CARDIFF UNIVERSITY

Cardiff University School of Engineering

CAN INFANT CPR PERFORMANCE BE IMPROVED

THROUGH THE PROVISION OF 'REAL TIME' FEEDBACK?

A Thesis submitted to Cardiff University for the

Degree of Doctor of Philosophy

By

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DECLARATION

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THESIS SUMMARY

Cardiac arrest (CA) is a significant health issue Worldwide. Paediatric sufferers have particularly poor outcomes, with high-rates of associated mortality and morbidity. Early cardiopulmonary-resuscitation (CPR), an emergency procedure which combines external chest-compressions with artificial-ventilations (rescue breaths), has been shown to improve CA outcomes. Researchers have, however, demonstrated CPR, even when delivered by highly-trained-rescuers is not currently being performed optimally. International guidelines have suggested the potential contribution of feedback systems (assistance), in improving the delivery of chest-compressions and rescue breaths to improve survival rates.

Thus, the main focus of this research was to design and develop a real-time CPR-performance-feedback-system, to monitor and assist rescuers in producing high-quality infant-CPR (iCPR). This was conducted as follows: assessment of current compressions by Basic Life Support (BLS) and 'lay' rescuers, design and development of a real-time feedback and performance system and the study of its effects during iCPR. All performances were compared against benchmarked quality standards.

During unassisted iCPR, BLS and 'lay' rescuer overall compression quality, that is those concomitantly achieving all four iCPR quality targets, was <3%. Assistance significantly improved BLS and 'lay' compression quality, to >61.4% and >24.6%, respectively. Assistance delivered more breaths, 5-32%, more quickly, 30-84%, complying with recommendations. Assisted compression count, after each ventilation, was 53% less than unassisted, complying with recommendations. There were no differences in the guideline compression duty cycle (DC), provided that compression time and peak depth were the same.

Unassisted compressions failed to show compliance with quality targets. Assistance produced significant improvements in the overall quality of compressions, reduced the time for breaths and regulated the compression counts after each ventilation. However, lay rescuers require additional training with the feedback system and iCPR simulation. Overall the real-time feedback system significantly improved iCPR performance, such that it could now be trialled to investigate possible improvements in clinical outcomes.

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LIST OF ABBREIVATIONS

CPR   Cardiopulmonary resuscitation

iCPR   Infant- Cardiopulmonary resuscitation

CC   Chest compression

CD   Compression Depth

RF   Release force

CR   Compression rate

DC   Duty cycle

IHCA   In-hospital cardiac arrest

OHCA   Out-of-hospital cardiac arrest

VF   Ventricular fibrillation

VT   Ventricular tachycardia

BLS   Basic Life Support

SIDS   Sudden infant death syndrome

AED   Automated external defibrillator

EMS   Emergency medical service

ICU   Intensive care unit

RCUK   Resuscitation Council UK

AHA   American Heart Association

ERC   European Resuscitation Council

ILCOR   International Liaison Committee on Resuscitation

APLS   Advanced Paediatric Life Support

ALSG   Advanced Life Support Group

EPLS   European Paediatric Life Support

PALS   Paediatric Advanced Life Support

ECC	Emergency cardiovascular care
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
LOE	Level of evidence
Co2	Carbon dioxide
NHS	National Health Service
AFFD	Accelerometer/force feedback device
CT	Computed tomography
ID	Internal anterior-posterior chest depth
V	Voltage
L	Litre
A	Ampere

1. INTRODUCTION

1.1. Research rationale

Cardiac arrest, a significant health issue both in the UK and worldwide, is caused by a range of conditions; including ventricular fibrillation, asphyxia hypoxia, acute coronary-artery occlusion, and coronary ischemia. The incidence of paediatric out-of-hospital cardiac arrest (OHCA) between December 2005 and March 2007, was 8.04 per 100,000 person-years (72.71 in infants, 3.73 in children, and 6.37 in adolescents), versus 126.52 per 100,000 person-years for adults [5]. Most infant OHCAs occurred in homes (93%) and were not witnessed (90%) [6]. However, the incidence of OHCA in children and young adults is higher than previously reported [7].

Cardiopulmonary resuscitation (CPR) is an accepted clinical method of attempting to retain the circulation of oxygenated blood to critical organs during a period of cardiac arrest. The survival rate reported between December 2005 and March 2007 for all paediatric OHCAs was 6.4% (3.3% for infants, 9.1% for children, and 8.9% for adolescents) versus 4.5% for adults [5]. Another recent study reports that the overall survival rate was 26.9% (3.8% in those 0–2 years of age, 40.0% in those 3–13 years of age, 36.7% in those 14–24 years of age, and 27.8% in those 25–35 years of age). Survival increased throughout the study period, from 13.0% in 1980- 89 to 40.2% in 2000-09 [7]. Still, the paediatric cardiac arrest survival rate of <4% needs further research, and advancements in CPR are needed to improve poor survival rate for paediatric patients.

1.2.   Cardiovascular system

The cardiovascular system consists of the heart, blood vessels, and blood. Continuous blood circulation is essential to sustain life, and thus blood is continually driven through the cardiovascular system by the heart (Figure 1-1). The heart is the most important muscular organ in the body, and normal heart function is vital for a healthy life. The heart is divided into right and left sides, with each side consisting of an atrium and a ventricle. Blood circulation involves pulmonary circulation and systemic circulations [8, 9]. The pulmonary capillary network surrounds the lung alveoli, allowing exchange of CO_2 and O_2. Pulmonary circulation transports oxygen-poor blood from the right ventricle to the lungs, where it is oxygenated in the capillaries and returned, riched with oxygen, to the left atrium. Systemic circulation transports oxygen- and nutrient-rich blood from the left ventricle to various systems in the body and returns deoxygenated blood to the right atrium of the heart. The coronary arteries, situated on the heart's surface, are responsible for the heart's blood circulation [8, 10].

Four valves (the tricuspid, pulmonary, mitral and aortic valves) regulate blood flow. The tricuspid valve is located between the right atrium and the right ventricle. The pulmonary valve is located between the right ventricle and the pulmonary artery. The mitral valve is located between the left atrium and the left ventricle, and the aortic valve is located between the left ventricle and the aorta. All, except for the mitral valve, have three flaps that open in only one direction due to pressure generated during heart contraction and relaxation phases. The mitral has only two flaps [1].

The heart pumping cycle is associated with changes in arterial and ventricular pressure. The cycle is split into four phases: filling, isovolumetric contraction, expulsion, and isovolumetric relaxation. The isovolumetric contraction and filling phases are known as systole, and the

isovolumetric relaxation and expulsion phases are known as diastole. Controlled by periodic electrical impulses, the pacemaker function for mechanical contraction of the heart begins with excitation of the sinoatrial node [1].

Vena cava · Pulmonary valve · **Right atrium** · Tricuspid valve · **Right ventricle** · Endocardium · Myocardium · Epicardium · Aorta · **Left atrium** · Bicuspid valve · Aortal valve · Papillary muscles · **Left ventricle**
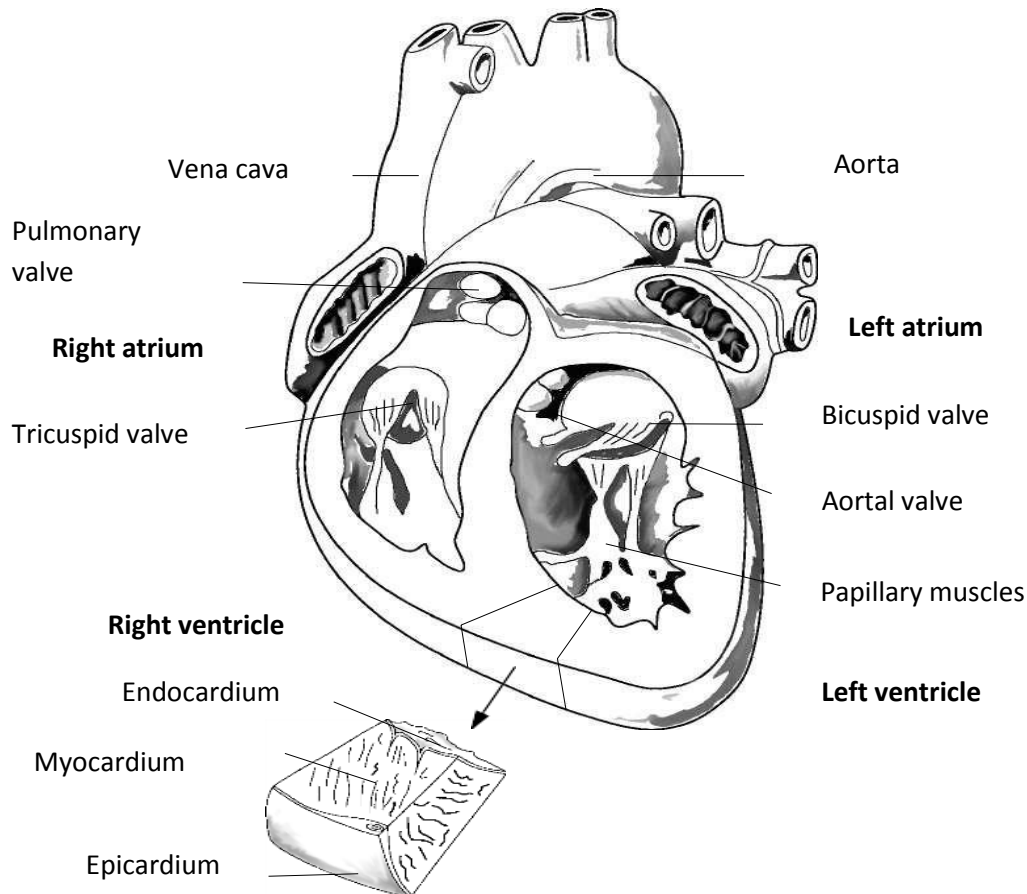
Figure 1-1: Human heart. Copied from [1].

1.3. Cardiopulmonary resuscitation

Chest compression, a fundamental and vital component of CPR, was invented by Kouwenhoven [11]. Chest compression should be the primary action and the highest priority when starting CPR in victims of sudden cardiac arrest [12] [13]. Blood flow to the heart, brain, and other vital organs is ensured by continued and uninterrupted chest compression in CPR, this

offers the best chance to recover from cardiac arrest [14,15]. The overall aim of CPR is to resume heart function and discharge the patient without physiological or neurological effects [14-16].

In Europe, cardiac arrest affects 49 to 83 per 100,000 individuals per year [17]. Approximately 6,000 children experience cardiac arrest annually in the United Kingdom [18]. The cardiac arrest survival rate in this population remains extremely poor [19-21]; hence, rates of mortality and morbidity are relatively high. Office for National Statistics (ONS) group showed that respiratory and cardiovascular disorders were the most common causes of infant deaths and, in 2014, accounted for 41% of such cases in England and Wales (www.ons.gov.uk). Almost six decades of CPR research have passed since its origination in 1960, yet the cardiac arrest survival rate remains extremely poor. Consequently, infant population cardiac arrest remains a significant health problem. In addition, international resuscitation guidelines recommend that treatment for infant patient cardiac arrest issues be based on the most relevant research studies [14-16].

Currently, iCPR is performed based on international guidelines that recommend a specific, evidence-based procedure that aims to maximise survivability following cardiac arrest. These guidelines describe four key targets to achieve optimal chest compressions in infant CPR performance: chest compression depth, chest release force, chest compression rate, and compression duty cycle [14, 15]. However, recent research studies show that chest compressions are still performed poorly during simulated iCPR [22-29].

The effects of poor-quality CPR performances are documented in clinical practices. However, insufficient chest compressions were observed during CPR both in hospital [30] and out of hospital [31]. Deeper compression during CPR (one-half external anterior-posterior diameter

compression depth) may cause damage to intrathoracic organs [22, 32-35]. Leaning, also called incomplete decompression of the chest between compressions during the chest release phase of CPR, is the common problem during CPR performance. Leaning during CPR increases intrathoracic pressure, which decreases coronary perfusion pressure and returns venous blood to the heart, thereby resulting in a reduced cardiac arrest survival rate [36-40]. There is a positive relationship between the number of compressions actually performed on the victim's chest and the chance of survival from cardiac arrest [41]. In addition, blood flow rate in neonates is most effective at a compression rate of ≥120 compressions/minute, as recommended by a mathematical study of cardiovascular physiology [42]. In animal models of cardiac arrest, compression performed at a rate of 120/minute produced higher myocardial perfusion pressure, increased left ventricular blood flow, and a more successful outcome from cardiac arrest than 60/minute and 80/minute compression rates [43-45]. In human subjects, compression performed at a rate of 120/minute has also produced better myocardial perfusion pressure than 60/minute and 80/minute compression rates [46]. Prolonged duty cycles reduce cerebral blood flow and the return of venous blood to the heart, resulting in reduced cardiac arrest survival rate [47-51]. Decreasing the duty cycle could increase short-term survival from cardiac arrest [13, 52]. An interruption in continuous chest compressions—which occur during pauses in CPR—affects coronary perfusion pressure [30, 31, 53].

Because cardiac arrest often results from, or is complicated by, asphyxia, maintaining the airway for cardiac arrest patients and providing ventilation (also called rescue breaths) are essential elements during paediatric CPR [14]. Animal studies show that rescue breaths during CPR after ventricular fibrillation (VF) or asphyxia resulted in an improved return of spontaneous circulation (ROSC), cardiac arrest, and neurological outcomes when compared to no-ventila-

tions during CPR [54-56]. The main purpose of rescue breathing during CPR is to retain sufficient oxygenation and to remove carbon dioxide (CO_2) [57]. CPR, comprising both chest compressions and rescue breaths, leads to better survival than hands-only CPR in children suffering cardiac arrest due to non-cardiac causes [58].

Chest compression in iCPR is often delivered poorly, even by well-trained rescuers [13]. Quality CPR can be achieved through real-time monitoring and feedback system that observes and assists resuscitators and results in a reduced human error during manual CPR [13] [59]. The provision of a feedback system during adult CPR improved overall chest compression quality by improving CPR quality measures: chest compressions depths, chest release forces, chest compression rate, and compression duty cycles [60-69].

The provisions of a real-time feedback system and its effects on CPR quality for Basic Life Support (BLS) (Basic Life Support-trained, e.g. police officers, firepersons, nurses) and lay resuscitators (i.e. those who have no experience in CPR) during iCPR have never been quantified. This research investigates the baseline performance of BLS and lays resuscitators and the effects of a real-time feedback system on CPR quality. Except for Resusci Baby QCPR (Laerdal Medical, Stavanger, Norway) iCPR training manikin, there is no real-time CPR feedback system available for use on infants.

1.4. Research aims and objectives

The primary aim of this research was to monitor resuscitators' CPR performances, assess the quality of chest compressions, and improve the quality of chest compressions during simulated iCPR. The following goals were identified to achieve these aims:

1. Design and develop a system that quantifies CPR performance to provide a measurement tool for CPR quality. Investigate the quality of chest compressions provided by BLS resuscitators during simulated iCPR on an infant manikin.

2. Investigate the quality of chest compressions provided by lay resuscitators during simulated iCPR on an infant manikin.

3. Investigate the rescue breath count, compression count between rescue breaths, and time consumed for delivering the rescue breaths.

4. Compare the chest compression quality of BLS and lay resuscitators both with and without real-time feedback performance system.

5. To develop a system that provides opportunity to enhance CPR quality.

6. Investigate and propose a new technique where there are obvious technical deficiencies versus the international guidelines.

1.5.   Thesis overview

Chapter 2 describes the current epidemiology of infant cardiac arrest, cardiac arrest causes, physiological processes associated with cardiac arrest, and current procedures and processes of infant cardiac arrest. This chapter further describes current evidence-based chest compression quality and key targets for iCPR. All quality targets—chest compression depth, chest release force, chest compression rate, compression duty cycle, and rescue breaths achieved during CPR—were recommended by international resuscitation guidelines. This chapter also describes existing CPR feedback devices. The connection between literature gaps and this research aim are highlighted in the following research question section. Chapter 3 describes the manikin details, details of accelerometer sensors and rubber pads, airflow sensors, data acquisition technique, power supply unit construction, prototype CPR feedback device details with

working principles, and LabVIEW-based performance feedback program working principle with a flowchart. The data obtained from the feedback device were stored on a hard drive for further analysis. A Matlab program was used for analysing the data and to determine the quality of the chest compressions. Chapter 3 further explains the data analysis technique used with CPR quality measure targets and working principles with a program flowchart. This chapter also defines the study coordination and participant details, such as BLS and lay resuscitator details and experimental procedures during simulated iCPR performances.

In Chapter 4, the analysed data of BLS and lay resuscitators' quality measures and simulated CPR performance on an infant training manikin are shown against their current guidelines-based on CPR quality targets. The performances were separated into three stages: continuous compression only on the training manikin for a period of 1 minute; 5-initial rescue breaths and continuous compressions on the training manikin for a period of 1 minute; and 5-initial rescue breaths and repeated cycles of 15 compressions followed by 2 rescue breaths on the training manikin for a period of 1-minute. CPR performance was also compared with and without the CPR performance feedback program. Simulated iCPR performance results and comparisons of current and new techniques for calculating the compression duty cycle are also described in this chapter.

Chapter 5 discusses the key findings of this research, compares the results with relevant literature, and describes the potential impact of this research in clinical and educational aspects of iCPR. Performance of the real-time feedback system is also detailed in this chapter. Chapter 6 summarises the principle findings of this research and directions for future research in iCPR.

2. LITERATURE REVIEW

2.1. Research background

2.1.1. Epidemiology of Cardiac Arrest

Cardiac Arrest (CA) is a significant worldwide health issue. Each year, between 49 and 83 per 100,000 individuals, including infants, experience Out of Hospital Cardiac Arrest (OHCA) [17, 70]. In-Hospital Cardiac Arrest (IHCA) incidence is 1 to 5 per 1,000 individuals per year [71]. In the United Kingdom, approximately 6,000 children experience CA each year [18]. Survival rates from OHCA paediatric CA remain poor, and outcomes vary significantly with the location and duration of CA [72]. The incidence of paediatric OHCA between December 2005 and March 2007 was 8.04 per 100,000 person-years versus 126.52 per 100,000 person-years for adults [5]. Most infant OHCAs occurred in homes (93%) and were not witnessed (90%) [6].

The incidence of OHCA in children and young adults are more common than reported in prior estimates [7]. Paediatric survival rate was recorded as 21.6% in a retrospective 5-year case series [73]. The survival rate reported between December 2005 and March 2007, for all paediatric OHCAs, was 6.4% (3.3% for infants, 9.1% for children, and 8.9% for adolescents), versus 4.5% for adults [74]. In general, approximately 1% to 6% of individuals suffer from OHCA and survival rates are slightly higher for in-hospital CA patients. A recent comprehensive study shows that only 17% of these infant patients were discharged alive [75-77]. A recent study reported that 68.4% of paediatric cardiac arrest occurred in private locations; 33.7% were witnessed while only 2.9% received bystander CPR. These results show that CPR training should be provided to lay person to increase the survival rates of paediatric OHCA patients [79].

Sudden cardiac death generally results from either ventricular fibrillation [17, 78, 79], asphyxial hypoxia [17, 79] or ischemia (circulatory failure) [73, 80, 81]. As the leading cause of death in Europe, sudden CA is responsible for the deaths of 700,000 individuals per annum (Sans et al., 1997). The recovery rate from CA is extremely poor [19, 80, 82], and survival rates are lower for children who experience CA. Recent investigations reported that survival rate from IHCA of children has improved substantially in the past few decades; 10% in the 1980s to greater than 25% in 2005 [81, 83]. However, OHCA survival rate in children has not changed much in the past 30 years, with survival rates of less than 10% [72, 74]. Only 4% of children who experience OHCA survive neurologically intact [20], compared to 17% of adults who suffer cardiac arrest in-hospital [84]. In the United States each year, 375,000 to 390,000 individuals experience CA either in or out of hospital [85]. A collective review by Young and Seidel [23] repoeted that the CA paediatric survival rate was lower than the neurological morbidity.

There is an immediate need to improve the outcomes of CA patients by developing new strategies, devices and a clear understanding of the physiological function of the heart.

2.1.2.   Epidemiological literature limitations

Infant CA epidemiological evaluation is lacking uniformity in case classifications, patient selection, data analysis method and study design. Case classification of infant CA remains inconsistent across the literature. Many studies combine respiratory arrests with CAs; also, several studies include aetiologies associated with increased risks of mortality, such as septic shock and traumatic arrests cases. Study sizes and time, designs, and geographical location varied extensively between studies. Also, inconsistencies in data abstraction and quality were observed in previous studies. Most infant CA studies focus primarily on the epidemiological characteristics of paediatric CAs, resulting in a lack of detailed infant-specific data.

2.2.   Chest compression

Chest compression, a fundamental and vital CPR component, has saved many patients' lives from CA [12]. The external closed chest compression technique, first coined by Kouwenhoven [11], is a crucial element of resuscitation and is the gateway to recovery for CA victims both in and out of the hospital. Chest compressions generate blood flow to vital organs by directly compressing the heart and increasing intrathoracic pressure through strong rhythmic pressure over the lower half of the sternum [86-90]. While performing CPR continuous deep compressions maintain sufficient circulation that is essential for saving CA patients [90]. Chest compressions, the first action when starting CPR— "Push hard and push fast in the middle of the chest, should be the highest priority and is the important phase in compressions" [12]. If someone unexpectedly experiences an abnormal heartbeat, the absence of breathing or breathing only in gasps, a rescuer should assume that the particular person is in CA [65].

The rescuer should immediately activate emergency response systems and begin compressions. CPR is not harmful. Inaction during CA is harmful, and CPR can be lifesaving [12]. Any delay in starting compressions during CA means a chance of a reduced survival rate. The most recent CPR guideline suggests that the importance of starting uninterrupted compressions early, to generate pulses, ensures blood flow to the heart, brain and vital organs and provide the best chance to recover from CA [14-16, 34]. High-quality bystanders CPR increases the proportion of patients who are discharged from the hospital alive, versus poor bystander CPR or no bystander CPR [91].

An external compression during CPR contributes to maintain the haemodynamic function of the heart [2] (Figure 2-1). According to the 'direct cardiac compression model', the left and right ventricles are compressed between the sternum and the vertebral column [11, 92]. This

compression produces a pressure gradient between the ventricles, aorta and pulmonary arteries that causes the mitral and tricuspid valves to propel blood from the ventricles and generate forward blood flow. During the decompression phase of the chest, negative pressure generated in the atria, supports a retrograde flow of blood that refills the heart and myocardium, prior to the next compression [93]. The 'thoracic pump model' regards the heart as a passive conduit without having a pumping function [94, 95]. Overall increase in intrathoracic pressure forces blood to flow from the thoracic to the systemic circulation [95]. During the compression phase, intrathoracic pressure propels blood from the heart into the systemic circulation. During the decompression phase, negative intrathoracic pressure promotes the return of venous blood to the thorax and heart in preparation for the next compression in pulmonary circulation [96, 97]. During iCPR, direct cardiac compression may play a greater role in maintaining the haemodynamics of the heart [98] and oxygen delivery to the myocardium and other vital organs [12].
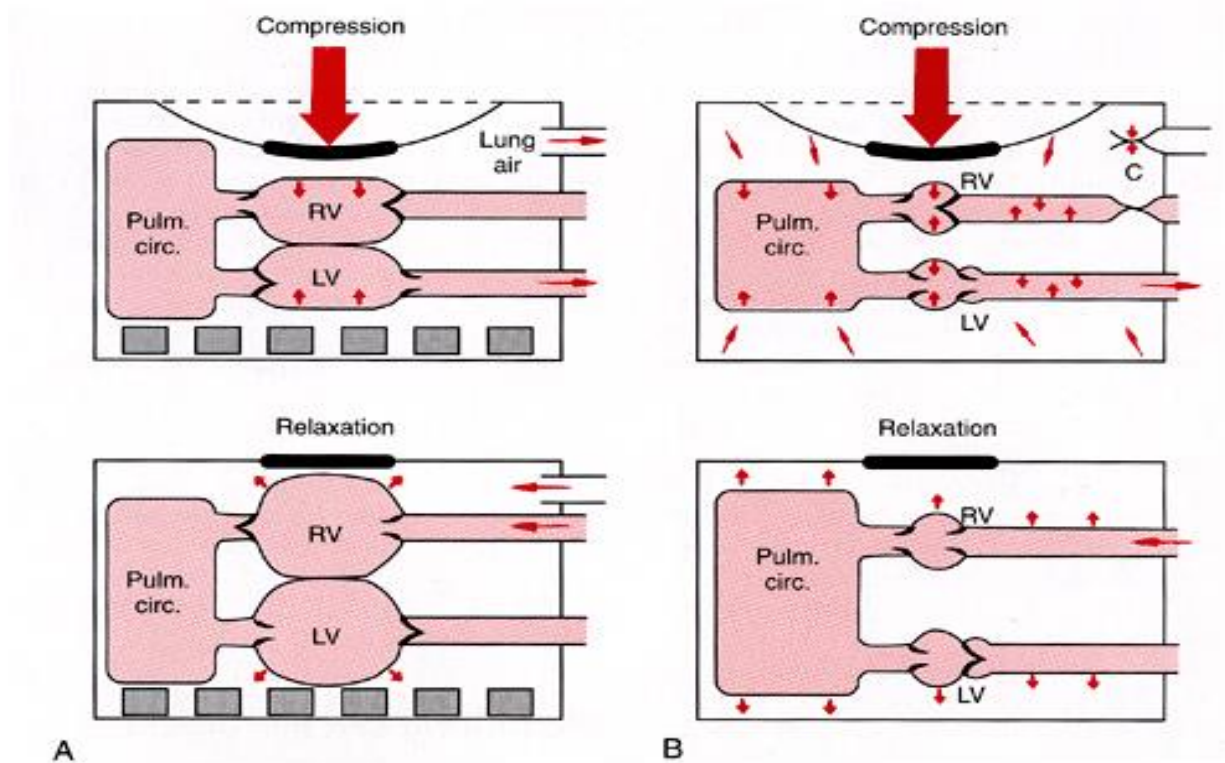
Figure 2-1: Haemodynamic mechanisms of blood flow during infant CPR. A, the direct cardiac compression and B, the thoracic pump chest compression models [2]. RV, right ventricle; LV, left ventricle; C, inspiratory impedance; Pulm Circ., pulmonary circulation.

The chest walls are thinner, and the ribs are more elastic in infants and young children when compared with the adults. Thus, a lower impression is enough to produce significant chest wall deflections. Only one or two fingers chest compressions are recommended during infant compressions [99]. Two compression techniques are recommended for use on infants; the two-thumb (TT) method where the hands of a single rescuer encircle the chest, and the two-finger (TF) method for two or more rescuers [14, 15, 100] (Figure 2-2). The TT method is usually recommended for compression on an infant [59, 101, 102] (Figure 2-2: Type A). According to the rescuer performance [60], as shown in Figure 2-2: Type B, rescuers will sometimes compress the sterunum with the tips of two fingers (e.g. the middle and index fingers). During the

TF method, compressions are performed by placing two fingers over the lower third of the sternum when the infant victim is in the supine position. The TT technique is performed by squeezing the thorax between the thumbs and fingers with both hands encircling the lower third of the thorax [14, 15] (Figure 2-2). In addition, in a study based on iCPR model, TT compression produces higher mean arterial pressure (MAP), systolic and diastolic blood pressure (SBP and DBP) and pulse pressures (PP), when compared with TF compressions during the clinically relevant duration of prolonged CPR. Also, rescuers found that the TT technique is easier to execute and less fatiguing than the TF method [29].

Two animal surrogate studies analysed the relative effectiveness of TT and TF iCPR. Seven infant swine weighing 8-10kg were used to evaluate relative SBP, DBP, mean arterial and coronary perfusion pressures during TT and TF CPR. Following the induced CA, 1,050 validation compressions were performed, resulting in the TT technique being statistically superior ($p<0.001$) across all haemodynamic outcomes [103]. SBP, 59.4 versus 41.6 mm Hg; DBP, 21.8 versus 18.5 mm Hg; mean arterial pressure, 34.2 versus 26.1 mm Hg; and coronary perfusion pressure, 15.1 versus 12.2 mm Hg [103]. The second animal surrogate study, using a 10kg infant swine, further evaluated both compression techniques. A total of 2,297 compressions were analysed in this study. The TT method produced significantly higher SBPs when compared with the TF. The diastolic blood pressures were not significantly different. Also, the TF technique was unable to achieve similar sternal compression forces when compared with TT technique. In this swine model of iCPR, TT compression is an easier and more effective method [104]. Since 2000, the American heart association, in collaboration with the International Liaison Committee on Resuscitation (ILCOR), preferred the TT compression technique for CPR of infants and newborns [105].
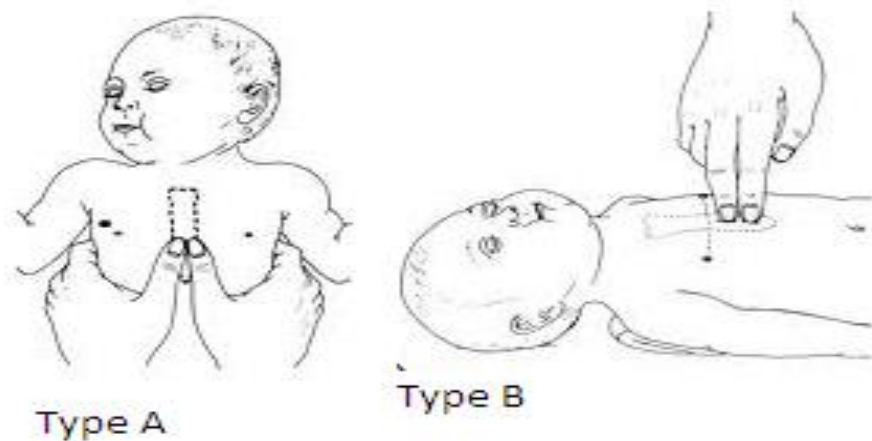
Figure 2-2: Finger position for chest compression on the infant's chest.
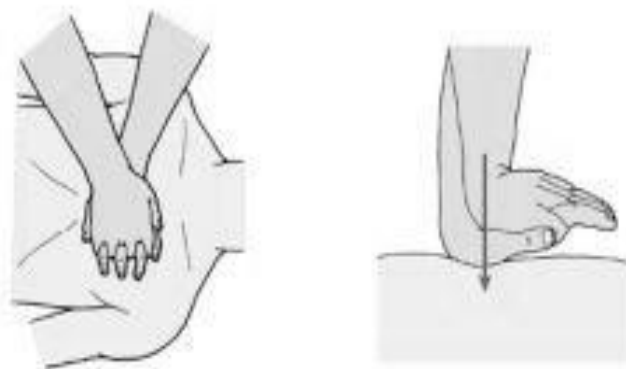
Figure 2-3: Hand position for chest compression on the adult chest.

In the literature, the effectiveness of TT and TF techniques was further investigated through the use of infant manikins. An instrumented infant manikin was used to assess the SBP, DBP and mean arterial pressure produced during simulated iCPR performances. The feedback system was employed to regulate the compression rate and depth during simulated CPR. Compression rate was regulated by a metronome and depth was regulated through oral instructions. This study reported that all three pressures were significantly increased with the TT technique [29]. However, the TT technique reduces the proportions of shallow compressions [106].

In adult chest compression, the rescuer should place the heel of the right hand in the centre of the patient's chest (between the nipples and the lower half of the sternum) and the heel of the left hand on top of the right hand, in such a way that the hands are overlapped and parallel. This procedure will help to produce more force on the chest (Figure 2-3), [12, 59].

2.2.1. Optimum location for chest compressions during infant CPR

The heart occupies a large proportion of the intrathoracic cavity in infants [99]. The most effective anatomical location for compression during iCPR has been investigated by observations made during cardiac surgery, X-rays, CT scans and post-mortem examinations. The optimum position for compression in an infant and young child is over the lower sternum, to a depth of at least one-third the anterior-posterior diameter of the chest [107]. The anatomical relationship between the heart, the thorax, sternum and diaphragm is similar in all age groups. The lower one-third of the sternum produces better blood pressure during CPR performance. The lower sternum compressions potentially increase the successful outcome of CA than CPR performed in the middle one-third of the sternum [107].

To reduce organ injuries and generate a higher cardiac output, continuous compressions are essential to achieving successful cardiac outcomes. Based on radiographic and angiographic imaging studies, the heart of the infant is reported to be located under the lower one-third of the sternum [108]. Also, another clinical study reported that the point of maximal (left ventricle) anterior-posterior heart is located under the lower quarter of the sternum. Therefore, it is hypothesised that during CPR, compressing the lower quarter of the sternum increases the cardiac output more than compressing at other points on the sternum [109] and that higher cardiac outputs could only be achieved by squeezing the heart at the level of the left ventricles [110].

2.2.2. Caution should be applied when animal and computational models are translated to humans during CPR

The safety and effectiveness of new drugs and methods are usually experimented on animal surrogates, before being approved for clinical practice [111]. Until the mid-1980s, canines were used extensively in CA research. In general, canines and human's cardiovascular functions are similar. However, the thoracic dimensions of the canine are different from the human; making a comparison of compression techniques difficult. Additionally, there are considerable differences in the size and shape of the chest, heart and brain, thus, potentially affecting the outcome [112]. Often porcine animal surrogates have been used to investigate chronic ischaemia, therapeutic angiogenesis, hypertrophic cardiomyopathy and CPR research. Porcine cardiac anatomy, coronary arteries and physiology resemble closely that of humans [113-115]. They are available at a lower cost than canines providing a wider availability of uniform sizes and ages for all stage of experiment modelling [112]. In addition, myocardial histology is similar in swine and humans [116]. After induction of myocardial ischaemia, both porcine and human myocardium biochemical and metabolic response is similar [117, 118].

The resting heart rate of the porcine model averages that of the human, whilst the mouse model has a high resting heart rate (500 beats/min) and the refractory period is too short [119]. Also, a recent study has reported that large white pigs are the favourable swine model for CA experiments; the baseline haemodynamics of the swine closely resemble the human haemodynamics as far as the pressure of the left ventricle and atrium are concerned [120]. Other than the swine and humans anatomical and physiological resemblances, swine models do not require much human care as canine models [121]. The swine model provides maximal translational information among current mammalian models of CA and CPR, allowing a convenient method of transferring information from research to clinical practice[122]. Discordance between animal

surrogate studies and human studies could be due to bias or failure to simulate clinical disease effectively in animal surrogates [123].

The selection of a clinically relevant model is one of the main hurdles to cardiac research. The animal surrogate studies of CA outcome measures, such as ROSC and neurologic outcomes, are chosen to mimic OHCA cases as a prelude to clinical studies. However, during animal-based studies, researchers should incorporate more clinical variables whilst mimicking clinical scenarios, any variance in the outcome variables would help clinicians during treatment of CA patients. Various important issues have not been investigated in animal studies. The main one is the timing of administration of CPR after CA. This is significant; the majority of adult arrest victims will have significant coronary artery disease and myocardial infarction [124]. Due to a lack of standardisation and non-uniform terminology, it is difficult to compare the clinical and laboratory results. However, for the successful development of treatments for CA, animal studies will remain a vital advantage [112].

Human body biological tissues can deform beyond their recoverable border when compressed excessively resulting in anatomical structural collapses and affecting their normal function [125]. Infant rib fractures are usually a rare event, due to the malleability of their rib structures. Infant rib fractures are usually caused by anterior-posterior compression of the chest when the chest is circled by both hands during CPR [126, 127]. The rib stiffness characteristics of animals are also another important consideration when data is transferred to humans, in particular, human infants. Although infant and adult manikins are often used in CPR research and training purposes, there are basic limitations in their bio-fidelity. Manikin chest stiffness characteristics may not accurately represent the size of a human body [26, 128]. Human and swine chest stiffness behaviours, during CPR, are comparatively similar, but there are differences in chest

viscosity at middle and deep compression depths. These differences needs to be a consideration when it is applied to humans [129].

2.2.3. Important measurements during the CPR episode

CPR quality is the most significant factor in CA survival rate [14-16, 130] because it impacts the outcome of a CA event [131]. Recent published CPR standards and recommendations (European CPR Council guidelines 2010 and American Heart Association guidelines 2010) are based on training for in and out of hospital healthcare professionals around the world. Early recognition of CA and implementation of CPR increases the chance of surviving CA. The following five measurements are key factors for assessing the quality of CPR:

1. Chest compression depth

2. Chest release force

3. Chest compression rate

4. Compression duty cycle

5. Pauses in chest compression

2.3. Compression depth

The quality of the CPR, in particular, a sufficient depth of compression is the key to the survival from the CA [132]. Once the signs of CA are identified, the resuscitator must start external compression to retain adequate circulatory function during the arrest. Compression depth is the most important element in CPR, playing the crucial role of pumping blood from the heart to the brain and other vital organs. Compression depth is also the most important quality measure during iCPR [14, 15]. Haemodynamic outcomes are associated with increased arterial

pressure, achieved by exact compression depth in both infant and adult human subjects [133, 134], greater coronary flow and increased cardiac output in animal subjects [135, 136]. Measuring compression depth is one of the more challenging variables in CPR quality. Many rescuers fear to do compressions, assuming that it may harm the patient. In addition, a rescuer's limited muscle strength frequently results in under compression of the chest less [57].

2.3.1.   Definition and recommended depth

Compression depth is defined as the maximum deflection of the sternum measured prior to the compression phase [22, 130] (Figure 2-4). European and UK resuscitation and American Heart Association Guidelines for CPR recommend an adequate compression depth of at least one third the external anterior-posterior (AP) diameter of the chest, approximately 4 cm in infants [15, 137-139]. European resuscitation guidelines recommend a compression depth at least 5 cm [12] [140], but not exceeding 6 cm; since >6cm would damage an adult's thoracic organs [57]. Thoracic over-compression, defined as a residual internal AP chest depth of <10 mm, may potentially cause intrathoracic trauma [32, 133, 139]. Exerting 50 kg of force (Figure 2-5) on a patient's sternum is enough to achieve adequate compression depth, which means that average-sized and fit rescuers are capable of delivering effective CPR in adult patients [3] (Figure 2-5). Insufficient compression depths were observed during CPR both in hospital [30] and out of hospital CA cases [31], compared with current European Resuscitation Council and American Heart Association guideline recommendations [12, 100].
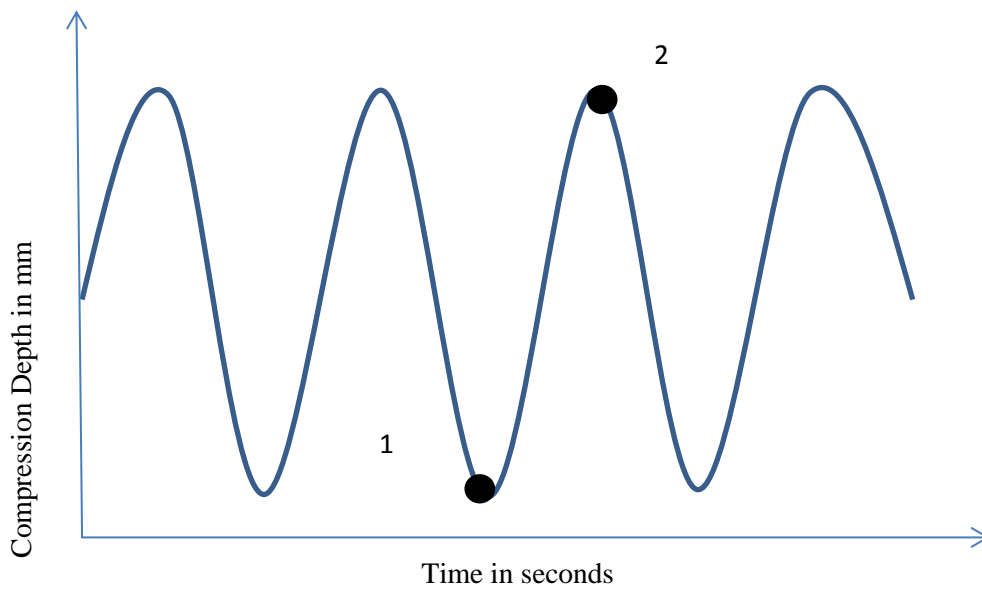
1 = Sternum initial position
2 = Max sternum deformation during chest compressions

Figure 2-4: Sternum deflection curve during chest compressions. The sternum deflection is the distance between two points such as the initial position of the chest and maximum deformation of the chest.
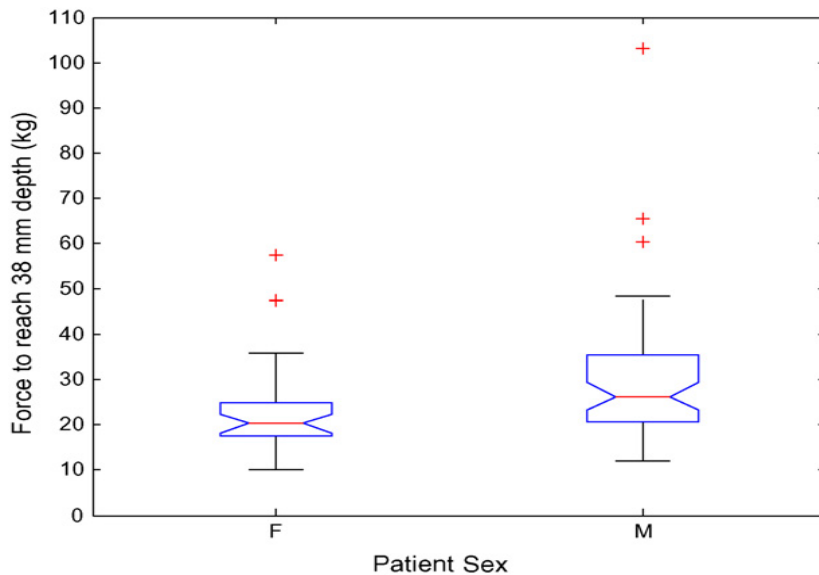
Figure 2-5: Minimum depth as recommended in the guidelines (38 mm for females [F] and 60 mm for males [M]) can be delivered by applying 50 kg force [3].

2.3.2.   The most effective compression depth based on scientific evidence for chest compressions during infant CPR

The systolic, mean arterial and pulse pressures increase when compressions are provided at one-half of the anterior-posterior diameter of the chest, compared with one-third external AP thoracic diameter. During CPR, compression depths of one-third of external AP diameter were radiographically appropriate for children aged from 3 months - 8 years [133]. The optimum compression depth for infants was further investigated using mathematical modelling based upon neonates (aged < 28 days) chest CT scan dimensions. It is recommended that a one-third external anterior-posterior compression depth should be more effective than a one-quarter external AP compression depth and a one-third AP compression depth is safer than a compression depth of one-half external AP diameter [32].

However, the maximum compression depth during CPR, should be limited. This is because radiological studies hypothesised that excessive compressions will reduce residual internal thorax depth. If this because <10mm an increased likelihood of causing intrathoracic trauma through the over-compression of the thorax may became apparent [32, 133, 139]. Eight canines weighing 6-12kg were used to investigate cardiac output and mean arterial pressure; both were linearly related to compression depth once compression depth ~15-30mm was exceeded [141]. Another study (used six piglets weighing between 4.5-6kg) reported that maximum intrathoracic pressures were proportional to compression depth, once the compression depth approximately 20% of the AP thoracic diameter was exceeded [98].

Research studies based on canine animal models have shown that deeper compressions result in relatively large changes in cardiac survival rate. At sternal displacements below the recommended depth, cardiac output is virtually zero, deep compressions lead to multiple rib fractures.

Provision of feedback might well lead to greater uniformity in the quality of compression and lessen the risk of the chest wall or visceral damage due to over compression[141].

Porcine-based animal studies also demonstrate a linear correlation between deeper compressions and survival rate. Coronary blood flow to the vital organs is directly related to proper compression depth during CPR in swine [135]. The recommended compression depth (1.3 to 2.5 cm) [142] resulted in little coronary flow in swine and dogs and is hardly likely to cause greater flow in humans [135]. Shallow compressions reduced the haemodynamics of the heart during CPR [134, 135]. Providing the exact compression depth would maintain favourable haemodynamic outcomes during CPR [133-135, 141]. Also, accurate compression depth would minimise intrathoracic trauma, through deep compression of the chest [32, 139]. The provision of high-quality compressions during CA is a vital element in the success of iCPR.

2.4.   Chest release force

Recent research studies show the importance of intrathoracic pressure during CPR compressions on CA victims. Active compressions and decompressions during CPR are associated with a better haemodynamic status of the heart [143]. Complete chest wall decompression improves haemodynamics by generating relatively negative intrathoracic pressure, thus pulling venous blood back to the heart. The heart valves are refilled to maximum volume, resulting in cardiac preload prior to the next compression [144-146].

Leaning or incomplete decompression is a common problem during CPR performance. Leaning during CPR increases intrathoracic pressure and decreases coronary perfusion pressure, which ultimately leads to reduced survival rate from CA [36]. A chest release force of about

10% of the subject's body weight also produces detectable intrathoracic pressure during compressions [38]. A residual leaning force of 10% and 20% (i.e., 1.8–3.6 kg), during compressions, considerably reduces coronary perfusion pressure, cardiac index and myocardial blood flow [37]. A residual leaning force of as little as 10% ($<$2.5 kg) is associated with a considerable increase in endotracheal pressure [38]. How fully the chest recoils at the end of each compression is partly determined by duty cycle [147]. Incomplete chest recoil decreases coronary perfusion pressure and increases intrathoracic pressure, which reduces the return of venous blood to refill the heart. This incomplete chest recoil is associated with a decreased CA survival rate [22, 38, 40, 148].

2.4.1.   Definition and recommended target

Chest release force or chest recoil is defined as the point where the minimum compression force is measured during the decompression phase of consecutive compression cycles [22]. Incomplete release (leaning) occurs when the force is not removed completely during the decompression phase [130]. Figure 2-6 describes how chest release force is measured during the compression cycle. Rescuers should allow complete chest wall decompression (recoil) during the duration of compression performance, as recommended in the European resuscitation guidelines [12]. Ideally, compression and decompression should take approximately the same amount of time [100].

Figure caption area:

= Full recoil (min chest compression force measured every cycle)
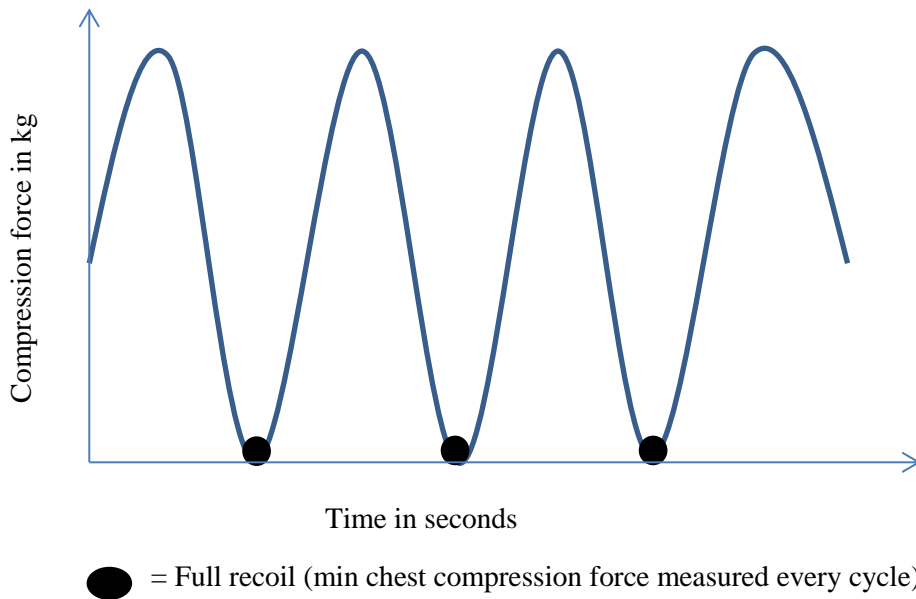
Figure 2-6: The decompression phase measured during the chest compression cycle.

2.4.2.   The most effective compression release force based on scientific evidence for chest compressions during infant CPR

International CPR guidelines recommend that during CPR the chest should be allowed to fully decompress after each compression [149-151]. During CPR for long periods of time, rescuer fatigue may have a greater effect on the chest recoil phase, since the rescuer's energy is significantly dissipated during the compression phase of the chest [152]. During the cycle of compression, incomplete chest wall decompression produces leaning on the sternum, which can create high intrathoracic pressure and reduce coronary perfusion blood pressure. These pressure variations result in a limited flow of venous blood for the heart to pump to the brain and other organs. The effects of intrathoracic pressure haemodynamics are shown in both animal and human laboratory research studies [39, 148, 153-156]. Due to the incomplete decompression of the chest wall, the combination of the right atrial pressure increases and the aortic

arterial pressure decreases, which immediately results in a considerably reduced coronary perfusion pressure to 15 mmHg that has been associated with poor survival outcomes in humans [155, 156].

A series of porcine compressions and release experiments were performed during which the chest was compressed to 100% of the target depth and released. Initially 100% release was permitted for 3 minutes; then 100% of the target depth was achieved and released by only 75% of the target depth for 1 minute (25% compression depth remained); then a further 100% of the target compression depth was performed followed by 100% release for 1 minute; resulting in coronary perfusion pressures of 23.3 ± 1.9 (100% release), 15.1 ± 1.6 (75% release) and 16.6 ± 1.9 (100% release),($p = 0.003$), respectively [154]. Animal models demonstrate that a 100% chest wall decompression significantly increases coronary perfusion pressure. Coronary perfusion pressure is a good predictor of CA outcome [155].

