compressions; V, total number of ventilations; COV, coefficient of variation for chest compression depth; T, correct technique application; LV, left ventricle located below technique; A, abdomen located below technique; TT, two-thumb chest compression technique; TF, two-finger chest compression technique; TT-S, two-thumb superimposed chest compression technique; TT-A, two-thumb alongside chest compression technique.

[128]. This study found that lower TT technique chest compression forces were required to generate a systolic blood pressure of 100 mmHg, when compared to the TF technique (10 psi vs. 10-15 psi) [128]. This was confirmed in a poor quality case report (LOE4) by Todres and Rogers, which reported on the systolic blood pressures generated during the resuscitation of a neonate receiving alternate TF and TT technique chest compressions after cardiac surgery (TT: 85-110 mmHg vs. TF: 45-50 mmHg) [129]. Finally, a further study reported two cases with the TT and TF chest compression techniques performed on preterm neonates during CPR [130]. Across both cases, the TT technique generated greater mean arterial and pulse pressures across both measures, despite utilising slower compression rates and reduced chest compression depths [130].

Two animal surrogate studies (LOE5) were identified that evaluated chest compression technique efficacy. Menegazzi *et al*. performed a poor quality randomised cross-over laboratory trial between the TF and TT techniques that compared the systolic, diastolic, mean arterial and coronary perfusion pressures generated in seven infant swine (weight: 8-10kg) [131]. Following an induced cardiac arrest, 1,050 compressions were analysed to demonstrate that the TT technique was statistically superior across all haemodynamic outcomes [131]. Both techniques were further investigated by a fair quality randomised cross-over study using 10kg infant swine. The TT chest compression technique was observed to produce greater systolic blood pressures, with the TF technique unable to attain similar sternal compression forces [132]. Neither study, however, demonstrated the adequate control of chest compression quality; with a lack of sternal compression force and chest compression rate standardisation a particular concern. Consequently the conclusions of these studies should be interpreted with care.

The effectiveness of the TT and TF infant chest compression techniques has also been extensively explored through the use of infant manikin studies (LOE5). A fair quality randomised cross-over study used an instrumented infant CPR manikin to estimate the systolic, diastolic and mean arterial pressures generated during simulated infant CPR [14]. A metronome regulated compression rates, whilst chest compression depths were regulated through verbal instructions. Whilst this study found all 3 pressures increased significantly with the TT technique [14], a good quality study by Whitelaw *et al*. reported that the TT technique reduced the proportion of shallow compressions [15].

In a series of good quality LOE5 publications by the University of Florida College of Medicine, an instrumented infant CPR manikin measured the peak chest compression pressures, depths and rates that were generated during simulated infant CPR [16-18]. Despite observing 2.3 fewer compressions delivered over each minute of CPR [18], all 3 studies in this series found that the TT technique was statistically superior across all measures, whilst also reducing rescuer fatigue [16-18]. The authors concluded that the efficacy of the TT chest compression technique may far outweigh the benefits of the extra compressions delivered by the TF technique [18]. Superior TT technique efficacy was further confirmed by two recent LOE5 infant manikin studies comparing the chest compression rates and depths provided during simulated infant CPR [19, 20]. These found TT technique chest compressions to be superior despite the surface that it was performed on or whether it was performed with a 3:1 compression-ventilation ratio, a 30:2 compression-ventilation ratio or continuous chest compressions [19, 20]. Whilst one of these studies was classified with a good quality of evidence [19], the second was reduced by one classification, to fair, due to losing participants to follow up [20].

One good quality LOE5 study also investigated the correct placement of the TT and TF chest compression techniques in neonatal subjects [134]. Defining incorrect placement as any point of compression located below the xiphisternal junction, the TT technique was observed to achieve a greater proportion of correct placements (77.0% vs. 6.7%) [134]. The authors hypothesised that, during neonatal CPR, the TF technique may result in a higher incidence of abdominal compression, and thus intra-abdominal trauma [134].

Novel chest compression techniques have also been explored in an attempt to establish techniques with a greater efficacy. A superimposed two-thumb technique, similar to the technique originally reported by Thaler and Stobie [128], was compared to the standard TT technique in a fair quality case series (LOE5) of 84 infant CT scans by investigating the anatomical structures located below the thumbs of each technique [133]. It was found that the reduced area of the superimposed thumbs technique significantly lowered the likelihood of liver and lungs being located below the point of compression, therefore directly transferring compressive forces to the heart and reducing injury risks [133].

2.2.4.2 Scientific evidence base establishing the most effective anatomical location for chest compressions during infant CPR

Eight articles were identified by this review that investigated the most effective chest compression location during infant CPR (Table 2-6). In two poor quality infant cadaver studies (LOE5), Thaler and Stobie reported that, to achieve systolic blood pressures of 100 mmHg, chest compressions performed at the lower sternum required significantly greater applied pressures than midsternal chest compressions (15-20 psi vs. 10-15 psi) [128, 135]. The study further collected frontal and lateral chest x-rays of the cadavers, locating the ventricles beneath the midsternum of infants and showing a downward progression of heart position with age [128, 135]. This downward progression with age was

Table 2-6: Articles included by this review that investigated the most effective chest compression location during infant CPR

First Author	Year	Study Location	Study Type	Study Design	Study Population	Level of Evidence	Quality of Evidence	Primary Measure	Key Recommendation
Thaler [128]	1963	Canada	Observational & Experimental	Case Series	Infant Radiological & Cadaver	LOE5	Poor	SBP, HP	MS *better than* LS
Thaler [135]	1964	Canada	Observational & Experimental	Case Series	Infant Radiological & Cadaver	LOE5	Poor	SBP, HP	MS *better than* LS
Finholt [136]	1986	USA	Observational	Case Series	Infant Radiological	LOE5	Fair	HP	LS *better than* MS
Orlowski [137]	1986	USA	Observational & Experimental	Case Series	Infant Radiological, Surgery, Autopsy & Cardiac Arrest	LOE4 & LOE5	Poor	SBP, DBP, MAP, HP	LS *better than* MS
Phillips [138]	1986	UK	Observational	Case Series	Infant Radiological	LOE5	Poor	HP	LS *better than* MS
Shah [139]	1992	India	Observational	Case Series	Infant Radiological	LOE5	Fair	HP	MS *better than* LS
Kao [140]	2009	Taiwan	Observational	Case Series	Infant Radiological	LOE5	Fair	HP	Inconclusive
You [141]	2009	South Korea	Observational	Case Series	Infant Radiological	LOE5	Fair	LV, LVOT, Ao, Li, Lu	LS *better than* MS

LOE, level of evidence; SBP, systolic blood pressure; HP, heart located below site; DBP, diastolic blood pressure; MAP, mean arterial pressure; LV, left ventricle located below site; LVOT, left ventricle outflow tract located below site; Ao, aortic arch located below site; Li, liver located below site; Lu, lungs located below site; MS, midpoint of the sternum; LS, lower third of the sternum.

further documented in a fair quality radiological case series (LOE5) of 210 paediatric subjects [139]. The centre of the heart was located beneath the midsternum in 85.4% of infants aged ≤6 months old and below the lower third of the sternum in 52.8% of infants aged 7-12 months old [139].

Orlowski published a case series recording heart position using five separate modalities; post-mortem examinations, observations during cardiac surgery, routine chest x-rays, a thoracic CT scan and by monitoring the performance of chest compressions during CPR [137]. This poor quality LOE4/LOE5 article concluded that the infant heart was located below the lower third of the sternum and that this was optimum location for performing infant CPR [137].This conclusion was supported by two additional LOE5 case series, published in the same year, which evaluated a combined total of 85 chest x-rays and 25 angiograms [136, 138].

Finally, two recent fair quality case series (LOE5) analysed a total of 111 infant CT scans [140, 141]. In the study performed by You *et al*., the left ventricle was located 24% along the sternum from the xyphoid process, leading to the hypothesis that the most effective location may be below the lower third of the sternum [141]. The study by Kao *et al*., however, remained inconclusive, finding that the heart was located below both the lower sternum and inter-nipple line in >90% of cases [140].

2.2.4.3 Scientific evidence base establishing the most effective chest compression depth or force for chest compressions during infant CPR

Seven articles were identified by this review that investigated the most effective infant chest compression depth (Table 2-7). In a poor quality LOE4 case series of 6 neonatal patients suffering a pulseless cardiac arrest, Maher et al. compared the blood pressures

Table 2-7: Articles included by this review that investigated the most effective chest compression depth or force during infant CPR

First Author	Year	Study Location	Study Type	Study Design	Study Population	Level of Evidence	Quality of Evidence	Primary Measure	Key Recommendation
Babbs [142]	1983	USA	Experimental	Randomised Cross-Over Study	Animal Surrogate	LOE5	Good	CO, MAP	CD >15-30mm required for measureable CO & MAP
Dean [116]	1987	USA	Experimental	Non-Randomised Cross-Over Study	Animal Surrogate	LOE5	Fair	IVP	CD >20% APD required for measurable change in IVP
Braga [143]	2009	USA	Observational	Case Series	Infant Radiological	LOE5	Fair	RID	1/3 *better than* 1/2 APD
Kao [140]	2009	Taiwan	Observational	Case Series	Infant Radiological	LOE5	Fair	CD	1/3 *better than* 1/2 APD
Maher [144]	2009	USA	Experimental	Case Series	Infant Cardiac Arrest	LOE5	Poor	SBP, DBP	1/2 *better than* 1/3 APD
Sutton [145]	2009	USA	Observational	Case Series	Live Infant Subjects	LOE5	Fair	CD	CD *target of* 38mm
Meyer [146]	2010	USA	Observational	Case Series	Infant Radiological	LOE5	Fair	RID, EF	1/3 *better than* 1/2 APD

LOE, level of evidence; CO, cardiac output; MAP, mean arterial pressure; IVP, maximum intrathoracic vascular pressure; RID, residual internal depth of >10mm; SBP, systolic blood pressure; DBP, diastolic blood pressure; CD; chest compression depth; EF, ejection fraction; APD, anterior-posterior diameter of the thorax.

Table 2-8: Articles included by this review that investigated the most effective chest release depth or force during infant CPR

First Author	Year	Study Location	Study Type	Study Design	Study Population	Level of Evidence	Quality of Evidence	Primary Measure	Key Recommendation
Zuercher [147]	2010	USA	Experimental	Randomised Cross-Over Study	Animal Surrogate	LOE5	Good	CI, MBF	RF *target of* <10% of maximum CF
Sutton [148]	2010	USA	Experimental	Non-Randomised Cross-Over Study	Live Infant Subject	LOE5	Fair	ETP	RF *target of* <2.5kg CF
Zuercher [149]	2011	USA	Experimental	Randomised Cross-Over Study	Animal Surrogate	LOE5	Good	CO, MBF	RF of 260g does not affect haemodynamics

LOE, level of evidence; CI, cardiac index; MBF, myocardial blood flow; CO, cardiac output; ETP, endotracheal pressure; RF, chest release force; CF, chest compression force generated at approximate chest compression depths of both one-third and one-half the external anterior-posterior (AP) thoracic diameters [144]. Chest compression depths of approximately one-half the AP diameter produced superior systolic blood (83.4 mmHg vs. 51.6 mmHg), mean arterial (48.0 mmHg vs. 37.5 mmHg) and pulse pressures (52.9 mmHg vs. 21.0 mmHg), when compared to chest compression depths of approximately one-third the AP diameter [144].

These conclusions were further supported by two laboratory studies that investigated the effects of chest compression depths in infant animal surrogates [116, 142]. The first was a good quality randomised cross-over study (LOE5) that used 8 canines (weight: 6-12 kg) to demonstrate that cardiac output and mean arterial pressure were both linearly related to compression depth, once a threshold depth of approximately 15-30mm was exceeded [142]. The second was a fair quality non-randomised cross-over study (LOE5) that used 6 piglets (weight: 4.5-6.0 kg) to demonstrate maximum intrathoracic vascular pressures that were proportional to compression depths, after a threshold depth of approximately 20% the AP thoracic diameter was exceeded [116].

Three fair quality radiological case series (LOE5) and one fair quality anthropometric case series (LOE5) measured the thoracic parameters of both infants and neonates [140, 143, 145, 146]. Two of these studies predicted that >90% of infant and neonatal cases would experience the over-compression of the thoracic (residual internal thorax depths of <10mm) during chest compressions to one-half the AP diameter [143, 146]. Only one such case was, however, predicted for chest compressions to one-third the AP diameter [143]. Estimated ejection fractions were further calculated to determine thoracic under-compression; predicting the under-compression of the thorax in 54% of neonatal cases for chest compression depths of one-quarter the external AP diameter and no cases for compression depths of one-third the external AP diameter [146]. Sutton *et al*. assessed the suitability of an absolute compression depth of 38 mm for infant CPR. This absolute depth was predicted as too shallow (<1/3 the AP thorax diameter) in 16.3% of all infant cases and too deep (≥1/2 the AP thorax diameter) in just 2% [145]. In the final study, it was demonstrated that current infant CPR guideline recommendations result in absolute chest compression depths that exceed current adult based recommendations [140].

2.2.4.4 Scientific evidence base establishing the most effective chest release depth or force for chest compressions during infant CPR

Three articles were identified by this review that investigated the most effective chest release depth during infant CPR (Table 2-8). The first analysed the effects of residual leaning forces on chest compression haemodynamics in ten piglet surrogates (weight: 10.7±1.2 kg). Compared to no leaning force, this good quality LOE5 study found that residual leaning forces of 3.6 kg and 1.8 kg decreased both the cardiac index (1.9 vs. 1.6 and 1.4 $L.M^{-2}.min^{-1}$) and the myocardial blood flow (39 vs. 30 and 26 $mL.min^{-1}.100g^{-1}$) generated during CPR [147]. As these residual leaning forces represent 10% and 20% of the chest compression force required to maintain adequate systolic blood pressures, this study concluded that chest release forces of >10% would substantially decrease both the cardiac index and myocardial blood flow [147].

The effect of residual leaning forces on intrathoracic pressure was also investigated in a good quality LOE5 study performed on 13 paediatric subjects aged from 6.5-87 months and weighing between 7.4-24.8 kg (six subjects were infants aged ≤1 year old) [148]. Incremental sternal forces, between 10-25% of the subject's body weight, were serially applied to the chest of the subject. In this study, increased endotracheal pressures (ETP) were significant at residual leaning forces as low as 10%, whilst leaning forces of 2.5kg were associated with a clinically significant increase in ETP (≥2.0cmH_2O) [148].

Finally, in a good quality LOE5 piglet surrogate study (weight: 10.8±1.9kg), the effects of a residual leaning force of 260g (the equivalent weight of a commercially available sternal accelerometer/force feedback sensor device) were investigated [149]. No significant adverse effects were observed for either cardiac output or myocardial blood flow during CPR. As this residual leaning force represented approximately 2.5% the piglet body weight, this study concluded that such small leaning forces do not prevent the full recoil of the chest and thus optimise the subsequent return of venous blood flow [149].

2.2.4.5 Scientific evidence base establishing the most effective chest compression rate for chest compressions during infant CPR

Seven articles were identified by this review that investigated the most effective infant chest compression rate (Table 2-9). In one of the earliest studies, 24 piglets (weight: 4-5 kg) were used to evaluate the effects of various chest compression and ventilation rates on systolic blood pressures and mean arterial pressures [151]. Although compression rates ranged between 60-160 min^{-1}, at ventilation rates of 30-40 min^{-1}, this poor quality LOE5 study remained inconclusive as to the benefit of any specific chest compression rate [151]. The consequences of performing chest compression rates of 40 and 120 min^{-1} were further investigated, using 12 infant canines, in another poor quality LOE5 study (weight: 3-11kg). When assessing systolic blood pressures, cerebral blood flow, PV_{CO2}, PV_{O2} and PA_{O2}; PA_{O2} was observed to be the only measure to improve at faster chest compression rates [152]. Hence, it was concluded that increased chest compression rates produced little haemodynamic advantage [152].

Table 2-9: Articles included by this review that investigated the most effective chest compression rate during infant CPR

First Author	Year	Study Location	Study Type	Study Design	Study Population	Level of Evidence	Quality of Evidence	Primary Measure	Key Recommendation
Fitzgerald [150]	1981	USA	Experimental	Randomised Cross-Over Study	Animal Surrogate	LOE5	Good	CO	CR *target of* 126 min^{-1}
Traub [151]	1983	Germany	Experimental	Randomised Cross-Over Study	Animal Surrogate	LOE5	Poor	SBP, MAP	Inconclusive
Fleisher [152]	1987	USA	Experimental	Non-Randomised Controlled Study	Animal Surrogate	LOE5	Poor	CI, CbBF	Inconclusive
Dean [153]	1990	USA	Experimental	Randomised Cross-Over Study	Animal Surrogate	LOE5	Fair	CbBF	Chest relaxation time *target of* >200ms
Dean [154]	1991	USA	Experimental	Non-Randomised Controlled Study	Animal Surrogate	LOE5	Fair	CbPP, CbBF, MPP, MBF	100 min^{-1} *better than* 150 min^{-1}
Berg [155]	1994	USA	Experimental	Pseudo-Randomised Cross-Over Study	Infant Cardiac Arrest	LOE2	Poor	PET_{CO2}	Inconclusive
Babbs [156]	2009	USA	Computational	Computational	Mathematical Model	LOE5	Good	SPP	CR *target of* 120 min^{-1}

LOE, level of evidence; CO, cardiac output; SBF, systolic blood flow; MAP, mean arterial pressure; CI, cardiac index; CbBF, cerebral blood flow; CbPP, cerebral perfusion pressure; MPP, myocardial perfusion pressure; MBF, myocardial blood flow; PET_{CO2}, end-tidal carbon dioxide pressure; SPP, systemic perfusion pressure

Table 2-10: Articles included by this review that investigated the most effective compression duty cycle during infant CPR

First Author	Year	Study Location	Study Type	Study Design	Study Population	Level of Evidence	Quality of Evidence	Primary Measure	Key Recommendation
Fitzgerald [150]	1981	USA	Experimental	Randomised Cross-Over Study	Animal Surrogate	LOE5	Good	CO	DC *target of* 40%
Dean [153]	1990	USA	Experimental	Randomised Cross-Over Study	Animal Surrogate	LOE5	Poor	CbBF	Chest relaxation time *target of* >200ms
Dean [154]	1991	USA	Experimental	Non-Randomised Controlled Study	Animal Surrogate	LOE5	Fair	CbPP, CbBF, MPP, MBF	30% *better than* 60%

LOE, level of evidence; CO, cardiac output; CbBF, cerebral blood flow; CbPP, cerebral perfusion pressure; MPP, myocardial perfusion pressure; MBF, myocardial blood flow

Twenty infant canines (weight: 6-12kg) were used to investigate optimum infant chest compression rates in the earliest article identified by this review [150]. Cardiac output, in this good quality LOE5 study, was found to be optimised at chest compression rates of 126 min^{-1} [150]. Optimal compression rates were further investigated, using infant swine surrogates (weight: 3.5-6.8 kg), by two fair quality LOE5 articles. Across both studies, optimum chest compression rates of 100-120 min^{-1} maximised both the cerebral and myocardial blood flows and pressures [153, 154]. Furthermore, in a good quality LOE5 computational model study, a seven compartment model of the cardiopulmonary system was developed and validated against experimental data from animal surrogates [156]. This was used to simulate the optimum compression rates for a given body mass, concluding that the optimum rates were inversely related to the body mass of the infant (3kg = 184 min^{-1}; 5kg = 157 min^{-1}; 10kg = 124 min^{-1}) [156].

Finally, one poor quality pseudo-randomised cross-over study (LOE2) investigated the effect of audiotape guided chest compression rates in three infant cardiac arrest subjects [155]. This study found that audiotape guided compression rates of both 100 min^{-1} and 140 min^{-1} improved end-tidal carbon dioxide pressures (PET_{CO2}) generated during CPR, compared to baseline performance (5 torr vs. 16 torr and 14 torr) (the torr is a traditional unit of pressure, where 1 torr is approximately equal to 1 mmHg) [155]. No significant differences were, however, found between these two chest compression rates [155].

2.2.4.6 Scientific evidence base establishing the most effective compression duty cycle for chest compressions during infant CPR

Three LOE5 animal surrogate studies were identified as evaluating the most effective compression duty cycle during infant CPR (Table 2-10). Twenty infant canines (weight: 6-12kg), in a good quality study, were used to investigate optimum compression duty cycles during infant CPR. Cardiac output, generated during CPR in these infant animal surrogates, was optimised at compression duty cycles of 40% [150]. Optimum compression duty cycles were further investigated by two studies using infant swine surrogates (weight: 3.5-6.8 kg). Across both studies, optimum compression duty cycles were observed between 30% and 50% [153, 154].

2.2.5 Limitations of the Literature

This systematic review evaluated articles with an extensive range of study designs. This considerable heterogeneity is perhaps the most important limitation when investigating infant CPR. Included articles were observed to vary considerably in study size, study type and, perhaps most importantly, the population of interest. All articles included by this review were classified with a level of evidence of 4 or 5, apart from one level of evidence 2 classified study [155]. Methodological quality was classified as “good” in 11 articles [15-19, 134, 142, 147, 149, 150, 156], with 15 articles classified as “fair” [14, 20, 116, 131-133, 136, 139-141, 143, 145, 146, 148, 154] and 12 articles as “poor” [127-130, 135, 137, 138, 144, 151-153, 155] quality studies.

Eight studies evaluated the effects of varying the characteristics of chest compressions provided in either post-mortem or infant cardiac arrest subjects [127-130, 135, 137, 144, 155]. Although these provided highly relevant results for establishing the most effective chest compression technique for infant CPR, they were subject to several critical limitations. Infant cardiac arrest subjects often presented with a variety of pre-existing pathological conditions, cardiac arrest rhythms and after having received a wide range of cardiovascular drugs, all of which can potentially bias study outcomes. The majority of these studies also failed to appropriately record, or control, the quality of chest compressions performed during CPR. The possibility of type-1 errors affecting results is therefore conceivable, where any confounding variable combination could be the actual cause of improved CPR efficacy. Research using infant subjects presents a unique challenge, however, with the unpredictable nature of infant cardiac arrest, its relatively low incidence and the ethical issues associated with obtaining informed consent all specific problems. Researchers are, therefore, frequently limited to observational studies, which can often be subjected to a number of confounding variables.

Medical imaging can be a more practical way to non-invasively examine infant subjects; with 11 such articles identified by this review [128, 133, 135-141, 143, 146]. Although medical imaging is a recognised technique for acquiring anatomical landmark location data, it also has its own set of unique limitations. The most important of these arises from the ethical issues of imaging physiologically 'healthy' infant subjects, usually resulting in the opportunistic use of medical images taken in the course of treating chronically ill patient cohorts, increasing the potential for the inclusion of more diverse anatomical configurations. Furthermore, the acquisition of images during spontaneous respiration may also affect precise thoracic measurements, due to the natural expansion-contraction cycles of the chest during respiration. These issues, although uncontrollable in living subjects, have a minimal effect and so are considered acceptable limitations for infant thorax imaging studies [140].

Perhaps the greatest current challenge in investigating infant chest compression efficacy is the paucity of infant subjects. Current ethical considerations significantly restrict CPR research in a clinical environment due to the risks to life. One approach to overcoming this problem is through the use of biomechanically representative surrogate models that represent the infant patient. Instrumented infant CPR manikins were used extensively to establish the current characteristics of infant chest compressions [14-20]. The use of these infant manikins is, however, questionable. Several outcomes were based on pressures generated in non-validated saline bag representations of the “arterial system” [14], whilst infant manikin biofidelity has been validated only by subjective expert opinion [157]. Animal surrogates were used 11 studies, often resulting in better control of chest compression and cardiac arrest characteristics when compared to infant subject studies [116, 131, 132, 142, 147, 149-154]. Even so, age matching animal surrogates to infants is also a challenge, as these can only be validated based on the developmental stages of the brain [158], the geometric characteristics of the thorax [159] or surrogate weight and age. Although animal and infant manikin studies are popular alternatives to performing research with infant human subjects, no substantial evidence exists that categorically validates the biofidelity of these surrogates.

2.2.6 Overview of Infant Chest Compression Quality Recommendations

Although cardiac arrests in the infant population are a rare event, the consequences of systemic hypoperfusion on the brain and vital organ systems are often severe. As even effective chest compressions only partially achieve baseline blood flow levels [31, 108, 109], the provision of high quality chest compressions that maximise cardiac output are essential to the success of infant CPR. The optimisation of the infant chest compression technique, however, remains a neglected area of resuscitation research and training.

The scientific evidence currently informing the quality of infant chest compressions was recently reviewed by the International Liaison Committee on Resuscitation (ILCOR) [1]. This has since formed the basis of both the European Resuscitation Council (ERC) and Resuscitation Council UK (RCUK) guidelines for infant CPR [2, 3]. These propose that chest compressions be performed using either the two-thumb (TT) hand encircling or two-finger (TF) technique at the lower third of the sternum, to depths of one-third the external anterior-posterior (AP) thoracic diameter (~4cm in infants), at compression rates of 100-120 min^{-1} and with the complete recoil of the chest [1-3]. The TT technique is favoured by the guidelines if two or more rescuers are present [1-3]. Optimum duty cycle targets were not recommended by the current guidelines, in an apparent bid to simplify instructions.

The scientific evidence base analysed by this systematic review supports current ERC and RCUK guideline recommendations for chest compressions during infant CPR. The TT chest compression technique was found to be more effective than the TF technique thorough a combination of 13 animal surrogate, manikin model and infant cardiac arrest studies [14-20, 128-132, 134]. Animal surrogates, alongside mathematical models, were used to establish that optimum chest compression rates were 100-120 min^{-1} [150, 153, 154, 156]; whilst the infant heart was radiologically located below the lower third of the sternum across the majority of studies [136-138, 141]. Considerable haemodynamic advantages may be gained by compressing the chest deeper than one-third the external AP thoracic diameter [116, 140, 142-146] and by also allowing the full recoil of the thorax during the chest release phase [149].

Further evidence, not identified by the ERC and RCUK guidelines, was highlighted by this systematic review for three additional chest compression quality targets. Maximum chest compression depth targets were limited by radiological research that hypothesised that a residual internal thorax depth of <10mm posed an increased likelihood of causing intrathoracic trauma through the over-compression of the thorax [143, 146]. Compression duty cycles of 30-50%, when performed at rates of 100-120min^{-1}, were observed to optimise the haemodynamics of CPR in animal surrogates [150, 153, 154]. Finally, the haemodynamics of CPR were further optimised by allowing the chest to recoil beyond a chest release force target of 10% the body weight of the patient [147, 148].

A lack of uniformity in study sizes, study types and populations all impede the adequate evaluation of the most effective chest compression technique during infant CPR. The scientific evidence informing current international infant chest compression guidelines is further limited by the inadequate control of potentially confounding variables and the use of biomechanically unrepresentative models. Poor quality studies with inadequate control of chest compression characteristics are likely to bias haemodynamic outcomes and yet no study has, to date, attempted to completely control all chest compression variables. The accepted use of surrogate models, inadequately validated as physiological alternatives, is driven by current difficulties in obtaining infant cardiac arrest subjects. It must be borne in mind, therefore, that current infant CPR guidelines still rely on a very low standard of scientific evidence.

2.2.7 Conclusions

The scientific evidence identified by this review indicate that chest compressions during infant CPR should be performed using either the TF or TT technique, at the lower third of the infant sternum, to depths between one-third the external AP thorax diameter and residual internal thorax depths of 10mm, at rates of 100-120min^{-1} and duty cycles of 30-50% and allowing the complete recoil of the chest. These findings support current ERC and RCUK chest compression guidelines, whilst suggesting three further quality targets not identified by these guidelines; including a maximum chest compression depth target (a residual internal depth of 10mm), a compression duty cycle target range (30-50%) and a release force target (<10% patient weight). The scientific evidence that currently informs these guidelines is, however, considerably limited by the inadequate control of confounding variables and, perhaps most importantly, through the investigation of un-representative surrogates. It must be borne in mind, therefore, that current infant CPR guidelines still rely on a very low standard scientific evidence base and remain, at best, consensus driven.

3 ESTABLISHING CHEST COMPRESSION QUALITY DURING SIMULATED INFANT CPR

3.1 Introduction

The primary goal of cardiopulmonary resuscitation (CPR) is to perfuse the vital organs of the body during cardiac arrest by mechanically generating sufficient levels of cardiac output. To maximise cardiac output, current international paediatric CPR guidelines emphasise the provision of high quality chest compressions during infant CPR [1-3]. Central to achieving this is the optimal provision of the four chest compression quality measures, namely; chest compression depths, chest release forces, chest compression rates and compression duty cycles [13].

Several studies have attempted to establish infant chest compression quality by simulating two-thumb (TT) and two-finger (TF) technique chest compressions on instrumented infant CPR training manikins [14-21]. Although the majority of studies concluded that the TT technique was superior, as it achieved deeper and more consistent compression depths [15-20], only compression depths and rates have been reported. The chest release forces and compression duty cycles performed during simulated infant CPR have never been documented. Furthermore, the proportion of chest compressions that achieved evidence based quality targets for all four quality measures were rarely evaluated.

Performance decay can also be detrimental to chest compression quality; particularly during lengthy CPR episodes [17, 20, 21, 160-164]. To avoid this, current resuscitation guidelines recommend the provision of continuous chest compressions for a maximum of two minutes by each resuscitator [1-3]. Previous research, however, reports chest compression depth decay after just one minute of simulated infant CPR [17, 20, 21]. No data exists to document performance decay for the remaining quality measures, whilst the exact onset of performance decay for all four chest compression quality measures remains unknown.

Quality indices have been proposed as a tool for assessing chest compression quality during CPR [165-168], reporting the proportion of compressions that attained evidence based targets for each quality measure. To date, this 'quality index approach' has never been fully applied during infant CPR, primarily due to the paucity in scientific evidence with which to establish chest compression quality targets. As discussed in Chapter 2, recent research advances may now provide sufficient evidence for targets to be defined for a quality index approach to benchmarking rescuer performance.

The primary aim of this study was to assess and compare the quality of TT and TF technique chest compressions performed during simulated infant CPR on an instrumented infant CPR training manikin. The secondary aim was to investigate the consequences of performance decay on all four chest compression quality measures during simulated infant CPR. The final aim was to develop a quality index approach for assessing chest compression quality against evidence based quality targets. This approach may be used to benchmark the effects of future developments and interventions on chest compression quality during infant CPR.

3.2 Chest Compression Quality

Whilst the issue of chest compression quality has been researched since the early 1960s, the first concerns about the quality of CPR performance trace back to adult research in the mid-1990s [169, 170]. These studies concluded that only half of all out-of-hospital cardiac arrest cases received high quality CPR from bystanders, with high quality CPR associated with improved survival to hospital discharge [169, 170]. CPR quality was, however, only subjectively determined by these studies, through either palpating the carotid or femoral pulse or from simple observations made by the attending EMS crew. It was not until after 2004 that researchers objectively quantified the quality of chest compressions provided during both in-hospital and out-of-hospital CPR [22, 23, 32, 33]. This revealed the extent to which poor quality chest compressions were provided during adult CPR [22, 23, 32, 33], whilst also concluding that suboptimal chest compressions were associated with inferior survival outcomes [32, 33].

Since this seminal research, the optimisation of chest compressions performed during infant CPR has become a principal focus of both research and practical training. The importance of chest compression quality was first emphasised in the 2005 version of the paediatric CPR guidelines [96-99]. These guidelines coined the phrase “push hard, push fast, minimise interruptions, allow full chest recoil, and don’t hyperventilate” to encourage high quality chest compressions [96-99]. These guidelines were further endorsed in a 2010 revision, proposing that infant chest compressions be provided through the use of either the two-thumb (TT) hand encircling or two-finger (TF) technique at the lower third of the sternum, to compression depths of at least one-third the external anterior-posterior (AP) thoracic diameter (~40mm in infants), at chest compression rates of 100-120 min^{-1} and allowing the complete recoil of the chest [1-3].

3.2.1 Importance of Measuring and Reporting Chest Compression Quality

The importance of certain chest compression measures, and how to best report them, depends on several specific reporting goals. The first is the requirement for individuals to evaluate CPR events for the purpose of chest compression quality improvement. For individual quality improvement, in both the practical training and clinical environments, it is important to identify opportunities for developing and refining chest compression technique. Reported measures must focus on variables which have a documented effect on outcome, which are quantifiable and, perhaps most importantly, can be realistically improved by the individual. Medical recording and measurement devices, implemented to report these measures both in real-time and during debriefing, can therefore be used to correct chest compression quality. These devices may also support quality reporting, monitoring the effects of any change in algorithms or standard operating procedures and to compare services between providers.

Secondly, several clinical resuscitation trials have recently failed to translate promising results from paediatric experimental research to clinical practice [171, 172]. Since chest compression quality data is not routinely collected in clinical resuscitation trials, it is unknown whether CPR quality is equivalent between experimental groups or whether it is sufficient to generate appropriate circulation. The quality of CPR must, therefore, be accounted for at the research protocol stage, with differences between groups assessed via logistic regression analyses. The measures required for reporting these differences include variables which have a documented effect on outcome, are measurable during CPR in clinical practice and are easily entered into a logistic regression analysis.

Finally, for the research community studying the impact of chest compression quality on outcome, detailed and precise definitions are required to be able to compare results across studies. Specific guidelines for this have been defined through a series of articles that aimed to standardise the reporting mechanisms for both cardiac arrest outcomes and CPR quality [32, 89]. These guidelines present consensus based definitions and recommendations for reporting core cardiac arrest statistics, developing a common language for CPR quality research and a comprehensive reporting mechanism.

3.2.2 Current Chest Compression Quality

Recent resuscitation research, assisted by CPR quality recording devices, large cardiac arrest registries and high-fidelity manikin studies, has focussed on providing objective data regarding the quality of chest compressions during actual and simulated cardiac arrests. Unfortunately, a common theme from all these studies was that performance frequently did not meet evidence based guideline recommendations. These deficiencies in care have been observed throughout the infant, paediatric and adult literature during in-hospital, out-of-hospital and simulated CPR.

As previously mentioned, to standardise the reporting of chest compression quality, the principal determinants of chest compression quality were formalised through a series of international collaborative conferences staged by the leading researchers in CPR quality [13]. These recommended a uniform system to both monitor and report the quality of chest compressions provided during CPR [13]. Specific quality measures recommended by these guidelines included chest compression depths, compressions with incomplete release, compression rates and compression duty cycles [13].

3.2.2.1 Chest Compression Depths

Chest compression depths are defined as the maximum posterior deflection of the sternum prior to chest recoil [13]. Deeper chest compressions have been shown to correlate with increased cardiac output in animal surrogates [31, 116, 142, 173], increased blood pressures in infant subjects [144] and increased defibrillation success and survival to hospital discharge in adult subjects [32, 33]. Current international guidelines, therefore, recommend that chest compressions target depths of at least one-third the external AP thoracic diameter, approximating this to absolute depths of ~40mm in infants [1-3].

Investigations into chest compression depth quality during infant CPR have, however, been restricted to manikin based studies; observing that even highly trained healthcare personnel provided shallow chest compressions during simulated infant CPR [15-20]. Across all six studies, no study documented a mean compression depth that exceeded 30mm [15-20], whilst Whitelaw *et al*. further reported that shallow chest compressions were provided by 71% of all emergency medical personnel [15]. Furthermore, in five of these studies, the TT chest compression technique was consistently reported to achieve greater chest compression depths than the TF technique [16-20]. Inadequate compression depths are not unique to infant CPR, with around one-third of chest compressions observed to be shallow during adult OHCA and IHCA [22, 23, 32, 33] and around 30% of chest compressions observed to be shallow during feedback guided CPR in the older paediatric population [41, 174].

3.2.2.2 Chest Release Forces

Current international infant resuscitation guidelines recommend that chest compressions should allow the complete release of the chest [1-3]. The incomplete release of the chest is described as a “leaning” phenomenon, where forces are not completely released from the chest between chest compressions [13]. Animal surrogate and paediatric human subject studies both support the importance of completely releasing the chest to optimise cardiac filling and haemodynamics during CPR [34, 147-149]. Although data is sparse regarding outcomes related to the incomplete chest release, these studies showed that leaning can increase right atrial and intrathoracic pressures, thus decreasing cerebral and coronary perfusion pressures, cardiac output and myocardial blood flow [34, 147-149].

The incomplete release of the chest is prevalent throughout adult resuscitation, with the majority of rescuers failing to achieve chest release forces of <2.5kg during both OHCA and IHCA [35, 175]. During paediatric CPR, >97% of chest compressions were found to have release forces of ≥0.5kg, whilst 50% had chest release forces of ≥2.5kg [42]. Chest release force quality during infant CPR has, however, never been established.

3.2.2.3 Chest Compression Rates

Chest compression rates are calculated from the reciprocal of the time between two subsequent chest compressions and are typically quantified as compressions per minute [13]. Current international resuscitation guidelines recommend that chest compressions target rates between 100-120 min^{-1} [1-3]. As chest compression rates fall a significant reduction in the likelihood of ROSC occurs [38, 39], whilst greater chest compression rates reduce both coronary blood flow [150, 153, 154] and the proportion of chest compressions that achieve target depths [176].

Investigations into chest compression rate quality during infant CPR were also restricted to manikin based studies [16, 17, 19, 21]; with the majority of these studies observing the provision of excessive chest compression rates during simulated infant CPR. Chest compressions were observed to exceed rates of 132 min^{-1} across a series of studies performed by the University of Florida College of Medicine [16, 17]. Two further studies observed compression rates between 112-118 min^{-1} for both infant chest compression techniques [19, 21]. This is reflected during both older paediatric and adult CPR in the in-hospital and out-of-hospital settings, where high quality compression rates are provided in only one-third to one-half of all chest compressions [22, 23, 41].

3.2.2.4 Compression Duty Cycles

Compression duty cycles describe the proportion of time with active compression of the chest, evaluating this for each chest compression cycle by calculating the area under the chest deflection curve divided by the product of the chest compression depth and cycle time [13]. Whilst current international infant CPR guidelines do not recommend a target range for compression duty cycles, the neonatal guidelines recognise the advantages of allowing a relaxation phase that is slightly longer than the compression phase [177]. Theoretical models describe the optimal duty cycle as a compromise between systemic and coronary perfusion [178]. Animal surrogate studies suggest that it is an important determinant of haemodynamic performance, recommending an optimal range between 30-50% [150, 153, 154]. In studies monitoring the quality of adult CPR in the clinical setting, compression duty cycles were observed to be 42% in studies of out-of-hospital CPR [23, 32] and 43% during in-hospital CPR [179]. In the simulated CPR setting, compression duty cycles have been documented to range from 45-50% across a total of three adult CPR manikin based studies [167, 176, 180]. Compression duty cycle quality has, however, never been reported for either infant or paediatric CPR.

3.2.2.5 Chest Compression Performance Decay

Effective chest compressions remain a fundamental aspect of high-quality CPR during cardiac arrest [1-3]. Chest compressions are, however, widely recognised as a physically demanding task that can lead to the deterioration of quality over time. Several studies, during both actual and simulated adult CPR, have established that a significant decay in chest compression depth quality occurs after only one minute [161-164]. These studies further noted that providers were often unaware of this decay in performance and only subjectively reported experiencing fatigue after 3-4 minutes [161-164].

Chest compression depth decay is also experienced during simulated infant CPR [17, 20, 21]. Performance decay was found to particularly affect the TF chest compression technique, with both Udassi *et al*. [17] and Huynh *et al*. [20] reporting a 1.5-5mm deterioration in chest compression depths by the second minute of CPR when using a 30:2 C:V ratio. This was in direct contrast to TT technique compression depth decay, where the deterioration in depth by the second minute of simulated infant CPR was <1mm [17, 20, 21]. No research exists, however, that documents chest release force, chest compression rate or compression duty cycle performance decay, whilst the exact onset of decay for all four quality measures also remains unknown. To avoid performance decay, therefore, current guidelines recommend that continuous chest compressions be performed by each resuscitator for a maximum of two minutes only [1-3].

3.3 Methodology

3.3.1 Infant Manikin Design

A popular, commercially available, infant CPR training manikin (Laerdal® ALS Baby, Laerdal Medical, Stavanger, Norway), representing a three month old 5kg male infant, was selected for use in this study. The external anterior-posterior (AP) thoracic diameter of the manikin, between the most anterior and posterior aspects of the manikin thorax at the lower third of the sternum, was measured to be 110mm. The chest compression stiffness and maximum achievable compression depth of the manikin were established using a MTS 858 Mini Bionix II (MTS, MN, USA) compression testing machine (Figure 3-1). The manikin chest was compressed at a rate of $0.5mms^{-1}$ between the most anterior aspect of the

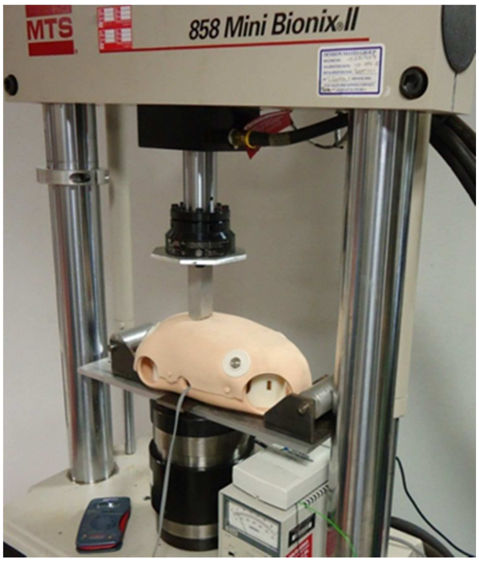

Figure 3-1: MTS 858 machine experimental set up to establish the compression stiffness and the maximum achievable compression depth of the manikin chest

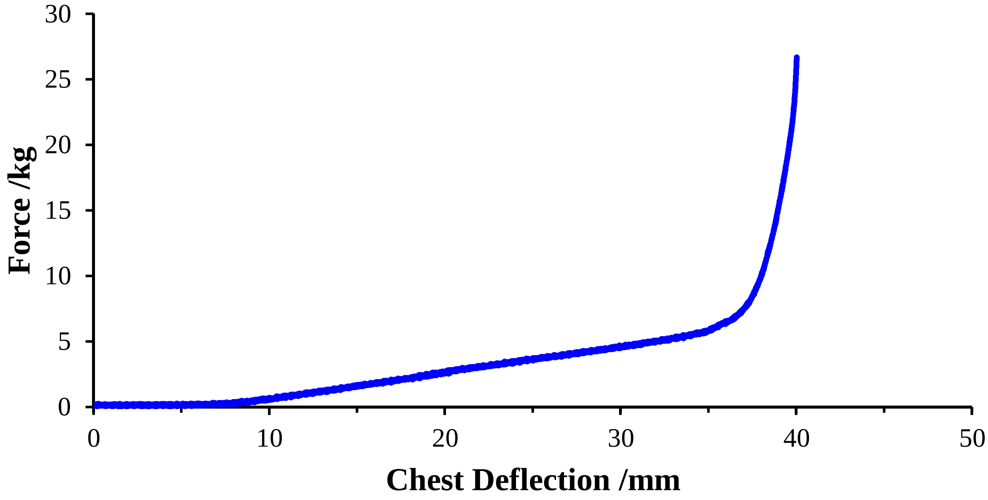

Figure 3-2: Anterior-posterior force-deflection properties of the Laerdal ® ALS Baby manikin chest

manikin thorax and a compression force of 26.4kg (Figure 3-2); a force equivalent to double the mean maximum achievable palmar pinch force for the dominant hand of a male adult [181]. This was repeated a total of three times. Chest deflections and chest compression forces were collected, at a sample rate of 24Hz, to characterise the mean force-deflection properties of the thorax. A mean (±σ) chest compression stiffness of 2.2±0.006Nmm^{-1} (defined between chest deflections of 15-30mm) and a mean (±σ) maximum achievable compression depth of 40.0±0.001mm were found.

The manikin was instrumented with a slider linear potentiometer (Min Slide Lin 100k, Maplin, Rotherham, UK), and powered by a 5V power supply, to record manikin chest deflections (Figure 3-3). Sensor selection was primarily based upon criteria including the cost effectiveness of the sensor, a maximum sensor height of 60mm (to fit inside the manikin chest during operation) and minimum sensing range of 40mm (to monitor the maximum chest deflections achieved during operation). The sensor selected for this

Figure 3-3: Laerdal ® ALS Baby manikin instrumented with linear potentiometer

study provided an inexpensive solution, particularly when compared to other solutions such as string pots or accelerometers. With a sensor length of 60mm and a maximum stroke length of 45mm, the sensor selected for this study was also capable of measuring the maximum chest deflections achieved during operation, without contacting the inside of the chest plate. Finally, sensor suitability was further based upon the accepted use of linear potentiometers in previous, peer reviewed, infant CPR manikin studies [16-18].

Sensor output was recorded using a data acquisition card and a customised LabVIEW software program (National Instruments, TX, USA), on a laptop computer, to record the output voltage signals. The manikin instrumentation was calibrated to record the chest compression depths and chest compression forces applied to the lower third of the manikin sternum during simulated infant CPR. The manikin chest was compressed by the MTS 858 machine, at a quasi-static rate of 0.5mms^{-1}, between the most anterior aspect of the manikin thorax and a chest compression force of 26.4kg. Chest deflections, chest compression forces and the sensor output voltage were recorded at a 24Hz sample rate. This was repeated a further three times, with deflection-voltage and force-voltage relationships were calculated from the first set of results. These relationships were applied to the remaining three sets of results to compare predicted and actual chest compression depths and forces (Figure 3-4). Mean regression gradients, with 95% confidence intervals [95% CI] and Pearson's correlation coefficients (R^2), for chest compression depths and chest compression forces were 0.996 [0.950, 1.042] mm (R^2=1) and 0.998 [0.952, 1.044] kg (R^2=0.998) respectively (calculated with SPSS 16.0, SPSS Inc., IL., USA).

The compression rate sensitivity of the manikin calibration relationships were assessed by compressing the manikin chest with sinusoidal waveforms performed at compression frequencies of 1Hz, 2Hz and 3Hz. The manikin chest was compressed by the MTS 858

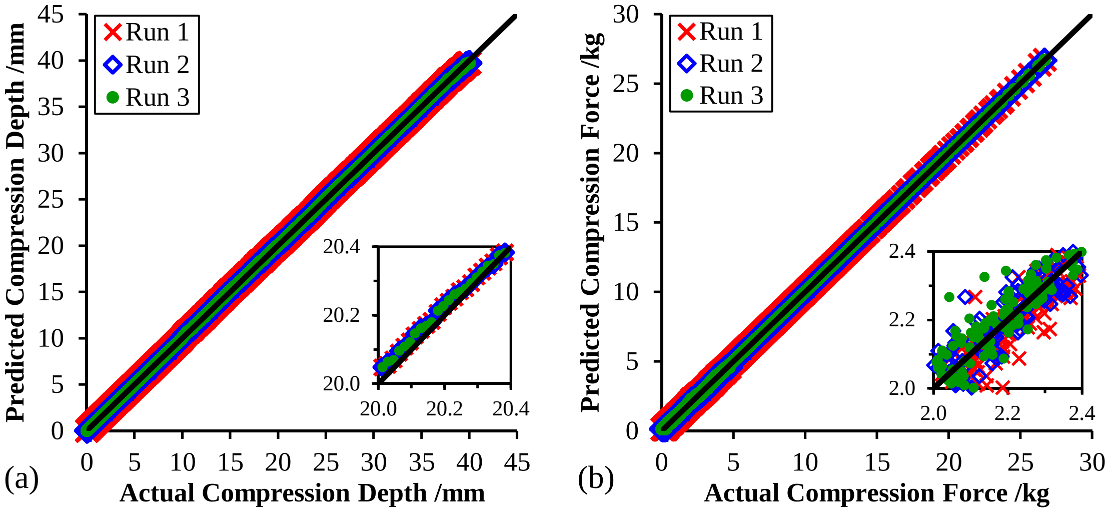

Figure 3-4: Actual versus predicted (a) chest compression depths and (b) chest compression forces as applied to the manikin chest

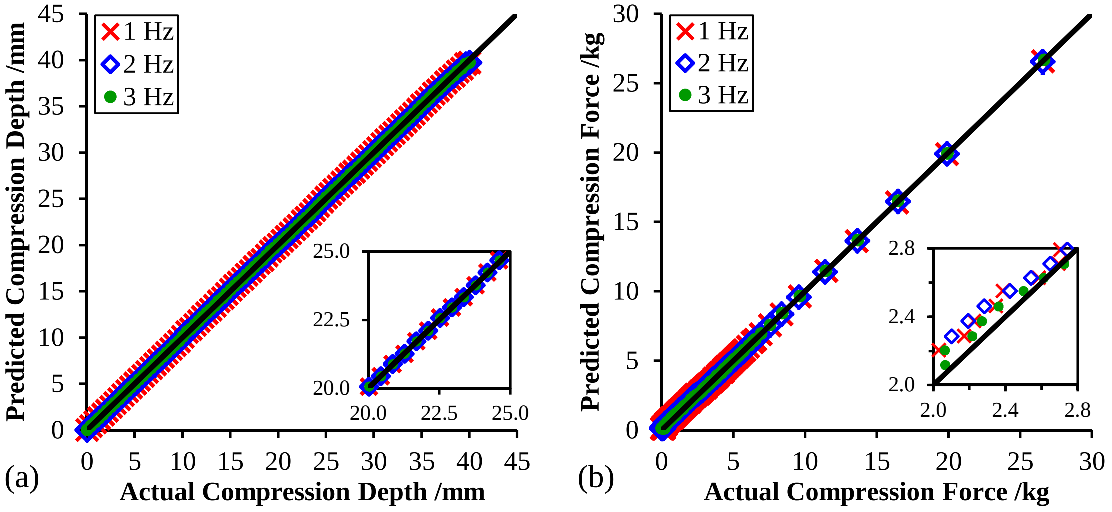

Figure 3-5: Actual versus predicted (a) chest compression depths and (b) chest compression forces for 1Hz, 2Hz and 3Hz chest compression frequencies

machine between the most anterior aspect of the manikin thorax and a 26.4kg chest compression force at each frequency. Chest deflections, chest compression forces and the sensor output voltage were recorded at sample rates of 48Hz (1Hz test), 96Hz (2Hz test) and 144Hz (3Hz test). Each test was performed for six cycles, with the fifth cycle compared, as above, to the deflection-voltage and force-voltage relationships developed during the quasi-static testing (Figure 3-5). Mean regression gradients, with 95% confidence intervals [95% CI] and Pearson's correlation coefficients (R^2), for chest compression depths and forces were 0.995 [0.763, 1.227] mm (R^2=1) and 0.978 [0.756, 1.200] kg (R^2=1) respectively (calculated with SPSS 16.0).

3.3.2 Study Coordination and Participants

This research study was approved by two local National Health Service (NHS) Health Boards in the South Wales region (IRAS 45342) and by both the CEO of the Advanced Life Support Group (ALSG) and the Working Group Chair of the ALSG run Advanced Paediatric Life Support (APLS) training course. Research ethical approval was obtained from the Cardiff University School of Engineering Ethics Committee, whilst Research Ethics Committee approval was not required, since NHS staff only were used in this study [182]. The approved Research Protocol, documentation and Letters of Approval for the study are presented in the Electronic Appendices.

Training course instructors were recruited to this study from two APLS training courses. Prior to testing, the Training Course and Medical Directors for each course confirmed their willingness to facilitate this study. Participant Information Sheets were circulated to all potential participants by the Training Course Director, at least one week prior to testing. Before testing, participants were briefed on the experimental procedures using the standardised Experimental Instruction Sheet. Any queries the participants had were answered and, once satisfied, the participants were asked to complete and sign the Participant Consent and Participant Details Forms. Individual results were reported back to the participant, via the Training Course Director, after study completion.

Twenty-two consenting instructors were recruited from two APLS training courses. The participant exclusion criteria for this study were: invalid APLS instructor certification, incomplete data acquisition, withdrawal of consent and participant health issues. Study demographics (gender, field of expertise and clinical experience) were collected via the Participant Details Forms. Study participants consisted of eight male and 14 female certified APLS instructors; 12 participants were doctors, seven were resuscitation officers and three were registered nurses. Mean (±σ) clinical experience was 17.4±7.7 years, whilst 11 participants were randomised to perform the TT technique first. A study sample size of 22 participants is able to adequately detect mean paired differences 0.6 times the standard deviation of the differences; assuming data normality, a two-sided significance level of <0.05 and >80% statistical power (calculated with G*Power 3.1.5 [183]).

3.3.3 Experimental Procedure

Prior to testing, the instrumented manikin was set up in a separate assessment room, on a flat table, with the laptop and peripheral equipment located below (Figure 3-6). Participants were assigned, via a table of randomised numbers, to a chest compression technique order (TT-TF or TF-TT) and instructed to perform continuous compressions (i.e. no ventilations required) for

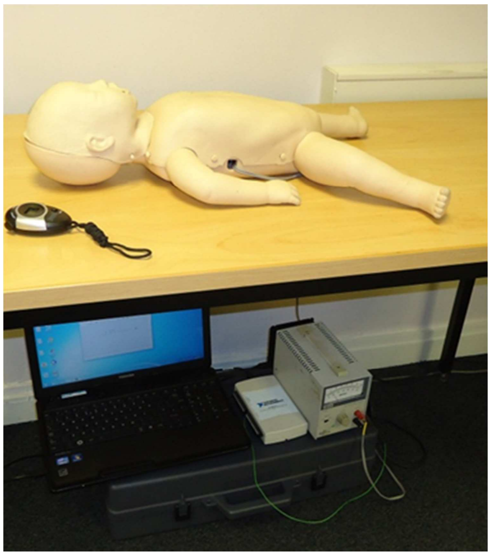

Figure 3-6: Experimental set up for testing

two minutes with each chest compression technique. Full recovery, during technique cross-over, was permitted for all participants. Chest compression depths and forces were recorded at a 50Hz sample rate throughout, with both the participant and investigator blinded to feedback. Participants were neither refreshed nor coached on either technique, nor briefed about the nature of the observations recorded.

3.3.4 Chest Compression Quality Measures

Chest compression quality measures for this study were adapted from internationally agreed guidelines for the uniform reporting of the measured quality of CPR (Figure 3-7) [13]. Chest compression depths were defined as the maximum chest deflection measured in the chest compression phase. Chest release forces were defined as the minimum chest compression force measured in the chest release phase. Chest compression rates were calculated from the inverse of the time between consecutive chest release forces. Compression duty cycles were calculated by dividing the area under the chest deflection curve by the product of the chest compression depth and time for each chest compression cycle. All four quality measures were calculated for each chest compression cycle, which were defined between consecutive chest release forces.

A quality index approach was developed to assess the quality of compression depths, release forces, compression rates and duty cycles, along with a quality index to characterise overall chest compression quality. For each quality index, the proportion of chest compressions that complied with quality targets for each measure was recorded. Chest compression depth and compression rate quality targets were based on current guideline recommendations; targeting depths of at least one-third the external AP chest diameter (≥36.7mm for this manikin) and a rate between 100-120min^{-1} [1-3]. A chest release force quality target of <2.5kg was defined to represent the chest compression force

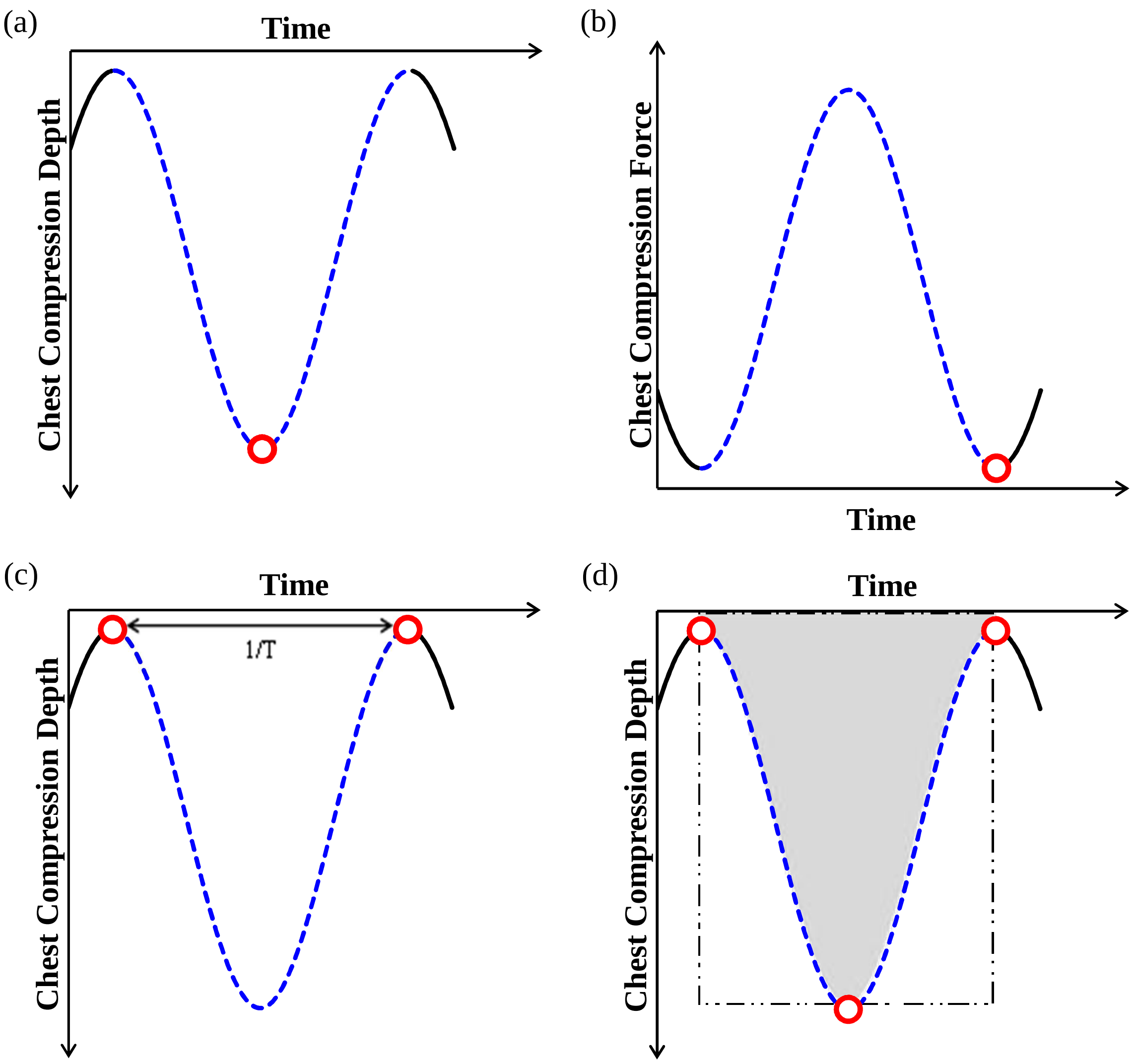

Figure 3-7: Example chest deflection curves defining (a) chest compression depths, (b) chest release forces, (c) chest compression rates and (d) compression duty cycles.
Each chest compression cycle is represented by a dashed line, the circular markers represent the points recorded for each quality measure, the shaded region represents the area under the chest deflection curve and the dashed-dotted box represents the product of the compression depth and the chest compression cycle time.

associated with a clinically significant increase in intrathoracic pressure in infants [148]. Finally, a compression duty cycle quality target of 30-50% was defined to represent the most effective range observed in infant animal surrogates [150, 153, 154].

Where multiple recommendations exist, secondary quality targets were also assessed. Using ERC & UKRC guideline recommendations, the proportion of chest compressions that achieved the approximated absolute chest compression depth target of ≥40mm were recorded [1-3]. A complete release force target of <10% the manikin weight (<0.5kg) was defined to represent the minimum chest compression force associated with a significant increase in intrathoracic pressure in infants and animal surrogates [147-149]. Also recorded for the secondary analysis were the proportion of chest compressions with excessive compression rates (>120min^{-1}) and prolonged duty cycles (>50%).

Finally, to assess overall chest compression quality during simulated infant CPR, the proportion of chest compressions that simultaneously achieved all four primary chest compression quality targets was calculated for each chest compression technique. This was repeated to record the proportion of chest compressions that also achieved three or more quality targets, two or more quality targets and at least one quality target.

3.3.5 Statistical Analysis

Median values for all four chest compression quality measures were recorded for each participant along with both the primary and secondary chest compression quality indices. Study results were reported either as means with standard deviations, or as medians with inter-quartile ranges, as appropriate. Mean paired differences between techniques were reported with 95% confidence intervals for all four chest compression quality measures. Performance decay was evaluated by analysing the changes in all four quality measures over the two minutes of chest compressions. Mean paired differences, comparing the first 15 seconds of chest compressions with the seven 15 second periods that followed, were reported with 95% confidence intervals. After testing for data normality (Shapiro-Wilk tests), all results were compared by either paired Student T-tests or Wilcoxon's signed rank tests as appropriate.

The effects of potential confounders, including gender, chest compression technique order, field of expertise and clinical experience, on all four quality measures were assessed. Data were tested for normality and homogeneity of variance (Shapiro-Wilk and Levene's tests). The effects of participant gender and chest compression technique order were analysed using either independent Student T-tests or Mann-Whitney U tests as appropriate. The effects of participant field of expertise were analysed using either one-way ANOVA or Kruskal-Wallis tests, as appropriate, whilst the effects of participant clinical experience were analysed by linear regression analyses. All statistical analyses were performed using the SPSS 16.0 statistical software package, with statistical significance considered at $p<0.05$ and all p-values considered to be two-sided, whilst post-hoc power analyses were performed with G*Power 3.1.5 [183].

3.4 Results

Simulated chest compression quality measures are illustrated against their evidence based quality targets in Figure 3-8 and summarised with their primary and secondary quality indices in Table 3-1. On average, participants compressed the chest significantly deeper with the TT chest compression technique than with the TF technique. This resulted in a greater proportion of chest compressions that achieved quality targets of one-third the external AP thoracic diameter, but failed to result in any chest compressions achieving depths of ≥40mm. A total of 16 (73%) participants achieved the primary chest

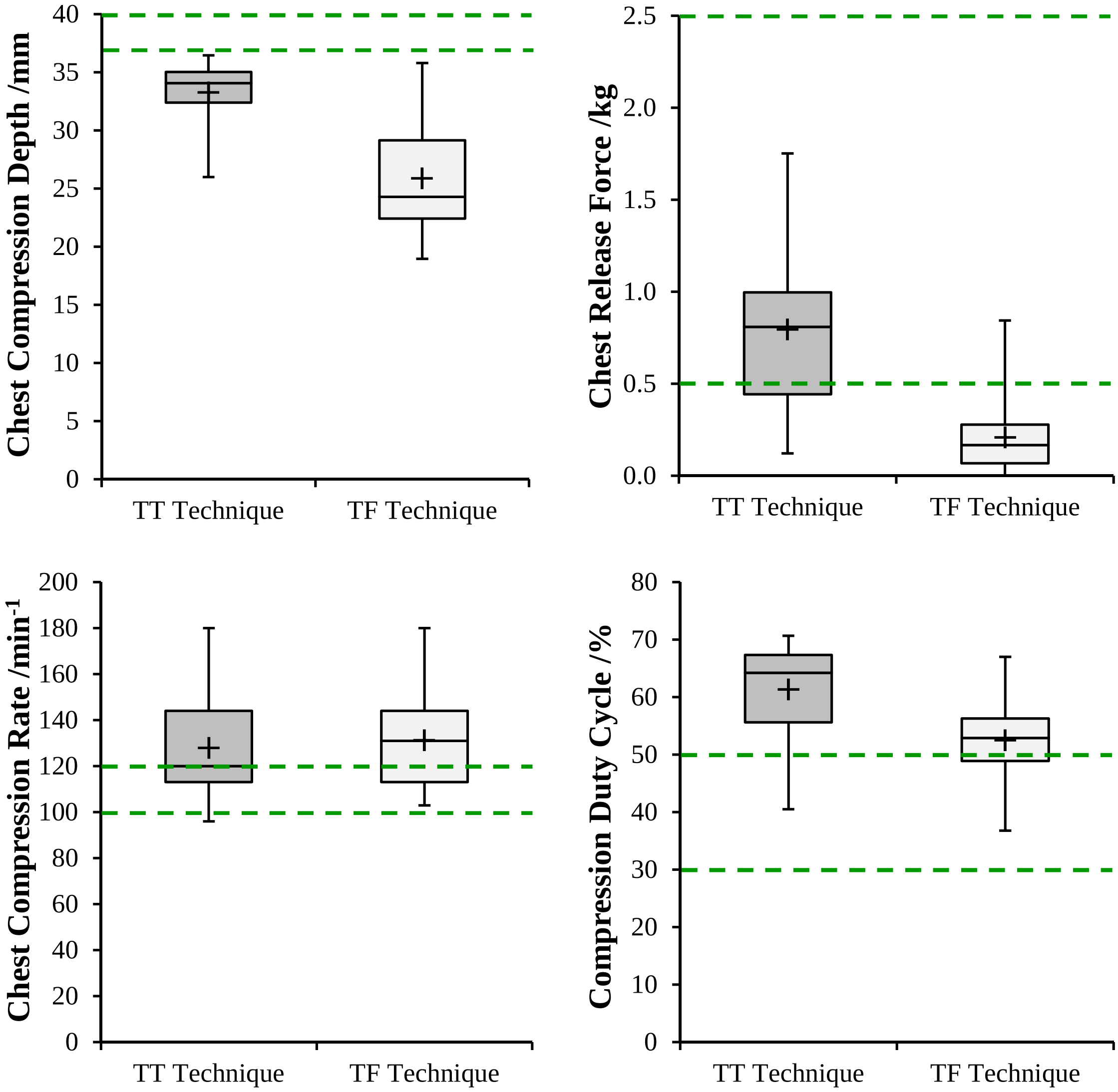

Figure 3-8: Illustration of the median chest compression depths, chest release forces, chest compression rates and compression duty cycles achieved by the two-thumb (TT) and two-finger (TF) chest compression techniques.

Current evidence based quality targets are illustrated by dashed lines. Chest compression depth targets were ≥36.7mm and ≥40mm, chest release force targets were <2.5kg and <0.5kg, chest compression rate targets were 100-120 min^{-1} and compression duty cycle targets were 30-50%. The centre line of the box plot represents the median value of the data, the upper and lower lines of the box plot represent the upper and lower quartiles of the data, the cross represents the mean value of the data and the whiskers represent the maximum and minimum values of the data.

Table 3-1: Simulated infant CPR chest compression quality measures and quality indices for the two-thumb (TT) and two-finger (TF) chest compression techniques

	TT Technique	TF Technique	Mean Paired Difference	*P*-value
Chest Compression Depths (CD)				
Mean Compression Depth /mm	33 ± 3	26 ± 5	7 [5, 10]	***<0.001****
Median Compression Depth /mm	34 [32, 35]	24 [22, 29]		***<0.001***†
CD Quality Index (≥36.7mm) /%	6 [0, 7]	0 [0, 0]		***<0.001***†
40mm CD Index (≥40mm) /%	0 [0, 0]	0 [0, 0]		1.00†
Chest Release Forces (RF)				
Mean Release Force /kg	0.8 ± 0.4	0.2 ± 0.2	0.6 [0.4, 0.7]	***<0.001****
Median Release Force /kg	0.8 [0.4, 1.0]	0.2 [0.1, 0.3]		***<0.001***†
RF Quality Index (<2.5kg) /%	100 [100, 100]	100 [100, 100]		0.32†
Complete RF Index (<0.5kg) /%	10 [0, 71]	100 [94, 100]		***<0.001***†
Chest Compression Rates (CR)				
Mean Compression Rate /min^{-1}	128 ± 21	131 ± 21	-3 [-7, 0]	0.052*
Median Compression Rate /min^{-1}	120 [113, 144]	131 [113, 144]		0.079†
CR Quality Index (100-120min^{-1}) /%	47 [3, 78]	39 [2, 72]		0.24†
CR Too Fast Index (>120min^{-1}) /%	33 [6, 97]	61 [17, 98]		0.053†
Compression Duty Cycles (DC)				
Mean Compression Duty Cycle /%	61 ± 8	53 ± 8	9 [6, 11]	***<0.001****
Median Compression Duty Cycle /%	64 [56, 67]	53 [49, 56]		***<0.001***†
DC Quality Index (30-50%) /%	0 [0, 7]	23 [4, 62]		***<0.001***†
Prolonged DC Index (>50%) /%	100 [93, 100]	77 [38, 96]		***<0.001***†

Mean quality measures are presented as mean values ± standard deviation, whilst both the median quality measures and quality indices are presented as median values [inter-quartile range]. Differences between quality measures (TT less TF) are presented as mean paired differences [95% confidence interval]. *P*-values were calculated from two-sided paired samples Student's T-tests (*) or Wilcoxon's Signed Rank tests (†).

compression depth quality target with the TT technique, whilst only two (9%) achieved this with the TF technique. No participant was observed to achieve the primary chest compression depth quality target (≥36.7mm) with >50% of chest compressions.

The TF chest compression technique was observed to both release the chest significantly further and significantly reduce the compression duty cycle, when compared to the TT technique. This improved the proportion of compressions that achieved compression duty cycle quality targets, with >99% of all chest compressions achieving chest release force quality targets. Consequently, this improved the proportion of compressions that completely released the chest, whilst also reducing the proportion of compressions with a prolonged duty cycle.

No significant differences were detected between the techniques for chest compression rates. Overall, less than 50% of chest compressions achieved current chest compression rate quality targets during simulated infant CPR, with excessive chest compression rates frequently provided by the majority of participants.

The overall chest compression quality indices achieved by the TT and TF chest compression techniques are illustrated in Figure 3-9. Overall chest compression quality was observed to be very poor for both techniques, with <1% of all chest compressions complying simultaneously with all four quality targets and with ~50% of chest compressions failing to

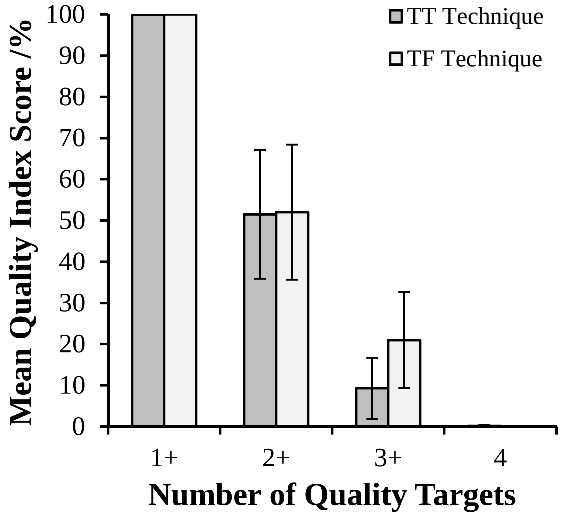

Figure 3-9: Mean overall quality indices for the two-thumb (TT) and two-finger (TF) chest compression techniques.
Error bars represent 95% confidence intervals.

achieve two or more quality targets. When comparing techniques, the TF technique was observed to achieve a greater proportion of chest compressions that complied with three or more chest compression quality targets only (mean paired difference: -12 [-20, -3]%; p=0.008).

The change in all four chest compression quality measures, over two minutes of chest compression only CPR, is illustrated for the TT and TF chest compression techniques in Figure 3-10. Performance decay was observed for TT technique compression depths and compression duty cycles, with a 1-1.5mm reduction in compression depth observed after 15 seconds and a 2-3% increase in compression duty cycle between 30-90 seconds. Performance decay was observed for TF technique compression depths, with a 1-1.5mm reduction in compression depth between 75-105 seconds. No significant decay in chest compression rate or chest release force performance was observed for either infant chest compression technique.

Of the potential confounders investigated, participant gender, field of expertise and clinical experience were all observed to have no significant effect on any of the quality measures achieved. Participants that performed the TT technique first were, however, found to provide faster TT technique compression rates than those that performed the TF technique first (mean difference: 18 [1, 36]min^{-1}; p=0.044; power=33%). Aside from this, no other quality measure was affected by chest compression technique order.

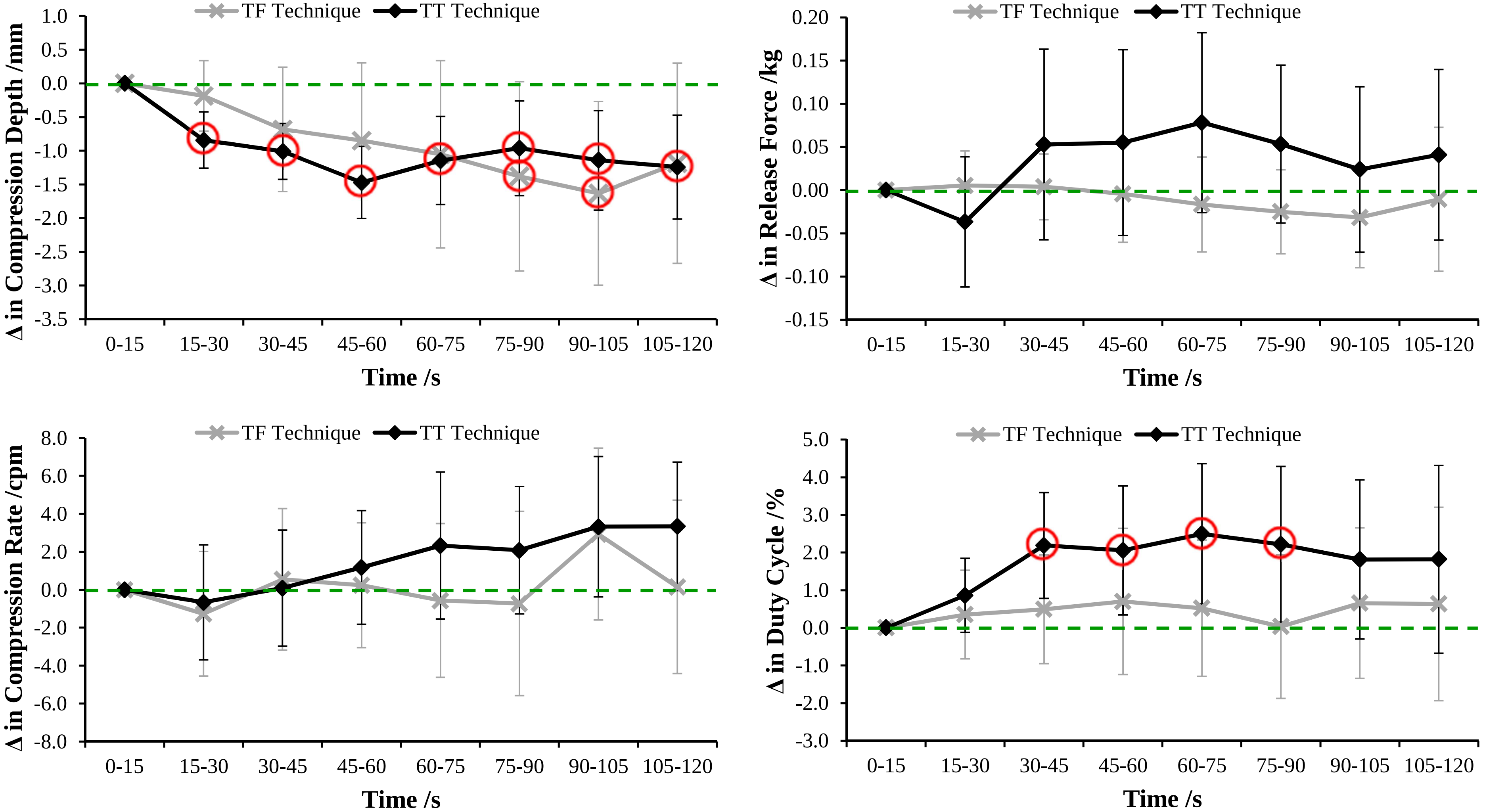

Figure 3-10: Change in chest compression quality measures during simulated two-thumb (TT) and two-finger (TF) technique chest compressions. The mean paired differences between the first 15 second epoch and all subsequent 15 second epochs are plotted with error bars representing 95% confidence intervals. *P*-values were calculated via two-sided paired samples Student's T-tests, with statistically significant values ($p<0.05$) circled.

3.5 Discussion

3.5.1 Summary of Principle Findings

This study is the first to evaluate the quality of chest compressions provided during simulated infant CPR against current evidence based chest compression quality targets. The results demonstrate that TT technique chest compressions achieve greater chest compression depths, whilst the TF technique releases the chest further and reduces the compression duty cycle. Consequently, this resulted in a greater proportion of chest compressions achieving chest compression depth quality targets for the TT technique and compression duty cycle quality targets for the TF technique. Despite this, overall chest compression quality was very poor for both techniques, with <1% of all chest compressions simultaneously achieving all four quality targets and ~50% failing to even achieve two quality targets. Performance decay was further reported for both TT and TF technique chest compression depths and TT technique compression duty cycles.

3.5.2 Comparison of Findings with Relevant Literature

Current European and UK Resuscitation Council guidelines emphasise the provision of high quality chest compressions during CPR [1-3]. Despite this, poor quality chest compressions remain prevalent during in-hospital and out-of-hospital cardiac arrests in the adult and paediatric populations [22, 23, 32, 41]. Poor quality chest compressions were also provided throughout this study by both infant chest compression techniques; with <1% of all chest compressions achieving all four chest compression quality targets and ~50% of all compressions failing to achieve even two. Fundamental to this was a combination of shallow compression depths, excessive compression rates and prolonged duty cycles, whilst the TT technique also failed to completely release the chest.

Increased chest compression depths have been observed to result in favourable haemodynamic outcomes, such as increased arterial pressures in infant and adult human subjects [30, 144] and increased coronary flow and cardiac output in animal surrogates [31, 142]. This has been strongly linked with increased defibrillation success and survival to hospital discharge after cardiac arrest in adult human subjects [32, 33]. Recent research, however, reports shallow chest compression depths, during both adult and older paediatric CPR and during simulated infant CPR on instrumented manikins [14-19, 22, 23, 32, 33, 41]. Despite the greater TT technique compression depths recorded in this study, a tendency to under-compress the chest was also observed. On average, 94% of all TT technique and 99% of all TF technique chest compressions failed to either achieve or surpass target chest compression depths of one-third the external AP thoracic diameter (≥36.7mm), whilst all chest compressions failed to achieve absolute chest compression depth targets of ≥40mm.

Incomplete chest release during CPR generates increased intrathoracic pressures in the chest release phase, consequently limiting return of venous blood to the heart and reducing both coronary and cerebral perfusion pressures [34, 35, 147, 148]. Whilst the incomplete release of the chest has been found in 25-50% of chest compressions during CPR in older paediatric subjects [41, 42], over 97% of chest compressions achieved target release forces during CPR in adult subjects [32]. The chest release force quality demonstrated by this study established that both techniques achieved >99% compliance with current release force quality targets, with only one participant failing to achieve 100% compliance whilst providing the TT technique. The TF technique was, however, observed to release the chest significantly further than the TT technique, resulting in a greater proportion of chest compressions that achieved the complete chest release force target of <0.5kg (<10% the manikin weight). As chest release forces of >10% a subject's body weight cause a measurable increase in intrathoracic pressure [147-149], the TF technique may, therefore, provide chest compressions that provide a superior return of venous blood to the heart during infant CPR.

Prolonged compression duty cycles, combined with increased chest compression rates, results in inadequate chest wall relaxation during CPR, adversely affecting myocardial blood flow, cardiac output, cerebral perfusion pressure and cerebral blood flow [150, 153, 154]. Whilst chest compressions, in both adults and paediatric subjects, achieve target rates [23, 32, 41], the compression rates reported in other simulated infant CPR studies are much faster than current targets and vary extensively between providers [16, 17, 19]. Similar results were observed in this study, with 33% of all TT and 61% of all TF chest compressions compressing the chest too fast and a large variation between providers. Although compression duty cycles during adult CPR are reported between 33-47% [23, 32, 35], duty cycles during paediatric CPR have never been quantified. In this analysis of compression duty cycle quality during simulated infant CPR, 0% of all TT technique chest compressions and 23% of all TF technique compressions complied with the quality targets, with both techniques providing prolonged duty cycles.

Participant performance decay is detrimental to chest compression quality during CPR [17, 20, 21, 161-164]. Previous research documents chest compression depth quality decay after just one minute of simulated infant CPR [17, 20, 21], primarily attributing this to participant fatigue. Performance decay affected both TT and TF technique chest compression depths and TT technique compression duty cycles in this study. The onset of TF technique compression depth decay (75-105 seconds) was observed to correspond with current research that indicates the onset of fatigue during the second minute of simulated infant CPR [17, 20, 21]. The onset of TT technique compression depth decay, however, occurred after just 15 seconds. As participant fatigue is unlikely to occur after 15 seconds, this may indicate that participants initially achieved the maximum achievable compression depth of the manikin. Finally, TT technique compression duty cycle performance decay was also unlikely to be related to participant fatigue, as its onset was observed from 30-90 seconds only and not for the final 30 seconds. Although it remains unknown why this decay in performance occurred, it may be that it was associated with an increase in chest release forces and decrease in chest compression depths which, due to the way duty cycles are calculated, can result in increased compression duty cycles.

3.5.3 Study Methodology

This study attempts throughout its design to minimise experimental bias and optimise data accuracy. The study obtained informed consent from certified APLS instructors, giving individuals a free choice, and adequate time, to consider participation. The use of a randomised, crossed-over, study design reduced the influence of confounding covariates by using each participant as their own control, whilst increasing the power of the statistical analyses. Experimental bias was reduced through blinding the participants to the study objectives and the separate assessment room. Instruction standardisation was provided by the Experimental Instruction Sheet, whilst the recovery period during each cross-over was employed to minimise the carry over effects of fatigue.

Advanced Paediatric Life Support (APLS) training course instructors were selected for the study, as the APLS course is a leading paediatric emergency life support course both taught and practiced throughout the World. Instructors are selected from outstanding candidates at courses and have successfully passed further assessment at a Generic Instructor Course [184]. The quality of CPR provided by the APLS instructors should, in theory, therefore represent the current ‘gold standard’ for chest compressions provided during infant CPR.

Chest compression only CPR was selected ahead of conventional CPR (i.e. provided with ventilations) in this study for a number of reasons. Although conventional CPR is recommended during unwitnessed out-of-hospital cardiopulmonary arrest in infants [1-3], no difference in chest compression quality is reported during simulated infant CPR [19]. Due to the time constraints of performing the study during an APLS training course, however, only one technique could be used. Chest compression only CPR was selected, therefore, as this would provide the greatest number of chest compressions for analysis from the two minutes of simulated infant CPR.

An important limitation of this study was the use of the infant CPR training manikin. Although infant CPR training manikins have been used extensively to investigate chest compression quality, their design is recognised as being flawed [14-21]. Previous studies highlighted chest compression stiffness as a key limitation to biofidelity [14-21], but fail to consider the effects of the maximum achievable compression depth (CDmax) of the manikin. For the commercially available infant CPR training manikin used by this study, the CDmax (defined as the chest deflection achieved at a chest compression force of 26.4kg) was observed to be 40mm. Unsurprisingly, all participants failed to achieve chest compression depths of 40mm. Since the internal AP chest depth of a three month old male infant is 56.2mm [143], chest compressions during this study may also have been restricted to unrepresentative depths by the mechanical constraints of the manikin. This may have prevented participants from being able to provide high quality chest compressions, whilst also potentially concealing the presence of chest compressions that over-compressed the thorax.

The development of a quality index approach in this study provided an important and flexible approach to benchmarking rescuer performance against evidence based chest compression quality targets. The quality targets utilised in this study were based on a combination of infant subject, adult subject, radiographic and animal surrogate studies. Only the chest compression depth and rate quality targets are currently recommended by international consensus opinion, whilst consensus opinion still remains to be reached regarding the provision of optimal chest release forces and compression duty cycles. This, however, reflects the current position of the scientific evidence base guiding current infant CPR recommendations. With future research, these infant specific targets, used for benchmarking chest compression quality during infant CPR, could be updated; affecting the quality index results of this study only.

This study aimed throughout its design to mitigate the effects of potential confounders. A randomised, crossed-over, study design was used to reduce the effects of confounding covariates, in addition to increasing the power of the statistical analysis, by using each participant as their own control. The effects of chest compression technique order, participant gender, field of expertise and clinical experience on all four chest compression quality measures were investigated; finding only that TT technique chest compression rates were affected by chest compression technique order. Although this may imply that participants that used the TT technique first increased their effort, the power of the statistical test was 33% implying that this difference may simply have been caused by type-II errors. More participants would have been required to adequately power the tests to determine if this was a confounder or due to type-II errors. Finally, despite being blinded to the objectives of the study, participants were aware of being observed, so their performance may have been influenced.

3.5.4 Impact of Research Findings

The results from this study may have several important clinical and educational implications. From this study it was observed that <1% of all chest compressions, regardless of technique, achieved current evidence based chest compression quality targets. Although performed during simulated infant CPR, these results could have serious implications if directly transferable to provider performance in clinical practice. Poor performance, for both recommended techniques, was due to a combination of shallow chest compression depths, excessive compression rates and prolonged compression duty cycles, whilst the TT technique also failed to completely release the chest.

Whilst no direct association has been observed between a strict compliance with current international recommendations and an improved survival outcome [149], evidence from animal surrogate studies and human observations, has suggested a positive correlation between evidence based guidelines and the optimisation of blood pressure and flow [30, 31, 34, 35, 142, 144, 147-150, 153, 154]. The provision of shallow chest compression depths in clinical practice would result in suboptimal forward blood flow during infant CPR [30, 31, 142, 144], thus reducing the perfusion of vital bodily organs, such as the brain. Furthermore, the incomplete release of the chest and provision of prolonged compression duty cycles would impede the return of venous blood to the heart and reduce coronary perfusion [34, 35, 147-150, 153, 154]. This may be a particular problem for the TT technique, which provided greater chest release forces and compression duty cycles during this study. Finally, excessive chest compression rates in clinical practice would result in the inadequate relaxation of the chest wall, impeding the venous return of blood to the heart and limiting forward blood flow [150, 153, 154].

If resuscitation providers were to deliver chest compressions that failed to achieve these quality targets, it is unlikely to result in the sudden termination of blood flow during CPR. Small deviations in chest compression quality from these optimised targets are, therefore, acceptable during CPR, as small deviations are unlikely to be considerably detrimental to survival. With ~50% of chest compressions failing to achieve even two of these quality targets, however, this study raises an important question over whether the current quality of chest compressions provided during infant CPR fail to optimise outcomes. As there is considerable scope for quality improvement, and current evidence suggests outcomes can be optimised through providing high-quality chest compressions, it would therefore seem reasonable to strive towards achieving current evidence based chest compression quality targets.

To improve current chest compression quality during infant CPR, resuscitators must be encouraged to achieve target compression depths for both recommended techniques. This may be easier to achieve and maintain when using the TT technique, as it performs deeper chest compressions and delays the onset of rescuer fatigue. Further improvements may also be achieved through educating rescuers to achieve the full release of the chest, particularly for the TT technique. This would improve the complete release of the chest and may also potentially improve compression duty cycle quality. Finally, improving the quality of compression rates may also be realised through regulation with a metronome.

As mentioned in the study limitations, it is also important to consider that this research focuses primarily on chest compression quality during simulated infant CPR. The use of an infant CPR manikin means that the chest compressions performed during this study may not represent those which are performed in a clinical environment. In fact, this is particularly relevant in this study, as the effects of a 40mm maximum achievable chest compression depth on chest compression quality are unknown. Further research on this particular issue is clearly required.

3.6 Conclusions

This study is the first to fully evaluate the compliance of simulated infant CPR chest compressions against current evidence based chest compression quality targets. The TT chest compression technique was observed to increase chest compression depths, whilst the TF technique reduced both chest release forces and compression duty cycles. TT technique chest compressions improved compression depth quality, whilst the TF technique provided a superior compression duty cycle quality. Overall, both techniques were found to rarely comply with all four chest compression quality targets, with excessive compression rates and prolonged duty cycles prevalent. Scope, therefore, remains for a considerable improvement in chest compression quality during simulated infant CPR. Future work should focus on ensuring that resuscitators are made aware of their performance against these evidence based quality targets. Prior to this, an infant CPR manikin must be developed with a more physiological maximum achievable chest compression depth.

4 CHEST COMPRESSION QUALITY USING A MORE 'PHYSIOLOGICAL' MANIKIN DESIGN

4.1 Introduction

Recent research reports the provision of poor quality chest compressions during simulated infant CPR, caused primarily by inadequate chest compression depths and a large variation in chest compression rate [14-19]. Chapter 3 further compliments this research by confirming the delivery of very poor quality chest compressions during simulated infant CPR, even by trained resuscitation instructors. Fundamental to this was a combination of shallow chest compression depths, excessive chest compression rates and prolonged compression duty cycles; whilst chest release force quality targets were achieved in the majority of chest compressions.

In response to the outcomes of previous research, current guidelines recommend that resuscitators "push hard, push fast" during infant CPR to encourage an improvement in chest compression quality [1-3]. Paediatric CPR training manikins have, however, been observed to have a maximum achievable chest compression depth (CDmax) of only one-third the external AP thoracic diameter of the manikin [17, 185]. These mechanical constraints may, therefore, have prevented resuscitators from achieving representative chest compression depths during simulated infant CPR; potentially affecting both chest compression quality and concealing the presence of thoracic over-compression. This was further observed in Chapter 3, where chest compression depths failed to exceed 40mm; the maximum achievable chest compression depth of the infant CPR training manikin used in the study (ALS Baby®, Laerdal Medical, Stavanger, Norway).

This emphasis on pushing hard and fast during infant CPR also raises concerns over a potential increase in the risks of CPR related trauma due to thoracic over-compression. Recent research has estimated that, if chest compressions are performed to one-half the external AP thoracic diameter, over 90% of young children would experience residual internal chest depths of <10mm; hypothesising that these depths could potentially cause intrathoracic trauma [143, 146]. As CPR related thoracic trauma may significantly impact survival and hamper patient recovery [186-188], it is important to establish whether infant chest compressions currently achieve potentially injurious depths during CPR. If so, based on the principle of non-maleficence in medicine (to “first, do no harm”) [189], it is important that the design of future interventions attempt to balance the haemodynamic advantages of performing deeper chest compression depths, against the negatives of providing potentially injurious chest compressions.

The primary aim of this study was to investigate the effects of a more ‘physiological’ infant CPR manikin design on chest compression quality and thoracic over-compression during simulated infant CPR. It was hypothesised that the use of a more representative manikin CDmax may improve overall chest compression quality, whilst also potentially highlighting the presence of thoracic over-compression.

4.2 Iatrogenic Trauma during Infant CPR

Cardiopulmonary resuscitation is a life-saving emergency procedure that can also cause iatrogenic trauma [186-188]. Injuries attributable to chest compressions during CPR are well documented in adults and can range from superficial bruises to multiple skeletal fractures [186, 187]. To provide chest compressions that optimise cardiac output during adult CPR, such injuries are considered to be a necessary consequence; particularly if they are considered not to be life threatening. Iatrogenic trauma resulting from adult

CPR, however, represents neither the incidence, nor the outcomes, that presents in the paediatric population [186-188]. Consequently, the literature must be fully appraised to evaluate the prevalence of CPR related trauma across the paediatric populations.

4.2.1 Epidemiology of Iatrogenic Trauma during CPR

Ten consecutive case series (Table 4-1) excluded the presence of trauma, abuse and pre-existing congenital abnormalities in investigating CPR related thoracic trauma [190-199]. Evidence of CPR related rib fractures were reported in four studies; reporting 29 cases in a population of 2,485 across all ten studies (incidence: 1.17%). Betz and Liebhardt reported two rib fracture cases in a series of 94 resuscitated children, aged from 5 days to 7 years old [191], whilst Bush *et al*. recorded a single case in 211 patients aged younger than 12 years [193]. Weber *et al*. observed seven acute rib fractures cases in 546 patients that suffered a sudden unexpected death in infancy; concluding that these were most likely the result of CPR [196]. Finally, Reyes *et al*. reported 19 rib fracture cases in 571 infants aged <6 months old; finding a significant increase in the incidence of CPR related rib fractures to 7.9% after adopting the 2005 AHA guidelines [199]. All rib fractures reported in all four studies were located either ventrally, at the sternochondral joints, or anterolaterally [191, 193, 196, 199]. Ribs I-IX were all report-

Table 4-1: Case series of cardiopulmonary resuscitation (CPR) related trauma

First Author	Year	Age Range /years	Study Size /*n*	CPR Related Trauma		
				Rib Fracture	Intrathoracic	Serious
Feldman [190]	1984	<8	50	-	-	-
Betz [191]	1994	<7	94	2	11	-
Spevak [192]	1994	<1	120	-	-	-
Bush [193]	1996	<12	211	1	6	3
Price [194]	2000	<10	324	-	3	1
Ryan [195]	2003	<14	153	-	7	-
Weber [196]	2009	<1	546	7	-	-
Matshes [197]	2010	<18	382	-	5	-
Ozer [198]	2010	<9	34	-	-	-
Reyes [199]	2011	<0.5	571	19	-	-

ed to be fractured during CPR, all but two cases presented with multiple rib fractures and fractures were bilateral in 55% (16/29) of cases [191, 193, 196, 199]. Importantly, no posterior rib fractures were recorded by any study; although several studies used rib fracture location to categorise the fracture mechanism (i.e. posterior rib fractures were used to exclude cases from study when investigating CPR trauma [196, 199]).

Four case studies report a further 18 CPR related rib fracture cases that the authors felt were not suggestive of abuse or trauma [200-203]. Thomas reported a single case from 24 rib fracture patients with four unilateral posterior arc fractures [200]. The presence of several pre-existing disorders, however, may have predisposed this case to rib fractures [200]. The remaining reports cited the TT chest compression technique as the probable cause of fracture [201-203], although only Matshes and Lew explicitly documented its use [203]. The majority of these fractures were located ventrally [201-203]; although Clouse and Lantz recorded posterior rib fractures in four cases [202]. Both Dolinak and Matshes and Lew could not adequately exclude the possibility of injuries caused by co-sleeping in 77% (10/13) of cases [201, 203], whilst Clouse and Lantz failed to explicitly confirm the absence of congenital abnormalities [202].

Intrathoracic injuries resulting from CPR trauma were recorded in five consecutive case series (Table 4-1) [191, 193-195, 197]. These describe 32 cases of intrathoracic trauma in a total population of 1164 across all five studies (incidence: 2.75%). Injuries tended to be pulmonary in origin (62.5%; 20/32), primarily presenting as pulmonary haemorrhages or contusions [191, 193-195, 197]. Only four instances (12.5%) of intrathoracic injury were considered, by their authors, to be life-threatening [193, 194]. These included atelectasis and haemorrhage of the lung (due to a central line puncture) [194], pneumothorax, a pulmonary interstitial haemorrhage and an epicardial haematoma [193].

4.2.2 Limitations of Epidemiological Literature

The studies included in this review have several limitations that may reduce their reliability. The presence of extensive heterogeneity between different studies is perhaps the most important factor when using pooled data to analyse the incidence of rib fractures. Rib fractures were documented at postmortem only, using a variety of both radiological and autopsy protocols, with technique sensitivity varying greatly between studies. Radiological protocols varied between plain frontal and oblique images of the thorax, whilst autopsy protocols may have contrasted due to regional variations in technique.

Poorly designed study methodologies may have enhanced the effects of heterogeneity between studies. Study sizes, geographical locations and lengths all varied extensively between studies. The retrospective nature of most studies introduced the potential risk of confounders and selection bias. The use of postmortem subjects may have resulted in the exclusion of cases that survived the cardiac arrest event [57]. Furthermore, the lack of consensus based injury classification and the inclusion of cases based on the characteristic location and presentation of CPR related fractures may have included cases that were injured during fatal trauma episodes, such as non-accidental trauma [204]. Perhaps most importantly, whilst autopsy was the primary rib fracture detection method used in the majority of these studies, it has been found to detect only 65% of acute rib fractures [205]. It is likely, therefore, that a substantial number of CPR related rib fracture cases may have been overlooked by the current literature.

4.3 Infant Thoracic Over-Compression Criterion

Minimising the potential for iatrogenic thoracic trauma through the over-compression of the thorax during infant CPR is critical to providing CPR safely. To monitor thoracic over-compression, it is important to develop an age-specific evidence based criterion to provide a threshold for evaluating the risks of iatrogenic thoracic trauma. This thoracic over-compression criterion is presented from the resuscitation literature below and was scaled for a three month old male infant.

A recent study by Braga *et al*. used computed tomography (CT) to estimate optimum chest compression depths for young children and infants [143]. Compression depths that could compress the chest to a residual internal depth of <10mm were prospectively defined as thoracic over-compression. The study concluded that chest compression depths of one-third the external anterior-posterior (AP) thoracic diameter were radiographically appropriate for children aged from 3 months to 8 years. Conversely, those targeting one-half the external AP diameter would compress the chest too far, resulting in a residual internal depth of <10mm in 96% of cases [143].

In a similar study using neonates aged <28 days, Meyer *et al*. coupled the radiographical estimation of optimal chest compression depths with a mathematical model calculating the approximate ejection fraction at compression depths of one-quarter, one-third and one-half the external AP diameter [146]. Thoracic under-compression was defined at a predicted ejection fraction of 50%, whilst a residual internal depth of <10mm was again defined as the over-compression of the thorax. This study concluded that current international infant chest compression depth recommendations of at least one-third the external AP diameter should be more effective than compression depths of one-quarter the external AP diameter and safer than compression depths of one-half the external AP diameter [146].

Using the equation reported by Braga *et al*. (Equation 4-1), the internal AP chest depth (*ID*) of a three month old male infant can be calculated as 56mm [143]. To facilitate the over-compression of the thorax, participants using the more 'physiological' infant CPR manikin design must be able to achieve maximum chest compression depths of 56mm.

Equation 4-1: $ID = 51.7 + 0.38*age(months) + 3.4*male(yes = 1, no = 0)$ [143]

As residual internal depths of <10mm are hypothesised to be a potential cause of iatrogenic intrathoracic trauma [143, 146], a thoracic over-compression criterion of 46mm was prospectively implemented for this modified infant CPR manikin study.

4.4 Methodology

4.4.1 Infant Manikin Design

The infant CPR training manikin (Laerdal® ALS Baby, Laerdal Medical, Stavanger, Norway), used in Chapter 3, was modified to allow the CDmax of the manikin to be varied between (i) the original manikin specification (i.e. 40mm; $CDmax_{40}$), and (ii) the physiological internal AP chest depth of a three month old male infant (i.e. 56mm; $CDmax_{56}$) [143]. Detailed descriptions and design drawings for these modifications are presented in Appendix A.4, along with the selection procedure used to select the spring for the 'physiological' infant manikin design (LC063HJ12S, Lee Springs, Berks, UK).

The chest compression characteristics of the modified manikin designs were established using the MTS 858 Mini Bionix II compression testing machine (MTS, MN, USA) and compared against the chest compression characteristics of the original manikin design (Figure 4-1). All three manikin chests were compressed at a rate of $0.5mms^{-1}$ between the most anterior aspect of the manikin thorax and a compression force of 26.4kg; a force equivalent to double the mean maximum achievable palmar pinch force for the dominant hand of a male adult [181]. This was repeated three times. Chest deflections

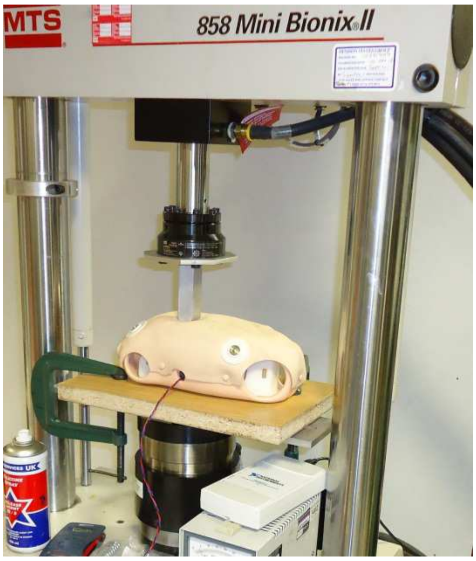

Figure 4-1: MTS 858 machine experimental set up to establish the compression stiffness and the maximum achievable compression depth of the modified manikin chest

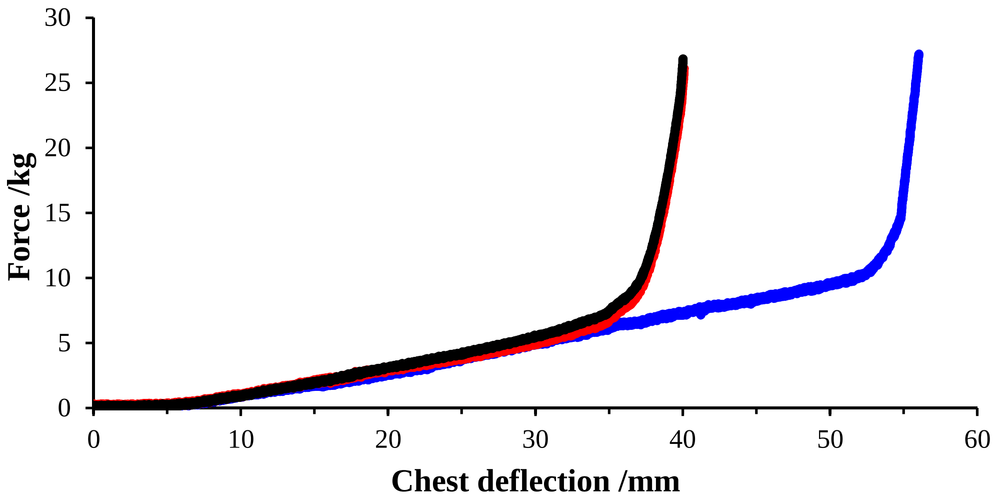

Figure 4-2: Anterior-posterior force-deflection properties of the original manikin and the more 'physiological' manikin at the 40mm and 56mm maximum achievable compression depth settings ($CDmax_{40}$ and $CDmax_{56}$).
The original manikin is illustrated by the black line, the $CDmax_{40}$ manikin setting is illustrated by the red line and the $CDmax_{56}$ manikin setting is illustrated by the blue line.

Table 4-2: Summary of properties for the original and more 'physiological' manikins at the 40mm and 56mm maximum compression depth settings ($CDmax_{40}$ and $CDmax_{56}$).

Manikin Property	Manikin Design		
	Original Manikin	$CDmax_{40}$ Manikin	$CDmax_{56}$ Manikin
Chest compression stiffness /Nmm^{-1}	2.2 ± 0.006	2.1 ± 0.009	2.1 ± 0.009
Maximum compression depth /mm	40.0 ± 0.001	40.1 ± 0.009	56.0 ± 0.009

Chest compression stiffness and maximum compression depth values are reported as mean (± standard deviation).

and chest compression forces were collected at a sample rate of 24Hz to characterise the force-deflection properties of all three manikin chests (Figure 4-2). Mean (±σ) chest compression stiffness (defined between chest deflections of 15-30mm) and mean (±σ) maximum compression depths were calculated for all three manikin designs (Table 4-2). Finally, the external anterior-posterior (AP) thoracic diameters (defined between the most anterior and posterior aspects of the manikin thorax) were measured to be 110mm for all three manikins.

4.4.2 Manikin Instrumentation and Calibration

The modified manikin design was instrumented with an infra-red distance measuring sensor to record manikin chest deflections (GP2Y0A41SK0F, Sharp Corporation, Osaka, Japan) and powered by a 5V power supply. Sensor selection was primarily based on criteria that included the cost effectiveness of the sensor, a maximum sensor height of 66mm (to fit inside the manikin chest during operation) and a minimum sensing range of 56mm (to monitor the maximum chest deflections during operation). The infra-red distance monitoring sensor selected for this study provided an inexpensive solution for measuring distance, particularly when compared to other solutions such as string pots or accelerometers. With an operational range of 4-30cm, and a sensor height of 13.5mm, the selected sensor was capable of measuring the maximum chest deflections achieved during operation - providing the sensor was located more than 40mm away from the reflective surface. This requirement was taken into consideration at the manikin design stage, with distances from 47-103mm measured during operation.