Another study investigated whether the residual leaning force of a 260g sternal accelerometer/force feedback device (AFFD) affects haemodynamics during CPR in a piglet model (10.8 $\pm$ 1.9kg) of ventricular fibrillation CA. No significant effects were observed for both CA outcomes and myocardial blood flow. Also, this study concluded that small leaning forces (approximately 2.5% the piglet weight) do not prevent the complete decompression of the chest and thus optimise the subsequent return of venous blood flow during CPR [157].

2.5.   Compression rate

There is a positive relationship between the number of compressions actually performed on CA victims and the chance of successful survival [158]. Blood flow rate in neonates is best at a

compression rate of ≥120 compressions/minute, as recommended by a mathematical study of cardiovascular physiology [42]. In animal models of CA, compression performed at the rate of 120/minute produces higher myocardial perfusion pressure, increased left ventricular blood flow and leads to a more successful outcome from CA than 60/minute and 80/minute compression rates [43-45]. Compressions performed at the rate of 120/minute in humans also produce better myocardial perfusion pressure than 60/minute and 80/minute compression rates [46]. A higher rate of compression results in a higher rate of return of spontaneous circulation (ROSC) [159]. A recent research study shows that compressions during the resuscitation cycle are often delivered at much lower rates than the recommended rates [159].

2.5.1. Definition and recommended target

The compression rate is determined by the frequency of compressions or the number of compressions delivered per minute during the compression series [22, 130, 160] (Figure 2-7). European resuscitation guidelines recommend that the compression rate for both infants and children should be at least 100 cycles/min, though not more than 120/min [100] [15].
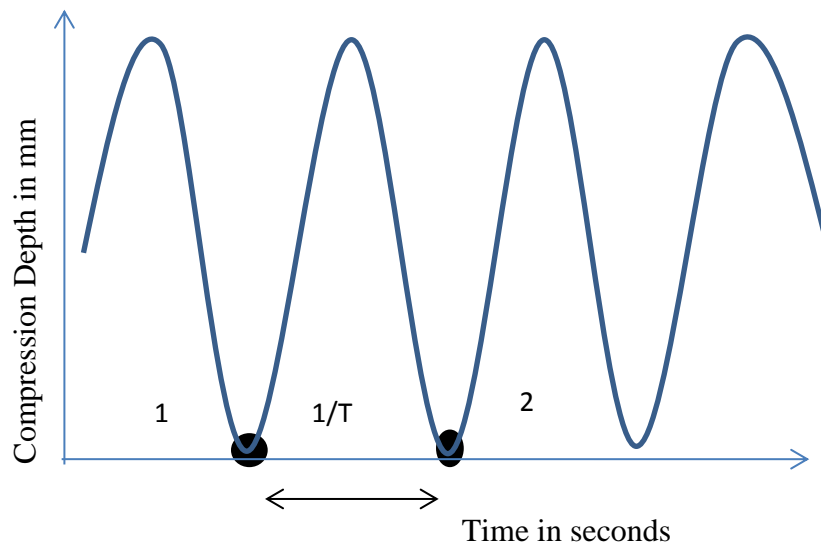
1 = Sternum initial position prior to compression
2 = Decompression of the chest (Chest release force ~ 0)

Figure 2-7: Chest compression rate calculations for each compression and decompression cycle.

2.5.2. The most effective compression rate based on scientific evidence for chest compressions during infant CPR

Twenty infant dogs weighing 6-12kg were used to investigate optimum infant compression rates during CPR by a mechanical chest compressor and ventilator. The study reported that maximum cardiac survival outcomes were observed at the compression rate of 126/min [51]. A compression rate of 120 cycles/min significantly improves the survival rate, both immediately and 24 hours after manual CPR in dogs, when compared with a compression rate of 60 cycles/min [45]. Another study focussing on infant swine surrogates weighing 3.5-6.8kg, reported optimum compression rates of 100-120/min, which increases cerebral blood pressure and myocardial blood flow during CPR [161, 162].

A 7-compartment mathematical model of the human cardiopulmonary system was developed and validated using the experimental data from dog surrogates (average weight: 10 kg) to simulate the optimum compression rates. For this algebraic model of pump filling, the compression rate for maximum flow scales inversely with the cube root of infant body weight (1kg = 267/min; 5kg = 157/min; 20kg = 99/min) [163].

2.6. Duty cycle

Duty cycle (i.e. the compression to release ratio) is another crucial element in the analysis of CPR quality. Mathematical modelling of mechanical CPR resulted in significant improvements in the coronary valve and pulmonary valve blood flow with a 50% duty cycle when compared with compression-relaxation cycles in which compressions constituted a greater percentage of the cycle [164]. Prolonged duty cycles reduce both the return of venous blood to the heart and cerebral blood flow, which leads to a reduced CA survival rate [47-51]. Decreasing the duty cycle could potentially shorten the period of survival from CA [13, 52]. However, a compression duty cycle between 30% and 50% can result in "good" coronary and cerebral perfusion [45, 165, 166]. In real life, a duty cycle at the rate of 50% is both easily achievable and highly recommended [12, 165]. Studies based on infant swine observed an optimum compression duty cycle between 30% and 50% [49, 162].

Duty cycle is partly associated with coronary blood flow, which depends on how fully the chest recoils at the end of each compression [147]. It is calculated by dividing the area under the chest deformation curve by the product of compression depth and time for each compression cycle [130] (Equation 1) (Figure 2-8). The current compression duty cycle calculation was recommended by Kramer-Johansen et al. (2007) when CPR performed manually. The equation is as follows:

$$C = \frac{A}{CD \times T} \quad ------1$$

where DC = duty cycle, A = area under the compression cycle, CD = compression depth, and

T = time spent for total compression cycle.
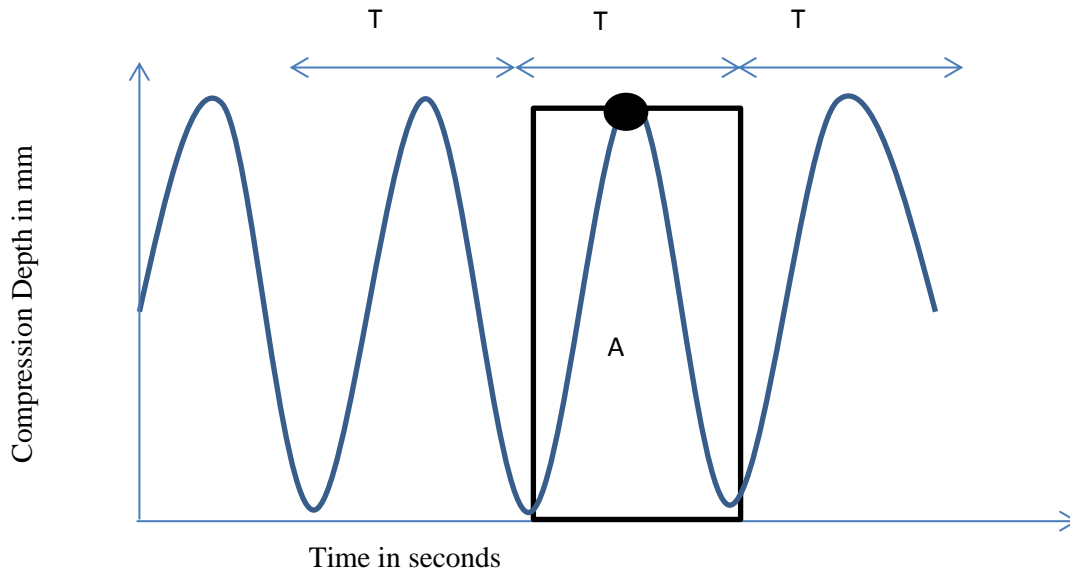
CD=Chest compression depth, A=Area under the curve

T= time spent for total chest compression cycle

Figure 2-8: The method of measuring the duty cycle of manual chest compressions.

2.6.1.   Recommendation target

Significant improvements were observed in the coronary valve and pulmonary valve blood

flow with a 50% duty cycle when compared with compression-relaxation cycles in which com-

pressions constituted a greater percentage of the cycle by mechanical and mathematical mod-

elling of pulmonary blood flow [164]. The effect of a varying duty cycle on clinical and phys-

iological outcomes has not yet been investigated [130]. Coronary perfusion blood flow is partly

limited by prolonged duty cycles(>50%) and partly by un-recoiled compression [147]. American resuscitation guidelines recommend a 50% compression duty cycle because it is easy to achieve with practice [12].

2.6.2.   The most effective compression duty cycle based on scientific evidence for chest compressions during infant CPR

Twenty infant canines weighing 6-12kg were used to evaluate the optimum compression duty cycle. Maximum cardiac output was observed at compression duty cycles of 40% [51]. Duty cycles were further examined using infant swine surrogates weighting 3.5-6.8kg. Optimum compression duty cycles and maximum cardiac output were observed between 30% and 50% [49, 162]. When comparing a 20% duty cycle with a 50% duty cycle, animal (dog) model-based studies showed no significant difference in neurological outcome after 24 hours [45, 166]. Rib and sternal fractures are the most common injuries caused by compressions [167]. In addition, duty cycle at the rate of 50% is easily achievable and highly recommended by American Heart Association guidelines [12, 165]. The international resuscitation guidelines recommended only the compression depth, complete decompression and compression rate [14, 15, 149]. However, the guidelines committee is still looking for strong evidence for the optimal compression duty cycle for iCPR. The remaining CPR quality target will be updated based on future paediatric research.

2.7.   Pauses in chest compression

Pauses between compressions (also called interruptions) are an important element of CPR quality [130] (Figure 2-9). Pauses in compressions are common in actual clinical practice, usually occurring during the compression sequences before and after rescue breaths [168] and Automated External Defibrillation (AED) analysis [169]. When compressions are paused, the actual

numbers of compression cycles delivered during CPR are insufficient. At least 60 compressions must be delivered each minute [57].

Quality CPR improves the chance of surviving CA [170, 171]. During the sudden arrest, however, coronary and cerebral blood pressure depend entirely on compressions. According to previous research studies, interruptions such as mouth-to-mouth ventilations and defibrillators require a period of rebuilding blood pressure to obtain the level of coronary perfusion pressure achieved before a pause [172]. Fewer interruptions ensure better-quality CPR [100]. To be effective, CPR must restore cerebral blood flow and adequate blood flow to organs. Pauses in compressions reduce both coronary perfusion blood pressure and survival rate [172]. The combination of insufficient and interrupted compressions and excessive ventilation rates reduces cardiac survival and coronary and cerebral blood flow [172, 173].

2.7.1.   Reasons for pauses

Pauses are defined as breaks between compressions that can be measured precisely by both the start and the end of the resuscitation series. Any pause longer than 1.5 seconds between two compressions is added to the no-flow time (pause duration) [130]. One study noted that the human delay component between compressions was longer when using an AED as compared to manual compressions [4] (Figure 2-9).
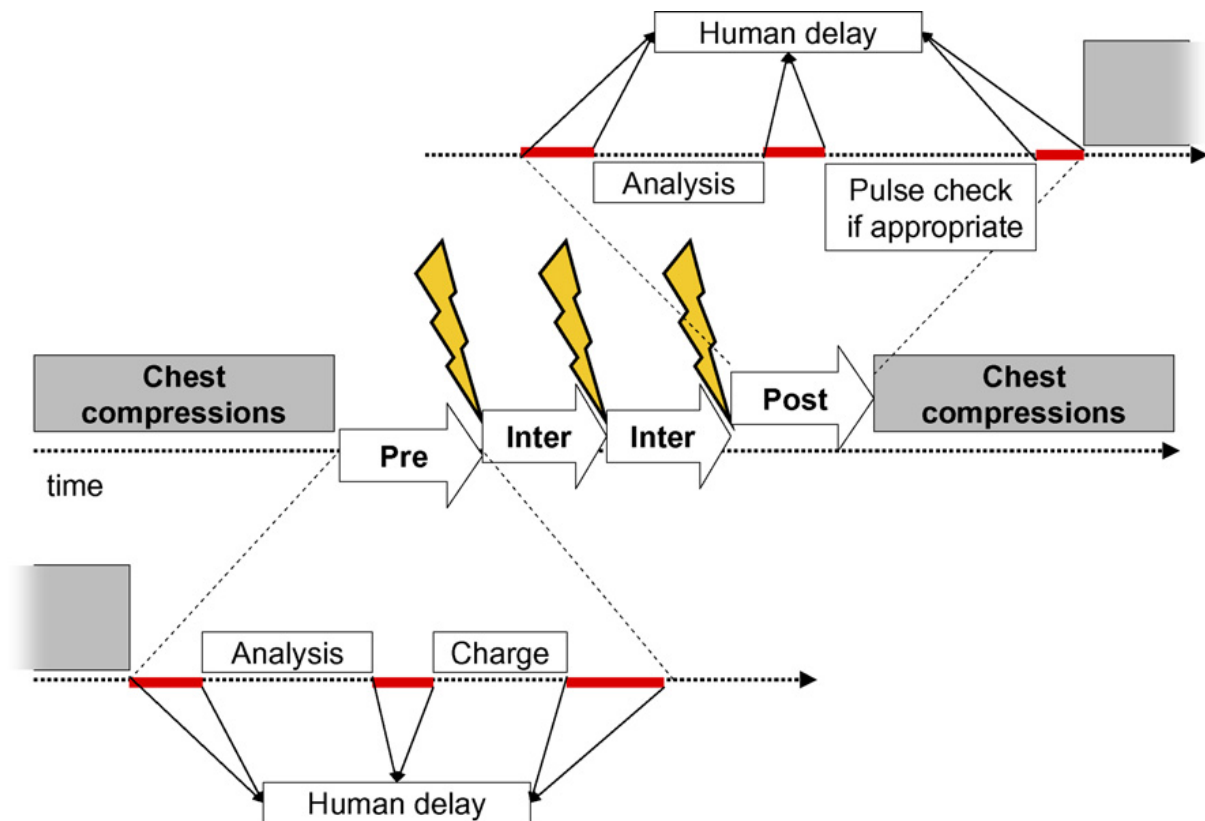
Figure 2-9: The figure demonstrates a chest compression situation with three defibrillation attempts in series with the time intervals. The image is copied from [4].

Two main parts of CPR treatment, ventilation and defibrillator, play a significant role in interrupting continuous compressions. The average time for two mouth-to-mouth ventilation periods, between continuous compressions, is 16-seconds. Therefore, there is no circulatory blood pressure support during nearly 60% of the resuscitation time as a result of a pause in ventilation [174]. Once the advanced airway system is available to the rescuers, the compression rescuer should give continuous compressions at the rate of 100/minute with no pause for ventilation, as recommended by CPR guidelines. The second rescuer should deliver a ventilation breath every 6 to 8 seconds (8 to 10 ventilations per minute) for adult patients [12].

Auto defibrillator attempts are another type of interruption that occurs between compressions. Figure 2-9 depicts three defibrillator attempts during continuous compressions: Attempt 1, the pre-shock pause, is from the last compression to shock. Attempt 2, the inter-shock pause, occurs between two shocks. Attempt 3, the post-shock pause, occurs before the next compression after the last shock. The human delay was calculated as the total pause time minus the time required for rhythm analysis, defibrillator charging and a manual pulse check if appropriate (i.e. organized post-shock rhythm) [4].

2.7.2. The effect of pauses on infant CPR

Animal studies show that pauses in CPR reduce coronary and cerebral blood flow, which lead to poorer survival rate [53, 175]. CPR with continuous compression produces superior, neurologically normal, 24-hour survival than standard ABC (airway, breath, and compression) CPR [176]. Research by Kern et al. (2002a) regarding continuous compression using the swine results show that continuous compression produces superior neurologically normal 24-hours survival than standard CPR [90]. As the compression fraction (the proportion of time spent performing compressions) seems to be a vital element of CA survival, increasing the compression fraction is an effective approach to improving the rate of survival [158].

2.8. Rescue breath

Once a person is identified as someone experiencing CA, a trained rescuer should start compression followed by mouth-to-mouth or bag-mask rescue breaths [12]. Maintaining the airway for CA patients and providing ventilation, also called rescue breaths, are essential elements during paediatric CPR because CA often results from, or is complicated by, asphyxia [14].

Animal studies showed that rescue breaths after ventricular fibrillation (VF) or asphyxia resulted in an improved return of spontaneous circulation (ROSC) and improved CA and neurological outcomes when compared with no ventilation during CPR [54-56]. The purpose of rescue breathing during CPR is to retain sufficient oxygenation and to remove CO_2 [57]. Previous population-based investigations of out-of-hospital paediatric CAs show that when breaths follow compressions during CPR, survival is better than for compression-only CPR for children in CA as a result of non-cardiac causes [58]. Successful paediatric CA resuscitation is based on rescue breathing. For asphyxial CA and prolonged CAs in both adults and children, conventional CPR with breaths is recommended for all trained rescuers [55, 56, 177-179]. However, studies reported that survival was worse with compression-only CPR (no rescue breaths) [58].

2.8.1.   Recommended tidal volume

Ideally, the tidal volume for paediatric rescue breathing should be between 400 and 800 ml/kg [150, 180]. Tidal volume for adults should be approximately 700 to 1000 ml over 2 seconds [12]. Each effective breath (chest rises) should take at least 1-second. If the chest has not risen, head repositioning and 1-second breaths are required [181].

2.8.2.   Hyperventilation

Rescuers consistently hyperventilate OHCA patients during resuscitaion. Hyperventilating during CPR is harmful as it increases intrathoracic pressure and decreases coronary perfusion [148]. Excessive ventilation results in a decrease of venous blood return to the heart [144] and thus, a lower rate of survival from CA [148, 153]. Animal experiments confirmed that hyperventilation could decrease coronary perfusion pressures during resuscitation efforts and worsen survival rate [148].

2.8.3. Compression-to-ventilation ratio

If a rescuer is alone, the recommended compression-to-ventilation ratio is 30:2. If two rescuers are present, the ratio changes to 15:2 [150]. However, if a child's breathing is not normal or is absent, one needs to carefully open the airway and deliver five initial rescue breaths before starting compressions [149]. If the child does not respond, the tongue may be obstructing the airway [182]. If this is the case, the airway should be opened using a head tilt and chin lift for both injured and non-injured victims. After the two ventilation breaths, the rescuer should immediately continue the next set of 30-compressions. This is a most common procedure; one needs to open the airway, using a head tilt and chin lift, for both injured and non-injured victims. After 2-rescue breaths, the rescuer should immediately continue the next set of 30-compressions [16].

2.9. Poor chest compression performance and its effects

While adequate compression depth is vital for achieving an adequate cardiac output, over-compressing the chest has its potential risks, such as rib fractures, cardiac contusion and other thoracic injuries [32]. Another research study shows that deeper compression depths (one-half external anterior-posterior depth) for children is not ideal and may not be safe [139]. Deeper compression depths during CPR may cause damage to intrathoracic organs through the over-compression of the thorax [22, 32-35]. However, recent studies have reported that under-compression depths, also known as shallow compression depths, are performed during CPR in both adult and infant populations [22, 30, 31, 35, 132, 183, 184] and during simulated CPR performance on infant manikins [22, 23, 28, 35, 185]. In addition, a previous study reported difficulty in delivering established targets of compression depths and rates during in-hospital children's CPR [186]. Therefore, current resuscitation guidelines recommended compression

depth of at least 1/3 of the AP diameter (i.e., approximately 4 cm in infants and approximately 5 cm in children), to avoid both thoracic injury and under-compression depths [14, 15].

Incomplete decompression of the chest between compressions (leaning) during the chest release phase is a common problem during CPR performance [187]. As previously mentioned, leaning increases intrathoracic pressure, thus decreasing coronary perfusion pressure and the return of venous blood to the heart and reducing the rate of survival from CA [36-40]. Recent research studies documented that rescuers often fail to achieve complete release depth in compressions during in-hospital, out-of-hospital and simulated CPR performance on the manikin in both adult and paediatric populations [40, 61, 183, 188]. Compression rates were often delivered below resuscitation recommendations; suboptimal compression rates directly correlated with poor return of spontaneous circulation [13]. However, in human subjects, compression performed at the rate of 120/minute has produced better myocardial perfusion pressure than compression rates of 60/minute and 80/minute [46]. Blood flow rate in neonates is best at a compression rate of ≥120 compressions/minute, as recommended by a mathematical study of cardiovascular physiology [42].

Prolonged duty cycle reduces both the return of venous blood to the heart and cerebral blood flow, which leads to a reduced CA survival rate [47-51]. Decreasing the duty cycle could increase the rate of short-term survival from CA [13, 52]. The mathematical modelling of mechanical CPR resulted in significant improvements in the coronary valve and pulmonary valve blood flow with a 50% duty cycle when compared with compression-relaxation cycles in which compressions constitute a greater percentage of the cycle [164]. The effect of varying

duty cycle on clinical and physiological outcomes has not yet been investigated [130]. However, a compression duty cycle varying between 30% and 50% can result in good coronary and cerebral perfusion [45, 165, 166].

2.10.   Limitation of the literature

This chapter reviewed articles with an extensive range of study designs such as post-mortem or infant CA subjects, animal surrogates, medical imaging and infant manikin. This considerable diversity would be the important limitation in investigating iCPR. The previous studies evaluated the effects of compressions by varying the characteristics of the post-mortem or infant CA subjects [133, 189-193]. These studies provide the most relevant results for standardising the most effective compression technique for iCPR; but, they were subject to several critical limitations. Often infant CA subjects brought in for CPR evaluation might have a variety of pre-existing pathological conditions, CA rhythms and extensive cardiovascular drugs. These conditions can potentially bias study results. Most of these studies failed to provide proper records, methods and quality of compressions performed during CPR. Having infant CA subjects for examinations is also a unique challenge, however, its relatively low incidence, unpredictable nature of CA and difficulties in obtaining ethical approval. So, researchers are often limited by observational studies using infant CA subjects.

Medical imaging techniques are more practical methods for non-intrusively examining infant subjects. These studies evaluate infant CA and CPR using medical imaging technique [32, 34, 107, 108, 139, 191, 192, 194-196]. Although medical imaging techniques are a familiar method for analysing human body anatomical data, they also have some unique limitations. Ethical approval is difficult to obtain for imaging healthy infant subjects. Most of the time, the

medical images were used for examining chronically ill infant patient cohorts, which has a more varied anatomical configuration. However, the natural expansion and contraction of the chest during respiration also affects image acquisition, during spontaneous respiration.

Current ethical approval policy significantly restricts CPR research in a clinical environment due to the risks to life. Biomechanically representative infant manikin surrogate models overcome this problem. Instrumented manikin studies are used mostly to establish the correct technique and characteristics of infant compression during CPR [22, 23, 25, 26, 28, 29, 35, 185, 197]. Most of these studies are based on pressure generated in non-validated saline water balloons representing the arterial system [29]. when compared with infant subject studies, animal surrogate studies often result in good control of compressions and CA characteristics [37, 49, 98, 103, 104, 136, 157, 161, 162]. However, age, weight and geometric characteristics of the thorax make matching animal surrogates with infants difficult [198]. Whilst biomechanically representative, infant manikin and animal surrogates' studies are the only current alternative for establishing current techniques and characteristics of infant CA.

2.11. CPR real-time feedback monitor

CPR is often performed poorly, even by well-trained rescuers [199-203]. In particular, depth and compression rate do not meet suggested guideline targets frequently [204]. Leaning on the chest between compressions is a common problem during CPR performance [187], and recent research studies have documented that rescuers often fail to achieve complete release depth during in-hospital, out-of-hospital and simulated CPR performance on the manikin in both adult and paediatric populations [40, 61, 183, 188]. Compression rates are often delivered below resuscitation recommendations [13]. Prolonged duty cycle reduced both the return of

venous blood to the heart and cerebral blood flow, leading to reduced CA survival rate [47-51].

Decreasing the duty cycle could increase the rate of short-term survival from CA [13, 52].

Data confirm that leaning during resuscitation in older children and adolescents can be reduced

by using a CPR feedback device [61]. Different methods have been evaluated to improve the

chest compression performance of rescuers and bystanders and ultimately improve the quality

of CPR [65, 67, 68, 205]. Real-time feedback monitors help rescuers to comply with recom-

mended guidelines [204, 206]. The CPR feedback device allows doctors and rescuers to con-

tinue delivering high-quality CPR [13, 204] for longer than 2 minutes [67]. The provision of

real-time feedback systems during adult CPR is well documented; compression depth, release

force and compression rate quality all were improved through the provision of feedback, during

adult CPR performances [60-63]. In addition, learners who used feedback devices during adult

CPR training had improved compression rate, depth, and recoil compared with learners per-

forming CPR without feedback devices [67, 207-212].

2.11.1.   Adult vs infant CPR feedback system

At present, there is a sufficient number of adult feedback systems available on the market.

Example adult CPR feedback systems, include the CPREzy™ chest compression pad, Pocket

CPR- iPhone application, Zoll PocketCPR, HeartStart-MRx™ and Laerdal CPRmeter.

Currently, there is no real-time *infant* feedback device available on the market. Adult real-time

feedback systems are unsuitable for infants. Infants and children are not miniature adults [99],

compression techniques and thoracic physiology are different than adults. Also, a few studies

report that skin and soft tissue injury happens during adult CPR with a feedback device, such

as Zoll Pocket CPR and HeartStart-MRx [213, 214]. The manufacturers should also redesign

the device, to minimise the risk of injury during chest compressions [215]. The infant's chest

is more sensitive and softer then adults. So, in future adult and infant real-time CPR feedback

devices design should be risk-free, both to rescuers and patients during continuous compressions. The feedback system may also provide a further benefit for clinical resuscitation trials and training purposes. A real-time iCPR feedback device would evaluate and standardise the compression provided during these trials.

2.11.2. Compression of present adult CPR feedback monitors

The present adult CPR feedback device compression study was based on the quality of chest compressions with the use of three CPR feedback devices (Zoll PocketCPR®, Laerdal CPRmeter®, iPhone app PocketCPR®) and standard BLS without feedback in a simulated setting. A study of the output of standard BLS without feedback devices showed that 'none of the CPR feedback devices (Zoll PocketCPR®, CPRmeter®, iPhone app PocketCPR®) improved the quality of chest compressions'. Use of PocketCPR® resulted in significant loss of CPR quality, due to insufficient decompression and incorrect compression points [213]. Also, most importantly, all feedback devices caused considerable delay in starting CPR, which may produce poor outcomes from CA [213]. Whilst using the CPREzy™ feedback device, 95% rescuers reported discomfort in their hands and wrists and the additional effort that was required to perform CPR correctly. It may be due to the hardness or narrowness of the compression plate. Whilst using the device, soft tissue injury occurred to rescuers [215]. However, interpretation of gastric inflations and injuries (e.g. blisters) occurred in rescuers palm while using the PocketCPR® and CPRmeter® [216]. Also, skin and soft tissue injury in patients after CPR with HeartStart-MRx™ have been reported [214]. As a result of this, the compression study showed [213] that there is an immediate need for an improved CPR feedback monitor to deliver quality chest compressions, as recommended by the European CPR Council and the American Heart Association. Currently, there is no CPR feedback device available for iCPR performance in clinical

practice. A "real-time" performance feedback device during iCPR may be valuable for monitoring and assisting rescuers while performing chest compressions on the infant's chest. However, the effect of a performance feedback system and quality of chest compressions has never been quantified. Recent advances in infant resuscitation study results may provide the required evidence to develop a real-time performance feedback system for iCPR.

2.12. Effect of mattress

Implementation of CPR feedback monitors with accelerometers could improve the quality of chest compressions [65, 67, 69, 139, 199, 201, 205, 217, 218]. However, if the patient is on a mattress, the compression depth may be overestimated as the mattress deforms when force is applied to the patient's chest. CPR feedback monitoring without a mattress deflection sensor resulted in inadequate compression depth of less than 50mm [217].

As the result of mattress deformation, an accelerometer between the patient and the mattress is essential for calculating the exact compression depth while CPR is performed [65, 199, 219]. The real chest compression depth can be calculated by subtracting the displacement of the second accelerometer (placed between patient and mattress) from the total displacement of the chest accelerometer.

2.13. Conclusions

Chest compression recommendations for iCPR are described in this review. CPR should be performed either by the TT or TF technique. Compression depth should be between one-third of the external anterior-posterior thorax diameter (approximately 4 cm in infants and 5 cm in children) and residual internal thorax depths of <10 mm. Allowing the complete chest wall

decompressions are important after each compression. The current recommended compression rate for infants is 100-120/min. Duty cycles of 30-50% are supported by scientific evidence [45, 165, 166]. Real-time CPR feedback systems remain to be developed for use in infants and children. Previous studies have investigated the quality of chest compressions performed by expert EPLS/APLS training course instructors. The quality of compressions provided by lay rescuers and BLS trained rescuers currently remain unknown. American Heart Association guidelines recommended that there must be an increase in the number of laypersons who learn, remember and perform CPR and improve the lay rescuer's and healthcare provider's compression quality [202].

2.14. Research aims and objectives

The principal aim of this research is to design and develop a real-time feedback device to investigate the quality of compressions during simulated iCPR. To achieve this aim, the following key objectives were identified.

1. Design and develop a system that quantifies CPR performance, to provide a measurement tool for CPR quality. Investigate the quality of chest compressions provided by BLS resuscitators during simulated iCPR on an infant manikin.

2. Investigate the quality of chest compressions provided by lay resuscitators during simulated CPR on an infant manikin.

3. Investigate the rescue breath count, compression count between rescue breaths and time consumed for delivering the rescue breaths.

4. Compare the chest compression quality of BLS and lay resuscitators both with and without real-time feedback performance system.

5. To develop a system that provides opportunity to enhance CPR quality.

6. Investigate and propose a new technique where there are obvious technical deficiencies versus the international guidelines.

3.   MATERIALS AND METHODS

Chest compression should be the primary action and the highest priority when starting CPR on victims of sudden CA [12, 30]. Continuous, uninterrupted compressions ensure blood flow to the heart, brain and vital organs, and provide the best chance of recovery [34, 100]. The quality of compression is a significant factor [65], and the quality of CPR depends on the following measures: compression depth, release force, rate and duty cycle.

European resuscitation guidelines recommend compressions of at least one-third of the AP diameter for paediatric patients (approximately 4 cm in infants and approximately 5 cm in children). Subsequent complete release force is important. Compression rate should be at least 100 cycles/minute and not more than 120/minute. Compression duty cycle should be between 30 and 50% [15]. Often, however, compression is delivered ineffectively even by well-trained rescuers [13]. Real-time feedback monitors help rescuers to comply with recommended guidelines [204, 206]. CPR feedback devices allow rescuers to continue to deliver high-quality CPR [13, 204]. The provision of a real-time feedback system during adult CPR is well documented. Compression depth, release force and compression rate quality are all improved through the provision of feedback during adult CPR performances [60-63]. Also, learners who used feedback devices during CPR training, had improved compression rates, depth and recoil, compared with learners performing CPR without feedback devices [67, 207-212]. At present, there are sufficient adult feedback systems available in the market. However, there is no feedback device available to guide rescuers during iCPR performances.

The first step in this research was to develop an apparatus to measure current iCPR performance, and to use it for improving the existing chest compression techniques. This will subsequently help in identifying opportunities for improving future performance of iCPR.

3.1.   Design specifications

The feedback device required the following specifications and features, to measure performance during the simulated iCPR:

➢ Ability to measure chest displacement: Chest deflection during compression is the most important measurement since it ensures continued blood flow to the brain and other vital organs.

➢ Ability to exclude mattress deformation: If the CA patient is on a mattress, this may deform when force is applied to the patient's chest, meaning that the compression depth may be overestimated. As a result, a mechanism to exclude this deformation is essential to calculate the exact compression depth while CPR is performed, which could be achieved by positioning a displacement sensor between the patient and the mattress.

➢ Ability to measure posterior displacement: When compression is performed with two thumbs, deflection occurs when the infant's posterior ribs are compressed. Posterior deflection depth is important for calculating the total deflection depth of an infant's chest.

➢ Ability to measure rescue breath count: Once CA is identified, initial rescue breaths and rescue breaths during compressions are critically important for maintaining sufficient oxygenation and removing CO_2 from the blood. This research mainly focuses on rescue breath counts and time required for delivering the rescue breaths.

➢ Applicable to all age groups: Whilst the first priority for this research is to develop a CPR feedback system for infants, a system suitable for all age groups is an advantage.

➢ Portability: Portability is a crucial part of the CPR feedback system as it will be used most frequently outside of hospital and ambulances.

➢ User-friendly: The system should power on easily, set up quickly when required, and have as few electrical wires as possible.

➢ Cost-effective: The sensors and other parts should be low-cost.

➢ Accuracy in readings: Accuracy is a critical factor in medical devices. The sensors were selected according to required specifications for accuracy.

➢ Repeatability: The device must be reliable for use during CPR. The power supply and sensors were selected based on quality specifications.

3.2. Prototype designs

The following designs were considered when finalising the design of the CPR feedback system.

1. Accelerometer-embedded glove

Accelerometer

Accelerometer-
embedded glove
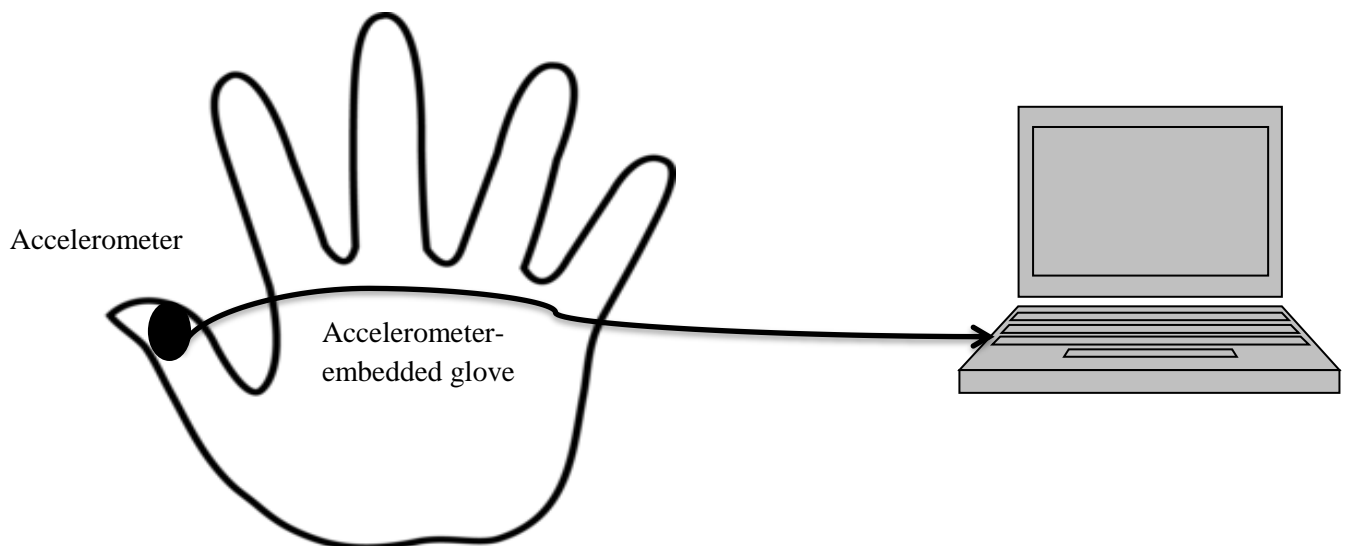
In this design, an accelerometer sensor was embedded in the thumb to measure chest deflections during compression. The accelerometer output signals are transferred to the laptop, which displays the chest deflections and analysis. This system is unable to measure chest defections

when CPR is performed with two fingers. The main limitation of the attached accelerometer is that rescuers cannot re-use the same glove on other patients, due to infection risk. Also, when rescuers are delivering rescue breaths, the accelerometer might produce unreliable results. Rescuers glove sizing is also a major consideration. The system also lacks an airflow sensor for counting rescue breaths and does not measure mattress deformation. Therefore, the single accelerometer-embedded glove technique is not suitable for an iCPR feedback system.

2. Force sensors for measuring chest displacement
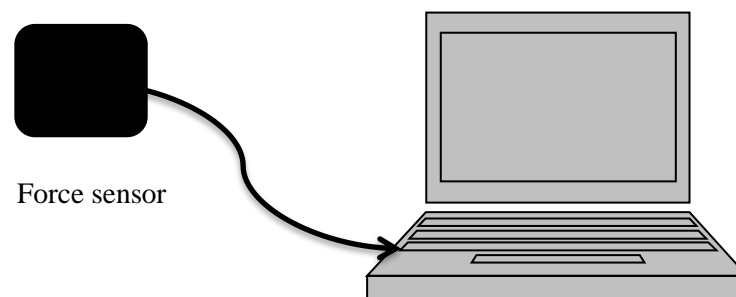
Force sensor

A force sensor measures the applied force during compressions and converts the information into measurements of chest deflections. This technique, however, would only deliver the exact chest deflection for the evaluated manikin stiffness and thus, is not suitable for clinical practice. The laptop then stores the force data on a hard drive for further analysis. The force sensor-based iCPR feedback device is appropriate only for training purposes and simulated CPR performance on the manikin. Depending on their age, every person has a different ribs and chest stiffness. Therefore, the force sensor-based feedback system is not suitable for clinical practice. The stiffness of a manikin chest can be evaluated with a material testing machine. Manikin chest deflection can be calculated using the force-displacement properties.

3. Single accelerometer and flow sensor-based chest displacement measuring method
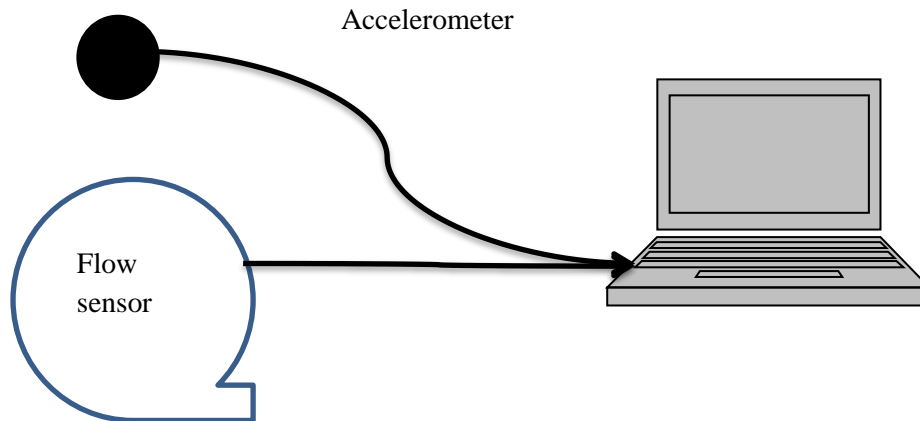
This system is based on an accelerometer sensor for measuring chest deflection and an airflow sensor for measuring rescue breaths. As the single accelerometer can measure anterior deflections only, it is unable to measure posterior deflections and mattress deformations. However, if a patient is on a mattress, the compression depth may be overestimated as the mattress deforms when force is applied to the patient's chest. An accelerometer between patient and mattress is needed to calculate the exact compression depth while CPR is performed on a mattress. Although the airflow rate sensor helps to measure rescue breath counts, performed during continuous compressions, the limited features of the single accelerometer technique make this prototype unsuitable for this research as an iCPR feedback system.

4. Dual accelerometers and flow sensor-based chest displacement device
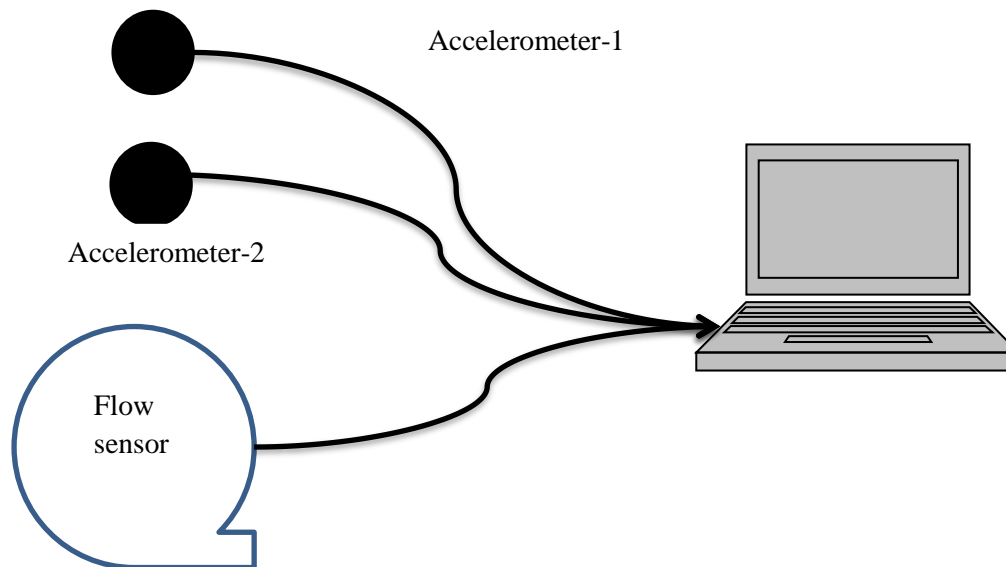
This prototype, based on dual accelerometers and an airflow sensor, adequately measures the anterior-posterior deflections simultaneously during compressions with two thumbs and can measure the anterior chest deflections and the mattress deformations simultaneously during compressions with two fingers. The airflow sensor can detect the rescue breaths. The features of this design fulfilled all primary requirements for monitoring iCPR and assisting resuscitators during simulated iCPR performances. The data acquired from both accelerometers and airflow sensor—both chest deflections and rescue breath count—are displayed on the laptop screen during CPR.

5. Laser sensor-based chest displacement rig

A laser displacement sensor was used to measure chest deflection during compressions. For correct laser beam reflection, the resuscitator is required to wear a small flat reflector plate on the rear side of the hand. This system whilst potentially produce good results during compression with two fingers, though would not measure thumb movement during compression with

two thumbs. Also, the bulky rig might disturb the resuscitators during continuous compressions. This system is also unable to measure mattress deformation and posterior deflections and thus, is unsuitable for iCPR feedback monitoring.

Laser displacement sensor

Laser beam

Chest compressions

Manikin

Rig
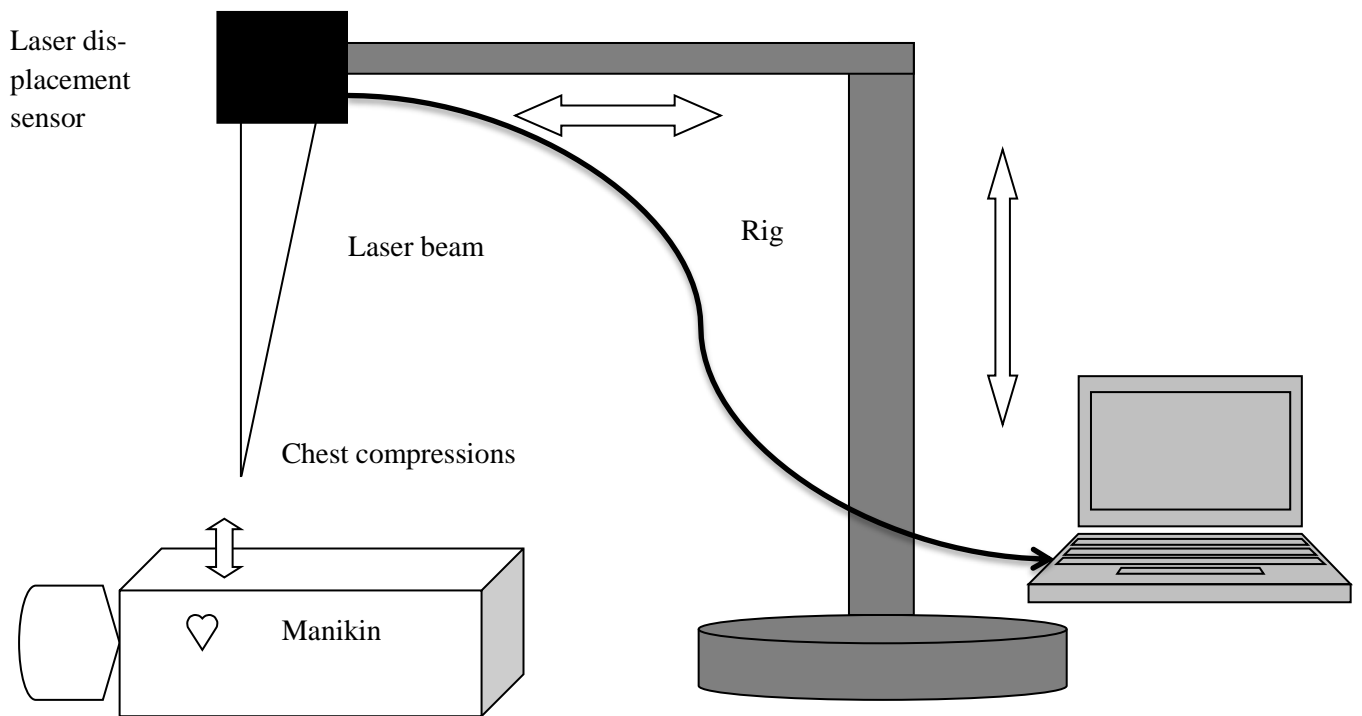
6. Flexible resister-based chest deflection measurement

A flexible resistor could detect chest deflection during compressions. Bending a resistor changes its resistance, relative to the amount of bend in the sensor. The flexible resistor converts the change in bend radius into electrical resistance and then converts it into a measurement of the deflection of the chest. The main issue with this technique is that the entire chest—not just the point of application—deforms during compressions.

Chest compressions

Flexible resistor

Manikin
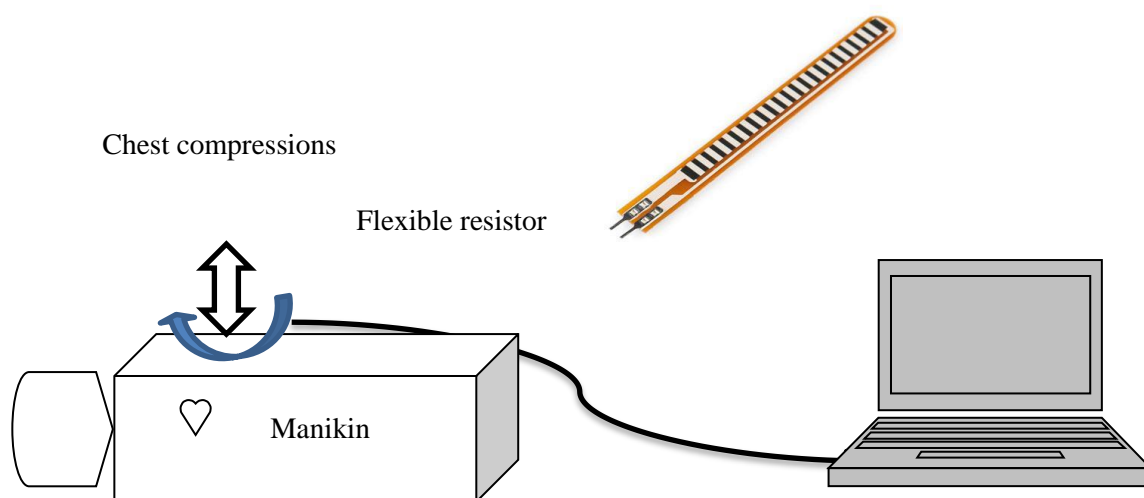
Thus, this method cannot accurately measure chest deflections. In addition, since the entire mattress deforms along with the patient, mattress deflection cannot be measured accurately. Therefore, the flexible resistor-based technique is not applicable for monitoring CPR feedback.

3.3. Systematically evaluating the prototype designs

Evaluating the prototype designs against the required specifications for monitoring CPR performance (Table 3-1) is essential for finalising the prototype CPR feedback device. The primary aims of the device are to measure the chest deflections of the manikin and count the

rescue breaths during simulated iCPR performances. Chest deflection depth is the most important element in CPR, playing the crucial role of pumping blood from the heart to the brain and other vital organs during CA. Compression depth is the most important quality measure during iCPR [14, 15]. However, if the patient is on a mattress, the compression depth may be overestimated as the mattress deforms when force is applied to the patient's chest. An accelerometer between the patient and the mattress is needed to calculate the exact compression depth while CPR is performed on the mattress. As with all medical device designs, reliability and accuracy are the most critical factors. A force sensor measures the applied force during compressions and converts the information into measurements of chest deflections. This technique, however, would only deliver the exact chest deflection for the evaluated manikin stiffness and thus, is not suitable for clinical practice.

This research observed that in a clinical practice, the posterior of the infant is also compressed whilst applying the TT technique, due to the pliant nature of the infant body. Thus, the present research aimed to measure infant's posterior deflection during TT chest compressions using an accelerometer. The purpose of rescue breathing, during CPR, is to retain sufficient oxygenation and to remove CO_2 [57]. Rescue breaths, the maintenance of the airway and provision of ventilation, are essential elements of paediatric CPR because CA often results from, or is complicated by, asphyxia [14]. The present research also considered rescue breath counting whilst compressions were performed on the infant manikin, thus informing the rescue breath setup in the proposed infant feedback device.