Sensor output was recorded using a data acquisition card and a customised LabVIEW software program (National Instruments, TX, USA) on a laptop computer to record the output voltage signals. Manikin instrumentation was calibrated at the $CDmax_{56}$ setting to record the chest compression depths and chest compression forces applied to the lower third of the manikin sternum during simulated infant CPR. The manikin chest was compressed by the MTS 858 machine, at a quasi-static rate of $0.5mms^{-1}$, between the most anterior aspect of the manikin thorax and a chest compression force of 26.4kg. Chest deflections, chest compression forces and sensor output voltage were recorded at a 24Hz sample rate. This was repeated a further three times, with deflection-voltage and force-voltage relationships calculated from the first set of results. These relationships were applied to the remaining three sets of results to compare predicted and actual chest compression depths and forces (Figure 3-4). Mean regression gradients, with 95% confidence intervals [95% CI] and Pearson's correlation coefficients (R^2), for chest compression depths and forces were 0.998 [0.954, 1.042] mm (R^2=1) and 0.955 [0.903, 1.007] kg (R^2=0.997) respectively (calculated with SPSS 16.0, SPSS Inc., IL, USA).

The compression rate sensitivity of the manikin calibration relationships were assessed at the $CDmax_{56}$ setting by compressing the manikin chest with a sinusoidal waveform at frequencies of 1Hz, 2Hz and 3Hz. The manikin chest was compressed by the MTS 858 machine between the most anterior aspect of the manikin thorax and a chest compression force of 26.4kg at each frequency. Chest deflections, chest compression forces and the sensor output voltage were recorded at sample rates of 48Hz (1Hz test), 96Hz (2Hz test) and 144Hz (3Hz test). Each test was performed for six cycles, with the fifth cycle compared, as above, to the deflection-voltage and force-voltage relationships developed during the quasi-static testing (Figure 3-5). Mean regression gradients, with 95% confidence intervals [95% CI] and Pearson's correlation coefficients (R^2), for chest compression depths and forces were 0.998 [0.771, 1.225] mm (R^2=1) and 0.945 [0.677, 1.213] kg (R^2=0.997) respectively (calculated with SPSS 16.0).

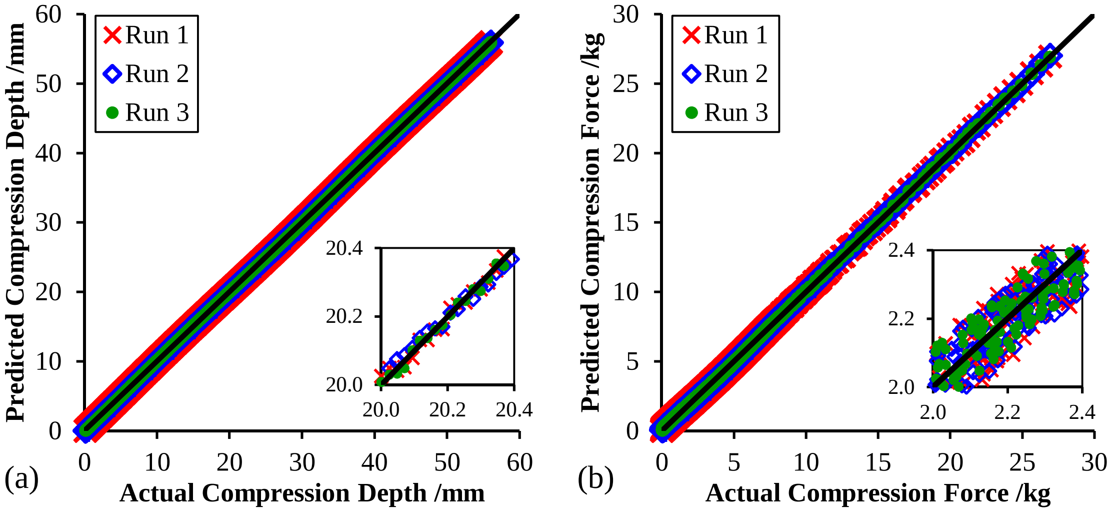

Figure 4-3: Actual versus predicted (a) chest compression depths and (b) chest compression forces as applied to the manikin chest using the 56mm maximum achievable chest compression depth setting

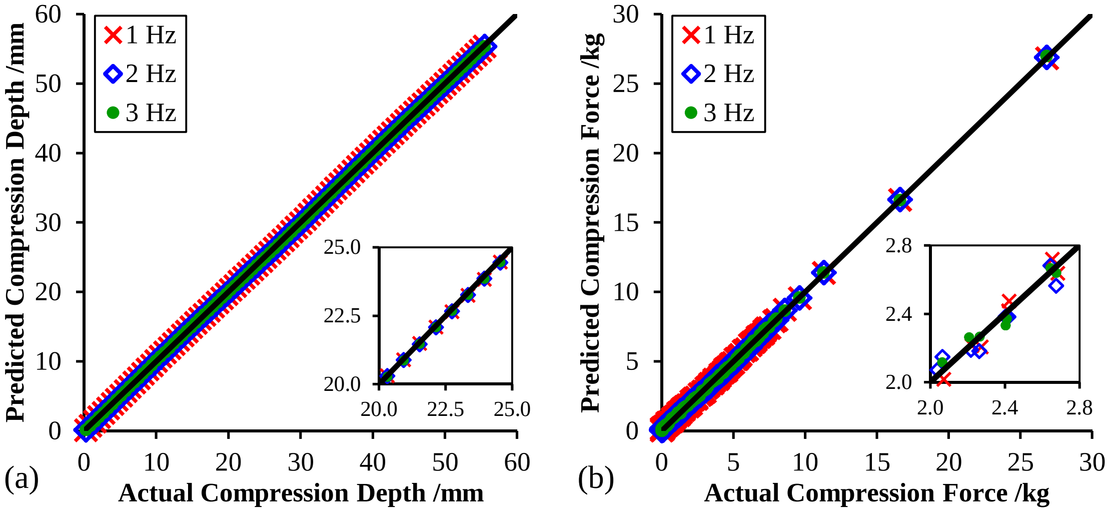

Figure 4-4: Actual versus predicted (a) chest compression depths and (b) chest compression forces for 1Hz, 2Hz and 3Hz chest compression frequencies

4.4.3 Study Coordination and Participants

This manikin study was approved by five National Health Service (NHS) Health Boards and Trusts across Wales and England (IRAS 45342) and by the Working Group Chair of the Resuscitation Council UK (RCUK) run European Paediatric Life Support (EPLS) training course. Research ethical approval was obtained from the Cardiff University School of Engineering Ethics Committee, whilst Research Ethics Committee approval was not required, since NHS staff only were used in this study [182]. The approved Research Protocol, documentation and Letters of Approval for the study are presented in the Electronic Appendices.

Training course instructors were recruited to this study from five EPLS training courses. As in Chapter 3, the Training Course and Medical Directors for each course confirmed their willingness to facilitate this study. Participant Information Sheets were circulated around all potential participants by the Training Course Director at least one week prior to testing. Before testing, the participants were briefed on the experimental procedures using a standardised Experimental Instruction Sheet. Any queries the participants had were answered and, once satisfied, the participants were asked to complete and sign the Participant Consent and Participant Details Forms. Individual results were reported back to the participant, via the Training Course Director, after study completion.

Forty consenting instructors were recruited to this study as participants from five EPLS training courses. Participant exclusion criteria for this study were: invalid instructor certification, incomplete data acquisition, withdrawal of consent and any participant health issues. Study demographics (gender, field of expertise and clinical experience) were collected via the Participant Details Forms. Study participants consisted of 18 male and 22 female certified EPLS instructors. Sixteen participants were resuscitation officers, 12 were doctors, eight were registered nurses, two were operating department practitioners and two were paramedics. Twenty-one participants were randomised to the $CDmax_{56}$ setting first, whilst sixteen participants performed the TT chest compression technique first. The mean (±σ) clinical experience was 19.0±7.7 years. A study sample size of 40 participants is able to adequately detect mean paired differences 0.45 times the standard deviation of the differences; assuming data normality, a two-sided significance level of <0.05 and >80% statistical power (calculated with G*Power 3.1.5 [183]).

4.4.4 Experimental Procedure

Prior to testing, the modified manikin was set up in a separate assessment room, on a flat table, with the laptop and peripheral equipment located below. Participants were assigned, via a table of randomised numbers, to an initial manikin setting ($CDmax_{40}$ or $CDmax_{56}$) and an initial chest compression technique (TT or TF). All participants were instructed to provide continuous chest compressions (i.e. no ventilations required) for four 90 second periods. This was performed using both techniques, and at both CDmax settings, in a randomised crossed-over sequence. Full recovery after each period was allowed for all participants. Chest compression depths and forces were recorded at a sample rate of 50Hz throughout, with both the participant and investigator blinded to performance feedback. Participants were neither refreshed nor coached on either chest compression technique and were blinded to the nature of the manikin modification, the observations recorded and the study objectives. Individual results were fed back to the participants after study completion.

4.4.5 Data Analysis

Data were recorded describing the chest compression depths, chest release forces, chest compression rates and compression duty cycles achieved for all four chest compression periods. Quality indices, as in Chapter 3, were used to calculate the proportion of chest compressions that complied with evidence based quality targets (Table 4-3). Finally, to determine overall chest compression quality, the proportion of chest compressions that achieved all four primary quality targets simultaneously was calculated. This was repeated for the proportion of compressions that achieved three or more quality targets, two or more quality targets and at least one quality target.

Table 4-3: Definitions of infant chest compression quality measures and quality targets.

Parameter	Definition	Target Range	Target Range Description
Chest Compression Depth	The maximum chest deflection achieved during each chest compression cycle*	36.7-46mm	European and UK Resuscitation Council guidelines recommend a compression depth of no less than one-third the external anterior-posterior (AP) chest diameter [1-3]. The upper threshold is proposed based upon the hypothesis that a residual internal AP chest depth of <10mm may potentially cause intra-thoracic trauma [143, 146].
Chest Release Force	The minimum chest compression force achieved during the release phase of each chest compression cycle	<2.5kg <0.5kg	A 2.5kg chest release force would cause a clinically significantly increase in intra-thoracic pressure and significantly limit the return of venous blood to the heart [148]. As a 0.5kg chest release force (10% of the manikin's weight) would also cause a measurable increase in inter-thoracic pressure [148], this was used as a secondary quality target.
Chest Compression Rate	The inverse of the time taken for each chest compression cycle and quantified as the number of compressions per minute	100-120min^{-1}	European and UK Resuscitation Council guidelines recommend a compression rate between 100-120 compressions per minute [1-3].
Compression Duty Cycle	Calculated for each chest compression cycle by dividing the area under the chest deflection curve by the product of the chest compression depth and chest compression cycle time.	30-50%	The most effect compression duty cycle range observed in infant animal surrogates [150, 153, 154].

* Chest compression cycles defined between consecutive chest release forces

Following the resuscitation based literature, thoracic over-compression was prospectively defined at a chest compression depth of 46mm. Chest compressions that exceed this criterion would result in a residual internal AP chest depth of <10mm for a 3 month old male infant [143]. The proportion of chest compressions that exceeded the thoracic over-compression criterion was calculated to quantify thoracic over-compression during simulated infant CPR. To further quantify thoracic over-compression, the maximum chest compression depths achieved by each participant were also recorded.

4.4.6 Statistical Analysis

Median values for all four chest compression quality measures were recorded for each participant, alongside the chest compression quality indices, the proportion of chest compressions that exceeded the proposed thoracic over-compression criterion and the maximum chest compression depths achieved by the study participants. Study results were reported either as means with standard deviations or medians with inter-quartile ranges. The mean paired differences between CDmax settings ($CDmax_{56}$ less $CDmax_{40}$) and infant chest compression techniques (TT less TF) were reported as means with 95% confidence intervals for all four chest compression quality measures. After testing for data normality (Shapiro-Wilk tests), results were compared by either paired Student T-tests or Wilcoxon's signed rank tests as appropriate.

The effects of potential confounders, including gender, manikin CDmax setting order, chest compression technique order, field of expertise and clinical experience, on all four quality measures were assessed. Data were tested for normality and homogeneity of variance (Shapiro-Wilk and Levene's tests). The effects of participant gender, manikin CDmax setting order and chest compression technique order were analysed using either independent Student T-tests or Mann-Whitney U tests as appropriate. The effects of participant field of expertise were analysed using either one-way ANOVA or Kruskal-Wallis tests, as appropriate, whilst the effects of participant clinical experience were analysed using linear regression analyses. All statistical analyses were performed using SPSS 16.0, with statistical significance considered at $p<0.05$ for all statistical tests and all p-values considered to be two-sided, whilst post-hoc power analyses were performed with G*Power 3.1.5 [183].

4.5 Results

Simulated chest compression quality measures are illustrated against their evidence based quality targets in Figure 4-5. For both TT and TF chest compression techniques, the more ‘physiological’ manikin design increased the chest compression depths and reduced the compression duty cycles achieved during simulated infant CPR (Table 4-4). Subsequently, this resulted in a greater proportion of chest compressions that complied with both the chest compression depth and the compression duty cycle quality targets. No significant differences between CDmax manikin settings were found for either chest release forces or chest compression rates. Excessive compression rates were common for both manikin settings, however, whilst chest release force targets were achieved by>99% of all chest compressions. Finally, the more ‘physiological’ manikin design also increased the proportion of chest compressions that achieved the complete release of the chest and reduced the proportion of compressions that both under-compressed the chest and prolonged the compression duty cycle.

For both CDmax manikin settings, the TT technique was observed to achieve greater chest compression depths than the TF technique, whilst the TF technique both released the chest further and reduced the compression duty cycle (Table 4-5). Consequently, at the $CDmax_{40}$ manikin setting, this improved the proportion of both TT technique chest

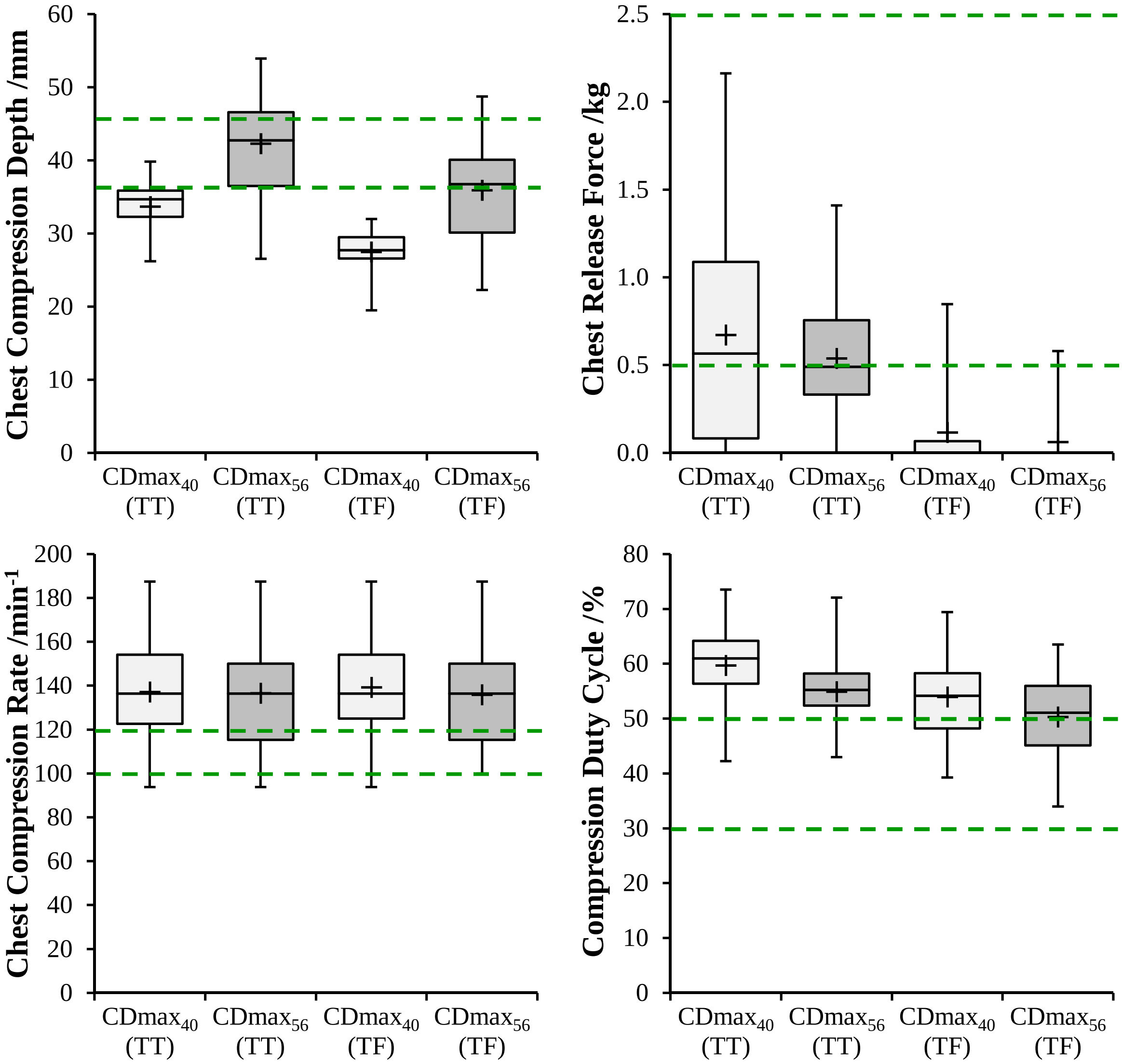

Figure 4-5: Illustration of median chest compression depths, chest release forces, chest compression rates and compression duty cycles achieved by the two-thumb (TT) and two-finger (TF) techniques using the 40mm and 56mm manikin designs ($CDmax_{40}$ & $CDmax_{56}$).

Current evidence based quality targets are illustrated by dashed lines. Chest compression depth targets were 36.7-46mm, chest release force targets were <2.5kg and <0.5kg, chest compression rate targets were 100-120min^{-1} and compression duty cycle targets were 30-50%. The centre line of the box plot represents the median value of the data, the upper and lower lines of the box plot represent the upper and lower quartiles of the data, the cross represents the mean value of the data and the whiskers represent the maximum and minimum values of the data.

Table 4-4: Changes in simulated chest compression quality measures and quality indices, between the 40mm and 56mm manikin settings ($CDmax_{40}$ and $CDmax_{56}$), for both the two-thumb (TT) and two-finger (TF) chest compression techniques.

	Two-Thumb Chest Compression Technique				Two-Finger Chest Compression Technique			
	$CDmax_{40}$	**$CDmax_{56}$**	**Mean Paired Difference**	***P*-value**	**$CDmax_{40}$**	**$CDmax_{56}$**	**Mean Paired Difference**	***P*-value**
Compression Depths (CD)								
Mean Compression Depth /mm	34 ± 3	42 ± 7	9 [7, 10]	***<0.001****	27 ± 3	36 ± 7	8 [7, 10]	***<0.001****
Median Compression Depth /mm	35 [32, 36]	43 [36, 47]		***<0.001***†	28 [27, 30]	37 [30, 40]		***<0.001***†
CD Quality Index (36.7-46mm) /%	7 [0, 18]	44 [2, 68]		***0.005***†	0 [0, 0]	34 [0, 81]		***<0.001***†
Under-Compression Index (<36.7mm) /%	93 [82, 100]	1 [0, 56]		***<0.001***†	100 [100, 100]	47 [12, 100]		***<0.001***†
Release Forces (RF)								
Mean Release Force /kg	0.7 ± 0.6	0.5 ± 0.3	-0.1 [-0.3, 0.0]	0.069*	0.1 ± 0.2	0.1 ± 0.1	-0.1 [-0.1, 0.0]	0.13*
Median Release Force /kg	0.6 [0.1, 1.1]	0.5 [0.3, 0.8]		0.17†	0.0 [0.0, 0.1]	0.0 [0.0, 0.0]		0.11†
RF Quality Index (<2.5kg) /%	100 [100, 100]	100 [100, 100]		0.18†	100 [100, 100]	100 [100, 100]		0.32†
Complete RF Index (<0.5kg) /%	41 [8, 89]	54 [17, 95]		***0.025***†	99 [89, 100]	100 [100, 100]		***0.007***†
Compression Rates (CR)								
Mean Compression Rate /cpm	137 ± 26	137 ± 24	-1 [-4, 3]	0.71*	139 ± 24	136 ± 24	-3 [-7, 0]	0.081*
Median Compression Rate /cpm	136 [123, 154]	136 [115, 150]		0.37†	136 [125, 154]	136 [115, 150]		0.11†
CR Quality Index (100-120cpm) /%	2 [0, 48]	2 [0, 36]		0.66†	2 [0, 32]	0 [0, 53]		0.54†
CR Too Fast Index (>120cpm) /%	98 [49, 100]	98 [28, 100]		0.68†	98 [55, 100]	99 [31, 100]		0.35†
Compression Duty Cycles (DC)								
Mean Compression Duty Cycle /%	60 ± 7	55 ± 6	-5 [-6, -3]	***<0.001****	54 ± 8	50 ± 7	-4 [-5, -2]	***<0.001****
Median Compression Duty Cycle /%	61 [56, 64]	55 [52, 58]		***<0.001***†	54 [48, 58]	51 [45, 56]		***<0.001***†
DC Quality Index (30-50%) /%	0 [0, 4]	7 [2, 20]		***<0.001***†	19 [2, 73]	38 [5, 88]		***0.004***†
Prolonged DC Index (>50%) /%	100 [96, 100]	93 [80, 98]		***<0.001***†	81 [27, 98]	62 [12, 94]		***0.002***†

Mean quality measures are presented as mean values ± standard deviation, whilst both the median quality measures and quality indices are presented as median values [inter-quartile range]. Differences between the manikin settings ($CDmax_{56}$ less $CDmax_{40}$) are given as the mean paired difference [95% confidence interval]. *P*-values were calculated from two-sided paired samples Student's T-tests (*) or Wilcoxon's Signed Rank tests (†) as appropriate.

Table 4-5: Changes in simulated chest compression quality measures and quality indices, between the two-thumb (TT) and two-finger (TF) techniques, for both the 40mm and 56mm manikin settings ($CDmax_{40}$ and $CDmax_{56}$).

	$CDmax_{56}$ Manikin Setting				$CDmax_{40}$ Manikin Setting			
	TT Technique	**TF Technique**	**Mean Paired Difference**	***P*-value**	**TT Technique**	**TF Technique**	**Mean Paired Difference**	***P*-value**
Compression Depths (CD)								
Mean Compression Depth /mm	42 ± 7	36 ± 7	6 [5, 8]	***<0.001******	34 ± 3	27 ± 3	6 [5, 7]	***<0.001******
Median Compression Depth /mm	43 [36, 47]	37 [30, 40]		***<0.001***†	35 [32, 36]	28 [27, 30]		***<0.001***†
CD Quality Index (36.7-46mm) /%	44 [2, 68]	34 [0, 81]		0.63†	7 [0, 18]	0 [0, 0]		***<0.001***†
Under-Compression Index (<36.7mm) /%	1 [0, 56]	47 [12, 100]		***<0.001***†	93 [82, 100]	100 [100, 100]		***<0.001***†
Release Forces (RF)								
Mean Release Force /kg	0.5 ± 0.3	0.1 ± 0.1	0.5 [0.4, 0.6]	***<0.001******	0.7 ± 0.6	0.1 ± 0.2	0.6 [0.4, 0.7]	***<0.001******
Median Release Force /kg	0.5 [0.3, 0.8]	0.0 [0.0, 0.0]		***<0.001***†	0.6 [0.1, 1.1]	0.0 [0.0, 0.1]		***<0.001***†
RF Quality Index (<2.5kg) /%	100 [100, 100]	100 [100, 100]		0.32†	100 [100, 100]	100 [100, 100]		0.18†
Complete RF Index (<0.5kg) /%	54 [17, 95]	100 [100, 100]		***<0.001***†	41 [8, 89]	99 [89, 100]		***<0.001***†
Compression Rates (CR)								
Mean Compression Rate /cpm	137 ± 24	136 ± 24	1 [-2, 3]	0.65*	137 ± 26	139 ± 24	-2 [-5, 1]	0.12*
Median Compression Rate /cpm	136 [115, 150]	136 [115, 150]		0.23†	136 [123, 154]	136 [125, 154]		0.75†
CR Quality Index (100-120cpm) /%	2 [0, 36]	0 [0, 53]		0.99†	2 [0, 48]	2 [0, 32]		0.93†
CR Too Fast Index (>120cpm) /%	98 [28, 100]	99 [31, 100]		0.36†	98 [49, 100]	98 [55, 100]		0.11†
Compression Duty Cycles (DC)								
Mean Compression Duty Cycle /%	55 ± 6	50 ± 7	5 [3, 6]	***<0.001******	60 ± 7	54 ± 8	6 [4, 7]	***<0.001******
Median Compression Duty Cycle /%	55 [52, 58]	51 [45, 56]		***<0.001***†	61 [56, 64]	54 [48, 58]		***<0.001***†
DC Quality Index (30-50%) /%	7 [2, 20]	38 [5, 88]		***<0.001***†	0 [0, 4]	19 [2, 73]		***<0.001***†
Prolonged DC Index (>50%) /%	93 [80, 98]	62 [12, 94]		***<0.001***†	100 [96, 100]	81 [27, 98]		***<0.001***†

Mean quality measures are presented as mean values ± standard deviation, whilst both the median quality measures and quality indices are presented as median values [inter-quartile range]. Differences between the chest compression techniques (TT less TF) are given as the mean paired difference [95% confidence interval]. *P*-values were calculated from two-sided paired samples Student's T-tests (*) or Wilcoxon's Signed Rank tests (†) as appropriate.

compressions that complied with the chest compression depth quality targets and TF technique chest compressions that complied with the compression duty cycle quality targets. At the $CDmax_{56}$ manikin setting, however, this was found to improve only the proportion of TF technique chest compressions that complied with the compression duty cycle quality targets. No significant differences were observed for chest compression rates. Finally, the TT technique was observed to reduce the proportion of compressions that under-compressed the chest, whilst the TF technique increased the proportion of compressions that achieved the complete release of the chest and reduced the proportion of compressions that prolonged the compression duty cycle.

The overall chest compression quality indices achieved by the TT and TF techniques at both CDmax settings are illustrated in Figure 4-6. Overall quality was observed to be very poor for both chest compression techniques; with <8% of all chest compressions at the $CDmax_{56}$ manikin setting and <1% of all chest compressions at the $CDmax_{40}$ manikin setting complying simultaneously with all four chest compression quality targets. The more ‘physiological’ manikin design was found to improve the proportion of TF

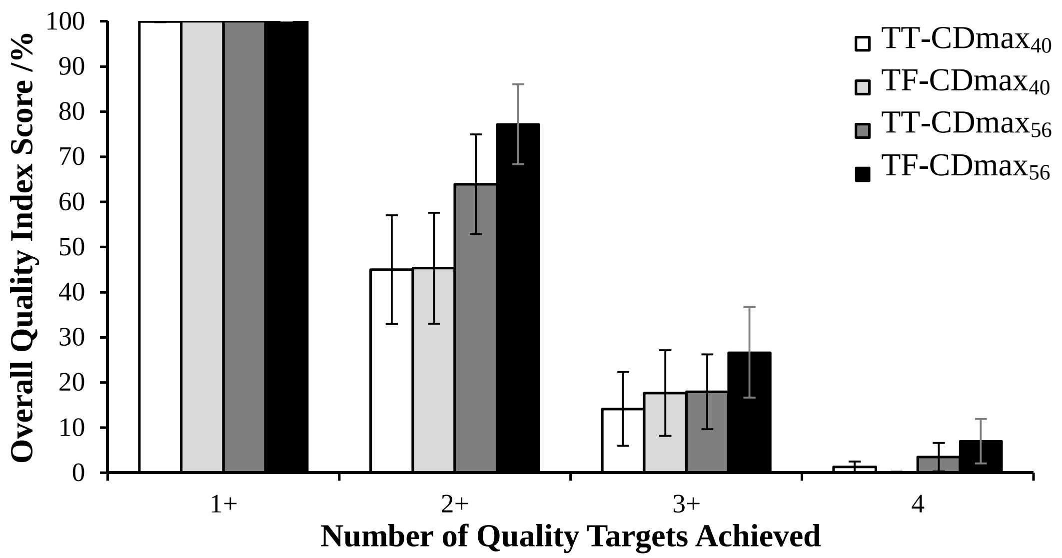

Figure 4-6: Mean overall quality indices achieved by the two-thumb (TT) and two-finger (TF) techniques using the 40mm and 56mm manikin designs ($CDmax_{40}$ and $CDmax_{56}$). Error bars represent 95% confidence intervals.

technique chest compressions that achieved all four quality targets (mean paired difference [95%CI]: 7 [2, 15]%, p=0.005), whilst also improving the proportion of TT and TF chest compressions that complied with both three or more quality targets (TT: 4 [0, 9]%, p=0.044; TF: 13 [5, 21]%, p=0.003) and two or more quality targets (TT: 26 [12, 40]%, p=0.001; TF: 35 [23, 46]%, p<0.001). When comparing techniques, the TF technique was observed to provide a greater proportion of chest compressions that achieved two or more quality targets at the $CDmax_{56}$ setting only (14 [28, 0]%, p=0.045).

The maximum chest compression depths achieved by each participant for each chest compression technique are illustrated for both CDmax manikin settings in Figure 4-7. On average, 33% of all TT technique and 7% of all TF technique chest compressions were found to exceed the proposed thoracic over-compression criterion at the $CDmax_{56}$ manikin setting (mean paired difference [95%CI]: 26 [15, 37]%, p<0.001), whilst no chest compressions were observed to exceed this at the $CDmax_{40}$ manikin setting. In total, 25 (62.5%) participants exceeded the proposed criterion at least once with the TT chest compression technique, whilst only 14 (35%) participants exceeded this with the TF technique. Two (5%) participants were further observed to exceed the thoracic over-compression criterion in 100% of all TT technique chest compressions.

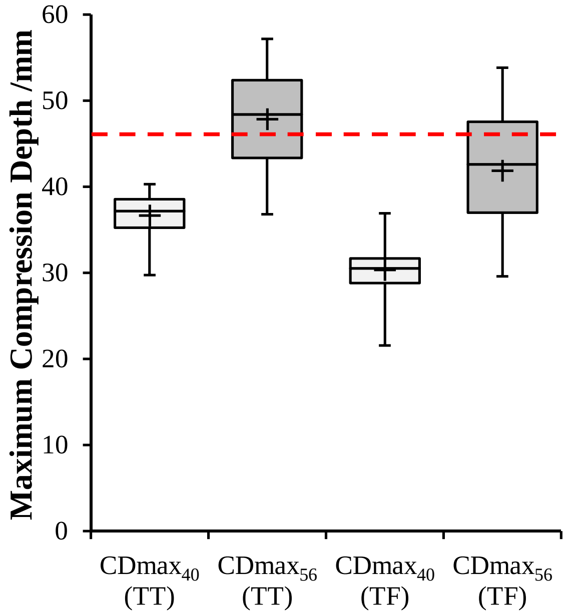

Figure 4-7: Maximum chest compression depths, illustrated against the thoracic over-compression criterion (46mm), for both two-thumb (TT) and two-finger (TF) chest compressions and using the 40mm and 56mm manikin settings ($CDmax_{40}$ and $CDmax_{56}$).
The centre line of the box plot represents the median value of the data, the upper and lower lines of the box plot represent the upper and lower quartiles of the data, the cross represents the mean value of the data and the whiskers represent the maximum and minimum values of the data.

Of the potential confounders investigated, CDmax setting order, clinical experience and field of experience were all found to have no significant effect on any of the four quality measures achieved. Male participants were observed to release the chest significantly further than female participants for both the TT chest compression technique at the $CDmax_{40}$ setting (mean difference [95%CI]: 0.4 [0, 0.7] kg, p=0.046, power=53%) and the TF technique at the $CDmax_{56}$ setting 0.1 [0, 0.2] mm, p=0.023, power=79%). For both manikin CDmax settings, participants that performed the TF chest compression technique first provided significantly greater TT technique chest compression depths than those that performed the TT technique first ($CDmax_{40}$: 2 [0, 4] mm, p=0.021, power=63%; $CDmax_{56}$: 5 [1, 9] mm, p=0.019, power=65%). Aside from these, no other quality measure was affected by either gender or technique order.

4.6 Discussion

4.6.1 Summary of Principle Findings

This study is the first to utilise a more ‘physiological’ manikin design during simulated infant CPR, with results demonstrating both increased chest compression depths and reduced compression duty cycles for both the TT and TF chest compression techniques. Consequently, the more ‘physiological’ design improved both chest compression depth and compression duty cycle quality, whilst also highlighting thoracic over-compression. When comparing techniques, the TF technique improved both compression duty cycle quality and the complete release of the chest and reduced the incidence of thoracic over-compression, whilst the TT technique reduced the under-compression of the thorax. Despite these individual improvements, overall chest compression quality remained very poor for both techniques, with <8% of all chest compressions complying simultaneously with all four quality targets.

4.6.2 Comparison of Findings with Relevant Literature

Current international CPR guidelines emphasise the provision of high quality chest compressions during infant CPR [1-3]. Despite this, Chapter 3 reports that substandard chest compressions were frequently delivered by trained resuscitation providers during simulated infant CPR. In this study, despite significant improvements in quality with the more 'physiological' manikin design, overall chest compression quality remained very poor; with <8% of all compressions achieving all four chest compression quality targets. Fundamental to this was the combination of inaccurate chest compression depths, excessive chest compression rates and prolonged compression duty cycles.

An important consideration for high quality chest compressions is to achieve adequate chest compression depths to both maintain favourable haemodynamic outcomes [30, 31, 142, 144] and improve the likelihood of survival [32, 33]. Recent research reports poor quality compression depths, during CPR in both adult and older paediatric subjects and when performing simulated CPR on instrumented infant manikins [14-19, 22, 23, 32, 33, 41]. When participants used the original manikin CDmax setting in this study, 7% of all TT and 0% of all TF chest compressions achieved chest compression depth quality targets (36.7-46mm). This is consistent with both previous infant CPR manikin studies [14-19] and Chapter 3, raising concerns over whether this reflects infant CPR in current clinical practice. Increased compression depths were observed, however, when participants used the more 'physiological' manikin design. This resulted in 44% of all TT and 34% of all TF chest compressions achieving targets, whilst reducing the proportion of compressions that under-compressed the chest. Thus, the more 'physiological' manikin design allowed providers to achieve current chest compression depth quality targets and may, therefore, be used to encourage improvements in chest compression depth quality.

Whilst an important consideration of CPR is to achieve an adequate chest compression depth, minimising the likelihood of trauma through thoracic over-compression is also a safety concern. Although CPR related trauma in young children and infants is traditionally considered rare, both rib fractures and intrathoracic injuries have been previously reported [187, 188, 191, 193-197, 199]. Chest compressions that achieve potentially injurious depths during infant CPR have, however, never been recorded. When using the more 'physiological' infant CPR manikin design, 33% of all TT and 7% of all TF chest compressions over-compressed the thorax. Clearly, as chest compressions are unable to over-compress the thorax with the original manikin design, the more 'physiological' manikin design may be used to highlight the provision of chest compressions that over-compress the thorax during simulated infant CPR.

Delivering effective chest compression rates, chest release forces and compression duty cycles during infant CPR is also essential to achieving optimal haemodynamics [34, 35, 147, 148, 150, 153, 154]. Incomplete chest release can generate increased intrathoracic pressures during CPR, whilst prolonged duty cycles and excessive compression rates result in inadequate chest wall relaxation, all of which limit the return of venous blood to the heart and reduce coronary and cerebral perfusion pressures [34, 35, 147, 148, 150, 153, 154]. Previous research reports the incomplete release of the chest in older paediatric subjects and excessive chest compression rates during simulated infant CPR [16, 17, 19, 41, 42]. Chapter 3 reported excessive compression rates and prolonged duty cycles for both techniques, whilst the TT chest compression technique failed to completely release the chest. Excessive compression rates and prolonged duty cycles were also reported in this study, whilst >99% of chest compressions complied with the chest release force quality targets (2.5kg). When participants used the more 'physiological' manikin design, however, both compression duty cycle quality and the complete release of the chest were improved for both infant chest compression techniques.

The TT chest compression technique is currently favoured by both the ERC and UKRC guideline recommendations for infant CPR [1-3], with previous research concluding the TT technique achieved deeper and more consistent chest compression depths than the TF technique [14-19]. In this study, the use of the TT chest compression technique increased the chest compression depths, chest release forces and compression duty cycles provided by the participant during simulated infant CPR, regardless of manikin design. When using the original manikin design, this resulted in an improved compliance with chest compression depth targets, whilst reducing compliance with both the compression duty cycle and the complete chest release targets. When using the more 'physiological' manikin design, the use of the TT technique was found to both reduce compliance with compression duty cycle targets and increase the incidence of thoracic over-compression, whilst the TF technique was found to increase the proportion of chest compressions that under-compressed the thorax.

4.6.3 Study Methodology

This study attempts throughout its design to minimise experimental bias. Informed consent was obtained from certified EPLS instructors and gave individuals a free choice, and adequate time, to consider participation. A randomised, crossed-over, study design was utilised to reduce the influence of confounders, whilst increasing the power of the statistical analyses. Participants were blinded to the study objectives and a separate assessment room was used for testing. Instructional standardisation was provided by the Experimental Instruction Sheet, whilst the carry over effects of fatigue were minimised by allowing full participant recovery between chest compression periods and by reducing each period to 90 seconds.

European Paediatric Life Support (EPLS) training course instructors were selected for this study to provide an alternative to the Advanced Paediatric Life Support (APLS) instructors used in Chapter 3. The EPLS course is also a leading paediatric emergency life support course, with its instructors similarly selected from outstanding candidates and having passed a Generic Instructor Course [206]. The selection of EPLS instructors as participants should, in theory, therefore represent the current ‘gold standard’ for chest compressions provided during infant CPR.

Each chest compression period in this study was limited to 90 seconds, compared to 120 seconds in Chapter 3, for several reasons. Due to the time constraints of performing the study during an EPLS training course, it was undesirable for chest compression periods to be 120 seconds. Each instructor would have been required to perform 8 minutes of testing, in addition to the experimental briefings and recovery periods, which could take them away from teaching for >10 minutes. Furthermore, as Chapter 3 reported that the onset of TF technique fatigue may have occurred between 75-90 seconds, it was decided that a 90 second chest compression period should not be exceeded to reduce the effects of participant fatigue. Despite this reduction in chest compression period time, one or two instructors mentioned they felt the experimental procedure took a little too much out of their teaching time. Due to this, it is recommended that future studies use a chest compression period of 60 seconds only.

Whilst this study highlights the importance of using a more ‘physiological’ CDmax to investigate chest compression quality, there is still a paucity of research defining infant thoracic biomechanics. A 56mm CDmax was used by this study to represent the internal

AP chest depth of a 3 month old male infant; however, it still remains unknown whether this manikin design appropriately represents the infant thorax. When considering the presence of intrathoracic organs, in particular, it may be hypothesised that compression depths may, in fact, be further constrained in clinical practice. Furthermore, due a lack of primary data, the infant thoracic over-compression criterion was defined based upon consensus opinion, rather than experimental data [143, 146], with the evidence based chest compression quality targets based on a combination of infant, adult, radiographic and animal surrogate studies. Both the more 'physiological' manikin design and thoracic over-compression criterion were, however, developed using best available evidence and so are likely to be an improvement on previous research and manikin designs.

Finally, this study attempted throughout its design to mitigate potential confounders. Whilst the randomised, crossed-over, study design aimed to reduce the effects of confounders, the effects of CDmax order, chest compression technique order, participant gender, field of expertise and clinical experience were investigated. Male participants were observed to release the chest further than female participants for the TT technique at the $CDmax_{40}$ manikin setting and the TF technique at the $CDmax_{56}$ manikin setting, whilst deeper TT technique compression depths were provided if the TF technique was performed first, regardless of manikin design. Though these results imply that men released the chest further and TT technique chest compression depths are affected by chest compression technique order, the power of all four statistical tests failed to exceed 80%. This implies that these differences could also be due to type-II statistical errors; however, more participants would be required to investigate if these confounding relationships held true. Finally, despite being blinded to the study objectives, participants were aware of being observed and their performance may have been influenced.

4.6.4 Impact of Research Findings

The results from this study may have several important clinical and educational implications. From this study it was confirmed that a more ‘physiological’ infant CPR manikin design may be used to deliver quality chest compression depths and highlight thoracic over-compression during simulated infant CPR. Although commercially available infant CPR training manikins have been used extensively to investigate CPR quality, their design is recognised as being flawed [14-19]. These studies highlighted chest compression stiffness as a key limitation to biofidelity [14-19], but failed to consider the effects of the maximum achievable chest compression depth of the manikin. This study confirms that current, commercially available, infant CPR manikins potentially limit the delivery of high quality chest compressions during simulated infant CPR, whilst also concealing the over-compression of the thorax. If true, then data acquired from infant CPR training manikins with unrepresentative chest compression characteristics should be interpreted with care.

Through the use of a more ‘physiological’ infant CPR manikin design, the chest compressions simulated in this study may better represent the quality of chest compressions performed during infant CPR in actual clinical practice. These chest compressions were observed to both compress the chest further and reduce compression duty cycles, when compared to results abstracted from both existing infant CPR manikin studies [14-19] and Chapter 3. Despite this, overall chest compression quality remained poor for both chest compression techniques, with <8% of all chest compressions found to achieve all four infant specific evidence based quality targets. Fundamental to this was a combination of inaccurate chest compression depths, excessive chest compression rates and prolonged compression duty cycles, whilst the TT technique failed to completely release the chest. Although performed during simulated CPR, these results could have several important implications, if directly transferable to clinical practice.

Deeper chest compressions have been observed to result in favourable haemodynamic outcomes, such as increased arterial pressures in both infant and adult subjects [30, 144] and increased coronary flow and cardiac output in animal surrogate models [31, 142]. Increased compression depths have also been linked with improved survival outcomes, such as increased defibrillation success and survival to hospital discharge after cardiac arrest in adults [32, 33]. Therefore, if the chest compression depths achieved using the more 'physiological' infant manikin design in this study represent the quality of chest compressions provided in clinical practice, trained healthcare resuscitators may provide better quality compression depths than previously believed. Despite this improvement in chest compression depth quality, however, over 50% of compressions failed to achieve current infant chest compression depth quality targets; leaving considerable opportunity for further improvement.

Although current international guidelines emphasise the generation of sufficient cardiac output during infant CPR by compressing the chest to adequate depths [1-3], little emphasis is placed upon restricting maximum depths to limit the risks of causing intrathoracic trauma. In this study, 33% of all TT technique and 7% of all TF technique chest compressions were found to exceed the proposed thoracic over-compression criterion, highlighting the potential for thoracic over-compression in clinical practice. In fact, over 60% of highly trained healthcare providers exceeded this criterion at least once with the TT technique, whilst 35% surpassed this at least once with the TF technique. This, therefore, raises a significant concern over the current safety of infant CPR.

In particular, this study raises concerns over the safety of current international recommendations to "push hard, push fast" during infant CPR [1-3]; particularly as this may encourage the over-compression of the thorax in clinical practice. This safety concern is reinforced in a recent study by Reyes *et al*. [199], which documented a recent increase in the incidence of CPR related rib fractures following the adoption of the 2005 AHA guidelines. Although, traditionally, the incidence of infant CPR trauma is considered rare [187, 188], Reyes *et al*. reported the presence of rib fractures in 7.9% of cases aged <6 months old that had suffered a cardiac arrest since 2005 [199]. As these guidelines recommended maximum chest compression depths of one-half the external AP thoracic diameter [207, 208], it was postulated by the authors that the increase in rib fractures may have been caused by thoracic over-compression during infant CPR [199]. In fact, a recent article highlighted a potential relationship between chest compression depth and iatrogenic injuries occurring during adult CPR [209]. In this study, iatrogenic trauma occurred more frequently when compression depths exceeded 60mm [209]; with this relating to depths of one-quarter the external AP thoracic diameter [210].

Care must, therefore, be maintained with the design of future interventions that attempt to improve chest compression quality during infant CPR, particularly if the intervention is to be used in clinical practice. Based on the principle of non-maleficence in medicine [189], future interventions must actively discourage the provision of potentially injurious chest compressions, whilst bearing in mind that greater chest compression depths are associated with improved haemodynamic [30, 31, 142, 144] and short-term survival [32, 33] outcomes. Clearly, further research is required to determine the optimum chest compression depths that may be 'safely' achieved during infant CPR (i.e. where the potential severity of iatrogenic thoracic trauma still represents a reasonable risk for the increased likelihood of saving a life).

Delivering effective chest compression rates, chest release forces and compression duty cycles during infant CPR are also essential in optimising haemodynamics [34, 35, 147, 148, 150, 153, 154]. The incomplete release of the chest in clinical practice would generate increased intrathoracic pressures, whilst prolonged duty cycles in combination with excessive compression rates would result in inadequate chest wall relaxation, both of which would limit the return of venous blood to the heart and reduce coronary and cerebral perfusion pressures [34, 35, 147, 148, 150, 153, 154]. Whilst improvements in quality were observed for both compression duty cycles and the complete release of the chest, the majority of chest compressions failed to achieve compression rate and duty cycle quality targets and ~46% of TT technique chest compressions failed to completely release the chest. It therefore appears that, without further intervention in either clinical practice or the training environment, optimum haemodynamics during infant CPR may not currently be achievable.

To improve current chest compression quality during infant CPR, resuscitators must be encouraged to achieve the relatively narrow therapeutic window for achieving quality chest compression depths. To achieve this, the TT chest compression technique must be discouraged from over compressing the thorax, whilst the TF technique must be encouraged to compress the chest further. Further improvements in chest compression quality may be achieved by educating resuscitators to completely release the chest during the release phase of each compression. This may improve the proportion of compressions that completely released the chest, whilst also potentially improving duty cycle quality. Finally, compression rates may also be improved through regulation with a metronome. Future work, to improve chest compression quality, should focus on the development of a real-time performance feedback system to ensure resuscitators are made aware of their performance against infant specific evidence based chest compression quality targets.

4.7 Conclusions

This study is the first to utilise a more ‘physiological’ manikin design during simulated infant CPR, with results demonstrating both increased chest compression depths and reduced compression duty cycles, for both the TT and TF chest compression techniques. This, in turn, improved compliance with both compression depth and duty cycle quality targets, whilst also highlighting the potential for thoracic over-compression. Despite this improved design, overall chest compression quality remained very poor; primarily due to excessive chest compression rates and prolonged compression duty cycles. The use of this novel manikin design as a training aid may ultimately encourage resuscitators to achieve better quality chest compressions, potentially improving infant CPR quality in clinical practice. Future work should focus on improving chest compression quality by ensuring that resuscitators are made aware of their performance, against infant specific evidence based quality targets, through developing a real-time performance feedback system.

5 EFFECTS OF PERFORMANCE FEEDBACK ON CHEST COMPRESSION QUALITY

5.1 Introduction

The provision of high quality chest compressions during CPR is vital to improving the current outcomes of infant cardiac arrest [1-3]. Poor quality chest compressions during simulated infant CPR are, however, reported both in Chapters 3 and 4 and throughout the literature [14-19]. Despite using a more ‘physiological’ infant CPR manikin design in Chapter 4, inaccurate chest compression depths, excessive chest compression rates and prolonged compression duty cycles all negatively influenced the quality of chest compressions provided. Consequently, <8% of chest compressions, provided by trained healthcare rescuers, achieved current evidence based quality targets for infant CPR.

Real-time audio-visual performance feedback has the potential to be a valuable tool for both monitoring and aiding resuscitator performance. The benefits of using existing feedback devices during CPR in both adult subjects and manikins are well documented; with the quality of chest compression depths, chest release forces and chest compression rates all improved by real-time performance feedback [32, 167]. The effects of real-time performance feedback on the quality of chest compressions provided during infant CPR have never been quantified. Fundamental to this was the paucity of scientific evidence on which to establish targets to optimise the provision of infant CPR. Recent advances in infant CPR research may now provide sufficient evidence to pave the way for the development of an appropriate performance feedback system for assisting rescuers during infant CPR.

The aim of this study was to evaluate the differences in chest compression quality, when real-time performance feedback was provided to a trained resuscitator, during simulated infant CPR. It was hypothesised that, with the provision of real-time performance feedback, resuscitators would be able to perform infant chest compressions to a much higher standard.

5.2 Feedback during Cardiopulmonary Resuscitation

Effective CPR is an essential link in the chain of survival for the treatment of cardiac arrests [1-3]. Chest compression performance has, however, been shown to be highly variable across both the paediatric and adult literature investigating quality in the out-of-hospital, in-hospital and simulated CPR settings [14-19, 22, 23, 32, 33, 39-42, 174]. Frequent causes of poor quality chest compressions included shallow chest compression depths, interruptions in chest compressions, excessive compression rates and hyperventilation [14-19, 22, 23, 32, 33, 39-42, 174]. This provision of sub-optimal compressions was further confirmed in both Chapters 3 and 4, observing that chest compressions were often performed with inaccurate chest compression depths, excessive chest compression rates and prolonged compression duty cycles during simulated infant CPR.

Although several studies have reported that chest compressions frequently fail to meet established evidence-based guidelines, it also appears that this substandard level of care can adversely affect both the haemodynamics and long-term outcomes of cardiac arrest. Increasing chest compression depths and rates to attain international recommendations results in favourable haemodynamics in both paediatric patients and animal surrogates [30, 31, 142, 144, 150, 153, 154], whilst also improving survival to hospital discharge in adults [32, 33, 39]. Similarly, minimising chest compression interruptions can increase the likelihood of defibrillation success and survival [27-29]. Most importantly, it has been shown in both paediatric and adult patients that the aggressive implementation of current guidelines can substantially improve both short-term outcomes, such as haemodynamics [30, 144], and long-term outcomes, such as survival to hospital discharge and favourable neurological outcomes [211, 212].

Current international resuscitation guidelines emphasise the provision of high-quality chest compressions during CPR, whilst stressing the importance of feedback in assisting rescuers in achieving this [1-3]. The evaluation of CPR effectiveness has, however, proven challenging. Traditional methods, such as palpation of the femoral or carotid pulse and pulse oximetry, do not correlate with successful outcomes and may mislead rescuers [213, 214]. One of the key innovations over the last decade has been the development of audio-visual feedback systems that assist chest compressions in achieving current international guidelines [22, 23, 32, 33, 39-42, 174]. The use of these systems has resulted in a significant improvement in quantitative measures of CPR quality and surrogate measures of survival (i.e. end-tidal CO_2 and myocardial blood flow) across human, animal surrogate and manikin based studies [22, 23, 32, 33, 39-42, 174].

A number of devices have been developed, which provide feedback to support rescuers during CPR, in both the practical training and clinical settings. These devices can range in complexity from simple metronomes, to guide chest compression rates, to more complex devices that both monitor and provide combined audio-visual feedback about actual CPR performance. The Q-CPR system (Philips Medical, Andover, MA) is designed to obtain information on the quality of CPR, via defibrillator pads and an accelerometer placed on the chest. This provides real time audio-visual feedback on chest compression depths, chest compression rates, chest release forces, compression duty cycles and no-flow durations during CPR. The CPREzy (Allied Health, Herts, UK) device combines pressure sensor feedback with a metronome to provide assistance on correct chest compression forces, release forces and compression rates. Performance feedback systems have also been implemented in high-fidelity CPR training manikins. The industry leading Resusci® Anne Skillreporter (Laerdal, Stavanger, Norway) provides real time visual feedback and post-event debrief feedback via a PC monitor. Chest compression quality measures fed back to the resuscitator include chest compression depths and rates, ratios of compressions to ventilations, hand positions, ventilation volumes and inflation rates.