Currently, there are adequate types of adult CPR feedback devices available in the market. Adult devices are not, however, applicable for use on infants and children, for whom at present there are no CPR feedback devices available. This present research proposes a real-time feedback system that may be capable of helping patients regardless of age. Portability and ease of

use are essential features for resuscitation-based medical devices, as it is often used in out-of-hospital and ambulances. Sometimes lay people will provide compression to a CA affected victim, so ease of use is an essential element of resuscitation device. Saving a life and not cost is the principal consideration in emergency application devices. Accuracy and repeatability are crucial considerations in all medical devices, which are dealing with patient life. Currently, accelerometer-based devices are widely used for measuring chest deflections, during CPR on adults. Accelerometers do not require any reference surface for measuring displacement, but instead, measure accelerations during movement, based on velocity and displacement.

Table 3-1: The prototype CPR feedback device designs and evaluation of prototypes devices against required features.

Prototype designs	Chest displacement measurement	Mattress deformation measurement	Posterior displacement measurements	Rescue breath count	Applicable for all age groups	Portable	User friendly	Cost effective	Accuracy in readings	Reputability	Final score
Weights	10	8	6	10	4	8	9	4	8	8	
Accelerometer embedded glove	100	0	0	0	40	80	90	40	80	80	510
Force sensors for measuring the chest displacement	70	0	0	0	0	80	90	40	40	80	400
Single accelerometer and flow sensor based chest displacement measuring method	100	0	100	0	40	80	90	40	80	80	610
Dual accelerometers and flow sensor based chest displacement device	100	80	60	100	40	80	90	40	80	80	750
Lased displacement sensor based chest displacement rig	100	0	0	0	40	40	45	20	10	10	265
Flexible resister based chest deflection measurement	60	0	0	0	20	80	45	40	40	40	325

Each features measures in the scale of 10 and the final score was multiplied with the each features weights for finalizing the prototype device.

The dual accelerometers and flow sensor-based CPR feedback device scores higher and fulfils all required specifications for simulated iCPR on the manikin (Table 3-1). The dual accelerometers can measure both chest deflections and mattress deformation performed with the two-finger technique. The accelerometers can also measure both the anterior and posterior deflections with two thumbs, and the flow sensor can measure the rescue breath count. No feedback device currently exists for iCPR—this could be the first device for measuring the anterior and posterior deflections simultaneously. However, since dual accelerometers are able to measure compression depths irrespective of a CA patient's age, this device could ostensibly be used on all CA patients during CPR.

The single accelerometer and flow sensor-based chest deflection measuring method scores second. This method cannot measure the mattress deformation during compressions when the patient is on the bed. Mattress deformation measurement is important, unless the compression depth may be overestimated as the mattress deforms when CPR is performed on the patient's chest. Therefore, an accelerometer is essential between the patient and the mattress to measure the exact compression depth.

The accelerometer embedded glove method scores third, as this method does not measure the rescue breath count and mattress deformation during CPR. Rescue breath is an essential component for successful paediatric CA resuscitation. Conventional CPR, with rescue breaths, is recommended for all resuscitators during CA resuscitation in both adults and children. Therefore, the single accelerometer-embedded glove technique is not suitable for an iCPR feedback system. The force sensor for measuring chest deflection technique is only suitable for training rescuers with manikins and not clinical practice. The ribs and chest stiffness are different for everyone according to their age. Also, this system does not measure the rescue breaths and

mattress deformation during CPR. Therefore, the force sensor based chest displacement technique is not suitable for an iCPR feedback system.

The flexible resister chest deflection technique is not suitable for both the manikin studies and the clinical practice, since when the chest is compressed it deforms, along with rescuer's hands and fingers, there is little variation in resistance during continuous compressions. The accuracy and repeatability of the compression depth is the most significant factor of CPR feedback devices. This flexible resistance strip method is not applicable for either the clinical or manikin-based studies. In case of fixed laser beam reflector, the laser displacement sensor provides high accuracy. However, during continuous compressions, it is difficult to maintain a fixed laser reflector on the surface of a hand. Also, during iCPR, rescuers may use only the fingers. Hence, laser displacement sensors may not provide accurate representations of chest deflections. Therefore, it could be concluded that laser-based chest deflection technique would not be suitable for CPR feedback, both in clinical and manikin-based studies.

3.4.   Detailed dual accelerometers and flow sensor-based proposed prototype design

The dual accelerometers and flow sensor-based iCPR device consists of the following parts and sensors:

> ➢ Accelerometers
> ➢ Airflow sensor
> ➢ Data acquisition unit (DAQ)
> ➢ Power supply
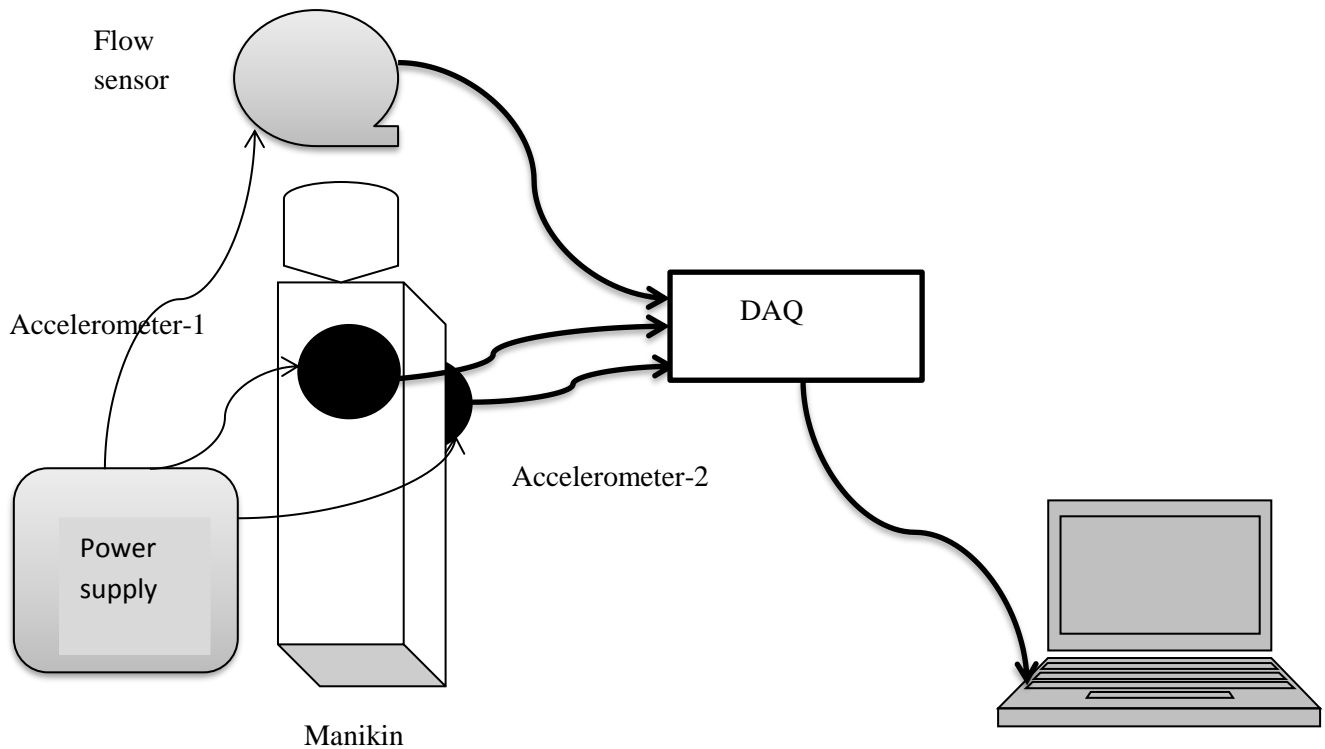
3.4.1. Accelerometer sensor

Accelerometers are single axis electromechanical devices, used to measure the proper acceleration (g-force) of a moving object. Accelerometers measure acceleration in meter per second squared (m/s^2) or in G-forces (g). A single unit of gravity on planet Earth is equivalent to an acceleration of 9.8 m/s^2, but this does vary slightly with distance/elevation above the Earth's surface and geographical location. Evaluation boards (Kionix KXPB5-2050 Evaluation Board Accelerometers) (Figure 3-1) (Datasheet attached in Appendix A.14) provide access to the pins of an accelerometer and contain all of the appropriate decoupling capacitors and pull-up resistors to allow easy connection to a prototyping system. Accelerometer output may be static or dynamic. Static output refers to the constant force of gravity on the sensor, and dynamic output is produced when an accelerometer is moved or vibrated. The operating voltage of the experimental accelerometer is 3.3 volts. The Kionix evaluation board accelerometers provide an

analog output, which is a continuous voltage change and is proportional to acceleration. The maximum swing of the present accelerometer is ±2g, which is sufficient range to work continuously with chest compression depths.

Figure 3-1: Kionix KXPB5-2050 Evaluation Board accelerometers.

The accelerometers were then embedded between two rubber sheets, to produce a rubber pad (Figure 3-2) that will provided a good grip for the resuscitator, both during simulated CPR on the training manikin and during clinical practice in future. Also, rubber pads would be unlikely to cause substantial trauma to the patient's chest during continuous compressions. The embedded accelerometers are moved up and down predominantly in the vertical plane during CPR, which produces acceleration with respect to the velocity of compression. Acceleration is then converted into displacement using a double integration method. Acceleration is converted to velocity in the first integration. In the second integration, velocity is converted to displacement

(Equation 2). The accelerometers were connected to a data acquisition unit (DAQ), to transfer the sensor output voltage to a computer. The sound and vibration suite function of LabVIEW was used to convert acceleration to displacement.

$$x(t) = \iint_0^t a(t)\ dtdt ----2$$

Where, x is the initial position of the accelerometer and a is the initial acceleration of the accelerometer.

Ideally, the position (x) of an accelerometer at any time (t) can be determined from the time dependent acceleration of that accelerometer's embedded rubber pad. Initially, the accelerometer output voltage is converted into the respective acceleration by using the sensor sensitivity characteristics. Then using the above equation (Equation 2), the acceleration is converted into the respective displacement. Equation 2 calculates the true position of the accelerometer, required during continuous simulated iCPR performances. Every time the performance feedback program acquires the analog voltage from the filter cap of each axis, at 200 Hz. The program reads the accelerometers voltage, which represents the position of the rubber pads at that time, such that there is a minimal error in the integration of the intrinsic sensor during the double integration of the accelerations.

The Kionix KXPB5-2050 Evaluation Board accelerometers operating voltage (V) of 3.3V. The zero-g-force offset is V/2 (1.65V), and output voltages above V/2 indicate positive accelerations whereas output voltages below V/2 indicate negative accelerations. Zero volts (0V) would be equal to -2g, and 3.3V would be equal to +2g. The sensitivity of accelerometers is the output voltage change per unit of input acceleration at a typical operating voltage and temperature, measured in mV/g-force, which is 0.66V/g-force.

Figure 3-2: Kionix KXPB5-2050 Evaluation board accelerometer embedded between rubber pads.

3.4.2. Accelerometer calibration

The modified infant manikin was instrumented with an infra-red distance measuring sensor to record the chest deflections during the simulated iCPR performances [23]. However, this infra-red chest deflection measurement technique is not transferable to real-time clinical practice. The accelerometer was placed on the infra-red sensor instrumented manikin's chest during compressions. The accelerometer displacement was compared with the infra-red sensors displacement and then the strength and direction of the linear correlation, also called the Pearson product moment correlation coefficient (r), was calculated. Accuracy of the accelerometer displacement was analysed by simultaneously recording accelerometer displacement and infra-red displacement at 200Hz sampling rate. For the accelerometer displacement and infra-red

displacement were: Run 1=0.97, Run 2=0.95. Run 3=0.96 (Figure 3-3). Infra-red and accelerometer displacements have a strong positive linear correlation, as r is nearly equal to +1. An r value of exactly +1 indicates a perfect positive fit. Positive values indicate a relationship between x and y variables, such that as values for infra-red increases, values for accelerometer also increase, which means that a predicated displacement has a strong correlation with the actual displacement. It was found infra-red sensor displacement has a direct relationship with accelerometer displacement, and therefore, predicted displacement has a linear correlation with actual displacement.

In addition, the root mean square error (RMSE) was calculated to measure the difference between predicated accelerometer displacement and actual infra-red sensor displacement output. For example, if the correlation coefficient quantity (r) is 1, the RMSE will be 0, because all of the points lie on the regression line and there are no errors. Here, however, the correlation coefficient does not equal 1, with the root mean square error equalling 3.6 Rms, which means that the accelerometer displacement is within 96% conformity of the infra-red displacement measures.
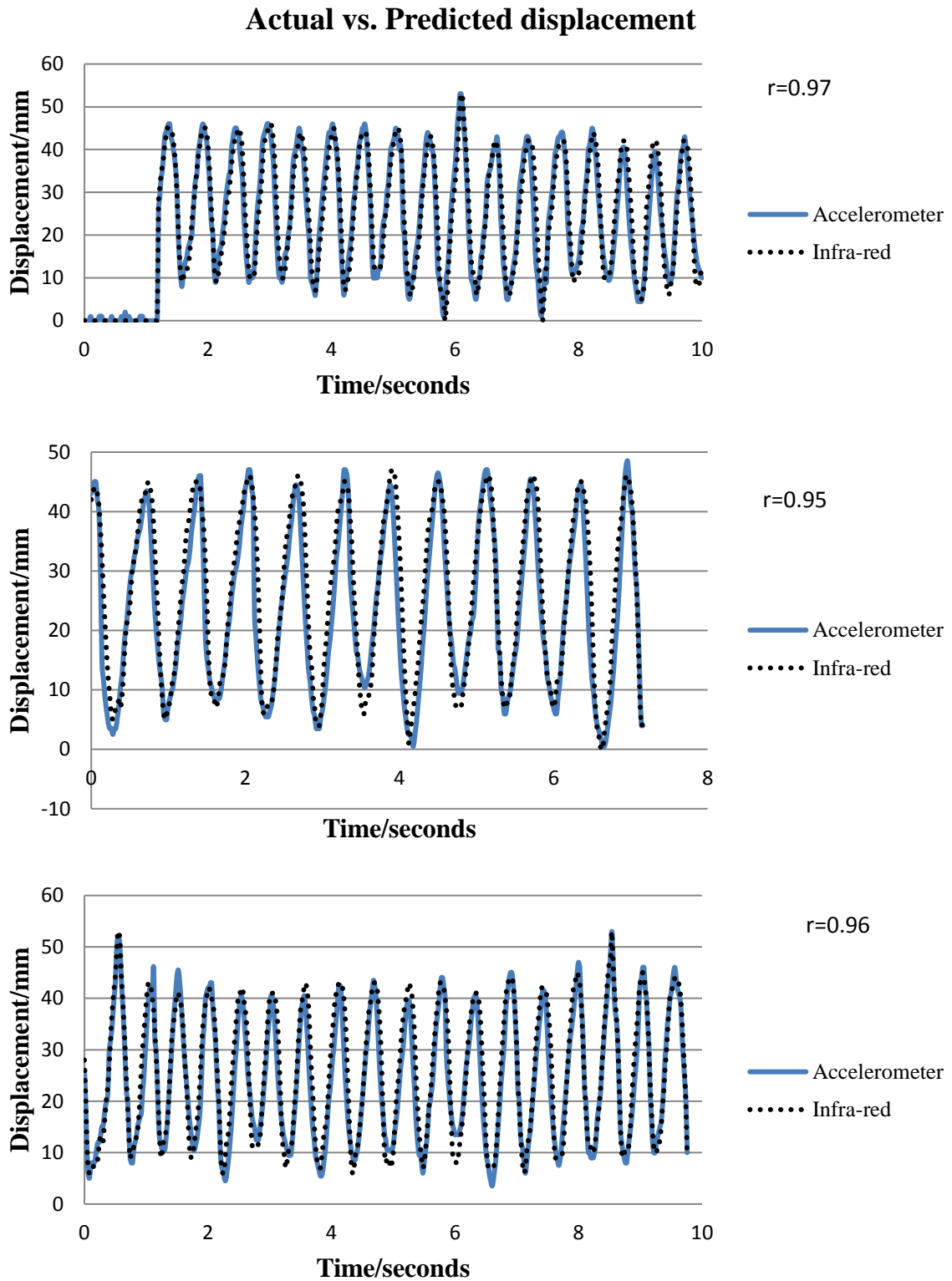
Figure 3-3: Actual displacement (infra-red) vs. predicted displacement (accelerometer) during simulated infant CPR performances.

3.4.3. Accelerometers orientation

During simulated CPR, the accelerometer orientation on the infant manikin is always top/bottom relative to the Earth's surface (figure 3-4). When an accelerometer is accelerated in the +X, +Y or +Z direction, the corresponding axis output will increase with respect to the device acceleration. During iCPR performances, if the sensor orientation is flat, the Z-axis only produces a 'proper acceleration'. Relatively, the X and Y-axis produce nearly zero accelerations (For reference, Appendix A.14, X/Y/Z Output Response versus Orientation to Earth's surface).

TOP

Accelerometer

Bottom

Earth's surface
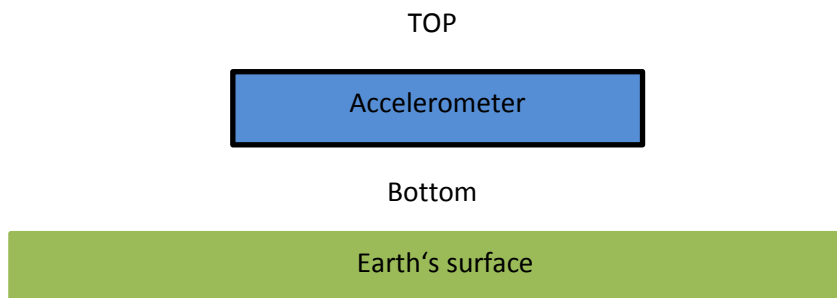
Figure 3-4: The accelerometer orientation during simulated infant CPR performances.

The experimental accelerometer was offset at a 20° angle (Figure 3-5) during chest compressions. The purpose of this experiment was to validate the accelerometer's accuracy when its orientation is out of plane (not perpendicular) with respect to the datum, Earth's gravitational acceleration. It can be assumed that a rescuer would predominantly compress the manikin chest perpendicular to the datum. When force is not applied perpendicular to the chest, the manikin chest would compress out of the plane. As a consequence, the direction of movement of the accelerometer would change. Hence, the accelerometer was fixed at an "offset" 20-degree angle to assess its compressions on the manikin chest (Figure 3-5). The obtained results are described in figure 3-6.

Figure 3-5: Accelerometer was offset at a 20-degree angle during chest compressions, using

a wooden wedge to produce a consistent angulation.

Actual vs. predicated displacement
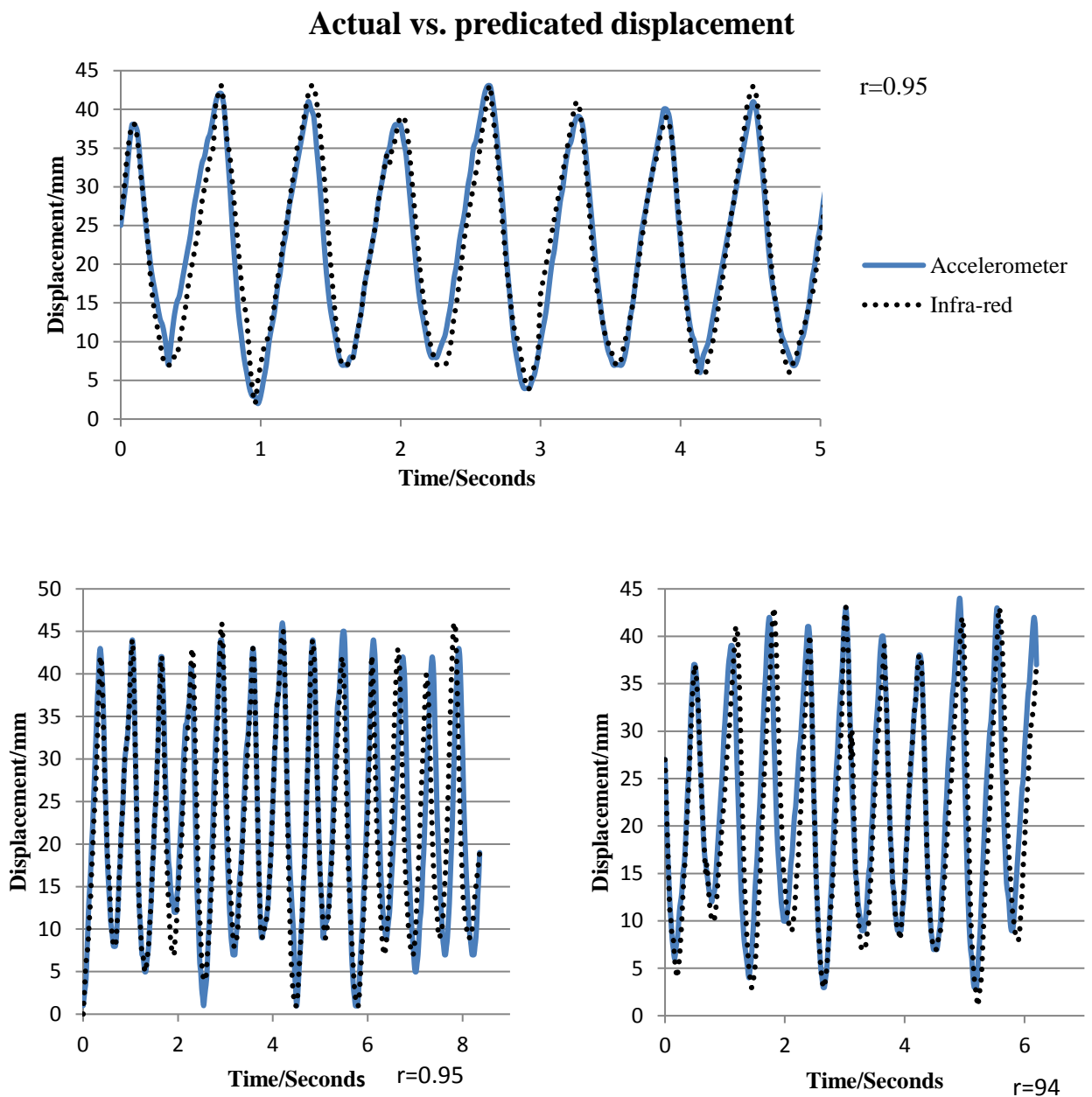
Figure 3-6: Actual displacement (infra-red) vs. predicted displacement (accelerometer) during simulated infant CPR performances. The accelerometer orientation is 20 degrees deviated against ground surface.

The accelerometers displacement (chest deflection) was compared with the infra-red sensors displacement and Pearson product moment correlation coefficient (r) calculated. The Pearson's r for the accelerometer displacement and infra-red displacement were as follows: Run 1=0.95, Run 2=0.95. Run 3=0.94 (Figure 3-6). Infra-red and accelerometer displacements show a strong positive linear correlation; r is close to +1. In addition, the root mean square error (RMSE) was calculated to measure the difference between predicated accelerometer displacement and actual infra-red sensor displacement output. The root mean square error was 4.4 Rms, which means that the accelerometer displacement is within 95% accuracy with the infra-red displacement.

3.4.4. Flow sensor

The flow sensor (Omron ®, model no. D6F-02A1-110) (Figure 3-7) (Datasheet attached in Appendix A.13) was used to measure the ventilation monitoring during CPR. This flow sensor is a precision unidirectional mass airflow sensor with fast response and stable output across a full range. The measuring range of the sensor is 0–2 litre/min. Ideally, the tidal volume, for paediatric rescue breathing, should be within the range of 400–800 ml/kg [150, 180]. The operating voltage is 10.8 V–26.4 V. After compressions, ventilation is the most significant element of CPR. Effective rescue breathing retains sufficient oxygenation and removes CO_2 [57]. If the rescuer is alone, the recommended compression-to-ventilation ratio is 30:2, and if there are two rescuers, the compression-to-ventilation ratio is 15:2 [150]. The present study evaluated ventilation in two ways, with 5 initial breaths and a compression-and-ventilation ratio of 15:2.

Figure 3-7: Image of Omron air flow sensor, model no. D6F-02A1-110.

3.4.5. Flow sensor calibration
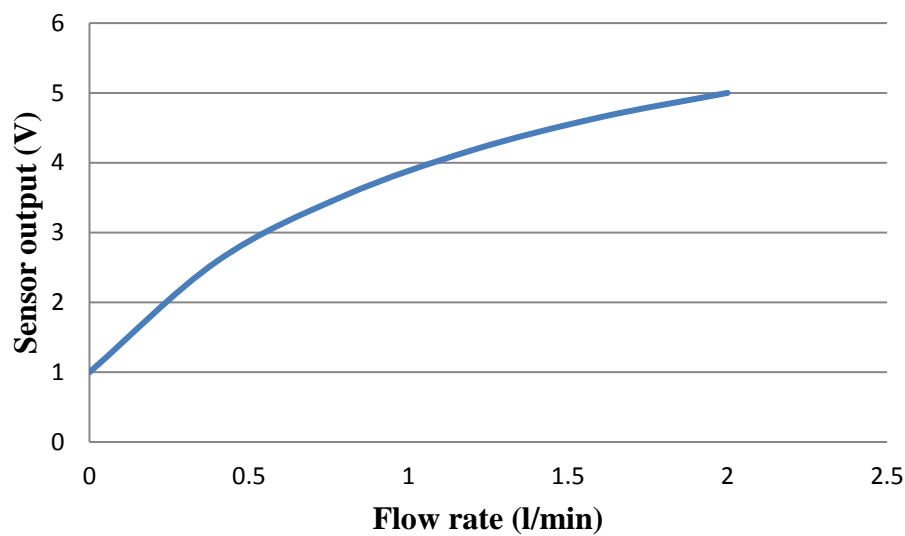
Figure 3-8: The flow sensor output voltage based on the input air flow rate. The maximum flow rate is 2l/min.

The flow sensor was calibrated based on the above graph (Figure 3-8), provided by Omron Electronics. The standard output voltage is 1 volt, when there is no air flow (0 L/min) and the peak output voltage is 5V when the flow rate reaches 2L/min. The flow sensor output voltage is connected with NI DAQ analog input channel to transfer data to the computer for further processing, such as converting voltage into flow rate, and storage. The present research investigated whether rescuers are delivering the required number and rate of rescue breaths during CPR and in particular, the initial rescue breath and subsequent breaths every 15-compressions.

3.4.6. Data acquisition unit (DAQ)

A National Instruments data acquisition unit (DAQ, Model no. NI USB 6008) (Figure 3-9) was used to acquire the signals from the sensors and transfer them to the computer. The DAQ unit provides eight single-ended analog input channels with a resolution of 12 bits and a maximum sample rate of 10kS/second. The two accelerometers and flow sensor require a total of seven analog channels for the iCPR feedback system. Data acquisition is a powerful, cost-effective and flexible process for acquiring sensor output voltages and transferring them to a computer (Figure 3-10). LabVIEW (National Instruments, TX, USA) software was used to write the program that converted the voltage into respective measurements. The maximum data sampling rate of the DAQ was 1 KHz.

Figure 3-9 : NI Data acquisition unit (DAQ, Model no. NI USB 6008).

Figure 3-10: The data transfer protocol from sensor to computer via DAQ.

3.4.7. Power supply unit

A lightweight and cost effective "in-house" power supply was developed to convert alternative current (240v, AC) into low voltage direct current (DC) Whilst removing current spikes, and regulating the voltage to 3.3V and 12V. The process allows the sensors to work efficiently without overheating (Figure 3-11).

Figure 3-11: In-house-made power supply unit.

3.5.   Prototype details and working principles

The accelerometer and flow sensor output voltages were transferred from the DAQ to the computer. Prior to beginning compressions, accelerometer 1 was placed on the manikin's chest, and accelerometer 2 was placed on the supporting surface. Accelerometer 1 was used for measuring infant chest deflections during compressions, with accelerometer 2, positioned on the rigid table supporting the manikin, constantly reporting zero deflection. In a real-life scenario, a patient who had collapsed from sudden CA would possibly be placed on a mattress before compressions were performed and/or during transport to the hospital in an ambulance. To evaluate the effectiveness of this system in such scenarios, the manikin and accelerometer

2 were positioned on a mattress and CPR performed using the two-finger (TF) method of compression. The actual displacements of the chest were calculated by subtracting the mattress deformation from actual chest deflection (Figures 3-12 and 3-13).
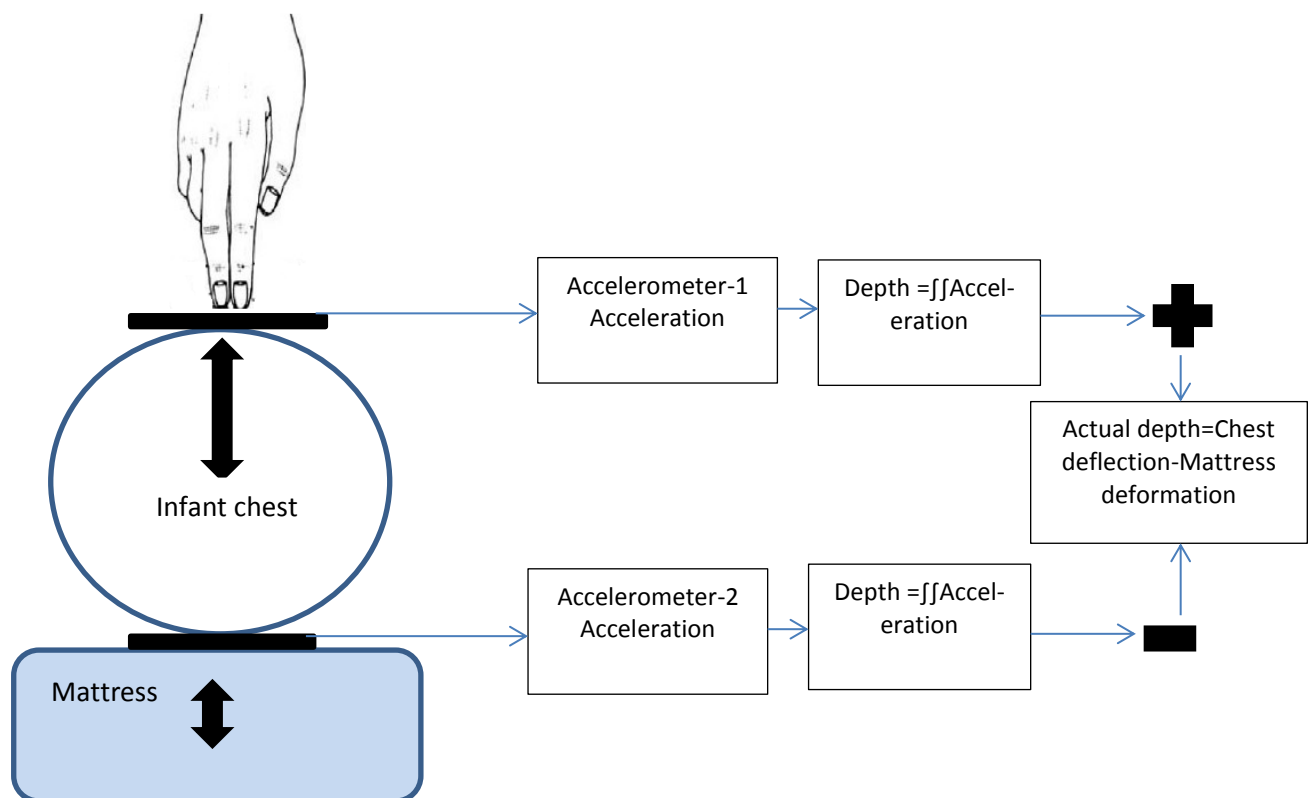
Figure 3-12: Actual chest deflection was calculated during two fingers CPR on a mattress.
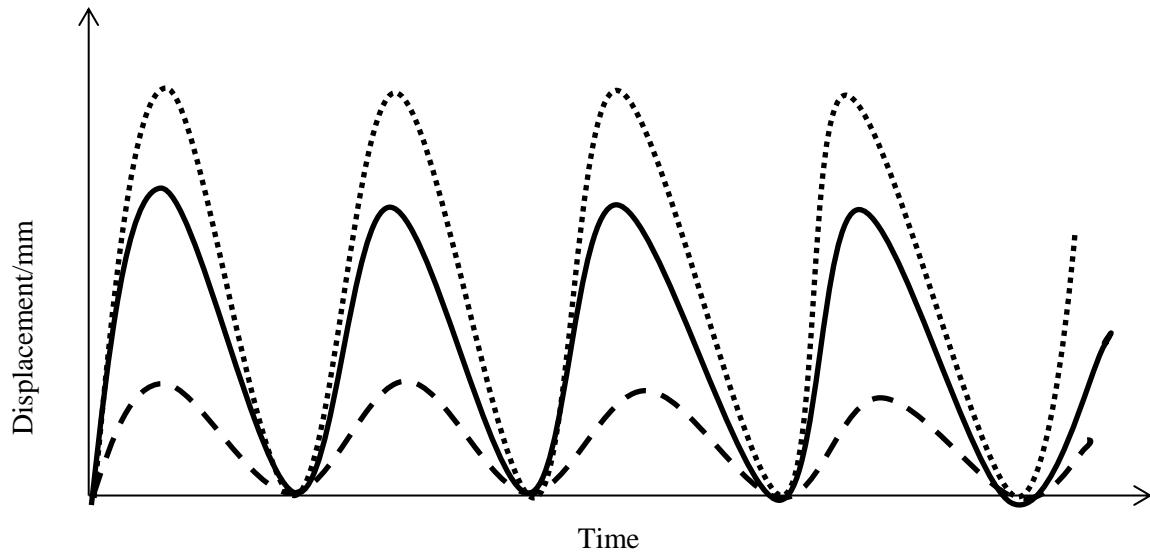
Figure 3-13: Dotted line: anterior chest deflection (accelerometer-1); dashed line: mattress deformation (accelerometer-2); continuous line: actual chest deflection=accelerometer 1 displacement –accelerometer 2 displacement.

When compressions were performed with two thumbs, accelerometer 2 was held under the infant manikin to measure posterior deflection. The anterior deflection (accelerometer 1) and posterior deflection (accelerometer 2) voltage signals were transferred to the computer via the DAQ for further analysis, such as converting acceleration voltage into displacement and displaying the real-time AP displacement on the computer screen. Actual deflections of the chest were calculated by sum of the anterior and posterior deflections (Figures 3-14 and 3-15). The performance feedback program collected accelerometer and flow meter sensor output voltages and analysed them before displaying them on the laptop screen in real time along with the audio feedback to the rescuer. These results assist the rescuers in achieving the current evidence-based quality measures for iCPR performance.
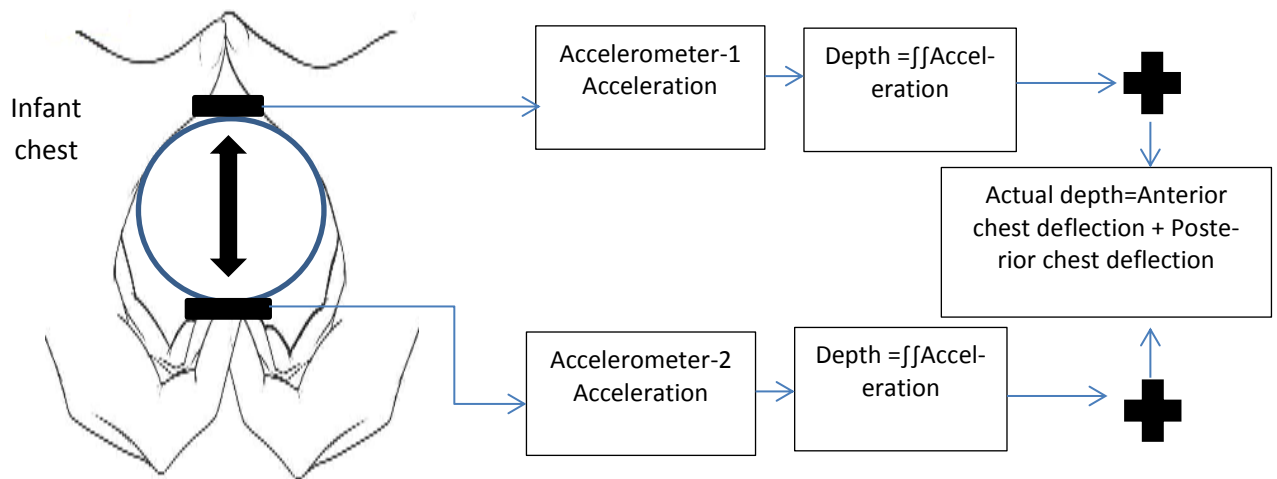
Figure 3-14: Actual chest deflections were calculated by adding the anterior deflection and the posterior deflection measured while CPR was performed with two thumbs.
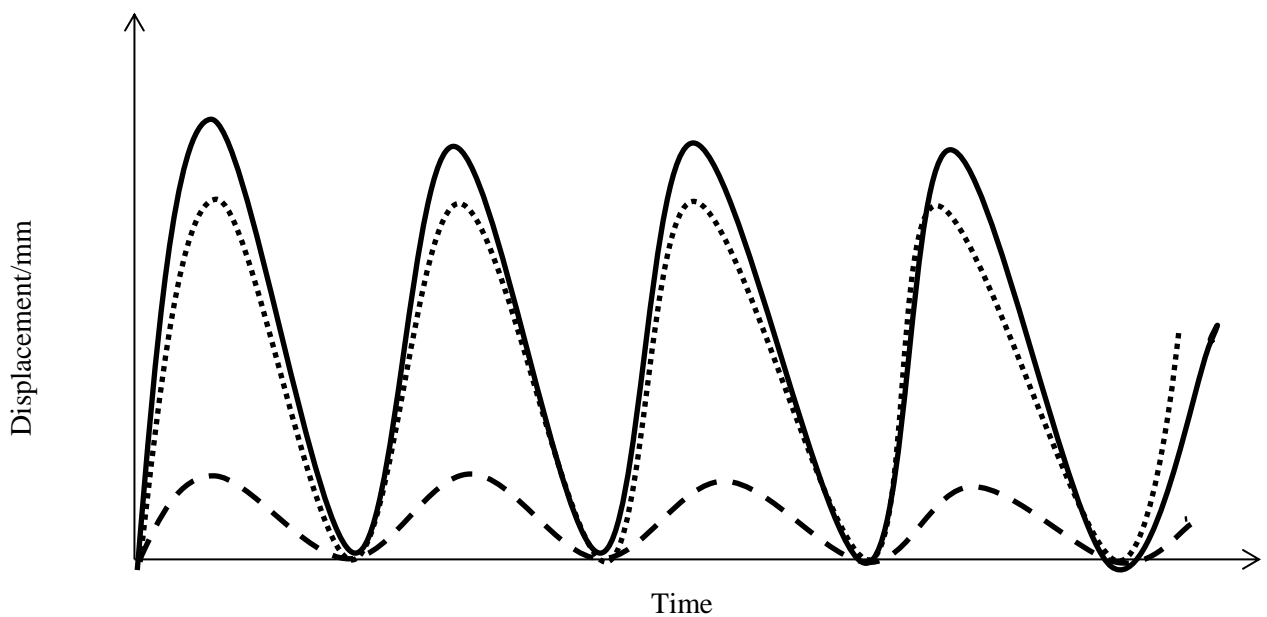
Figure 3-15: Dotted line: Anterior chest deflection (accelerometer-1); dashed line: posterior chest deflection (accelerometer-2); continuous line: actual chest deflection=accelerometer 1 displacement + accelerometer 2 displacement.

3.6.   Manikin design

Laerdal® ALS CPR infant training baby manikin (Laerdal® ALS Baby, Laerdal Medical, Stavanger, Norway) (Figure 3-16) was selected for use in this research study. This manikin represents a three-month-old, 5kg male infant and is commercially available. This original manikin was modified during a previous study to allow a maximum compression depth of 53mm. The physical compression characteristics of the modified manikin were evaluated using an MTS 858 material testing machine, compressed at a rate of 1 mm/second.   Mean compression stiffness was calculated as 3.63 ± 0.006 N/mm (Figure 3-17). The external AP thoracic diameter (the most antero-posterior of the manikin thorax) of the manikin was measured to be 105mm.
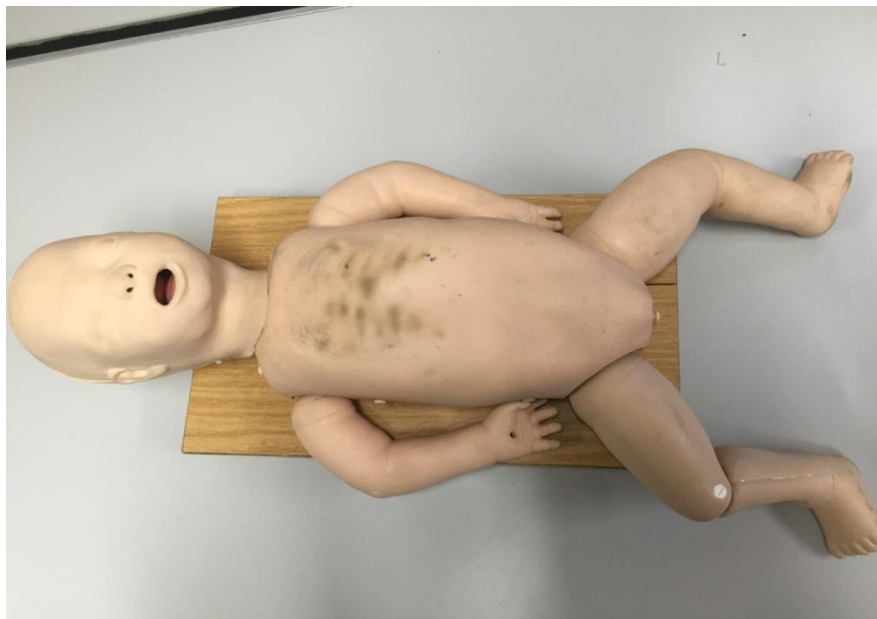
Figure 3-16: The modified manikin with a maximum compression depth of 53mm.
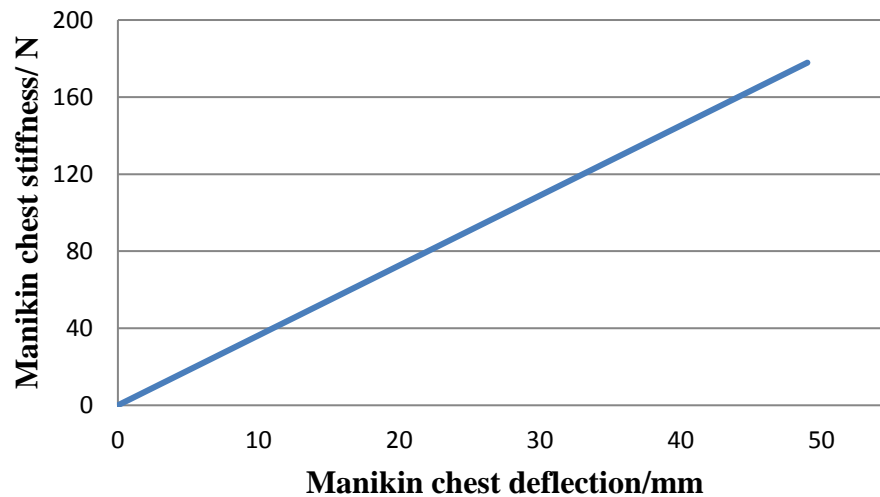
Figure 3-17: Modified infant manikin antero-posterior force-deflection properties. Maximum achievable compression depth was 53mm.

3.7.   Methods

The simulated CPR performance on the infant manikin study was approved by the Ethics Committee, Cardiff University School of Engineering, Cardiff, UK. The approved research protocol, documentation and approval letters are attached in Appendix A.8 and A.12. The simulated CPR performance studies were conducted across two populations, with distinctly different levels of expertise: BLS (Basic Life Support-trained, e.g. police officers, firepersons) resuscitators and lay resuscitators (i.e. those who have no experience in CPR).

3.8. BLS resuscitators

Twenty-eight BLS resuscitators were recruited for this study. Participant Details (Appendix A.11) and Participant Consent forms (Appendix A.10) were distributed to all potential resuscitators before conducting experiments. The participants were briefed on the experimental procedure using the standard experimental sheet and research protocol before beginning the simulated CPR performance. All questions were answered and once the resuscitators were satisfied, they were asked to sign the Participant Consent and Participant Details forms. Individual participants' results were shown to every participant after their simulated CPR performance completion. Gender, the field of expertise, clinical experience, current certification, time since last certification and number of previous infant resuscitations performed were collected via the Participant Details Form. The study comprised 9 male and 19 female participants, all of whom were certified in Paediatric Life Support (PLS), a BLS-equivalent qualification specific to the paediatric population (Table 3-2).

Fourteen (50%) participants were randomised to the 'feedback' group and the remaining participants to the 'no-feedback' group. The no-feedback group's 'mean time since last instructor certification' was 2.3 ($\pm$1.2) years, whilst mean clinical experience was 6.9 ($\pm$2.2) years. The feedback group's 'mean time since last instructor certification' was 2.5 ($\pm$1.3) years, whilst mean clinical experience was 5.3 ($\pm$3.1) years.

Table 3-2: Comparison of demographics for the 'no feedback' and 'feedback' groups

	No Feedback Group	Feedback Group	P-value
Total Number of Participants	14	14	1
Gender			
Male n(%)	5 [29]	4 [35]	0.84
Female n(%)	9 [71]	10 [65]	0.72
Field of expertise			
Registered Nurse /n(%)	14 [88]	14 [88]	1
Mean clinical experience ±SD /years	6.9±2.2	5.3±3.1	0.79
Current certification			
PLS /n(%)	14 [88]	14 [88]	1
Mean time since last certification ±SD /years	2.3±1.2	2.5±1.3	0.12
Number of infant resuscitations performed			
None /n(%)	0 [0]	5 [29]	0.1
<5 /n(%)	3 [36]	1 [6]	0.22
5-10 /n(%)	7 [43]	4 [24]	0.36
11-20 /n(%)	4 [24]	2 [15]	0.65
>20 /n(%)	0 [0]	4 [24]	0.1
χ-squared tests were used to calculate the p-value to compare differences between group			
PLS, Paediatric Life Support			

The significant 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 two groups (Table 3-2). A study sample size of 14 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 3.0.10 [220]).

3.9.   Lay resuscitators

Thirty-eight lay participants were recruited for this study. Participant Details form and Participant Consent forms were distributed to all potential participants prior to conducting the experiments. Participants were also briefed on the experimental procedure using the standard experimental sheet and research protocol before beginning the simulated CPR performance. All

questions were answered, and once the lay participants were satisfied, they were asked to sign the Participant Consent and Participant Details forms. Individual participants' results were shown to every participant after their simulated CPR performance completion. Gender, the field of expertise, clinical experience, current certification, time since the last certification, and a number of previous infant resuscitations performed were collected via the Participant Details form. Study participants consisted of 20 male and 18 female lay rescuers (Table 3-3).

Table 3-3: Comparison of demographics for the 'no feedback' and 'feedback' groups			
	No Feedback Group	Feedback Group	P-value
Total Number of Participants	19	19	1
Gender			
Male n(%)	8(42)	12 (63)	0.19
Female n(%)	11(58)	7 (37)	0.19
Field of expertise	None	None	-
Current certification	None	None	-
Number of infant resuscitations performed	None	None	-
χ-squared tests were used to calculate the p-value to compare differences between group			

The significant difference between the demographics of both groups was 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 3-3). A study sample size of 19 participants per group was able to adequately detect a mean difference of 0.8 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 3.0.10 [220]).

3.10. Experimental procedure

The manikin, feedback device and laptop were set up in a separate room before recruiting the BLS participants for simulated CPR performance (Figure 3-18). Participants were randomly

assigned to either the no-feedback group or the feedback group. All participants were instructed to engage in three stages of simulated CPR: continuous compression only for a period of 1-minute; 5-initial rescue breaths through an air flow sensor and continuous compressions on the training manikin for a period of 1-minute; and 5-initial rescue breaths through the air flow sensor followed by 15-compressions and 2-rescue breaths for a period of 1-minute. Compression depth and release force against time were recorded at a sample rate of 200Hz throughout the CPR episode. Full recovery was allowed for all participants after each CPR episode. No-feedback group participants were blinded to performance feedback, but feedback group participants were permitted to benefit from performance feedback.
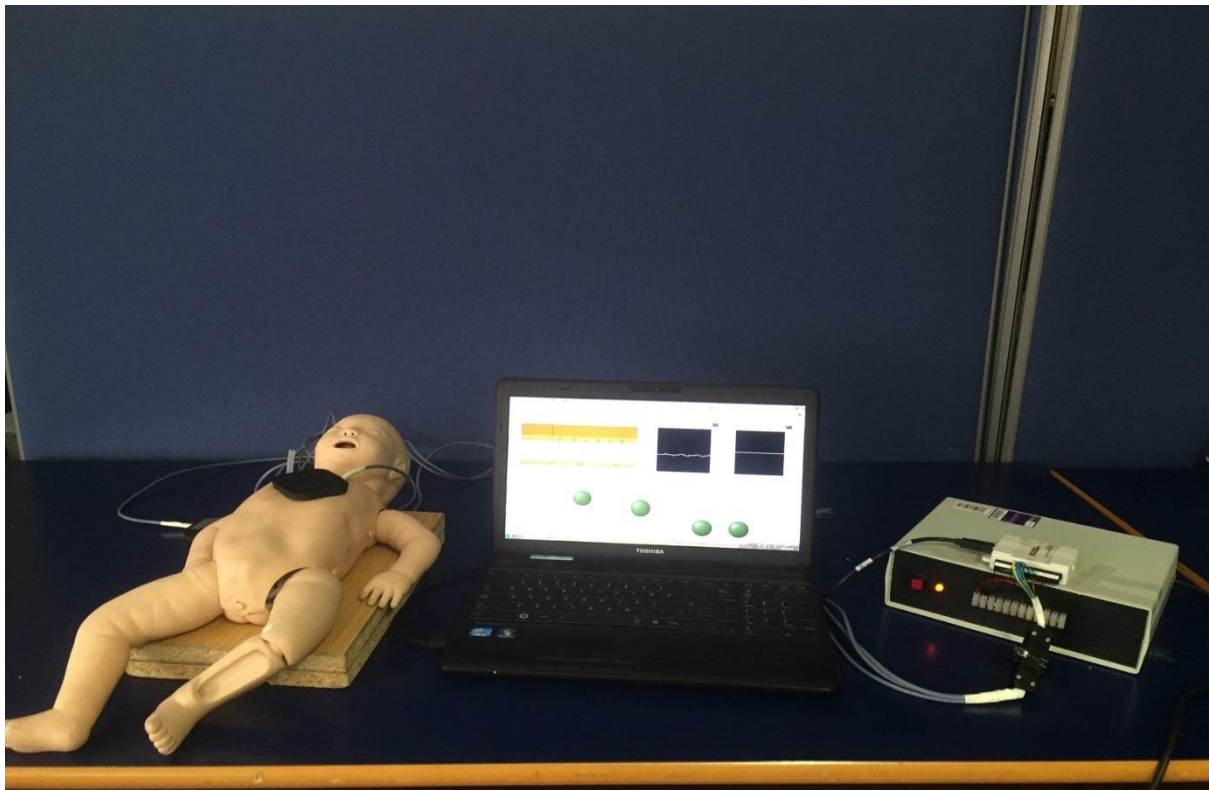
Figure 3-18: The feedback device and laptop were set up in a separate room before recruiting the participants for simulated CPR performance.