Using these innovative technological systems, quantitative CPR quality information can be recorded, analysed and fed back to the rescuer to correct substandard CPR provision. As current systems are capable of providing both real-time and post-event feedback for all four chest compression quality measures, feedback enabled devices have been used in several trials throughout the literature [32, 40-42]. In two before/after designed trials (i.e. studies using retrospective controls) the provision of real-time feedback was shown to improve the quality of CPR delivered by both EMS and in-hospital providers [32, 40]. In the first of these studies, feedback increased the mean chest compression depths achieved during CPR from 34mm to 38mm, consequently improving the proportion of chest compressions that achieved guideline compression depths from 24% to 53% [32]. This was reflected in the second study, which demonstrated improved compliance with international guidelines through the reduction of inter-participant variability [40]. In the older paediatric population, two studies further confirmed the positive effects of feedback on chest compression quality [41, 42]. Both studies reported that the provision of feedback resulted in a compliance of over 70% for chest compression depths, leaning forces and compression rates [41, 42].

Simulation has been shown to be an effective tool in teaching resuscitation skills. The use of real-time feedback and audio prompt manikins has been consistently observed to improve the quality of chest compressions during simulated CPR [215-218]. The majority of these studies demonstrate improved chest compression depths and rates with the provision of feedback, increasing the proportion of chest compressions that comply with current international guidelines [215-218]. Only one study was performed using a paediatric manikin, however, with a voice advisory manikin (VAM) providing audio-visual feedback during training [215]. This VAM system was reported to have improved chest compression skill acquisition, when compared to instructor based training, resulting in ~65% of VAM trained resuscitators achieving >70% correct chest compressions [215].

Despite clearly augmenting chest compression quality, questions have been raised with regards to whether feedback can actually improve patient outcomes. None of the above studies demonstrate a significant increase in either long-term or short-term survival with the provision of feedback [32, 40-42]; although these studies were not powered to report survival outcomes. A recent multicentre cluster randomised controlled trial performed by Hostler *et al*., however, evaluated the effectiveness of real-time audio-visual feedback on the quality and outcome of CPR in 1,500 out-of-hospital cardiac arrest cases [219]. Despite being appropriately powered, this study found no significant benefit to the clinically relevant outcomes, such as return of spontaneous circulation or survival to hospital discharge [219]. Improvements in chest compression quality were, however, reported; with increased chest compression depths and reduced chest compression rates both improving conformity with current international guideline targets [219].

Whilst this raises the question over whether CPR quality is, in fact, related to survival, a number of important limitations affect the generalisability of the study conclusions. The differences in chest compression depths and rates were minimal [219], suggesting that resuscitators were already well trained in providing quality chest compressions during CPR. Return of spontaneous circulation rates in the no feedback arm were over 40%

[219], implying that pre-hospital care was excellent. Finally, the feedback targets were based on AHA 2005 guidelines [207, 208], resulting in suboptimal compression depths when compared to current targets [3, 220, 221]. Current evidence, therefore, indicates that real-time feedback devices are effective adjuncts to assisting providers in achieving pre-programmed chest compression quality targets. It is, however, the task of resuscitation researchers to determine optimum quality targets for infant chest compressions that will translate into improved survival outcomes.

5.3 Methodology

5.3.1 Infant Manikin Design

This study utilised the commercially available infant CPR manikin (Laerdal® ALS Baby, Laerdal Medical, Stavanger, Norway) previously described in Chapter 4 to enable a more 'physiological' maximum achievable chest compression depth (i.e. an increase in CDmax from 40mm to 56mm [143]). As previously detailed, the modified manikin was instrumented with an infra-red distance measuring sensor and powered by a 5V power supply. Manikin instrumentation was calibrated to record the chest deflections and chest compression forces applied to the lower third of the sternum. Sensor output was recorded on a laptop, at a sample rate of 50Hz, via a Data Acquisition Card and a customised LabVIEW software program (National Instruments, TX, USA).

5.3.2 Performance Feedback Program

This study developed a real-time performance feedback program to both monitor and assist resuscitator performance during simulated infant CPR using LabVIEW software (National Instruments, TX, USA). The performance feedback program used the sensor

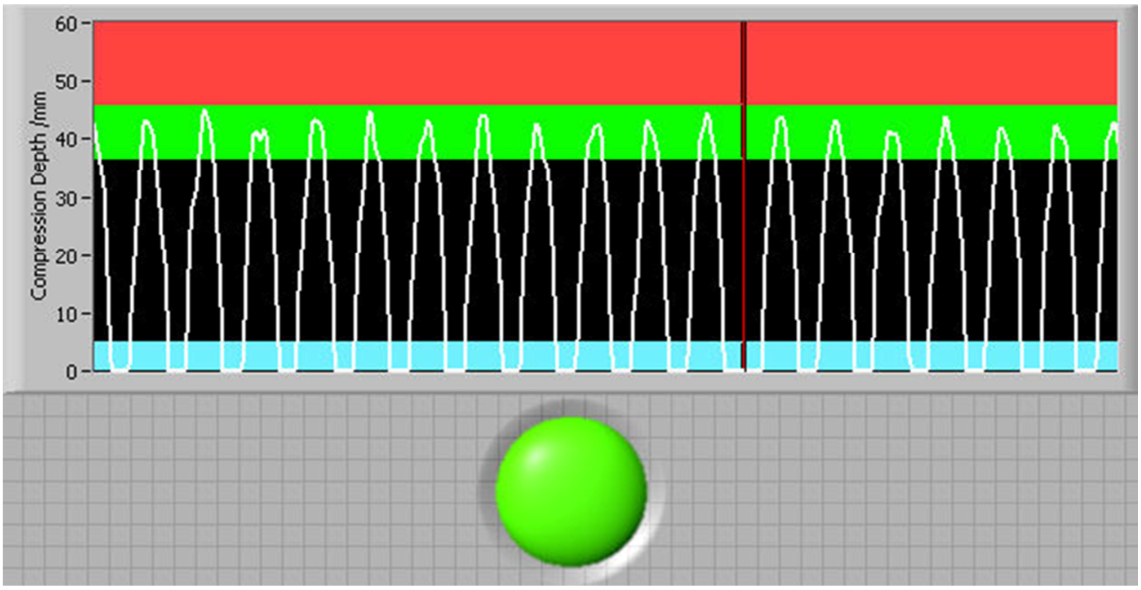

Figure 5-1: The performance feedback program user interface.
The chest deflection trace (in white) is updated in real-time. The chest compression depth target region (36.7-46mm; in green) and complete chest release force target region (<0.5kg (7mm); in blue) are displayed alongside the thoracic over-compression region (>46mm; in red). A green flashing 'LED' and audible metronome both provided compression rate guidance at 110bpm.

output to provide audio-visual feedback to the participant, assisting them in achieving the current evidence based quality targets for infant CPR (Figure 5-1). A real-time chest deflection 'trace', as performed by the participant, was displayed against the chest compression depth (36.7-46mm) and complete release force (<0.5kg) quality targets (where a chest deflection of 7mm corresponded with a chest release force of 0.5kg). An audio-visual metronome provided the resuscitator with a target chest compression rate of 110min^{-1}, whilst the over-compression of the thorax was discouraged by highlighting the occurrence of thoracic over-compression (chest compression depths >46mm).

The LabVIEW block diagram for the performance feedback program is shown in Figure 5-2. For the 'Chest Deflection Program', the sensor output signal and a ground (0v) signal were recorded at a sample rate of 50Hz by the DAQ Assistant. The sensor output signal was first filtered by passing the signal through a low pass (10Hz) Butterworth filter. The filtered signal was then split into two separate signals and calibrated to both record the chest deflections and chest compression forces applied to the lower third of the sternum (Calibrated Signal - Data Collection) and display, in real time, the chest deflection trace (Calibrated Signal - Deflection Trace). The ground signal was split into three separate signals and used to provide constants for the quality target regions shown in Figure 5-2. For the ‘Metronome Program’, a flashing LED and audible metronomic tone (frequency 300Hz, duration 30ms) were programmed, via a case structure control loop, to flash/beep every 544ms to provide an 110bpm audio-visual metronome.

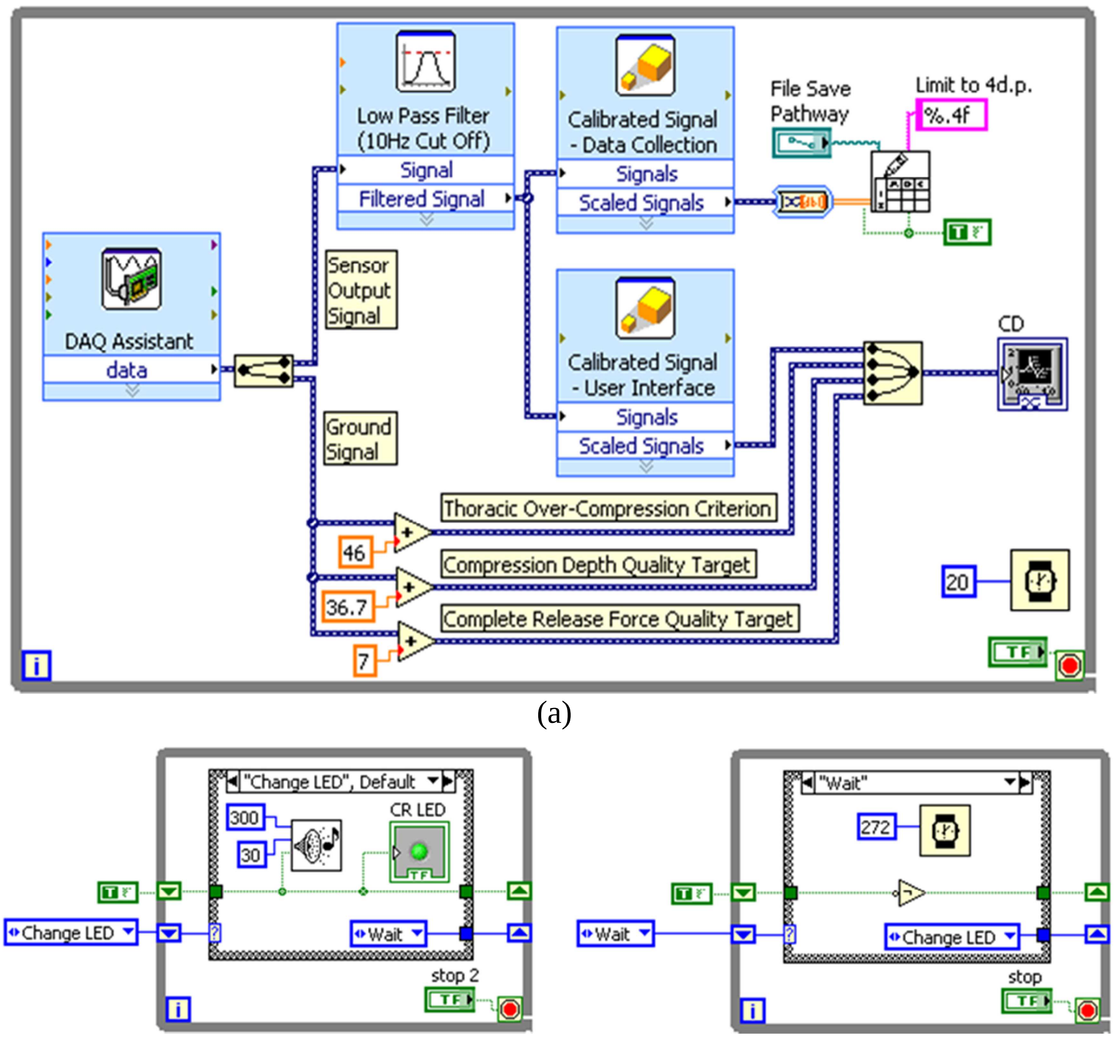

Figure 5-2: LabVIEW block diagrams for the performance feedback program.
These illustrate (a) the ‘Chest Deflection Program’, (b) the ‘Metronome Program’ “Change LED” case and (c) the ‘Metronome Program’ “Wait” case.

5.3.3 Study Coordination and Participants

This manikin study was approved by seven National Health Service Health (NHS) Boards and Trusts across Wales and England (IRAS 103570). This study was further approved by the Working Group Chair of the Resuscitation Council UK run European Paediatric Life Support (EPLS) training course and both the CEO and Working Group Chair of the Advanced Life Support Group run Advanced Paediatric Life Support (APLS) training course. Ethical approval for the research was obtained from the Cardiff University School of Engineering Ethics Committee, whilst Research Ethics Committee approval was not required, since, again, NHS staff only were used in this study [182]. The approved Research Protocol, documentation and Letters of Approval for the study are presented in the Electronic Appendices.

Training course instructors were recruited to this study from five EPLS and two APLS training courses. As in Chapters 3 and 4, the Training Course and Medical Directors for each course confirmed their willingness to facilitate this study. Participant Information Sheets were circulated around all potential participants by the Training Course Director, at least one week prior to testing. Before testing, the participants were briefed on the experimental procedures using a standardised Experimental Instruction Sheet. Any queries the participants had were answered and, once satisfied, the participants were asked to complete and sign the Participant Consent and Participant Details Forms. Individual results were reported back to the participant, via the Training Course Director, after study completion.

Sixty-nine consenting instructors were recruited to this study as participants from five EPLS and two APLS training courses. The exclusion criteria were: invalid EPLS/APLS instructor certification, incomplete data acquisition, withdrawal of consent and any participant health issues. Demographics (gender, field of expertise, clinical experience, current certification, time since last certification and number of previous infant resuscitations performed) were collected via the Participant Details Forms. Study participants consisted of 31 male and 38 female certified EPLS and APLS training course instructors (Table 5-1). Thirty-four participants were doctors, 24 were resuscitation officers, eight were registered nurses, two were paramedics and one was an operating department practitioner. Thirty-four (49.3%) participants were randomised to the 'feedback' group, whilst 33 (47.8%) participants were randomised to perform the TT chest compression technique first. Mean time since last instructor certification was 2.1 (±0.8) years, whilst mean clinical experience was 17.8 (±7.7) years.

Table 5-1: Comparison of demographics for the 'no feedback' and 'feedback' groups

	No Feedback Group	Feedback Group	*P*-value
Total Number of Participants /n	35	34	0.90
Gender			
Male /n(%)	14 (40)	17 (50)	0.40
Female /n(%)	21 (60)	17 (50)	0.40
Field of expertise			
Resuscitation Officer /n(%)	14 (40)	10 (29)	0.36
Doctor /n(%)	16 (46)	18 (53)	0.55
Registered Nurse /n(%)	5 (14)	3 (9)	0.48
Paramedic /n(%)	0 (0)	2 (6)	0.15
Operating Department Practitioner /n(%)	0 (0)	1 (3)	0.31
Mean clinical experience ±SD /years	18.7 ± 8.4	16.8 ± 6.9	0.33
Current certification			
APLS /n(%)	20 (57)	22 (65)	0.52
EPLS /n(%)	24 (69)	21 (62)	0.55
PLS /n(%)	9 (26)	5 (15)	0.26
PILS /n(%)	13 (37)	10 (29)	0.50
NLS /n(%)	6 (17)	5 (15)	0.78
Mean time since last certification ±SD /years	2.0 ± 0.8	2.1 ± 0.8	0.77
Number of infant resuscitations performed			
None /n(%)	2 (6)	1 (3)	0.57
<5 /n(%)	8 (23)	8 (24)	0.95
5-10 /n(%)	6 (17)	10 (29)	0.23
11-20 /n(%)	5 (14)	5 (15)	0.96
>20 /n(%)	14 (40)	10 (29)	0.36

APLS, Advanced Paediatric Life Support; EPLS, European Paediatric Life Support; PLS, Paediatric Life Support; PILS, Paediatric Immediate Life Support. P-values were calculated via χ-squared tests to compare differences between group demographics.

The differences between the demographics of both groups were compared by χ-squared tests (SPSS 16.0, SPSS Inc., IL, USA), with no significant differences observed between the demographics of the two groups (Table 5-1). A study sample size of 34 participants per group is able to adequately detect a mean difference 0.7 times the standard deviation of the differences; assuming data normality, a two-sided significance level of <0.05 and >80% power (calculated with G*Power 3.1.5 [183]).

5.3.4 Experimental Procedure

Prior to testing, the modified manikin was set up in a separate assessment room, with the laptop and peripheral equipment located on a flat table (Figure 3-6). Participants were assigned, via a table of randomised numbers, to either the control ('no feedback') group or the interventional ('feedback') group and a chest compression technique order (TT-TF or TF-TT). All participants were instructed to provide continuous chest compressions (i.e. no ventilations required) in two stages. Stage 1, termed the 'baseline' stage, required all participants to provide two 60 second periods of TT and TF technique chest compressions, without feedback, in their assigned randomised cross-over order.

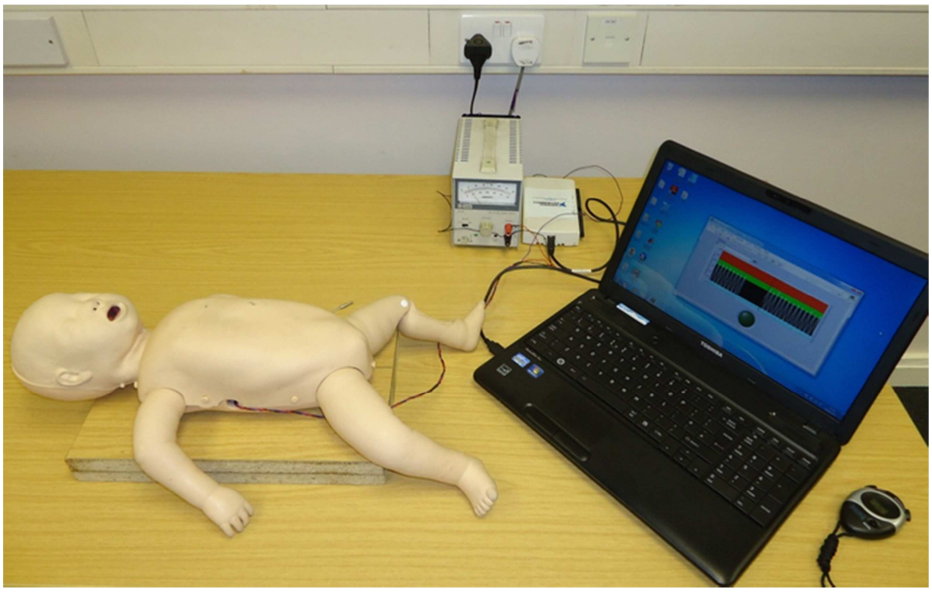

Figure 5-3: Experimental set up for testing

Stage 2, termed the 'experimental' stage, required all participants to repeat this procedure, whilst the performance feedback program was provided to the 'feedback' group. Full recovery was permitted for all participants after each period. Chest compression depths and chest compression forces were recorded at a 50Hz sample rate throughout. Participants were neither refreshed nor coached on either chest compression technique and were blinded to the nature of the manikin modification. Individual results were fed back to the participants after study completion.

5.3.5 Data analysis

Data were recorded for each participant, describing median chest compression depths, chest release forces, chest compression rates and compression duty cycles achieved for all four chest compression periods. Quality indices, adopted from Chapter 3, were used to calculate the proportion of chest compressions for each participant that complied with current quality targets (Table 4-3). The proportion of chest compressions that exceeded the thoracic over-compression criterion was also calculated to quantify thoracic over-compression, whilst maximum chest compression depths were also recorded. Finally, to determine overall chest compression quality, the proportion of chest compressions that simultaneously achieved all four primary quality targets was calculated. This was repeated for the proportion of chest compressions that achieved three or more quality targets, two or more quality targets and at least one quality target.

Descriptive data are reported either as means with standard deviations (±σ) or medians with inter-quartile ranges for each infant chest compression technique. Mean differences between the 'feedback' and 'no feedback' groups are reported with 95% confidence intervals. After testing for data normality (Shapiro-Wilk tests), results were statistically analysed by either independent Student T-tests or Mann Whitney U tests as appropriate.

Table 5-2: Definitions of infant chest compression quality measures and quality targets.

Parameter	Definition	Target Range	Target Range Description
Chest Compression Depth	The maximum chest deflection achieved during each chest compression cycle*	36.7-46mm	European and UK Resuscitation Council guidelines recommend a compression depth of no less than one-third the external anterior-posterior (AP) chest diameter [1-3]. The upper threshold is proposed based upon the hypothesis that a residual internal AP chest depth of <10mm may potentially cause intra-thoracic trauma [143, 146].
Chest Release Force	The minimum chest compression force achieved during the release phase of each chest compression cycle	<2.5kg <0.5kg	A 2.5kg chest release force would cause a clinically significantly increase in intra-thoracic pressure and significantly limit the return of venous blood to the heart [148]. As a 0.5kg chest release force (10% of the manikin's weight) would also cause a measurable increase in inter-thoracic pressure [148], this was used as a secondary quality target.
Chest Compression Rate	The inverse of the time taken for each chest compression cycle and quantified as the number of compressions per minute	100-120min^{-1}	European and UK Resuscitation Council guidelines recommend a compression rate between 100-120 compressions per minute [1-3].
Compression Duty Cycle	Calculated for each chest compression cycle by dividing the area under the chest deflection curve by the product of the chest compression depth and chest compression cycle time.	30-50%	The most effect compression duty cycle range observed in infant animal surrogates [150, 153, 154].

* Chest compression cycles defined between consecutive chest release forces

Mean paired differences between the TT and TF techniques are also reported with 95% confidence intervals. Again, after testing for data normality (Shapiro-Wilk), results were statistically evaluated by either paired Student T-tests or Wilcoxon's signed rank tests.

The effects of potential confounders, including gender, chest compression technique order, field of expertise, clinical experience, instructor certification, time since last certification and total number of infant resuscitations, were assessed for all four quality measures. Data were tested for normality and homogeneity of variance (Shapiro-Wilk and Levene's tests). The effects of participant gender and chest compression technique order were analysed using either independent Student T-tests or Mann-Whitney U tests as appropriate. The effects of field of expertise, certification and number of infant resuscitations performed were analysed using either one-way ANOVA or Kruskal-Wallis tests, as appropriate, whilst the effects of clinical experience and time since last certification were analysed using linear regression analyses. Statistical significance was considered at $p<0.05$ for all tests and all p-values were two-sided. All statistical analyses were performed with SPSS 16.0, whilst post-hoc power analyses were performed with G*Power 3.1.5 [183].

5.4 Results

5.4.1 Baseline Stage

No significant differences in performance were observed between the 'no feedback' and 'feedback' groups during the baseline stage; where real-time performance feedback was withheld from both groups (Appendix A.5). Both the TT and TF chest compression techniques rarely complied with the chest compression depth, chest compression rate and compression duty cycle quality targets, whilst >99% of all chest compressions achieved the chest release force quality targets. Consequently, overall chest compression quality remained very poor for both techniques; with <9% of chest compressions simultaneously achieving all four evidence based quality targets.

When comparing chest compression techniques, the TT technique was found to achieve greater chest compression depths, whilst the TF technique released the chest further and reduced compression duty cycles (Appendix A.5). This improved the proportion of TF technique compressions that complied with compression duty cycle quality targets. No significant differences were observed between chest compression rates. TT technique chest compressions reduced the proportion of compressions that under-compressed the chest, whilst the TF technique both increased the proportion that completely released the chest and reduced the proportion that provided prolonged compression duty cycles.

The maximum chest compression depths achieved by each participant, for each infant chest compression technique, are illustrated in Appendix A.5. The ‘no feedback’ group exceeded the proposed thoracic over-compression criterion with 36% of TT technique and 9% of TF technique chest compressions, whilst the ‘feedback’ group exceeded this with 35% of TT technique and 19% of TF technique compressions. No significant differences were observed between the feedback groups for either technique, whilst the TT technique provided a greater proportion of chest compressions that over-compressed the thorax across both groups.

5.4.2 Experimental Stage

The simulated chest compression quality measures performed during the experimental stage are illustrated in Figure 5-4 against the evidence based quality targets for infant CPR. Performance feedback reduced both TT and TF technique chest compression rates and compression duty cycles, whilst increasing TF technique chest compression depths and reducing TT technique chest release forces (Table 5-3). Subsequently, the provision of feedback resulted in an improved proportion of TT and TF chest compressions that achieved chest compression depth, chest compression rate and compression duty cycle quality targets and TT technique chest compressions that completely released the chest. Finally, the provision of feedback was also found to reduce the proportion of TT and TF chest compressions with excessive chest compression rates and prolonged compression duty cycles, whilst also reducing the proportion of TF technique chest compressions that under-compressed the thorax.

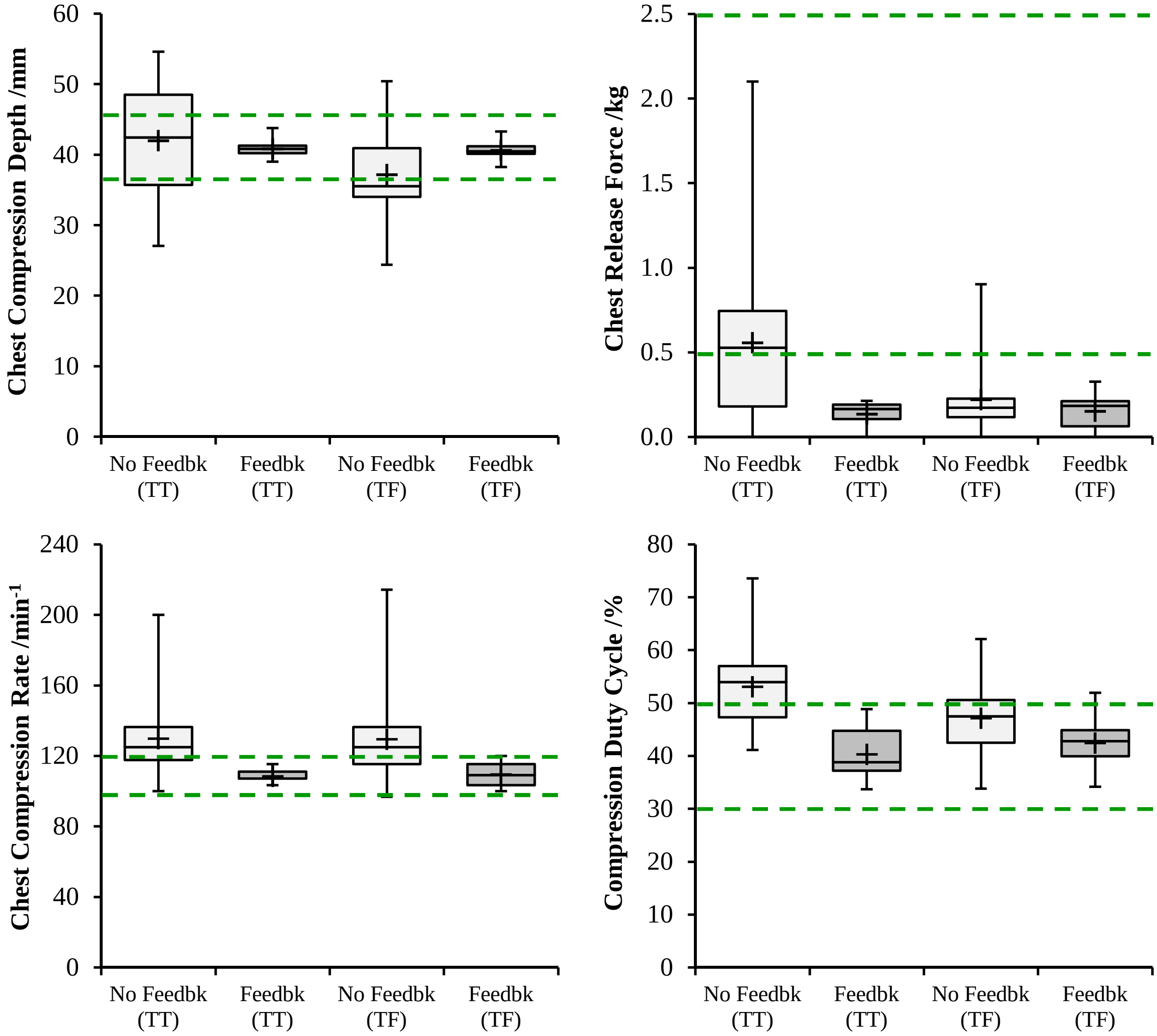

Figure 5-4: Illustration of median chest compression depths, chest release forces, chest compression rates and compression duty cycles, for both the two-thumb (TT) and two-finger (TF) techniques, as performed by the 'no feedback' (No Feedbk) and 'feedback' (Feedbk) groups at the experimental stage.

Current evidence based quality targets are illustrated by dashed lines. Chest compression depth targets were 36.7-46mm, chest release force targets were <2.5kg and <0.5kg, chest compression rate targets were 100-120min^{-1} and compression duty cycle targets were 30-50%. The centre line of the box plot represents the median value of the data, the upper and lower lines of the box plot represent the upper and lower quartiles of the data, the cross represents the mean value of the data and the whiskers represent the maximum and minimum values of the data.

Table 5-3: Changes in simulated chest compression quality measures and quality indices, between the ‘no feedback’ and ‘feedback’ groups, for both the two-thumb (TT) and two-finger (TF) chest compression techniques at the experimental stage.

	Two-Thumb Chest Compression Technique				Two-Finger Chest Compression Technique			
	No Feedback Group	**Feedback Group**	**Mean Difference**	***P*-value**	**No Feedback Group**	**Feedback Group**	**Mean Difference**	***P*-value**
Compression Depths (CD)								
Mean Compression Depth /mm	42 ± 8	41 ± 1	-1 [-4, 1]	0.38*	37 ± 6	41 ± 1	3 [1, 5]	***0.002****
Median Compression Depth /mm	42 [36, 48]	41 [40, 41]		0.41†	36 [34, 41]	40 [40, 41]		***0.002***†
CD Quality Index (36.7-46mm) /%	20 [1, 78]	99 [96, 100]		***<0.001***†	21 [3, 53]	97 [93, 99]		***<0.001***†
Under-Compression (<36.7mm) /%	1 [0, 67]	1 [0, 3]		0.22†	72 [3, 95]	1 [1, 4]		***0.001***†
Release Forces (RF)								
Mean Release Force /kg	0.6 ± 0.5	0.1 ± 0.1	-0.4 [-0.6, -0.3]	***<0.001****	0.2 ± 0.2	0.2 ± 0.1	-0.1 [-0.1, 0.0]	0.10*
Median Release Force /kg	0.5 [0.2, 0.7]	0.2 [0.1, 0.2]		***<0.001***†	0.2 [0.1, 0.2]	0.2 [0.1, 0.2]		0.85†
RF Quality Index (<2.5kg) /%	100 [100, 100]	100 [100, 100]		0.16†	100 [100, 100]	100 [100, 100]		0.31†
Complete RF (<0.5kg) /%	47 [5, 97]	99 [96, 100]		***<0.001***†	96 [85, 100]	97 [93, 100]		0.48†
Compression Rates (CR)								
Mean Compression Rate /min^{-1}	130 ± 20	108 ± 4	-21 [-28, -15]	***<0.001****	129 ± 23	109 ± 5	-20 [-28, 12]	***<0.001****
Median Compression Rate /min^{-1}	125 [118, 136]	107 [107, 111]		***<0.001***†	125 [115, 136]	109 [103, 115]		***<0.001***†
CR Quality Index (100-120min^{-1}) /%	20 [1, 74]	92 [85, 96]		***<0.001***†	34 [1, 73]	87 [83, 93]		***<0.001***†
Too Fast (>120min^{-1}) /%	80 [14, 99]	1 [1, 2]		***<0.001***†	58 [7, 99]	3 [1, 6]		***<0.001***†
Compression Duty Cycles (DC)								
Mean Compression Duty Cycle /%	53 ± 7	40 ± 4	-13 [-15, -10]	***<0.001****	47 ± 7	42 ± 4	-5 [-7, -2]	***0.002****
Median Compression Duty Cycle /%	54 [47, 57]	39 [37, 45]		***<0.001***†	47 [42, 51]	43 [40, 45]		***0.002***†
DC Quality Index (30-50%) /%	18 [4, 77]	93 [85, 96]		***<0.001***†	72 [44, 88]	93 [84, 96]		***<0.001***†
Prolonged DC (>50%) /%	82 [23, 96]	4 [1, 11]		***<0.001***†	28 [9, 56]	5 [3, 9]		***<0.001***†

Mean quality measures are presented as mean values ± standard deviation, whilst both the median quality measures and quality indices are presented as median values [inter-quartile range]. Differences between the feedback groups (‘feedback’ less ‘no feedback’) are presented as the mean difference [95% confidence interval]. P-values were calculated from two-sided independent samples Student’s T-tests (*) or Mann Whitney U tests (†) as appropriate.

Table 5-4: Changes in simulated chest compression quality measures and quality indices, between the two-thumb (TT) and two-finger (TF) techniques, for both the 'no feedback' and 'feedback' groups at the experimental stage.

	'No Feedback' Group				'Feedback' Group			
	TT Technique	TF Technique	Mean Paired Difference	*P*-value	TT Technique	TF Technique	Mean Paired Difference	*P*-value
Compression Depths (CD)								
Mean Compression Depth /mm	42 ± 8	37 ± 6	5 [4, 6]	***<0.001****	41 ± 1	41 ± 1	0 [0, 1]	0.37*
Median Compression Depth /mm	42 [36, 48]	36 [34, 41]		***<0.001***†	41 [40, 41]	40 [40, 41]		0.25†
CD Quality Index (36.7-46mm) /%	20 [1, 78]	21 [3, 53]		0.53†	99 [96, 100]	97 [93, 99]		0.13†
Under-Compression (<36.7mm) /%	1 [0, 67]	72 [3, 95]		***<0.001***†	1 [0, 3]	1 [1, 4]		0.18†
Release Forces (RF)								
Mean Release Force /kg	0.6 ± 0.5	0.2 ± 0.2	0.3 [0.2, 0.5]	***<0.001****	0.1 ± 0.1	0.2 ± 0.1	0.0 [-0.1, 0.0]	0.38*
Median Release Force /kg	0.5 [0.2, 0.7]	0.2 [0.1, 0.2]		***<0.001***†	0.2 [0.1, 0.2]	0.2 [0.1, 0.2]		0.29†
RF Quality Index (<2.5kg) /%	100 [100, 100]	100 [100, 100]		0.18†	100 [100, 100]	100 [100, 100]		0.32†
Complete RF (<0.5kg) /%	47 [5, 97]	96 [85, 100]		***<0.001***†	99 [96, 100]	97 [93, 100]		0.12†
Compression Rates (CR)								
Mean Compression Rate /min^{-1}	130 ± 20	129 ± 23	0 [-2, 3]	0.77*	108 ± 4	109 ± 5	-1 [-3, 1]	0.21*
Median Compression Rate /min^{-1}	125 [118, 136]	125 [115, 136]		0.96†	107 [107, 111]	109 [103, 115]		0.098†
CR Quality Index (100-120min^{-1}) /%	20 [1, 74]	34 [1, 73]		0.37†	92 [85, 96]	87 [83, 93]		***0.017***†
Too Fast (>120min^{-1}) /%	80 [14, 99]	58 [7, 99]		0.32†	1 [1, 2]	3 [1, 6]		***<0.001***†
Compression Duty Cycles (DC)								
Mean Compression Duty Cycle /%	53 ± 7	47 ± 7	6 [4, 8]	***<0.001****	40 ± 4	42 ± 4	-2 [-4, 0]	***0.019****
Median Compression Duty Cycle /%	54 [47, 57]	47 [42, 51]		***<0.001***†	39 [37, 45]	43 [40, 45]		***<0.001***†
DC Quality Index (30-50%) /%	18 [4, 77]	72 [44, 88]		***<0.001***†	93 [85, 96]	93 [84, 96]		0.69†
Prolonged DC (>50%) /%	82 [23, 96]	28 [9, 56]		***<0.001***†	4 [1, 11]	5 [3, 9]		0.30†

Mean quality measures are presented as mean values ± standard deviation, whilst both the median quality measures and quality indices are presented as median values [inter-quartile range]. Differences between the chest compression techniques (TT less TF) are presented as the mean paired difference [95% confidence interval]. *P*-values were calculated from two-sided paired samples Student's T-tests (*) or Wilcoxon's Signed Rank tests (†) as appropriate.

When comparing chest compression techniques for the ‘no feedback’ group, the TT technique achieved greater chest compression depths, whilst the TF technique released the chest further and reduced compression duty cycles (Table 5-4). This improved the proportion of TF technique chest compressions that complied with the compression duty cycle quality targets and that completely released the chest. The TT technique further reduced the proportion of compressions that under-compressed the chest, whilst the TF technique increased the proportion that completely released the chest. When comparing techniques for the ‘feedback’ group, the TT technique was observed to reduce compression duty cycles, whilst improving the proportion of compressions that achieved chest compression rate quality targets. No significant differences in chest compression depths or chest release forces were found between techniques for the ‘feedback’ group.

The overall chest compression quality indices achieved by both feedback groups are illustrated in Figure 4-6. For both chest compression techniques, the use of performance feedback was observed to considerably improve overall chest compression quality; with

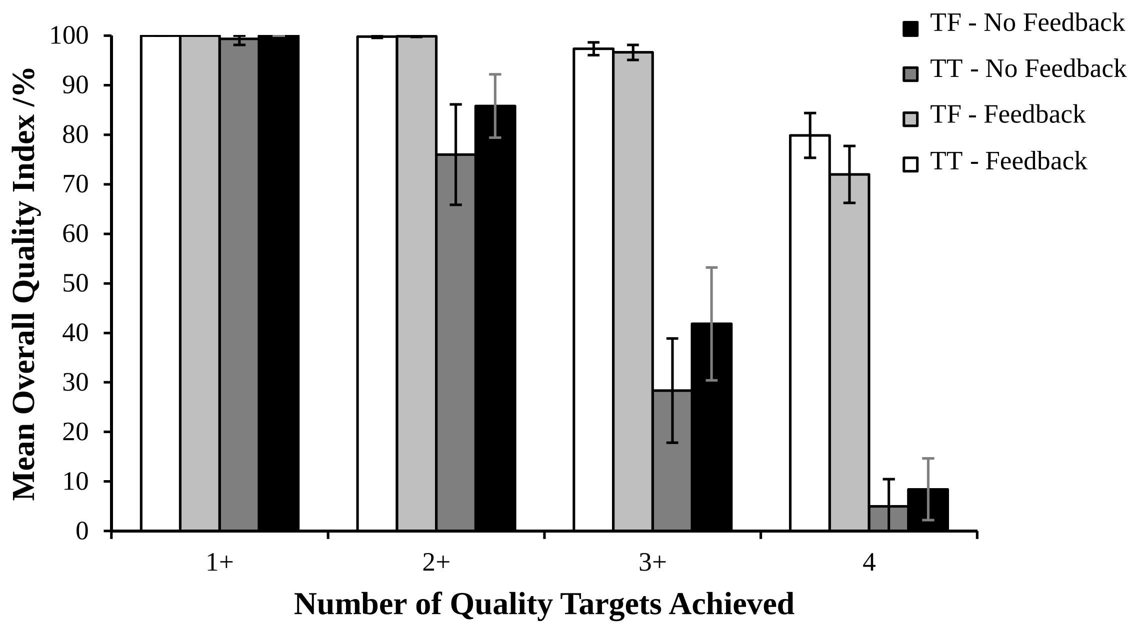

Figure 5-5: Mean overall quality indices achieved by the ‘no feedback’ and ‘feedback’ groups for the two-thumb (TT) and two-finger (TF) techniques at the experimental stage. Error bars represent 95% confidence intervals.

<9% of chest compressions performed by the 'no feedback' group, and 75% of TF technique and 80% of TT technique chest compressions performed by the 'feedback' group, complying simultaneously with all four chest compression quality targets. The provision of feedback was, therefore, observed to improve the proportion of TT and TF technique chest compressions that achieved all four quality targets (mean paired difference [95% CI]; TT: 75 [68, 82]%, $p<0.001$; TF: 64 [55, 72]%, $p<0.001$), three or more quality targets (TT: 69 [59, 79]%, $p<0.001$; TF: 55 [44, 66]%, $p<0.001$) and two or more quality targets (TT: 24 [14, 34]%, $p<0.001$; TF: 14 [8, 20]%, $p<0.001$). When comparing techniques, only the TT technique provided a greater proportion of chest compressions that complied with all four chest compression quality targets (8 [1, 15]%, $p=0.031$).

The maximum chest compression depths achieved by each participant for each chest compression technique are illustrated for both feedback groups in Figure 4-7. The 'no feedback' group exceeded the proposed thoracic over-compression criterion with 33% of all TT technique and 12% of all TF technique chest compressions, whilst the 'feedback' group exceeded this with <1% of all chest compressions. Feedback provision was therefore found to reduce the incidence of thoracic over-compression for both chest compression techniques (mean difference [95%CI]; TT: -32 [-46, -18]%, $p<0.001$; TF: -11 [-21, -1]%, $p=0.032$), whilst the TT

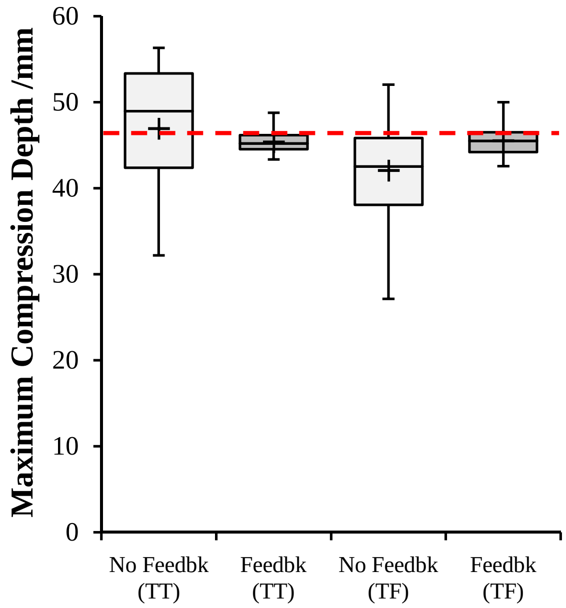

Figure 5-6: Maximum chest compression depths, illustrated against the thoracic over-compression criterion (46mm), for both two-thumb (TT) and two-finger (TF) chest compressions, as performed by the 'no feedback' (No Feedbk) and 'feedback' (Feedbk) groups at the experimental stage.
The centre line of the box plot represents the median value of the data, the upper and lower lines of the box plot represent the upper and lower quartiles of the data, the cross represents the mean value of the data and the whiskers represent the maximum and minimum values of the data.

technique achieved a greater proportion of chest compressions that over-compressed the chest for the ‘no feedback’ group only (‘no feedback’: 21 [10, 31]%, $p<0.001$; ‘feedback’: 0 [-1, 0]%, $p=0.039$). For the ‘no feedback’ group, 22 (62.9%) participants exceeded the proposed criterion at least once with the TT chest compression technique, whilst nine (25.7%) exceeded this with the TF technique. Three (8.6%) participants were observed to exceed the proposed criterion with 100% of TT technique chest compressions, with only one (2.9%) participant found to do this with the TF technique.

5.4.3 Confounding Variables

Of the potential confounders investigated, participant field of expertise, instructor certification, time since last certification and total number of infant resuscitations were all found to have no significant effect on any of the four quality measures achieved. When provided with performance feedback, female participants were found to release the chest significantly further than males, for both chest compression techniques (mean difference [95%CI]; TT: -0.1 [-0.1, 0.0]kg, $p=0.041$, power=55%; TF: -0.1 [-0.1, 0.0]kg, $p=0.008$, power=78%). For both the ‘baseline’ and ‘experimental’ stages, participants from the ‘no feedback’ group were found to provide significantly reduced TF technique chest compression rates, if they performed the TT technique first (‘baseline’ stage: -18 [-33, -3]min^{-1}, $p=0.021$, power=65%; ‘experimental’ stage: -17 [-32, -2] min^{-1}, $p=0.024$, power=63%). Finally, during the ‘experimental’ stage, an increase in clinical experience decreased TT and TF technique compression rates for the ‘no feedback’ group (linear regression; TT: -0.14min^{-1}/year, $R^2=0.12$, $p=0.042$, power=6%; TF: -0.14min^{-1}/year, $R^2=0.15$, $p=0.023$, power=6%) and increased TT technique compression duty cycles for the ‘feedback’ group (0.584%/year, $R^2=0.13$, $p=0.034$, power=38%). Aside from these differences, gender, technique order and clinical experience had no further effects.

5.5 Discussion

5.5.1 Summary of Principle Findings

This study is the first to investigate the effects of real-time performance feedback during simulated infant CPR, with results demonstrating a considerable improvement in overall chest compression quality. With the provision of real-time performance feedback, 75% of all TF and 80% of all TT technique chest compressions simultaneously achieved all four evidence based quality targets. When feedback was withheld, however, <9% of chest compressions achieved all four quality targets. Specifically, feedback improved the quality of chest compression depths, chest compression rates and compression duty cycles, whilst also reducing the incidence of thoracic over-compression and improving the complete release of the chest for the TT chest compression technique. When real-time performance feedback was withheld, the TF technique was found to improve both duty cycle quality and the complete release of the chest, whilst reducing the incidence of thoracic over-compression. When performance feedback was provided, the TT chest compression technique was observed to improve compression rate quality only.

5.5.2 Comparison of Findings with Relevant Literature

Current international paediatric guidelines emphasise the provision of high quality chest compressions during infant CPR [1-3]. Despite this, both Chapters 3 and 4 reported that substandard chest compressions were frequently performed by trained resuscitators during simulated infant CPR. This was further supported by this study, both at the baseline stage and by the control group, with >91% of all chest compressions failing to achieve all four evidence based quality targets. Overall chest compression quality was, however, considerably improved through the provision of real-time performance feedback; with

75% of all TF and 80% of all TT technique chest compressions achieving all four evidence based quality targets. Fundamental to this was the provision of high quality chest compression depths, chest release forces, chest compression rates and compression duty cycles during feedback assisted CPR.

The provision of high quality chest compression depths is a particular challenge during infant CPR, principally due to the very narrow therapeutic window (~10mm) between the under and over-compression of the thorax. Resuscitators in this study achieved chest compression depth quality targets in ~20% of chest compressions when providing infant CPR without feedback assistance. This was consistent with the substandard quality of compression depths recorded in Chapter 4; where the majority of TT and TF technique chest compressions were found to either under or over-compress the thorax. With the provision of real-time performance feedback, considerable improvements were found for both TT and TF chest compression depth quality indices; with >97% of chest compressions achieving current compression depth quality targets. Fundamental to this was the standardisation of chest compression depths, which reduced the inter-participant variation and increased TF technique compression depths. Consequently, this resulted in a reduction in the under and over-compression of the thorax. The provision of real-time performance feedback therefore appears vital in ensuring that resuscitators achieve current compression depth quality targets during infant CPR. This is essential for maintaining favourable haemodynamic outcomes [30, 31, 142, 144], whilst also minimising the risks of trauma through the over-compression of the infant thorax [143, 146].

The complete release of the chest during CPR reduces intrathoracic pressures during the chest release phase, improving the return of venous blood to the heart and increasing both coronary and cerebral perfusion pressures [34, 35, 147-149]. Without the provision of real-time performance feedback, >99% of TT and TF technique chest compressions were found to comply with current chest release force quality targets (<2.5kg), whilst the TF technique achieved a greater proportion of chest compressions that completely released the chest (<0.5kg). This was consistent with the results from Chapter 4, raising concerns over the ability of the TT technique to completely release the thorax. With the provision of real-time performance feedback, however, the TT technique was observed to achieve the complete release of the chest in >99% of chest compressions; emulating the high quality chest release forces provided by the TF technique. Thus, the provision of real-time performance feedback appears vital in ensuring resuscitators completely release the chest with the TT technique during infant CPR. As the TT technique is currently favoured by international resuscitation guidelines [1-3], the provision of real-time performance feedback may therefore be essential to maximising the return of venous blood to the heart.

Fundamental to the considerable improvement in overall chest compression quality, was a significant reduction in TT and TF technique chest compression rates. Increased chest compression rates can result in the inadequate relaxation of the chest wall during CPR, adversely affecting cardiac output, cerebral perfusion pressure and cerebral blood flow [150, 153, 154]. Excessive compression rates are frequently reported during simulated infant CPR, both by previous research [16, 17, 19] and in Chapters 3 and 4. This trend was continued with the no feedback group in this study; with 80% of TT and 58% of TF technique chest compressions observed to compress the chest too fast. With real-time performance feedback provided, however, both TT and TF compression rates were considerably reduced, increasing the proportion of compliant chest compressions to 92% for the TT technique and 87% for the TF technique. The use of an audio-visual metronome, therefore, appears essential to providing high quality chest compression rates. If transferable to clinical practice, chest compression rate guidance could allow full chest wall relaxation during infant CPR, optimising the return of venous blood to the heart prior to recirculation.

High quality compression duty cycles are fundamental to optimising the return of venous blood to the heart [150, 153, 154]. Prolonged duty cycles result in inadequate chest wall relaxation during CPR, adversely affecting cardiac output, cerebral perfusion pressure and cerebral blood flow [150, 153, 154]. Prolonged duty cycles were, however, reported in both Chapters 3 and 4, with >60% of chest compressions failing to achieve current compression duty cycle quality targets. Similarly, when feedback was withheld in this study, prolonged compression duty cycles were provided in 82% of TT and 28% of TF technique chest compressions. With real-time performance feedback provided, compression duty cycles were significantly reduced for both the TT and TF techniques; resulting in 93% of chest compressions achieving current infant compression duty cycle quality targets for both techniques. Thus, whilst the real-time performance feedback program did not specifically attempt to directly enhance duty cycle performance, it appears the provision of real-time performance feedback is fundamental to the delivery of high quality duty cycles during infant CPR.

The TT chest compression technique is currently favoured by international guidelines [1-3], with previous research concluding that the TT technique achieved deeper and more consistent chest compression depths during simulated infant CPR [15-19]. Chapter 4 challenged this research, however, by reporting that TT technique chest compressions increased the incidence of thoracic over-compression, whilst also reducing compression duty cycle compliance and the complete release of the chest. Similar results were also found in this study, with increased chest compression depths, chest release forces and compression duty cycles all provided by the TT technique. When real-time performance feedback was provided, however, the TT technique was observed to reduce compression duty cycles and improve chest compression rate compliance only. Unsurprisingly these differences were minimal, as the aim of the real-time performance feedback program was to standardise and optimise chest compression performance regardless of technique.

5.5.3 Study Methodology

This study attempts throughout its design to minimise experimental bias. A prospective randomised controlled study design was selected, to minimise allocation bias in group assignment. It obtained informed consent from certified EPLS/APLS instructors and gave instructors a free choice, and adequate time, to consider participation. Participants were blinded to the study objectives, whilst no participants were lost to follow up during the ‘experimental’ stage. Finally, the standardisation of instructions was provided by the Experimental Instruction Sheet, whilst the effects of fatigue were reduced by allowing full participant recovery and by reducing the chest compression period to 60 seconds.

All participants were certified European Paediatric Life Support (EPLS) and Advanced Paediatric Life Support (APLS) training course instructors. Both are leading paediatric emergency life support training courses, which are both taught and practiced throughout the World [184, 206]. Instructors are selected from outstanding candidates at training courses and have successfully passed further assessment at Generic Instructor Courses [184, 206]. It can be assumed, therefore, that this study analysed chest compressions provided by highly trained resuscitators, representing the ‘gold standard’ for chest compression quality. The use of highly trained training course instructors, however, may not typically represent the demographics of the population most likely to provide infant CPR. The quality of chest compressions provided by this cohort may therefore exceed the quality of chest compressions provided by Basic Life Support (BLS) or EPLS/APLS trained rescuers or laypersons.

Perhaps the most important aspect of the study was the real-time performance feedback program. Whilst the effects of only one form of feedback were evaluated by this study, other forms exist which could influence the results differently. Corrective feedback (i.e. input only provided when chest compression performance does not meet guidelines), for example, has been used extensively in previous studies to improve the quality of chest compressions delivered in adult human subjects and CPR manikins [32, 40-42, 215-218]. The effects of feedback training also cannot be ruled out, where the presence of a progressive learning curve may have resulted in an improvement in chest compression quality over time, particularly as participants gained more experience with the interface.