3.10.1. Data analysis

Each participant's simulated CPR performance was recorded, including compression depth, compression release force, compression rate and compression duty cycle, achieved in all three compression stages. Quality indices were used to calculate the proportion of compressions for each participant that complied with current quality targets. The CPR quality measures and quality targets for BLS resuscitator performance on the simulated training baby manikin are as follows:

- ✓ Compression depth: Target: 35–43mm. European and UK resuscitation guidelines and American Heart Association Guidelines for Cardiopulmonary Resuscitation recommend an adequate compression depth at least one-third of the external AP diameter of the chest, approximately 4cm in infants [15, 137, 138]. Thoracic over-compression, causing a residual internal AP chest depth of <10mm, may potentially cause intrathoracic trauma [32, 133].

- ✓ Release force: Target: <2.5kg. A 2.5kg chest release force during the decompression phase would significantly increase intrathoracic pressure and hinder the return of venous blood to the heart [38].

- ✓ Compression rate: Target: 100–120 compression cycles/min. European and UK resuscitation guidelines and American Heart Association Guidelines for Cardiopulmonary Resuscitation recommend a compression rate of at least 100 compression cycles per minute, but not more than 120 compression cycles per minute [15, 137, 138].

- ✓ Compression duty cycle: Target: 30–50%. Compression duty cycle oscillating between 30% and 50% can result in "good" coronary and cerebral perfusion [45, 165, 166].

Hence, the most effective and highly recommended duty cycle ranges were between 30% and 50% [69, 100]. Studies on infant animals support the same [49, 162].

The thoracic over-compression measure was calculated to quantify thoracic over-compressions. Finally, to calculate the overall quality of compressions, the proportion of compressions that simultaneously achieved all four primary quality targets was calculated. Simulated CPR performance data are presented either as means with standard deviations or medians with interquartile ranges for each infant compression stage. The no-feedback and feedback groups' mean differences are reported with 95% confidence intervals. After testing for data normality, results were statistically analysed by independent Student T-tests.

3.11. Baseline compression performance of BLS rescuers

BLS rescuers simulated iCPR performances on the infant manikin were evaluated against current guidelines-based quality targets for iCPR [14-16]. However, guidelines recommended the targets for only compression depth, release force and compression rate. Compression duty cycle target was (30-50%) recommended by previous studies [12, 49, 162]. Participants were asked to perform continuous compression only for a period of 1-minute. Each participant's simulated CPR performance data were recorded, including compression depth, compression release force, compression rate and compression duty cycle, achieved during continuous compression stages. Quality indices were used to calculate the proportion of each participant's compressions that complied with the current quality targets. CPR quality measures and quality targets for BLS resuscitators' performance on the simulated training baby manikin are illustrated in Figure 3-19.
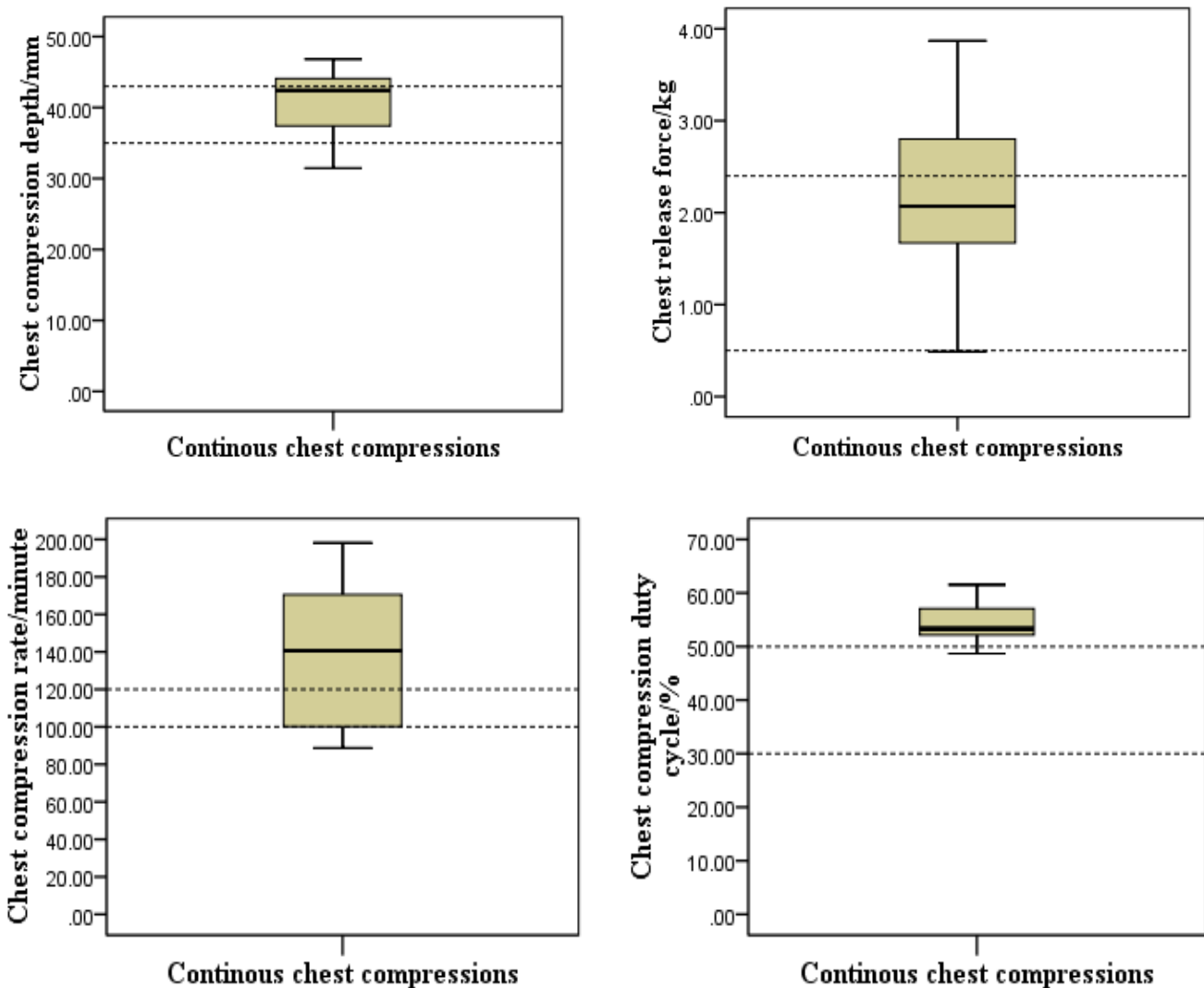
Figure 3-19: Illustration of mean compression depths, release forces, compression rates, and duty cycles achieved by BLS resuscitators using the two-thumb (TT) technique without feedback. Current evidence-based quality targets are illustrated by dashed lines: compression depth targets (35–43mm), release force targets (<2.5 and <0.5), compression rate targets (100–120 compressions/min), and duty cycle targets (30–50%). Box plot represents: centre line of the box—median value of the data, the upper and lower lines of the box—upper and lower quartiles, whiskers—the maximum and minimum values of the data.

3.11.1. Baseline study results

BLS resuscitators simulated iCPR performance on the manikin resulted in deep compression depth, shallow compression depth, excessive compression rate and prolonged compression rate (Figure 3-19). Only 43.4% of the compressions achieved the "good" compression depth (35–43mm) recommended by resuscitation guidelines during iCPR. However, in the BLS group, the over-compression rate (>43mm), also called the thoracic injury index, was 21.3%. The target release force is <2.5kg. Release force quality index (<2.5 kg) for the no-feedback group was only 60.2%, while the complete release force quality index (<0.5 kg) for this group was 4.2%. The BLS resuscitators' compression rate quality index (100–120 cycles/minute) was only 18.1%. For the BLS rescuers, 65.6% of the compression cycles were too fast (>120 compressions/minute) and 16.3% of the compression cycles were too slow (<100/minute). Also, for the BLS rescuers group, the quality compression duty cycles (30–50%) were only 16.4% and prolonged duty cycles (>50%) were 83.6%. Only 1.4% of all chest compressions performed by the BLS resuscitators in the baseline (no-feedback) study were consistent with the four ranges of "good" CPR technique. If these levels of compression quality are consistent with performance in clinical practice, then it is possible that this result could be hindering the survival rate of CA infants. Thus, this research entails designing and developing a real-time feedback system to assist resuscitators during simulated iCPR performances and ultimately, in clinical practice.

3.12.   Programming method and control

3.12.1. Performance feedback program

The performance feedback program is a real-time feedback program to both monitor and assist rescuers (visually and orally), while performing CPR on the simulated infant training manikin.

LabVIEW software was used to write the feedback program (National Instruments, TX, USA). LabVIEW is an integrated development environment designed specifically for engineers and scientists. It is a graphical programming language that uses a dataflow model instead of sequential text lines, which saves time and provides graphical representation to users. In addition, LabVIEW is designed to interoperate with Matlab software to create sequential line programming to solve problems.

The performance feedback program acquires output voltages from the accelerometers and the flow meter sensor to analyse them and then displays them on the laptop screen in real time along with audio feedback to the rescuer. In turn, these results assist the rescuers in achieving current evidence-based quality measures for iCPR (Figure 3-20). The working procedure of the feedback program is described in a flowchart format in Figure 3-21 and the audio-visual metronome program flowchart is shown in Figure 3-22.
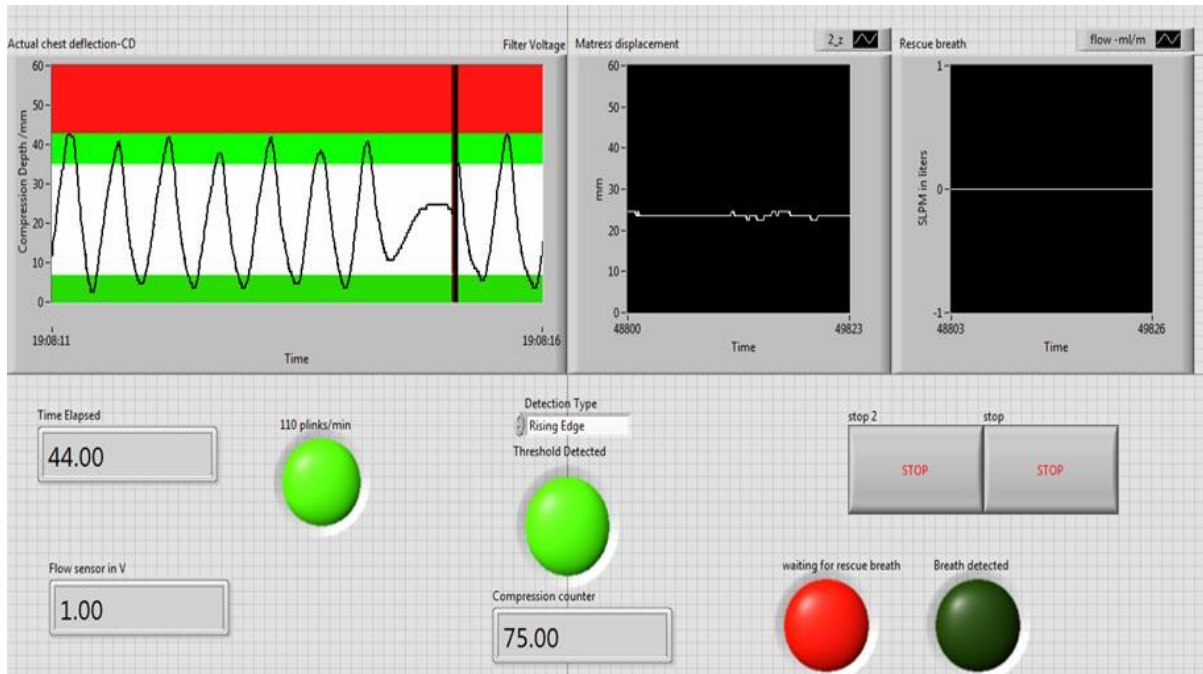
Figure 3-20: Performance feedback program user's view (front panel of LabVIEW).

Figure 3-20 is the resuscitator's view of the performance of feedback program, which consists of actual chest deflection traces, mattress deflection measures, rescue breath quantity measures, rescue breath reminder LEDs, compression rate indicator LED, total compression cycle counter indicator and total time elapsed indicator in seconds. Real-time actual chest deflections are calculated based on the compression method used by the resuscitator. If the rescuer performed two-finger compressions, accelerometer 2 (mattress displacement) would be subtracted from accelerometer 1 (infant's chest) data to calculate the actual deflection of the chest. If the rescuer used the two-thumb technique, both accelerometer displacements would be added to calculate the actual displacement. The actual chest deflections would then be displayed on the screen. The actual displacement window is divided into different colours such as green, white, and red. The bottom green represents the complete decompression (7mm, <2.5kg) and the top green represents the quality compression depth region (35–43mm) (at least one-third of the external AP diameter of the infant's chest). The red colour represents over-compression (>43mm) and the white colour represents under-compression (between 7mm and 35mm). The mattress deformation window shows the accelerometer 2 displacements, and the rescue breath window shows the quantity of rescue breaths as the rescuer blows air through the flow sensor.

The rescue breath reminder LED turns red and alerts the rescuer that a rescue breath is needed after every 15-compressions. The breath detected LED flashes once for every given rescue breath. The compression rate indicator flashes in green along with an audible metronome, both providing compression rate guidance of 110 beats per minute (bpm). The compression counter indicates the number of compressions performed during a particular episode. The time elapsed indicator shows the duration of a particular CPR episode. However, this iCPR feedback system does not provide feedback for compression duty cycle during simulated infant compressions.

Start

Check,
is DAQ
Ready

NO

DAQ-Error

YES

Sampling rate is
200Hz

Channel - 3

Channel - 1

Channel - 2

Accelerometer's output

Flow sensor output
voltage

Convert the voltage into accelera-
tion (m/s^2)

Convert the voltage into air
flow rate (lit/min)

Go to
A

Go to B
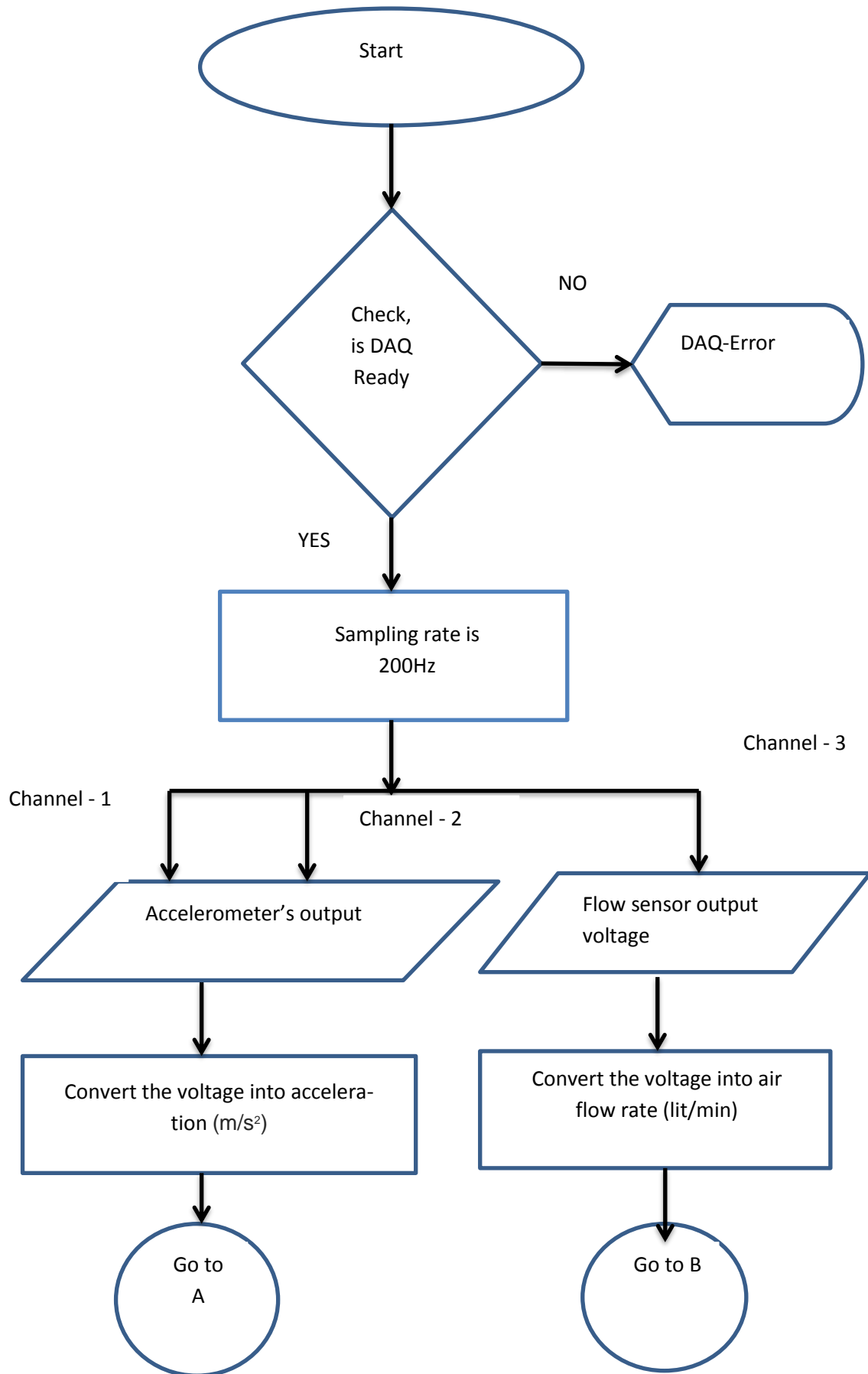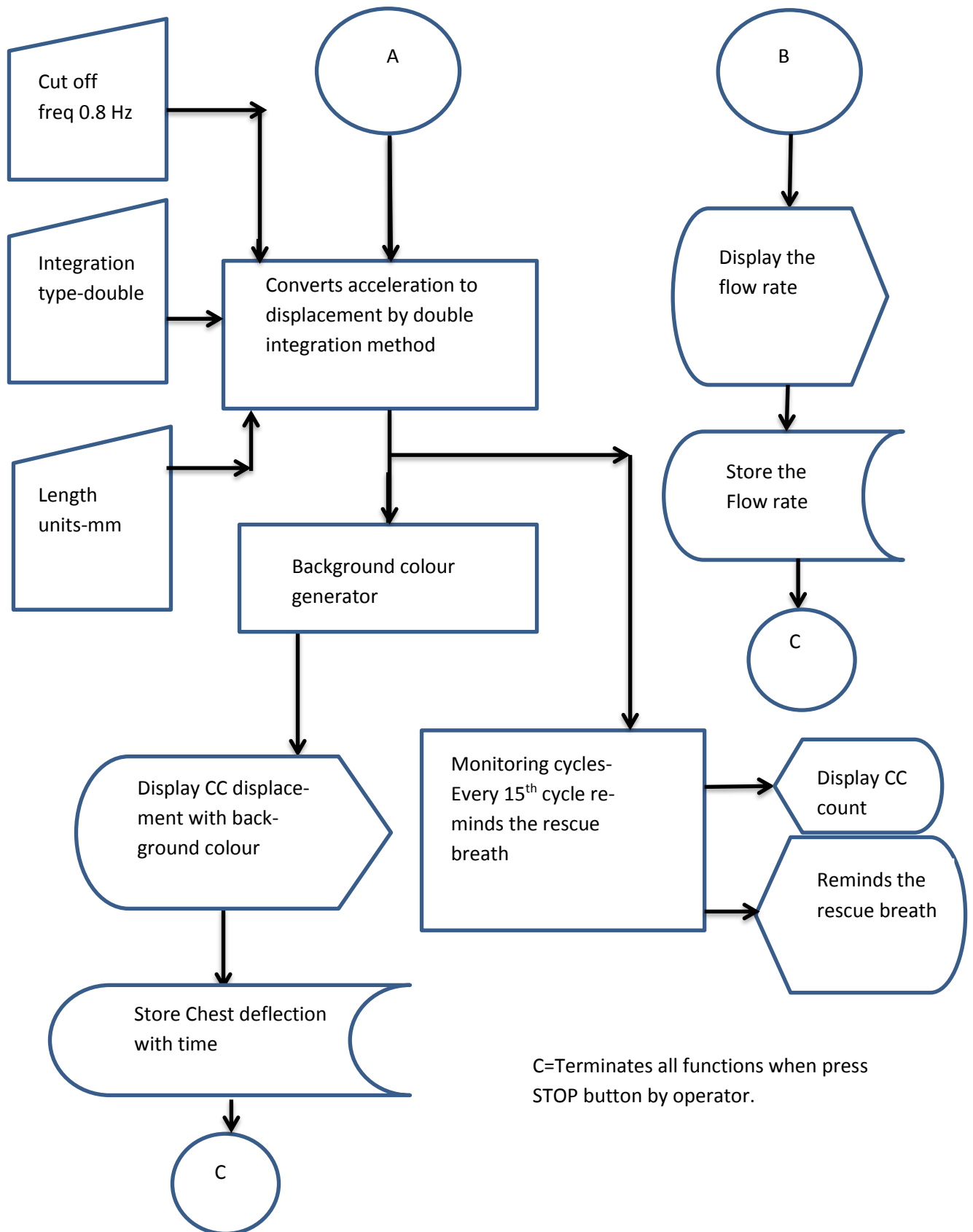
Figure 3-21: Performance feedback program flowchart.
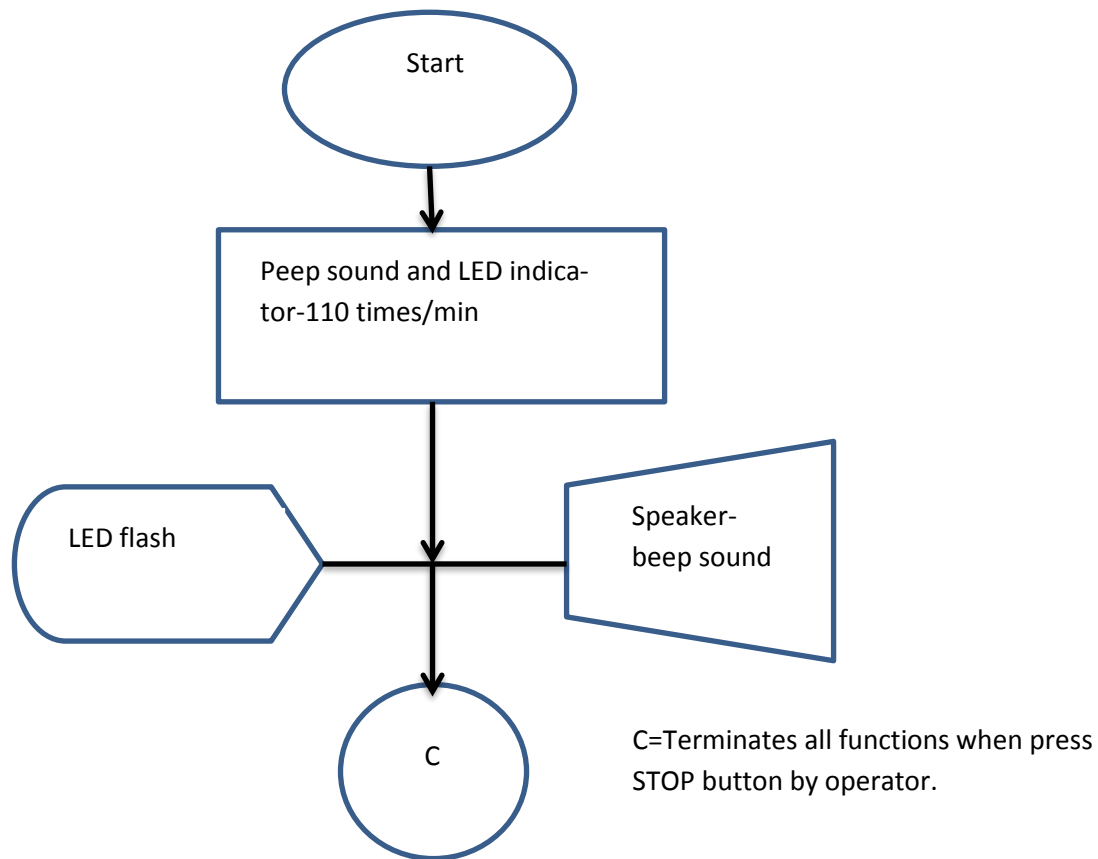
Figure 3-22: Flowchart of the audio-visual metronome program.

3.12.2. Working principles of the performance feedback program

The performance feedback program comprises two parts: the front panel (Figure 3-20), which shows the real-time trace of the user's CPR performance on the infant training manikin, and the block diagram (Figures 3-21 and 3-22). The block diagram, also called the coding part, actually collects the data from the accelerometers and flow sensor, while participants perform CPR on the manikin, and displays the performance on the laptop screen and records the data for further analysis. The LabVIEW block diagram is attached in Appendix A.1-A.3. A real-time CPR performance is displayed on the laptop screen as a 'white line trace' against the compression depth (35–43mm) and release depth (<7mm). A release depth of 7mm corresponds to a release force of 2.5kg.

The front panel of the performance feedback program consists of an actual chest deflection feedback window, a mattress deflection window, a rescue breath window, a time elapse, a compression counter and LED indicators. While participants performed simulated CPR on the manikin, a real-time CPR performance was displayed on the actual chest deflection window as a 'white line trace' against the compression depth and release depth. The top green block represents a compression depth of 35–43mm, which is an ideal depth and complies with current CPR guideline quality measures. The total diameter of the manikin is 110mm. So, one-third of the depth is 35mm, whereas the over-compression of the thorax (compression depth >43) is indicated by highlighting the occurrence in the topmost red colour block. The bottom green block represents the complete release force (<7mm). A release depth of 7mm correlates with a chest release of force 2.5kg.

During CPR both on the flat surface and on the mattress, accelerometer 1 was placed on the manikin chest (Figure 3-23). When CPR was performed on the flat surface, accelerometer 2 was placed on the surface and did not provide any output. During CPR performed on the mattress, accelerometer 2 was placed under the manikin to measure mattress deformation. If mattress deformation is not measured, the chest deflection depth during compression over-estimated than actual deflection.

Actual Chest deflection = Manikin chest deflection - Mattress deformation.

Rescue breaths were monitored and recorded using a flow sensor. Initially, the breath window shows a flat line, but it displays the amount of breath in litres/minute during rescue breaths procedure. The time elapsed section shows the total CPR episode duration in seconds. Each compression is indicated by a blinking green LED on the compressions counter and increments

are shown on the counter. After every 15th compression, the red "waiting for rescue breath"

LED will light, alerting the rescuer that two rescue breaths are needed.
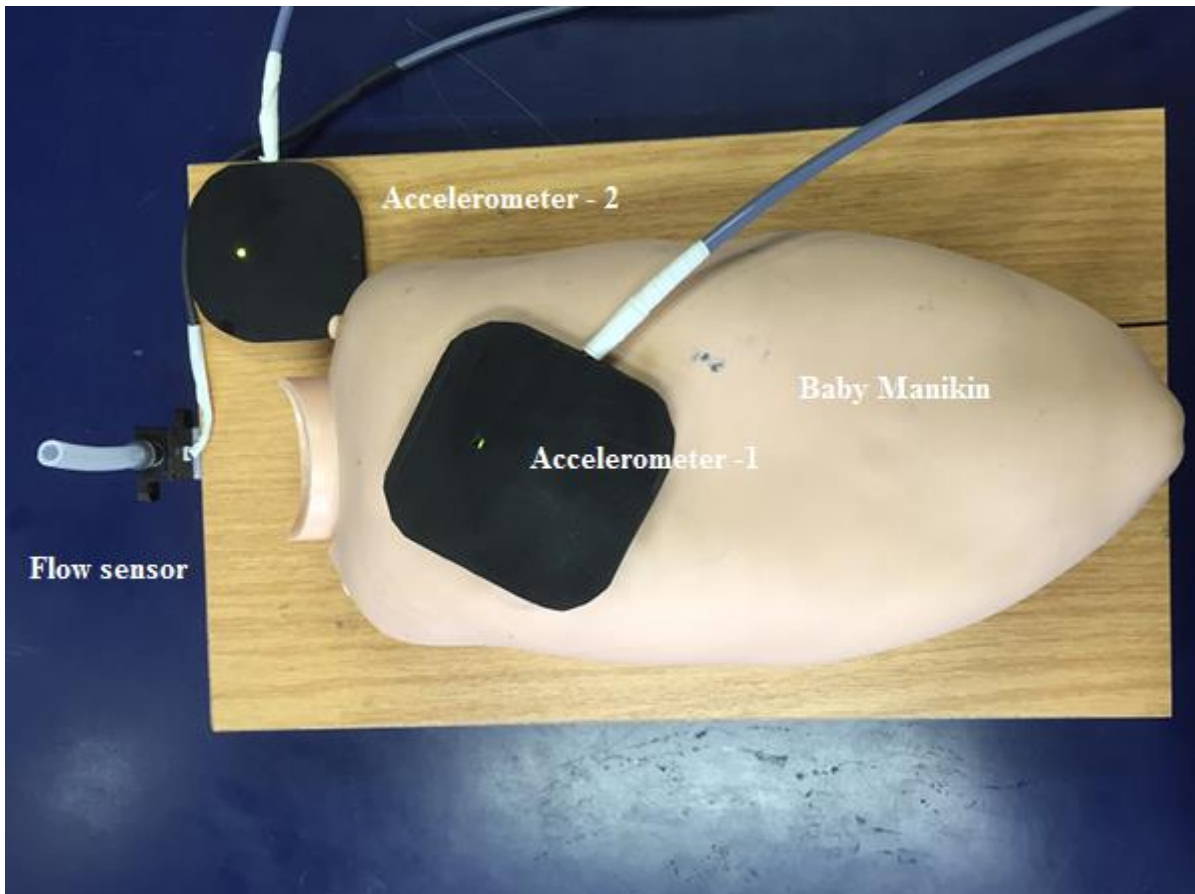
Figure 3-23: Sensor placements on the manikin.

The "breath detected" green LED' blinks once to indicate to the rescuer that the rescue breath

was received. Simultaneously, an audio-video metronome program flashes a green LED that

provides the rescuer with a target compression rate of 110/minute and emits a beeping sound.

Every beep and/or LED blink means that the resuscitator should compress the manikin chest.

3.13. Hardware working principle

Figure 3-24 shows the hardware connection diagram of the feedback device sensors, power supply and laptop. Both accelerometers and the air flow sensor are initially connected to the power supply unit. The accelerometer's operating voltage is 3.3V and the airflow sensor's operating voltage is 12V. The accelerometer and airflow sensor output voltages are then connected to the DAQ. From the DAQ, the computer obtains the sensor outputs using the performance feedback LabVIEW program to display the resuscitator's CPR performance and then stores the data on the hard drive for further analysis.
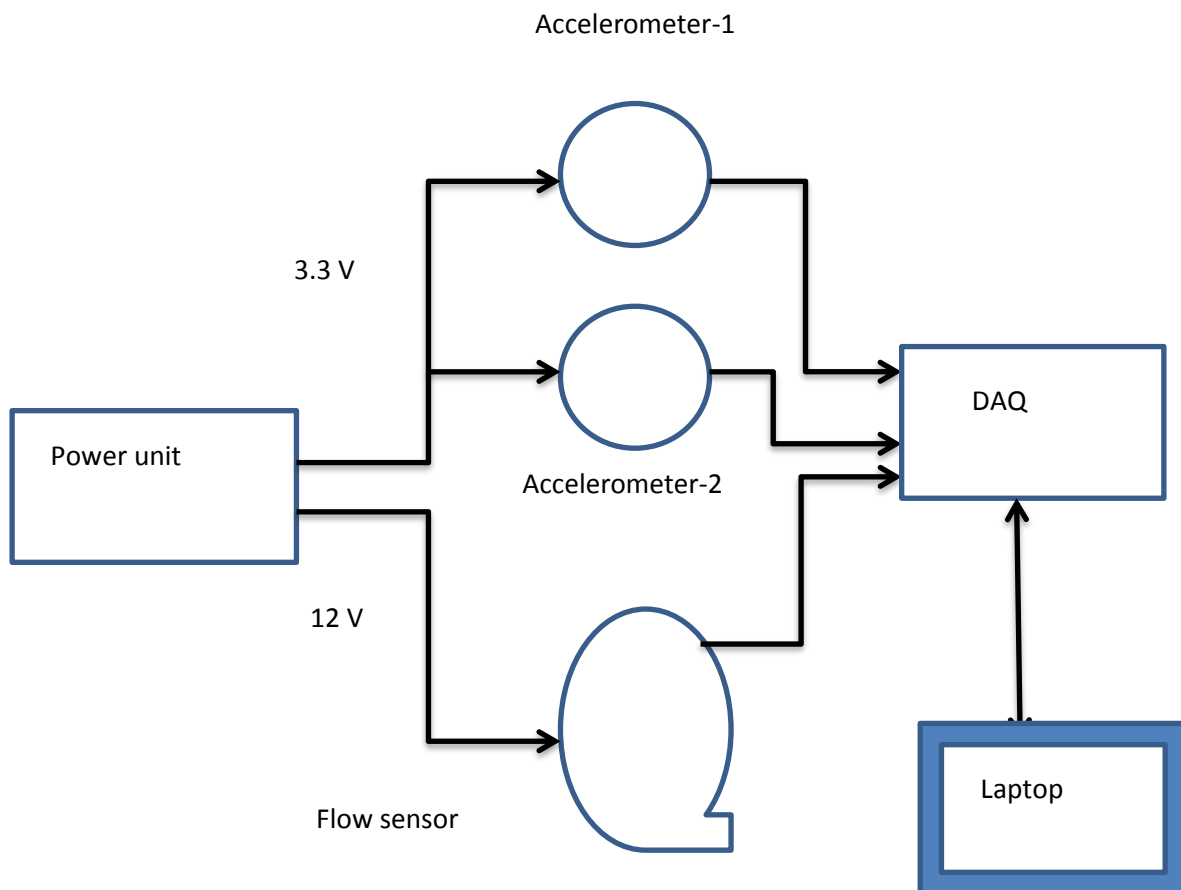
Figure 3-24: Sensors, power supply, and DAQ connection diagram.

3.14. Data analysis technique

3.14.1. Introduction

A Matlab program (The Math Works, US) was used to analyse the participants' CPR quality measures; such as compression depth, release force, compression rate and compression duty cycle for each CPR compression episode. Internationally accepted guidelines [130] were adapted to measure the quality of the resuscitators' simulated CPR performance on the training infant manikin. Compression depth was defined as the maximum sternum deflection, during the compression phase. Release force was defined as the minimum compression force in the decompression phase. Compression rate was defined as the number of compressions delivered per minute during the CPR episode. The compression rate was calculated from the inverse of the time between consecutive chest release forces. Compression duty cycle was defined as the fraction of the time with active mechanical or hand pressure on the chest. This was calculated by dividing the area under the chest deformation curve by the product of compression depth and time for each compression cycle. All CPR quality measures were analysed and calculated using the Matlab program.

The overall CPR quality index was characterised and developed using the a Matlab program by assessing the quality of each element involved in CPR, including compression depth, compression release force, compression rate and compression duty cycle. Quality indicators (Chapter 2, Literature review) were used to calculate the CPR quality for each participant. The thoracic over-compression index was also calculated, since some deaths, as a consequence of CPR, have previously been attributed to over-compression. Overall CPR quality was calculated by the proportion of cycles that achieved all four primary quality targets versus the total cycles delivered in a single CPR episode.

```
            ┌─────────────┐
            │    Start    │
            └──────┬──────┘
                   ↓
        Import data from hard disk
                   ↓
            ◇ Is vector ◇ ────────→ Input must be a vector
                   ↓
        ◇ Is vectors same length ◇ ──→ Inputs must be a same length
                   ↓
        Separate CC depth, release force and respective time points
                   ↓
        Separate recoiled and un-recoiled compression cycles
                   ↓
        Calculate compression rate and duty cycle for each cycle
                   ↓
        Export calculated data to hard disk
                   ↓
                 ( A )
```

Start

Import data from hard disk

Is vector

Input must be a vector

Is vectors same length

Inputs must be a same length

Separate CC depth, release force and respective time points

Separate recoiled and un-recoiled compression cycles

Calculate compression rate and duty cycle for each cycle

Export calculated data to hard disk

A

A

Calculate the Episode duration and total number of cycles

Calculate total quality compression cycles and mean compression depth

Calculate total quality decompression cycles and mean release force

Calculate total quality compression rate cycles and mean compression rate

Calculate total quality Duty cycles and mean duty cycle

Calculate thoracic injury index and total injury index cycles

B

Figure 3-25: Flowchart of the CPR data analyser using Matlab.

3.15.   Working principle

After completion of each CPR episode, the performance feedback LabVIEW program (Figure 3-20) stores the participant's simulated CPR performance data on a computer hard drive as a Microsoft excel file. Every file consisted of three important columns: time count, manikin chest deflection and rescue breath flow rate. Before feeding the participants' performance data to the Matlab program, the actual time is calculated from the time count and stored in one separate column in the same file. As a first step, Matlab verifies that all columns are actual vector data and that each column is of equal length. If data fails any of these conditions, Matlab program displays the respective error message on the screen.

Matlab calculates CPR quality measures based on the internationally accepted method [130]. The Matlab-based CPR data analyser, "in-house" developed program, simplifies the data analysis work (Figure 3.25). The Matlab codes are attached in Appendix A.4 - A.6 and a typical sample plot is attached in Appendix A.7. An example of a typical Matlab program output is as follows:

Episode duration (Seconds):   62.3

Total no of cycles: 124

Mean Compression depth (mm):   40.77

CD quality index (35-43mm) (%):   87.10

Secondary CD quality index (>=36mm) (%):   85.48

mean release force (kg):   1.09

Release depth quality index (>2.5kg) (%):   96.77

Secondary complete RF index(>0.5kg) (%):	19.35
Mean compression rate(cpm):	112.7
Compression rate quality index (100-120 cpm%):	91.93
Mean Duty cycle (%):	41.82
Duty cycle quality index (30-50%):	98.39
Overall CPR quality index (%):	87.09
Deepest compression is (>43mm):	43
no of injuries cycles achieved:	1.00
Thoracic injury index (%):	0.81
Number of no flow times:	0.00
Total quality compression depth cycles:	108
Total target cycles-release force:	120
no of quality compression rate cycles:	114
no of quality duty cycle:	122
Overall CPR quality cycles	101

3.16. Sample data analysis of single BLS rescuer's 5-initial compressions quality

Single participant CPR performance, on the infant manikin, was selected to represent how this research analysed the data, which was recorded during simulated CPR performances. The four quality measures such as compression depth, compression rate, release force, and compression

duty cycle are compared against evidence-based quality target ranges. In total, performances were divided into three groups. The first performance consisted of compression only for a period of 1-minute. The second consisted of 5 initial rescue breaths and continuous compressions for a period of 1-minute. The final performance consisted of 5-initial breaths and repeated cycles of 15-compressions and 2-breaths for a period of 1-minute. The detailed results are described in the following 'Results' chapter. Moreover, the quality of the 5-initial compressions at the start, and after each ventilation pause, was also analysed. This present research is hoping that, if the rescuer starts the compressions with high quality, they will continue with the same quality throughout the full CPR episode.

3.16.1. Example analysis of single BLS compressions using the two-thumb compression technique without and with feedback: continuous compressions only.

Single-participant CPR performances were selected from the no-feedback and feedback groups; because these single rescuers were the best reflection of remaining rescuers performance. Figure 3-26 demonstrates the single-BLS CPR performance without the assistance of performance feedback software, followed by another single BLS rescuer with the assistance of CPR feedback software. The first stage comprised BLS rescuer performance of continuous compressions only, for approximately 1 minute, without ventilation.

Continuous chest compressions-No Feedback

Continuous chest compressions-Feedback
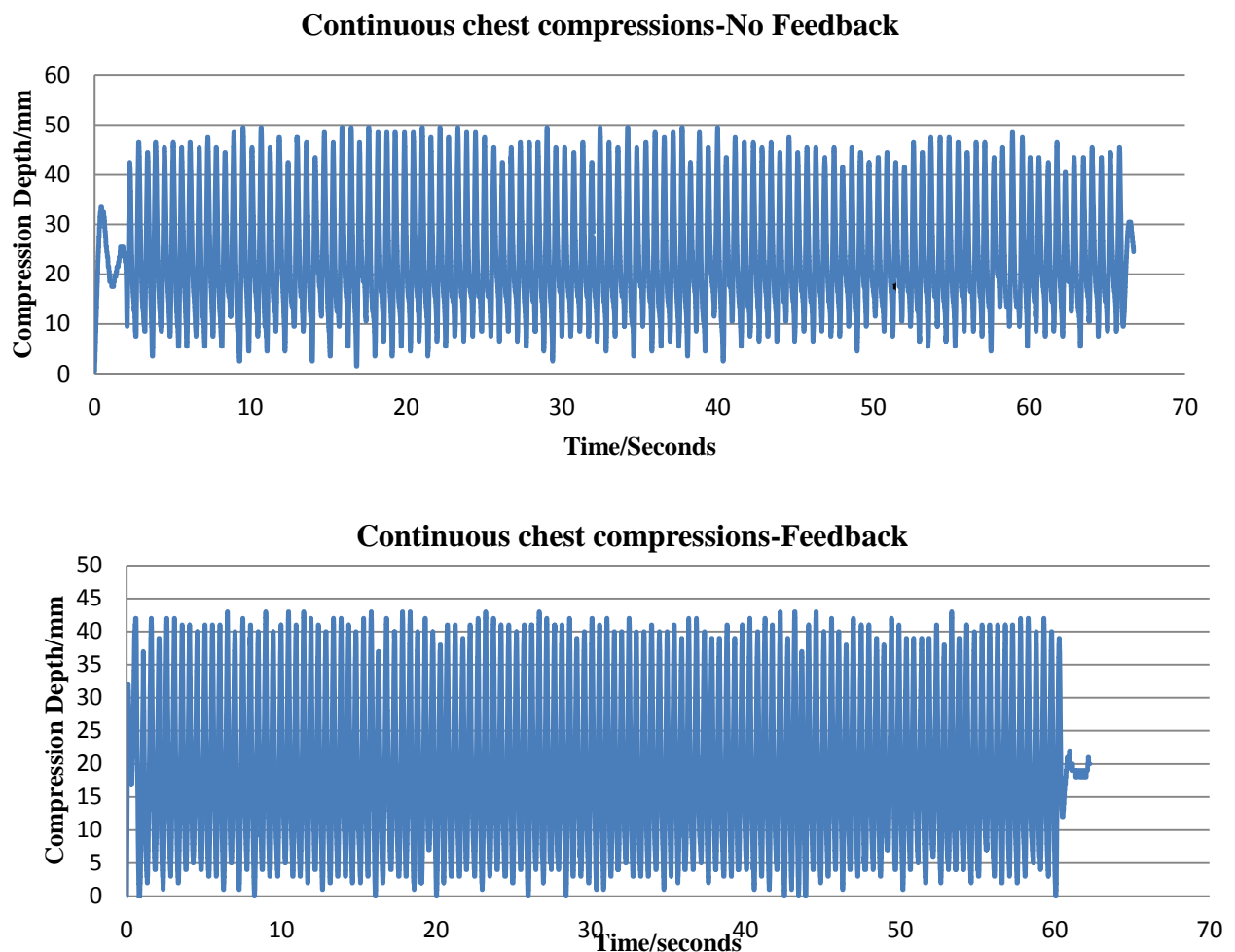
Figure 3-26: No-feedback and feedback rescuer CPR performance: continuous compressions without ventilation.

3.16.2. Comparison of single-BLS CPR performance with and without feedback.

It was found that the single-rescuer no-feedback mean depth was 44.9mm and mean '5-initial compressions' depth was 42.7mm. It was also found that only 2 of the 5 initial compressions achieved the target compression depth.   With feedback, the single-rescuer mean depth was 40.7mm and mean 5-initial compression depth was 41.2mm.   All 5-initial compressions achieved the depth target. Release force targets were <2.5kg and <0.5kg. The single-rescuer

no-feedback mean release force was 2.57kg. Mean release force of 5-initial compressions was 2.8kg. The results showed that only 1 out of the 5 compressions achieved the complete release depth. The feedback single-rescuer mean release force was 1.09kg. Mean release force of 5-initial compressions was 1.85kg. All 5 initial compressions achieved complete release prior to the next compression.

The target compression rate is 100–120/min. The no-feedback participants achieved mean rates of 104/minute and the '5 initial compressions' mean rate of 95/minute. Only 3 achieved the international guidelines, while the remaining two were not in the range. Feedback participants' mean rates were 113/minute, and the 5-initial compressions mean rate was 117/minute. All 5-initial compressions reached the recommended target range.

The recommended compression duty cycle target is 30–50%. It was found that without feedback, the single-participant mean duty cycle was 53.3% and the mean '5 initial compressions duty cycle' was 54.9%. None of the duty cycles achieved the recommended range. With feedback, however, the single-participant mean duty cycle was 41.8% and the mean 5-initial compressions duty cycle was 42.1%. Of the 5-initial compressions, all the duty cycles achieved the recommended range.

3.16.3. Example analysis of single BLS rescuer compressions using two-thumb compression technique without and with feedback: 5 initial rescue breaths and continuous compressions

Single-BLS rescuer CPR performances were selected from both the no-feedback and feedback groups. Figure 3-27 compares the CPR performance of a single BLS participant without feedback assistance and single BLS with feedback. All BLS performances consisted of 5-initial rescue breaths and continuous compressions for the duration of approximately 1-minute. Figure 3-28 shows the breath count against time for single BLS rescuers without and with feedback.
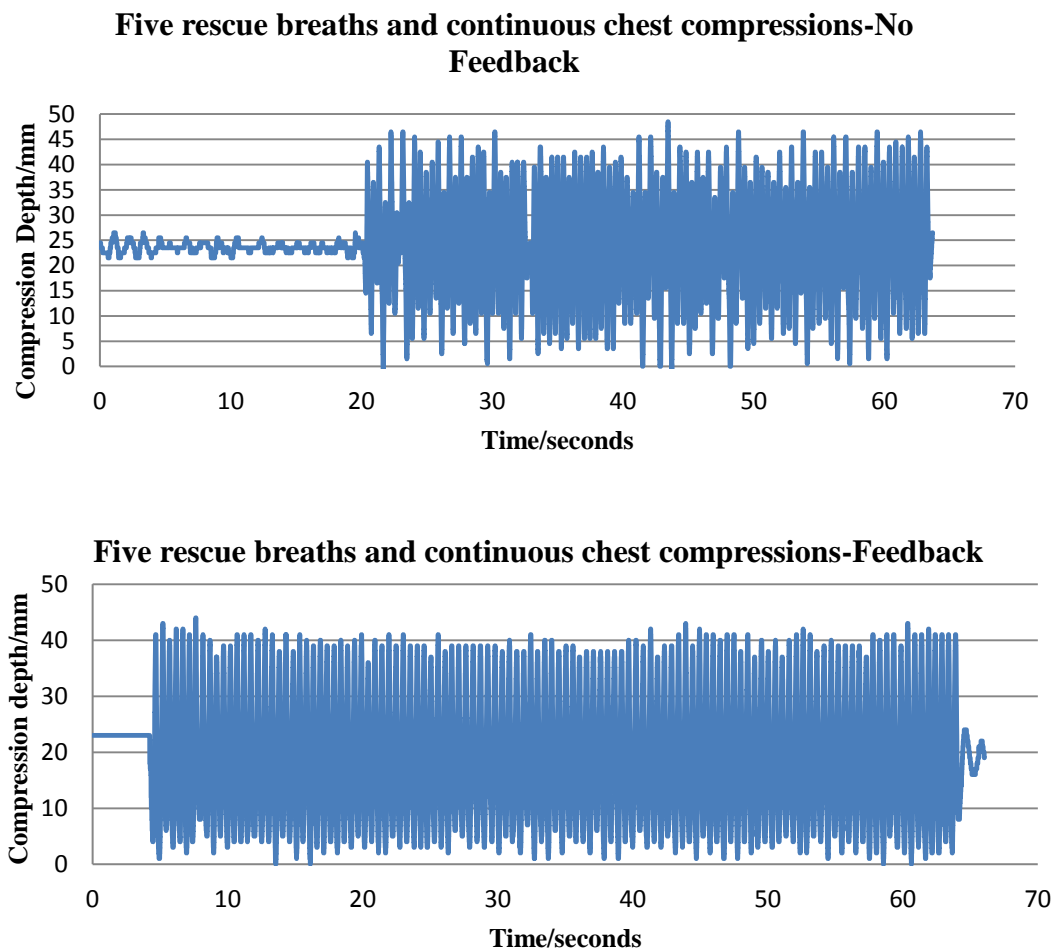
Figure 3-27: No-feedback and feedback rescuer CPR performance: 5-initial breaths and continuous compressions.

3.16.4. Comparison of single-BLS rescuer CPR performance with 5-initial breaths, with and without feedback.

Mean compression depth for the no-feedback single rescuer was 40.8mm and the mean depth of 5 initial compressions was 39.9mm. After the 5-initial breaths, the 5-initial compressions quality targets were analysed. after ventilation, only 2 out of the 5 initial compressions achieved the target depth. However, for the single rescuer with feedback, the mean depth was 39.6mm and the mean 5-initial compressions depth was 41.6mm. After ventilation, all 5-initial compressions achieved the target depth.

 Release force targets are <2.5kg and <0.5kg. The single-rescuer no-feedback mean release force was 2.69kg. Mean force of 5-initial compressions was 3.7kg. Of 5-initial compressions, only 2 achieved the complete release depth after the 5-initial breaths. The feedback single-rescuer mean release force was 1.24kg and the force of 5-initial compressions was 1.4kg. All 5-initial compressions achieved complete release depth prior to the next compression.

The target compression rate is 100–120/min. The no-feedback participant's mean rate was 131/minute, and the 5-initial compressions mean rate was 135/minute. None of the 5-initial compressions achieved the international guidelines range. The feedback participant's mean rate was 116/minute; after the ventilation, the 5-initial compressions mean rate was 118/minute. It was found that 4 out of the 5-initial compressions successfully achieved the target range. The duty cycle target for CPR compressions is 30–50%. Without feedback, the single-participant mean duty cycle was 59.9%, and the mean 5-initial compressions duty cycle after ventilation was 60.6%. Of the 5-initial compressions, after 5 breaths, none of the duty cycles

achieved the recommended range. The single-participant mean duty cycle with feedback was 49.5% and the mean 5-initial compressions duty cycle was 42.2%. The results showed that all of the 5-initial compressions met the recommended duty cycle range targets.

3.16.5. Comparison of single BLS rescuer rescue breath performance: 5 initial breaths, no-feedback and feedback

Five-Initial rescue breaths without feedback

Five-Initial rescue breaths with feedback
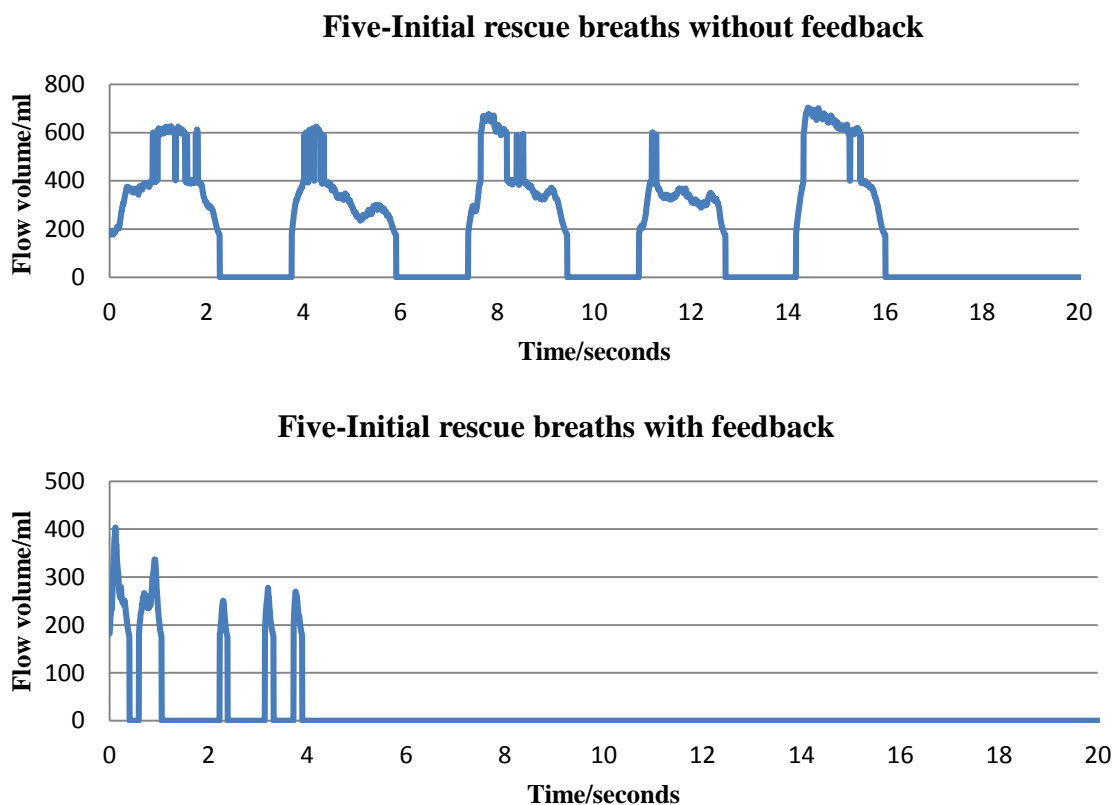
Figure 3-28: No-Feedback and feedback rescuer CPR performance: 5-initial breaths count and time spent delivering the 5-breaths.

Performance of 5-initial breaths by a single BLS rescuer, both with and without feedback, was selected to compare the breath count against time. The no-feedback participant took 16 seconds to deliver the 5-initial breaths and 4 seconds to start the compressions. In total, the no-feedback BLS participant took 20 seconds to deliver the 5-initial breaths before starting the continuous compressions. However, the BLS rescuer with feedback took only 4 seconds to provide 5-

initial breaths and only 0.5 seconds to start compression. In total, the rescuer with feedback took 4.5 seconds to deliver the 5-initial breaths. There was no difference in breath count between no-feedback and feedback, and both delivered exactly the required 5-initial breaths.

3.16.6. Example analysis of single BLS rescuer compressions using two-thumb compression technique, without and with feedback: 5-initial breaths, then 15-continuous compressions and 2-breaths

CPR performance of a single BLS rescuer was selected from both the no-feedback and feedback groups. Figure 3-29 shows the performance of the single BLS rescuer without feedback, followed by a single BLS rescuer with feedback. All BLS performances consisted of 5-initial breaths, followed by 15 continuous compressions and then 2-breaths, for approximately 1 minute. Figure 3-30 shows the breath count and time spent delivering each set of breaths, 5-initial breaths and 2-rescue breaths during compressions and the number of ventilation pauses for the single BLS rescuer without and with feedback.

Five rescue breaths, 15 compressions, and 2 rescue breaths without feedback

Five rescue breaths, 15 compressions, and 2 rescue breaths with feedback
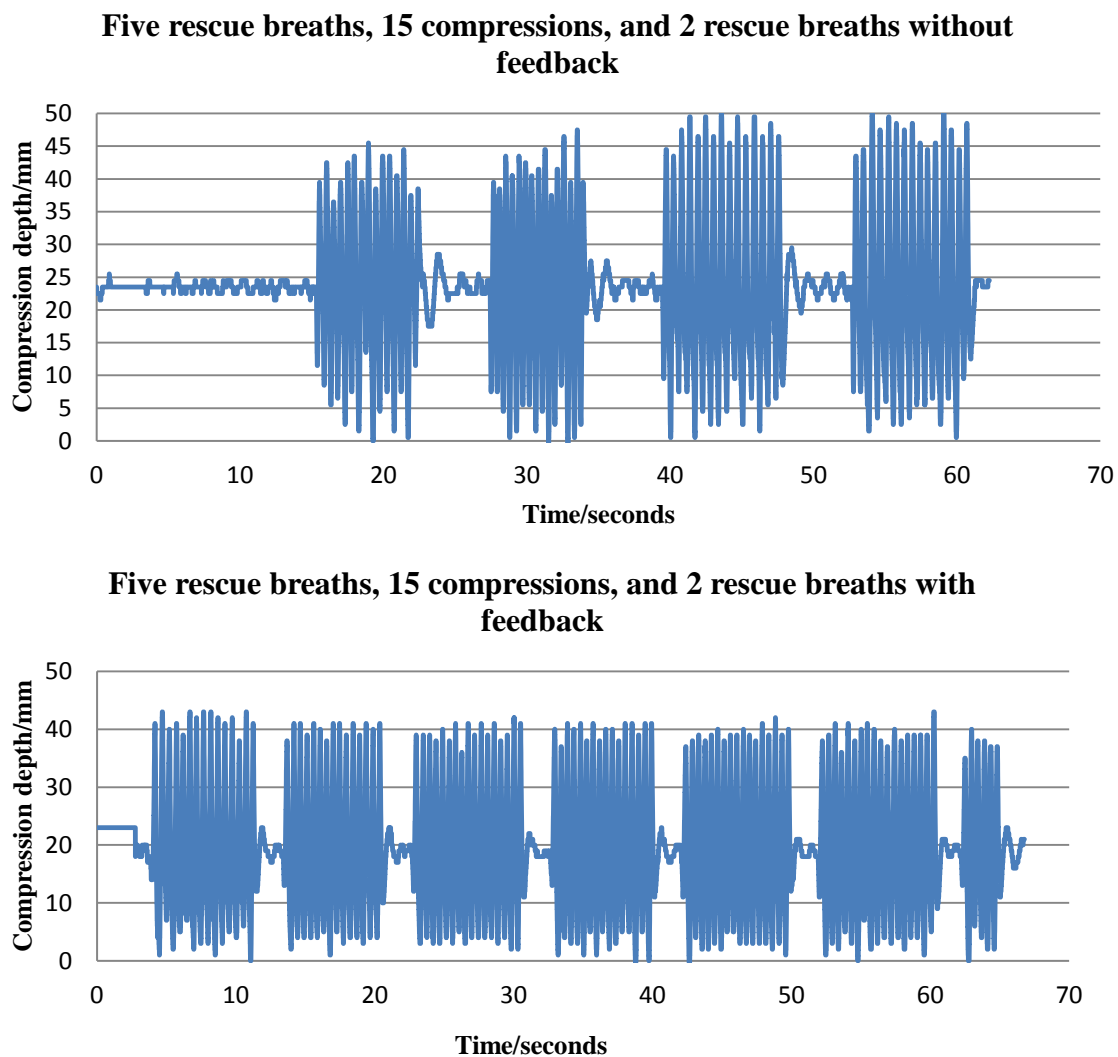
Figure 3-29: No-feedback and feedback rescuer CPR performances – 5 initial rescue breaths, 15 continuous compressions and 2 rescue breaths.

3.16.7. Comparison of single BLS rescuer CPR performance with 5 initial breaths followed by 15 compressions and 2 rescue breaths, with and without feedback, and findings.

The no-feedback single rescuer mean compression depth was 43.8mm, and the mean of the '5-initial compression depths' of each ventilation pause was 43.6mm. After the 5-initial rescue breaths and every 2 breaths during compressions, the '5-initial compressions' quality targets were analysed and compared with the recommended target. The no-feedback single BLS res-

cuer has 4 breath pauses including 5-initial breaths. It was found that after each set of ventilation, only 8 out of 20-initial compressions achieved the target depth. However, the single rescuer with feedback mean depth was 39.4mm. The feedback single BLS rescuer has 7 breath pauses. The mean of the 35 initial depths, after each set of ventilation pauses, was 39.2mm. Out of 35-initial compressions, after each ventilation episode, all 35 achieved the target depth.

Release force targets are <2.5kg and <0.5kg. The single BLS rescuer without feedback mean release force was 1.71kg. The mean release force of '5 initial compressions' after each set of ventilation pauses was 2.03kg. Only 10 compressions achieved the complete release depth out of 20-initial compressions, after each rescue breath pause. The feedback single rescuer mean release force was 1.4kg. The mean release force of '5 initial compressions' after each set of ventilation was 1.1kg. All 35-initial compressions achieved complete release prior to the next compressions.

The target compression rate is 100–120/min. The mean compression rate for the no-feedback BLS single rescuer was 111/min and the mean rate of 5-initial compressions, after each breath pause was 120/min. Of 20 initial compressions after each breath pause, only 8 compressions achieved the target rate. The mean rate of the participant with feedback was 112/min; after each ventilation pause, the mean rate of 5-initial compressions was 116/min. Of the 35 initial compressions, 32 achieved the target range.

The duty cycle target for the CPR compressions is 30–50%. The mean duty cycle for the no-feedback single BLS participant was 56.8% and 56.9%, for the 5 initial compressions after each ventilation pause. Only 2 of 20 duty cycles, after each set of ventilation, achieved the recommended target range. For the single participant with feedback, the mean duty cycle was

43.2% and 43.6% for the 5 initial compressions, after every set of ventilation pauses. In total, of the 35 compression cycles, there were 7 breath pauses, including the 5 initial breaths. Out of 35, all 35 initial compressions achieved the target compression duty cycle range.

After 5 initial breaths, the target number of compressions between each set of 2 rescue breaths was 15. The mean compression count, between each 2-breath interval, was exactly 15 for the no-feedback single BLS participant. The compression count for the participant with feedback was 16.2.

3.16.8. Comparison of single BLS rescuer breath performance: 5 initial breaths, then 2 breaths during continuous compressions, with and without feedback.

The performance of 5 initial breaths and 2 breaths after every 15 compressions by single BLS rescuers, both with and without feedback, were selected to compare the breath count against time (Figure 3-30). The no-feedback participant took 11.5 seconds to deliver the 5 initial breaths and then took 2 seconds to start the 15 continuous compressions. In total, before stating compressions, the no-feedback BLS participant took 13.5 seconds to deliver the 5 initial breaths. The mean time for delivering 2 breaths during compressions was 4.4 seconds for the no-feedback participant, and the 2 breaths were only delivered 3 times. The single participant with feedback spent only 2.5 seconds delivering the 5 initial breaths and took only 1.5 seconds to start the 15 continuous compressions. In total, the feedback participant took 4 seconds to deliver the 5 initial breaths. The mean time for delivering 2 breaths during compressions was 2.3 seconds, and the 2 breaths were delivered 3 times.

The breath count showed no difference between no-feedback and with feedback rescuers, as both participants delivered exactly the required 5 initial breaths. For the mean count of 2

breaths during compressions, the no-feedback BLS rescuer was 3.33 times, and the feedback

rescuer was exactly 2 breaths.

Five initial rescue breaths, then 15 compressions and 2 rescue breaths without feedback

Five initial rescue breaths, then 15 compressions and 2 rescue breaths with feedback
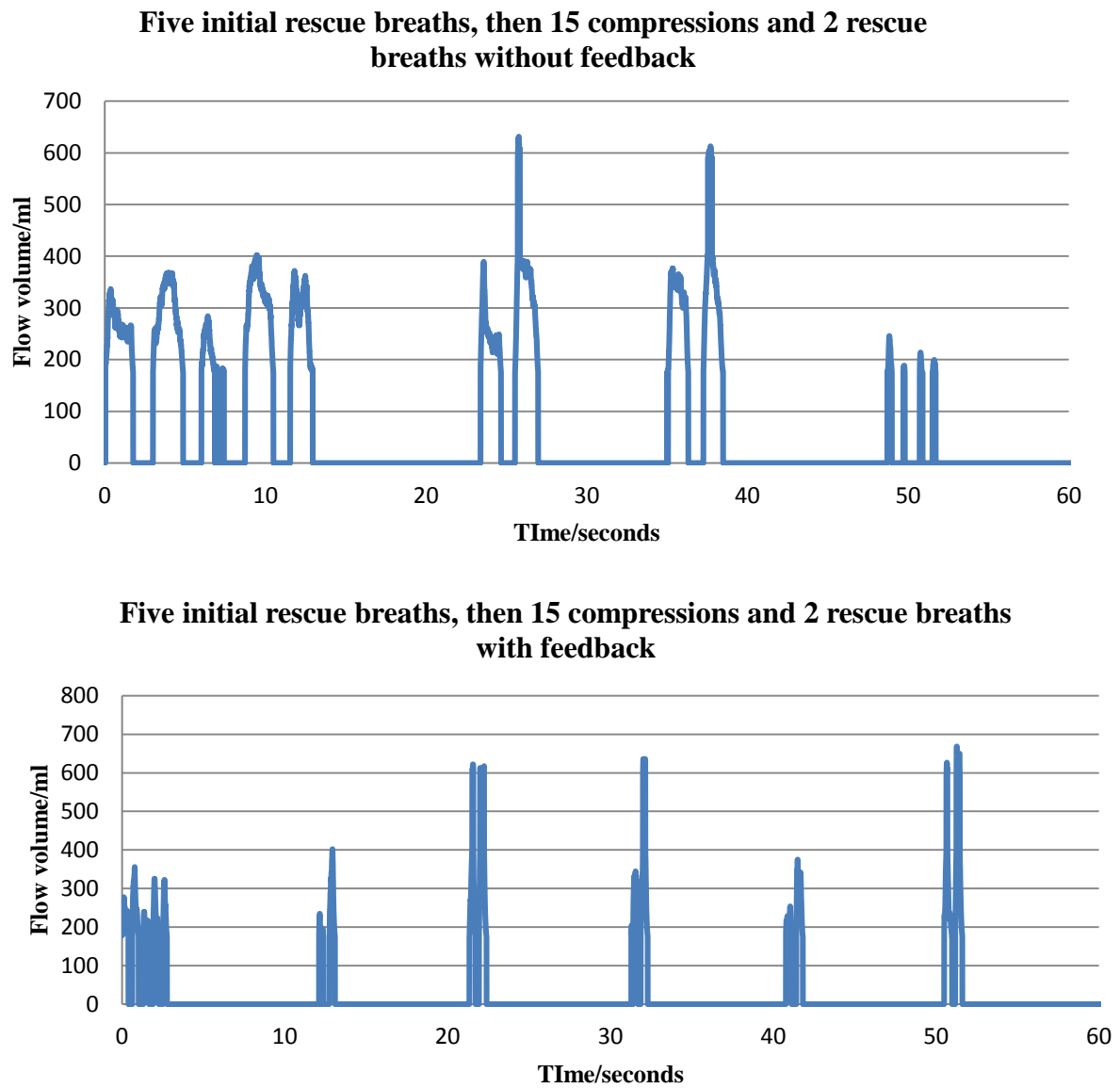
Figure 3-30: No-feedback and feedback groups' CPR performance – 5-initial breaths and 2-breaths during compressions count and time spent delivering each set of rescue breaths.

3.17.   Summary

The Material and Methods chapter discussed the device design and working principles, sensor validation, participant details, baseline study results, performance feedback program details, data analysis method using Matlab and sample data analysis. The following Results chapter compares the performance of 'BLS and lay' rescuers in simulated CPR performance on an infant manikin and quality measures, such as compression depth, compression release force, compression rate and duty cycle are compared with evidence-based quality targets. In addition, rescue breath counts are analysed with and without the feedback system. This research encountered the fundamental problem with the current method for measuring the compression duty cycle. Therefore, this research proposed a new technique for measuring duty cycle, which is presented in the following result chapter in detail.

4.   RESULTS

Chapter 4 is structured into four sections to describe the participants' performance with and without feedback assistance during the simulated CPR performance on an infant manikin. The structure of this chapter is specified in the following table.

Structure of results chapter		
Section 4.1 and 4.3	BLS rescuers performance	All 4-key measure performance with and without feedback assistance and overall compression performance quality.
Section 4.4 and 4.6	Lay rescuers performance	All 4-key measure performance with and without feedback assistance and overall compression performance quality.
Section 4.7	Rescue breath and compression count during breath performance	Compared BLS and lay rescuers performance without and with feedback assistance individually.
Section 4.8	New technique for measuring the compression DC	Example duty cycle calculations and BLS and lay rescuers performance without and with feedback assistance are detailed in 4.8.3-4.8.6.

4.1.   Introduction: BLS rescuers

The performance of BLS rescuers in simulated CPR performance on an infant training manikin and quality measures are shown against current guidelines-based CPR quality targets in Figure 4-1. Performances were separated into three groups. The first performance consisted of compression only for a period of 1-minute. The second consisted of 5-initial rescue breaths through an air flow sensor and continuous compressions on the training manikin for a period of 1-

minute. The final performance consisted of 5-initial breaths through the air flow sensor and repeated cycles 15-compressions and 2-breaths for a period of 1-minute. BLS rescuers' CPR performance was compared with and without the CPR performance feedback program; CPR performance feedback was intended to assist the rescuer in maintaining compression depth, compression rate, release force, and compression duty cycle against current quality target ranges (Figure 4-1:4-4).

The following key variables were compared between the no-feedback and feedback group CPR performances. The details are as follows:

Stage 1: compression only vs 5-initial compressions

    ✓ Including compression depth, release forces, compression rates, and compression duty cycle in current quality target range for both groups, compared with international recommended guidelines.

Stage 2: Initial 5-breaths and initial 5-continuous compressions

    ✓ Including compression depth, release forces, compression rates, and compression duty cycle in current quality target range for both groups, compared with international recommended guidelines.

    ✓ Rescue breath count and consumed time for delivering 5-initial breaths were compared between groups.

Stage 3: Initial 5 rescue breaths, initial 5-compressions, and 2-rescue breaths

    ✓ Including compression depth, release forces, compression rates, and compression duty cycle in current quality target range for both groups, compared with international recommended guidelines.

    ✓ Number of compressions performed after each 2-rescue breath.

✓ Rescue breath count and consumed time for delivering 5-initial breaths and 2-rescue breaths between compressions were compared between groups.

4.2. BLS Rescuers CPR simulated performances quality measures and quality indices between the no-feedback and feedback groups for two-thumb technique

BLS rescuers' simulated CPR performance on an infant manikin and their quality measures are illustrated against current guidelines-based quality targets for iCPR in Figure 4-1:4.4. The simulated CPR performance group, with performance feedback system, improved compressions when compared with the no-feedback group, achieving improved compression depth target, release force, compression rate, and compression duty cycle. In addition, feedback also reduced the deep-compression depth and under-compression depths, excessive and sluggish compression rates, prolonged compression duty cycles, and reduced advanced compression prior to complete release. Detailed data analysis and results are presented in Appendix A.15.

4.2.1. Compression depth achieved by BLS rescuers without and with feedback

Compression depth performance-BLS rescuers
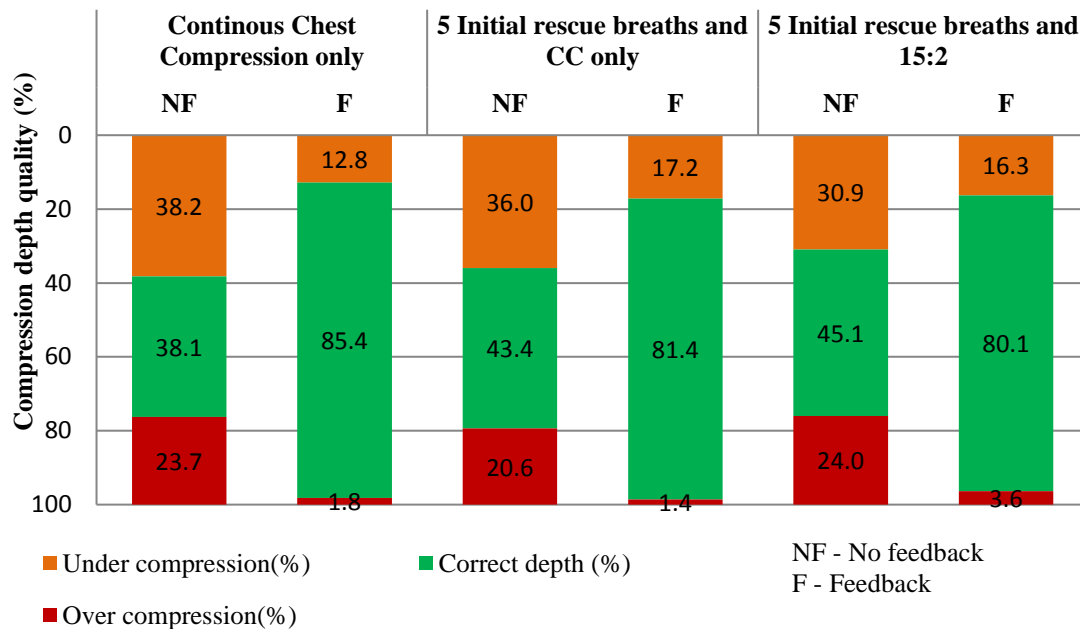
Figure 4-1: Illustration of compression depths achieved by BLS rescuers without and with feedback by the two-thumb (TT) technique. Current evidence-based correct compression depth quality target for this study is 35–43mm.

Continuous compressions only: the target compression depth (35–43mm) quality index was 38.1% for the no-feedback group and 85.4% for the feedback group (Figure 4-1). The performance feedback program improved the quality index by 47.3%. The no-feedback group's under-compression quality index (<35mm) was 38.3%, while this measurement was only 12.8% for the feedback group. The feedback program significantly reduced under-compressions by 25.5%. Over-compression (>43mm), also called the thoracic injury index, was 23.7% in the no-feedback group and only 1.8% in the feedback group. Performance feedback significantly reduced the thoracic injury index from 23.7% to 1.8%, a difference of 21.9%.

Five initial breaths and continuous compressions only: The target depth quality index of the no-feedback group was 43.4%, versus 81.4% for the feedback group (Figure 4-1). The performance feedback improved the quality index by 38%. The no-feedback group's under-compression quality index (<35mm) was 36%, while the feedback groups was only 17.2%. The feedback program reduced under-compressions by 18.2%. In the no-feedback group, over-compression (>43mm), also called the thoracic injury index, was 20.6%, while in the feedback group it was only 1.4%. Performance feedback significantly reduced the thoracic injury index by 19.2%.

Five initial breaths, then 15 continuous compressions and 2 rescue breaths (15:2): The target depth quality index of the no-feedback group was 45.1%, compared to 80.1% for the feedback group (Figure 4-1). The performance feedback program improved the quality index by 35%. The no-feedback group's under-compression quality index (<35mm) was 30.9%, while the feedback groups was only 16.3%. The feedback program reduced the under-compressions to 14.6%. Over-compression (>43mm), also called the thoracic injury index, was 24% in the non-feedback group only 3.6% in the feedback group. Performance feedback significantly reduced the thoracic injury index by 21.4%.

4.2.2.   Release force achieved by BLS rescuers without and with feedback

Release force performances-BLS rescuers
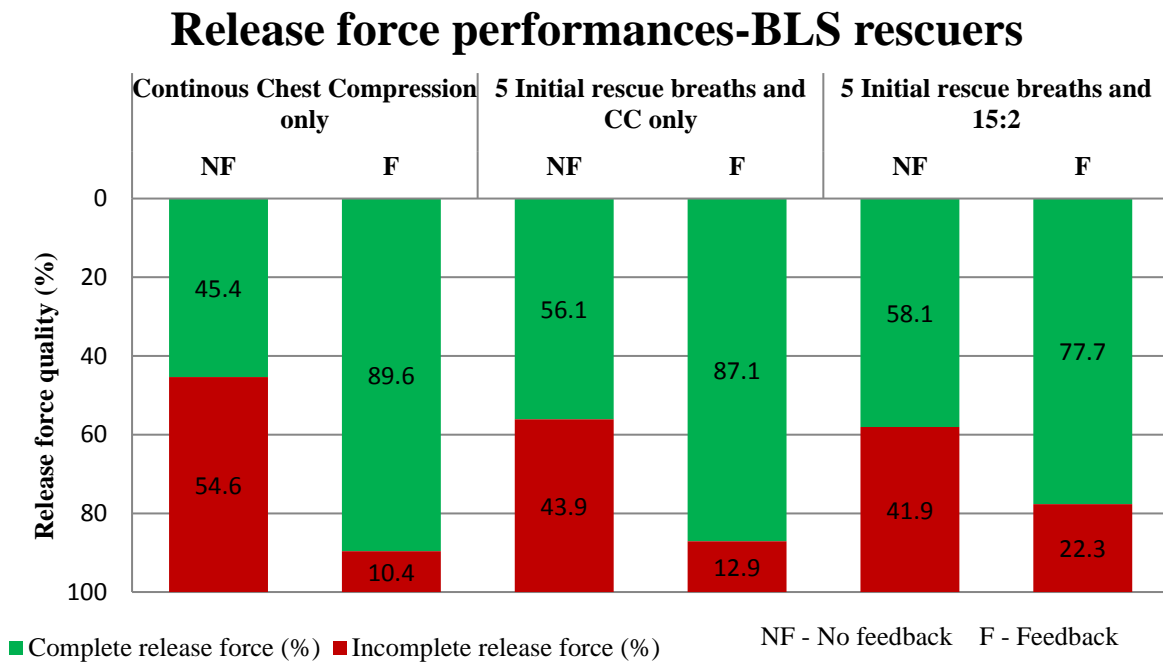
Figure 4-2: Illustration of release force achieved by BLS rescuers without and with feedback by the two-thumb (TT) technique. Current evidence-based correct compression depth quality target is <2.5kg.

Continuous compressions only: Release force quality index (<2.5 kg) for the no-feedback group performance was 45.4%, versus 89.6% for the feedback group (Figure 4-2). The performance feedback improved the quality by 44.2%. The no-feedback group incomplete release force quality was 54.6%. The feedback group considerably reduced the incomplete release force by 10.4%.

Five initial breaths and continuous compressions only: Release force quality index was 56.1% for the no-feedback group and 87.1% for the feedback group (Figure 4-2). Incomplete

release force quality index was 43.9 % for the no-feedback group, verses 12.9% for the feedback group. Performance feedback enhanced the quality by 31%.

Five initial breaths, then 15 continuous compressions and 2 rescue breaths (15:2): The BLS no-feedback group complete release force performance was 58.1%, compared to 77.7% for the feedback group (Figure 4-2). The no-feedback group's incomplete release force quality index was 41.9%, while the no-feedback groups was 22.3%. Performance feedback improved the quality by 19.6%.

4.2.3. Compression rate achieved by BLS rescuers without and with feedback
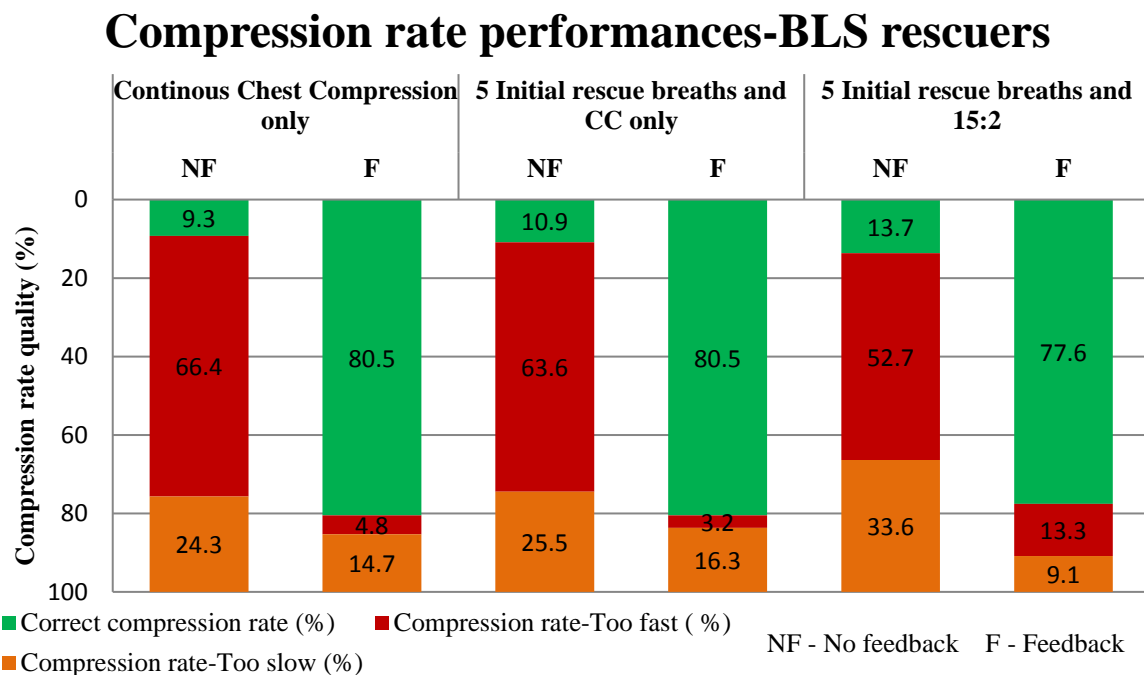
Figure 4-3: Illustration of compression rate achieved by BLS rescuers without and with feedback by the two-thumb (TT) technique. Current evidence-based correct compression rate quality targets (100–120 compression/min).

Continuous compressions only: Significant differences were observed when comparing compression rate for the no-feedback and feedback groups. The mean compression rate was 136/minute for the no-feedback group, versus 110/minute for the feedback group ($p<0.01$). The feedback group's compression rate quality index (100–120 cycles/minute) was 80.5%, while the no-feedback group's quality cycles were 9.3% (Figure 4-3) ($p<0.001$). For the no-feedback group, 66.4% of the cycles were "too fast" (>120 compressions/minute) and 24.3% of the cycles were "too slow" (<100/minute). However, the feedback group's cycles were "too fast" only 4.8% and "too slow" only 14.7%.

Five initial breaths and continuous compressions only: The BLS no-feedback group's mean compression rate was 135/minute, while the feedback groups were 109/minute ($p<0.01$). The feedback group's rate quality index was 80.5%, compared to 10.9% for the no-feedback group ($p<0.001$) (Figure 4-3). Significant differences were observed when comparing compression rate for the no-feedback and feedback groups. For the no-feedback group, 63.6% of the compression cycles were "too fast" and 25.5% of the cycles were "too slow. However, the feedback group's cycles were "too fast" only 3.2% and "too slow" only 16.3%.

Five initial breaths, then 15 continuous compressions and 2 rescue breaths (15:2): The BLS no-feedback group's mean compression rate was 142/minute, while the feedback groups were 107/minute ($p<0.0001$). The mean difference between groups was 35. The no-feedback group's rate quality index was 13.7%, versus 77.6% for the feedback group ($p<0.0001$) (Figure 4-3). Significant differences were observed when comparing compression rates for the no-feedback and the feedback groups. For the no-feedback group, 52.7% of the cycles were "too fast" and 33.6% were "too slow". For the feedback group, only 13.3% of the compression cycles were "too fast" and 9.1% were "too slow."

4.2.4. Compression duty cycle achieved by BLS rescuers without and with feedback

Compression duty cycle performance-BLS rescuers

	Continous Chest Compression only		5 Initial rescue breaths and CC only		5 Initial rescue breaths and 15:2	
	NF	F	NF	F	NF	F

Duty cycle quality (%)

Correct duty cycle (green):
- NF (CCC only): 15.5
- F (CCC only): 87.4
- NF (5 breaths + CC only): 16.4
- F (5 breaths + CC only): 85.1
- NF (5 breaths + 15:2): 18.5
- F (5 breaths + 15:2): 79.2

Prolonged duty cycles (red):
- NF (CCC only): 84.4
- F (CCC only): 12.6
- NF (5 breaths + CC only): 83.6
- F (5 breaths + CC only): 14.9
- NF (5 breaths + 15:2): 81.4
- F (5 breaths + 15:2): 20.8

■ Correct duty cycle (%) ■ Prolonged duty cycles(%)   NF - No feedback   F - Feedback

Figure 4-4: Illustration of compression duty cycle achieved by BLS rescuers without and with feedback by the two-thumb (TT) technique. Current evidence-based correct compression duty cycle quality target is 30-50%.

Continuous compressions only: The BLS no-feedback group's mean compression duty cycle was 55%, compared to 44.7% for the feedback group. Mean duty cycles in between groups were statistically significant ($p<0.0001$), with a mean difference of 10.3. For the no-feedback group, the quality compression duty cycles (30–50%) were only 15.5% and prolonged duty cycles (>50%) were 84.4%. The feedback group's quality compression cycles were 87.4%, and prolonged duty cycles were only 12.6% (Figure 4-4).

Five initial breaths and continuous compressions only: The BLS no-feedback group's mean duty cycle was 56.3%, versus 45.4% for the feedback group. Mean duty cycles between groups

were statistically significant ($p<0.0001$), with a mean difference of 10.9. For the no-feedback group, the quality duty cycles were only 16.4%, and prolonged duty cycles were 83.6%. The feedback group's quality duty cycles were 85.1% and prolonged duty cycles were only 14.9% (Figure 4-4).

Five initial breaths, then 15 continuous compressions and 2 rescue breaths (15:2): The no-feedback group's mean compression duty cycle was 55.7%, and the feedback group's mean duty cycle was 46.5%. Mean duty cycles between the groups were statistically significant ($p<0.0001$), with a mean difference of 9.2. The quality duty cycles for the non-feedback group were only 18.5% and prolonged duty cycles were 81.4%. In contrast, the feedback group's quality cycles were 79.2%, and prolonged duty cycles were 20.8% (Figure 4-4).

4.2.5. The overall compression quality indices achieved by no-feedback and feedback benefitted BLS rescuer group participants

The overall compression quality indices achieved by the BLS no-feedback and feedback groups benefitted from feedback (Figure 4-5). The performance feedback program improved overall CPR quality by improving the individual CPR quality measures: compression depth, compression release force, compression rate, and compression duty cycle.
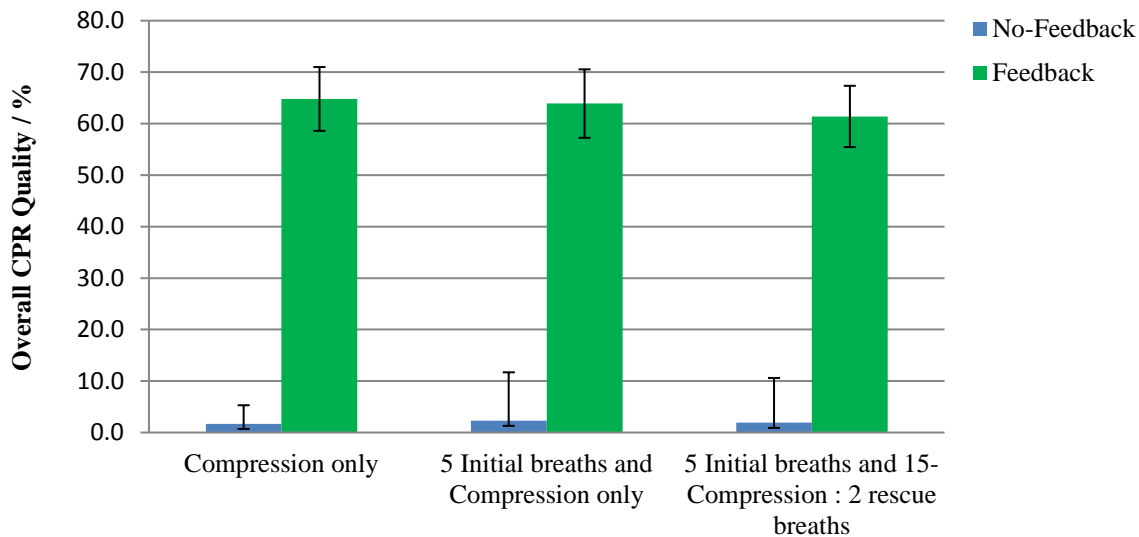
Figure 4-5: Overall simulated CPR quality index of the BLS no-feedback and feedback groups. Each CPR measure is presented as quality index ± standard deviation.

Figure 4-5 shows the overall quality of the groups' simulated CPR performance. For the 'continuous compressions only' stage, the no-feedback group's overall performance was 1.7% and the feedback group's overall performance was 64.8%. In stage 2, '5 initial breaths and continuous compressions only', the no-feedback group's overall performance was 2.3% and the feedback group's overall performance was 63.9%. For stage 3, '5 initial breaths, then 15 compressions and 2 breaths', the no-feedback group's overall performance was 1.9%, compared to 61.4% for the feedback group's. The feedback performance program helped the rescuers to achieve the CPR quality targets.

4.3.   Analysis of BLS rescuers' 5-initial compressions using TT compression technique, without and with feedback

Continuous compressions only: Twenty-eight BLS rescuers were recruited for this study, 14 in the no-feedback group and 14 in the feedback group. The no-feedback group's mean depth of 5-initial compressions was 41.7mm. Of 70 initial compressions, only 26 achieved the depth

target. The mean depth of 5-initial compressions for the feedback group was 40.4mm. Of 70 initial compressions, 66 achieved the depth target. The no-feedback group's mean release force of 5-initial compressions was 2.6kg. Of 70 initial compressions, only 23 achieved complete release depth. The feedback group's mean release force of 5-initial compressions was 1.3kg. Of 70 initial compressions, 68 achieved complete release prior to the next compression. The mean rate of 5-initial compressions for the no-feedback group was 131/minute. Only 11 of 70 initial compressions achieved the international guidelines; the remaining 59 were not in range. The feedback participants' 5-initial compressions' mean rate was 110/minute. Of 70 initial compressions, 65 reached the recommended target range of compression rate. The mean 5-initial compressions duty cycle for the no-feedback group was 56%. Of 70 initial compressions, only 17 duty cycles achieved the recommended range. In contrast, the feedback group's mean 5-initial compressions duty cycle was 43%. Of 70 initial compressions, 67 compression duty cycles achieved the recommended range.

Five initial breaths and continuous compressions only: The mean 5-initial compressions depth was 42.1mm for the no-feedback group. The compression quality targets were analysed after the 5-initial breaths. Of 70 initial compressions, after ventilation, only 25 achieved the depth target. The mean 5-initial compressions depth for the feedback group was 39.1mm. Of 70 initial compressions, after ventilation, 67 achieved the depth target. The no-feedback group's mean release force of 5-initial compressions was 3.1kg. Of 70 compressions, only 29 achieved complete release depth after the 5-initial breaths. The feedback group's mean release force of 5-initial compressions was 1.1kg. Of 70 cycles, 66 achieved complete release depth prior to the next compression. The mean rate of 5-initial compressions for the no-feedback group was 132/minute. Only 4 of 70 compressions achieved the international guideline range.

After ventilation, the feedback group's mean rate for 5-initial compressions was 112/minute. Of 70 compressions, 62 successfully achieved the target range. The no-feedback group's mean duty cycle for 5-initial compressions after ventilation was 54.6%. Of the 70 initial compressions after 5 breaths, only 19 duty cycles achieved the recommended range. However, the feedback groups mean '5-initial compression', duty cycle was 44%. Of the 70 initial compressions, 66 duty cycles achieved the recommended range.

Five initial breaths, 15 continuous compressions, and 2 breaths: The mean depth of the no-feedback group's 5-initial compressions was 41.4mm. After the 5-initial breaths and every 2 breaths during compressions, the 5-initial compressions quality targets were analysed and compared with the recommended target. The BLS no-feedback group had 59 breath pauses, including the 5-initial breaths. Of 295-initial compressions, after each set of ventilations, only 119 achieved the depth target. The mean depth of the BLS feedback group's 5-initial compressions after each set of ventilation pauses was 40.4mm. The BLS feedback group had 84 breath pauses. Of 420 initial compressions, after each ventilation episode, 404 achieved the target depth. The BLS no-feedback group's mean release force for 5-initial compressions after each set of ventilations was 2.8kg. Only 118 of 295-initial compressions achieved complete release depth after each breath pause. For the BLS feedback group, the mean release force for 5-initial compressions after each set of ventilations was 1.2kg. Of 420 initial compressions after each ventilation episode, 411 achieved complete release prior to the next compression.

The BLS no-feedback group's mean compression rate of 5-initial compressions after each rescue breath pause was 154/minute. Of 295 compressions after a rescue breath pause, only 56

compressions achieved the international recommended target compression rate. The BLS feedback group's mean rate of 5-initial compressions was 109/minute. Of 420 compressions, 388 compressions achieved target. The BLS no-feedback group's mean duty cycle for the 5-initial compressions after each ventilation was 54.7%. Only 92 duty cycles achieved the recommended target range, out of 295 after each set of ventilations. The corresponding mean duty cycle for the feedback group was 44%. In total, 84 breath pauses including the 5-initial breaths, 420 compression cycles were compared with the recommended target. Of these, 410 initial compressions achieved the target compression duty cycle range.

4.4. Introduction: lay rescuers

The simulated CPR performance of lay rescuers on an infant training manikin and quality measures are shown against current guidelines-based CPR quality targets in Figure 4-9. The performances were separated into three stages: continuous compression only for a period of 1 minute; 5-initial breaths through an air flow sensor and continuous compressions on the training manikin for a period of 1 minute; and 5-initial breaths through the air flow sensor followed by repeated cycles of 15 compressions and 2 breaths. CPR performance was compared with and without the CPR performance feedback program; CPR performance feedback was intended to assist the rescuer in maintaining compression depth, compression rate, release force, and duty cycle against the current quality target range (Figure 4-9:4-9).

The following key variables were compared between no-feedback and feedback group CPR performances. The details are as follows:

Stage 1: compression only vs 5-initial compressions

- ✓ Compression depth, release forces, compression rates, and duty cycle in current quality target range of both groups, compared with international recommended guidelines.

Stage 2: Initial 5-breaths and initial 5-continuous compressions

- ✓ Compression depth, release forces, compression rates, and duty cycle in current quality target range of both groups, compared with international recommended guidelines.
- ✓ Rescue breath count and time consumed for delivering 5-initial breaths compared between groups.

Stage 3: Initial 5 rescue breaths, initial 5-compressions, and 2-rescue breaths

✓ Compression depth, release forces, compression rates, and duty cycle in current quality target range of both groups, compared with international recommended guidelines.

✓ Number of compressions performed after each 2-rescue breath.

✓ Rescue breath count and consumed time for delivering 5-initial breaths and 2-breaths between compressions were compared between groups.

4.5. Lay rescuer overall simulated CPR performance quality measures against current guidelines-based CPR quality targets

The quality measures of lay rescuers' simulated CPR performance on an infant manikin are illustrated against current guidelines-based quality targets for iCPR in Figure 4-6:4-9. The simulated CPR performance group with performance feedback benefitted from enhanced compression quality targets of compression depth, release force, compression rate, and compression duty cycle when compared with the no-feedback group. In addition, feedback reduced the deep-compression depth and under-compression depths, excessive and sluggish compression rates, prolonged compression duty cycles, and reduced advanced compression prior to complete release. Detailed data analysis and results are presented in Appendix A.17.

4.5.1. Compression depth achieved by lay rescuers without and with feedback

Compression depth performance-Lay rescuers

|	Continous Chest Compression only		5 Initial rescue breaths and CC only		5 Initial rescue breaths and 15:2	
	NF	F	NF	F	NF	F
Under compression(%)	37.5	9.7	41.0	5.7	39.9	10.1
Correct depth (%)	42.3	88.0	39.0	91.7	36.8	84.9
Over compression(%)	20.2	2.3	20.0	2.6	23.3	5.0

NF - No feedback
F - Feedback
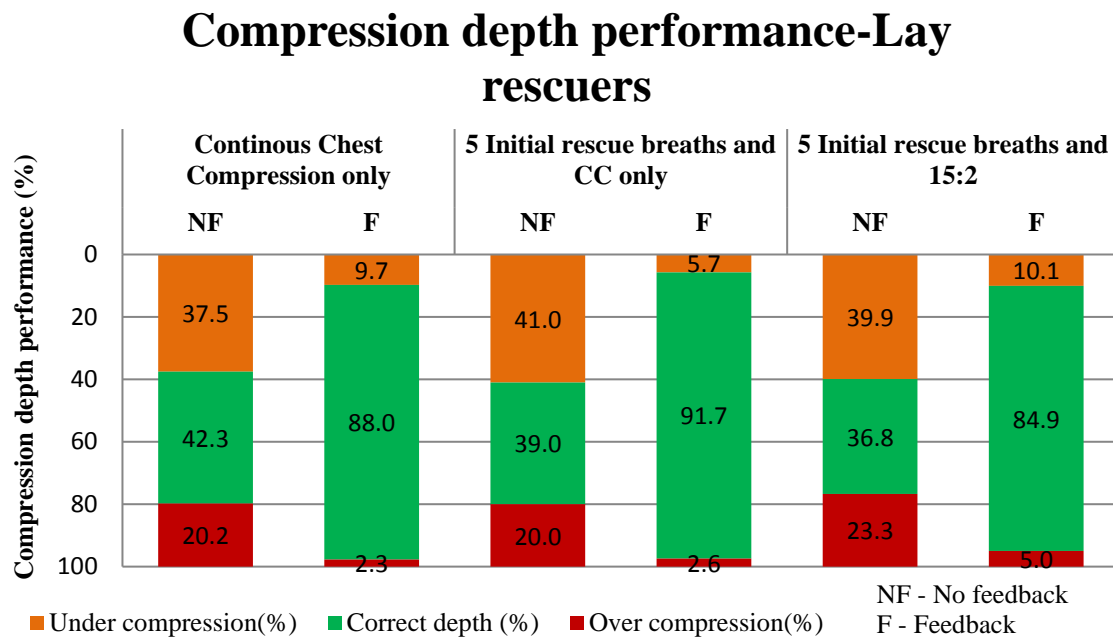
Figure 4-6: Illustration of compression depths achieved by lay rescuers without and with feedback by the two-thumb (TT) technique. Current evidence-based correct compression depth quality target for this study is 35–43mm.