This study used the more ‘physiological’ manikin design, described in Chapter 4, to investigate the effects of real-time performance feedback on chest compression quality. With the paucity in scientific research defining the biomechanics of the infant thorax, however, it remains unknown whether this manikin design appropriately represents the infant thorax. A maximum achievable chest compression depth of 56mm was used by the manikin to represent the internal AP chest depth of a 3 month old male infant [143]. When considering the intra-thoracic organs, in-vivo chest compression depths may, in fact, be further limited. Previous studies also highlight chest compression stiffness as a key limitation to manikin biofidelity, with current manikin chest compression stiffness derived solely from expert clinical opinion [157]. Until further research is performed in the field of infant thoracic biomechanics, however, this will remain an unavoidable limitation for infant CPR manikin based studies.

The use of evidence based quality targets by the real-time performance feedback system was essential to encouraging high quality chest compressions during simulated infant CPR. The ability of the performance feedback system to optimise chest compression quality is, however, only as good as the understanding used to inform the feedback. The quality targets used in this study were based on a combination of infant subject, adult subject, radiographic and animal surrogate studies. Only chest compression depth and chest compression rate targets are currently recommended by international consensus opinion [1-3], with consensus opinion still to be reached regarding chest release forces and compression duty cycles. This, however, reflects the current position of scientific evidence guiding infant CPR guidelines. With future paediatric research, it is expected that the targets for benchmarking chest compression quality will be updated.

Finally, this study aimed to quantify the effects of potential confounding variables. The effects of chest compression technique order, participant gender, field of expertise, clinical experience, instructor certification, time since last certification and total number of infant resuscitations were all investigated. When provided with feedback, female participants were observed to release the chest further for both techniques, whilst the 'no feedback' group reduced TF technique chest compression rates if they performed the TT technique first. During the 'experimental' stage, clinical experience was found to decrease TT and TF technique compression rates for the 'no feedback' group and increase TT technique compression duty cycles for the 'feedback' group. Though these results imply the presence of confounding variables, the statistical power of all seven tests failed to exceed 80%. This implies that these differences could also be result of type-II statistical errors. Lastly, despite being blinded to the study objectives, the participants were aware of being observed and their performance may have been affected, particularly by their perceptions of the merits of feedback.

5.5.4 Impact of Research Findings

The results from this study may have several important clinical and educational implications. This study establishes the benefits of introducing real-time performance feedback during simulated infant CPR, with the provision of feedback resulting in a considerable improvement in chest compression quality. With the provision of real-time performance feedback, overall chest compression quality was improved from less than 9%, to over 70%, of all chest compressions simultaneously achieving all four evidence based quality targets, regardless of chest compression technique. Fundamental to this improvement in quality was the provision of accurate chest compression depths, appropriate chest compression rates, reduced compression duty cycles and the complete release of the chest.

Although performed during simulated infant CPR, the effects of real-time performance feedback on chest compression quality in this study could have important implications if directly transferable to infant CPR in clinical practice. The provision of accurate chest compression depths would maintain favourable haemodynamic outcomes [30, 31, 142, 144], whilst also minimising the likelihood of iatrogenic trauma through thoracic over-compression [143, 146]. The complete release of the chest and provision of shortened compression duty cycles would reduce intrathoracic pressures during the release of the chest, promoting the return of venous blood to the heart and myocardial perfusion [34, 35, 147-150, 153, 154]. Finally, the provision of optimum compression rates and compression duty cycles in clinical practice would improve chest wall relaxation, improving the return of venous blood to the heart prior to recirculation [150, 153, 154]. The provision of real-time performance feedback in clinical practice may therefore result in high quality chest compressions that optimise forward and retrograde blood flow, improve vital organ perfusion and reduce the likelihood of thoracic trauma.

This research may provide the fundamental basis for a system that is able to improve chest compression quality during infant CPR in clinical practice. Real-time performance feedback systems have been successfully translated into clinical practice for both adult and paediatric subjects to enhance CPR performance [32, 40-42]. Whilst results typically report an improvement in chest compression quality, real-time performance feedback has so far failed to influence survival [219]. As previously hypothesised, this failure to influence survival may be due to the minimal differences in chest compression quality between the control and intervention arms of the study. As considerable differences in quality were observed for both chest compression techniques in this study, potential therefore remains for such a real-time performance feedback system to influence the outcomes of infant cardiac arrests.

To further optimise outcomes, it is essential to design curricula that implement effective educational strategies that both facilitate learning and ensure skill retention. The use of a real-time performance feedback system, as a teaching aid, may allow trainees to immediately adjust performance to achieve infant specific evidence based quality targets within a training environment. This may promote the performance and retention of high quality psychomotor skills for chest compressions during simulated infant CPR, which, in turn, may transfer into clinical practice. Furthermore, this system may use the overall quality index as a compound quality parameter to both benchmark trainee performance and provide a grading criterion.

This real-time performance feedback system may be further utilised to standardise and optimise the chest compressions provided during clinical resuscitation trials. Several trials have failed to translate promising results from experimental research into clinical practice. As chest compression quality data were not routinely collected during these trials, it remains unknown whether chest compression quality was equivalent between experimental groups or whether it was even sufficient to generate adequate circulation. It can be speculated that, if poor quality chest compressions are the major determinant of survival, any differences caused by the studied medications, interventions or devices will be hard to demonstrate, severely confounding the trial. The ability to use feedback would facilitate the provision of high-quality, standardised, chest compressions during infant CPR, promoting optimal haemodynamics and uniformity across the trial. Finally, performance feedback may be used to collect detailed data for determining the chest compression quality characteristics that optimise the outcomes of infant cardiac arrest.

5.6 Conclusions

This study is the first to explore the effects of real-time performance feedback on the quality of chest compressions provided during simulated infant CPR. The provision of real-time performance feedback considerably improved the compliance of both infant chest compression techniques with all four evidence based quality targets, whilst also reducing the risks of thoracic over-compression. Scope, therefore, remains for the transfer of this technology into both educational and clinical practice. If these results enable similar improvements in clinical practice, real-time performance feedback could, for the first time, support resuscitators in performing high quality chest compressions during infant CPR.

6 GENERAL DISCUSSION

Cardiac arrests in the infant population require the prompt delivery of cardiopulmonary resuscitation (CPR), with external chest compressions remaining an essential aspect of CPR. The principal aim of external chest compressions is to both establish and maintain the haemodynamic perfusion of the vital organs by mechanically generating sufficient cardiac output during the low-flow phase of cardiac arrest [30, 31, 34, 35, 142, 144, 147-150, 153, 154]. Consequently, high quality chest compressions are imperative to optimising the haemodynamics of infant CPR [1-3]. The principal focus of this research was, through a series of investigations, to monitor, evaluate and improve the quality of chest compressions performed during simulated infant CPR. The following sections discuss the principle findings of this research, comparing these findings against relevant literature and analysing the potential impact of this research on the clinical and educational aspects of infant CPR.

6.1 Comparison with Relevant Literature

6.1.1 Chest Compression Depths

The quality of chest compressions performed during infant CPR are critical to the outcomes of infant cardiac arrest, with no quality measure more important to outcome than the chest compression depth [1-3]. Increased chest compression depths are associated with improved haemodynamic outcomes, such as increased arterial pressures, in both infant and adult human subjects [30, 144] and greater coronary flow and cardiac output in animal surrogates [31, 142]. This, in turn, has been strongly associated with increased defibrillation success and short term survival outcomes after cardiac arrest in adult human subjects [32, 33]. Despite this emphasis on providing deeper chest compressions during CPR, it has been hypothesised that chest compressions performed to depths of one-half the external AP thoracic diameter may cause iatrogenic thoracic trauma [140, 143, 145, 146].

Current infant resuscitation guidelines therefore recommend compressing the chest to at least one-third of the external AP chest diameter (approximating this to absolute chest compression depths of 40mm) [1-3]. Recent research has, however, reported shallow compression depths during CPR performed both in the adult and older paediatric populations [22, 23, 32, 33, 41] and during simulated infant CPR on instrumented manikins [15-21]. Across the six studies reporting the quality of simulated infant CPR, neither infant chest compression technique achieved mean chest compression depths in excess of 30mm (Table 6-1) [16-21], whilst Whitelaw *et al*. observed the provision of shallow chest compressions by 71% of emergency medical personnel [15]. Furthermore, across five of these studies, the TT chest compression technique was consistently observed to achieve greater chest compression depths than the TF technique [16-20].

The chest compression depths achieved in this research, when using the commercially available infant manikin design, were consistent with this literature. When compared to the TF chest compression technique, the TT technique was observed to achieve deeper chest compression depths. Despite the greater chest compression depths experienced by the TT technique, a tendency for both chest compression techniques to under-compress

Table 6-1: Chest compression depths achieved by the two-thumb (TT) and two-finger (TF) chest compression techniques during simulated infant CPR across the literature

	Haque* (2008) [16]	Udassi† (2009) [17]	Udassi† (2010) [18]	Christman‡ (2011) [19]	Huynh† (2012) [20]	Hemway* (2012) [21]
TT Technique	14.4±2.8	13.8±2.5	15	27.2±5.7	26±7	26.2±6.1
TF Technique	9.5±2.6	8.7±1.9	11	22.1±4.6	22±7	-

Chest compression depths are presented as a mean ± standard deviation where available. * CPR performed at a 15:2 compression-to-ventilation ratio; † CPR performed at a 30:2 compression-to-ventilation ratio; ‡ CPR performed with continuous chest compressions. Where multiple compression-to-ventilation ratios are reported, results are presented from the compression-to-ventilation ratio nearest to continuous chest compressions.

the chest was observed. Increased chest compression depths were, however, documented with the more 'physiological' infant manikin design. These compression depths far exceeded those reported across the existing literature, resulting in a greater proportion of chest compressions that both achieved current compression depth quality targets and that over-compressed the thorax. Consequently, when compared to previous research, the chest compressions documented in this research may better represent the quality of chest compressions provided in clinical practice.

Despite these increased chest compression depths, less than half of all TT and one-third of all TF technique chest compressions were observed to achieve current compression depth quality targets. With the provision of real-time performance feedback, however, the quality of compression depths provided during simulated infant CPR was considerably improved for both techniques. Feedback assisted CPR resulted in >97% of all chest compressions achieving current infant chest compression depth quality targets. Fundamental to this improvement was the standardisation of chest compression depths, which both reduced inter-participant variation and improved chest compression depth accuracy. Chest compression depths of this quality have never previously been reported, with fewer feedback assisted chest compressions achieving current compression depth targets during CPR in the adult and older paediatric populations [32, 41] and simulated adult CPR [166, 167, 222]. The provision of real-time performance feedback, in combination with a more 'physiological' infant CPR manikin, therefore appears vital in ensuring that resuscitators achieve compression depth quality targets during simulated infant CPR.

6.1.2 Chest Release Forces

Current international infant resuscitation guidelines recommend that chest compressions should allow the complete release of the chest during infant CPR [1-3]. The incomplete release of the chest is described as a “leaning” phenomenon, where forces are not completely released from the chest between compressions [13]. This can result in increased intrathoracic pressures during the chest release phase of CPR, reducing both the return of venous blood to the heart and the coronary and cerebral perfusion pressures [34, 35, 147, 148]. Reduced chest release forces are, therefore, vital to encouraging the provision of high quality chest compressions during CPR to optimise haemodynamics.

Despite international guideline recommendations to completely release the chest, many studies have reported the failure of chest compressions to completely release the chest during out-of-hospital, in-hospital and simulated CPR, in both the adult and paediatric populations [35, 41, 42, 175]. Emergency medical service personnel maintained residual leaning depths in 46% of all adult out-of-hospital cardiac arrest cases [35]. During adult in-hospital cardiac arrests, leaning forces exceeded 2.5kg in over 90% of episodes and could affect up to 44% of chest compressions in any given cardiac arrest episode [175]. Despite this, less than 12% of all compressions were reported as incompletely releasing the chest [175]. During in-hospital paediatric CPR, over 97% of compressions achieved chest release forces of ≥0.5kg, whilst 50% achieved chest release forces of ≥2.5kg [42]. Leaning forces were reduced with the provision of feedback, however, resulting in 73% of compressions achieving release forces of 2.5kg [42]. This was further supported by a study that evaluated feedback assisted chest compressions during paediatric CPR, which found that 77% of feedback assisted chest compressions achieved leaning force quality targets of <2.5kg [41].

This research was, therefore, the first to assess the chest release forces achieved during simulated infant CPR, whilst also being the first to evaluate the effects of real-time performance feedback on release force quality. The chest release force quality, demonstrated during unassisted infant CPR, established that both the TT and TF chest compression techniques achieved over 99% compliance with chest release force targets of <2.5kg. Chest release forces of this quality have never previously been documented, with fewer chest compressions reported to achieve current chest release force quality targets during both adult and paediatric CPR [35, 41, 42, 175]. The TF technique was, however, consistently reported to release the chest further than the TT technique. Consequently, this resulted in a greater proportion of TF technique chest compressions that achieved the complete release of the chest (<0.5kg), raising concerns over the ability of the TT technique to completely release the chest during infant CPR.

The provision of the more ‘physiological’ infant manikin design was found to increase the proportion of chest compressions that achieved the complete release of the chest for both techniques. Despite these improvements, around 50% of TT technique chest compressions failed to achieve targets for the complete release of the chest. With the assistance of real-time performance feedback, however, TT technique chest compressions were found to completely release the chest in 99% of compressions; thus emulating the high quality chest release forces provided by the TF technique. Fundamental to this improvement was the feedback program function that highlighted when providers failed to completely release the chest. The provision of real-time performance feedback, therefore, appears vital in ensuring resuscitators achieve the complete release of the chest during simulated infant CPR.

6.1.3 Chest Compression Rates

The optimisation of haemodynamics during infant CPR is also a function of the rate and number of chest compressions delivered per minute. Current international resuscitation guidelines, therefore, recommend that providers target chest compression rates between

100-120 min^{-1} [1-3]. Reduced chest compression rates result in a significant decrease in the likelihood of ROSC [38, 39], whilst increased chest compression rates reduce both coronary blood flow [150, 153, 154] and the proportion of compressions that achieve target depths [176]. The provision of accurate compression rates is, therefore, essential to ensuring the delivery of high-quality chest compressions during infant CPR.

Investigations into chest compression rate quality during infant CPR have been primarily restricted to manikin based studies [16, 17, 19, 21], with the majority of these studies reporting the provision of excessive compression rates (Table 6-2). Chest compressions were reported as exceeding mean compression rates of 132min^{-1}, for both the TT and TF chest compression techniques, across two studies performed by the University of Florida College of Medicine [16, 17]. In the most recent studies, performed by the Weill Cornell Medical College, mean compression rates were documented to range between 112min^{-1} and 118min^{-1} for both chest compression techniques [19, 21]. Furthermore, during both adult and older paediatric CPR performed in both the in-hospital and out-of-hospital environments, high quality compression rates were provided in only one-third to one-half of all chest compressions [22, 23, 41].

Chest compression rates during simulated infant CPR were further evaluated throughout this research. The chest compression rates demonstrated during unassisted infant CPR

Table 6-2: Chest compression rates achieved by the two-thumb (TT) and two-finger (TF) chest compression techniques during simulated infant CPR across the literature

	Haque (2008)* [16]	Udassi (2009)† [17]	Christman (2011)‡ [19]	Hemway (2012) † [21]
TT Technique	132±24	138±24	118±22	225±41#
TF Technique	150±33	146±34	116±24	-

Chest compression rates are reported as compressions per minute, unless otherwise stated, and presented as mean values ± standard deviation. * CPR performed at a 15:2 compression-to-ventilation ratio; † CPR performed at a 30:2 compression-to-ventilation ratio; ‡ CPR performed with continuous chest compressions; # Chest compression rates reported as the chest compression rate over 2 minutes. Where multiple compression-to-ventilation ratios are reported, results are presented from the compression-to-ventilation ratio nearest to continuous chest compressions.

established that both the TT and TF chest compression techniques provided excessive compression rates, regardless of manikin design. Mean chest compression rates ranged between 128-139min^{-1} for both techniques, corresponding with the research performed by University of Florida College of Medicine [16, 17]. This resulted in <50% of chest compressions achieving current infant chest compression rate quality targets of 100-120min^{-1}, with the majority of compressions reported to have provided excessive chest compression rates.

High-quality chest compression rates were achieved through the provision of real-time performance feedback. Feedback assisted CPR resulted in a significant reduction in chest compression rates (~130min^{-1} to ~110min^{-1}), for both infant chest compression techniques, resulting in 92% of all TT technique and 87% of all TF technique chest compressions achieving current chest compression rate quality targets. Fundamental to this improvement in quality was the regulation of compression rates by the audio-visual metronome implemented by the real-time performance feedback program. This regulation of compression rate is further observed across the adult and paediatric literature, with compression rates during feedback assisted CPR significantly reduced through the use of either corrective feedback or audio-visual metronomes [32, 40, 41, 167, 219]. The provision of audio-visual metronomes to regulate chest compression rates therefore appears fundamental to ensuring that resuscitators achieve current infant compression rate quality targets during simulated infant CPR.

6.1.4 Compression Duty Cycles

Associated with the requirement to provide high-quality chest compression rates during infant CPR, is the delivery of high-quality compression duty cycles. Compression duty cycles describe the proportion of time for each chest compression cycle where the chest is actively compressed [13]. Whilst current international infant resuscitation guidelines do not recommend a compression duty cycle quality target range, neonatal guidelines recognise the advantages of allowing a relaxation phase that is slightly longer than the compression phase [177]. Prolonged durations of active chest compression, relative to the total chest compression cycle time, result in a significant decrease in the return of venous blood to the heart; reducing cardiac output, myocardial perfusion pressure and cerebral blood flow [150, 153, 154]. Although arguably the least understood of the chest compression quality measures, the provision of reduced compression duty cycles during infant CPR is fundamental to encouraging optimal haemodynamics.

The current quality of the compression duty cycles performed during either paediatric or infant CPR has never been reported. In research monitoring the quality of adult CPR in the clinical environment, compression duty cycles were reported to be 42% in studies of out-of-hospital CPR [23, 32] and 43% during in-hospital CPR [179]. In the simulated CPR setting, duty cycles ranged from 45-50% across three adult manikin based studies [167, 176, 180]. Feedback assisted chest compressions were reported to reduce the duty cycles provided during simulated CPR to 39.4% [167], whilst no significant differences were observed during feedback assisted CPR provided in clinical practice [32]. This research was, therefore, the first to evaluate the quality of compression duty cycles performed during simulated infant CPR, whilst also being the first to investigate the effects of real-time performance feedback on duty cycle quality.

The compression duty cycles achieved in this research, when using the commercially available infant manikin design, demonstrated that both chest compression techniques provided prolonged duty cycles with over 77% of chest compressions. The TF chest compression technique was consistently observed to perform better quality duty cycles than the TT technique, with less than 1% of all TT technique chest compressions documented to achieve compression duty cycle quality targets. With the provision of the more 'physiological' infant CPR manikin design, compression duty cycles were reduced by ~5% for both techniques. Consequently, this resulted in a significant improvement in duty cycle quality for both techniques. Despite the provision of better quality compression duty cycles with the more 'physiological' infant CPR manikin design, duty cycles ranged between 47% and 55%. This resulted in over 82% of all TT technique, and over 28% of all TF technique, chest compressions failing to attain current infant compression duty cycle quality targets.

Compression duty cycle quality was significantly improved for both techniques through the provision of real-time performance feedback. Despite no specific attempt to directly improve compression duty cycle quality, feedback assisted CPR resulted in 93% of all chest compressions, performed by both techniques, achieving current compression duty cycle quality targets. Fundamental to this improvement was the standardisation of the other three chest compression quality measures, which reduced compression duty cycles through a combination of accurate chest compression depths, reduced compression rates and the complete release of the manikin chest. In particular, a reduction in compression rate has been previously associated with a decrease in compression duty cycle during simulated adult CPR [176]. Real-time performance feedback therefore appears central to indirectly ensuring that resuscitators achieve current compression duty cycle quality targets during simulated infant CPR.

6.1.5 Overall Chest Compression Quality

This research developed a quality index approach to benchmarking resuscitator performance against current infant specific, evidence based, chest compression quality targets.

The ‘overall chest compression quality index’ was established to provide a single composite measure to evaluate chest compression depth, chest release force, chest compression rate and compression duty cycle quality during infant CPR. This single composite measure reported the proportion of chest compressions that simultaneously achieved all four primary infant chest compression quality targets. This was additionally developed to report the proportion of chest compressions that also achieved three or more quality targets, two or more quality targets and at least one quality target.

Many studies throughout the literature independently report the four chest compression quality parameters recommended by current international guidelines for monitoring the measured quality of CPR [13]. Several adult CPR manikin based studies have, however, reported the use of a single composite measure to analyse several quality parameters in combination [166-168]. In two recent studies, the proportion of chest compressions that achieved AHA guideline targets were reported during both unassisted and feedback assisted CPR [166, 168]. Defining these chest compressions as simultaneously achieving guideline chest compression depth and rate targets, both studies found the proportion of guideline compliant chest compressions was considerably increased through providing audio-visual feedback (78-81%), when compared to unassisted CPR (10-15%) [166, 168]. Cason *et al*. developed a composite measure to report the percentage of ‘correct’ chest compressions achieved during unassisted CPR, auditory feedback and visual feedback assisted CPR [167]. Defining these ‘correct’ chest compressions as simultaneously achieving compression depth, compression rate and release pressure targets, this study found that visual feedback (78%) improved the proportion of ‘correct’ chest compressions, when compared to both auditory (65%) and no feedback (45%) [167].

The overall chest compression quality index attained during unassisted simulated infant CPR was observed to be very poor for both infant chest compression techniques. Less than 9% of all TT and TF chest compressions simultaneously achieved all four evidence based chest compression quality targets, regardless of infant CPR manikin design, with less than 50% of chest compressions achieving three or more quality targets. With the prevalence of excessive compression rates observed during simulated infant CPR and the inclusion of compression duty cycle targets in the overall quality index, it is perhaps unsurprising that these are the worst results for unassisted CPR across the literature [166-168].

The provision of real-time performance feedback, however, considerably improved the quality of chest compressions provided during simulated infant CPR. Real-time performance feedback resulted in 75% of all TF technique and 80% of all TT technique chest compressions simultaneously achieving all four chest compression quality targets, with >98% of compressions performed by both techniques achieving three or more quality targets. These results correspond with the composite measures reported across the literature [166-168], to demonstrate that high quality chest compressions can be attained during simulated infant CPR, with the assistance of real-time performance feedback.

6.1.6 Performance Decay

Effective chest compressions remain fundamental to the provision of high-quality CPR during cardiac arrest [1-3]. Chest compressions are widely recognised as a physically challenging task that can lead to significant deteriorations in chest compression efficacy over time. Performance decay may, therefore, be considerably detrimental to the quality of chest compressions provided over time, with any decrease in quality likely to affect the haemodynamics of CPR.

Several studies, during both actual and simulated adult CPR, report compression depth performance decay after just one minute of CPR, attributing this primarily to resuscitator fatigue [161-164]. These studies further noted that providers were often unaware of this decay in performance and only subjectively reported experiencing fatigue after 3-4 minutes [161-164]. Compression depth decay has also been reported during simulated infant CPR [17, 20, 21]. Performance decay was observed to particularly affect the TF chest compression technique, with both Udassi *et al*. [17] and Huynh *et al*. [20] reporting a 1.5-5mm deterioration in chest compression depths after one minute of CPR using a 30:2 ratio. This was in contrast to the TT technique, where chest compression depths had only decayed by <1mm by the second minute of CPR [17, 20, 21].

This research was the first to report performance decay for all four chest compression quality measures over two minutes of simulated infant CPR, whilst also determining the exact onset of decay over this period for all four quality measures. Performance decay was observed to affect both TT and TF technique compression depths and TT technique compression duty cycles. The onset of TF technique compression depth decay (75-105 seconds) corresponded with current research indicating an onset of fatigue in the second minute of simulated infant CPR [17, 20]. The onset of TT technique compression depth decay, however, occurred after 15 seconds. As previously discussed this was unlikely to be because of fatigue and may have been an indication of participants achieving the maximum achievable chest compression depth of the infant CPR manikin. Finally, TT technique compression duty cycle performance decay was also unlikely to be related to participant fatigue, as its onset was observed from 30-90 seconds only and not for the final 30 seconds. No decay in chest compression quality was found for either the chest release forces or chest compression rates.

6.2 Strengths and Limitations

This research attempts throughout its design to minimise the potential for experimental bias. All studies were prospectively designed to reduce sources of bias and confounders, whilst participants were randomly allocated to study groups to minimise allocation bias. Informed and timely consent was obtained from all EPLS/APLS instructors recruited to this research, whilst all three studies were performed following the principles of Good Clinical Practice [223]. Participants were blinded to the objectives of all three studies and a separate assessment room was used for testing. The standardisation of instructions was provided by the Experimental Instruction Sheets, whilst the carry over effects of fatigue were minimised by allowing full recovery between chest compression periods.

All participants recruited to this research were certified EPLS/APLS training course instructors. As previously discussed, these are leading paediatric emergency life support training courses, which use instructors that have successfully passed further assessment at a Generic Instructor Course [184, 206]. Consequently, it may be assumed that this research analysed chest compressions provided by elite resuscitators during simulated infant CPR, representing the current ‘gold standard’ for infant chest compression quality. The use of EPLS/APLS training course instructors may, however, not represent the typical demographics of the population most likely to provide infant CPR. The quality of chest compressions provided throughout this research may therefore not represent the quality provided in practice by either Basic Life Support (BLS) or EPLS/APLS trained rescuers or laypersons. Quantifying the quality of chest compressions provided by these specific populations will be of interest to future research.

An important limitation of this research was the use of infant CPR training manikins to measure the quality of chest compressions performed during simulated infant CPR. Although infant CPR manikins have previously been used to investigate chest compression quality, their design is acknowledged as flawed [14-21]. Previous studies highlight chest compression stiffness as a key limitation to biofidelity [14-21], but failed to consider the effects of the maximum achievable chest compression depth (CDmax) of the manikin design. Chapter 3 reported that the CDmax of the Laerdal ® ALS Baby CPR training manikin was just 40mm, leading to the hypothesis that this manikin may have mechanically constrained chest compressions during simulated infant CPR. Chapter 4 confirmed this particular issue by describing an increase in compression depths with the provision of a more 'physiological' CDmax. Whilst this highlighted the importance of biofidelic manikin designs when investigating CPR quality, a paucity of research that adequately defines the biomechanics of the infant thorax remains. The more 'physiological' infant CPR manikin was, however, developed using the best available scientific evidence and so is likely to be a major improvement on current infant CPR manikin designs.

The chest compression quality targets, systematically abstracted from the international literature, were used throughout this research for both the quality index analyses and the real-time performance feedback program. The chest compression quality targets used in this study were based on a combination of infant subject, adult subject, radiographic and animal surrogate studies. Furthermore, due a lack of primary data, the infant thoracic over-compression criterion was defined based upon consensus opinion, rather than experimental data [143, 146]. Only the chest compression depth and rate quality targets have been recommended by current international consensus opinion [1-3], whilst international consensus opinion is still to be reached for maximum chest compression depths and the provision of optimal chest release forces and compression duty cycles. This, however, reflects the current state of the scientific evidence guiding current infant CPR guidelines. With future paediatric research, it is expected that the targets for benchmarking infant chest compression quality will be updated.

Perhaps the most important aspect of the research was the development of the real-time performance feedback program. Whilst the effects of only one form of feedback were evaluated by this study, other forms exist which could influence the results differently. Corrective feedback (i.e. input only provided when chest compression performance does not meet guidelines), for example, has been used extensively across previous studies to improve the quality of chest compressions delivered in adult human subjects and CPR manikins [32, 40-42, 215-218]. Despite the excellent results achieved in this research, further gains could be achieved by implementing future feedback styles. The effects of feedback training also cannot be ruled out, where a progressive learning curve may have resulted in an improvement in chest compression quality over time, as the participants gained experience with the performance feedback interface. The presence of such a progressive learning curve may, however, have important implications for skill retention.

Finally, this research attempted to mitigate the effects of potential confounders throughout all three studies. Randomised, crossed-over, study designs were used in Chapters 3 and 4 to reduce the effects of confounding covariates, by using each participant as their own control, whilst Chapter 5 used a randomised controlled study design to eliminate any carry over bias from the earlier use of the real-time performance feedback program. The potential confounders assessed throughout this research included chest compression technique order, gender, field of expertise and clinical experience; whilst Chapter 5 further considered instructor certification, time since last certification and total number of infant resuscitations. Although all three Chapters observed the potential for confounding variables, the statistical power of all statistical tests failed to exceed 80% for all potential confounders, implying that this difference may simply have been caused by type-II errors. More participants would have been required to adequately power these statistical tests to determine if these differences were due to confounders or type-II errors. Finally, despite being blinded to the study objectives, participants were aware of being observed and so their performance may have been affected.

6.3 Impact of Research

6.3.1 Infant CPR Training Manikins

From this research it was established that the more ‘physiological’ infant CPR manikin design may be used to deliver better quality chest compressions and highlight thoracic over-compression during simulated infant CPR. Although commercially available infant CPR manikins have been used to extensively investigate infant CPR quality, both across the literature and in this research, their design is recognised as being biomechanically flawed [14-21]. Several studies highlight chest compression stiffness as a limitation to manikin biofidelity [14-21], but only this research considers the effects of the maximum achievable chest compression depth of the manikin design. This research confirmed that current, commercially available, infant CPR training manikin designs potentially limit resuscitators from performing high quality chest compressions, whilst also concealing the presence of thoracic over-compression. If this is the case, then research performed on infant CPR manikins with unrepresentative chest compression characteristics should be interpreted with care.

Whilst this study highlighted the importance of using a more ‘physiological’ maximum achievable chest compression depth to investigate chest compression quality, there still remains a paucity of research that defines the biomechanical characteristics of the infant thorax. As has been discussed, it remains unknown whether the more ‘physiological’ infant CPR manikin design developed by this research is biomechanically representative. Further research in this particular field is clearly required to ensure the biofidelity of future infant CPR training manikin designs are improved.

6.3.2 Chest Compression Quality during Unassisted Infant CPR

Through the use of a more ‘physiological’ infant CPR manikin design, the unassisted chest compressions simulated in this research may better represent the quality of chest compressions provided during infant CPR in clinical practice. Despite this, the overall quality of chest compressions remained poor for both chest compression techniques; with <9% of chest compressions found to achieve all four infant specific evidence based quality targets. Fundamental to this was a combination of inaccurate chest compression depths, excessive chest compression rates and prolonged compression duty cycles, with the TT technique also failing to completely release the chest. Although these poor quality chest compressions were performed during simulated infant CPR, these results could have a number of important implications if directly transferable to clinical practice.

Deeper chest compressions have been observed to result in favourable haemodynamic outcomes, such as increased arterial pressures in both infant and adult subjects [30, 144] and increased coronary flow and cardiac output in animal surrogate models [31, 142]. Increased compression depths have also been linked with improved survival outcomes, such as increased defibrillation success and survival to hospital discharge after cardiac arrest in adults [32, 33]. Therefore, if the chest compression depths achieved using the more ‘physiological’ infant manikin design represent the quality of chest compressions provided in clinical practice, trained healthcare resuscitators may be providing better quality chest compression depths than previously thought. Despite this improvement in chest compression depth quality, over 50% of unassisted chest compressions performed during unassisted infant CPR failed to achieve current chest compression depth quality targets; leaving considerable room for improvements in quality.

Although current international guidelines emphasise the generation of sufficient cardiac output by compressing the chest to an adequate depth during infant CPR [1-3], little emphasis is placed upon restricting maximum compression depths to limit the risks of causing intrathoracic trauma. When performing simulated infant CPR using the more ‘physiological’ manikin, 33% of all TT technique and 7-12% of all TF technique chest compressions exceeded the proposed thoracic over-compression criterion; highlighting the potential provision of chest compressions that over-compress the thorax in clinical practice. This research, therefore, raises a significant concern over the current safety of infant CPR.

In particular, this research raises a concern over current international recommendations to “push hard, push fast” during infant CPR [1-3]; primarily as this may encourage the over-compression of the thorax in clinical practice. This safety concern is reinforced by a recent study highlighting a potential relationship between chest compression depths and the likelihood of iatrogenic injuries occurring during adult CPR [209]. Trauma was documented more frequently when compression depths exceeded 60mm [209], relating to compression depths greater than one-quarter the external AP thorax diameter [210]. With 33% of TT technique, and 7-12% of TF technique, chest compressions achieving chest compression depths that exceeded 40% of the external AP thorax diameter during simulated infant CPR, concerns may be raised if these results correspond with the chest compressions provided in clinical practice.

Delivering effective chest compression rates, chest release forces and compression duty cycles are also essential to optimising haemodynamics during infant CPR [34, 35, 147, 148, 150, 153, 154]. In this research, the majority of participants provided excessive chest compression rates and prolonged compression duty cycles during simulated infant CPR, whilst ~50% of TT technique chest compressions failed to completely release the chest. The incomplete release of the chest would generate increased intrathoracic pressures in clinical practice, whilst prolonged compression duty cycles and excessive chest compression rates would result in inadequate chest wall relaxation, both of which would limit the return of venous blood to the heart and reduce coronary and cerebral blood flow [34, 35, 147, 148, 150, 153, 154]. This may be a particular problem for the TT technique, which was observed to provide greater chest release forces and compression duty cycles throughout this research. It therefore appears that, without further interventions in either the clinical or training settings, optimal haemodynamics during unassisted infant CPR may not currently be achievable.

To improve the quality of chest compressions provided during unassisted infant CPR, resuscitators must be encouraged to achieve the relatively narrow therapeutic window for achieving quality chest compression depths. To achieve this, the TT chest compression technique must be discouraged from over compressing the thorax, whilst the TF technique must be encouraged to compress the chest deeper. Further improvements in chest compression quality may be achieved by educating resuscitators to completely release the chest during the release phase of each compression. This may improve the proportion of compressions that completely release the chest, whilst also potentially improving duty cycle quality. Finally, improving the quality of chest compression rates may also be realised through regulation with a metronome. The real-time performance feedback program developed by this research attempted to implement all these functions in an attempt to simultaneously improve the quality of all four quality measures.

6.3.3 Real-Time Performance Feedback

This research established the benefits of introducing real-time performance feedback during simulated infant CPR, with the provision of feedback resulting in a considerable improvement in chest compression quality. With the provision of real-time performance feedback, overall chest compression quality was improved from less than 9%, to over 70%, of all chest compressions simultaneously achieving all four evidence based quality targets, regardless of chest compression technique. Fundamental to this improvement in quality was the delivery of accurate chest compression depths, reduced compression duty cycles, appropriate chest compression rates and the complete release of the chest.

Although performed during simulated infant CPR, the effects of real-time performance feedback on chest compression quality in this research may have important implications if directly transferable to infant CPR in clinical practice. The provision of accurate chest compression depths would maintain favourable haemodynamic outcomes [30, 31, 142, 144], whilst also minimising the likelihood of iatrogenic thoracic trauma through the over-compression of the thorax [143, 146]. The complete release of the chest and the provision of shortened compression duty cycles would reduce intrathoracic pressures during the release of the chest, promoting the return of venous blood to the heart and the perfusion of the myocardium [34, 35, 147-150, 153, 154]. Finally, the provision of optimal compression rates and compression duty cycles would improve the relaxation of the chest wall, improving the return of venous blood to the heart prior to recirculation [150, 153, 154]. The provision of real-time performance feedback in clinical practice may therefore result in chest compressions that optimise both forward and retrograde blood flow, improve vital organ perfusion and reduce the risks of iatrogenic thoracic trauma.

This research may provide the fundamental basis for a system that is able to improve the quality of chest compressions provided during infant CPR in clinical practice. Real-time performance feedback systems have been successfully translated into clinical practice to enhance CPR performance in the adult and older paediatric populations [32, 40-42]. With results reporting marginal improvements in chest compression quality, the use of real-time performance feedback has so far failed to influence survival outcomes [219]. With the considerable improvements in quality observed for both infant chest compression techniques performed in this research, potential therefore remains for a real-time performance feedback system to improve the outcomes of infant cardiac arrest.

Real-time performance feedback may be further used to standardise the quality of chest compressions provided during clinical trials. Several recent clinical trials have failed to successfully translate promising results from experimental research into clinical practice [171, 172], with the quality of chest compressions performed during these trials cited as a potential confounding variable. Finally, it is essential to design a curriculum that aims to implement effective educational strategies to facilitate learning and ensure skill retention. The use of a real-time performance feedback system as a teaching aid may allow trainees to immediately adjust their performance to achieve current chest compression quality targets within the training environment. This may promote the acquisition and retention of high quality psychomotor skills for chest compressions during simulated infant CPR, which, in turn, may transfer into clinical practice to improve the outcomes of infant cardiac arrests.

7 CONCLUSIONS

7.1 Research Conclusions

The main aim of this research was to monitor, evaluate and engineer an improvement in the quality of chest compressions provided during simulated infant CPR. The objectives of this research are summarised, with their corresponding conclusions, below:

1. Establish a technique to benchmark resuscitator performance against evidence based infant CPR chest compression quality targets.
    - Infant specific, evidence based, quality targets for chest compression depths, chest release forces, chest compression rates and compression duty cycles were systematically abstracted from the literature.
    - An overall chest compression quality index, defined as the proportion of chest compressions that simultaneously achieved all four quality targets, was developed to benchmark performance during simulated infant CPR.
2. Investigate the quality of chest compressions provided by trained healthcare re-suscitators during simulated infant CPR on a commercially available manikin.
    - Overall chest compression quality was very poor, with less than 1% of all chest compressions simultaneously complying with all four quality targets.
    - Fundamental to this was the provision of inadequate compression depths, excessive compression rates and prolonged duty cycles.
    - When comparing chest compression techniques, the TT technique provided better quality compression depths, whilst the TF technique provided better quality duty cycles and released the chest further.
    - Chest compressions appeared to be mechanically restricted by the maximum achievable chest compression depth of the commercially available manikin.

3. Design an instrumented infant CPR training manikin able to monitor both chest compression quality and thoracic over-compression during simulated infant CPR.
    - A novel infant CPR manikin was designed to have a maximum achievable chest compression depth that represented the physiological internal AP chest depth of a three month old male infant.
    - A thoracic over-compression criterion was defined based on the hypothesis that a residual internal AP chest depth of less than 10mm may potentially cause intrathoracic trauma.
4. Assess chest compression quality and the presence of thoracic over-compression using this novel infant CPR manikin.
    - The more ‘physiological’ infant CPR manikin design improved both chest compression depth and compression duty cycle quality.
    - Despite these improvements, less than 9% of unassisted chest compressions were observed to simultaneously comply with all four quality targets.
    - When comparing chest compression techniques, the TF technique provided better quality duty cycles and released the chest further, whilst the TT technique reduced thoracic under-compression.
    - Both chest compression techniques were documented to over-compress the thorax; with the TT technique particularly predisposed to providing chest compressions that over-compressed the thorax.
5. Develop a performance feedback system to assist resuscitators in achieving high quality chest compression during simulated infant CPR.
    - A real-time performance feedback program was developed to demonstrate resuscitator performance, in real-time, against the infant specific evidence based quality targets.

6. Evaluate the effects of the performance feedback system on chest compression quality and thoracic over-compression during simulated infant CPR.
    - The provision of real-time performance feedback considerably improved the proportion of TT (80%) and TF (75%) technique chest compressions that simultaneously complied with all four quality targets.
    - Real-time performance feedback further reduced the proportion of chest compressions that over-compressed the thorax to less than 1%.
    - Fundamental to this considerable improvement in chest compression quality was the provision of accurate compression depths, slower compression rates, reduced duty cycles and the complete release of the chest.

Fundamentally, this research found that the quality of chest compressions provided during unassisted simulated infant CPR rarely complied with infant specific evidence based quality targets. The use of a more 'physiological' infant CPR manikin highlighted that commercially available infant CPR manikins may restrict resuscitators from performing high quality chest compressions, whilst also concealing chest compressions that over-compress the thorax. Finally, the provision of real-time performance feedback during simulated infant CPR considerably improved chest compression quality by promoting accurate compression depths, appropriate compression rates, reduced duty cycles and the complete release of the chest. It is hoped that the future implementation of real-time performance feedback in clinical practice may result in high quality chest compressions during infant CPR, thus improving the current outcomes of infant cardiac arrest.

7.2 Directions for Future Research

The primary aim of this research was to engineer an improvement in the quality of chest compressions performed during simulated infant CPR. In achieving this aim, several research topics have been identified that would benefit from further investigation. These topics fall into five central categories; the effects of real-time performance feedback on CPR skill acquisition and retention, the quality of chest compressions performed by lay persons and BLS trained resuscitators, the design and development of biofidelic infant CPR training manikins, the expansion of the current scientific evidence base informing the international resuscitation guidelines and, finally, monitoring and improving chest compression quality during infant CPR in clinical practice.

7.2.1 Effect of Feedback on Skill Acquisition and Retention

Further research is required to determine the effects of real-time performance feedback on skill acquisition and retention. As chest compression quality during infant CPR is directly related to survival outcomes, several studies have indicated that implementing feedback assisted training programs may be important to improving survival outcomes from cardiac arrests. Whilst this research observed that real-time performance feedback assisted providers in achieving high quality chest compressions, it was not the remit of this research to investigate whether the provision of real-time performance feedback also resulted in the short-term acquisition and long-term retention of high quality chest compressions. To thoroughly investigate the effects of feedback on skill acquisition and retention, it is proposed that chest compression quality is evaluated, subsequent to feed-back assisted training, at regular intervals during unassisted simulated infant CPR. This research would be expected to impact future guidelines recommending optimum booster training and chest compression quality re-evaluation frequencies.

7.2.2 Layperson and BLS Provider Chest Compression Quality

Whilst this research investigated the quality of chest compressions performed by highly trained EPLS/APLS training course instructors during simulated infant CPR, the quality of chest compressions provided by both layperson and Basic Life Support (BLS) trained resuscitators currently remains unknown. As laypersons or BLS trained resuscitators are usually the first responder to a cardiac arrest, it would be of benefit to further quantify the quality of chest compressions provided by these specific providers. This may lead to further developments in the real-time performance feedback program to specifically aid these providers in achieving high-quality chest compressions during infant CPR.

7.2.3 Biofidelic Infant CPR Training Manikins

This research concluded that the quality of chest compressions performed when using commercially available infant CPR training manikins may fail to represent the quality of chest compressions provided in clinical practice. The use of a more 'physiological' infant CPR manikin design resulted in increased chest compression depths and reduced compression duty cycles during simulated infant CPR, whilst also highlighting thoracic over-compression. Whilst this research emphasises the importance of using representative manikins to investigate chest compression quality, there is still a paucity of research defining infant thoracic biomechanics. Further research in this particular area is, however, required to ensure that the biofidelity of future infant CPR training manikin designs are improved. Of specific research interest would be the chest compression stiffness characteristics, the maximum chest deflections and compression forces achieved during CPR and whether the infant thorax demonstrates any viscoelastic properties. This may be investigated through monitoring the chest compression forces and chest deflections provided in clinical practice using force and distance measuring sensors.

7.2.4 Improving the Scientific Evidence Base

The development and use of the chest compression quality index approach throughout this research was limited by the absence of good quality studies, performed specifically in the infant population. Quality targets for maximum chest compression depths, chest release forces and compression duty cycles were identified by this research as requiring consensus opinion in current international infant CPR guidelines. The current scientific evidence base for the chest release force and compression duty cycle quality targets may only be improved through monitoring these quality measures during CPR, as described previously. A therapeutic window for chest compression depths that aims to maximise the haemodynamics of CPR and minimise the risks of thoracic injury may, however, be determined for the paediatric population through non-clinical research. To thoroughly investigate this, it is first suggested to perform a manikin based study to establish the minimum compression depth window that may be effectively achieved by resuscitators assisted by real-time performance feedback across a range of manikins. These minimum windows may then be used in a radiological study to determine age-specific therapeutic chest compression depth windows across the paediatric population. This research would aim to impact future ERC and RCUK paediatric CPR guidelines, if completed prior to the start of the 2015 ILCOR evidence evaluation process.

7.2.5 Improving Chest Compression Quality in Clinical Practice

This research may provide the fundamental basis for a system that is able to improve the quality of chest compressions provided during infant CPR in clinical practice. Although widely developed for the adult and older paediatric populations, real-time performance feedback systems remain to be developed for use in children aged less than 8 years old. With the considerable differences in quality observed for both infant chest compression techniques performed in this research, potential remains for a real-time performance feedback system to contribute in improving the outcomes of infant cardiac arrest.

Such a feedback system may also carry further benefits for clinical resuscitation trials. Real-time performance feedback would provide an opportunity to both standardise and optimise the chest compressions provided during these trials. The ability to use a real-time performance feedback system in such a trial would facilitate the provision of high quality chest compressions during infant CPR, promoting optimal haemodynamics and uniformity across prospectively designed clinical trials. This may reduce the potential confounding effects of chest compression quality, thus hopefully assisting in translating successful experimental research into positive cardiac arrest outcomes.

Finally, it is essential to design curricular that implement effective educational strategies to facilitate skill acquisition and retention. The use of a real-time performance feedback system, as a teaching aid, may allow trainees to immediately adjust their performance to achieve current, evidence based, chest compression quality targets. This may promote high quality chest compression psychomotor skills during simulated infant CPR, which, in turn, may transfer into clinical practice to improve infant cardiac arrest outcomes.