Continuous compressions only: The target compression depth (35–43mm) quality index of the no-feedback group was 42.3%, compared to 88% for the feedback group ($p<0.001$) (Figure 4-6). The performance feedback program improved the quality index by 45.7% − statistically extremely significant. The no-feedback group's under-compression quality index (<35mm) was 37.5%, versus 9.7% for the feedback group. The performance feedback program significantly reduced under-compressions to 27.8%. The over-compression rate, also called the thoracic injury index, was 20.2% for the no-feedback group, but only 2.3% for the feedback group. Performance feedback significantly reduced the thoracic injury cycles index from 20.2% to 2.3%, a difference of 17.9%.

Five initial breaths and continuous compressions only: The correct compression depth quality index for the no-feedback group was 39%, compared with 91.7% for the feedback group ($p<0.0001$); extremely statistically significant (Figure 4-6). The performance feedback program improved the quality index by 52.7%. The under-compression quality index was 41% for the no-feedback group but only 5.7% for the feedback group ($p<0.0001$). The feedback program significantly reduced under-compression by 35.3%. The rate of over-compression was 20% for the no-feedback group but only 2.6% for the feedback group ($p<0.0001$). Performance feedback significantly reduced the thoracic injury compression cycle index from 20% to 2.6%, a change of 17.4%.

Five initial breaths, then 15 continuous compressions and 2 rescue breaths (15:2): The target depth quality index of the no-feedback group was 36.8%, versus 84.9% for the feedback group ($p<0.001$) — highly statistically significant (Figure 4-6). The performance feedback program improved the quality index by 48.1%. The no-feedback group's under-compression quality index was 39.9%, compared to only 10.1% for the feedback group ($p<0.0001$). The performance feedback program significantly reduced under-compressions to 29.8%. Over-compressions, also called the thoracic injury index, were 23.3% for the no-feedback group but only 5% for the feedback group ($p<0.0001$). The performance feedback significantly reduced the thoracic injury index from 23.3% to 5%, an 18.3% improvement.

4.5.2. Release force achieved by lay rescuers without and with feedback
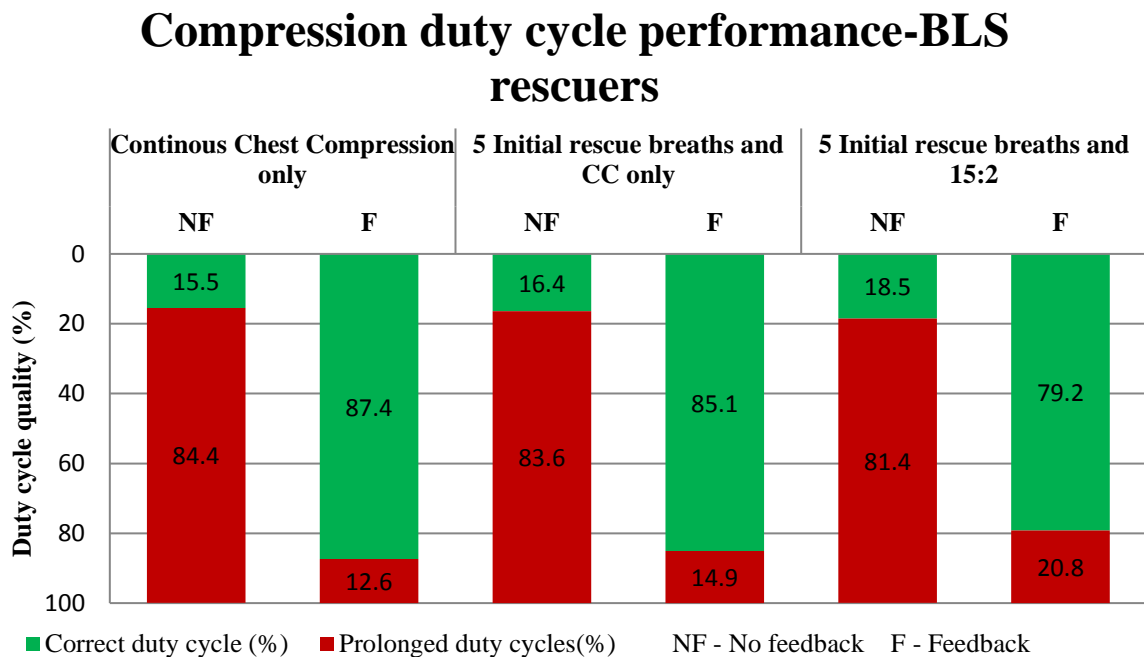
Release depth performances-lay rescuers
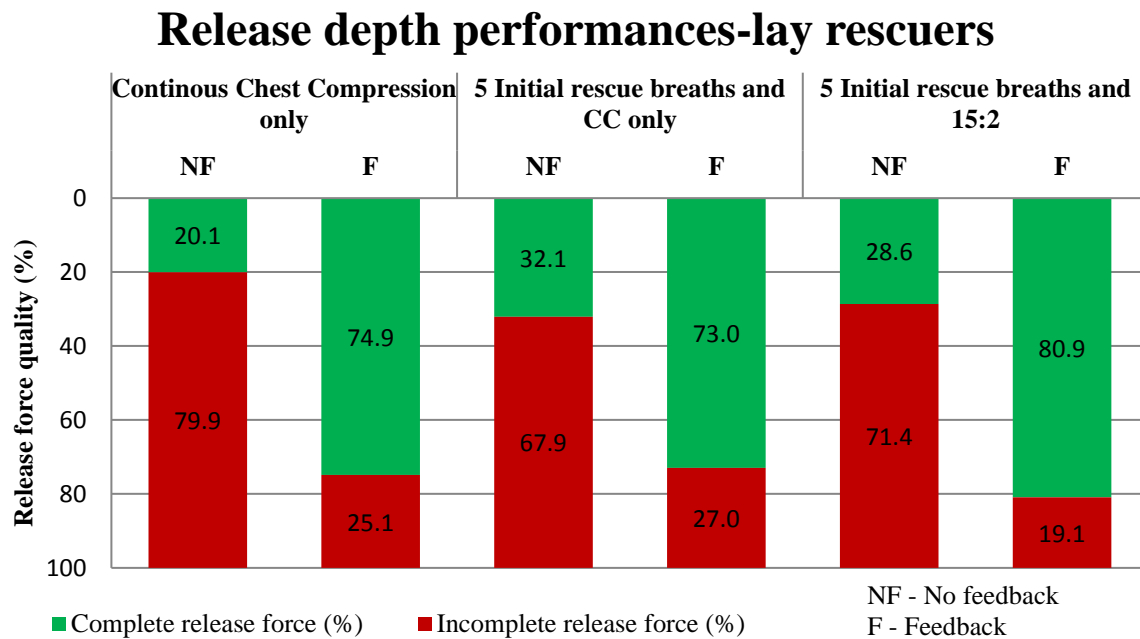
Figure 4-7: Illustration of release force achieved by lay rescuers without and with feedback by the two-thumb (TT) technique. Current evidence-based correct compression depth quality target is <2.5kg.

Continuous compressions only: Release force quality index (<2.5 kg) for the no-feedback group performance was only 20.1%, compared to 74.9% for the feedback group (*p*<0.01) – highly statistically significant (Figure 4-7). The performance feedback improved the quality by 54.8%. The no-feedback group incomplete release force quality was 79.9%. The feedback group considerably reduced the incomplete release force by 25.1%.

Five initial breaths and continuous compressions only: Release force quality index was only 32.1% for the no-feedback group and 73% for the feedback group (*p*<0.05) (Figure 4-7). The performance feedback program improved the quality by 40.9%. Incomplete release force quality index was 67.9% for the no-feedback group, verses 27% for the feedback group.

Five initial breaths, then 15 continuous compressions and 2 rescue breaths (15:2): Release force quality index for the no-feedback group performance was only 28.6%, versus 80.9% for the feedback group (*p*<0.01) (Figure 4-7). The performance feedback program significantly improved the quality by 52.3%. The no-feedback group's incomplete release force quality index was 71.4%, compared to only 19.1% for the feedback group.

4.5.3. Compression rate achieved by lay rescuers without and with feedback
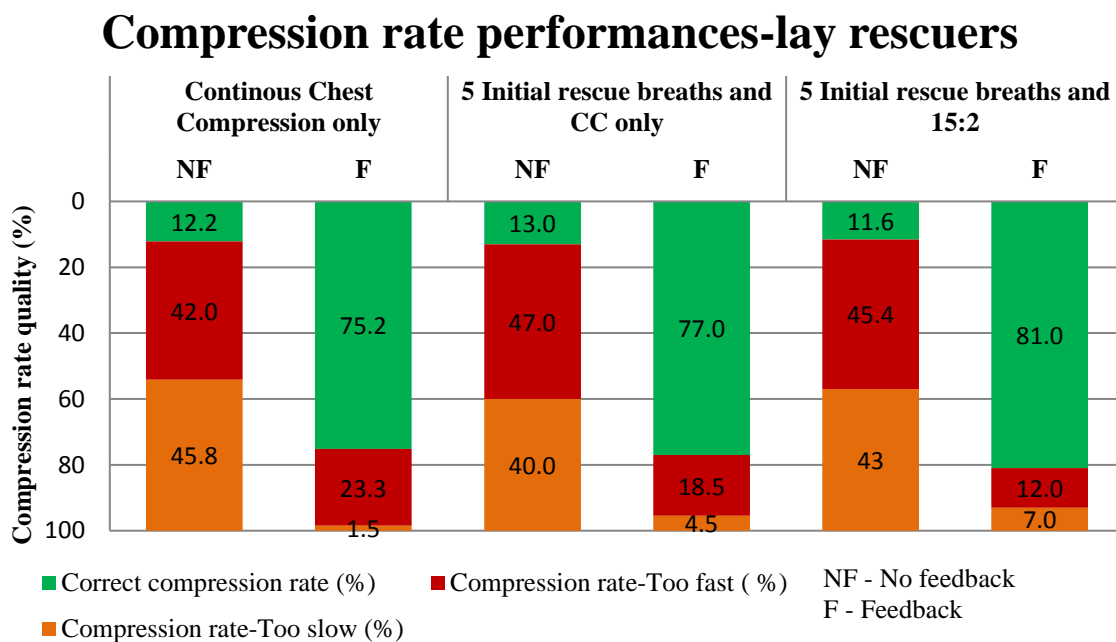
Figure 4-8: Illustration of compression rate achieved by lay rescuers without and with feedback by the two-thumb (TT) technique. Current evidence-based correct compression rate quality targets (100–120 compression/min).

Continuous compressions only: The mean compression for the lay no-feedback group was 101 cycles/minute, compared to the feedback group's rate of 107/minute. No significant difference was observed when comparing compression rates for both groups. The no-feedback group's compression rate quality (100–120 cycles/minute) was only 12.2%; the feedback

groups was 75.2% (*p*<0.01), which are statistically significant (Figure 4-8). For the no-feed-back group, 42% of the compression cycles were "too fast" (>120/minute) and 45.8% of the compression cycles were "too slow" (<100/minute). In contrast, the feedback group's compression cycles were "too fast" only 23.3% and "too slow" only 1.5%.

Five initial breaths and continuous compressions only: The lay no-feedback group's mean compression rate was 106/minute, while the feedback groups were 107/minute — no significant differences were observed when comparing the mean rate for both groups. The no-feedback compression rate quality was only 13%, versus and the feedback group's rate of 77% (*p*<0.01) (Figure 4-8) — statistically highly significant. For the no-feedback group of rescuers, 47% of the compression cycles were "too fast" and 40% of the compression cycles were "too slow. In contrast, the feedback group's compression cycles were "too fast" only 18.5% and "too slow" only 4.5%.

Five initial breaths, then 15 continuous compressions and 2 rescue breaths (15:2): The lay no-feedback group's mean compression rate was 98/minute, while the feedback group's rate was 105/minute. No significant difference was observed when comparing rates for the no-feedback and feedback groups. The no-feedback group's compression rate quality was only 11.6%, compared to the feedback group's rate of 81% (*p*<0.001) — high significant difference was observed. (Figure 4-8). For the no-feedback group of lay rescuers, 45.4% of the cycles were "too fast" and 43% of the cycles were "too slow". In contrast, the feedback group rescuers' cycles were "too fast" only 12% and "too slow" only 7%.

4.5.4.   Compression duty cycle achieved by lay rescuers without and with feedback

Compression duty cycle performance-lay rescuers
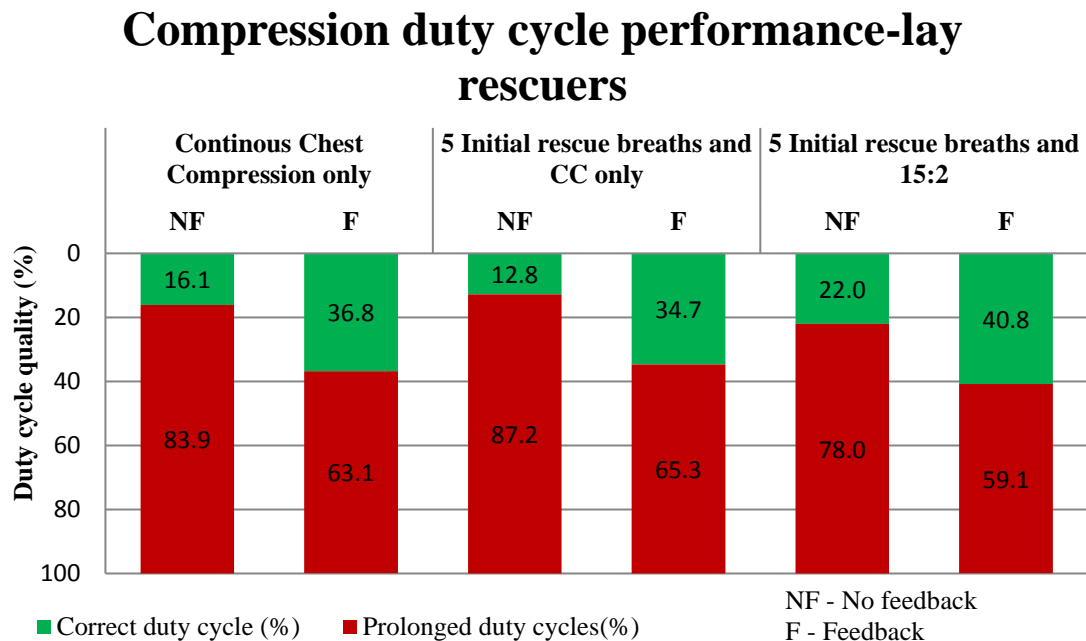
Figure 4-9: Illustration of compression duty cycle achieved by lay rescuers without and with feedback by the two-thumb (TT) technique. Current evidence-based correct compression duty cycle quality target is 30-50%.

Continuous compressions only: The lay no-feedback group's mean compression duty cycle was 73%, compared to 60% for the feedback group. Mean duty cycles between groups were statistically significant ($p<0.0001$); still the feedback group performance was not improved significantly. The quality compression duty cycles (30–50%) for the no-feedback group were only 16.1%, and prolonged duty cycles (>50%) were 83.9%. The feedback group's quality of compression duty cycles was 36.8%, and prolonged duty cycles were 63.1% (Figure 4-9).

Five initial breaths and continuous compressions only: The lay no-feedback group's mean compression duty cycle was 72%, and the feedback groups was 60%. The difference in mean duty cycles between groups was statistically significant ($p<0.0001$). However, the feedback

group performances have not achieved the recommended target. For the no-feedback group, the duty cycles were only 12.8%, and prolonged duty cycles were 87.2%. The feedback group's compression duty cycles were 34.7% (Figure 4-9), and prolonged duty cycles were 65.3%.

Five initial breaths, then 15 continuous compressions and 2 rescue breaths (15:2): The lay no-feedback group's mean compression duty cycle was 69%, versus 59% for the feedback group. Mean compression duty cycles between groups were statistically significant ($p<0.0001$); however, the feedback group performances have not achieved the recommended target. The quality duty cycles were only 22% for the no-feedback group, and the prolonged duty cycles was 78%. The feedback group's quality cycles index was 40.8% (Figure 4-9), and prolonged duty cycles were 59.1%.

4.5.5. Overall compression quality indices achieved by no-feedback group lay rescuers and feedback-benefitted lay rescuer group participants

The overall compression quality indices achieved by no-feedback group of lay rescuers and feedback group lay rescuers are shown in Figure 4-10. The performance feedback program improved the rescuers' overall CPR quality by improving individual CPR quality measures such as compression depth, release force, and compression rate. Lay rescuers' duty cycle performance is still not improved.
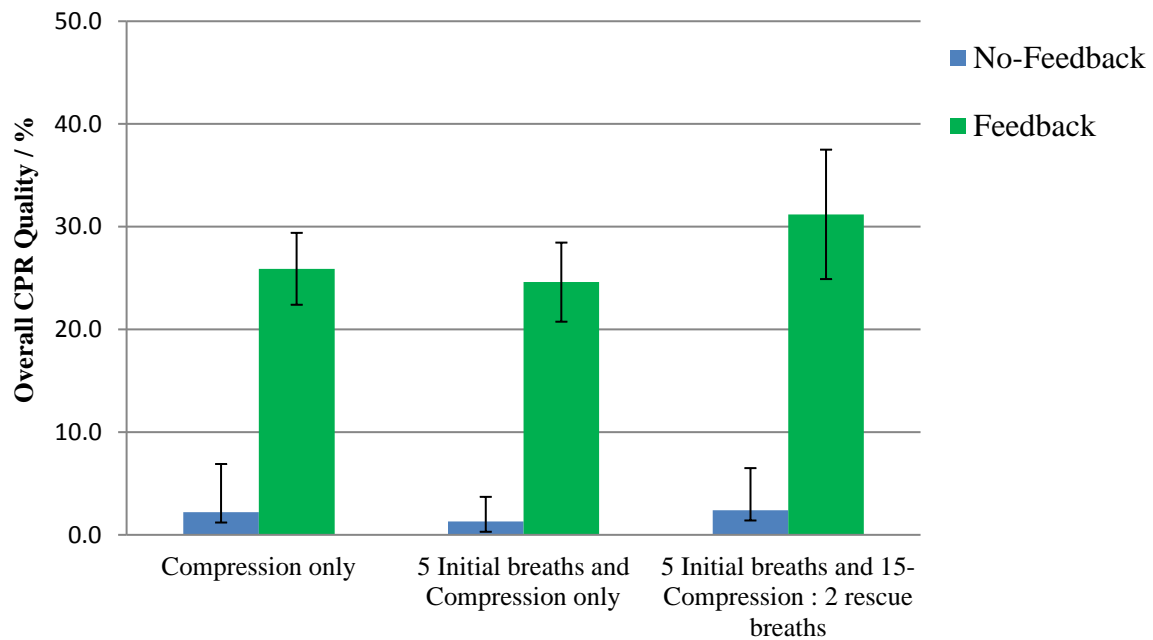
Figure 4-10: Overall simulated CPR quality index of no-feedback group lay rescuers vs. feedback group lay rescuers. Each CPR measure is presented as quality index ± standard deviation.

The overall CPR quality indices achieved by the no-feedback and feedback groups are illustrated in Figure 4-10. For the overall quality index of compression-only CPR without rescue breath, the no-feedback group achieved only 2.2%. In contrast, the feedback group achieved 25.9%. For stage 2 (5-initial breaths and compression only), the no-feedback group' overall CPR performance quality index was only 1.3%, while feedback group's overall CPR quality index was 24.6%. In stage 3 (5-initial rescue breaths followed by 15 compressions and 2 rescue breath), the no-feedback group's overall CPR performance quality index was only 2.4%, versus 31.2% for the feedback group. The feedback performance program helped the lay rescuers to achieve the high-quality compression depth, release depth and compression rate targets and marginally for the compression duty cycle.

4.6.   Analysis of lay rescuer's 5-initial compressions using the TT technique, without and with feedback

Continuous compressions: The rescuers without feedback achieved a mean 5-initial compressions depth of 39.8mm. Of 95-initial compressions, only 33 achieved the compression depth target. The lay rescuers with feedback achieved a mean 5-initial compressions depth of 40.6mm. Of 95-initial compressions, 83 achieved the depth target. The no-feedback group's mean release force of 5-initial compressions was 3.90kg. Only 22 or 95-initial compressions achieved complete release depth. Rescuers with feedback achieved a mean release force of 1.37kg for 5-initial compressions. Of 95-initial compressions, 86 achieved complete release prior to the next compression.

The no-feedback lay groups mean rate for 5-initial compressions was 91/minute. Only 8 of 95-initial compressions achieved the international guidelines; the remaining compressions were not in range. In contrast, the feedback group achieved a mean range of 110/minute for 5-initial compressions. Of 95-initial compressions, 88 were in recommended target range of compression rate. The mean duty cycle of 5-initial compressions was 74.5% for the no-feedback group. Of 95-initial compressions, only 8 achieved the recommended range. The feedback group's 5-initial compressions mean duty cycle was 52.5%. Of 95-initial compressions, only 53 achieved the recommended range.

Five initial breaths and continuous compressions: The no-feedback group of rescuers achieved a mean depth of 40.9mm for 5-initial compressions. The 5-initial compressions quality targets were analysed after the 5-initial breaths; of 95-initial compressions after ventilation, only 32 achieved the depth target. In contrast, while the feedback group's mean depth for 5-initial compressions was similar, at 40.7mm, 92 of 95-initial compressions after ventilation

achieved the depth target. The no-feedback group's mean release force for 5-initial compressions was 4.20kg. Only 20 of 95 compressions achieved complete release depth the 5-initial breaths. The feedback group's mean release force of 5-initial compressions was 1.35kg. Of 95-initial compression cycles, 87 achieved complete release depth prior to the next compression. The no-feedback group participants '5-initial compressions' mean rate was 105/minute. Out of the 95-initial compressions, only 11 achieved the international guidelines range. At the same time, feedback group participants after the ventilation the '5-initial compressions' mean rate was 110/minute. Out of the 95-initial compressions, 91 successfully achieved the target range. The no-feedback group's mean duty cycle for 5-initial compressions after ventilation was 71.1%. Of the 95-initial compressions after 5 breaths, only 10 compression duty cycles achieved the recommended range. The feedback group's corresponding mean duty cycle was 50.6%. Of the 95-initial compressions, 55 achieved the recommended range.

Five initial breaths, 15 continuous compressions, 2 breaths: The no-feedback group's mean depth for 5-initial compressions was 40.5mm. Compressions administered after the 5-initial breaths and after every 2 rescue breaths were analysed and compared with the recommended targets. The no-feedback group produced 74 breath pauses, including the 5-initial rescue breaths. Of 370 initial compressions after each set of ventilations only 113 achieved the depth target. In contrast, the feedback lay group's mean 5-initial compression depth after each set of ventilation pauses was 41.1mm. The feedback group produced 106 breath pauses. Of 530 initial compressions after ventilation episodes, 454 achieved the target depth.

The no-feedback group's mean release force for 5-initial compressions after each set of ventilation pauses was 4.1kg. Only 51 of 370 initial compressions achieved complete release depth after each breath pause. In comparison, the feedback lay group's mean release force was 1.54kg. Of 530 initial compressions after ventilation episodes, 469 achieved complete release

prior to the next compression. The no-feedback lay group's mean compression rate for 5-initial compressions after each breath pause was 115.9/minute. Only 24 of 370 initial compressions achieved the international recommended target compression rate after each rescue breath pause. The feedback group's mean rate of 5-initial compressions was 112.1/minute. Of the 530 initial compressions, 462 achieved the target range. The mean duty cycle of 5-initial compressions after each ventilation pause was 70.1% for the no-feedback group. Of 370 initial compressions after each set of ventilations, only 21 duty cycles achieved the recommended target range. The feedback group's mean duty cycle for 5-initial compressions after every set of ventilation pauses was 51.9%. In total, this group had 106 rescue breath pauses, including the 5-initial rescue breaths, out of 530 compression cycles when compared with the recommended target. Of 530 initial compressions, only 273 achieved the target compression duty cycle range.

4.7.   Rescue breath performance without and with feedback system

4.7.1. Comparison of BLS rescuers' rescue breath performance without and with feed-
back group: 5 initial breaths

Performances by 5-initial breaths by BLS rescuers, both with and without feedback, were se-
lected to compare breath count against time. For the no-feedback group, the mean value for
delivering 5-initial rescue breaths was 4.9 seconds, followed by 3.2 seconds to start compres-
sions. In total, the no-feedback participants took 8.1 seconds to deliver 5-initial breaths prior
to starting continuous compressions. In contrast, the BLS group with feedback spent only 3.9
seconds providing the 5-initial rescue breaths and took only 1.4 seconds to start compressions.
In total, feedback participants took 5.3 seconds to deliver the 5-initial breaths. Mean time for
delivering 5-initial breaths between the groups was statistically extremely significant
($p<0.001$), with a mean difference of 2. The target breath count prior to starting continuous
compressions was 5. The no-feedback group's mean breath count was 3.5, compared to the
feedback group's mean breath count of 4.9. Mean count for delivering the target 5-initial
breaths between the groups was considered as very statistically significant ($p<0.01$).

4.7.2. Rescue breath pauses during continues compression

All BLS rescuers were asked to perform 5-initial breaths and continuous compressions for a
period of one minute, such that the target breath pauses during continuous compressions was
1. The no-feedback group's mean breath pause count was 0.88, and feedback group's breath
pause count was exactly 1. The mean difference between the groups was 0.12 ($p=0.13$). No
significant difference was observed between the groups' breath counts.

4.7.3. Comparison of BLS rescuers' breath performance without and with feedback: 5 initial breaths, then 2 breaths during continuous compressions

The performance of BLS rescuers during 5-initial rescue breaths and 2 breaths after every 15 compressions, both with and without feedback, was selected to compare breath count against time. The no-feedback group took 5.6 seconds to deliver the 5-initial breaths and 3.2 seconds to start the 15 continuous compressions. In total, the BLS no-feedback group took 8.8 seconds to deliver the 5-initial rescue breaths prior to the start of compressions. This group's mean time to deliver 2 rescue breaths during compressions was 2.4 seconds. The feedback group participants spent only 3.8 seconds delivering the 5-initial breaths and only 1.2 second to start 15 continuous compressions. In total, CPR feedback participants took 5 seconds to deliver the 5-initial rescue breaths. The mean time taken to deliver 2 rescue breaths during compressions was 1.9 seconds for the feedback group.

The breath count between the no-feedback and feedback groups was a mean count of 5-initial rescue breaths. The no-feedback group delivered 3.6 breaths, while the feedback group delivered 4.9. The mean count of 2 rescue breaths during compressions was 1.8 for the no-feedback group and 2 for the feedback group. Mean time for deliver 5-initial breaths and 2-breaths during compressions, between groups was extremely statistically significant (*p<0.0001).

4.7.4. Rescue breath pauses during continues compression

Mean breath pauses were 4.2 for the no-feedback group and 6.1 for the feedback group. Mean difference between the groups was 1.9 (p<0.001). This difference is considered statistically significant between the groups.

4.7.5. Compression count during 15:2

The target compression count after the 5-initial breaths was 15 between each set of 2-breaths. For the BLS participants with no feedback, the mean compression count between each 2-breath interval was 23. The corresponding count for the feedback group was 15. Mean compression count between breaths are considered as statistically significant *(p<0.05)*.

4.7.6. Comparison of lay rescuers' breath performance: 5 initial breaths, no-feedback and feedback

Lay rescuers' performance of 5-initial breaths, both with and without feedback, were selected to compare breath count against time. The no-feedback took 4.6 seconds to administer the 5-initial breaths and 3.6 seconds to start compressions. In total, the no-feedback lay group took 8.2 seconds to deliver the 5-initial breaths prior to starting continuous compressions. In contrast, the feedback group took only 3.4 seconds to provide 5-initial rescue breaths and only 1.7 second to start compressions. In total, the feedback group took 5.1 seconds to deliver the 5-initial breaths.

The target breath count prior to starting continuous compression was 5. The no-feedback group's mean breath count was 3.3, while the feedback group's count was 4.8. Mean count for delivering 5-initial breaths between groups difference is considered to be extremely statistically significant *(p<0.0001)*.

4.7.7. Rescue breath pauses during continues compression

All rescuers were asked to perform 5-initial breaths and continuous compressions for a period of one minute. The target breath pauses during continuous compressions is 1. Both group's mean breath pause counts were 1; no significant difference was observed between the groups.

4.7.8. Comparison of lay rescuer breath performance: 5 initial breaths, then 2 breaths during continuous compressions, with and without feedback.

The lay rescuers' performances of both with and without feedback, during 5-initial breaths followed by 2 breaths after every 15 compressions were selected to compare the breath count against time. The no-feedback group's mean time to deliver the 5-initial breaths was 4.6 seconds. The group took an additional 3.3 seconds to start the 15 continuous compressions, for a total of 7.9 seconds spent delivering the 5-initial breaths before beginning compressions. The no-feedback group's mean time for delivering a 2-breath sequence during compressions was 3.8 seconds, and mean count of breath pauses was only 3.9. The feedback group spent just 3.4 seconds delivering the 5-initial breaths and only 1.5 seconds to start 15 continuous compressions. In total, the feedback group took only 4.9 seconds to deliver the 5-initial breaths. The mean time for delivering 2 breaths during compressions was 1.8 seconds for the feedback group. The mean count of rescue breath pauses was 5.6. Mean time for delivering 5-initial breaths between groups difference is considered to be extremely statistically significant ($p<0.0001$).

The breath count for both groups was a mean of 5-initial rescue breaths. The no-feedback group delivered only 3.1 breaths, while the feedback group delivered 4.78 ($p<0.01$). The mean count for 2 breaths during compressions was 1.7 for the no-feedback group and 1.9 for the feedback group. Mean 5-initial breath count between groups consider as very statistically significant and mean 2-breaths count during compressions between groups considered to be not quite statistically significant.

4.7.9. Rescue breath pauses during continuous compression

Mean breath pauses were 3.9 times for the no-feedback lay group and 5.6 times for the feedback group. Mean breath count between groups was statistically significant (p<0.01), with a difference of 1.7. The overall compression quality indices achieved by the no-feedback group lay rescuers and feedback benefitted rescuer group participants.

4.7.10. Compression count during 15:2

The target compression count after the 5-initial rescue breaths was 15 between each 2-breath sequence. The no-feedback group lay participant's mean compression count for each 2-breath interval was 26.2, compared to the feedback participant's count of 15.2. Mean compression count between breaths are considered as very statistically significant (p<0.001).

4.7.11. Confined rescue breath results

4.7.11.1.   BLS rescuers

Stage 2: Unassisted BLS rescuers took 8.1 seconds to deliver 5-initial breaths prior to starting the compressions, which is 62% higher than the guidelines recommended target time. In contrast, the feedback BLS group rescuers took only 5.3 seconds to deliver 5-initial breaths, which is only 6% higher than the target time. Unassisted BLS rescuers delivered 30% fewer breaths than recommended and the feedback group only 2% fewer than recommended during the 5-initial breaths phase—complying with the guidelines recommended target count.

Stage 3: Unassisted BLS rescuers took 8.8 seconds to deliver 5-initial breaths prior to starting the compressions and 2.4 seconds for delivering the 2 rescue breaths during compressions, which is 76% and 20% higher than the guidelines recommended target time. The feedback

participants took 5 seconds to deliver the 5-initial rescue breaths and 1.9 seconds for delivering the 2 rescue breaths, which is 0% and 5% quicker than the guidelines recommended target time; comply with the guidelines recommended time. Unassisted BLS rescuers delivered 29% fewer breaths than recommended during 5-initial rescue breaths phase and 10% fewer than the recommended count during 2-rescue breath phase. The feedback group delivered only 2% fewer than recommended during the 5-initial breaths phase—complying with the guidelines recommended target count.

4.7.11.2. Lay rescuers

Stage 2: Unassisted lay rescuers took 8.2 seconds to deliver 5-initial breaths prior to starting the compressions, which is 64% higher than the guidelines recommended target time. In contrast, the feedback lay group rescuers took only 5.1 seconds to deliver 5-initial breaths, which is only 2% slower than the target time. Unassisted lay rescuers delivered 34% fewer breaths than recommended and the feedback group only 3% fewer than recommended during the 5-initial breaths phase—complying with the guidelines recommended target count.

Stage 3: Unassisted lay rescuers took 7.9 seconds to deliver 5-initial breaths prior to starting the compressions and 3.8 seconds for delivering the 2 rescue breaths during compressions, which is 58% and 90% higher than the guidelines recommended target time. The feedback participants took 4.9 seconds to deliver the 5-initial rescue breaths and 1.8 seconds for delivering the 2 rescue breaths, which is 2% and 10% quicker than the guidelines recommended target time—complying with the guidelines recommended time. Unassisted lay rescuers delivered 38% fewer breaths than recommended during 5-initial rescue breaths phase and 15% fewer than the recommended count during 2-rescue breath phase. The feedback group delivered only 6% fewer than recommended during the 5-initial breaths phase and 5% fewer breaths during 2-breaths phase—complying with the guidelines recommended target count.

4.8.   New technique for measuring the compression duty cycle

Compression duty cycle is the amount of time a patient's chest is in an active compression phase. The current International Liaison Committee on Resuscitation (ILCOR) and internationally accepted guidelines has adapted the uniform reporting of measured CPR qualities. Duty cycles are typically calculated by dividing the area under a deflection curve by the product of the compression depth and the time of each compression cycle [130]. There is a fundamental problem with the current method for calculating the duty cycle, as there is no difference between the result of a "good" actual compression cycle and a "really bad" mirror image of the actual compression cycle. The ILCOR-recommended formula (equation-2) for calculating duty cycle is as follows:

$$DC = \frac{A}{CD \times T} \quad -----2$$

Where, DC = duty cycle, A = area, CD = compression depth, and T = time.

4.8.1. Example duty cycle calculation of single actual compression cycle and mirror image of the actual compression cycle based on ILCOR method.

The single actual compression cycle (Figure 4-11) was obtained from a rescuer's simulated CPR performance. The compression duty cycle was calculated by the ILCOR-recommended method.
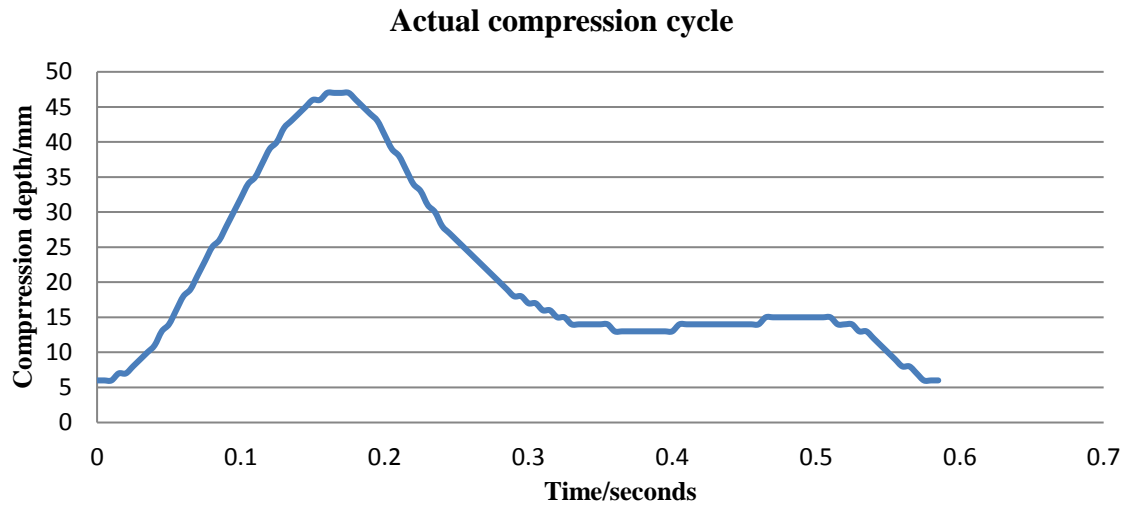
Figure 4-11: The single actual compression cycle.
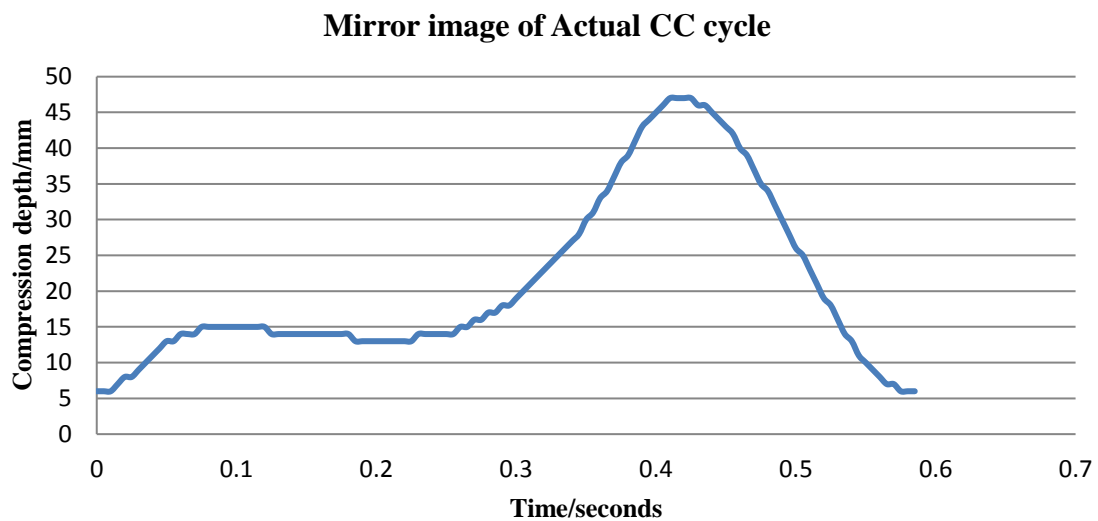
Figure 4-12: The mirror image of single actual the compression cycle.

4.8.1.1.Duty cycle calculations: ILCOR method

Table 4-1: Compression duty cycle result comparison-ILCOR method		
	Actual compression cycle	Mirror image of actual compression cycle
Area under the curve	12.325	12.325
Total time	0.585	0.585
Compression depth	47	47
Duty cycle/%	44.8%	44.8%

The compression duty cycle was calculated using the ILCOR internationally adopted uniform method (Table 4-1). The area under the compression curve, the total time spent to perform a complete compression cycle and achieve peak compression depth measures were used to calculate the compression duty cycle according to ILCOR guidelines. The compression duty cycle of an actual compression cycle and the mirror image of the actual compression cycle produced a value of 44.8%. There is no difference between them, the implication being that one cannot discriminate between a "good" duty cycle and a "bad" duty cycle using the ILCOR method.

4.8.2. Duty cycle calculations: new method

The proposed new method for calculating the compression duty cycle is based on cycle time rather than the area under the compression curve. The areas under the compression curve and compression depth details are not required. The compression cycle starting time, peak compression depth, achieved time and cycle complete release force, achieved time are the details only required for calculating compression duty cycle (equation-3).
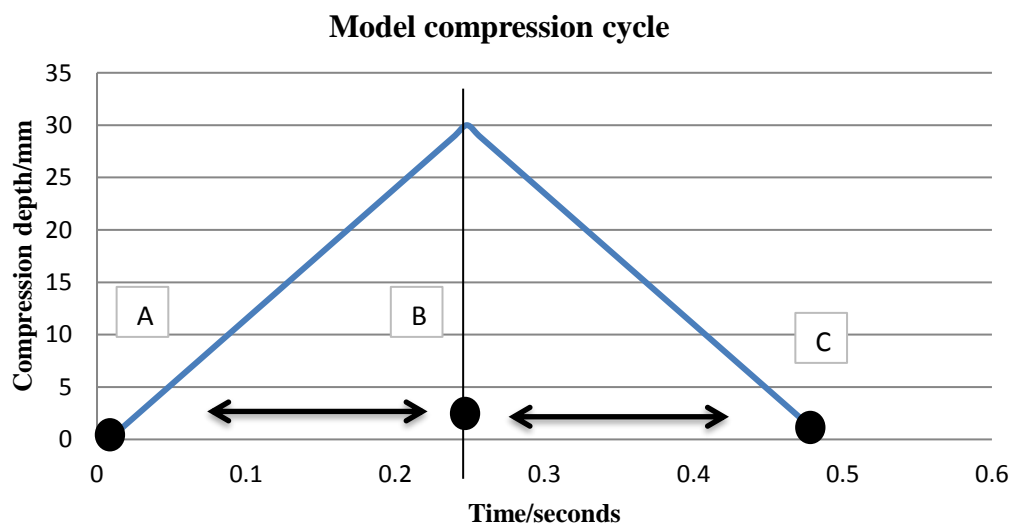
Figure 4-13: Model compression cycle with calculation points. A: Compression start time, B: Peak compression depth achieved time, and C: decompression time.

$$DC = \frac{(Compression\ depth\ achieved\ time\ (B) - Compression\ starting\ time\ (A)}{Total\ time\ (C - A)} - -3$$

Where DC = duty cycle, A = compression starting time, B = compression depth time, and C - decompression time.

Compression starting time (A) = 0.0 seconds; compression depth achieved time (B) = 0.248 seconds; decompression time (C) = 0.48 seconds; total time of complete compression cycle (C-A) = 0.48 seconds; Duty cycle (%) = (0.48-0.0)/0.48=50%,

Whereas, the model compression duty cycle based on ILCOR-method calculations are as follows: Area under the curve (A) = 7.2; total time = 0.48 seconds; peak compression depth = 30mm; DC = 7.2 / (30 x 0.488) = 0.491 =49%.

At this stage, no obvious differences were observed. The new method-based compression duty cycle was 50%, and ILCOR-based compression duty cycle was 49%.
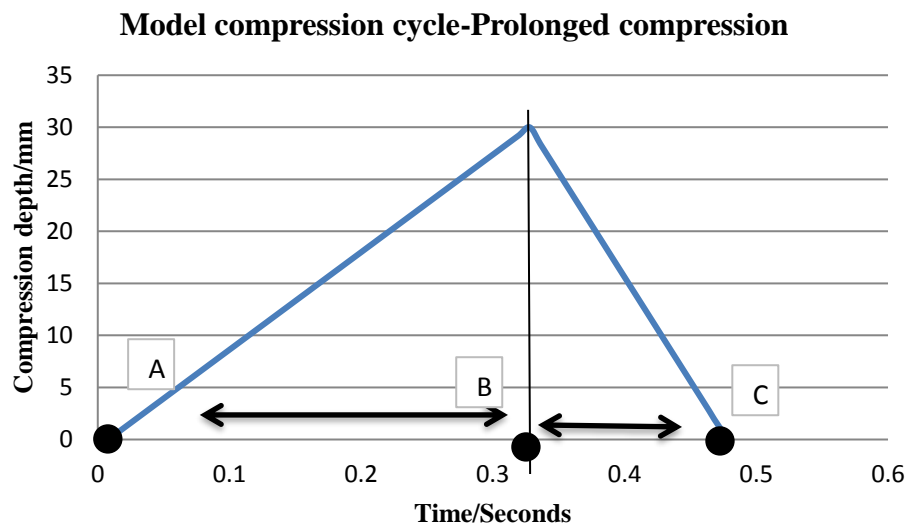
Figure 4-14: Model compression cycle: prolonged compression with calculations points. A = Compression begin time, B = Peak compression depth achieved time, and C = decompression time.

Compression duty cycle calculations based on the new method are as follows:

Compression starting time (A) = 0.0 seconds; compression depth achieved time (B) = 0.328 seconds; decompression time (C) = 0.48 seconds; total time of complete compression cycle (C-A) = 0.48 seconds; duty cycle (%) = (0.328-0.0)/0.48 = 0.683 = 68.3%

Whereas the model compression cycle based on ILCOR-method calculations are as follows:

Area under the curve (A) = 7.0512; total time = 0.48 seconds; peak compression depth = 30mm; DC = 7.0512 / (30 x 0.48) = 0.4896 = 49%.

An immense difference was observed at this stage. The new method-based compression duty cycle result was 68.3%, versus a compression duty cycle result of 49% using the ILCOR method. The ILCOR guidelines-based measurement technique produced the exact same duty cycle results for the model compression cycle and the model prolonged compression cycle. No differences were observed in the ILCOR-guided compression duty cycle calculation method as long as the time and peak compression depths were the same.

4.8.2.1.Duty cycle calculations: new method

Table 4-2: Compression duty cycle result comparison-New method		
	Actual compression cycle	Mirror image of actual compression cycle
Compression starting time	0	0
Peak compression depth time	0.165	0.42
Decompression time	0.585	0.585
Total time	0.585	0.585
Duty cycle/%	28.2%	71.8%

The compression duty cycle was calculated using the new method (Table 4-2). The compression starting time, peak compression depth achieved time, decompression time, and total consumed time for a full compression cycle were taken into account in calculating the

compression duty cycle using the new method. The actual compression cycle (Figure 4-12) was 28.2%, and its mirror image (Figure 4-12) was 71.8%. With the new method, there is a substantial difference in duty cycle results between the actual compression duty cycle and its mirror image.

4.8.3. Compression duty cycle achieved by BLS rescuers without and with feedback using new method

Compression duty cycle performance-BLS
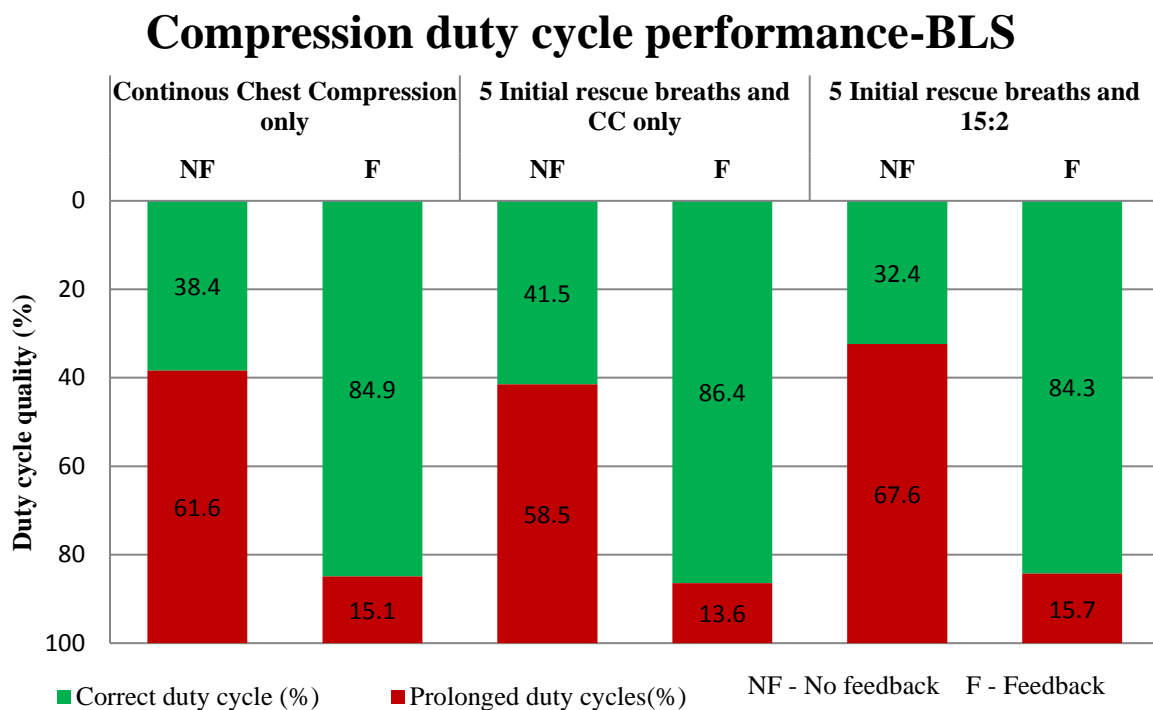
Figure 4-15: Illustration of compression duty cycle achieved by BLS rescuers without and with feedback by the two-thumb (TT) technique. Current evidence-based correct compression duty cycle quality target is 30-50%.

Continuous compressions only: Figure 4-15 shows the results of using the new method to calculate BLS rescuers' performance of the compression duty cycle during simulated CPR. Results were calculated for both the no-feedback and feedback groups. The no-feedback

group's mean compression duty cycle was 47.6%, compared to 44.6% for the feedback group. Mean duty cycles between groups were not statistically significant, and the mean difference was only 3%. Quality compression duty cycles (30–50%) were 38.4% and prolonged duty cycles (>50%) were 61.6% for the no-feedback group. The feedback group's quality compression cycles were 84.9%, and prolonged duty cycles were only 15.1% — duty cycle quality and prolonged duty cycles between groups were extremely statistically significant (p<0.0001). The performance feedback program significantly improved the rescuers' performance and compression duty cycle target.