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APPENDIX A: THESIS APPENDICES

A.1: Epidemiology of Infant Cardiac Arrest Data Tables

A.1.1 Incidence and Demographics of Infant Cardiac Arrest

Table 3: Demographics and incidence for out-of-hospital cardiac arrests

First Author	Year	Demographics Reported*	Demographics			Incidence (/100,000 infants per year)
			Age /yrs	Male /n(%)	Neonates /n(%)	
Young	2004	328 (100)	-	-	59 (18)	-
Lopez-Herce	2005	25 (100)	-	-	2 (8)	-
Atkins	2009	277 (100)	0.3	160 (58)	-	72.71
Kitamura	2010	-	-	-	-	65.9
Li	2010	40 (100)	-	-	11 (28)	-
Lin	2010	114 (100)	-	-	29 (25)	-
Park	2010	299 (100)	0.3	169 (57)	-	67.1
Bardai	2011	-	-	-	-	33.8
Moler	2011	44 (100)	-	-	5 (11)	-
Nitta	2011	343 (100)	-	193 (56)	-	65.5
Abe	2012	3189 (100)	-	1855 (58)	-	-

* Cases with demographic information known, reported as a proportion of infants included in each study

Table 4: Demographics for in-hospital cardiac arrests

First Author	Year	Demo-graphics Reported*	Demographics	
			Male /n(%)	Neonates /n(%)
Suominen	2000	74 (100)	-	28 (38)
De Mos	2006	44 (100)	-	18 (41)
Meaney	2006	167 (100)	95 (57)	62 (37)
Rodriguez-Nunez	2006	57 (100)	-	9 (16)
Samson	2006	432 (100)	-	130 (30)
Tibballs	2006	66 (100)	-	29 (44)
Meert	2009	184 (100)	-	63 (34)
Wu	2009	122 (100)	-	44 (36)
Berens	2011	173 (100)	-	84 (49)

* Cases with demographic information known, reported as a proportion of infants included in each study

A.1.2 Outcomes of Infant Out-of-Hospital Cardiac Arrest

Table 5: Survival outcomes for out-of-hospital cardiac arrests

First Author	Year	Arrests with CPR Attempted*	ROSC /n(%)		Survival Outcomes /n(%)		
			Transient ROSC	Sustained ROSC	Survival to Admission	Survival to Discharge	Long Term Survival†
Young	2004	328 (100)	-	-	-	23 (7)	-
Lopez-Herce	2005	25 (100)	-	7 (28)	-	-	3 (12)
Atkins	2009	277 (100)	14 (5)	-	-	9 (3)	-
Kitamura	2010	2082 (100)	69 (3)	-	-	146 (7)‡	-
Li	2010	40 (100)	-	10 (25)	-	2 (5)	2 (5)+
Lin	2010	114 (100)	-	39 (34)	-	-	-
Park	2010	299 (100)	-	-	44 (15)	8 (3)	-
Bardai	2011	45 (100)	-	-	-	4 (9)	-
Moler§	2011	44 (100)	-	NA	-	13 (30)	-
Nitta	2011	343 (100)	68 (20)	-	-	18 (5)‡	-
Abe	2012	3189 (100)	126 (4)	-	-	264 (8)‡	-

* Cases with CPR attempted, reported as a proportion of infants included in each study; † Defined as survival to one year unless otherwise specified; ‡ Patient survival to one month; + Patient survival to three months; § Study included cases with sustained ROSC only; CPR, cardiopulmonary resuscitation; ROSC, return of spontaneous circulation; Transient ROSC, any period of ROSC; Sustained ROSC, ROSC of ≥20 minutes

Table 6: Neurological outcomes for out-of-hospital cardiac arrests

First Author	Year	Criteria for Favourable Neurological Outcome	Outcome at Discharge /n(%)		Long Term Outcome /n(%)*	
			Outcomes Known†	Favourable Outcomes	Outcomes Known‡	Favourable Outcomes
Kitamura	2010	CPC 1/2	146 (100)	36 (25)+	-	-
Li	2010	PCPC 1/2 or no change	2 (100)	1 (50)	2 (100)	1 (50)
Bardai	2011	PCPC 1/2	4 (100)	3 (75)	-	-
Nitta	2011	CPC 1/2 or no change	18 (100)	4 (22)+	-	-

* Defined as survival to 3 months; † Neurological outcomes known, reported as proportion of infants that survived to hospital discharge; ‡ Neurological outcomes known, reported as a proportion of cases that survived to three months; + Patient survival to one month; PCPC, pediatric cerebral performance category; CPC, cerebral performance category

A.1.3 Outcomes of Infant In-Hospital Cardiac Arrest

Table 7: Survival outcomes for in-hospital cardiac arrests

First Author	Year	Arrests with CPR Attempted*	Sustained ROSC /n(%)	Survival Outcomes /n(%)		
				24 Hour Survival	Survival to Discharge	Long Term Survival[†]
Suominen	2000	74 (100)	-	-	-	16 (22)
Reis	2002	79 (100)	-	30 (38)	-	16 (20)
Guay	2004	88 (100)	-	-	-	30 (34)
Akcay	2006	49 (100)	-	-	9 (18)	-
De Mos	2006	44 (100)	-	-	11 (25)	-
Meaney	2006	167 (100)	101 (60)	84 (50)	55 (33)	-
Rodriguez-Nunez	2006	57 (100)	35 (61)	-	23 (40)	-
Meert	2009	184 (100)	NA	-	100 (54)	-
Wu	2009	122 (100)	74 (61)	62 (51)	29 (24)	-
Berens	2011	173 (100)	-	-	53 (31)	-
Haque	2011	44 (100)	-	-	5 (11)	-
Lopez-Herce	2012	246 (100)	-	-	100 (41)	-

* Cases with CPR attempted, reported as a proportion of the study size; [†] Defined as survival to one year; CPR, cardiopulmonary resuscitation; ROSC, return of spontaneous circulation; Sustained ROSC, ROSC of ≥20 minutes

Table 8: Neurological outcomes for out-of-hospital cardiac arrests

First Author	Year	Criteria for Favourable Neurological Outcome	Outcome at Discharge /n(%)		Long Term Outcome /n(%)*	
			Outcomes Known[†]	Favourable Outcomes	Outcomes Known[‡]	Favourable Outcomes
Reis	2002	PCPC 1/2/3 or no change	-	-	16 (100)	14 (88)
Meaney	2006	PCPC 1/2/3 or no change	55 (100)	31 (56)	-	-
Wu	2009	PCPC 1/2/3 or no change	29 (100)	25 (86)	-	-

* Defined as survival to 3 months; † Neurological outcomes known, reported as proportion of infants that survived to hospital discharge; [‡] Neurological outcomes known, reported as a proportion of cases that survived to three months; [+] Patient survival to one month; PCPC, pediatric cerebral performance category

A.1.4 Initial Cardiac Rhythm

Table 9: First documented cardiac rhythms for out-of-hospital cardiac arrests

First Author	Year	Cardiac Rhythm Acquired*	Shockable Pulseless Rhythms	Non-Shockable Pulseless Rhythms			Other/ Un-specified†
				Non-Shockable Rhythms	Asystole	PEA	
Atkins	2009	205 (74)	8 (4)	172 (84)	-	-	25 (12)
Park	2010	299 (100)	1 (0)	230 (77)	-	-	62 (21)
Bardai	2011	29 (64)	1 (3)	28 (97)	-	-	-
Nitta	2011	343 (100)	3 (1)	320 (93)	286 (83)	334 (10)	20 (6)
Abe	2012	3189 (100)	105 (3)	-	-	-	-

* Cases with cardiac rhythms known, reported as a proportion of infants included in each study (all other results report the number of cases as a proportion of the total infant cases with cardiac rhythms known); † Includes reported but unspecified cardiac rhythms; PEA, pulseless electrical activity

Table 10: First documented cardiac rhythms for in-hospital cardiac arrests

First Author	Year	Cardiac Rhythm Acquired*	Shockable Pulseless Rhythms	Non-Shockable Pulseless Rhythms			Pulsatile Rhythms	
				Non-Shockable Rhythms	Asystole	PEA	Pulsatile Rhythms	Brady-cardia
Meaney	2006	128 (77)	17 (13)	63 (49)	30 (23)	33 (26)	48 (38)	42 (33)
Samson	2006	432 (100)	91 (21)	-	-	-	-	-

* Cases with cardiac rhythms known, reported as a proportion of infants included in each study (all other results report the number of cases as a proportion of the total infant cases with cardiac rhythms known); PEA, pulseless electrical activity

A.1.5 Aetiology of Infant Out-of-Hospital Cardiac Arrest

Table 11: Aetiology of out-of-hospital cardiac arrests

First Author	Year	Aetiology Known*	Presumed Cardiac Arrest	Acute Respiratory Compromise	Central Nervous System	SIDS	Other
Atkins	2009	277 (100)	205 (74)	15 (5)	-	37 (13)	20 (7)
Park	2010	299 (100)	85 (28)	75 (25)	-	-	139 (46)
Nitta	2011	343 (100)	117 (34)	125 (36)	6 (2)	-	117 (34)

* Cases with aetiologies known, reported as a proportion of the study size (all other results report the number of cases as a proportion of the total cases with aetiologies known); SIDS, sudden infant death syndrome

Table 12: Prevalence of SIDS related out-of-hospital cardiac arrests

First Author	Year	Aetiology Known*	SIDS
Young	2004	328 (100)	136 (41)
Lopez-Herce	2005	25 (100)	12 (48)
Patterson	2005	213 (100)	59 (28)
Gerein	2006	190 (100)	102 (54)
Atkins	2009	277 (100)	37 (13)
Deasy	2010	77 (100)	40 (52)
Li	2010	40 (100)	17 (43)
Lin	2010	114 (100)	43 (38)

* Cases with aetiologies known, reported as a proportion of the study size (all other results report the number of cases as a proportion of the total cases with aetiologies known); SIDS, sudden infant death syndrome

A.1.6 Aetiology of Infant In-Hospital Cardiac Arrest

Table 13: Pre-existing pathological conditions diagnosed prior to in-hospital cardiac arrest

First Author	Year	Conditions Known*	Cardiac Aetiology			Respiratory Compromise	Infection/ Septicaemia	Metabolic/ Electrolytic	Malignancy	Trauma	Toxico-logical	None
			Cardiac Failure	Hypoten-sion	Arrhyth-mia							
Meaney	2006	167 (100)	135 (81)	71 (43)	40 (24)	106 (63)	32 (19)	33 (20)	5 (3)	3 (2)	1 (1)	2 (1)

* Cases with pre-existing pathological conditions known, reported as a proportion of the study size (all other results report the number of cases as a proportion of the total cases with pre-existing pathological conditions known)

Table 13: Aetiologies of precipitating events preceding in-hospital cardiac arrest

First Author	Year	Aetiology Known*	Cardiac Aetiology		Respiratory Compromise		Metabolic/ Electrolytic	Toxico-logical	Un-known
			Hypotension	Arrhythmia	Respiratory	Airway Obstruction			
Meaney	2006	167 (100)	103 (62)	67 (40)	77 (46)	14 (8)	18 (11)	2 (1)	5 (3)

* Cases with aetiologies known, reported as a proportion of the study size (all other results report the number of cases as a proportion of the total cases with aetiologies known)

A.1.7 Event Characteristics of Infant Out-of-Hospital Cardiac Arrest

Table 15: Location of out-of-hospital cardiac arrests

First Author	Year	Location Known*	Private Location		Public Location
			Total Private Location	Home/ Residence	
Atkins	2009	277 (100)	266 (96)	-	11 (4)
Park	2010	299 (100)	272 (91)	-	27 (9)
Nitta	2011	343 (100)	320 (93)	320 (93)	-

* Cases with locations known, reported as a proportion of the study size

Table 16: Witness status for out-of-hospital cardiac arrests

First Author	Year	Witness Status Known*	Total Arrests Witnessed	Witness Category		
				Bystander	Family Member	EMS
Atkins	2009	277 (100)	47 (17)	39 (14)	-	8 (3)
Park	2010	299 (100)	80 (27)	-	-	-
Bardai	2011	29 (64)	11 (38)	-	-	-
Nitta	2011	343 (100)	33 (10)	27 (8)	-	6 (2)
Abe	2012	3189 (100)	759 (24)	299 (9)	486 (15)	-

* Cases with witness statuses known, reported as a proportion of the study size; EMS, emergency medical service

Table 17: Prevalence of bystander cardiopulmonary resuscitation (CPR) for out-of-hospital cardiac arrests

First Author	Year	Bystander CPR Data Known*	Bystander CPR Performed	Bystander AED Performed
Atkins	2009	277 (100)	102 (37)	0 (0)
Kitamura	2010	2082 (100)	995 (48)	-
Park	2010	299 (100)	10 (3)	-
Bardai	2011	29 (64)	19 (66)	-
Abe	2012	3189 (100)	1463 (46)	6 (0)

* Cases with witness statuses known, reported as a proportion of the study size; AED, automated external defibrillator

Table 18: Emergency Medical System (EMS) interventions for out-of-hospital cardiac arrest

First Author	Year	Core EMS Times /min			EMS Interventions /n(%)			
		EMS Times Known*	EMS Response Time	ED Arrival Time	EMS Ints. Known†	Mechanical Ventilation	Resuscitation Drugs	AED
Atkins	2009	-	-	-	232 (84)	214 (92)	46 (20)	-
Park	2010	298 (100)	6	16.9	299 (100)	126 (42)	-	1 (0)
Bardai	2011	29 (64)	12.2	-	-	-	-	-
Nitta	2011	343 (100)	7	-	-	-	-	-
Abe	2012	3189 (100)	6.73	28.57	3189 (100)	455 (14)	55 (2)	75 (2)

* Cases with core EMS times known, reported as a proportion of the study size; † Cases with EMS interventions known, reported as a proportion of the study size; ED, emergency department; AED, automated external defibrillator

A.1.8 Event Characteristics of Infant In-Hospital Cardiac Arrest

Table 19: Location of in-hospital cardiac arrests

First Author	Year	Study Setting	Location Known*	ICU	Other Wards
Tibballs	2006	In-hospital	66 (100)	57 (86)	9 (14)

* Cases with locations known, reported as a proportion of the study size; ICU, intensive care unit

Table 20: Pre-arrest interventions in place prior to in-hospital cardiac arrests

First Author	Year	Pre-arrest Interventions Known*	Mechanical Ventilation	Patient Monitoring			Vasoactive Infusion
				ECG	Pulse Oximeter	Arterial Catheter	
Meaney	2006	167 (100)	123 (74)	162 (97)	161 (96)	78 (47)	89 (53)

* Cases with pre-arrest interventions known, reported as a proportion of the study size; ECG, electrocardiograph

Table 21: Interventions implemented in in-hospital cardiopulmonary resuscitation (CPR)

First Author	Year	CPR Interventions Known*	Open Chest CPR	ECMO	Resuscitation Drugs			
					Epinephrine	Atropine	Sodium Bi-carbonate	Calcium
Meaney	2006	167 (100)	25 (15)	22 (13)	132 (79)	49 (29)	120 (72)	95 (57)
Srinivasan	2008	703 (100)	-	-	-	-	-	310 (44)

* Cases with CPR interventions known, reported as a proportion of the study size; ECMO, extracorporeal membrane oxygenation

A.2 Database Search Strategies to Establish Infant Chest Compression Quality Recommendations

Table 1: Medline database search strategy using MeSH terms and keywords

1	exp Infant/ *(896169)*
2	exp Infant, Newborn/ *(475786)*
3	(Infant* or Newborn* or Neonat* or Baby or Babies).tw. *(506997)*
4	exp Animals/ *(16529234)*
5	exp Models, Animal/ *(389512)*
6	exp Animal Experimentation/ *(5768)*
7	(Animal* or Animal Model* or Animal Experiment*).tw. *(769709)*
8	(Swine* or Porcine* or Pig* or Dog* or Pupp* or Canin*).tw. *(543765)*
9	exp Manikins/ *(2773)*
10	(Manikin* or Mannequin*).tw. *(2278)*
11	exp Cardiopulmonary Resuscitation/ *(10506)*
12	exp Resuscitation/ *(69363)*
13	exp Heart Massage/ *(2469)*
14	(Cardiopulmonary Resus* or CPR or Resus*).tw. *(47212)*
15	(Heart Massage or Cardi* Massage).tw. *(1206)*
16	((Chest or Thora* or Stern* or Abdom* or Cardi*) adj5 Compress*).tw. *(5328)*
17	(Two-finger or Two Finger).tw. *(174)*
18	(Two-thumb or Two Thumb or Hand Encircl* or (Chest adj5 Encircl*)).tw. *(28)*
19	(Compress* adj5 (Method* or Techni* or Maneuv* or Manoeuv*)).tw. *(4375)*
20	((Compress* or Heart) adj5 (Position* or Locat* or Site*)).tw. *(5095)*
21	(Compress* adj5 (Depth* or Force*)).tw. *(3679)*
22	((Release or Leaning) adj5 (Depth* or Force*)).tw. *(757)*
23	((Recoil or Decompression) adj5 (Depth* or Force*)).tw. *(200)*
24	(Compress* adj5 (Rate* or Frequenc*)).tw. *(2095)*
25	(Duty Cycle).tw. *(1635)*
26	(Compression adj5 (Ratio* or Fraction* or High Impulse or Duration))).tw. *(1491)*
27	or/1-10 *(16729199)*
28	or/11-16 *(97114)*
29	or/17-26 *(17998)*
30	and/27-29 *(1277)*

Number of articles retrieved by each line of the search strategy code is shown in *(italics)*; MeSH, medical subject heading; exp, exploded MeSH search term; tw, keyword search in title and abstract only; or, Boolean logic "or" operator; and, Boolean logic "and" operator; * keyword truncation; adj5, retrieves articles where two keywords appear, in no specific order, within 5 words of each other

Table 2: Embase database search strategy using MeSH terms and keywords

1	exp Infant/ *(567270)*
2	exp Newborn/ *(515292)*
3	exp Baby/ *(15662)*
4	(Infant* or Newborn* or Neonat* or Baby or Babies).tw. *(689475)*
5	exp Animal/ *(19117202)*
6	exp Animal Model/ *(686669)*
7	exp Animal Experiment/ *(1688365)*
8	exp Swine/ *(176399)*
9	exp Dog/ *(346549)*
10	exp Puppy/ *(884)*
11	(Animal* or Animal Model* or Animal Experiment* or Swine* or Porcine* or Pig* or Dog* or Pupp* or Canin*).tw. *(1632200)*
12	(Manikin* or Mannequin*).tw. *(3095)*
13	exp Resuscitation/ *(66158)*
14	exp Heart Massage/ *(3659)*
15	(Cardiopulmonary Resus* or CPR or Resus* or Heart Massage or Cardi* Massage).tw. *(67238)*
16	((Chest or Chest Wall or Thora* or Stern* or Cardi*) adj5 Compress*).tw. *(6579)*
17	(Two-finger or Two Finger or Two-thumb or Two Thumb or Hand Encircl* or (Chest adj5 Encircl*)).tw. *(242)*
18	(Compress* adj5 (Method* or Techni* or Maneuv* or Manoeuv*)).tw. *(6894)*
19	((Compress* or Heart) adj5 (Position* or Locat* or Site*)).tw. *(7552)*
20	(Compress* adj5 (Depth* or Force*)).tw. *(4789)*
21	((Release or Leaning) adj5 (Depth* or Force*)).tw. *(934)*
22	((Recoil or Decompression) adj5 (Depth* or Force*)).tw. *(287)*
23	(Compress* adj5 (Rate* or Frequenc*)).tw. *(2553)*
24	(Duty Cycle or (Compression adj5 (Ratio* or Fraction* or High Impulse or Duration))).tw. *(3511)*
25	or/1-12 *(19657751)*
26	or/13-16 *(99227)*
27	or/17-24 *(24601)*
28	and/25-27 *(1673)*

Number of articles retrieved by each line of the search strategy code is shown in *(italics)*; MeSH, medical subject heading; exp, exploded MeSH search term; tw, keyword search in title and abstract only; or, Boolean logic “or” operator; and, Boolean logic “and” operator; * keyword truncation; adj5, retrieves articles where two keywords appear, in no specific order, within 5 words of each other

Table 3: ISI Web of Science database search strategy

(TS=(Infant* OR Newborn* OR Neonat* OR Baby OR Babies OR Animal* OR Animal Model* OR Animal Experiment* OR Swine* OR Porcine* OR Pig* OR Dog* OR Pupp* OR Canin* OR Manikin* OR Mannequin*)) AND (TS=(Cardiopulmonary Resus* OR CPR OR Resus* OR Heart Massage OR Cardi* Massage OR ((Chest OR Thora* OR Stern* OR Abdom* OR Cardi*) NEAR/5 Compress*))) AND (TS=(Two-finger OR Two Finger OR Two-thumb OR Two Thumb OR Hand Encircl* OR (Chest NEAR/5 Encircl*) OR (Compress* NEAR/5 (Method* OR Techni* OR Maneuv* OR Manoeuv*)) OR ((Compress* OR Heart) NEAR/5 (Position* OR Locat* OR Site*)) OR (Compress* NEAR/5 (Depth* OR Force*)) OR ((Release OR Leaning) NEAR/5 (Depth* OR Force*)) OR ((Recoil OR Decompression) NEAR/5 (Depth* OR Force*)) OR (Compress* NEAR/5 (Rate* OR Frequenc*)) OR (Compress* NEAR/5 (Release OR Recoil OR Decompress*)) OR Duty Cycle OR (Compress* NEAR/5 (Ratio* OR Fraction* OR High Impulse OR Duration)))) *(596)*

Number of articles retrieved by the search strategy code is shown in *(italics)*; TS, topic search; * keyword truncation; OR, Boolean logic "or" operator; AND, Boolean logic "and" operator; NEAR/5, retrieves articles where two keywords appear, in no specific order, within 5 words of each other

Table 4: Scopus database search strategy

TITLE-ABS-KEY(infant* OR newborn* OR neonat* OR baby OR babies OR animal* OR animal model* OR animal experiment* OR swine* OR porcine* OR pig* OR dog* OR pupp* OR canin* OR manikin* OR mannequin*) AND TITLE-ABS-KEY(cardiopulmonary resus* OR cpr OR resus* OR heart massage OR cardi* massage OR (compress* W/5 chest) OR (compress* W/5 chest wall) OR (compress* W/5 thora*) OR (compress* W/5 stern*) OR (compress* W/5 abdom*) OR (compress* W/5 cardi*)) AND TITLE-ABS-KEY(two-finger OR two finger OR two-thumb OR two thumb OR hand encircl* OR (chest W/5 encircl*) OR (compress* W/5 method*) OR (compress* W/5 techni*) OR (compress* W/5 maneuv*) OR (compress* W/5 manoeuv*) OR (compress* W/5 position*) OR (compress* W/5 locat*) OR (compress* W/5 site*) OR (heart W/5 position*) OR (heart W/5 locat*) OR (heart W/5 site*) OR (compress* W/5 depth*) OR (compress* W/5 force*) OR (release W/5 depth*) OR (release W/5 force*) OR (leaning W/5 depth*) OR (leaning W/5 force*) OR (recoil W/5 depth*) OR (recoil W/5 force*) OR (decompress* W/5 depth*) OR (decompress* W/5 force*) OR (compress* W/5 rate*) OR (compress* W/5 frequenc*) OR (duty cycle) OR (compress* W/5 ratio*) OR (compress* W/5 fraction*) OR (compress* W/5 high impulse) OR (compress* W/5 duration)) *(14)*

Number of articles retrieved by the search strategy code is shown in *(italics)*; TITLE-ABS-KEY, title, abstract and keyword search term; * keyword truncation; OR, Boolean logic "or" operator; AND, Boolean logic "and" operator; W/5, retrieves articles where two keywords appear, in no specific order, within 5 words of each other

Table 5: Cochrane database search strategy

(infant* or newborn* or neonat* or baby or babies or animal* or (animal model*) or (animal experiment*) or swine* or porcine* or pig* or dog* or pupp* or canin* or manikin* or mannequin*):ti,kw,ab and ((cardiopulmonary resus*) or cpr or resus* or (heart massage) or (cardi* massage) or (chest compress*) or (thora* compress*) or (stern* compress*) or (abdom* compress*) or (cardi* compress*)):ti,kw,ab and ((two-finger) or (two finger) or (two-thumb) or (two thumb) or (hand encircl*) or (chest encircl*) or (compress* method*) or (compress* techni*) or (compress* maneuv*) or (compress* manoeuv*) or (compress* position*) or (compress* locat*) or (compress* site*) or (heart position*) or (heart locat*) or (heart site*) or (compress* depth*) or (compress* force*) or (release depth*) or (release force*) or (leaning depth*) or (leaning force*) or (recoil depth*) or (recoil force*) or (decompression depth*) or (decompression force*) or (compress* rate*) or (compress* frequenc*) or (compress* release) or (compress* recoil) or (compress* decompress*) or (duty cycle) or (compress* ratio*) or (compress* fraction*) or (compress* duration) or (high impulse)):ti,kw,ab *(190)*

Number of articles retrieved by the search strategy code is shown in *(italics)*; ti.kw.ab, title, keyword, and abstract search term; * keyword truncation; or, Boolean logic “or” operator; and, Boolean logic “and” operator

Table 6: British Nursing Index (BNI) database search strategy

(SU.EXACT.EXPLODE("Infants" OR "Infants : Disorders" OR "Neonates : Disorders" OR "Neonates") OR AB,TI(Infant* OR Newborn* OR Neonat* OR Baby OR Babies) OR AB,TI(Animal* OR Animal Model* OR Animal Experiment* OR Swine* OR Porcine* OR Pig* OR Dog* OR Pupp* OR Canin* OR Manikin* OR Mannequin*)) AND (SU.EXACT.EXPLODE("Resuscitation") OR AB,TI(Cardiopulmonary Resus* OR CPR OR Resus* OR Heart Massage OR Cardi* Massage) OR AB,TI((Chest NEAR/5 Compress*) OR (Chest Wall NEAR/5 Compress*) OR (Thora* NEAR/5 Compress*) OR (Stern* NEAR/5 Compress*) OR (Abdom* NEAR/5 Compress*) OR (Cardi*NEAR/5 Compress*))) AND (AB,TI(Two-finger OR Two Finger OR Two-thumb OR Two Thumb OR Hand Encircl* OR (Chest NEAR/5 Encircl*) OR ((Compress* NEAR/5 Method*) OR (Compress* NEAR/5 Techni*) OR (Compress* NEAR/5 Maneuv*) OR (Compress* NEAR/5 Manoeuv*)) OR (((Compress* NEAR/5 Position*) OR (Compress* NEAR/5 Locat*) OR (Compress* NEAR/5 Site*)) OR ((Heart NEAR/5 Position*) OR (Heart NEAR/5 Locat*) OR (Heart NEAR/5 Site*))) OR ((Compress* NEAR/5 Depth*) OR (Compress* NEAR/5 Force*)) OR (((Release NEAR/5 Depth*) OR (Release NEAR/5 Force*)) OR ((Leaning NEAR/5 Depth*) OR (Leaning NEAR/5 Force*))) OR (((Recoil NEAR/5 Depth*) OR (Recoil NEAR/5 Force*)) OR ((Decompression NEAR/5 Depth*) OR (Decompression NEAR/5 Force*))) OR ((Compress* NEAR/5 Rate*) OR (Compress* NEAR/5 Frequenc*)) OR Duty Cycle OR ((Compression NEAR/5 Ratio*) OR (Compression NEAR/5 Fraction*) OR (Compression NEAR/5 High Impulse) OR (Compression NEAR/5 Duration)))) *(5)*

Number of articles retrieved by the search strategy code is shown in *(italics)*; SU.EXACT.EXPLODE, exploded exact subject search term; AB,TI, abstract and title keyword search term; * keyword truncation; OR, Boolean logic “or” operator; AND, Boolean logic “and” operator; NEAR/5, retrieves articles where two keywords appear, in no specific order, within 5 words of each other

Table 7: Cumulative Index to Nursing and Allied Health Literature (CINAHL) database search strategy

((MH "Infant+") OR (MH "Infant, Newborn+") OR (MH "Animals") OR (MH "Animals, Laboratory") OR (MH "Models, Biological") OR (MH "Swine") OR (MH "Dogs") OR (MH "Models Anatomic+") OR infant* OR newborn* OR neonat* OR baby OR babies OR animal* OR animal model* OR animal experiment* OR swine* OR porcine* OR pig* OR dog* OR pupp* OR canin* OR manikin* OR mannequin*) AND ((MH "Resuscitation+") OR (MH "Resuscitation, Cardiopulmonary+") OR (MH "Heart Massage") OR cardiopulmonary resus* OR cpr OR resus* OR heart massage OR cardi* massage OR (chest N/5 compress*) OR (chest wall N/5 compress*) OR (thora* N/5 compress*) OR (stern* N/5 compress*) OR (abdom* N/5 compress*) OR (cardi* N/5 compress*)) AND (two-finger OR two finger OR two-thumb OR two thumb OR hand encircl* OR (chest N/5 encircl*) OR (compress* N/5 method*) OR (compress* N/5 techni*) OR (compress* N/5 maneuv*) OR (compress* N/5 manoeuv*) OR (compress* N/5 position*) OR (compress* N/5 locat*) OR (compress* N/5 site*) OR (heart N/5 position*) OR (heart N/5 locat*) OR (heart N/5 site*) OR (compress* N/5 depth*) OR (compress* N/5 force*) OR (release N/5 depth*) OR (release N/5 force*) OR (leaning N/5 depth*) OR (leaning N/5 force*) OR (recoil N/5 depth*) OR (recoil N/5 force*) OR (decompress* N/5 depth*) OR (decompress* N/5 force*) OR (compress* N/5 rate*) OR (compress* N/5 frequenc*) OR (duty cycle) OR (compress* N/5 ratio*) OR (compress* N/5 fraction*) OR (compress* N/5 high impulse) OR (compress* N/5 duration)) *(12)*

Number of articles retrieved by the search strategy code is shown in *(italics)*; MH, medical subject heading search term; + exploded search term; * keyword truncation; OR, Boolean logic “or” operator; AND, Boolean logic “and” operator; N/5, retrieves articles where two keywords appear, in no specific order, within 5 words of each other

A.3 Standardised Critical Appraisal and Data Extraction (CADE) Form

Reviewer Name:		**Date:**	

SECTION A: Study details

Author(s) (4 maximum)

....

....

Publication Title

....

....

....

Journal Reference (Journal Title, Volume, Part, Pages)

....

Year of Publication

....

SECTION B: Study Type

Please provide ***your*** opinion on the study type which best applies to the data set of interest to our review, even if this differs from what has been stated in the study:

Study Type: please select appropriate study type		**Yes** ✓
Experimental Study Designs	Randomised Controlled Clinical Trial	
	Randomised Cross-over Clinical Trial	
	Randomised Controlled Laboratory Study	
	Randomised Cross-over Laboratory Study	
Observational Study Designs	Cohort (Longitudinal) Study	
	Case-Control Study	
	Cross Sectional Study	
	Case Series (≥3 cases that meet criteria)	
	Case Report (<3 cases that meet criteria)	

SECTION C: Key Questions

Please select which question(s) this study addresses (more than one option may be selected):

Key Question	Yes ✓	Comment
1. In infants receiving CPR, does any specific chest compression technique, as opposed to standard care, improve outcomes?		
2. In infants receiving CPR, do chest compressions performed at any specific location, as opposed to standard care, improve outcomes?		
3. In infants receiving CPR, does any specific chest compression depth/force, as opposed to standard care, improve outcomes?		
4. In infants receiving CPR, does any specific chest release depth/force, as opposed to standard care, improve outcomes?		
5. In infants receiving CPR, does any specific chest compression rate, as opposed to standard care, improve outcomes?		
6. In infants receiving CPR, does any specific compression duty cycle, as opposed to standard care, improve outcomes?		
If the study does not address any of the questions listed above, please **EXCLUDE** and complete **Section G**.		

Clarification of terms:

1. *Infant*: 0-1 year old child (see selection criteria overleaf)
2. *CPR*: Cardiopulmonary resuscitation
3. *Chest compressions*: Application of cyclical compression and release forces to the chest that aim to sustain blood flow during cardiac arrest
4. *Chest compression depth/force*: maximum depth/force attained during the chest compression phase
5. *Chest release depth/force*: minimum depth/force attained during the chest release phase
6. *Chest compression rate*: The inverse of the time for each chest compression cycle
7. *Compression duty cycle*: The fraction of each chest compression cycle with active chest compression

SECTION D: Selection Criteria

Inclusion criteria summary:

- All clinical studies involving post-mortem or live infants aged 1 year old or less.
- All radiological studies involving post-mortem or live infants aged 1 year old or less with the subject in the supine position only.
- All laboratory studies involving live animals weighing 12kg or less.
- All laboratory studies involving manikins designed to represent infants aged 1 year old or less.
- All mathematical models involving models designed to represent infants aged 1 year old or less and validated against age or weight appropriate human or animal experimental data.

Please select any of the following exclusion criteria which apply to the study:

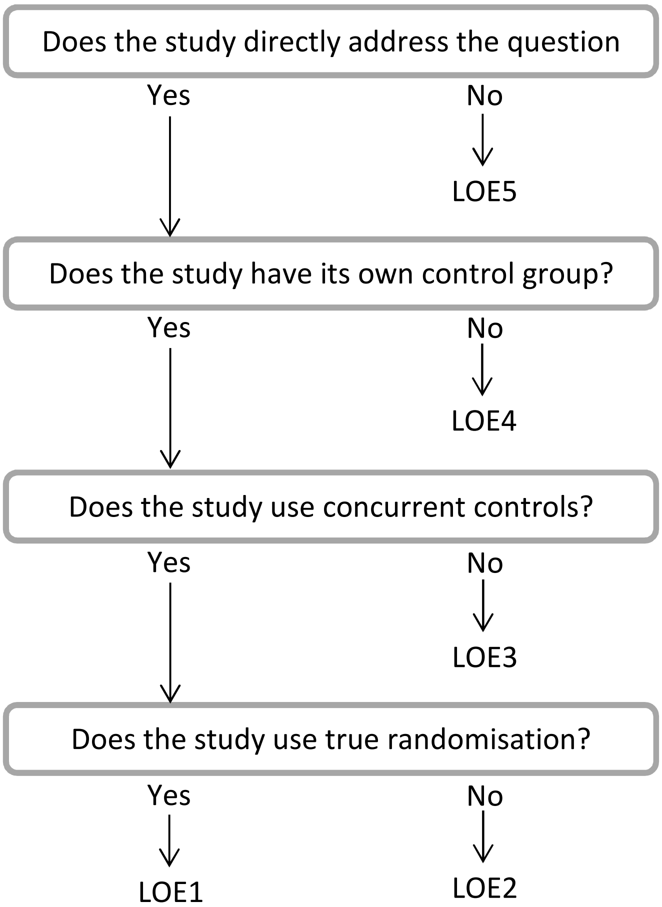
Exclusion Criteria	**Yes** ✓	Comment
Study relates to adults or children aged over 1 year old - either *exclusively* or where relevant data relating to 0-1 year old children *cannot be extracted*		
Study relates to animal surrogates weighing greater than 12kg - either *exclusively* or where relevant data relating to 0-12kg animal subjects *cannot be extracted*		
Study uses post-mortem animal subjects - either *exclusively* or where relevant data relating to live animal subjects *cannot be extracted*		
Study relates to instrumented CPR training manikins that represent adults or children aged over 1 year old		
Study relates to mathematical models that represent adults or children aged over 1 year old - either *exclusively* or where relevant data relating to models representing 0-1 year old children *cannot be extracted*		
Study relates to mathematical models that have not been validated against age/weight specific human or animal experimental data		
If any of the above criteria relate to the study, please **EXCLUDE** and complete **Section G**.		

SECTION E: Level of Evidence Classification*

Please provide ***your*** evaluation of the Level of Evidence classification of this study:

Level of Evidence	Description	Yes ✓	Comment
LOE1	Randomised controlled trials (RCTs) or meta-analysis of RCTs		
LOE2	Studies using concurrent controls without true randomisation (e.g. “pseudo”-randomised)		
LOE3	Studies using retrospective controls		
LOE4	Studies without a control group (e.g. case series or reports)		
LOE5	Studies not directly related to the specific population (e.g. different populations, radiological studies, animal models, mechanical models, mathematical models)		

Decision tree for Level of Evidence allocation*:



* Adapted from the ILCOR 2010 Evidence Evaluation Process.
Morley, P.T., et al., *Part 3: Evidence evaluation process: 2010 International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science with Treatment Recommendations.* Resuscitation, 2010. **81 Suppl 1**: p. e32-40.

SECTION F(i): Methodological Quality of Evidence Classification*

Please provide ***your*** evaluation of the Quality of Evidence classification of this study, using the Quality of Evidence assessment criteria associated with the relevant Level of Evidence classification determined in **Section E**.

LEVEL OF EVIDENCE 1 Study

Quality of Evidence assessment criteria (randomised controlled or crossed-over trial):

- Was the assignment of patients to treatment randomised?
- Was the randomisation list concealed?
- Were all patients who entered the trial accounted for at its conclusion?
- Were the patients analysed in the groups to which they were randomised?
- Were patients and clinicians "blinded" to which treatment was being received?
- Aside from the experimental treatment, were the groups treated equally?
- Were the groups similar at the start of the trial?

Quality of Evidence assessment criteria (meta-analysis of randomised controlled or crossed-over trials):

- Were specific objectives of the review stated (based on a specific clinical question in which patient, intervention, comparator, outcome (PICO) were specified)
- Was study design defined?
- Were selection criteria stated for studies to be included (based on trial design and methodological quality)?
- Were inclusive searches undertaken (using appropriately crafted search strategies)?
- Were characteristics and methodological quality of each trial identified?
- Were selection criteria applied and a log of excluded studies with reasons for exclusion reported?

Please provide ***your*** evaluation of the Quality of Evidence classification of this study:

Quality of Evidence	**Description**	**Yes ✓**	Comment
Good	Has achieved most/all of the relevant quality assessment criteria		
Fair	Has achieved some of the relevant quality assessment criteria		
Poor	Has very few of the relevant quality assessment criteria (but sufficient value to the review)		

* Adapted from the ILCOR 2010 Evidence Evaluation Process.
Morley, P.T., et al., *Part 3: Evidence evaluation process: 2010 International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science with Treatment Recommendations.* Resuscitation, 2010. **81 Suppl 1**: p. e32-40.

LEVEL OF EVIDENCE 2 Study

Quality of Evidence assessment criteria (studies using concurrent controls without true randomisation):

- Were comparison groups clearly defined?
- Were outcomes measured in the same (preferably blinded), objective way in both groups?
- Were known confounders identified and appropriately controlled for?
- Was follow-up of patients sufficiently long and complete?

Please provide ***your*** evaluation of the Quality of Evidence classification of this study:

Quality of Evidence	**Description**	**Yes ✓**	Comment
Good	Has achieved four of the relevant quality assessment criteria		
Fair	Has achieved three of the relevant quality assessment criteria		
Poor	Has less than two of the relevant quality assessment criteria (but sufficient value to the review)		

Quality of Evidence assessment criteria (meta-analyses of studies using concurrent controls without true randomisation):

- Were specific objectives of the review stated (based on a specific clinical question in which patient, intervention, comparator, outcome (PICO) were specified)
- Was study design defined?
- Were selection criteria stated for studies to be included (based on trial design and methodological quality)?
- Were inclusive searches undertaken (using appropriately crafted search strategies)?
- Were characteristics and methodological quality of each trial identified?
- Were selection criteria applied and a log of excluded studies with reasons for exclusion reported?

Please provide ***your*** evaluation of the Quality of Evidence classification of this study:

Quality of Evidence	**Description**	**Yes ✓**	Comment
Good	Has achieved most/all of the relevant quality assessment criteria		
Fair	Has achieved some of the relevant quality assessment criteria		
Poor	Has very few of the relevant quality assessment criteria (but sufficient value to the review)		

LEVEL OF EVIDENCE 3 Study

Quality of Evidence assessment criteria (studies using retrospective controls):

- Were comparison groups clearly defined?
- Were outcomes measured in the same (preferably blinded), objective way in both groups?
- Were known confounders identified and appropriately controlled for?
- Was follow-up of patients sufficiently long and complete?

Please provide ***your*** evaluation of the Quality of Evidence classification of this study:

Quality of Evidence	Description	Yes ✓	Comment
Good	Has achieved four of the relevant quality assessment criteria		
Fair	Has achieved three of the relevant quality assessment criteria		
Poor	Has less than two of the relevant quality assessment criteria (but sufficient value to the review)		

LEVEL OF EVIDENCE 4 Study

Quality of Evidence assessment criteria (case series studies):

- Were outcomes measured in an objective way?
- Were known confounders identified and appropriately controlled for?
- Was follow-up of patients sufficiently long and complete?

Please provide ***your*** evaluation of the Quality of Evidence classification of this study:

Quality of Evidence	Description	Yes ✓	Comment
Good	Has achieved three of the relevant quality assessment criteria		
Fair	Has achieved two of the relevant quality assessment criteria		
Poor	Has achieved one of the relevant quality assessment criteria (but sufficient value to the review)		

LEVEL OF EVIDENCE 5 Study

Quality of Evidence assessment criteria (studies that are not directly related to the specific population):

Please provide ***your*** evaluation of the Quality of Evidence classification of this study:

Quality of Evidence	**Description**	**Yes ✓**	Comment
Good	Randomised controlled or crossed-over studies (equivalent of LOE1 study)		
Fair	Studies without randomised con-trols (equivalent of LOE2 or LOE3 studies)		
Poor	Studies without any controls and studies with inadequate control of potential confounders		

SECTION F(ii): Methodological Quality of Evidence Reclassification

Radiological Study Reclassification

Classify as ***Fair*** if radiological case series, but reduce to ***Poor*** if no/incomplete exclusion criteria reported in study

Missing Data Reclassification

Reduce classification by one if missing data in study

Chest Compression Quality Reclassification

Please provide ***your*** evaluation of the study on the adequacy of its attempt to standardise the following measures by selecting from the options below:

Quality Measure	Adequately Controlled	Adequately Recorded	Neither	Measure of Interest*	Comment
Technique†					
Location					
Compression Depth/Force					
Release Depth/Force					
Compression Rate					
Duty Cycle					

* Quality measure has the same significance as if it was adequately controlled; † If a mechanical device is used, quality measure to be classed as adequately controlled

Based on the above, please re-evaluate ***your*** classification of the Quality of Evidence of this study:

Quality of Evidence	Description	Yes ✓	Comment
Good	All quality measures adequately controlled		
Fair	All quality measures either adequately controlled or recorded		
Poor	At least one quality measure not adequately controlled or recorded		

SECTION F(iii): Final Methodological Quality of Evidence Reclassification

Please provide ***your*** final evaluation of the Quality of Evidence classification of this study:

Quality of Evidence	**Yes ✓**	Comment
Good		
Fair		
Poor		

SECTION G: Final Decision

FINAL DECISION	Yes ✓	No ×	Comment
Is the study included? If so, provide justification below.			
If excluded, should it be kept for background information, introduction or discussion?			

Conclusions and Comments	Comment
Key points meriting inclusion	
Weaknesses, potential confounders and limitations	

Evaluation of Evidence	Score
Level of Evidence	
Quality of Evidence	

SECTION H: Data Extraction

Please complete the following sections as best as possible:

Please select the population this study investigates (more than one option may be selected):

Population	**Yes ✓**	Comment
Infant Cardiac Arrest Study		
Live Infant Clinical Study		
Infant Cadaver Study		
Infant Radiological Study		
Animal Surrogate Study		
Manikin Experimental Study		
Mathematical Model Study		
Other Population		

Population Extract all data relevant to the study population. Include data such as age range, weight range, genders, ethnicity, species, etc. Include details on any population selection criteria used by the study.

Study aims Extract all data relevant to the study aims. Include details of any hypotheses tested.

Methodology Extract all data relevant to the study methodology. Include details on any techniques used for data collection, any equipment used, any use of randomisation, any use of blinding, etc.

Outcomes Extract all data relevant to the study outcomes. Include details on any outcome measures including blood pressures, chest compression quality characteristics (depth, rate etc.), return of spontaneous circulation (ROSC), survival etc.

Study conclusions Extract the study conclusions.

Additional Information Include any additional information if extra space was required

A.4 Detailed Description and Design Drawings for the More ‘Physiological’ Infant CPR Manikin Modifications

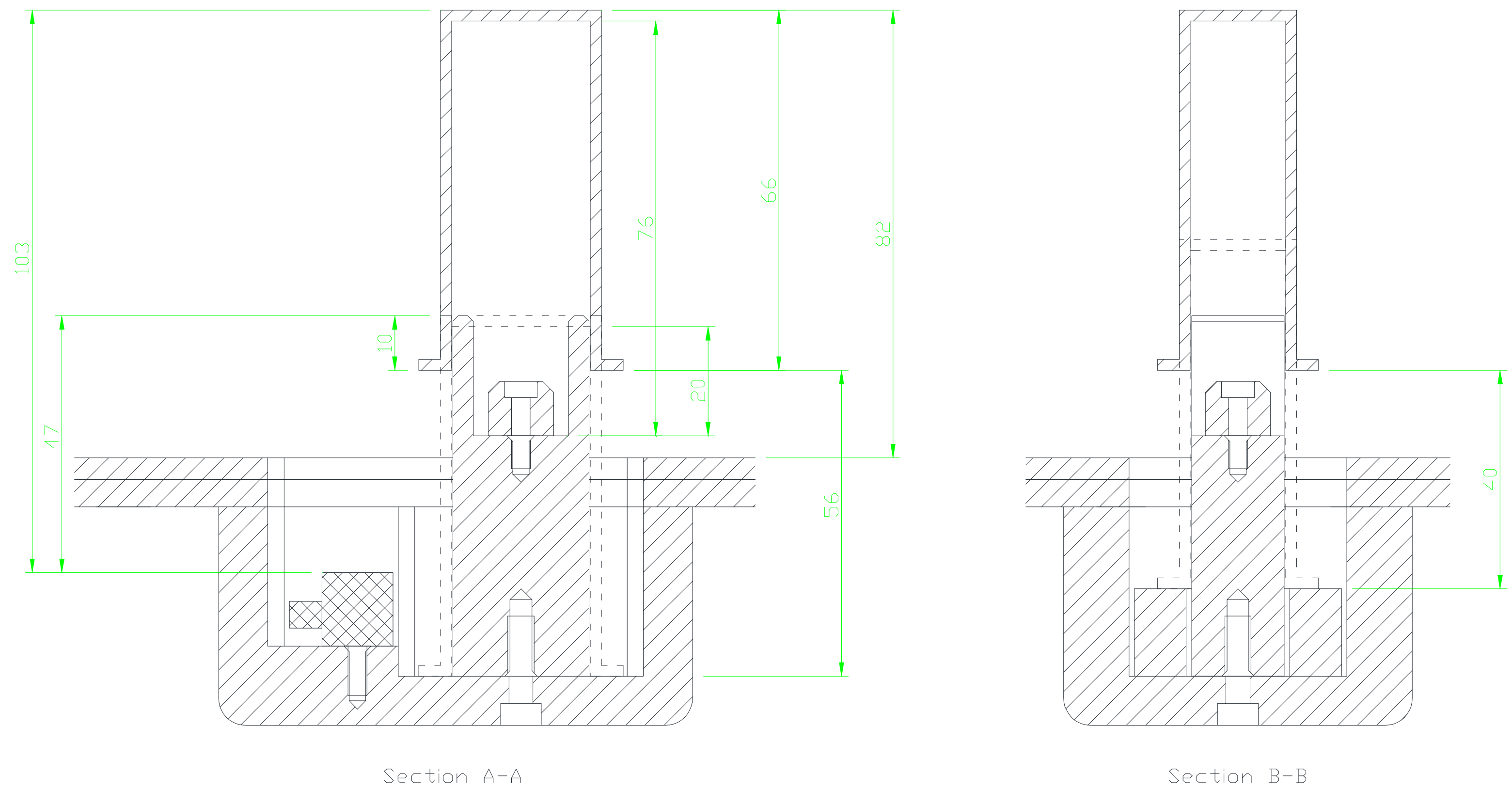


Figure 1: Assembly drawings for the more “physiological” (Section A-A) and original (Section B-B) modified manikin designs.
Drawings demonstrate the required slider stroke lengths for the original (40mm) and more “physiological” (56mm) designs, the maximum permissible slider displacement to maintain consistency with the chest diameter of the original manikin (82mm), the required free length of the spring (76mm), the maximum solid length of the spring (20mm) and the minimum distance required to ensure slider and slider rail interaction (10mm). The drawings further illustrate the location of the IR distance measuring device (cross hatched), whilst demonstrating the minimum (47mm) and maximum (103mm) distances to be measured during operation.

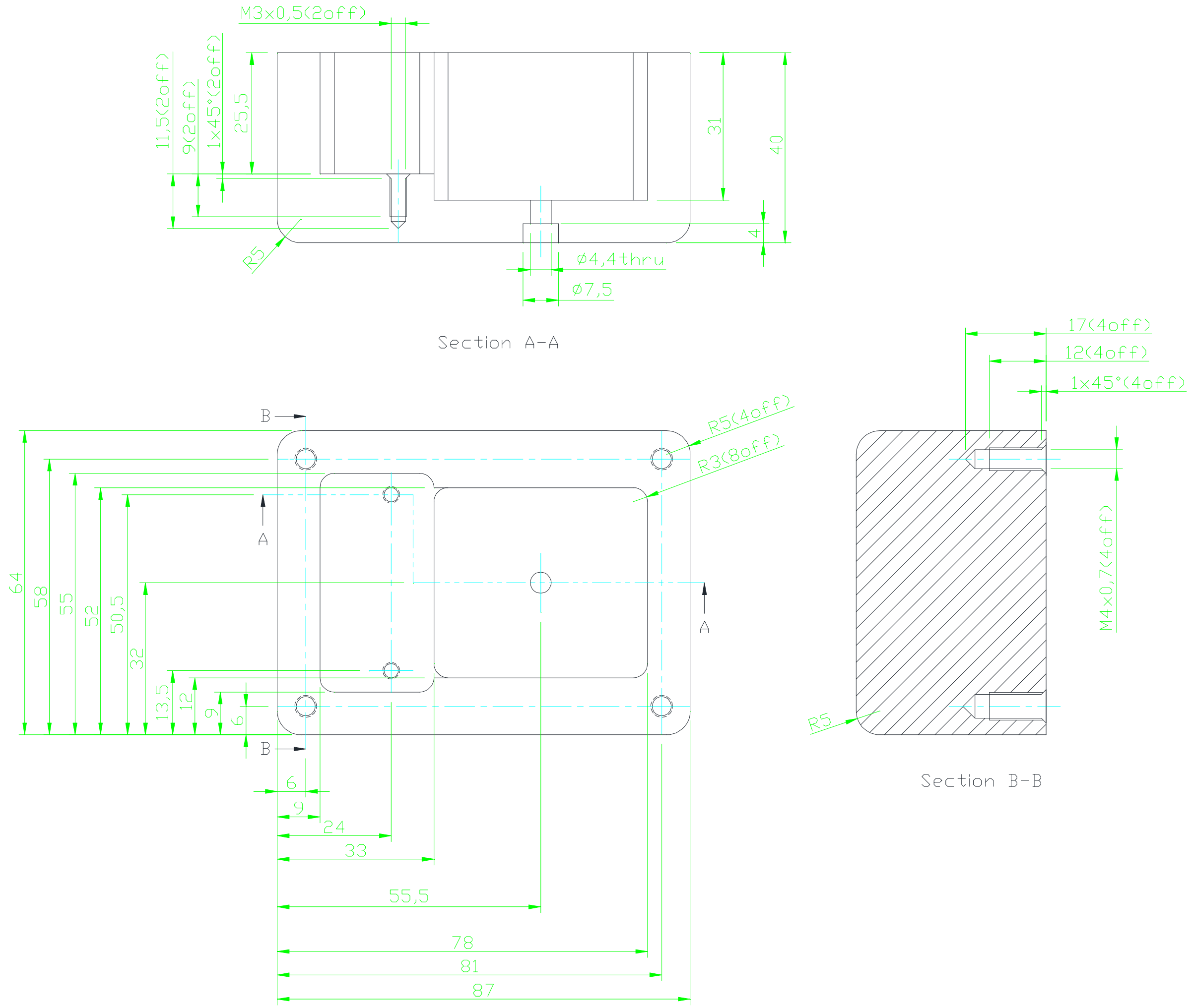


Figure 2: Design drawing for the chest displacement extension housing, machined from acetal.

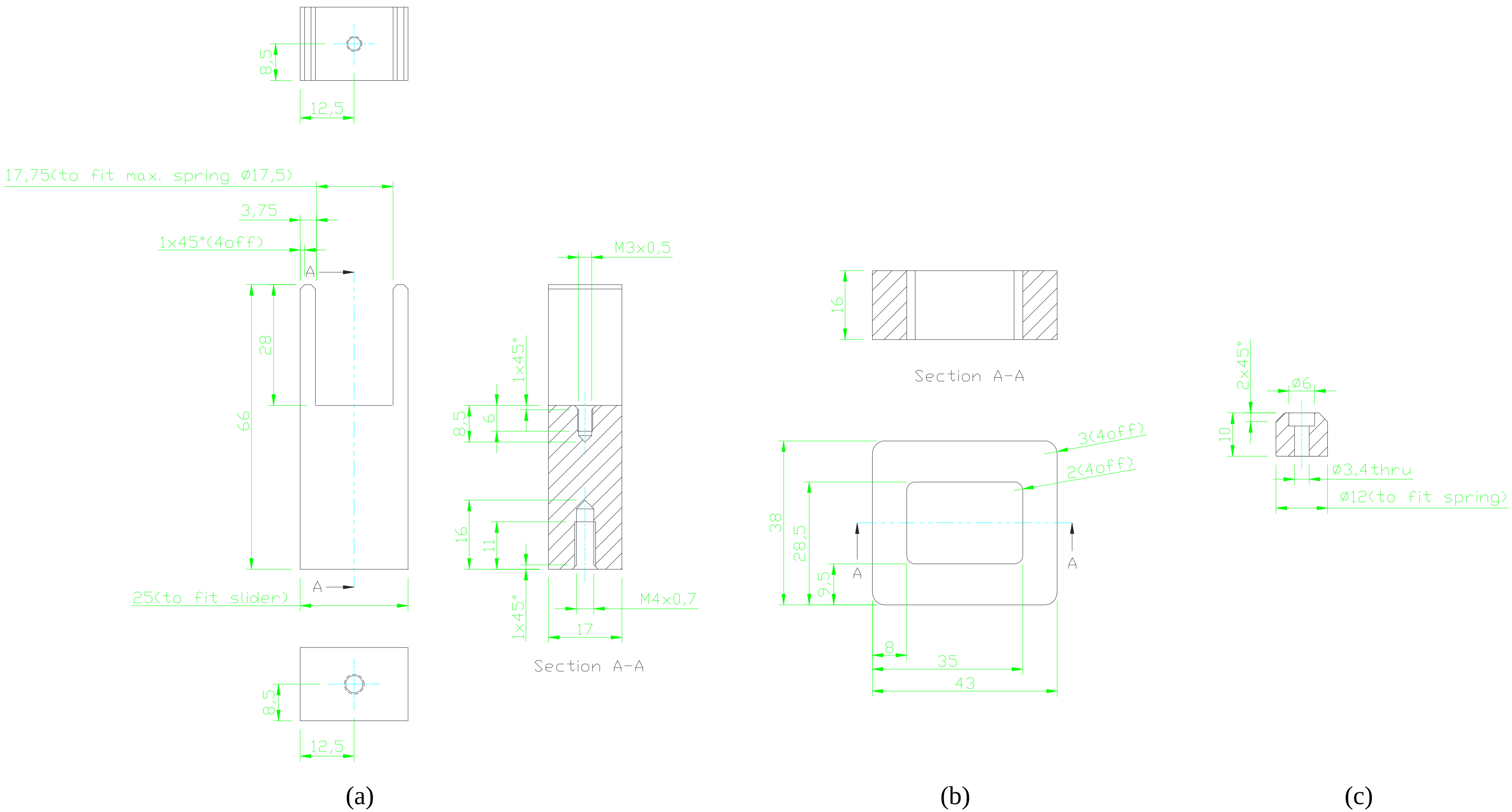


Figure 3: Design drawings for (a) the slider rail, (b) the mechanical stop and (c) the spring retainer, machined from aluminium (a, c) and acetal (b).

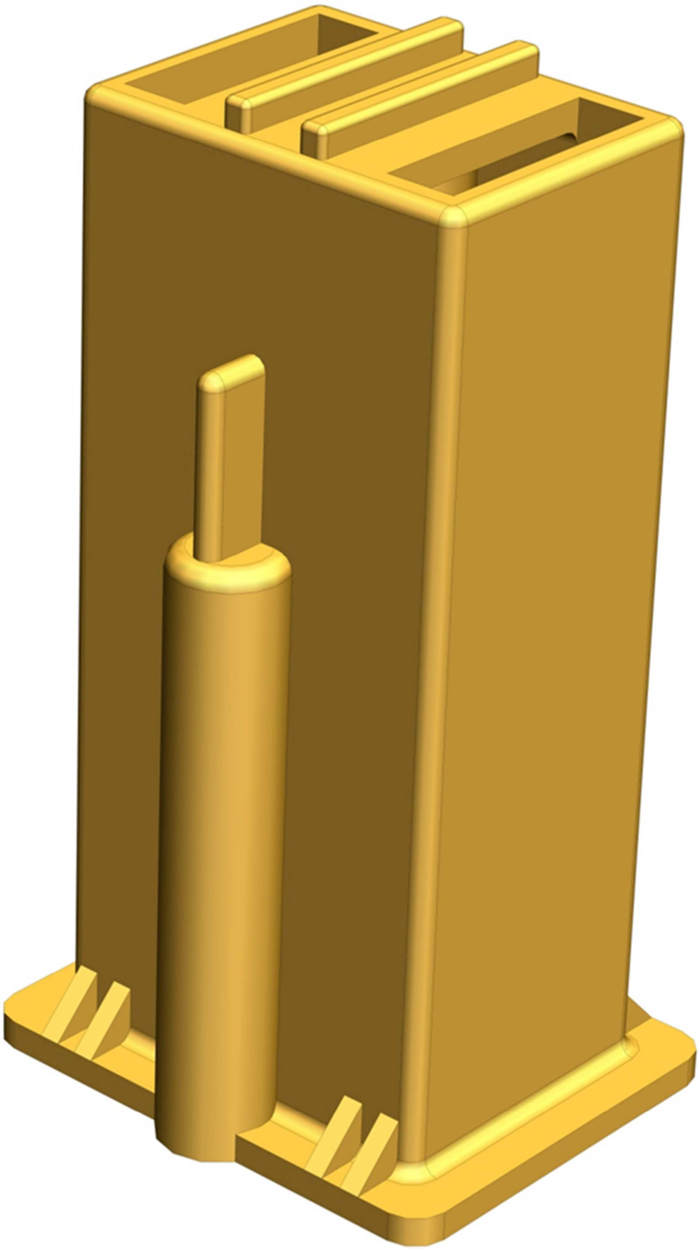


Figure 5: 3D Solidworks model for slider mechanism.
Formed via stereolithography using Accura® si 50. Slider mechanism modified from the original manikin mechanism through the extending its length to 66mm and adding two ribs for extra support on the top; all other aspects remained consistent.

Manikin Spring Selection Procedure

As described in above, this novel manikin design required a compression spring with an inner diameter of greater than 12mm, a free length of approximately 76mm and a solid length of less than 20mm. Four springs (Table 1) with these required dimensions were sourced across a range of spring stiffness rates from Lee Springs Ltd (Berkshire, UK). To select the most appropriate spring for the manikin, the chest compression stiffness of the manikin chest was established for all four springs at the $CDmax_{40}$ setting using the MTS 858 Mini Bionix II compression testing machine (MTS, MN, USA). For all four springs, the manikin chest was compressed at a rate of $0.5mms^{-1}$ from the most anterior aspect of the manikin thorax to a chest deflection of 30mm. This was repeated a further three times, with chest deflections and chest compression forces collected at a 24Hz sample rate to characterise the force-deflection properties of the manikin thorax. Mean (±σ) chest compression stiffness rates (defined between chest deflections of 15-30mm) for each spring were calculated and reported against the stiffness of the original manikin (Table 1). The most appropriate spring, selected for use in this study, was therefore the LC063HJ12S compression spring (Lee Springs Ltd, Berkshire, UK).

Table 1: Manikin chest compression stiffness characteristics for the original manikin and the novel manikin using all four sourced springs

Manikin Spring	Original	LC055H12M	LC055HJ12M	LC063HJ12M	LC063HJ12S
Stiffness /Nmm^{-1}	2.2 (±0.009)	1.8 (±0.009)	1.7 (±0.009)	2.4 (±0.009)	2.1 (±0.009)

Manikin chest compression stiffness values are reported as mean (± standard deviation).

A.5 Chapter 5 Baseline Stage Results

Table 1: Changes in simulated chest compression quality measures and quality indices, between the ‘no feedback’ and ‘feedback’ groups, for both the two-thumb (TT) and two-finger (TF) chest compression techniques performed at the ‘baseline’ stage.

	Two-Thumb Chest Compression Technique				Two-Finger Chest Compression Technique			
	No Feedback Group	**Feedback Group**	**Mean Difference**	***P*-value**	**No Feedback Group**	**Feedback Group**	**Mean Difference**	***P*-value**
Compression Depths (CD)								
Mean Compression Depth /mm	42 ± 8	42 ± 8	0 [-4, 3]	0.87*	38 ± 6	38 ± 7	1 [-2, 4]	0.62*
Median Compression Depth /mm	44 [35, 48]	43 [36, 49]		0.81†	37 [34, 42]	37 [34, 44]		0.67†
CD Quality Index (36.7-46mm) /%	10 [1, 72]	19 [0, 75]		0.89†	31 [7, 79]	30 [1, 58]		0.41†
Under-Compression (<36.7mm) /%	1 [0, 72]	1 [0, 62]		0.95†	57 [1, 93]	50 [1, 93]		0.91†
Release Forces (RF)								
Mean Release Force /kg	0.6 ± 0.5	0.5 ± 0.4	0.0 [-0.2, 0.2]	0.81*	0.2 ± 0.3	0.3 ± 0.4	0.1 [-0.1, 0.2]	0.29*
Median Release Force /kg	0.4 [0.2, 0.9]	0.5 [0.2, 0.8]		0.85†	0.2 [0.0, 0.2]	0.2 [0.1, 0.4]		0.48†
RF Quality Index (<2.5kg) /%	100 [100, 100]	100 [100, 100]		0.16†	100 [100, 100]	100 [100, 100]		1.00†
Complete RF (<0.5kg) /%	57 [11, 94]	58 [6, 86]		0.83†	97 [71, 100]	93 [60, 100]		0.40†
Compression Rates (CR)								
Mean Compression Rate /min^{-1}	131 ± 18	139 ± 22	7 [-2, 17]	0.14*	133 ± 24	140 ± 20	7 [-3, 17]	0.20*
Median Compression Rate /min^{-1}	125 [120, 140]	140 [121, 150]		0.096†	130 [120, 140]	133 [125, 153]		0.12†
CR Quality Index (100-120min^{-1}) /%	11 [0, 68]	0 [0, 20]		0.055†	9 [1, 63]	0 [0, 33]		0.067†
Too Fast (>120min^{-1}) /%	89 [31, 100]	99 [56, 100]		0.11†	91 [27, 99]	100 [67, 100]		0.12†
Compression Duty Cycles (DC)								
Mean Compression Duty Cycle /%	53 ± 8	54 ± 7	1 [-3, 4]	0.63*	47 ± 8	51 ± 8	3 [0, 7]	0.084*
Median Compression Duty Cycle /%	51 [48, 57]	52 [49, 60]		0.62†	47 [43, 53]	50 [45, 55]		0.099†
DC Quality Index (30-50%) /%	39 [3, 66]	32 [1, 64]		0.67†	67 [15, 91]	53 [7, 83]		0.23†
Prolonged DC (>50%) /%	61 [34, 97]	68 [36, 99]		0.67†	29 [4, 85]	47 [17, 93]		0.10†

Mean quality measures are presented as mean values ± standard deviation, whilst both the median quality measures and quality indices are presented as median values [inter-quartile range]. Differences between the feedback groups (‘feedback’ less ‘no feedback’) are presented as the mean difference [95% confidence interval]. *P*-values were calculated from two-sided independent samples Student’s T-tests (*) or Mann Whitney U tests (†) as appropriate.

Table 2: Changes in simulated chest compression quality measures and quality indices, between the two-thumb (TT) and two-finger (TF) techniques, for both the 'no feedback' and 'feedback' groups at the 'baseline' stage.

	'No Feedback' Group				'Feedback' Group			
	TT Technique	TF technique	Mean Paired Difference	*P*-value	TT Technique	TF technique	Mean Paired Difference	*P*-value
Compression Depths (CD)								
Mean Compression Depth /mm	42 ± 8	38 ± 6	5 [3, 6]	***<0.001****	42 ± 8	38 ± 7	3 [2, 5]	***<0.001****
Median Compression Depth /mm	44 [35, 48]	37 [34, 42]		***<0.001***†	43 [36, 49]	37 [34, 44]		***<0.001***†
CD Quality Index (36.7-46mm) /%	10 [1, 72]	31 [7, 79]		0.40†	19 [0, 75]	30 [1, 58]		0.93†
Under-Compression (<36.7mm) /%	1 [0, 72]	57 [1, 93]		***0.001***†	1 [0, 62]	50 [1, 93]		***0.003***†
Release Forces (RF)								
Mean Release Force /kg	0.6 ± 0.5	0.2 ± 0.3	0.3 [0.2, 0.5]	***<0.001****	0.5 ± 0.4	0.3 ± 0.4	0.2 [0.1, 0.3]	***<0.001****
Median Release Force /kg	0.4 [0.2, 0.9]	0.2 [0.0, 0.2]		***<0.001***†	0.5 [0.2, 0.8]	0.2 [0.1, 0.4]		***<0.001***†
RF Quality Index (<2.5kg) /%	100 [100, 100]	100 [100, 100]		0.18†	100 [100, 100]	100 [100, 100]		1.00†
Complete RF (<0.5kg) /%	57 [11, 94]	97 [71, 100]		***<0.001***†	58 [6, 86]	93 [60, 100]		***<0.001***†
Compression Rates (CR)								
Mean Compression Rate /min^{-1}	131 ± 18	133 ± 24	-1 [-5, 2]	0.45*	139 ± 22	140 ± 20	-1 [-4, 2]	0.57*
Median Compression Rate /min^{-1}	125 [120, 140]	130 [120, 140]		0.86†	140 [121, 150]	133 [125, 153]		0.75†
CR Quality Index (100-120min^{-1}) /%	11 [0, 68]	9 [1, 63]		0.75†	0 [0, 20]	0 [0, 33]		0.35†
Too Fast (>120min^{-1}) /%	89 [31, 100]	91 [27, 99]		0.25†	99 [56, 100]	100 [67, 100]		0.95†
Compression Duty Cycles (DC)								
Mean Compression Duty Cycle /%	53 ± 8	47 ± 8	5 [3, 7]	***<0.001****	54 ± 7	51 ± 8	3 [1, 5]	***0.005****
Median Compression Duty Cycle /%	51 [48, 57]	47 [43, 53]		***<0.001***†	52 [49, 60]	50 [45, 55]		***0.002***†
DC Quality Index (30-50%) /%	39 [3, 66]	67 [15, 91]		***0.002***†	32 [1, 64]	53 [7, 83]		***0.010***†
Prolonged DC (>50%) /%	61 [34, 97]	29 [4, 85]		***<0.001***†	68 [36, 99]	47 [17, 93]		***0.008***†

Mean quality measures are presented as mean values ± standard deviation, whilst both the median quality measures and quality indices are presented as median values [inter-quartile range]. Differences between the chest compression techniques (TT less TF) are presented as the mean paired difference [95% confidence interval]. *P*-values were calculated from two-sided paired samples Student's T-tests (*) or Wilcoxon's Signed Rank tests (†) as appropriate.

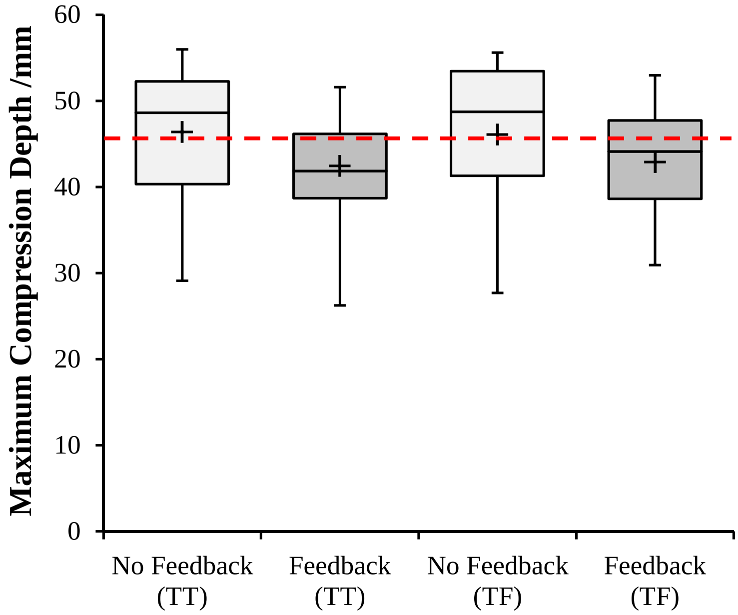


Figure 1: Maximum compression depths, illustrated against the thoracic over-compression criterion (46mm), as performed by the 'feedback' and 'no feedback' groups for both the two-thumb (TT) and two-finger (TF) chest compression techniques performed at the 'baseline' stage.

The centre line of the box plot represents the median value of the data, the upper and lower lines of the box plot represent the upper and lower quartiles of the data, the cross represents the mean value of the data and the whiskers represent the maximum and minimum values of the data.

APPENDIX B: THESIS PUBLICATIONS

Do chest compressions during simulated infant CPR comply with international recommendations?

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ABSTRACT

Background Morbidity and mortality remain high following infant cardiac arrest. Optimal cardiopulmonary resuscitation (CPR) is therefore imperative.
Objective Comparison of two-thumb (TT) and two-finger (TF) infant chest compression technique compliance with international recommendations.
Design Randomised cross-over experimental study.
Methods Twenty-two certified Advanced Paediatric Life Support (APLS) instructors performed 2 min continuous TT and TF chest compressions on an instrumented infant CPR manikin. Compression depth (CD), release force (RF), compression rate (CR) and duty cycles (DCs) were recorded. Quality indices were developed to calculate the proportion of compressions that complied with internationally recommended targets, and an overall quality index was used to calculate the proportion that complied with all four targets.
Results Mean CD was 33 mm and 26 mm ($p<0.001$; target ≥36.7 mm), mean RF was 0.8 kg and 0.2 kg ($p<0.001$; target <2.5 kg), mean CR was 128/min and 131/min ($p=0.052$; target 100–120/min) and mean DCs was 61% and 53% ($p<0.001$; target 30–50%) for the TT and TF techniques, respectively. With the exception of RF, the majority of compressions failed to comply with targets. The TT technique improved median CD compliance (6% vs 0% ($p<0.001$)), while the TF technique improved median DC compliance (23% vs 0% ($p<0.001$)). Overall compliance with all four targets was <1% for both techniques ($p=0.14$).
Conclusions Compliance of APLS instructors with current international recommendations during simulated infant CPR is poor. The TT technique provided improved CD compliance, while the TF technique provided superior DC compliance. If this reflects current clinical practice, optimisation of performance to achieve international recommendations during infant CPR is called for.

What is already known on this topic

- Outcome of infant cardiopulmonary resuscitation (CPR) remains poor.
- Manikin studies demonstrate a superior compression depth quality with the two-thumb technique and rapid compression rates for two-thumb and two-finger techniques.
- Chest release forces, duty cycles and compliance of chest compression during simulated infant CPR against international targets are unknown.

What this study adds

- With the exception of release forces, chest compressions failed to comply with internationally recommended targets.
- The two-thumb technique improved compression depth compliance, while the two-finger technique improved duty cycle compliance.
- Each technique rarely complies with all four chest compression targets.

INTRODUCTION

Current cardiac arrest outcomes in the infant population continue to exhibit undesirably high morbidity and mortality.[1 2] Since effective closed chest cardiopulmonary resuscitation (CPR) achieves only 50% cerebral and 15–25% coronary baseline blood flow levels,[3–5] the provision of quality chest compressions to maximise cardiac output is essential to its success. To improve infant survival rates, current European (ERC) and UK Resuscitation Council (UKRC) guidelines recommend the delivery of high-quality chest compressions during infant CPR using either the two-thumb (TT) or two-finger (TF) chest compression technique.[6 7]

Fundamental to providing quality chest compressions are the four quality measures identified by the internationally agreed guidelines for the uniform reporting of the measured quality of CPR: chest compression depth; chest release force; chest compression rate; and compression duty cycles (ie, the proportion of each compression cycle with active chest compression).[8] Previous studies have attempted to compare TT and TF technique quality by simulating chest compressions on instrumented infant CPR training manikins.[9–14] Although the majority conclude that the TT technique is statistically superior overall,[9–13] only the quality of chest compression depths and compression rates were characterised. As neither chest release forces nor compression duty cycles were evaluated by any study, it remains unclear whether the TT chest compression technique is in fact superior.

The aim of this study was to assess Advanced Paediatric Life Support (APLS) instructor performance during simulated infant CPR on an instrument CPR manikin. The study was designed to compare the differences between TT and TF technique, assessing chest compression compliance with all four internationally recommended chest compression quality measures.

▶ http://dx.doi.org/10.1136/archdischild-2012-303116

To cite: Martin PS, Kemp AM, Theobald PS, *et al*. *Arch Dis Child* 2013;**98**:576–581.

METHODS

Infant manikin design

A commercially available CPR training manikin (Laerdal ALS Baby; Laerdal Medical, Stavanger, Norway), representing a 3-month-old 5 kg male infant, was instrumented with a linear potentiometer. Sensor output was recorded via a data acquisition card (National Instruments, Austin, Texas, USA) at a sample rate of 50 Hz, and transferred to a custom LabVIEW software programme (National Instruments) on a laptop to record output voltage. The manikin instrumentation was calibrated to measure chest deflections and chest compression forces at the lower third of the sternum (error ±0.07 mm and ±0.07 kg), and calibration was checked before and after testing, demonstrating no change in measurement errors. Finally, the external diameter of the manikin thorax, between the most anterior and posterior aspects of the thorax at the lower third of the sternum, was measured as 110 mm.

Experimental procedure

This randomised crossover experimental study was approved by two local National Health Service health boards in the South Wales region. Twenty-two certified APLS instructors were recruited as participants from two APLS training courses. Before testing, the instrumented manikin was set up in an assessment room, on a flat table, with the laptop and peripheral equipment located securely below. Instructors were randomly assigned to an initial chest compression technique (TT or TF) and instructed to perform continuous chest compressions (ie, no requirement to perform ventilations) for 2 min for each technique (the maximum time for which a resuscitator is expected to perform continuous chest compressions[7]). Full instructor recovery was permitted between techniques. Manikin chest deflections were continuously recorded throughout, with both the instructor and investigator blinded to performance feedback. Instructors were neither refreshed nor coached on technique, nor briefed about the nature of the observations being made or the study objectives. Individual results were fed back to the instructor after study completion.

Chest compression quality

Chest compression quality measures for this study were adapted from internationally agreed guidelines for the uniform reporting of the measured quality of CPR (figure 1).[8] Chest compression depths were defined as the maximum chest deflections measured during the chest compression phase. Chest release forces (kg) were defined as the minimum chest compression forces measured during the chest release phase. Chest compression rates were calculated from the inverse of the time between consecutive chest release forces (and quantified as compressions/min). Compression duty cycles were calculated by dividing the area under the chest deflection curve by the product of compression depth and cycle time for each compression cycle—that is, this combines the compression and the period of release, as demonstrated in figure 1. All quality measures were calculated for each chest compression cycle, which were defined between consecutive chest release forces.

To characterise chest compression compliance, quality indices were developed for compression depths, release forces, compression rates and duty cycles, along with a quality index to characterise overall chest compression compliance. For each quality index, the proportion of chest compressions that complied with internationally recommended targets was calculated for each instructor. Chest compression depth and compression rate targets were based on ERC and UKRC guideline recommendations: targeting depths of 'at least one-third' the external anterior–posterior (AP) chest diameter (≥36.7 mm for this

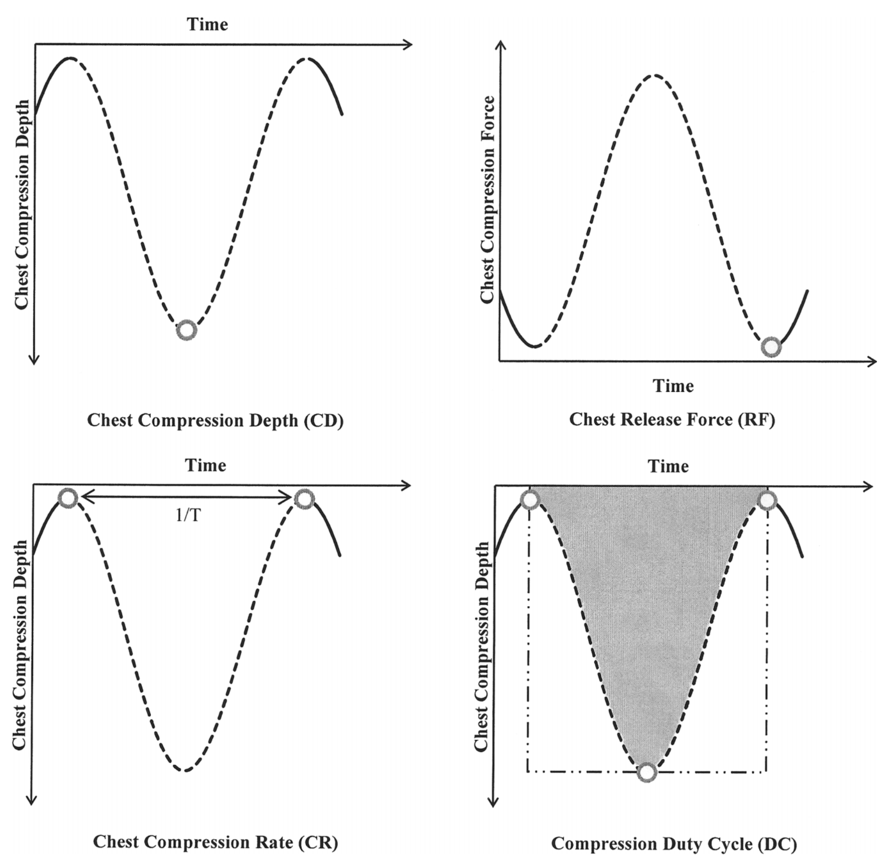

Figure 1 Example chest deflection curves defining chest compression depth (CD), chest release force (RF), chest compression rate (CR) and compression duty cycle (DC). Each chest compression cycle is represented by a dashed line, the circular markers represent the points recorded for each quality measure, the shaded region represents the area under the chest deflection curve for the chest compression cycle, and the dashed and double dotted lined box represents the product of the CD and the chest compression time. CR is calculated by the inverse of the time between consecutive release forces. DC is calculated by the area under the chest deflection curve (shaded region), divided by the product of the CD and the time between consecutive release forces (dashed and double dotted lined box).

manikin model) and a rate between 100 and 120 compressions/min.[6 7] A chest release force target of <2.5 kg was defined to represent the residual chest compression force associated with a clinically significant increase in intrathoracic pressure in infants.[15] Finally, a duty cycle target of 30–50% was defined to represent the most effective duty cycle range observed in infant animal surrogates.[16–18] Secondary chest compression depth and release force targets were also analysed. Using the ERC and UKRC guidelines, targets of approximated infant chest compression depth targets of 40 mm and a release force of <0.5 kg (<10% of manikin weight) were determined to represent the complete release of the chest.[6 7] To determine overall compliance, the proportion of chest compressions that achieved all four primary chest compression targets was also calculated for each technique.

Statistical analysis

Median values for all four chest compression quality measures were recorded, along with the five chest compression quality indices, for each instructor. Depending on data normality, study results were reported as either mean±SD or median (IQR). Paired differences between techniques were reported as mean (95% CI). Results were compared statistically by paired Student t test or Wilcoxon's signed rank test as appropriate. The number of instructors that achieved quality index scores of 0%, 0–25%, 25–50%, 50–75%, 75–100% and 100% for each quality measure and for overall compliance was also evaluated for each technique and statistically compared by McNemar tests. Statistical significance was considered at $p<0.05$ for all tests, and all p values were two-sided. Statistical analyses were performed using the SPSS V.16.0 statistical software package. A minimum sample size of 22 instructors was required to adequately detect a mean paired difference 0.6 times the standard deviation of the differences, assuming data normality, a two-sided significance level of <0.05 and >80% power.

RESULTS

The 22 study participants (eight male) were certified APLS instructors: 12 doctors, seven resuscitation officers and three registered nurses. Overall, 5180 and 5600 chest compression cycles were recorded, without interruptions, for the TT and TF techniques, respectively.

Simulated chest compression quality measures and indices are summarised in table 1 and illustrated against their internationally recommended targets in figure 2. Instructors achieved greater mean compression depths with the TT technique (TT: 33±3 mm vs TF: 26±5 mm ($p<0.001$); target ≥36.7 mm), while releasing the chest further (TT: 0.8±0.4 kg vs TF: 0.2±0.2 kg ($p<0.001$); target <2.5 kg) and reducing the compression duty cycle (TT: 61±8% vs TF: 53±8% ($p<0.001$); target 30–50%) with the TF technique. Mean chest compression rates were observed to exceed recommended targets for both techniques (TT: 128±21/min vs TF: 131±21/min ($p<0.052$); target 100–120/min).

For both techniques, instructors were observed to achieve a median release force compliance of 100%, median compression rate and duty cycle compliances of <50%, and a median compression depth compliance of <6%. When techniques were compared, instructors displayed improved compression depth compliance when using the TT technique, and superior duty cycle compliance when using the TF technique. For the secondary analyses, all chest compressions failed to achieve depths of 40 mm, while a greater proportion of compressions achieved complete release (<0.5 kg) of the chest for the TF technique. Despite these improvements, however, overall chest compression compliance remained poor for both techniques, with <1% of all chest compressions complying simultaneously with all four recommended chest compression targets.

The number of instructors that achieved quality index scores of 0%, 0–25%, 25–50%, 50–75%, 75–100% and 100% are illustrated for each quality index and for the overall quality index in figure 3. For both techniques, no instructor achieved >50% compression depth compliance, while compression rate and duty cycle compliance were inconsistent and varied across the group. When using the TT technique, a greater number of instructors complied with compression depth targets, whereas, when using the TF technique, more complied with duty cycle targets. Overall, no instructor was observed to achieve >2% compliance with all four chest compression targets.

Table 1 Quality measures and indices for two-thumb (TT) and two-finger (TF) technique chest compressions

	TT technique (n=22)	TF technique (n=22)	Mean paired difference (TT less TF)	p Value
Compression depth (CD)				
Mean compression depth (mm)	33±3	26±5	7 (5 to 10)	<0.001
CD quality index (≥36.7 mm) (%)	6 (0, 7)	0 (0, 0)		<0.001
Secondary CD quality index (≥40 mm) (%)	0 (0, 0)	0 (0, 0)		1.00
Release force (RF)				
Mean release force (kg)	0.8±0.4	0.2±0.2	0.6 (0.4 to 0.7)	<0.001
RF quality index (<2.5 kg) (%)	100 (100, 100)	100 (100, 100)		0.32
Secondary complete RF index (<0.5 kg) (%)	10 (0, 71)	100 (94, 100)		<0.001
Compression rate (CR)				
Mean compression rate (cpm)	128±21	131±21	−3 (−7 to 0)	0.052
CR quality index (100–120 cpm) (%)	47 (3, 78)	39 (2, 72)		0.24
Compression duty cycle (DC)				
Mean compression duty cycle (%)	61±8	53±8	9 (6 to 11)	<0.001
DC quality index (30–50%) (%)	0 (0, 7)	23 (4, 62)		<0.001
Overall quality index (%)	0 (0, 0)	0 (0, 0)		0.14

Values are given as mean±SD, except for the cardiopulmonary resuscitation (CPR) chest compression quality indices, which are given as the median value (IQR). Differences are given as the mean paired difference (95% CI). p Values are calculated using two-tailed paired sample Student t tests, except for the CPR chest compression quality indices, which are calculated using Wilcoxon's signed rank tests.
cpm, compressions per minute.

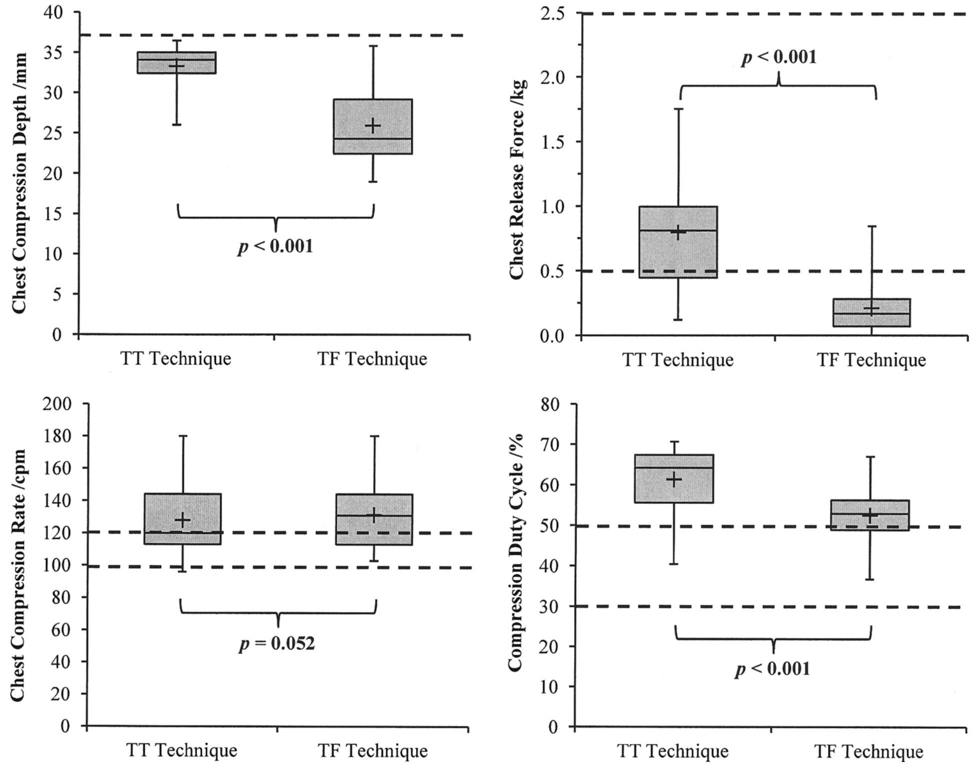

Figure 2 Illustration of median instructor two-thumb (TT) and two-finger (TF) technique chest compression depths (CD), chest release forces (RF), chest compression rates (CR) and compression duty cycles (DC) against internationally recommended targets (illustrated by dashed lines). CD targets were ≥36.7 mm, RF targets were <2.5 kg and <0.5 kg, CR targets were 100–120 compressions/min, and DC targets were 30–50%.

DISCUSSION

This study is the first to evaluate the compliance of simulated infant CPR chest compressions provided by trained APLS instructors against current international recommendations. The results show that instructors achieved greater chest compression depths with the TT technique, while releasing the chest further and reducing the compression duty cycle with the TF technique. A greater proportion of compressions complied with compression depth targets of 'no less than one-third the external AP chest diameter' when the TT technique was used, while a greater proportion complied with compression duty cycle targets of 30–50% when the TF technique was used. Despite these individual improvements, overall quality was poor for both techniques, with <1% of all chest compressions achieving all four chest compression targets.

Despite current ERC and UKRC guidelines emphasising the delivery of high-quality chest compressions during CPR,[6 7] this study suggests that overall chest compression compliance during simulated infant CPR is poor. Fundamental to this was a combination of shallow chest compressions, excessive compression rates and prolonged duty cycles. This is consistent with clinical reports on both adult and older paediatric populations,[19–22] thus it is likely that poor-quality chest compressions remain prevalent during infant CPR.

Increased chest compression depths result in favourable haemodynamic outcomes, such as improved arterial pressures in both infant and adult human subjects, and superior coronary flow and cardiac output in animal surrogates.[5 23–25] However, shallow chest compressions have been reported during CPR in both adult and older paediatric subjects and during simulated CPR on instrumented infant manikins.[9–13 19–22] Despite greater TT technique compression depths being recorded by this study, this tendency to under-compress the chest was also observed. On average, 94% of all chest compressions failed to achieve or surpass target depths of one-third the external AP chest diameter, while all chest compressions failed to achieve guideline-approximated chest compression depth targets of 40 mm. The precise reasons for this are not yet clear, although it is possible that compression was restricted by the manikin design, which does not precisely match the internal diameter of the infant thorax. Other possibilities include reluctance on the part of the providers to over-compress in this simulated scenario.

Prolonged compression duty cycles, combined with increased compression rates, results in inadequate chest wall relaxation, impeding the venous return of blood to the heart and adversely affecting cardiac output, cerebral perfusion pressures and cerebral blood flow.[16–18 26] While CPR chest compressions in adult and older paediatric subjects achieve target rates,[19–22] the compression rates achieved during simulated CPR in infant manikins have been found to be faster than current targets and vary extensively between providers.[10 11 13] Similar results were observed in this study, with >50% of chest compressions exceeding target rates and a large inter-participant variation. Although compression duty cycles of 33–47% during adult CPR have been reported,[19 21 27] compression duty cycles during paediatric CPR have never been quantified. In this analysis of compression duty cycle compliance during infant CPR, 0% of all TT chest compressions and 23% of all TF chest compressions complied with infant compression duty cycle targets, with neither technique allowing adequate time for full chest recoil.

Incomplete chest release during CPR has been observed to generate increased intrathoracic pressures during the chest release phase, consequently limiting the return of venous blood to the heart and reducing coronary and cerebral perfusion pressures.[15 27–29] While incomplete release during CPR in older paediatric subjects has been observed in 25–50% of chest compressions,[22 30] >97% of chest compressions achieved target release forces during CPR in adults.[19] The chest release force compliance demonstrated by this study establishes that both techniques during simulated infant CPR achieved >99% compliance with current release force targets. On assessment of the

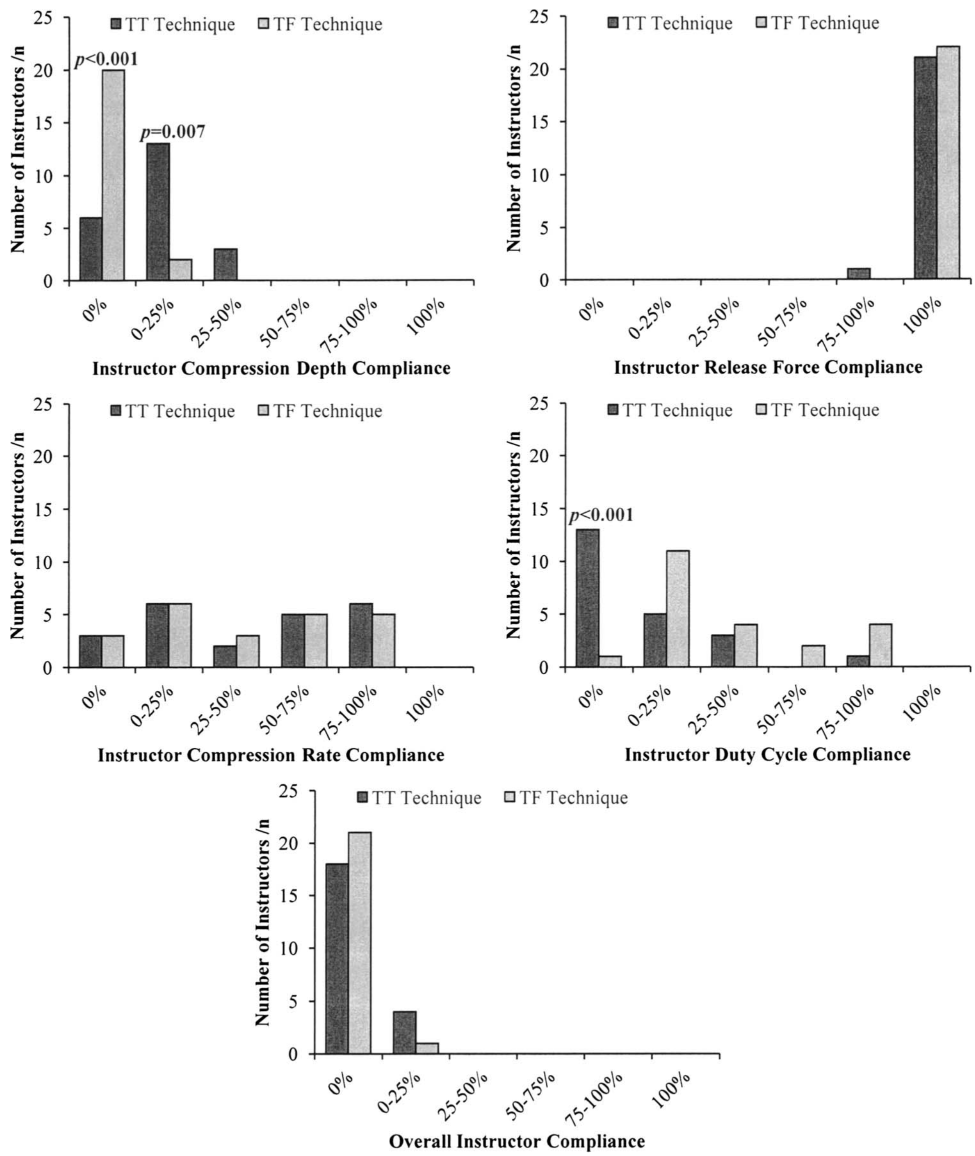

Figure 3 Number of instructors who achieved quality index scores of 0%, 0–25%, 25–50%, 50–75%, 75–100% and 100% for chest compression depth compliance (target ≥36.7), chest release force compliance (target <2.5 kg), chest compression rate compliance (target 100–120/min), compression duty cycle compliance (target 30–50%) and overall compliance. p Values, calculated by McNemar tests, indicate a significant difference between the two techniques, two-thumb (TT) and two-finger (TF).

complete release of the chest, however, instructors were found to achieve complete release targets of <0.5 kg (<10% of the manikin weight) more often when using TF technique. As chest release forces of as little as 10% of the body weight of the subject cause a measurable increase in intrathoracic pressure,[15] the TF technique may therefore provide a superior return of venous blood to the heart.

This study has three key limitations. First, although infant CPR training manikins have been extensively used for investigating CPR quality, their design is recognised as intrinsically flawed.[9–14] For the manikin used in this study, a maximum achievable chest compression depth of 40 mm was defined at an applied force of 26 kg (a force equivalent to double the mean maximum palmar pinch force for the dominant hand of a male adult[31]). As the mean internal AP thoracic depth of a 3-month-old boy is ~56.2 mm,[32] instructor chest compression depths may have been restricted by the manikin to unrepresentative depths. Second, the chest compression targets developed by this study were derived from a combination of human subject, radiographic and animal surrogate studies. This, however, reflects the current scientific evidence guiding internationally recommended infant chest compression targets, and, with future research, these targets for benchmarking resuscitator performance may be updated. Finally, despite being blinded to the study objectives, the instructors would have been aware of being observed and therefore their performance may have been affected.

To improve the current compliance of infant CPR chest compressions, instructors must be encouraged to achieve target compression depths for both recommended techniques. This may, however, be easier to achieve and maintain with the TT technique, as it performs deeper chest compressions and delays fatigue.[10–12] Further improvements may also be achieved by educating resuscitators to allow a greater time for full chest recoil. This would maintain the excellent chest release force compliance observed in this study and may potentially improve compression duty cycle compliance. Finally, improving the quality of compression rates may also be realised through regulation with audiovisual aids. Through targeting improvements in all four chest compression quality measures and using quality indices as a performance benchmarking tool, a future improvement in overall chest compression compliance may be possible.

CONCLUSIONS

This study is the first to fully evaluate the compliance of simulated infant CPR chest compressions against current internationally recommended targets. Overall, either technique rarely complied with all four targets, with excessive chest compression rates and prolonged compression duty cycles prevalent. The TT technique demonstrated improved compression depth compliance, while the TF technique provided superior duty cycle compliance. Thus, there remains scope for a considerable improvement in the quality of infant chest compressions. Future work should focus on ensuring that APLS instructors are made aware of their performance against international recommendations.

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Contributors PSM: instrumented manikin, conducted all experiments, contributed to writing of manuscript. MDJ: designed study, supervised instrumentation, contributed to manuscript. PST: supervised experimental work, contributed to statistical analysis, contributed to manuscript. SAM: contributed to study design, contributed to manuscript. AMK: contributed to study design, contributed to manuscript.

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Data sharing statement Further detailed analysis of the inter-subject variation is available, as is a detailed breakdown of each individual's results plotted against time. This could be made available if required.

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Simulation and education

Does a more "physiological" infant manikin design effect chest compression quality and create a potential for thoracic over-compression during simulated infant CPR?☆

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ABSTRACT

Poor survivability following infant cardiac arrest has been attributed to poor quality chest compressions. Current infant CPR manikins, used to teach and revise chest compression technique, appear to limit maximum compression depths (CDmax) to 40 mm. This study evaluates the effect of a more "physiological" CDmax on chest compression quality and assesses whether proposed injury risk thresholds are exceeded by thoracic over-compression.

A commercially available infant CPR manikin was instrumented to record chest compressions and modified to enable compression depths of 40 mm (original; $CDmax_{40}$) and 56 mm (the internal thoracic depth of a three-month-old male infant; $CDmax_{56}$). Forty certified European Paediatric Life Support instructors performed two-thumb (TT) and two-finger (TF) chest compressions at both CDmax settings in a randomised crossover sequence. Chest compression performance was compared to recommended targets and compression depths were compared to a proposed thoracic over-compression threshold.

Compressions achieved greater depths across both techniques using the $CDmax_{56}$, with 44% of TT and 34% of TF chest compressions achieving the recommended targets. Compressions achieved depths that exceeded the proposed intra-thoracic injury threshold. The modified manikin ($CDmax_{56}$) improved duty cycle compliance; however, the chest compression rate was consistently too high. Overall, the quality of chest compressions remained poor in comparison with internationally recommended guidelines.

This data indicates that the use of a modified manikin ($CDmax_{56}$) as a training aid may encourage resuscitators to habitually perform deeper chest compressions, whilst avoiding thoracic over-compression and thereby improving current CPR quality. Future work will evaluate resuscitator performance within a more realistic, simulated CPR environment.

1. Introduction

Current European and UK Resuscitation Council's (ERC; UKRC) guidelines for infant cardiopulmonary resuscitation (CPR) emphasise that improved chest compression quality may improve survival rates.[1,2] The International Liaison Committee of Resuscitation (ILCOR), ERC and UKRC recommend the use of either the two-thumb (TT) or two-finger (TF) chest compression technique. Current chest compression recommendations include: compression depths of at least one-third the external anterior–posterior (AP) thoracic diameter (≈40 mm); compression rates of 100–120 min^{-1}; complete release of the chest; 30–50% duty cycle (i.e. the proportion of each cycle with active chest compression).[1–6]

The ERC and UKRC recommend that resuscitators push "hard and fast" to achieve the chest compression guidelines.[1,2] Whilst the maximum chest compression depth (CDmax) of industry-leading infant resuscitation manikins broadly correlate with the minimum clinical requirement (≈40 mm), manikin-based studies typically report that participants perform shallow chest compressions across a broad range of rates.[7–11] The prevention of excessively deep chest compressions is also important as, for example, chest compression depths >46 mm have the potential to cause intra-thoracic injury in 90% of patients and thus hinder the possibility of full recovery.[12–18]

Previous studies have used manikins to investigate resuscitator performance[7–11]; however, with a CDmax limited to ≈40 mm, it is argued that this may have prevented resuscitators from achieving representative chest compressions.[11,19] This study develops a more "physiological" manikin design, thus enabling resuscitators to perform chest compression on a more representative model. The study

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will determine whether the new design encourages improved chest compression performance during training and greater compliance with the recommended guidelines, whilst also evaluating whether resuscitators inadvertently perform chest compressions to excessive depths.

2. Methods

2.1. Modified infant manikin design

A commercially available CPR training manikin (Laerdal® ALS Baby; Laerdal Medical, Stavanger, Norway), representing a three month old 5 kg male infant, was modified to allow CDmax to be varied between the original manikin specification (i.e. 40 mm; $CDmax_{40}$), and the physiological internal chest depth of a three month old male infant (i.e. 56 mm; $CDmax_{56}$).[12] Manikin chest deflections, during simulated CPR, were measured by an infra-red sensor (Sharp Corporation, Osaka, Japan), with the 50 Hz output recorded on a laptop computer via a data acquisition card and inhouse LabVIEW software program (both National Instruments, TX, USA). The conformity of this "physiological" manikin, versus the original manikin, was confirmed by comparing the magnitude of force required to achieve chest compressions to equal depths on a servo-hydraulic test machine (MTS 858 Mini Bionix II; MTS, MN, USA). Finally, the external AP thoracic diameters of both manikins, between the most anterior and posterior aspects of the manikin thorax at the lower third of the sternum, were measured as 110 mm. Thus, a third of the external AP thoracic depth corresponded to 36.7 mm.

2.2. Experimental protocol

Consenting participants with European Paediatric Life Support (EPLS) instructor certification were recruited from five EPLS training courses, following Research & Development approval. The manikin, laptop and peripheral equipment were arranged on a level table. Participants were blinded both to the study aims and to the initial assignment of either $CDmax_{40}$ or $CDmax_{56}$. By employing a randomised crossover sequence, all participants performed: $CDmax_{40}$ & TT; $CDmax_{40}$ & TF; $CDmax_{56}$ & TT; $CDmax_{56}$ & TF. Participants performed continuous chest compressions (i.e. without ventilations) for 90 s. Full recovery was allowed between each combination and individual results were conveyed to each participant on completion of the study.

2.3. Data analysis

Data was recorded describing the compression depths, release forces, compression rates and compression duty cycles achieved by each participant. Quality indices were used to calculate the proportion of chest compressions that complied with internationally recommended targets for each measure. Compression depth and rate targets were based upon current recommendations, targeting depths of at least one-third the external anterior–posterior (AP) chest diameter (i.e. ≥36.7 mm) and rates between 100 and 120 min^{-1}.[1,2] Release force targets were comparable to a chest compression force associated with a clinically significant increase in intra-thoracic pressure (i.e. <2.5 kg),[20] whilst duty cycle targets (i.e. 30–50%) represented the most effective range observed in infant animal surrogates.[4–6] Finally, to determine overall compliance, the proportion of chest compressions that simultaneously achieved all four targets was also calculated for each technique.

Thoracic over-compression was prospectively defined at a chest compression depth that would result in a residual internal AP chest depth of <10 mm in a 3 month old male infant (i.e. >46 mm).[12] The proportion of chest compressions that exceeded this thoracic over-compression criterion was calculated for each participant to assess thoracic over-compression during simulated CPR. To further quantify the extent of thoracic over-compression, the maximum chest compression depths achieved by each participant were also recorded for each infant chest compression technique.

Median values for all four chest compression quality measures were recorded for each participant, alongside the chest compression quality indices, the proportion of compressions that exceeded the proposed thoracic over-compression criterion and the maximum chest compression depths achieved. Study results were reported either as means with standard deviations or as medians with inter-quartile ranges [IQR]. The mean paired differences between CDmax settings ($CDmax_{56}$ less $CDmax_{40}$) and infant chest compression techniques (TT less TF) were reported as means with 95% confidence intervals [95% CI].

Results were statistically analysed by using either paired Student's *t*-tests or Wilcoxon's signed rank tests. Statistical significance was considered at $p < 0.05$ for all tests and all *p*-values were two-sided. All statistical analyses were performed using the SPSS 16.0 statistical software package (SPSS Inc., IL, USA). A minimum sample size of 32 participants was required to adequately detect a mean paired difference 0.5 times the standard deviation of the differences; assuming data normality, a two-sided significance level of <0.05 and >80% power.

3. Results

Forty certified EPLS instructors (22 female) participated in this study: 16 were resuscitation officers; 12 were doctors; eight were registered nurses; two were operating department practitioners and two were paramedics. The simulated chest compression quality measures observed by this study are illustrated against internationally recommended targets in Fig. 1.

For both the TT and TF techniques, the more "physiological" manikin design was observed to increase chest compression depths and reduce compression duty cycles (Tables 1 and 2). Subsequently, this improved the median proportion of chest compressions that complied with both the chest compression depth targets (i.e. 36.7–46 mm) and the compression duty cycle targets (i.e. 30–50%). Despite these improvements, however, overall compliance remained very poor for both $CDmax_{40}$ and $CDmax_{56}$, with <8% of all chest compressions simultaneously complying with all four internationally recommended targets.

At both $CDmax_{40}$ and $CDmax_{56}$, the TT technique was observed to achieve greater compression depths than the TF technique, whilst the TF technique both released the chest further and reduced the compression duty cycle (Tables 3 and 4). Consequently, at $CDmax_{40}$, this improved the median proportion of TT technique chest compressions that complied with chest compression depth targets and the median proportion of TF technique chest compressions that complied with compression duty cycle targets. At $CDmax_{56}$, however, this was found to improve the median proportion of TF technique chest compressions that complied with compression duty cycle targets only.

The maximum chest compression depths achieved by each participant for each technique are illustrated for both $CDmax_{40}$ and $CDmax_{56}$ in Fig. 2. On average, 33% TT technique and 7% TF technique chest compressions were observed to exceed the proposed thoracic over-compression criterion at $CDmax_{56}$ (mean paired difference [95%CI]: 26[15,37]%; $p < 0.001$), whilst no compressions exceeded this at $CDmax_{40}$. In total, 25 (62.5%) participants exceeded the proposed criterion at least once when providing TT technique chest compressions, whilst only 14 (35%) participants exceeded this with the TF technique. Two (5%) participants were further observed

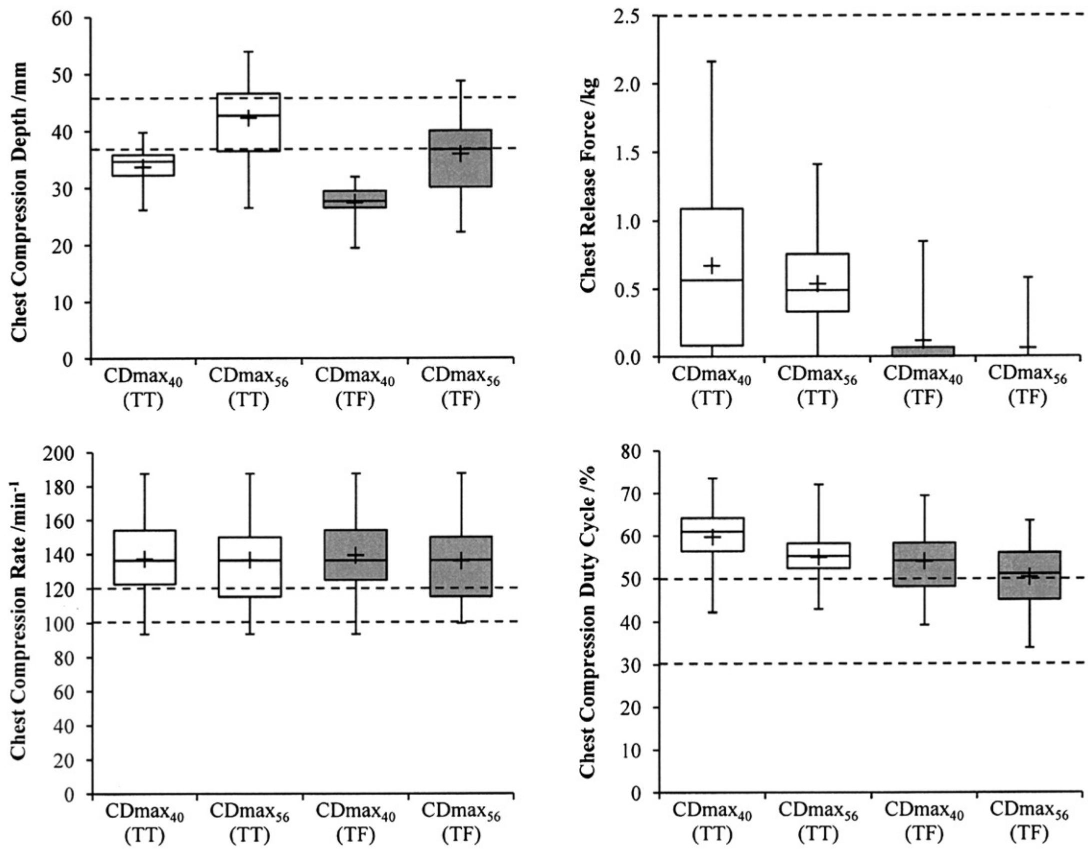

Fig. 1. Simulated chest compression quality measures, illustrated against internationally recommended targets, for both two-thumb (TT) and two-finger (TF) chest compressions using the 40 mm and 56 mm manikin compression depth settings (CDmax40 and CDmax56). Compression depth targets were 36.7–46 mm, release force targets were <2.5 kg, compression rate targets were 100–120 min^{-1} and duty cycle targets were 30–50%.

to exceed the thoracic over-compression criterion in 100% of all TT technique chest compressions.

4. Discussion

This study is the first to utilise a more "physiological" infant manikin design during simulated CPR, with results demonstrating improved chest compression depth and compression duty cycle compliance for both infant chest compression techniques. Despite these improvements, chest compression quality remained poor for both chest compression techniques, with <8% of all chest compressions complying with all four quality targets and both TT and TF chest compression techniques observed to over-compress the thorax.

An important consideration for quality chest compressions is to achieve adequate compression depths to maintain favourable haemodynamic outcomes.[21–24] When participants used the $CDmax_{40}$ manikin setting, only 7% of TT and 0% of TF chest compressions complied with target chest compression depths (i.e. 36.7–46 mm). This poor compliance is consistent with that

Table 1
Change in simulated chest compression quality measures and quality indices, between the 40 mm and 56 mm manikin compression depth settings ($CDmax_{40}$ and $CDmax_{56}$), for two-thumb chest compressions.