Five initial breaths and continuous compressions only: The BLS no-feedback group's mean compression duty cycle was 47%, versus 44.5% for the feedback group. The mean duty cycles between groups were not statistically significant. For the no-feedback group, the quality compression duty cycles (30–50%) were 41.5% (Figure 4-15) and the prolonged duty cycles (>50%) were 58.5%. The feedback group's quality compression cycles were 86.4%, and prolonged duty cycles were only 13.6%— duty cycle quality and prolonged duty cycles between groups were extremely statistically significant (p<0.0001) (Figure 4-15).

Five initial breaths, then 15 continuous compressions and 2 rescue breaths (15:2): The BLS no-feedback group's mean compression duty cycle was 46.2%, compared to 42.5% for the feedback group. Mean duty cycles between groups were not statistically significant. The quality compression duty cycles (30–50%) for the no-feedback group were 32.4%, and prolonged duty cycles (>50%) were 67.6%. The feedback group's quality compression cycles were 84.3%, and prolonged duty cycles were only 15.7% —duty cycle quality and prolonged duty cycles between groups were extremely statistically significant (p<0.0001) (Figure 4-15).

The performance feedback program significantly improved the rescuers' performance and compression duty cycle target. The feedback group significantly improved all three CPR qualities (CD, RF and CR) in the current CPR guidelines range and also considerably improved the recommended duty cycle target (Figure 4-1:4-3 and 4-15).

4.8.4. Overall compression quality indices achieved by BLS rescuer groups without and with feedback: compression duty cycle measures based on new method

The overall compression duty cycle for simulated CPR performance was calculated using the new method. The overall compression quality indices achieved by the BLS rescuers, both without and with feedback (Figure 4-16). The performance feedback program significantly improved the overall CPR quality by improving the individual CPR quality measures of compression depth, compression release force, compression rate, and compression duty cycle.
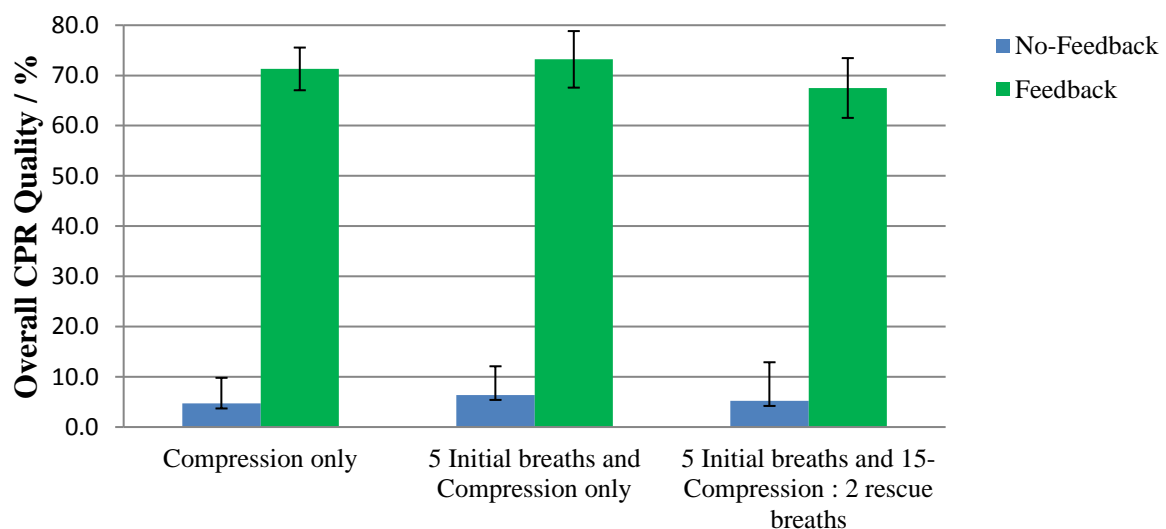
Figure 4-16: Overall simulated CPR quality index of BLS rescuers no-feedback group vs. feedback group. Each CPR measure is presented as quality index ± standard deviation.

Figure 4-16 shows the overall simulated CPR performance qualities of BLS rescuers with and without feedback on the infant manikin. The no-feedback group's overall CPR performance

quality was only 4.7%, versus 71.3% for the feedback group in the continuous compressions-only. For stage 2—5-initial rescue breaths and continuous compressions only—the no-feedback group's overall CPR performance was only 6.4%, compared to the feedback group's overall performance of 73.2%. For stage 3, 5-initial rescue breaths followed by a cycle of 15 compressions and 2 rescue breaths, the no-feedback group's overall CPR performance was 5.2%, while the feedback group's performance was 67.5%. The feedback performance program helped the BLS rescuers to achieve the CPR quality targets. Detailed data analysis and results are presented in Appendix A.16.

4.8.5. Compression duty cycle achieved by lay rescuers without and with feedback using new method
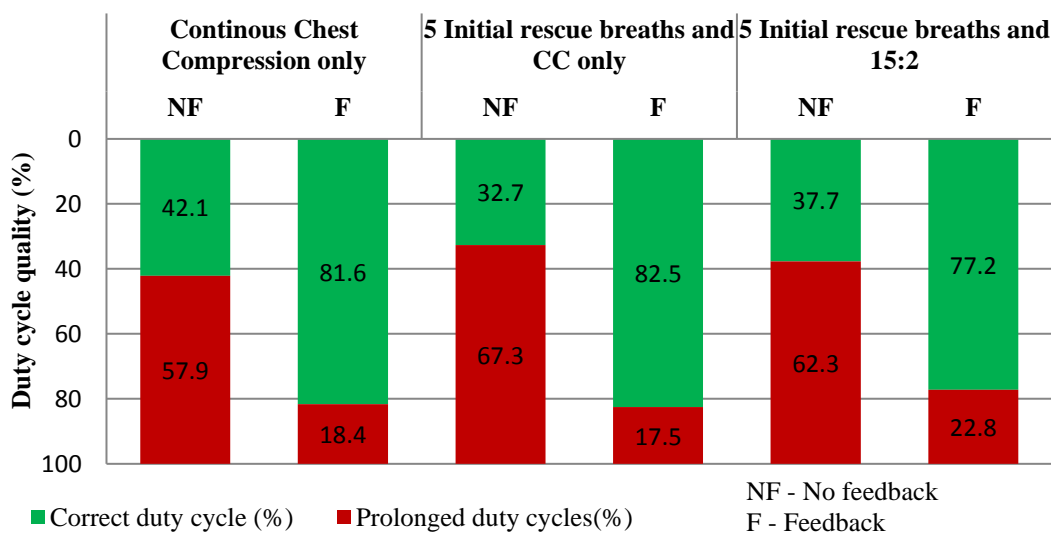
Figure 4-17: Illustration of compression duty cycle achieved by lay rescuers without and with feedback by the two-thumb (TT) technique. Current evidence-based correct compression duty cycle quality target is 30-50%.

Continuous compressions only: Figure 4-17 shows the results of calculating the simulated CPR compression duty cycle for lay rescuers using the new method. Both no-feedback and feedback groups were evaluated. The mean compression duty cycle was 53.7% for the lay no-feedback group, compared to 46% for the feedback group. The mean duty cycles between groups were statistically significant ($p<0.001$). The quality compression duty cycles (30–50%) were only 42.1% for the no-feedback group (Figure 4-17), and prolonged duty cycles (>50%) were 57.9%. The feedback group's quality compression cycles were 81.6%, and prolonged duty cycles were only 18.4%. —duty cycle quality and prolonged duty cycles between groups were extremely statistically significant ($p<0.0001$).

Five initial breaths and continuous compressions only: The no-feedback lay group's mean compression duty cycle was 52.9%, compared to 46.5% for the feedback group. Mean duty cycles between the groups were statistically significant ($p<0.05$). For the no-feedback group the quality compression duty cycles (30–50%) were only 32.7%, and prolonged duty cycles (>50%) were 67.3%. In comparison, the feedback group's quality compression cycles were 82.5%, and prolonged duty cycles were only 17.5% —compression duty cycle quality and prolonged duty cycles between groups were extremely statistically significant ($p<0.0001$) (Figure 4-17).

Five initial breaths, then 15 continuous compressions and 2 rescue breaths (15:2):

The lay no-feedback group's mean compression duty cycle was 52.7%, versus 47% for the feedback group. Mean duty cycles between groups were statistically significant ($p<0.05$). The quality compression duty cycles (30–50%) were only 37.7% for the non-feedback group, and prolonged duty cycles (>50%) were 62.3%. The feedback group's quality compression cycles were 77.2%, and prolonged duty cycles were only 22.8% (Figure 4-17) —compression duty

cycle quality and prolonged duty cycles between groups were extremely statistically significant (p<0.0001).

The performance feedback program significantly improved the rescuers' performance and compression duty cycle target. The feedback group significantly improved all three CPR qualities (CD, RF and CR) in the current CPR guidelines range and also considerably improved the recommended duty cycle target (Figure 4-6:4-8 and figure 4-17).

4.8.6. Overall compression quality indices achieved by no-feedback and feedback lay rescuer groups: compression duty cycle measures based on new method

Overall simulated CPR performances of the compression duty cycle were calculated using the new method. This calculation evaluated the overall compression quality indices achieved by the no-feedback and feedback groups of lay rescuer group participants. The performance feedback program improved overall CPR quality by improving the individual CPR quality measures of compression depth, compression release force, compression rate, and compression duty cycle.
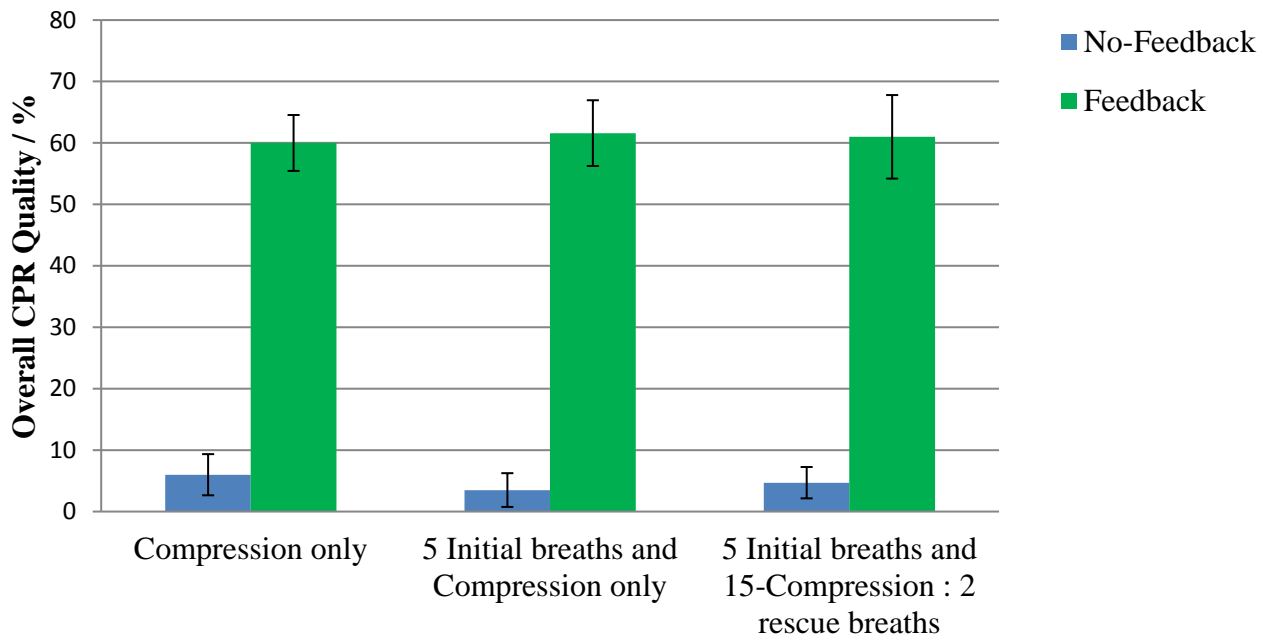
Figure 4-18: Overall simulated CPR quality index of the no-feedback group lay rescuers vs. feedback group rescuers. Each CPR measure is presented as quality index ± standard deviation.

Figure 4-18 shows the overall simulated CPR performance qualities of lay rescuers, both with and without feedback, on the infant manikin. For stage 1, consisting of continuous compressions only, the no-feedback group's overall performance quality was 6%, versus 60% for the feedback group. For stage 2, 5-initial rescue breaths and continuous compressions only; the no-feedback group's performance was 3.5%, compared to 61.6% for the feedback group. For stage 3, comprising 5-initial rescue breaths followed by sequences of 15 compressions and 2-rescue breaths, the no-feedback group's overall performance was 4.7%, while the feedback group's performance was 61%. The feedback performance program helped the rescuers to achieve the CPR quality targets. Detailed data analysis and results are presented in Appendix A.18.

5. DISCUSSION

Paediatric cardiac arrest (CA) patients have both high mortality and high morbidity. The survival rate, following a CA episode, is extremely poor [1, 2]. Immediate, early recognition of CA and administration of CPR is required to increase the odds of surviving. The external closed compression technique is one of the most crucial elements of CPR, which is the gateway to recovering CA victims, both in and out-of-hospital. CA occurs when the heart stops pumping blood to the brain and other vital organs. The primary aim of external compression, during CA, is to mechanically generate an adequate amount of blood flow and pressure to maintain haemodynamic perfusion around the body [1, 3-12]. Present research is aimed to develop a real-time CPR feedback system that would monitor, measure, and if necessary improve the quality of compression performance during simulated CPR performance on an infant manikin. The following sections deatil the principal findings of a series of investigations, comparing these findings against current CPR guidelines and significant literature, and analysing the relevance and prospective impact of this research, both in clinical and educational aspects of CPR. This study also considered the quality of '5-initial compressions' after each ventilation pause at each stage, both with and without feedback assistance. The reasoning behind measuring the quality of 5-initial compressions is that if these compressions achieve the target, then it is likely that subsequent compressions will also be of high quality.

5.1   Comparison of results with relevant literature

5.1.1   Chest compression depth

Compression depth is considered as the most important quality measure during iCPR [13, 14]. Haemodynamic outcomes are associated with increased arterial pressure, which is achieved by deep compression depths in both infant and adult human subjects [4, 9], and greater coronary

flow and increased cardiac output in animal subjects [10, 12]. Deeper compression depths, of greater than one-half the external AP diameter compression depth, may cause damage to intrathoracic organs [15-19]. However, under-compression, also known as shallow compression depth during CPR, is reported by recent studies in both adult and infant populations [20-24] and during simulated CPR performance on infant manikins [18, 19, 25-27]. As a result of thoracic injury and shallow compression depths, current resuscitation guidelines recommend that compression depths are at least one-third of the AP chest diameter in all children (i.e., approximately 4cm in infants and approximately 5cm in children) [13, 14, 28].

The compression depths achieved in this research study with a more physiological infant manikin were consistent with the literature. The deep compression depths, under-compression depths and current quality compression depth targets were observed in this research. A more physiological manikin (designed by Martin *et al.* [18]) was used to measure deep compression depths during simulated CPR performances. Consequently, when compared with recent research studies, the compression depths in this research may better represent the quality of compression depths by BLS and lay rescuers during CPR training and in clinical practice.

This study is the first to design and develop a real-time iCPR feedback system and investigate the effect of real-time feedback during simulated iCPR, resulting in a significant improvement in overall infant compression quality. The unassisted participants were to perform without feedback assistance, while the feedback assisted group participants were provided with performance feedback assistance. Achievement of adequate compression depth is crucial for maintaining favourable haemodynamic outcomes [4, 9, 10, 12]. The unassisted BLS and lay rescuer target compression depth (i.e. 35–43 mm) quality index was <46%. This poor performance is consistent with the previously reported simulated infant CPR studies [18, 25, 27, 29, 30]. This

poor performance, delivered by BLS CPR providers, has raised concerns, as this replicates the current clinical practices during iCPR both in and out-of-hospital. However, a lack of understanding and self-confidence might provide clarification for why lay providers delivered poor performance. Most of the infant CAs (93%) occurs in private locations [31-34]. Often the lay population employ CPR in public places or patient's houses. Good bystander CPR is associated with a shorter CA recovery times. High-quality bystander's CPR increases the proportion of patients who are discharged from the hospital alive compared to poor bystander CPR or no bystander CPR [34]. This study suggests that education and BLS training are essential for bystanders prior to performing CPR. The unassisted group achieved (>20%) deep compressions and (>31%) shallow compressions. Thus, deep compressions potentially cause iatrogenic intrathoracic organ injury through the over-compression of the thorax [4, 15, 17, 35]. Recent studies observed that shallow compressions were performed during simulated iCPR on instrumented manikins [27, 29, 30, 36]. The shallow compression depth is also consistent with the previously reported simulated CPR performance. The provision of shallow compressions in clinical practice would reduce blood flow during iCPR [4, 9, 10, 12].

The group provided with real-time feedback assistance achieved the recommended target depth >80% of the time during TT compressions. The real-time feedback system "encouraged the providers" leading to greater uniformity in the target compression depth range. Fundamental to this improvement in compression depth quality was the real-time feedback monitor displaying 'actual chest deflection traces' on a laptop screen window. Further, the window was divided into colours, which assisted providers in maintaining in the target range. The improved compression depth quality, achieved with real-time feedback, also reduced the deep compres-

sion depths (<5%) (over 1/3 of the AP diameter) and shallow compression depths. This potentially reduced intrathoracic trauma [4, 15, 35] and increased the favourable haemodynamics of the heart [9, 10]. The quality of compression depth is the most significant performance indicator of a successful outcome during iCPR [13, 14]. The previous simulated iCPR performance investigations of European Paediatric Life Support (EPLS) and/or APLS certified CPR providers' - performance compression depth quality index without feedback assistance, achieved only 20% and with feedback assistance, achieved 99% using TT technique [25]. This result supports the current performance of BLS and lay rescuers performance with and without the feedback system. In addition, another study also reported that, when CPR is performed in children, rescuers failed to achieve adequate compression depth to develop sufficient blood pressure and tissue perfusion [4]. Compression depth quality of BLS and lay rescuers performance against currently recommended compression quality standards have never been previously quantified. The provision of real-time performance feedback confirms that resuscitators achieve compression depth quality targets more frequently during simulated iCPR.

This study also considered the 'depth quality' of the 5-initial compressions at each stage, with and without feedback. The aim of exploring the initial five-compression depth quality after each pause was to investigate whether a compression provider, given a "good start", could continue the quality of compression until the next breath pause. The BLS and lay unassisted group achieved only <45% of the 5-initial target compression depths. The BLS and lay feedback assisted groups achieved >94% and >85% of the target compression depth, respectively. The unassisted BLS and lay group initial performance was poor. Only less than half of the compressions achieved the target depth. Consequently, the poor-quality compressions were sustained until the next breath pause (overall quality of compression depth was <46%). The feedback assisted groups initial compressions, after each pause, mostly achieved the target

depth; the high-quality compressions were continued until the remaining compressions' overall compression depth quality was >80%. Thus, if the compression providers have a "good start" that can assist in achieving adequate continuous compression depths. In addition, if people were trained regularly with a feedback system, it would potentially help them to maintain their 'muscle memory'. The real-time feedback system confirmed that quality targets could be better achieved during simulated CPR performance on the infant manikin.

5.1.2   Chest release force

International infant resuscitation guidelines recommend that rescuers should allow the chest wall to release completely (recoil or decompression) after each compression [13, 14, 28]. The 'leaning' phenomenon between compressions, also called incomplete decompression of the chest, is when the applied force is not completely removed from the chest between compressions during the chest release phase. Leaning is the most common problem during CPR performance [37]. Leaning increases intrathoracic pressure and thus, decreases coronary perfusion pressure and the return of venous blood to the heart, which ultimately leads to a reduced survival rate [3, 5, 6, 38, 39]. Active compressions and decompressions, during CPR, are associated with a better haemodynamic status of the heart [40]. Complete chest wall decompression improves haemodynamics by generating relatively negative intrathoracic pressure and thus, pulling venous blood back to the heart. This complete chest wall decompression refills the heart with the maximum amount of blood and provides cardiac preload prior to the next compression [41-43]. The chest release force, about 10% of a subject's body weight, also produces detectable intrathoracic pressure during continuous compression [39]. Several previous research studies reported that resuscitators often fail to achieve the complete release depth in

compressions, during in- and out-of-hospital and simulated CPR performance on a manikin, in both adult and paediatric populations [6, 20, 44, 45].

During in-hospital paediatric CPR, leaning force was reduced significantly with the provision of feedback; resulting in 73% of compressions achieving the release force of <2.5kg [45]. This result was further supported by another investigation [46], using the feedback during paediatric CPR, which reported that 77% of the compressions achieved the leaning force quality target of <2.5kg. This investigation was the first to evaluate the BLS and lay rescuers chest release force quality, achieved with and without real-time feedback assistance during simulated iCPR. The introduction of an 'in-house', more physiological infant manikin design provided an opportunity to investigate the proportion of complete chest wall releases during simulated continuous chest compressions. The BLS and lay groups without feedback assistance using TT technique, achieved <58% and <32% respectively, which complies with the chest release force quality target of <2.5kg.

The poor performance delivered by BLS rescuers during simulated performances has raised concerns over whether repeats in the clinical practices during iCPR both in and out hospitals would reduce cardiac survival rate. The lay rescuers understanding about CA and self-confidence are significantly limited and could be a source of poor decompression performance.

The BLS group with feedback achieved >78% quality compressions, whilst the lay group with feedback achieved >73%. Previous investigations, focussing on iCPR performance by trained clinicians, reported a 47% performance ratio without feedback and 99% with feedback, using the TT technique [25]. Fundamental to this, was the real-time feedback system displaying real-time compression traces on the laptop screen during simulated performances. The bottom green threshold represents the complete decompression (7mm, <2.5kg) in the real-time window. Providers who failed to comply with the target release depth, which can be easily

recognised via the live indicator, were more aware of their failure. The provision of real-time feedback assistance appears important in achieving consistency in the complete release of the chest during simulated iCPR.

This research also examined release force quality for the '5-initial compressions phase' of CPR, both with and without feedback assistance. Five initial compressions performance quality of the BLS unassisted group achieved only <45% of the target release force and the unassisted lay group achieved only <23% of the target compression release force. The BLS and lay feedback assisted groups achieved >96% and >88% of the target release force, respectively. The provision of real-time feedback assistance to the resuscitators improved the quality of compression cycles. The real-time feedback system confirmed that quality targets can be better achieved during simulated CPR performance on the infant manikin. It was found that compressions' quality could be improved by using a feedback system for providing regular training and incorporating this feedback system into real-time clinical practice. This may help them to perform high-quality compressions in clinical practice.

5.1.3   Chest compression rate

There is a positive relationship between the number of compressions actually performed on a CA victim's chest and their chance of successful survival following the arrest [46]. Blood flow rate in neonates is suggested to be optimal at a compression rate of ≥120/min, as recommended by the mathematical study of cardiovascular physiology [47]. In animal models of CA, compression performed at a rate of 120/min produced higher myocardial perfusion pressures, increased left ventricular blood flow and a more successful outcome from CA than 60/minute and 80/minute rates [48-50]. The same is true in adult subjects: compression performed at a rate of 120/min has produced better myocardial perfusion pressure than 60/minute and 80/min

rates [51]. Thus, international infant resuscitation guidelines recommend that during compression performance, the rate should be at least 100/min but no greater than 120/minute, for both infants and children [13, 14, 28]. A compression rate of between 100/minute and 120/minute is recommended to deliver high-quality CPR and to achieve the greatest likelihood of successful outcomes from CA [28].

This research also examined the quality of the compression rates during simulated iCPR. Unassisted feedback participants constantly performed compressions "too quickly" on the manikin. The BLS and lay participants, without feedback assistance, achieved compression rate quality targets of only <14%. The BLS rescuers exceeded the internationally recommended targets; mean compression rate was >135/minute. This poor performance is consistent with the previously reported infant simulated CPR studies. Recent studies reported that the mean compression rate exceeded 130/minute [18, 19, 26, 27]. In addition, the compression rate was very poor, both in the hospital and out of the hospital patients. It was found that only one-third to one-half of all compressions were high-quality compression rates, provided in both adult and paediatric patients [18, 20, 23, 24].

The BLS rescuers consistently performed rapid compressions (>53%) without feedback assistance, and one-fourth of compressions were performed too slowly (>24.3%). However, lay rescuers performing compression rates without feedback, almost half of compressions were 'too fast' (>42%) and half of the compressions were 'too slow' (>40%). A recent study concluded that compressions are often delivered at rates much lower than the recommended guidelines during clinical practice [24]. Sluggish compressions significantly reduced the possibility of ROSC [7, 11, 52, 53], whilst rapid compressions considerably reduced both coronary blood flow and the proportion of compressions that achieve guidelines recommended target depth and increases leaning force [7, 11, 53, 54]. Moreover, the compression rates vary extensively

among providers. Sluggish compression rates may contribute to resuscitation failure [55]. Therefore, our finding has revealed a significant problem in current CPR clinical performance by BLS rescuers. The lay rescuers do not have any experience with CPR before they were performing compressions on the manikin. Therefore, their knowledge about CA and CPR performance was limited; as a result, lay rescuers delivered poor decompression performance. The excessive and sluggish compressions were the cause, which significantly reduced the quality of simulated compression rate. The unassisted BLS and lay groups target compression rate was exceeding 190/min and 200/min in a few cases. The lay rescuers target compression rate was recorded at 70/min in some incidences. Laboratory studies also have shown that slow compression rates do not produce sufficient blood flows to sustain resuscitation [50]. However, higher rates are associated with improved measures of perfusion [56].

The provision of 'real-time audio-visual metronome CPR performance feedback' has significantly improved compression rate quality. The BLS feedback assisted groups achieved a >78% conformity with the international resuscitation guidelines. The lay group with feedback achieved >75%. Delivering the optimum compression rate is vital to reach high-quality compressions during iCPR in clinical practice. The flashing LED indicator, and audible metronome combined feedback system regulates providers to deliver the simulated compression rate within the target range. The previous simulated iCPR study also supports the current performance of BLS and lay rescuers performance; EPLS and/or APLS certified CPR providers' performance compression rate, without feedback assistance, achieved only 20% and with feedback assistance achieved 92% using TT technique [25]. This significant improvement is achieved by reducing the excessive and slow compressions. If the regulated compression rate is transferred to clinical practice, it is anticipated that it could improve the optimal venous blood return to

the heart prior to recirculation, which would improve the successful clinical outcome. Moreover, real-time feedback with flashing lights and sounds improves the concentration of the rescuers during compressions by maintaining optimum compression rates. This research recommends a real-time CPR feedback system during clinical practice to reduce human error in compressions.

This study also considered the quality of 5-compressions at each stage, with and without feedback assistance. The BLS unassisted group population achieved only <19% of the 5-initial compressions target compression rate and the lay group without feedback, only <12%. In contrast, the BLS and lay feedback assisted groups achieved >92% and >87% of the target compression rate, respectively. This investigation assessed the benefits of assisting CC providers with feedback at the start of the compression cycle. Unassisted provider's performance was poor at the start of the compressions after each pause; the same quality performance reflects the remaining compressions. The feedback assisted group performance was significantly improved. Improved confidence and feedback were the main reasons behind this improved performance. The provision of real-time feedback with audio-visual metronome assistance helped to regulate the rescuers' compression rates and improved the quality of compression cycles. The compression rate reduction using the feedback, if transferred to the clinical practice could improve the optimal venous blood return to the heart prior to recirculation, which might improve the successful clinical outcome.

5.1.4   Chest compression duty cycle

The compression duty cycle is the fraction of the time that the chest is actively compressed during each compression cycle. Compression duty cycle is considered as a crucial element of CPR [37]. Current infant resuscitation guidelines do not recommend a quality target for the compression duty cycle, even though a prolonged duty cycle reduces the return of venous and

cerebral blood to the heart and subsequently leads to a reduced CA survival rate [8, 11, 53, 55, 57-59]. However, neonatal guidelines identify the advantages of compression phase being "slightly" quicker than relaxation phase of the compressions [60]. The mathematical modelling of mechanical CPR resulted in significant improvements in the coronary and pulmonary perfusion pressure with a 50% duty cycle when compared with compression-relaxation cycles in which compressions constitute a greater percentage of the cycle [61]. The effect of varying the duty cycle on clinical and physiological outcomes has not yet been investigated [37]. However, a compression duty cycle oscillating between 30% and 50% can result in "good" coronary and cerebral perfusion [50, 62, 63]. A real-life duty cycle of 50% is easily achievable [64]; therefore, a duty cycle of 50% is highly recommended [62, 64]. Infant swine studies also observed an optimal compression duty cycle of between 30% and 50% [7, 53].

The present study has investigated the compression duty cycle quality of BLS and lay rescuers during simulated iCPR with and without real-time feedback assistance. Unassisted feedback participants constantly compressed the infant chest 'slowly' and released 'quickly'. The quality of the compression duty cycle was calculated between 30–50% for these investigations. Rescuers have to achieve the target compression duty cycle since it is important for a cardiac refill of sufficient blood prior to the next compression. The BLS and lay groups, without feedback assistance, achieved compression duty cycle quality targets of only <18.5% and <22% respectively. This poor-quality result is consistent with the previously reported simulated infant based manikin studies [18, 25]. This poor quality of compression duty cycles achieved by BLS responders during simulated performances has raised concerns becasuse if repeated during the clinical practice of iCPR, both in- and out-of-hospital survival rates could be reduced. Untrained laypersons, however, do not manage to deliver CPR correctly without any assistance

or adjust themselves instinctively to achieve a high quality of compression duty cycles. In addition, lay rescuer's understanding and self-confidence were also limited.

The unassisted BLS and lay rescuers achieved the quality of prolonged compression duty cycles (>78%). Prolonged durations of active compressions significantly reduce the cerebral blood flow, myocardial perfusion pressure and cardiac output; most importantly reducing the venous blood return to the heart before the next compression [7, 11, 52, 53]. In addition, incomplete decompression of the chest and prolonged compression duty cycles reduce the coronary perfusion and limit the return of venous blood to the heart [3, 39, 53, 65-67].

Feedback benefitted the BLS group in all stages, resulting in >79% of all compressions achieving the recommended quality targets, versus the assisted lay group achieving only 34.7-40.8%. While the feedback system does not provide any guidance to enhance the quality of compression duty cycle, whilst provides remining targets such as depth, release depth and rate. Even though, the assisted group's compression duty cycle quality was considerably improved, along with the remaining quality measures. The previous study of simulated iCPR performance investigations of EPLS and/or APLS certified CPR providers' performance unassisted compression duty cycle quality index, achieved only 18% and with assistance, achieved 97% using TT technique [25]. This result also supports the current performance of BLS and lay rescuers performance with and without feedback. Fundamental to this considerable improvement in duty cycle quality was that this research provides real-time feedback assistance to the other three compression quality measures. That is, the proportion of compressions that achieved the quality by reducing the proportion of prolonged duty cycles through the combination of correct depth, reduced decompression depth and appropriate rates.

Nevertheless, assisted BLS rescuers achieved a considerable amount of quality duty cycle targets. In addition, this study suggests that future iCPR feedback systems should incorporate a

provision to regulate the compression duty cycle. Lay rescuers may have never previously performed CPR and are not related to the field of medicine. Lay rescuers compressed the infant chest 'slowly' and released 'quickly'. BLS rescuers are knowledgeable and trained in CA basics, so they may have had some limited exposure to performing simulated compressions on a manikin. Lay rescuers have no previous experience with CA patients or medicine and lack knowledge of cardiac circulation. Thus, lay rescuers need additional training in simulated iCPR performance with feedback devices and need to learn the basics of CA and the blood circulation system to improve the overall quality of the CPR.

This study also considered the quality of the compression duty cycle for 5-initial compressions at each stage, both with and without assistance. The BLS unassisted group achieved only <31% of the 5-initial compressions; for the unassisted lay group, only <20% of the 5-initial compressions achieved the target compression rate. The assisted BLS and lay groups achieved >94% and >51% of the target compression duty cycles, respectively.

Unassisted provider's performance was poor at the start of the compressions after each pause; the same quality performance reflects the remaining compressions. The assisted group performance was better than the unassisted group. The reason could be that assistance provides positive support at the start of compressions, which improved confidence during CPR performances. The provision of real-time feedback significantly regulated the performance of the duty cycle and improved the quality of the compression cycles.

5.1.5   New method of calculating compression duty cycle

The current method for calculating the compression duty cycle was proposed by Kramer-Johansen *et al*. It is calculated by dividing the area under the chest deformation curve by the

product of compression depth and time for each compression cycle [37]. The current International Liaison Committee on Resuscitation (ILCOR) and internationally accepted guidelines adopted this uniform reporting of measured CPR quality.

The present study sought to utilise the compression duty cycle as a quality indicator and whilst doing so, encountered a shortcoming with the current calculation. The calculation could not discriminate between those duty cycle waveforms which had a quick compression, and slow decompression and those who had a slow compression and quick decompression. Hence, there was no difference in results between an actual single compression cycle and the mirror image because the calculations were dependent upon the compression depth, the area under the curve and time. A new technique based on the compression cycle time (the cycle starting time), peak compression depth, achieved time and cycle decompression depth achieved time was formulated to overcome these limitations.

The DC calculated using the current technique; the key variables such as Area, Depth and Time (ADT-DC) are required for calculating the duty cycle. A single sample compression duty cycle and its mirror image duty cycle were both 44.8%, which indicates a mistake in the current technique. The new technique, which is based on effective compression time (ECT-DC), resulted in a single sample compression duty cycle of 28.2% and a mirror image of 71.8%.

Current resuscitation guidelines do not recommend an optimum compression duty cycle targets for infants, even though a prolonged duty cycle (>50%) reduces the return of venous and cerebral blood to the heart and subsequently leads to a reduced CA survival rate [8, 11, 53, 55, 57-59]. Neonatal guidelines identified the advantages of the compression phase being slightly quicker than the relaxation phase [60]. The mathematical modelling of mechanical CPR has resulted in significant improvements in the coronary and pulmonary valve blood flow with a 50% duty cycle, when compared with compression-relaxation cycles in which compressions

constitute a greater percentage of the cycle [61]. The effect of varying duty cycle on clinical and physiological outcomes has not yet been investigated [37]. However, a compression duty cycle evaluated using animal surrogates oscillating between 30% and 50% resulted in good coronary and cerebral perfusion [50, 62, 63]. A real-life duty cycle of 50% is easily achievable in practice [64]; therefore, a duty cycle of 50% is highly recommended [62, 64]. Infant swine studies also observed an optimal compression duty cycle of between 30% and 50% [7, 53].

This present study examined the compression duty cycle quality of BLS and lay providers during simulated iCPR, with and without real-time feedback assistance. In addition, two different methods to derive the compression duty cycle measure were used in this study. The ADT-DC derive method quality performance were discussed in section 5.1.4 and the ECT-DC method, which derived the DC by dividing the active compression time by total time for each cycle. This research reported that the ADT-DC method has a fundamental error; no differences were observed in the ADT-DC derived method compression duty cycle, whilst the time and peak compression depths were the same. Thus, the ADT-DC method cannot discriminate whether a particular compression is "good" or "bad"'. A study to derive model compression cycles was conducted; one with a good quality compression duty cycle (50%, Figure 4.13) and another with a prolonged duty cycle (Figure 4.14). Good quality compression duty cycle measures were calculated using both methods. At this stage, no significant differences were observed (compression DC=49%). The prolonged compression duty cycle measures were also derived using both methods and a significant difference in quality was observed at this stage. ADT-DC method produced a 49% DC, compared to 68.3% derived using the ECT-DC. Therefore, it is recommended that as a result of these findings, the Resuscitation Council should consider the ECT method a more reliable method to derive the compression duty cycle in the future.

The quality of the DC for the simulated CPR performance target was calculated to be between 30–50% for these investigations using the ECT-DC. The unassisted BLS resuscitators' compression duty cycle performance was <41.5%, and the lay rescuers' performance was <37.7% for all stages of compression performance that achieved the recommended infant compression duty cycle quality targets. This poor-quality result is consistent with previously reported simulated infant based manikin studies [18, 25]. If BLS and lay providers were to deliver the same quality of compression duty cycles in clinical practice, it is likely that this would result in a reduced survival rate from CA. Fundamental to addressing poor quality DCs is that the providers compress the chest 'slowly' and release more 'quickly'. The untrained laypersons do not manage to deliver CPR correctly without assistance or adjust their performance. This must, in part, be explained by the lay rescuers not understanding CA and lacking self-confidence. Moreover, the unassisted BLS and lay groups DC quality targets were calculated using the ADT-DC method, resulting in <18.5% and <22% conformity, respectively. It was also found that there were significant differences between the results of the ADT-DC derived and the new ECT-DC method.

This study is the first to investigate the provision of a real-time feedback system to assess compression DC performance during simulated iCPR. The provision of feedback produced a significant improvement in overall DC performance by the BLS and lay providers. The feedback system benefitted both BLS and lay group participants in achieving the recommended infant compression DC quality targets in >84.3% and >77.2% of all compressions performed, respectively. Results for the same CPR performances were calculated using the current ADT-DC method as follows: assistance benefitted the BLS group in all stages, resulting in >78% of all compressions achieving the recommended quality targets. The assisted lay group achieved only >34.7% - 40.8%. There were significant differences between the currently recommended

compression DC results and the new method. Fundamental to this considerable improvement was that this study provided real-time feedback assistance to the other three compression quality measures. The proportion of compressions that achieved the quality by reducing the proportion of prolonged compression duty cycles, through a combination of correctly delivered compression depths, reduced decompression depths and appropriate compression rates. Nevertheless, feedback assisted BLS rescuers achieved a considerable amount of quality DC targets. This study suggests that future iCPR feedback systems should incorporate a provision to regulate the compression DC.

The overall CPR performance quality of the unassisted BLS and lay providers was only $<6.4\%$, based on the ECT-DC calculation method; with feedback assistance, BLS and lay providers achieved $67.5\%–73.2\%$ and $60\%–61.6\%$, simultaneously achieving all four CPR quality measures. The overall quality was significantly increased when compared with the ADT-DC technique. The feedback performance program assists rescuers in achieving CPR quality targets. The primary aim of this study was to assess how rescuers perform simulated iCPR, with and without feedback assistance. Unassisted providers delivered very poor performance. The BLS CPR performance raises significant concerns if it is translated into clinical practice. However, real-time feedback assistance produced significant improvements in CPR performance, with more frequent compressions, simultaneously achieving all four compression quality targets. With the assistance of a real-time feedback system, high-quality compressions can be achieved during simulated CPR performances. This study reports the fundamental problem with the current ADT-DC measuring technique and provides a viable alternative for the calculation of compression DCs to consider in the future.

5.1.6 Rescue breaths

Effective compressions and rescue breaths are the most vital interventions during CPR [68-71]. Maintaining the airway for CA patients and providing ventilation, also called 'rescue breaths', are essential elements during paediatric CPR because CA often results from,, or is complicated by, asphyxia [13]. Infants OHCA survival probability may be improved by a bystander witnessing the arrest and providing the rescue breathing at first sight of arrest [72]. Animal studies show that rescue breaths after ventricular fibrillation (VF) or asphyxia resulted in the improved return of spontaneous circulation (ROSC) and improved CA and neurological outcomes when compared with no ventilation during CPR [73-75]. The main purpose of rescue breaths during CPR is to retain sufficient oxygenation and remove CO_2 [76]. Previous population-based investigations of out-of-hospital paediatric CAs showed that when rescue breaths follow compressions during CPR, the survival rate is greater than for compression-only CPR for children in CA as a result of non-cardiac causes [77]. Successful paediatric CA resuscitation is based on rescue breathing; for asphyxial CA and prolonged CAs in both adults and children, conventional CPR with rescue breaths is recommended for all trained rescuers [74, 75, 78-80]. Recent studies reported that OHCA infant cases witnessed by a bystander who administered rescue breathing survival rate was twofold higher than that witnessed by a bystander who did not provide rescue breathing [72, 77, 81].

5.1.5.1. Rescue breath delivery time

In case of no sign of life, European Resuscitation Council Paediatric Guidelines for Resuscitation 2015 recommend to immediately start compressions followed by rescue breathing at a ration of 15 compression to 2 ventilations [28]. However, if breathing is not normal, guidelines recommend 5-initial rescue breathing before starting the compressions at a ratio of 15:2 [28]. In addition, the guidelines recommend that each breath should take about only '1 second',

which is sufficient to make the infant chest visibly rise [28, 82]. This research examined the rescue breath count against time of 5-initial rescue breaths and 2 rescue breaths during compressions at the rate of a 15:2 compressions-to-ventilation ratio.

The unassisted BLS population took 62-76% greater time and the unassisted lay population took 58-64% greater time than the guidelines' recommended target time to deliver 5-initial breaths through the flow sensor. The unassisted BLS and lay participants took 20% and 90% greater time than the recommended target time to deliver the 2-rescue breaths during compressions. In conclusion, 'unassisted group took 20-90%' greater time than the recommended target time to deliver a 'single breath'. The prolonged time for delivering rescue breaths significantly reduces the number of compressions provided in a given time. This research finding is consistent with previously reported results that healthcare professionals spend only 50% of the total CPR time performing active compressions during in-hospital and OHCA occurrences [23]. In children's resuscitation, both hypocarbia and hypercarbia originated CAs are associated with higher mortality [83]. Therefore, 2015 European paediatric guidelines recommended that the child with ROSC should usually be ventilated at 12-24 breath min^{-1}, according to their age normal values [28]. This research reflects the significant problem in current CPR clinical performance delivered by BLS rescuers. The lay rescuers have no previous knowledge of rescue breathing and CPR, prior to being required to perform rescue breaths through the airflow sensor; therefore, their poor performance is to be expected.

This study is the first to design and develop a real-time iCPR feedback system, which includes rescue breathing and the first to investigate the effect of real-time feedback during simulated iCPR rescue breath performance. The study resulted in a significant improvement in overall rescue breath performance delivered by BLS and lay providers. The real-time feedback assisted BLS rescuers took only 6% and lay population took only 2% greater time to deliver 5-

initial rescue breaths than the guidelines recommended target time. In contrast, the BLS and lay feedback-assisted population were 5% and 10% quicker than the target time to deliver 2-rescue breaths during compressions. In conclusion, the 'feedback assisted group' were 30-84% quicker than the unassisted group in delivering a 'single breath', in compliance with recommendations. Optimum CPR technique for infants and children's CA interventions includes compressions with rescue breaths. Rescue breathing is an important part of the resuscitation sequence for rescuing children in CA because asphyxial (respiratory problems) often initiate CA [74, 78, 84-87] and ventricular fibrillation [88-90]. An animal surrogate study used swine to simulate paediatric asphyxial CA and reported that compressions and simulated mouth-to-mouth ventilation improved systemic oxygenation, coronary perfusion pressures, early ROSC and 24-hr survival, compared with no "bystander" CPR or 'compression without ventilation' approaches [91]. However, oxygenation and ventilation are vital for survival from ventricular fibrillation (VF) CA. During VF CA, myocardial blood flow is limited and subsequently oxygen delivery also. Arterial oxygenation and pH become progressively important over the time of effective resuscitation [75, 92].

The American Heart Association recommends that if there is inadequate breathing with a pulse (≥60/min), providers must deliver rescue breaths at a rate of about 12-20 breaths per min [71]. However, during this research, rescue breath performance in the without feedback assistance BLS and lay providers was 'very slow' compared to the target time for delivering a 'single breath'. In contrast, during feedback assistance, both BLS and lay providers were 'very quick' compared to the unassisted group and nearly achieved the recommended time of 1 second per single breath. If providers spend more time ventilating, less time is available for actively compressing per minute. In contrast, if rescuer performs quickly, as recommended in the guide-

lines, the target time for delivering ventilation will yield ventilation intervals and active compressions. Real-time feedback monitor and a reminder for ventilation are key ingredients to the fundamental improvements in rescue breath quality. The rescue breath reminder LED turns red and alerts that a rescue breath is needed after every 15 compressions. The breath detected LED flashes (green) once for every ventilation provided. Maintaining patient airway and optimum rescue breaths are essential during paediatric CPR [71]. Whilst, rescue breath delivery consumption time is most vital; 2015 paediatric guidelines recommend that for non-specialists (e.g. teachers, school nurses, life guards), five initial breaths followed by one minute of CPR should be provided before they seek expert assistance [28]. This research is the first investigation to report on compression counts between 2 rescue breaths. If this improved feedback-assisted performance is reflected in clinical practice, CA victims will receive more rescue breaths and compressions in more regular intervals, with fewer distractions. This may increase the likelihood of CA survival.

5.1.5.2. Rescue breath count

The present research is also the first to investigate the rescue breath count against the recommended target breath count, with and without feedback assistance. European Resuscitation Council Guidelines for Paediatric Resuscitation recommends that if a child's breathing is not normal or is absent, one needs to carefully open the airway and deliver 5-initial rescue breaths before starting compressions; then continue compressions and breaths in a ratio of 15:2 [28]. The target breath count prior to starting continuous compressions is 5. The BLS and lay unassisted groups delivered 29% and 36% fewer breaths than recommended breath count. The target count of 2 rescue breaths during compressions was 10% fewer than the target for the BLS unassisted group. The unassisted lay group delivered 15% fewer breaths than the target

breath count. In conclusion, unassisted groups delivered 15-36% fewer breaths than the recommended target count. This investigation reflects the significant problem in current CPR clinical performance delivered by BLS rescuers.

It was expected that the lay rescuers would perform ineffectively. They were neither previously experienced nor previously knowledgeable about CPR. This insufficient breath would reduce the oxygen level and increases the CO_2 saturation of the blood, which potentially worsens survival rates. In contrast, the feedback BLS and lay groups delivered 27% and 32% more breaths than the unassisted group breaths count, respectively. In conclusion, the assisted groups delivered 5-32% more breaths compared to the unassisted groups, and therefore they complied with the recommended target count. Fundamental to this improvement in rescue breath count was the real-time feedback monitor reminding the providers to perform rescue breaths. The breath detected LED flashes (green) once for every given ventilation. Real-time feedback during simulated iCPR assists the providers in delivering the target number of rescue breaths at recommended intervals. As per the guideline recommendations, 12-20 breaths per min are essential [71]. In addition, recent guidelines recommend 12-24 breaths per min according to the patient's age normal values [28]. If providers fail to deliver the required quantity of breaths, this will reduce the survival rate. However, if a real-time feedback system is employed in clinical practice, it would help rescuers to maintain the ventilation consumption time and quantity within the target range, which could improve the outcomes.

5.1.5.3. Rescue breath pauses

The present research further investigated the number of pauses taken by rescuers for delivering rescue breaths during one minute of simulated iCPR. The final CPR performance consisted of 5-initial breaths through the airflow sensor and repeated 15-compressions cycles and 2-breaths

for the period of 'one-minute'. The unassisted BLS and lay groups mean breath pauses were 'only 4.2 times and 3.9 times', respectively. In conclusion, patients receive '<9 breaths only for 1-minute period', which is significantly less than the recommended guidelines. Although, it was found that poor quality of ventilation ('only 4.2. times and 3.9 times') pauses were performed during simulated iCPR, these results could produce significant implications if directly transferred to clinical practice. Both the BLS and lay providers often missed the target compression and ventilation ratio (15:2). Compared with simulated performance, providers have a lot more stress and physical work in clinical practice. In child resuscitation from CA, both hypocarbia and hypercarbia originated CAs are associated with a higher mortality [83]. Therefore, 2015 European paediatric guidelines recommended that the child with ROSC should usually be ventilated at 12-24 breaths min^{-1}, according to their normal age values. This study implies that a provider's rescue breath performance would be poor in clinical practice delivered by both BLS and lay rescuers. The lay rescuers delivered poor breath performance as they had no previous experience.

The feedback assisted BLS and lay provider's mean breath pauses were '6.1 times and 5.6 times', respectively, resulting in patients receiving '>14 breaths min^{-1}'. In particular, BLS providers provided '>17 breaths min^{-1}'. The improved breath count is provided by a real-time feedback system breath alert facility; a reminder LED turns red and alerts the providers once every 15 compressions that a rescue breath is needed. The breath detector LED flashes green once for every given ventilation through the air flow sensor. The target number of rescue breaths per min^{-1} has been achieved using the feedback assistance. The guideline recommends at-least 12 breaths per min during the performance of CA in clinical practice [28, 71]. The feedback assisted both BLS and lay rescuers in achieving the target range of rescue breath quantity during simulated CPR. The feedback system, if tranferable to clinical practice, could

enable patients to receive more rescue breaths at correct intervals and more active compressions in a given time. Thus, the system could optimise haemodynamics of the heart and increase the oxygen concentration in the blood, during the infant CA resuscitation sequence.

5.1.5.4. Compression counts between each 2-rescue breaths

This research is the first investigation to report on compression counts between 2-rescue breaths for the period of one minute during simulated iCPR. The final stage investigation consists of 5-initial rescue breaths through the airflow sensor and repeated cycles of 15 compressions and 2-rescue breaths. The target compression counts after 5-initial rescue breaths were 15 times between each 2-rescue breath. The unassisted BLS and lay providers mean compressions between 2-rescue breaths was '23 times and 26.2 times', respectively. There is no significant difference observed between the groups' performances. An increase in the number of compressions between rescue breaths will reduce both the rescue breath pauses and quantity. Continuous deep compressions maintain sufficient circulation that is essential for saving CA patients [51, 52, 93, 94]. Therefore, previous studies and resuscitation guidelines highlighted the importance of providing adequate ventilation in paediatric CPR [28, 71, 72, 78, 82].