Two-thumb chest compression quality	$CDmax_{40}$	$CDmax_{56}$	Mean paired difference ($CDmax_{56}$ – $CDmax_{40}$)	*P*-value
Compression depths (CD)				
Mean compression depth/mm	34 ± 3	42 ± 7	9 [7,10]	***<0.001****
CD quality index (36.7–46 mm)/%	7 [0,18]	44 [2,68]	24 [8,41]	***0.005***†
Release forces (RF)				
Mean release force/kg	0.7 ± 0.6	0.5 ± 0.3	−0.1 [−0.3, 0.0]	0.064*
RF quality index (<2.5 kg)/%	100 [100,100]	100 [100,100]	0 [0,0]	0.4†
Compression rates (CR)				
Mean compression rate/cpm	137 ± 26	137 ± 24	−1 [−4,3]	0.71*
CR Quality Index (100–120 cpm)/%	2 [0,48]	2 [0,36]	0 [−7,6]	0.66†
Compression duty cycles (DC)				
Mean compression duty cycle/%	60 ± 7	55 ± 6	−5 [−6,−3]	***<0.001****
DC Quality index (30–50%)/%	0 [0,4]	7 [2,20]	10 [2,18]	***<0.001***†
Overall CPR quality index/%	0 [0,0]	0 [0,1]	3 [−1,6]	0.068†

Values are given as the mean value ± standard deviation, except quality indices which are given as the median value [inter-quartile range]. Differences are presented as mean paired differences [95% confidence intervals], with *p*-values calculated from two-sided paired samples Student's *t*-tests (*) or Wilcoxon's signed rank tests (†).

Table 2
Change in simulated chest compression quality measures and quality indices, between the 40 mm and 56 mm manikin compression depth settings ($CDmax_{40}$ and $CDmax_{56}$), for two-finger chest compressions.

Two-finger chest compression quality	$CDmax_{40}$	$CDmax_{56}$	Mean paired difference ($CDmax_{56} - CDmax_{40}$)	*P*-value
Compression depths (CD)				
Mean compression depth/mm	27 ± 3	36 ± 7	8 [7,10]	***<0.001****
CD quality index (36.7–46 mm)/%	0 [0,0]	34 [0,81]	39 [27,52]	***<0.001***†
Release forces (RF)				
Mean release force/kg	0.1 ± 0.2	0.1 ± 0.1	−0.1 [−0.1, 0.0]	0.13*
RF quality index (<2.5 kg)/%	100 [100,100]	100 [100,100]	0 [0,0]	0.32†
Compression rates (CR)				
Mean compression rate/cpm	139 ± 24	136 ± 24	−3 [−7,0]	0.081*
CR Quality index (100–120 cpm)/%	2 [0,32]	0 [0,53]	3 [−3,8]	0.54†
Compression duty cycles (DC)				
Mean compression duty cycle/%	54 ± 8	50 ± 7	−4 [−5,−2]	***<0.001****
DC quality index (30–50%)/%	19 [2,73]	38 [5,88]	12 [1,23]	***0.004***†
Overall CPR quality index/%	0 [0,0]	0 [0,1]	7 [2,12]	***0.005***†

Values are given as the mean value ± standard deviation, except quality indices which are given as the median value [inter-quartile range]. Differences are presented as mean paired differences [95% confidence intervals], with *p*-values calculated from two-sided paired samples Student's t-tests (*) or Wilcoxon's signed rank tests (†).

Table 3
Change in simulated chest compression quality measures and quality indices, between the two-thumb (TT) and two-finger (TF) chest compression techniques, for compressions performed at the 40 mm maximum chest compression depth setting ($CDmax_{40}$).

$CDmax_{40}$ chest compression quality	TT technique	TF technique	Mean paired difference (TT − TF)	*P*-value
Compression depths (CD)				
Mean compression depth/mm	34 ± 3	27 ± 3	6 [5,7]	***<0.001****
CD quality index (36.7–46 mm)/%	7 [0,18]	0 [0,0]	17 [8,26]	***<0.001***†
Release forces (RF)				
Mean release force/kg	0.7 ± 0.6	0.1 ± 0.2	0.6 [0.4, 0.7]	***<0.001****
RF quality index (<2.5 kg)/%	100 [100,100]	100 [100,100]	0 [0,0]	0.18†
Compression rates (CR)				
Mean compression rate/cpm	137 ± 26	139 ± 24	−2 [−5,1]	0.12*
CR quality index (100–120 cpm)/%	2 [0,48]	2 [0,32]	0 [−5,4]	0.93†
Compression duty cycles (DC)				
Mean compression duty cycle/%	60 ± 7	54 ± 8	6 [4,7]	***<0.001****
DC quality index (30–50%)/%	0 [0,4]	19 [2,73]	−22 [−30,−14]	***<0.001***†
Overall CPR quality index/%	0 [0,0]	0 [0,0]	1 [0,2]	0.14†

Values are given as the mean value ± standard deviation, except quality indices which are given as the median value [inter-quartile range]. Differences are presented as mean paired differences [95% confidence intervals], with *p*-values calculated from two-sided paired samples Student's *t*-tests (*) or Wilcoxon's signed rank tests (†).

reported in previous simulated infant CPR studies and has raised concerns over whether this reflects current clinical practice during infant CPR.[7–11] A significant increase in compression depths were recorded, however, when participants performed chest compressions using the more "physiological" CDmax setting. This resulted in 44% of TT and 34% of TF chest compressions complying with target depths, whilst 33% of TT and 7% of TF chest compressions exceeded the thoracic over-compression criterion

Table 4
Change in simulated chest compression quality measures and quality indices, between the two-thumb (TT) and two-finger (TF) chest compression techniques, for compressions performed at the 56 mm maximum chest compression depth setting ($CDmax_{56}$).

$CDmax_{56}$ chest compression quality	TT technique	TF technique	Mean paired difference (TT − TF)	*P*-value
Compression depths (CD)				
Mean compression depth/mm	42 ± 7	36 ± 7	6 [5,8]	***<0.001****
CD quality index (36.7–46 mm)/%	44 [2,68]	34 [0,81]	2 [−14,18]	0.63†
Release forces (RF)				
Mean release force/kg	0.5 ± 0.3	0.1 ± 0.1	0.5 [0.4, 0.6]	***<0.001****
RF quality index (<2.5 kg)/%	100 [100,100]	100 [100,100]	0 [0,0]	0.32†
Compression rates (CR)				
Mean compression rate/cpm	137 ± 24	136 ± 24	1 [−2,3]	0.65*
CR quality index (100–120 cpm)/%	2 [0,36]	0 [0,53]	−3 [−8,2]	0.99†
Compression duty cycles (DC)				
Mean compression duty Cycle/%	55 ± 6	50 ± 7	5 [3,6]	***<0.001****
DC quality index (30–50%)/%	7 [2,20]	38 [5,88]	−25 [−34,−15]	***<0.001***†
Overall CPR quality index/%	0 [0,1]	0 [0,1]	-4 [−9,2]	0.43†

Values are given as the mean value ± standard deviation, except quality indices which are given as the median value [inter-quartile range]. Differences are presented as mean paired differences [95% confidence intervals], with *p*-values calculated from two-sided paired samples Student's *t*-tests (*) or Wilcoxon's signed rank tests (†).

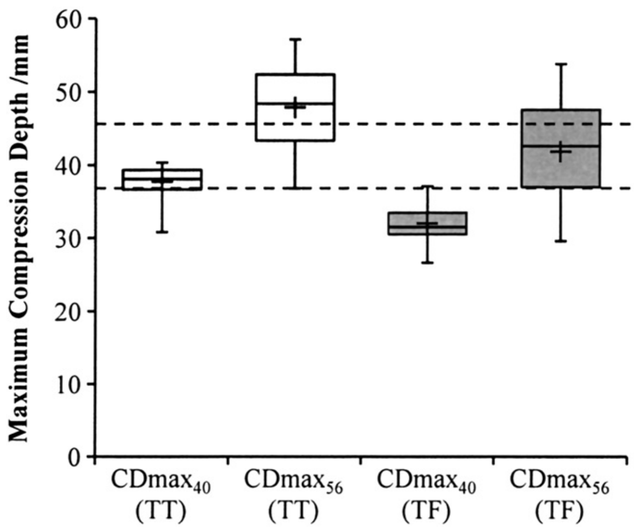

Fig. 2. Maximum chest compression depths, illustrated against the chest compression depth target (36.7 mm) and the proposed thoracic over-compression criterion (46 mm), for both two-thumb (TT) and two-finger (TF) chest compressions using the 40 mm and 56 mm manikin compression depth settings ($CDmax_{40}$ and $CDmax_{56}$).

(46 mm). By allowing chest compressions to achieve and surpass recommended depths, the more "physiological" manikin design may therefore encourage improved chest compression depths during simulated infant CPR and raise awareness of the potential for thoracic over-compression and thus injury.

Delivering effective compression rates, release forces and compression duty cycles during infant CPR are also essential to achieving optimal haemodynamics.[4–6,20,25–27] Previous research reports the incomplete release of the chest in older paediatric subjects and excessive compression rates during simulated infant CPR,[8,9,11,28,29] whilst compression duty cycles have never been quantified during paediatric CPR. The excessive compression rates reported throughout this study support this research, whilst over 99% of chest compressions were observed to comply with chest release force targets. Chest compressions were further characterised by prolonged duty cycles when participants performed chest compressions using the original manikin. When participants used the more "physiological" manikin CDmax design, however, a significant improvement in duty cycle compliance was recorded for both chest compression techniques.

The TT chest compression technique is currently favoured by guideline recommendations during infant CPR, with previous research concluding that the TT technique achieved deeper and more consistent compression depths than the TF technique.[7–11] In this study, however, the use of the TT technique increased the compression depths, release forces and compression duty cycles provided by the participant during simulated infant CPR, regardless of manikin design. When using the original manikin design, this resulted in an improved compliance with chest compression depth targets and a reduced compliance with compression duty cycle targets. When using the more "physiological" manikin design, however, the use of the TT technique reduced compliance with the compression duty cycle targets and increased the likelihood of thoracic over-compression, whilst the use of the TF technique increased the under-compression of the thorax.

Study limitations prevent a direct translation from the simulated CPR environment into clinical practice. A CDmax of 56 mm was used in this study to represent the internal AP chest depth of a 3 month old male infant. When considering the presence of intra-thoracic organs, however, it may be hypothesised that chest compression depths would, in fact, be further limited. The chest compression targets used in this study were derived from a combination of human subject, radiographic and animal surrogate studies,[1,2,4–6,20] which reflects the current scientific evidence guiding infant chest compression targets.[3] The criterion for thoracic over-compression was based upon consensus opinion from two peer reviewed journal articles.[12,13] Additional limitations include the observation of participants, that participants were not subjected to any additional clinical distraction or stresses, and that they were using a manikin.

This study confirms that a more "physiological" infant CPR manikin design enables the delivery of quality chest compression depths and highlights thoracic over-compression during simulated infant CPR. Further research is required, however, to improve our understanding of infant thoracic biomechanics, and its relation to both infant CPR quality and thoracic trauma, before informing current CPR guidelines and developing future CPR training manikins.

5. Conclusions

This study is the first to develop a more "physiological" manikin design that enabled resuscitators to perform chest compressions to greater depths. This manikin design improved the compliance of both chest compression depths and compression duty cycles with internationally recommended targets, whilst introducing the potential risks of thoracic over-compression during infant CPR. Despite this, overall chest compression compliance during simulated infant CPR remained very poor primarily due to chest compression rates that were too fast. The use of this modified manikin design as a training aid may ultimately encourage resuscitators to habitually perform deeper chest compressions, thus improving current infant chest compression quality in clinical practice.

Conflict of interest statement

There are no competing financial interests, organisational ties or other relationships which may create an actual or apparent conflict of interest in regard to our study.

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Simulation and education

Real-time feedback can improve infant manikin cardiopulmonary resuscitation by up to 79%—A randomised controlled trial

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ABSTRACT

Setting: European and Advanced Paediatric Life Support training courses.
Participants: Sixty-nine certified CPR providers.
Interventions: CPR providers were randomly allocated to a 'no-feedback' or 'feedback' group, performing two-thumb and two-finger chest compressions on a "physiological", instrumented resuscitation manikin. Baseline data was recorded without feedback, before chest compressions were repeated with one group receiving feedback.
Main outcome measures: Indices were calculated that defined chest compression quality, based upon comparison of the chest wall displacement to the targets of four, internationally recommended parameters: chest compression depth, release force, chest compression rate and compression duty cycle.
Results: Baseline data were consistent with other studies, with <1% of chest compressions performed by providers simultaneously achieving the target of the four internationally recommended parameters. During the 'experimental' phase, 34 CPR providers benefitted from the provision of 'real-time' feedback which, on analysis, coincided with a statistical improvement in compression rate, depth and duty cycle quality across both compression techniques (all measures: $p < 0.001$). Feedback enabled providers to simultaneously achieve the four targets in 75% (two-finger) and 80% (two-thumb) of chest compressions.
Conclusions: Real-time feedback produced a dramatic increase in the quality of chest compression (i.e. from <1% to 75–80%). If these results transfer to a clinical scenario this technology could, for the first time, support providers in consistently performing accurate chest compressions during infant CPR and thus potentially improving clinical outcomes.

1. Introduction

Survival rates following paediatric cardiac arrest are extremely low.[1–4] A return of spontaneous circulation (ROSC) is achieved in approximately 60% of paediatric patients following in-hospital cardiac arrest, with newborns and infants (i.e. <1 year olds) having the greatest likelihood of neurologically-intact survival (~20%).[1,2] By direct comparison, only 2–9% of such patients will achieve neurological survival if they suffer an out-of-hospital cardiac arrest.[3–9]

The importance of high quality chest compressions during infant cardiopulmonary resuscitation (CPR) is recognised by both the European and UK Resuscitation Councils.[10,11] Recent publications, however, describe the poor chest compression performance of Advanced Paediatric Life Saver (APLS)-certified *instructors* during simulated infant CPR, typified by inconsistent chest compression depths, excessive compression rates and prolonged compression duty cycles.[12–15] Even when utilising a manikin with enhanced "physiological" characteristics, APLS-certified *instructors* could still only achieve an *overall* chest compression quality <1% when compared to the targets of the four internationally recommended parameters (chest compression depth, chest compression rate, duty cycle, release force; summarised in *Online Table 1* and schematically in Fig. 1).[15]

Supplementary material related to this article found, in the online version, at http://dx.doi.org/10.1016/j.resuscitation.2013.03.029.

Whilst the effect of instantaneous performance feedback during adult CPR has previously been reported, this study is the first to investigate the hypothesis that instantaneous feedback will improve the performance of chest compression quality during simulated, *infant* CPR.

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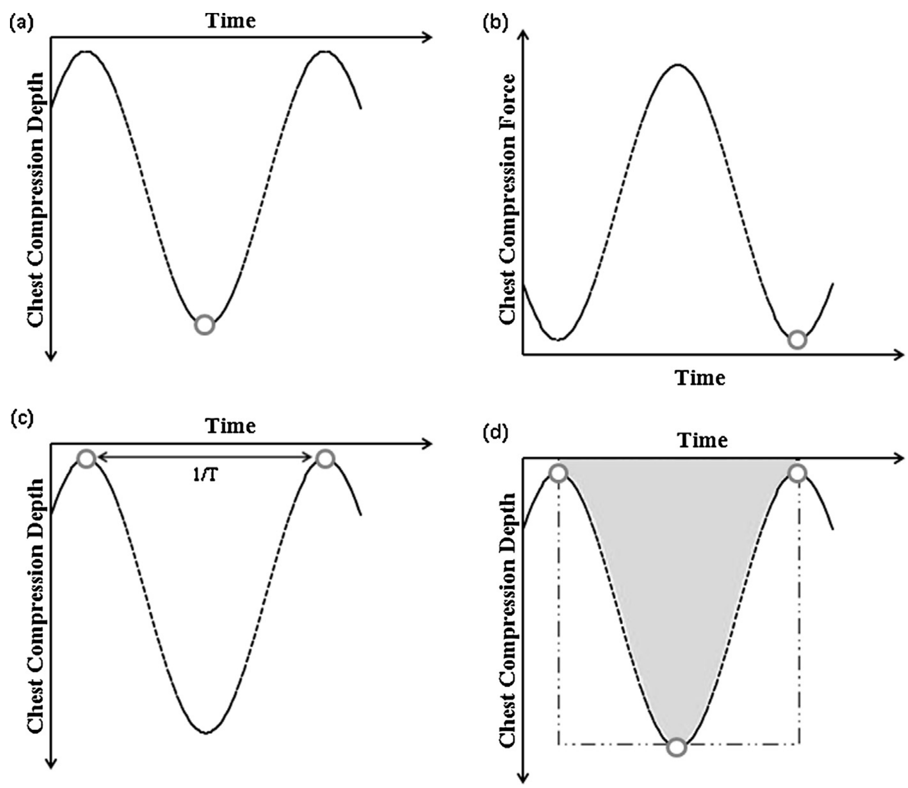

Fig. 1. Example chest deflection curves defining (a) chest compression depths, (b) chest release forces, (c) chest compression rates and (d) compression duty cycles. Each chest compression cycle is represented by a dashed line, with the circular markers defining the point/range reported for each internationally recommended target. The shaded region represents the area under the chest deflection curve and the dashed-dotted box represents the product of the chest compression depth and the chest compression cycle time.

2. Methods

Sixty-nine European Paediatric Life Support (EPLS) and/or APLS certified CPR providers were recruited from seven EPLS/APLS training courses, and were evaluated when performing two-thumb (**TT**) and two-finger (**TF**) technique chest compressions during simulated, chest compression-only, infant CPR. The flow of participants through the study is described in Fig. 2. Providers were excluded if there was >4 years since certification.

This study utilised a commercially available CPR manikin (Laerdal® ALS Baby, Laerdal Medical, Stavanger, Norway), representing a three month old 5 kg male infant. The manikin had previously been modified to enable a more “physiological” maximum chest compression depth (i.e. an increase from 40 mm to 56 mm),[15,16] whilst maintaining a chest compression stiffness consistent with that of the original design.[15] The manikin was instrumented to measure chest deflections through analysing the output voltage of an infra-red distance measuring sensor (Sharp Corporation, Osaka, Japan). This data was continually recorded at 50 Hz onto a laptop computer, using data acquisition hardware and software (National Instruments; TX, USA).

Real-time feedback software was developed in-house using the Labview computer programme (National Instruments; TX, USA). A real-time chest deflection ‘trace’ was presented to providers on a laptop screen, with specific zones demarcated to indicate achievement of the appropriate compression depth (CD) and release force (RF) targets (available as an *online figure*). An audible and visual metronome provided providers with information describing the required compression rate (CR). Providers were exposed to a short period (<20 s) of software training prior to performing each chest compression technique.

Supplementary material related to this article found, in the online version, at http://dx.doi.org/10.1016/j.resuscitation.2013.03.029.

CPR providers were allocated to either the ‘no feedback’ or ‘feedback’ group, before being assigned to first perform either the **TT** or **TF** chest compression technique, both based on a pre-randomised order generated by the principal investigator using an Excel spreadsheet. All providers performed continuous chest compression-only CPR without feedback for 60 s then, after a period of full recovery, performed CPR using the alternative technique. This was termed the ‘baseline’ phase of the investigation. The sequence of chest compressions was then repeated, either with or without the introduction of feedback depending upon the earlier allocation, forming the ‘experimental’ phase of the study. Prior to the experimental stage, group allocation was concealed from both the provider and investigator; however, as with similar feedback studies, the nature of the investigation meant that blinding was not possible after this stage.

Overall chest compression quality was defined by the proportion of **TT** and **TF** chest compressions that simultaneously achieved the four targets.[14,15] Secondary outcome measures included the relative quality of each parameter, the proportion of chest compressions that over or under compressed the thorax, or were too fast, or too prolonged. Descriptive data for both the primary and secondary outcomes are presented either as means with standard deviations (±SD), or as medians with inter-quartile ranges [IQR], whilst mean differences between the no-feedback and feedback groups are reported with 95% confidence intervals [95% CI] for each chest compression technique (**TT** and **TF**). Results were statistically analysed by using either independent Student *T*-tests or Mann–Whitney *U* tests. Statistical significance was considered at $p < 0.05$ for all tests and all *p*-values were two-sided. All statistical

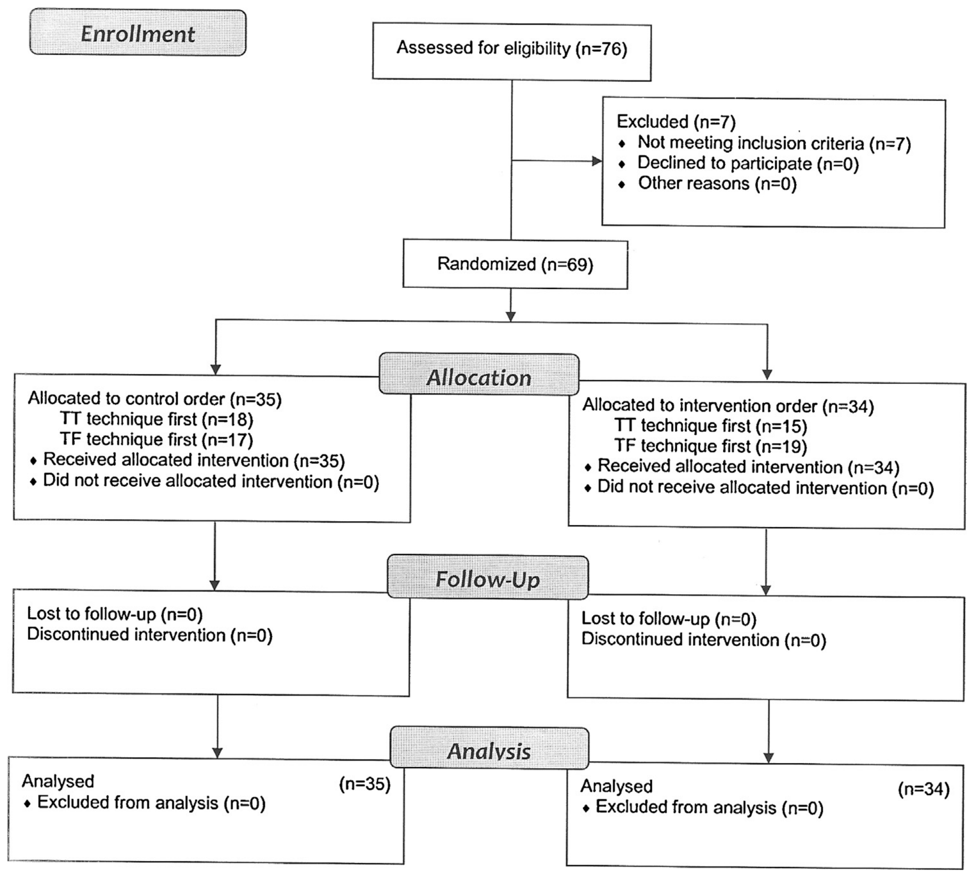

Fig. 2. CONSORT flow diagram describing the progression of participants through our study.

analyses were performed using the SPSS 16.0 statistical software package (SPSS Inc., IL, USA). A minimum sample size of 33 participants per group was required to adequately detect a mean paired difference 0.7 times the standard deviation of the differences; assuming data normality, a two-sided significance level of <0.05 and >80% power.

3. Results

The demographics of the 69 APLS and/or EPLS certified CPR providers that participated in this study are available in *Online Table 2*.

Supplementary material related to this article found, in the online version, at http://dx.doi.org/10.1016/j.resuscitation.2013.03.029.

3.1. 'Baseline' phase

Less than 1% of chest compressions simultaneously achieved the four internationally recommended targets, with a relatively consistent performance of **TT** and **TF** chest compressions between the 'no-feedback' and 'feedback' groups during the baseline phase of chest compressions (**TT**: $p = 0.59$; **TF**: $p = 0.051$; *Online Table 3*).

Supplementary material related to this article found, in the online version, at http://dx.doi.org/10.1016/j.resuscitation.2013.03.029.

3.2. 'Experimental' phase

The provision of real-time feedback coincided with 75% of **TF**, and 80% of **TT**, technique chest compressions simultaneously achieving all four targets (*Online Table 4*). The improvements evident in the *overall* quality (i.e. between the feedback and no-feedback groups in the experimental phase) of both chest compression techniques were highly significant (**TT** and **TF**: $p < 0.001$, *Online Table 4*) and summarised in Fig. 3.

Supplementary material related to this article found, in the online version, at http://dx.doi.org/10.1016/j.resuscitation.2013.03.029.

3.2.1. Chest compression depth

Providers who received real-time feedback demonstrated increased CD quality (Fig. 4), thereby performing the vast majority of **TT** chest compressions within the optimal range. This is represented by a highly significant increase ($p < 0.001$) in *CD* quality from

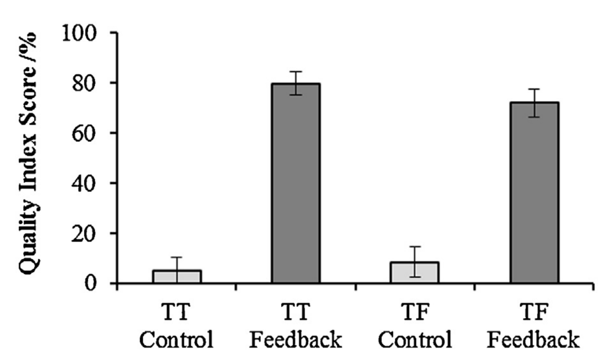

Fig. 3. Overall quality index scores for the two-thumb (**TT**) and two-finger (**TF**) chest compression techniques as performed by both the feedback and control groups at the experimental stage. Data are presented as mean values with 95% confidence intervals.

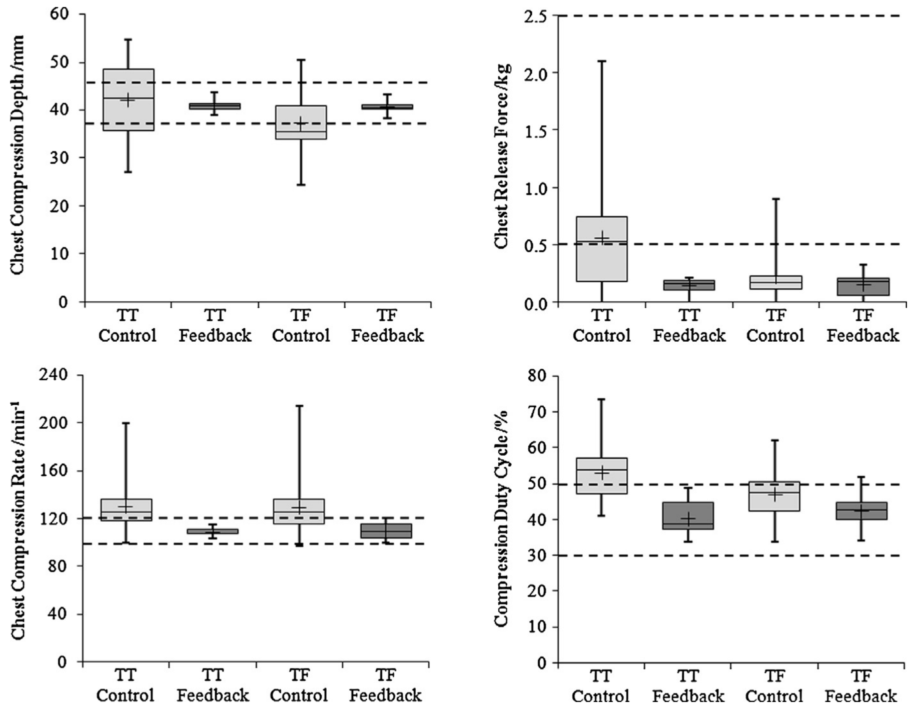

Fig. 4. Simulated chest compression quality measures, illustrated against evidence based quality targets, for both two-thumb (**TT**) and two-finger (**TF**) chest compressions, as performed by the feedback and control groups at the experimental stage. Chest compression quality targets are illustrated by dashed lines. Compression depth targets were 36.7–46 mm, release force targets were <2.5 kg and <0.5 kg, compression rate targets were 100–120 min^{-1} and duty cycle targets were 30–50%.

20% to 99% for **TT** chest compressions (*Online Table 4*). Feedback coincided with a significant improvement ($p < 0.001$) in the quality of **TF** chest compressions, increasing from 21% to 97% (*Online Table 4*). During the experimental phase 33% of **TT**, and 12% of **TF**, chest compressions exceeded the proposed thoracic over-compression criterion in the 'no feedback' group, whilst only 1% of **TT** and **TF** technique chest compressions exceeded this in the 'feedback' group.

3.2.2. Release force

Providers consistently achieved the required RF (i.e. <2.5 kg) across both compression techniques, with and without feedback (*Online Table 4*). The complete release of the chest (i.e. <0.5 kg), however, was significantly improved for the **TT** technique with the provision of feedback (47–99%; $p < 0.001$).

3.2.3. Chest compression rate

Chest compression rate was consistently performed too quickly without feedback. The mean and median value for both **TT** and **TF** chest compression techniques exceeded the internationally recommended targets (*Online Table 4*), whilst some providers performed chest compressions at approximately twice the recommended rate (Fig. 4). The provision of feedback coincided with a significant reduction in the *CR* of both **TT** and **TF** ($p < 0.001$); hence, the *CR* quality (*Online Table 4*) increased significantly (each: $p < 0.001$) from 20% to 92% (**TT**) and 34% to 87% (**TF**).

3.2.4. Compression duty cycle

Chest compression duty cycles were prolonged when providers compressed without feedback, thereby recording a *DC* that exceeded the internationally recommended targets. The *DC* quality improved significantly ($p < 0.001$) from 18% to 93% (**TT**) and 72% to 93% (**TF**) on the provision of feedback (*Online Table 4*).

4. Discussion

This study is unique in demonstrating how 'real-time' feedback during simulated infant CPR leads to a dramatic improvement in quality, with 75% (**TF**) and 80% (**TT**) of chest compressions simultaneously achieving the four, internationally recommended targets. This compares to an *overall* quality <1% when performing chest compressions without feedback.

Providers achieved relatively high *CD* quality (∼20%) versus other data when performing chest compressions without feedback (*Online Table 4*),[14] although this is likely to have been due to the greater compression depths achievable through using the "physiological" manikin.[14] Real-time feedback encouraged the performance of **TT** and **TF** chest compressions to a *consistent* depth, whilst also improving the *accuracy* of the **TF** technique (the **TT** technique was performed accurately without feedback). The improved *CD* quality achieved with feedback reduced the extent of excessive chest compressive, thus almost negating the theoretical risk of iatrogenic heart and great vessel injury.[16] Improved quality was also demonstrated by *deeper* compressions, which are recognised to achieve improved haemodynamics.[17–20] Subsequently, the provision of feedback appears vital in ensuring that providers achieve the very narrow therapeutic window between under and over-compression (i.e. <1 cm) and, as noted elsewhere, provides CPR providers with an ability to retain this performance despite the effects of fatigue.[21]

Excessive chest compression rates have been widely reported during the performance of **TT** and **TF** simulated infant CPR.[14,15,22] The results of the chest compressions performed by the 'no-feedback' group correlate with this trend, with only 20% (**TT**) and 42% (**TF**) of compressions meeting the target and compression rates exceeding 200 min^{-1} recorded in some instances. Provision of the flashing and audible metronome on the feedback software coincided with a highly statistical improvement and providers delivering chest compressions within the target range. This reduction in rate, if transferable to clinical CPR scenarios, could allow for optimal venous return in to the heart prior to recirculation, which the International Liaison Committee for Resuscitation (ILCOR) has previously stipulated is a criterion for maximising the likelihood of a successful clinical outcome.[23]

A successful duty cycle is also important in ensuring sufficient opportunity for cardiac refill prior to the next compression. Infant-focussed manikin studies have previously reported duty cycles exceeding the 50% upper threshold,[14,15] which was consistent with the no-feedback **TT** compressions reported in this study (*DC* quality = 18%); however, no-feedback performance of **TF** CPR was *accurate* (*DC* quality = 72%). Whilst the feedback software did not provide any information specific to enhancing the duty cycle performance, significant improvements (**TT** and **TF**: $p < 0.001$) in *DC* quality were achieved in the delivery of both chest compression techniques (i.e. **TT** and **TF** increased to 93%).

Our data showed no differences in quality between the two provider groups at the baseline stage; however, designing this study as a randomised controlled trial ensures that the differences in chest compression performance during the experimental phase are not due to biasing of the two experimental cohorts. As all providers were EPLS and/or APLS *instructors*, it can be inferred that our base-line data represents a ‘best-case’ scenario versus chest compression quality delivered by a non-expert. It is also possible, however, that the expertise of these providers may have hindered their performance, by perceiving our experimental setup to be too contrived, although this was mitigated as far as possible by embedding our investigation within the formal EPLS/APLS training sessions.

Real-time feedback has previously been successfully transferred to adult clinical practice, enhancing CPR performance. Whilst results typically report a significant improvement in chest compression quality, this appears not to influence the likelihood of ROSC or discharge.[23–25] Closer investigation, however, indicates that this adult data is typically supported by relatively weak statistical significance (i.e. that there is relatively little difference between the baseline and feedback data) versus those reported in this study.[21,23–25] Hence, it is anticipated that the dramatic improvements in chest compression quality reported in infant simulated CPR – which were typically significant to $p < 0.001$, have a greater potential to influence clinical outcome should they be transferable to a clinical scenario.

Our baseline data provides a strong indication that even APLS/EPLS trained CPR providers are currently unable to perform chest compressions in the manner prescribed by bodies such as the International Liaison Committee for Resuscitation (ILCOR) and the European Resuscitation Council. Given that neurologically intact survival following infant CPR remains poor despite the publication of multiple guidelines, it is proposed that only when the majority of resuscitators are actually achieving these prescribed targets will publication of further guidelines have a significant impact on survival. Hence, there is an obvious need for the introduction of technology such as that presented in our study.

5. Conclusion

The study demonstrated that the provision of real-time feedback during simulated infant CPR coincided with a dramatic improvement in *overall* infant chest compression quality (from 1% to 75–80%). Should these result transfer to clinical practice, then this technology will enable CPR providers to perform the vast majority of chest compressions to within the targets of internationally recommended parameters, thereby having great potential to influence survival following infant cardiac arrest.

Conflict of interest statement

Dr. Ian Maconochie is Co-chair of the Paediatric Task Force for ILCOR 2015, and a member of the European and the UK Resuscitation Councils. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Acknowledgements

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Association of Paediatric Emergency Medicine

G186 CHEST COMPRESSION PERFORMANCE DURING INFANT CPR

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10.1136/adc.2011.212563.200

Aims The 2010 International Liaison Committee of Resuscitation (ILCOR) guidelines highlighted the need to perform quality chest compressions during paediatric cardiopulmonary resuscitation to improve current outcomes. The guidelines emphasised infant chest compression target rates of 100–120 cpm, depths of 4cm and complete release. This study aims to determine the performance of two-thumb (TT) and two-finger (TF) chest compressions against these guideline targets.

Methodology A randomised, cross-over study was designed to investigate rescuer performance during TT and TF chest compressions. 12 certified advanced paediatric life support instructors performed each technique for 2 min on a commercially available infant CPR training manikin. The manikin was instrumented with a linear potentiometer, allowing the measurement of anteroposterior chest deflections. Participants were instructed to perform continuous compressions, without ventilations, and neither technique was refreshed or coached. Chest compression rates (CR), depths (CD) and residual leaning depths (remaining depth during chest release phase; LD) were recorded. Normalised performance scores were developed quantifying how accurately (A_{CR}, A_{CD}, A_{LD}) and consistently (C_{CR}, C_{CD}, C_{LD}) individuals performed each target relative to the ILCOR guidelines. Overall individual performance scores (A_{CPR}, C_{CPR}) were averaged from their respective scores, and mean scores describe cohort performance. Scores ≤1 indicate that chest compressions were more comparable to the guideline targets. Shapiro-Wilk tests evaluated distribution normality and results were statistically compared using paired parametric (paired Student's t test) or non-parametric (Wilcoxon signed rank test) tests.

Results Performance scores for each technique are presented in figure 1. Relatively poor accuracy scores are demonstrated by both techniques, with the exception of TF technique leaning depths. While it can be observed that TT chest compressions were performed with greater accuracy (A_{CPR}: 1.70 vs 1.85) and consistency (C_{CPR}: 0.74 vs 0.90) than TF chest compressions, neither technique was performed to ILCOR guidelines.

Conclusions The performance of the TT technique showed a greater compliance with the 2010 ILCOR guidelines than the TF technique; however, guideline targets were rarely met by either technique. The results of this manikin-based study indicate that there is a need to improve the accuracy of both chest compression techniques during infant CPR, which could potentially improve survivability.

Measure	TT Technique / Mean (S.D.)	TF Technique / Mean (S.D.)	*p*-value	Interpretation
CR /cpm	126.1 (23.7)	131.7 (25.5)	0.006■	$CR_{TF}>CR_{TT}$; both > CR_{target}
CD /mm	27.32 (2.48)	21.05 (5.45)	0.001■	$CD_{TT}>CD_{TF}$; both < CD_{target}
LD /mm	3.81 (2.57)	1.65 (1.62)	0.019*	$LD_{TT}>LD_{TF}$; LD_{TT} > CR_{target}
A_{CR}	2.38 (1.65)	2.65 (1.75)	0.182*	TT≈TF; both poor A_{CR}
C_{CR}	1.38 (0.32)	1.75 (0.63)	0.009■	TT<TF; both poor C_{CR}
A_{CD}	1.46 (0.38)	2.43 (0.64)	0.001■	TT<TF; both poor A_{CD}
C_{CD}	0.33 (0.09)	0.64 (0.28)	0.004■	TT<TF; both good C_{CD}
A_{LD}	1.25 (0.70)	0.48 (0.30)	0.003*	TF<TT; TF only, good A_{LD}
C_{LD}	0.52 (0.26)	0.30 (0.20)	0.004*	TF<TT; both good C_{LD}
A_{CPR}	1.70 (0.53)	1.85 (0.83)	0.209*	TT<TF; both poor A_{CPR}
C_{CPR}	0.74 (0.15)	0.90 (0.28)	0.041*	TT<TF; both good C_{CPR}

■ Paired Student's t-test
* Wilcoxon signed rank test

Abstract G186 Figure 1 Table of results comparing measures and performance scores between two-thumb (TT) vs two-finger (TF) techniques

P09 THE USE OF COCHRANE REVIEWS IN CLINICAL GUIDELINES FOR RESPIRATORY DISEASE IN CHILDREN IN THE UNITED KINGDOM – A SYSTEMATIC REVIEW

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Aims Cochrane reviews (CRs) summarise best evidence and should be used for guideline recommendations. We assessed the use of CRs in UK guidelines for lower respiratory disease in children and the agreement between the guideline recommendations and the CRs.

Methods We searched Embase, Pubmed and the websites of guideline commissioning agencies for clinical guidelines. For each guideline recommendation, we identified relevant CRs in the Cochrane Library. We noted whether the CRs were cited in the guidelines and if they agreed with the guideline recommendations. Two investigators independently assessed CRs for relevance and agreement. We investigated the influence of the guideline commissioning agency and the topic, upon whether CRs were cited and whether their conclusions were followed. We investigated factors influencing the use of CRs, using logistic regression.

Results We identified 21 guidelines which made 1025 recommendations, of which 555 were recommendations for treatment of lower respiratory disease in children. For 115 of these 555 recommendations (21%) we identified a CR which could inform the recommendation. Approximately, one third of these recommendations (40/115) did not use any of the available CRs or used only some. The guideline commissioner had a significant influence on the use of CRs ($p = 0.03$), with BTS guidelines performing best. Guidelines on some topics eg cystic fibrosis were significantly more likely to cite CRs than others eg asthma ($p = 0.007$). In 20/115 guideline recommendations there was not full agreement with the CR Conclusion 9 (8%) disagreed, 6 (5%) partial agreement and 5 (4%) the guideline made a strong recommendation not supported by the CR.

Conclusion In spite of the work of the Cochrane collaboration, there are still many treatment decisions where there is no systematic review to inform guideline recommendations. However, we have shown that, even where a CR exists, guideline writers may not make use of it or may make recommendations contrary to the findings of the review. Guideline writers should describe their search strategy and reasons for not including high quality evidence.

P10 SURVEILLANCE OF HYPOCALCAEMIC SEIZURES SECONDARY TO VITAMIN D DEFICIENCY IN CHILDREN IN THE UK

doi:10.1136/archdischild-2013-304107.010

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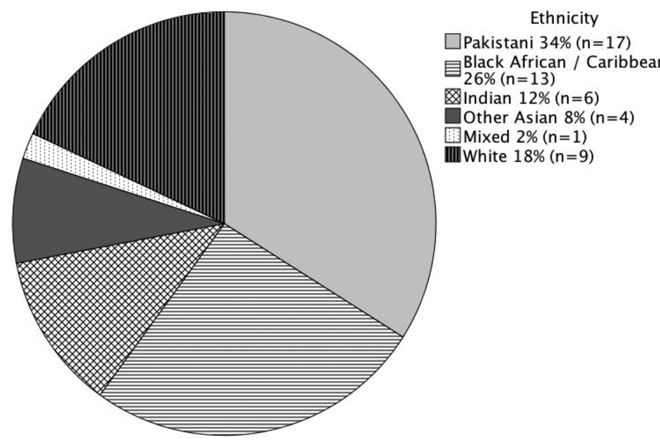
Background Reports suggest that rickets is an increasing concern among children in the UK, despite national recommendations for vitamin D supplementation during pregnancy and early childhood. However, there is limited epidemiological data to quantify these concerns, existing studies being limited to regional case series.

Methods Prospective national surveillance of hypocalcaemic seizures secondary to vitamin D deficiency in children aged 0–15 years, across the UK and Ireland via the British Paediatric Surveillance Unit (BPSU) system. We report results for the first 13 months of surveillance (September 2011 to September 2012).

Results 70 case notifications were received; 44 were confirmed cases, 6 probable cases, 17 reported in error or duplicates, and 3 unconfirmed cases for which details are pending. 90% of the 50 confirmed and probable cases were infants ($n = 45$), with three cases aged 1 year (6%) and two aged 14 years (4%). This equates to an incidence of 5.2 per 100,000 in infants. There was a male predominance of 76% ($n = 38$). Ethnic distribution of cases is shown in the figure 1. 60% of children ($n = 30$) had multiple seizures, and 24% ($n = 11$) had seizures lasting > 10 minutes. 66% of cases did not exhibit any other clinical features of vitamin D deficiency ($n = 33$), 26% had clinical rickets ($n = 13$), and 8% had failure to thrive ($n = 4$). None of the children had fractures or intracranial haemorrhage. I.v. calcium gluconate was given in 48% of cases ($n = 24$) and anti-seizure medication in 26% ($n = 13$), with 42% ($n = 21$) not receiving any acute treatment. There were no deaths, and only one child had sequelae on discharge; an extravasation burn from i.v. calcium gluconate.



Abstract P10 Figure 1 Distribution of cases by ethnicity

Conclusions Although a relatively uncommon presentation of vitamin D deficiency, between September 2011 to September 2012 approximately one child has a seizure secondary to vitamin D deficiency per week in the UK. This suggests that current implementation of public health policy is not successful at preventing complications of severe vitamin D deficiency in children. Further studies are required to investigate the epidemiology of rickets more broadly in the UK.

P11 CAN REAL-TIME PERFORMANCE FEEDBACK IMPROVE CHEST COMPRESSION QUALITY DURING SIMULATED INFANT CPR? A RANDOMISED CONTROLLED TRIAL

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Aims Current International Liaison Committee on Resuscitation (ILCOR) guidelines emphasise the provision of high quality chest compressions during infant cardiopulmonary resuscitation (CPR). Recent research, however, reports that <1% of all chest compressions achieve all four internationally recommended quality targets during simulated infant CPR. This study aimed to determine if 'real-time performance feedback' improved the quality of chest compressions provided during simulated infant CPR.

Methods Sixty-nine certified European and Advanced Paediatric Life Support (EPLS and APLS) training course instructors were recruited from seven EPLS/APLS training courses. Instructors were randomly allocated to either a 'no-feedback' or 'feedback' group, and performed 60 seconds of two-thumb (TT) and two-finger (TF) chest compressions on a "physiological" CPR manikin instrumented to measure chest deflections. Baseline data were recorded for both groups without feedback, before chest compressions were repeated in the experimental phase with the 'feedback' group receiving real-time performance feedback. Chest compression depths, chest release forces, chest compression rates and compression duty cycles were recorded for all participants. Quality indices were calculated to report the proportion of chest compressions that achieved internationally recommended quality targets for each measure, with an overall quality index calculated to report the proportion of chest compressions that simultaneously achieved all four quality targets. Results were compared between the 'no-feedback' and 'feedback' groups.

Results Baseline data were consistent with other studies, with < % of chest compressions simultaneously achieving all four internationally recommended quality targets. During the experimental stage (Table 1), the provision of real-time performance feedback improved the quality of the chest compression depths, chest compression rates and compression duty cycles provided by both techniques (all measures: $p < 0.001$). This enabled the 'feedback' group to simultaneously achieve all four quality targets in 75% of TF and 80% of TT technique chest compressions, whilst <1% of chest compressions achieved this for the 'no-feedback' group.

Conclusions Real-time performance feedback considerably increased the quality of chest compressions provided during simulated infant CPR. If these results transfer into clinical practise this technology could, for the first time, support resuscitators in performing high quality chest compressions during infant CPR and thus potentially improve future outcomes.

P12 CHILD DEATHS DUE TO INJURY IN FOUR UK COUNTRIES: 1980 TO 2010

doi:10.1136/archdischild-2013-304107.012

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Aims To examine trends in child deaths due to injury England, Scotland, Wales and Northern Ireland between 1980 and 2010.

Methods Data from death certificates from children who died aged 28 days to 18 years between 1980 and 2010 were obtained from the national statistics agencies in the four countries. Injury deaths, including poisoning, was defined by an external cause code (from the International Classification of Diseases) recorded as the underlying cause of death. We estimated rates of injury deaths per 100,000 resident children by sex, age group (28 days to nine years, and 10 to 18 years), time period, country of residence and type of injury (accidental or non-accidental). Mortality rates were adjusted for reporting delay.

Results Child mortality due to injury has declined in all four countries of the UK. England consistently experienced the lowest mortality rate throughout the study period. For children aged 28 days to nine years, differences in mortality rates between England and the other three countries declined over the study period, whereas for children aged 10 to 18 years, differences in mortality rates increased. Inter-country differences were largest for boys aged 10 to 18 years with mortality rate ratios of 1.34 (95% confidence interval 1.13, 1.60) for Wales, 1.66 (1.46, 1.89) for Scotland and 1.83 (1.52, 2.21) for Northern Ireland compared to England (the baseline). The decline in mortality due to injury was accounted for by a decline in accidental deaths; no declines were observed for any age groups for non-accidental deaths, that is deaths caused by self-harm, assault or from undetermined intent.

Conclusions Whilst child deaths from injury have declined in all four UK countries, substantial differences in mortality rates remain between countries, particularly for older boys. This group stands to gain most from policy interventions to reduce deaths from injury and poisoning in children.

P13 'EFFORT OF BREATHING' IS NOT AN IMPORTANT PARAMETER IN A PAEDIATRIC EARLY WARNING SCORING SYSTEM

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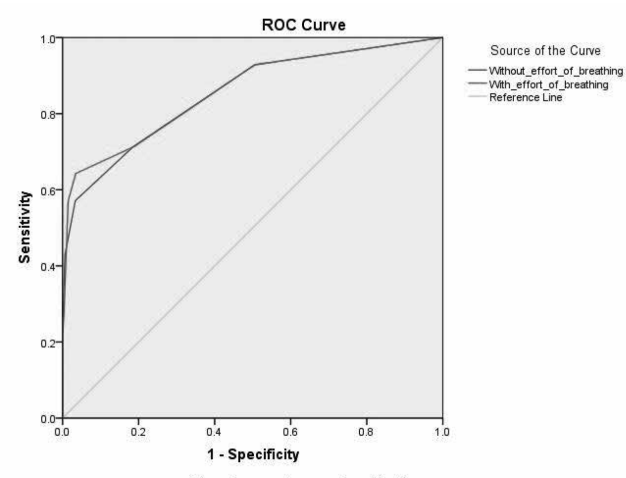
Aims Across the UK there is diverse practise in the use of Paediatric Early Warning Scores (PEWS). Many scoring systems are in use and include different physiological parameters to identify children at risk of life-threatening deterioration. Unlike adult practise, PEWS often comprise of both objective and subjective criteria. 'Effort of breathing' is a subjective parameter commonly included in paediatric scoring systems. Determining a child's effort of breathing is influenced by factors including appropriate exposure of the patient as well as clinical skill, experience and acumen of the scorer.

As part of a study assessing the validity of PEWS charts, a large data set was collected. Analysis of the NHS Institute PEWS chart is made here.

Method Physiological parameters were collected retrospectively from a cohort of 1537 children aged 0–16 years attending a district general hospital's Children's Emergency Department over a 5 week period. Admission to Paediatric High Dependency or Intensive Care were used as proxy outcome measures for serious and life-threatening deterioration.

Results Data was complete for 967 records. At a best cut-off score of 3, NHS Institute PEWS had a sensitivity of 64.3% (95% CI 35.6–86.0), specificity of 96.5% (95% CI 95.1–97.6), positive predictive value of 21.4% (95% CI 10.8–37.2) and negative predictive value of 99.5% (95% CI 98.7–99.8). The area under the Receiver Operating Characteristic curve (AUC) (figure 1) was 0.86 (95% CI 0.74–0.98, $p < 0.01$). If 'effort of breathing' was excluded from NHS Institute PEWS the AUC was 0.85 (95% CI 0.74–0.97, $p < 0.00$).



Abstract P13 Figure 1 Receiver operating characteristic curve for NHS Institute PEWS with and without effort of breathing.

Conclusion The NHS Institute PEWS is a valid tool with good diagnostic accuracy in recognising children at risk of serious and life-threatening deterioration at triage in the Emergency Department. The predictive power did not change when 'effort of breathing' was excluded. It is reassuring that such a subjective parameter does not undermine the value of the scoring system. However, further work is needed to determine whether other subjective measures have any value in paediatric early warning tools.

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Letter to the Editor

Increased incidence of CPR-related rib fractures in infants – Is it related to changes in CPR technique?

Sir,

The article entitled "Increased incidence of CPR-related rib fractures in infants – Is it related to changes in CPR technique?"[1] is a valuable addition to the clinical and forensic literature, assessing the causes of infant rib fractures. We would value further clarification of a number of points, however.

Clarification of the selection criteria is sought to adequately identify the study cohort population. Including cases based on the "characteristic locations" of CPR related rib fractures only (anterior, antero-lateral and lateral rib fractures) may incur a negative selection bias, possibly excluding CPR related cases of posterior or postero-lateral rib fracture.[2] Whilst the inclusion of acute rib fracture cases only may result in a positive selection bias, possibly including cases inflicted during fatal traumatic episodes, such as non-accidental trauma[3]; indeed, the study appears to lack a consensus-based classification of abusive and non-abusive trauma. Within the described cohort, there were potentially two premature infant cases (Case #8 and Case #12) and one case of birth trauma (Case #9), both of which are recognised associations with rib fractures that were not specified as excluded during cohort selection.[4,5] Hence, further clarification of the selection criteria is important in ascertaining the validity of this cohort.

Our particular concern, however, is that confounding variables, unintentionally concealed by this study, may be the cause behind the increase in rib fracture incidence reported by the authors. In our opinion, it is important to appreciate how these factors were considered and whether they influenced the reported rib fracture incidence. Such factors may include: changes in post-mortem techniques, radiographic protocols or personnel over the study period; the heightening in the awareness of rib fracture coexistence with CPR; and the CPR technique performed. The latter factor is especially pertinent, given that the 2005 ILCOR update of the CPR guidelines recommended the use of either the two-finger (TF) or two-thumb (TT) hand encircling technique during infant CPR.[6] Whilst this study appears to assume that the TT technique was used exclusively for all CPR episodes, clarifying the CPR techniques used during each case is essential to determining whether this technique significantly influences rib fracture incidence.

In conclusion, this article was presented as providing the potential to inform future resuscitation guidelines, forensic pathology outcomes and legal proceedings in child abuse cases. We are of the opinion, however, that further methodological clarifications are essential before such conclusions be fully accepted.

Conflict of interest statement

To the best knowledge of the authors of this letter, we are unaware of any no competing financial interests, organizational ties or other relationships which may create an actual or apparent conflict of interest in regard to our study.

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