The main purpose of rescue breaths is to maintain sufficient oxygenation and remove CO_2 [76]. Previous population-based investigations of out-of-hospital paediatric CAs showed that when rescue breaths follow compressions, during CPR, survival rate is improved compared with compression-only CPR, for children in CA as a result of non-cardiac causes [77]. Successful paediatric CA resuscitation is based on rescue breathing; for asphyxial CA and prolonged CAs in both adults and children, conventional CPR with rescue breaths is recommended for all trained rescuers [74, 75, 78-80]. Recent studies reported that for OHCA infant cases,

where a rescuer administered rescue breathing, the survival rate was two times higher than a rescuer who did not provide rescue breathing [72, 77, 81]. The present study is the first to investigate the effects of real-time performance feedback on the quantity of compressions performed between 2-rescue breaths during simulated iCPR. The feedback assisted BLS and lay group's mean compression count between 2-rescue breaths was '15 and 15.2 times', respectively. The provision of real-time feedback assistance significantly regulated the time for delivering the initial rescue breaths, the quantity during compressions, the number of rescue breaths pauses, and the compression counts between 2-rescue breaths during the simulated iCPR performance.

The feedback system displayed live compression counts and reminders to deliver 2-rescue breaths after every 15 compressions. Delivering rescue breaths to infants in CA, in accordance with the guidelines and at regular intervals, could result in an improved outcome. The foundation for an improvement in compression counts is because of the feedback system display of live compression counts and reminders to deliver 2-rescue breaths after every 15-compressions. Compression count improved significantly towards the target compression count for the assisted groups. This present study is the first to report compression counts between 2 rescue breaths. Compression count improved significantly towards the target for the assisted groups. If the result is reflected in clinical practice, CA victims will receive more rescue breaths at regular intervals with fewer distractions, and this may increase the likelihood CA survival.

In conclusion, the provision of real-time feedback assistance significantly regulated the time for delivering the initial rescue breaths, improved the rescue breath quantity during compressions, increased rescue breaths pause between compressions and regulated the compression counts between the 2-rescue breaths. Delivering rescue breaths to infants in CA, in regular

intervals and according to guidelines, could result in an improved outcome from CA. If rescuers take a long time to deliver the rescue breaths, this reduces the active compression count time and increases the rescue breath interval.

5.1.7   Overall chest compression quality

The present research was developed to monitor and assist resuscitators' in improving their quality index against current evidence-based quality targets while performing compressions on infant manikin of CA. The overall compression quality index was a single composite measure, a combination of compression depth, release force, compression rate and compression duty cycle, to evaluate a rescuer's overall compression performance during CPR. The overall compression quality index was calculated by measuring all four infant compression quality targets achieved simultaneously during CPR performance. Numerous simulated adult CPR performance-based manikin studies reported the use of a single composite measure to evaluate the provider's chest compressions performance [34, 95, 96].

For the unassisted BLS rescuer group, simulated CPR performance was very poor at all stages. Overall quality for all three stages of simulated CPR was >2.3%. Similarly, the unassisted lay rescuers exhibited an overall compression quality of >2.4% in all three stage of simulated CPR performance. Inadequate and excessive compression depth and excessive compression rate were observed in the unassisted BLS population. Similarly, unassisted lay rescuers exhibited inadequate and excessive compression depth and excessive and sluggish compression rates. However, excessively prolonged compression duty cycles were observed in both unassisted BLS and lay groups. During iCPR resuscitation sequence in clinical practice, delivering quality compression depth, release force, compression rate and compression duty cycles are significant to optimising the heart haemodynamics [3, 7, 11, 13, 28, 39, 53, 65, 67, 97-100]. Poor-

quality compression performance, delivered by BLS and lay CPR providers during simulated iCPR, could have affect outcome rates if directly transferred to current clinical performance.

Previous international guideline recommendations were "push hard, push fast" during iCPR [13, 14]. This approach may encourage the participant's over-compression of the thorax and deliver faster compressions in clinical practice. However, current infant guidelines removed the "push hard, push fast" phrase. This poor-quality performance, and that reported elsewhere, has raised concerns over whether simulation replicates the current clinical practices of iCPR. In particular, the previous investigation of unassisted 'expert' European paediatric life support- (EPLS) and/or Advanced Paediatric Life Support- (APLS) certified rescuers reported the TT method during a simulated iCPR performance on infants has achieved an overall quality index of less than 1% [25]. This result also supports the current performance of unassisted BLS and lay rescuers. OHCA is one of the largest public health issues due to higher CA incidences and lower survival rates [103-105]. Almost 93% of the infant CA cases occur in private locations [31-34]. Often the lay population are the first responders to initiate CPR at out of hospital locations. Therefore, the lay providers CPR quality is also important. Good bystander's CPR is associated with a shorter CA arrest. High-quality bystander's CPR increases the proportion of patients who are discharged from the hospital alive compared with poor bystander CPR or no bystander CPR [34]. This present study suggests that education and BLS training is necessary for bystanders before they perform CPR.

Overall compression quality improved significantly in the assisted groups. Overall compression quality for all stages was >61.4% and >24.6% for the assisted BLS and lay groups, respectively, in all stages. These groups' compressions also simultaneously achieved all four compression quality targets. The previous similar investigation of EPLS and/or APLS rescuers

performance during simulated iCPR, using TT technique, achieved 80% conformity with assistance [25]. The overall performance of the lay rescuers was poorer than the BLS rescuers, even with the provision of real-time feedback, because the lay resuscitators' compression duty cycle performance was very poor. Lay rescuers have never performed CPR previously and are not related to the field of medicine. Lay rescuers compressed the infant chest 'slowly' and released 'quickly'. BLS rescuers have studied and are trained in CA basics, so they have previously performed simulated compressions on the manikin chests. Lay rescuers, having no previous experience with CA patients or medicine and lack knowledge of cardiac circulation. Most frequently, lay people witness and respond to OHCA; so, the bystander's compression quality is significant. Quality bystander CPR performances increase the proportion of successful outcomes compared to poor, or no bystander CPR [34]. Thus, lay rescuers need further training in simulated iCPR performance with feedback devices and need to learn the basics of CA and the blood circulatory system to improve the overall quality of the CPR. This research suggests that if lay rescuers could finish the BLS training course before attempting the CPR practice it could improve the understand of CPR basics. The assisted and unassisted feedback results comform with previous research reports based on the composite measure quality index [25, 95, 96, 101, 102]. With the assistance of a real-time feedback system, high-quality compressions can be achieved during simulated CPR performances.

5.2 Research impacts

5.2.1 Infant CPR training manikin design

The original manikin was modified during a previous study [25] to allow resuscitators to achieve a compression depth of more than the 1/3 of the AP diameter, which allowed the recording of thoracic over-compression during simulated CPR performances. The commercially

available infant manikin has a limited compression depth and whilst widely used to investigate the qualities of simulated CPR performance on infants, the limited compression depth and compression stiffness are not recognised as biofidelic [13, 18, 19, 26, 27, 29, 106]. The present study recorded thoracic over-compression and assisted resuscitators in improving the quality of their CPR.

5.2.2. Research strength

'Good clinical practice for clinical trials' principles were followed for simulated CPR performance in both studies [107]. Participants were unaware of the purposes of this research. To avoid interruption, their original CPR performances and all other performances were recorded in a separate room. The real-time feedback system does not provide feedback assistance for compression duty cycles. The design and development of the real-time CPR performance feedback system were the most important phase of this research. In addition to developing this feedback assistance device, outstanding improvements in results were achieved through this research. The participants gained experience and learning, and the performance feedback device assistance will improve the compression quality of resuscitators over time. Thus, this could increase the survival rate from CA in future.

5.2.3. Unassisted chest compression quality during simulated CPR performances

The unassisted compression quality index of simulated CPR performance on the infant manikin reflects the actual scenario of iCPR in clinical practice. The present study shows that the overall compression quality index remains poor for both BLS and lay rescuers. Overall compression quality was calculated using the number of compressions that simultaneously achieved all four CPR quality targets against resuscitation guidelines. The overall compression quality for unassisted BLS rescuers was poor, at just <2.3%. Similarly, the overall compression quality index for lay resuscitators was <2.4%. High-quality CPR is vital to temporarily support

cardiac output, perfusion to vital organs, and enable ROSC via improved myocardial perfusion [108]. The fundamental indicators of poor-quality compression performance were thoracic over compression, shallow compression, failure to completely release, fast or slow compression rate cycles and prolonged duty cycles. Poor survival rate could result if these levels of compression quality were performed in clinical practice.

The resuscitation guidelines recommended target compression depths that have been observed in this research. These target depths have resulted in favourable haemodynamic outcomes from CA [28, 109]. Compression depth is the most important quality measure during iCPR [13, 14]. Haemodynamic outcomes are associated with increased arterial pressure, achieved by deep compression depths in both infant and adult human subjects [4, 9] and characterised by greater coronary flow and increased cardiac output in animal subjects [10, 12]. If resuscitators were trained on a more physiological manikin with a performance feedback system, they would be better trained to deliver guideline quality compressions during clinical practice.

The under-compression quality index was 30.9–36% for the unassisted BLS rescuer group and 37.5–41% for the unassisted lay group. In contrast, the under-compression quality index was <17% for the assisted BLS group and <10.1% for the assisted lay resuscitators. The deep compression quality index was 20.6–24% for the unassisted BLS group and 20–23.3% for the unassisted lay group. The provision of the feedback system considerably reduced over-compression of the thorax. The deep compression quality index for the assisted BLS group was <3.6% of all compressions, compared to <5% of all compressions for the assisted lay group. The feedback assistance program significantly improved the quality of compressions. Over 45% of unassisted compressions on the infant manikin during simulated CPR performance failed to achieve the resuscitation guidelines target. These results clearly reflect that the resuscitators need to improve their compression quality significantly.

These research findings relate to the safety of infant compressions because of the potentially deleterious effects of over compression. Increasing compression depths increase the risks of intrathoracic injury due to over-compression of the thorax. The simulated iCPR performances show that >20% of the unassisted group exceeded the proposed thoracic over-compression barrier. Deeper compression depths during CPR (one-half external AP diameter compression depth) may cause damage to intrathoracic organs [4, 15, 17, 19, 20, 25, 35]. In clinical practice, more frequent over-compression cycles would lead to more intrathoracic injury to infant CA victims.

Quality compression depths, release force, compression rate and compression duty cycles are critical for delivering quality compressions, and quality compressions are vital for enhancing the haemodynamics during iCPR [3, 5, 11, 14, 39, 53, 66, 82, 99]. In this research, most of the unassisted group participants delivered excessive compression rates, incomplete chest releases and prolonged compression duty cycles. The release force quality index of BLS resuscitators was only <58%; 42% of the compressions failed to achieve the target complete release depth in all stages of performance. The release force quality index of lay resuscitators was only <32%; 68% of the compressions failed to achieve the target complete release depth in all stages of simulated CPR performance. Several previous research studies reported that resuscitators often fail to achieve the complete release depth during in-hospital, out-of-hospital and simulated CPR performances on a manikin, in both adult and paediatric populations [6, 20, 44, 45]. Failing to completely decompress the chest fails to relieve intrathoracic pressure, which in turn limits the return of venous blood to the heart and could reduce CA survival rate. Complete recoil can generate negative intrathoracic pressure and thus improve venous return and cardiac output [3, 39, 66, 67].

In this present study, excessive and sluggish compression rates and prolonged compression duty cycles were observed in the unassisted. In animal models of CA, compressions performed at a rate of 120/min produced higher myocardial perfusion pressures, increased left ventricular blood flow and a more successful outcome from CA than 60/min and 80/min rates [48-50]. The same appears true in adults: compression performed at a rate of 120/min produced better myocardial perfusion pressure than 60/min and 80/min rates [51]. The compression rate quality index of BLS rescuers was only <14%; >53% of the compressions were observed at a faster rate than the recommended values and >24.3% of the compressions were too slow. The compression rate quality index of lay resuscitators was only <13%; >42% of the compressions were observed at a faster rate than the recommended one and >40% of the compressions were too slow as compared to the target. The BLS rescuers frequently exceed the internationally recommended targets; mean compression rate was >135/min. This poor performance is consistent with that of previously reported infant simulated CPR studies. Recent studies reported that the mean compression rates exceed 130/min [18, 19, 26, 27]. Sluggish compressions significantly reduce the possibility of ROSC [7, 11, 52, 53]. The excessive compression rates and prolonged compression duty cycles would reduce the likelihood of complete chest release during CPR, resulting in limited venous return and reduced coronary and cerebral blood flow [3, 7, 8, 11, 39, 66, 67].

Current infant resuscitation guidelines do not recommend a quality target for the compression duty cycle, even though a prolonged duty cycle reduces the return of venous and cerebral blood to the heart and subsequently leads to a reduced CA survival rate [8, 11, 53, 55, 57-59]. However, a compression duty cycle oscillating between 30% and 50% can result in good coronary and cerebral perfusion [50, 62, 63]. The unassisted BLS and lay groups achieved compression duty cycle quality targets of only <18.5% and <22%, respectively. This poor-quality result is

consistent with previously reported simulated infant based manikin studies [18, 25]. In addition, incomplete decompression of the chest and prolonged compression duty cycles would also reduce the coronary perfusion and limit the return of venous blood to the heart [3, 39, 53, 65-67].

The guidelines highlight the importance of high-quality compressions in terms of depth, complete decompression, rate and reducing the time without compressions [14, 28]. Excessive time consumption, irregular breathing intervals and reduced quantity of breath were observed in the unassisted group during the phase 5-initial breaths and compressions only and the phase of 5-initial breaths followed by cycles of 15-compressions and 2 - breaths. These groups' rescue breath counts were also less than recommended.

The 'unassisted BLS and lay population took 20-90%' greater time than the guideline's recommended target time to deliver a 'single breath'. Whilst, the unassisted group delivered '15-36% fewer breaths' compared to the recommended target count. Infants suffer from both hypocarbia and hypercarbia originated CAs, which are associated with higher mortality [83]. Successful paediatric CA resuscitation is based on rescue breathing; for asphyxial CA and prolonged CAs in both adults and children, conventional CPR with rescue breaths is recommended for all trained rescuers [74, 75, 78-80]. The guidelines recommended that each breath should take about only '1-second', which is sufficient to make the infant chest visibly rise [28, 82]. The prolonged time for delivering rescue breaths significantly reduced the number of compressions provided. This research finding is consistent with the previously reported results; health care professionals spend only 50% of their time on compressions during in-hospital and out-of-hospital CPR episodes [23]. Therefore, depending on a child's age, the latest European Resuscitation Council recommendations are that a child with ROSC should usually be

ventilated at 12-24 breath per min [28]. This study reports the significant problem in current CPR clinical performance.

In addition, the unassisted BLS and lay group's mean breath pauses were 'only 4.2 times and 3.9 times', respectively. Providers delivered '<9 breaths only for 1-minute period', which is significantly less than recommended. The main purpose of rescue breaths, during CPR, is to retain sufficient oxygenation and remove CO_2 [76]. Animal studies show that rescue breaths, during CPR, after ventricular fibrillation (VF) or asphyxia resulted in improved ROSC, CA, or neurological outcomes when compared with no-ventilations during CPR [73-75]. During the infant resuscitation sequence, guidelines recommended that victims should be ventilated at 12-24 breath per min [28]. This present study reports that provider's rescue breath performance is delivered by both BLS and lay rescuers.

The unassisted BLS and lay providers mean compressions between 2 rescue breaths was 23 times and 26.2 times, respectively. If the number of compressions increases between rescue breaths, this will reduce both the number of rescue breaths and their associated pauses. The recommended compression-to-ventilation ratio for iCPR is 15:2 [28]. It was also found that CPR performance by the unassisted rescuers was very poor. The real-time CPR performance feedback system will improve the overall quality of CPR by improving all four quality measures and rescue breath delivery time and count.

5.3 Principal findings of the research

A real-time feedback system and performance feedback program is the first such system for use in providing immediate feedback for rescuers performing CPR on an infant during simulated performances and could be used for clinical practices in future. The system was designed and developed during the duration of this study, and is used to analyse and assist providers

during simulated iCPR performances in real time, against evidence-based, infant-specific quality targets of compression depth, compression release force, compression rate, compression duty cycles, and rescue breaths. This real-time feedback consists of the following features; a colour-coded chart for maintaining accurate compression depth and decompression depth, a compression counter, an audible metronome for maintaining appropriate compression rate, breath reminder, the time elapsed indicator and data storage. The study developed real-time infant feedback system capable of measuring mattress deformation during TF compression technique and infant's posterior deflections during TT compressions.

This study is the first to quantify chest compression performance of BLS and lay rescuers versus four CPR quality targets defined by international guidelines. Unassisted providers poor performance established the dramatic need of real-time feedback assistance during their CPR performance on the manikin. This research embedded the sensors between two rubber sheets to produce a rubber pad that provided a good grip for the resuscitator, both during simulated CPR and clinical practice in future. Rubber pads would seem a reasonable compromise to avoid causing excessive trauma to the patient's chest during compressions.

5.4   The real-time performance feedback system

A real-time feedback system for simulated CPR infant performance was developed as part of this research. Regardless of age, the system can be used for clinical trials in the future. Compression quality in the 'feedback-benefitted population' improved significantly. Overall simulated iCPR performance in the BLS population with feedback improved from <2.3% to 61.4–64.8% with all compressions, simultaneously achieving all four CPR quality measure guidelines-recommended targets. For the same criteria, the overall performance of the lay rescuers with feedback improved from <2.4% to 24.6–25.9%. The lay rescuers' compression duty cycle

performance was very poor; the feedback system does not provide feedback assistance for compression duty cycle. The feedback system played a major role in improving CPR performance by assisting the resuscitators in delivering accurate compression depth and complete release via a colour-coded display and audio-visual metronome assistance for compression rate. If this feedback could enable improved compression quality in clinical practices, it may have significant effects on CA outcomes. In future, CPR real-time feedback system including the live compression duty cycle feedback must be considered.

The recommended compression depth provision by guidelines would increase haemodynamic outcomes [4, 9, 10, 12] and reduce intrathoracic injuries caused by deeper compression depths during CPR (more than one-half external AP diameter compression depth) [15-19]. Complete chest wall decompression and shortened compression duty cycles would improve haemodynamics by generating relatively negative intrathoracic pressure. This pressure pulls venous blood back to the heart, refills the heart valves with a maximum amount of blood and allows for favourable perfusion of the myocardium, which provides cardiac preload before the next compression [3, 5-8, 11, 39, 41-43]. The optimum compression rates with compression duty cycles directly correlate with the return of venous blood to the heart prior to the next compression, thus, improving perfusion of the myocardium and heart haemodynamics [7, 11, 53]. However, a compression duty cycle oscillating between 30% and 50% can result in good coronary and cerebral perfusion [50, 62, 63]. A real-life duty cycle of 50% is easily achievable [64]; therefore, a duty cycle of 50% is highly recommended [62, 64]. Infant swine studies also observed an optimal compression duty cycle of between 30% and 50% [7, 53].

The main intention of rescue breaths during CPR is to retain sufficient oxygenation and remove CO_2 [76]. Previous population-based investigations of out-of-hospital paediatric CAs show

that when rescue breaths follow compressions during CPR, survival is better than for compression-only CPR for children in CA as a result of non-cardiac causes [77]. Successful paediatric CA resuscitation is based on rescue breathing; for asphyxial CA and prolonged CAs in both adults and children, conventional CPR with rescue breaths is recommended for all trained rescuers [74, 75, 78-80]. Recent studies reported that OHCA infant cases witnessed by a bystander who administered rescue breathing survival rate was twofold higher than that witnessed by a bystander who did not provide rescue breathing [72, 77, 81]. The real-time CPR performance feedback system provision in clinical practice may result in good-quality compressions and rescue breaths that enhance the venous blood flow to the heart and from the heart to the vital organs, reducing thoracic injury, blood oxygen proportion and thus significantly improving CA survival outcomes.

Lay rescuers CPR quality performance is also as equally important as BLS CPR provider's performance. Almost 93% of the infant CA occurs in out-of-hospital locations [31-34]. Often the lay population are the first responders to initiate CPR at out-of-hospital locations, such as in public locations and patient's house. Therefore, the lay providers CPR quality is also most significant. Good bystander CPR is associated with a shorter CA. High-quality bystander CPR increases the proportion of patients who are discharged from hospital alive compared to poor bystander CPR or no bystander CPR [34]. While training with a manikin, if trainers include a real-time feedback system for practice, providers will learn more quickly and effectively. The feedback system will show in which area of compression depth, release depth, compression rate or duty cycle they are struggling to achieve the target. Then trainers could concentrate on that particular target and assist them in producing high-quality overall compressions during simulated infant performances. If BLS and lay providers were to keep practising with the real-time feedback system, their quality of performance could be improved to achieve current

evidence-based compression quality targets. This present study informs the design of a future system, which should include an indicator (visual, audible or kinaesthetic), which provides information with respect to target thresholds which would warn the rescuer to strive towards better quality compressions.

The international resuscitation guidelines recommend a 30:2 compression-to-ventilation ratio for lone-resuscitator infant-and-child CPR. The ratio drops to 15:2 for infant-and-child CPR with two rescuers [82]. However, if the child's breathing is abnormal or absent, the rescuer should open the airway carefully and deliver 5-initial rescue breaths before beginning compressions [28]. If the child does not respond, the tongue may be obstructing the airway [110]. This is most often the situation, and one must open the airway using a head tilt and chin lift, for both injured and non-injured victims. After the 2-rescue breaths, the rescuer should immediately continue the next set of 30 compressions [71]. In addition, the guidelines recommend that each breath should take about 1 second [28, 82]. During this study, the 'feedback assisted group were 30-84% quicker' than the unassisted group in delivering a 'single breath'. The assisted group delivered 5- 32% more breaths than the unassisted group. The assisted group's rescue breath count performance complies with quality standards. Recent nationwide population-based studies of out-of-hospital paediatric CAs showed that, when following the compressions with rescue breaths CPR, the survival was better as opposed to the hands-only CPR provided for children in CA due to non-cardiac causes [77].

The feedback assisted BLS and lay providers mean breath pauses were '6.1 times and 5.6 times' per minute, respectively. Thus, resulting in, patients receiving '>14 breaths per min'; in particular, BLS providers gave '>17 breaths min^{-1}'. Successful resuscitation during a paediatric CA is based on rescue breathing. Conventional CPR, with rescue breaths, is recommended for all trained rescuers for asphyxial CA and prolonged CAs in both adults and children [74, 75,

78-80]. The assisted population experienced major improvement in rescue breathing, delivering time and quantity by reducing the delivering time, as recommended by guidelines for delivering the rescue breaths. The proportion of patients discharged from the hospital will be increased for those who received quality bystander CPR than poor bystander CPR or no bystander CPR [34].

An American OHCA registry study reported that, for infants, compression with breath bystander CPR was associated with higher survival rates and neurologically favourable survival, whereas those who received compression-only CPR without rescue breaths outcomes were similar to no bystander CPR outcomes. There is no significant difference between compression-only CPR and no bystander CPR. During iCPR, there was no benefit unless rescue breaths were provided [111]. Consequently, compression-only CPR is not recommended for children in either OHCA or IHCA setting, except in situations such as "providers are unwilling or unable to deliver breaths" [112]. The real-time feedback program helped resuscitators to deliver adequate rescue breath times during simulated iCPR performances.

This present study indicated that the provision of a real-time feedback system in clinical practice might significantly improve compression quality significantly during CPR. In recent years, CPR real-time feedback systems for adults have been successfully installed in clinical practice [45, 113-115]. A recent study reported a difficulty in delivering established targets of compression depths and rates during in-hospital children's CPR [116]. To date, there is no real-time CPR feedback device specifically for infants in clinical practice. The real-time infant feedback CPR device is recommended when available in clinical practice to improve the quality of chest compressions [117].

This device can also be used for CPR training purposes. Moreover, it is the first such system for use in providing instant feedback for rescuers performing CPR on an infant. When required, this system will enable rescuers to quickly produce effective CPR. However, currently available all adult CPR feedback devices (CPR meter, iPhone app and Pocket CPR) cause delay in the initiation of CPR and may, therefore, worsen outcome [113].

Overall compression quality improved significantly in the assisted groups; therefore, this study suggests that both BLS and lay providers should perform simulated performance more frequently with real-time feedback assistance. Thus, assisting rescuers to improve their quality and achieve current evidence-based chest compression quality targets. Hence, this study has demonstrated that practising with real-time feedback during training would support in achieving quality compression targets.

The present real-time feedback system can measure the quality index of resuscitators during simulated CPR performances. Simulated iCPR performance study is an alternative method of assessing for variability and complexity of CPR performed in clinical practice. The outcomes were observed during and after providers chest compression performance to understand the problem. The feedback system also records the resuscitator's CPR performances data of all four CPR quality measures and rescue breaths performance with time, which can be used to evaluate the resuscitators' CPR quality measures during clinical trials and training. The recorded data can provide trainers and resuscitators with information such that they can adjust their CPR performances. This device is novel because the system has a breath reminder, a colour-coded chart for maintaining precise compression depth and release depth, a compression counter, an audible metronome for maintaining appropriate compression rate, data storage and time elapsed indicator. In future, this device could be used for training and in clinical practice.

The provision of real-time feedback system significantly improved the compression quality of all four evidence-based quality targets, whilst also potentially reducing the deep compression damage to intrathoracic organs. Therefore, if this system was employed in clinical practice in future, it could improve the quality of compressions and ventilations during iCPR in clinical practice. If these improvements were replicated in clinical practice, real-time feedback could support providers in performing high-quality compressions during iCPR. Real-time feedback is an essential device for learning and skills retention of CPR. The use of real-time feedback system in training setting would be a better choice; trainees can instantaneously adjust their performance to achieve current compression quality targets within the training environment. However, learning and refreshing of CPR skills could be arranged for more training people with few instructors. Later, self-training and retention of CPR skills without an instructor also possible to perform quality CPR in future. This high-quality training may transfer to clinical practice that could improve the successful infant CA outcomes.

6. CONCLUSIONS

6.1. Research conclusions

The main aims of this research study were to evaluate and, if needed enhance, the performance of lay and BLS rescuers during simulated iCPR. Evidence-based, infant-specific quality targets for chest compression depth, compression release force, compression rate, compression duty cycles, and rescue breaths were derived from the literature. Overall quality of compressions was measured by the proportion of compressions simultaneously achieving all four quality targets during infant simulated CPR performances. The objectives of this research are summarised below with their corresponding conclusions:

> ➢ A real-time feedback system and performance feedback program was designed and developed to validate and assist rescuers during simulated iCPR performances in real time, against quality targets. This device is novel because the system has a breath reminder, a colour-coded chart for maintaining accurate compression depth and decompression depth, a compression counter, an audible metronome for maintaining appropriate compression rate, and data storage. The time elapsed indicator shows the duration of the particular CPR episode.

> ➢ The system designed is novel, capable of measuring infant posterior deflections during two-thumb compressions and mattress deformations during two-finger compressions. Moreover, it is the first such system for use in providing immediate feedback for rescuers performing CPR on an infant. When required, it will produce immediate CPR feedback for rescuers. The data are stored on a laptop

and can be used retrospectively to assess the quality of rescuers' CPR performance. This system could be used for the future development of clinical practice.

➢ This study is the first to quantify chest compression performance of BLS and lay rescuers versus four CPR quality targets defined by international guidelines. Here, it has been established that less than 3% of all compressions are actually performed in line with the guidelines. In addition, the proportion of deep compression cycles was >20% (BLS; 20.6–24%, lay rescuers; 20–23.3%). Subsequently, there is a dramatic need to develop solutions that provide immediate support for the delivery of compressions with greater accuracy, which may ultimately serve to improve survivability.

➢ This research is first to report a substantial delay when BLS and lay rescuers performed unassisted CPR, taking 7.9–8.8 seconds to deliver 5-initial breaths. During compressions, rescuers took 2.4–3.8 seconds to deliver 2-breaths, which is 20–90% more time than resuscitation guidelines recommend for delivering a single breath. This study is the first to evaluate rescue breath performance with an in-house-developed feedback system that regulates the time for delivery of breaths. Feedback-assisted BLS rescuers took 5–5.3 seconds and lay rescuers took 4.9–5.1 seconds to deliver 5-initial breaths. During compressions, BLS rescuers took 1.9 seconds and lay rescuers took 1.8 seconds for delivering 2-breaths, which complied with the resuscitation guidelines' recommended time for delivering a single breath. Feedback-assisted rescuers were almost 30–84%

quicker than unassisted rescuers in delivering breaths, permitting compliance with infant specific guideline targets.

➢ This study is the first to report that unassisted rescuers and numbers of breaths were compared against guideline recommendations. Rescuers delivered 29–36% fewer breaths than recommended during the 5-initial breaths phase, and 10–15% fewer than recommended during the compression 2-breaths phase. Feedback-assisted rescuers delivered 5–32% more breaths than unassisted rescuers, also achieving compliance with recommended targets. Because the feedback system regulates the time and required breath counts, cardiac arrest victims will receive breath at the regular recommended interval and in the recommended amounts.

➢ This study evaluated the number of compressions performed between breath pauses during 15:2 (the target was 15 compressions). BLS population performed 23 compressions, and the lay population performed 26.2 compressions. A feedback-assisted BLS population performed exactly 15 compressions, and a lay population performed 15.2.

➢ Compression counts, which also comply with recommended guidelines. The feedback system regulates the compression counts between breath pauses. Therefore, cardiac victims receive recommended compressions between ventilation pauses.

➢ This infant simulated CPR performance is the first to report that the real-time CPR performance feedback system significantly improved the quality of BLS rescuers (from <2.3% to >61.4%) and lay rescuers (from <2.4% to >24.6%) in terms of compressions simultaneously achieving quality targets. In addition, real-time performance feedback reduced the proportion of deep compressions by BLS (<3.6%) and lay rescuers (<5%). A significant improvement in BLS rescuers' chest compression quality was the delivery of accurate compression depth, complete decompression of the chest, appropriate compression rates, and proper compression duty cycle.

➢ This study is the first to report that lay rescuers compress the chest too 'slowly' and release too 'quickly' to achieve a satisfactory overall quality of chest compressions.

➢ This study has identified that the current ILCOR-adapted compression duty cycle method has a fundamental problem in that it cannot determine between a "good" or "bad" duty cycle. No differences in results were observed whilst applying the ILCOR compression duty cycle calculation method, as long as 'the total cycle time and peak compression depth was same'.

➢ This study successfully developed a new method for discriminating between those compressions, which, whilst satisfying the target depth requirement, do or do not satisfy the guideline relationship between compression and relaxation time.

Fundamentally, this research observed that the quality of chest compressions provided during unassisted simulated iCPR hardly complied with infant-specific, evidence-based quality targets. Finally, the provision of a real-time feedback system during simulated iCPR performances significantly improved the quality of chest compressions by promoting precise compression depth, proper chest recoil, suitable compression rate, and proper compression duty cycle. Lay rescuers also will improve their compression quality by providing proper training with a simulated infant manikin. With the implementation of real-time feedback systems in future clinical practice, rescuers could produce higher-quality chest compressions during iCPR, thus improving the rate of survival after cardiac arrest.

Direction for future work

6.2.   Further Development of the Feedback System:

This research has identified the potential benefits of iCPR feedback systems, though this prototype has a number of functional deficiencies that would prevent its use within clinical practice. Further work would be valuable in developing this system, to better integrate into the multi-person, multi-functional environment that is consistent with an Emergency Department; hence, the focus should include embedding the accelerometers into a more convenient location – perhaps as a glove or to be worn on the arm. The data would then ideally be communicated to a computer or any other handheld devices wirelessly, and data processed in the device and the chest compression performances displayed on the screen. Also, the control system should produce vibrations and/or LED indicators to alert the user upon imperfect CPR technique, given that they may also be reviewing other information, especially within a clinical environment. A more integrated sensor would also be of value to the layperson and the BLS rescuer.

The accelerometer sensor-embedded glove should be manufactured in different sizes like small, medium and large as fits for every rescuer's hand sizes. In addition, the control system must have a select switch for choosing compression technique (TT or TF) and a victim's age group.

6.3.   Using the device for enhanced training

This study has highlighted the potential for using feedback to enhance iCPR performance within lay and BLS populations, bring it significantly closer to the established international guidelines. Such an improvement would appear likely to achieve more positive outcomes of infant CA; hence, there is potentially great value in this system being integrated into formal CPR training, be this at BLS-level or even during school-based education. There are clearly several hurdles that exist in taking this prototype design out into the community, though there are several potential benefits that may be gained by performing this additional work.

6.4. More physiological manikin

This research used the modified commercially available manikin reported by Dr. Philip Martin [35] to investigate the performance of the BLS and lay rescuers. This has provided the opportunity to measure over-compression, whilst also better representing the physiology of the infant human that the rescuers would experience if they ever need to perform CPR. Additionally, a more-physiological manikin could enhance the fundamental understanding of iCPR technique, by incorporating functionally vital organs such as heart, liver and rib cage. Heart and liver could be filled with artificial blood, to enable a better understanding of how the haemodynamics correlate with chest compressions. Such a device would be research-focussed, though may represent an enhanced experimental-model, versus the animal models that are typically used to understand the fundamental science.

6.5. Acceptance of new Compression Duty Cycle technique

The lay rescuers, even with feedback assistance, produced prolonged compression duty cycles. It has been observed that most of the rescuers compress the chest too 'slowly' and release too 'quickly' which will reduce cardiac survival rate. This study reported a new technique to calculate duty cycle; hence, further work and efforts are required to more widely publicise this measure, with a view of it eventually being incorporated into the next international guidelines.

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8.   APPENDIX

A.1. Infant CPR performance feedback program-LabVIEW Block Diagram
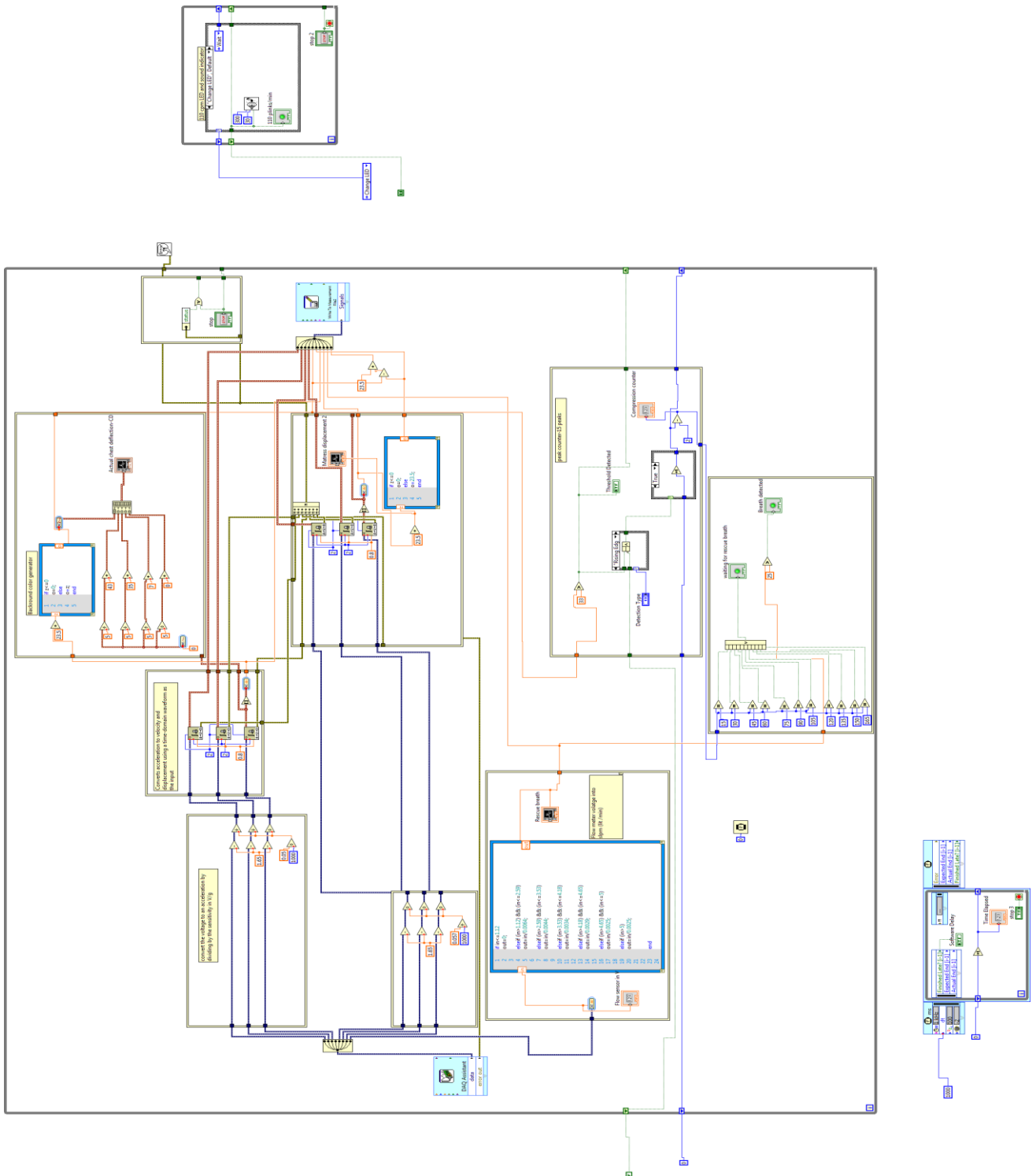
A.2. Total time elapse indicator –LabVIEW BLOCK Diagram
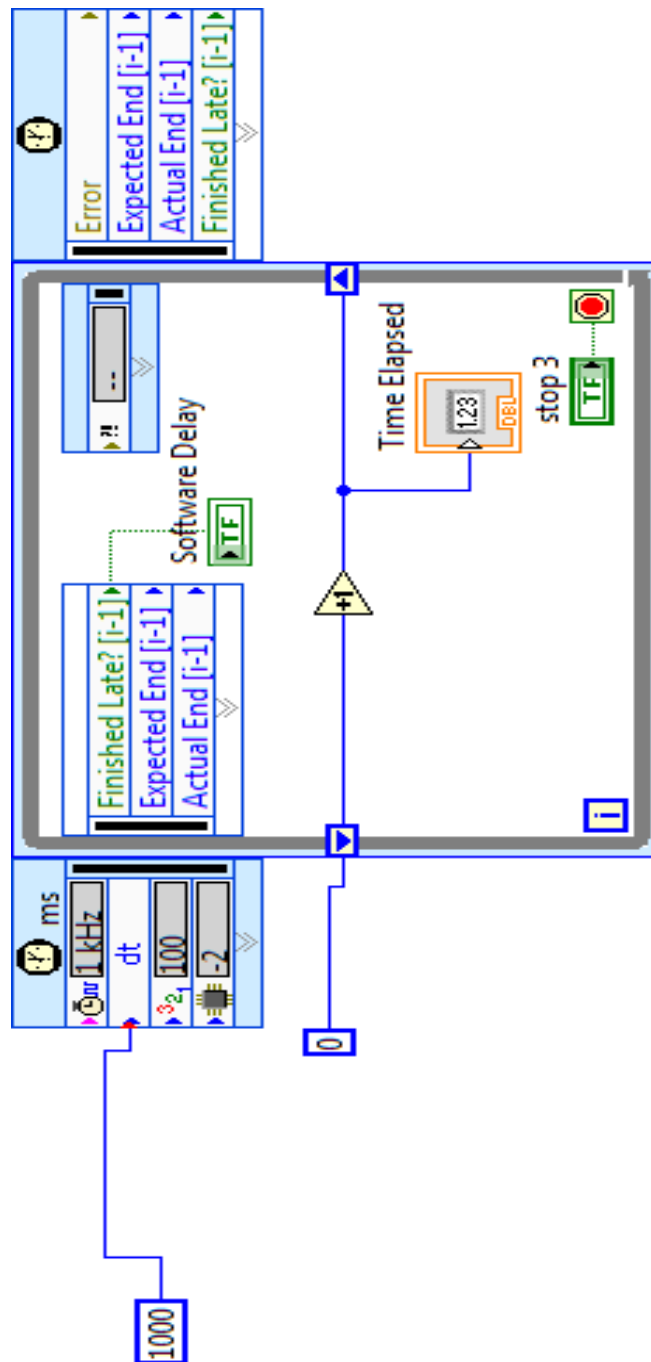
A.3. Audio-visual metronome for regulate the compression rate- LabVIEW Block Diagram
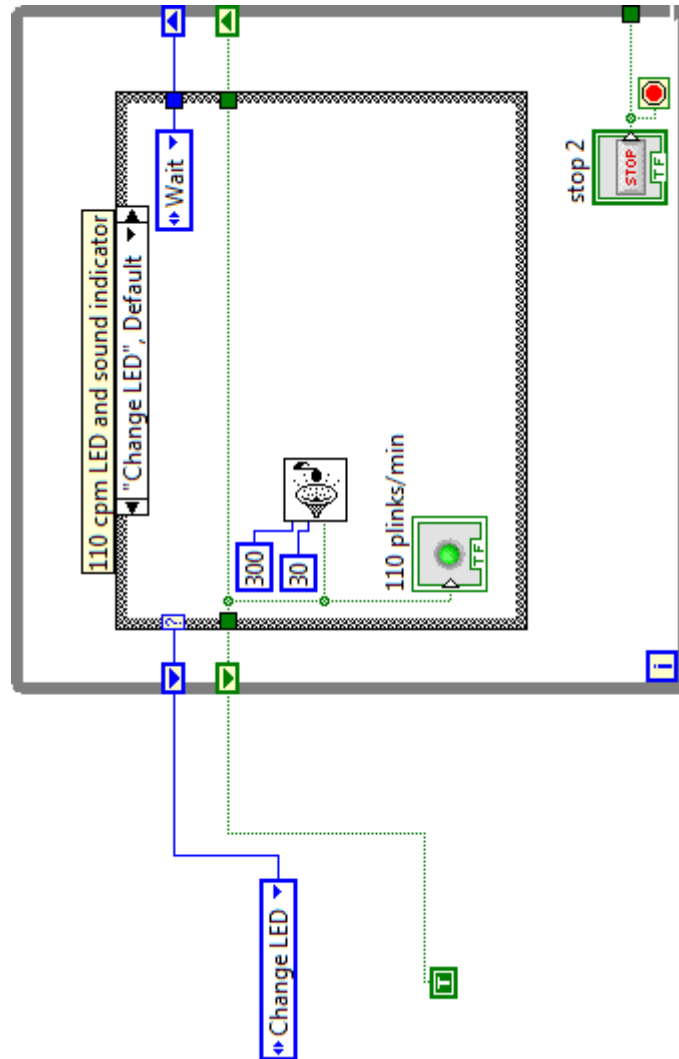
A.4. Matlab code-Analysing the CPR data generated by LabVIEW feedback program

```matlab
%This Matlab program is developed by Jeyapal Kandasamy for analyse the
%compression rate, compression depth release force and compression duty cycle from
%the set of data...

clear all
close all


%load the XL sheet
time= xlsread('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx','cpr','B:B');
disp= xlsread('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx','cpr','D:D');

if ~isvector(disp)
    error('Input must be a vector;');
end

%check if input data are same length
if length(time)~=length(disp)
    error('Input data vectors must be the same length')
end

%check to make sure data is all real
if or(sum(isreal(time)==0)>0,sum(isreal(disp)==0)>0)
    error('All input data must be real valued')
end

%use mean to provide AC filtering; centering peaks about origin
%d=disp-mean(disp);


%the location and peak values and
% small values of accelerometer displacement

start = 1;
[up_loc, upper_peak] = peakfinder(disp);
[lp_loc, lower_peak] = peakfinder(-disp);
%, 'MINPEAKHEIGHT',xx

%[upper_peak,up_loc]=findpeaks(disp);un
%[peak,loc1]=findpeaks(disp);
%[min,loc2]=findpeaks(-disp,'MINPEAKHEIGHT',-4.5);
%[lower_peak1,lp_loc]=findpeaks(-disp);
upper_peak=upper_peak;
lower_peak=-lower_peak;
peakest=min(lower_peak);
peakest=-peakest;
```

```matlab
%upper_peak=peakest+upper_peak;
%lower_peak=peakest+lower_peak;
%disp=peakest+disp;

%Pick the peak points eaualiant time
%t=peak point equalant time
up_time=zeros(1,length(up_loc));
for i=1:length(up_loc);
  up_time(i)=time(up_loc(i));
  % i+1;
end

lp_time=zeros(1,length(lp_loc));
for i=1:length(lp_loc);
  lp_time(i)=time(lp_loc(i));
  % i+1;
end
lp_time=lp_time';

  %saperate recoiled and unrecoiled compressions
  recoil=zeros(1,length(lower_peak));
  recoil_time=zeros(1,length(lp_time));
  for i=1:length(lower_peak)
    if lower_peak(i)<-17.85
        recoil(i)=lower_peak(i);
        recoil_time(i)=lp_time(i);
    else
        unrecoil(i)=lower_peak(i);
        unrecoil_time(i)=lp_time(i);
    end
  end
recoil=recoil';
unrecoil=unrecoil';

%total deflection
tot_def=upper_peak+lower_peak;
%tot_def=upper_peak;

%Compression Rate
cr=zeros(1,length(lp_time));
for i=2:length(lp_time)
   cr(i)=60/(lp_time(i)-lp_time(i-1));
end

%Duty cycle
trapeze=zeros(1,length(disp));
%if (up_time(1)-lp_time(1))>0
for i=1:length(disp)
```

```matlab
   if i<length(disp)
      j=i;
  trapeze(j)= (disp(j)+disp(j+1)/2)*(time(j+1)-time(j));
 % trapeze(j)=sqrt(0.5*(time(j+1)-time(j))*(disp(j)+disp(j+1))^2);
  i=i+1;
     end
end
 trapeze=trapeze';

%%%% trapz total%%%%
trapz_total=zeros(1,length(lp_loc));
trapz_move=zeros(1000,0);

 %trapz_move=zeros(1,length(lp_loc));
for i=1:length(lp_loc)
    if i<length(lp_loc)

  j=lp_loc(i);
  k=lp_loc(i+1);
  k=k-1;

trapz_move=trapeze(j:k);
trapz_total(i)=sum(trapz_move);
i=i+1;
trapz_move=zeros(1000,0);

    end

end
trapz_total=trapz_total';

%%%area of square

area_square=zeros(1,length(trapz_total));

for i=1:length(trapz_total)
    if i<length(trapz_total)

  cycle_time(i)=(lp_time(i+1)-lp_time(i));
area_square(i)=(upper_peak(i)*cycle_time(i));
i=i+1;


    end

end
area_square=area_square';
cycle_time=cycle_time';
```

```
dc=zeros(1,length(trapz_total));
%%%Duty cycle calculation
for i=1:length(trapz_total)
  if i<length(trapz_total)

  dc(i)=(trapz_total(i)/(area_square(i)));


  i=i+1;
  end
end
dc=(dc*100);
dc=dc';

 %trapz_total= trapz_total';
   %if i<length(up_time)
      %j=i;
   %active_t(j)=up_time(j+1)-lp_time(j);
   %active_t(j)=up_time(j)-lp_time(j);
  % tot_t(j)=lp_time(j+1)-lp_time(j);
   %comp_dc(j)=(active_t(j)/tot_t(j))*100;
 %%end
%comp_dc=comp_dc';
%decompression duty cycle

%%%% if i<length(up_time)
  % recoil_t(k)=lp_time(k+1)-up_time(k);
  % tot_t(k)=lp_time(k+1)-lp_time(k);
  % recoil_dc(k)=(recoil_t(k)/tot_t(k))*100;
 % end
%end

%recoil_dc=recoil_dc';
%zero_cross=find(disp==0);
%zero_loc=zeros(1,length(zero_cross));
% a=zero_cross;
% d=diff(a);
%b=find(d>30);
%c(1:length(a))=0;
%c(b)=a(b);

%%z=[a,c];

%c(c==0)=[];
%zero_loc=c;
%zero_loc=zero_loc';
%for i=1:length(zero_loc)
```

```matlab
%   z(i)=disp(zero_loc(i));
 %  zt(i)=time(zero_loc(i));
%end
%zt=zt';
%zero_time=zt;
%zero_disp=z';
%dc=zeros(1,length(up_time));
%for i=1:length(up_time)
 %   if i<length(up_time)
  %  dc(i)=up_time(i+1)-up_time(i);
   % dc(i)=dc(i)*100;
    %end
%end
%dc=dc';

% for i=1:length(zero_cross)
%    j=j+1;
%    check=circshift(a,[0,1]);
%    check=a(1)-a(2);
%
%
%
%    if check > 25
%        zero_loc(j)=zero_cross(i);
%
%     end
% end

%Original figure and original figure with peak points in red color
low_lim=zeros(1,length(disp));
up_lim=zeros(1,length(disp));
up_lim2=zeros(1,length(disp));
low_lim(1:end)=0;
up_lim(1:end)=36;
up_lim2(1:end)=45;

figure
subplot(2,1,1);plot(time,disp);
ylabel('Displacement');
xlabel('Time');
subplot(2,1,2);plot(time,disp);
ylabel('Dispalcemet');
xlabel('Time');
hold on
subplot(2,1,2);plot(up_time,upper_peak,'ro');
subplot(2,1,2);plot(lp_time,lower_peak,'ro');
hold on
```

```
subplot(2,1,2);plot(time,low_lim,'g');
subplot(2,1,2);plot(time,up_lim,'g');
subplot(2,1,2);plot(time,up_lim2,'g');
drawnow;
%xlsPasteTo('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx','cpr',300, 400,'T20')

%Exporting data to the xl sheet


   columnheader = {'Up_Time','Upper Peak','Lpeak_time','Lower Peak'...,
      'tot_def'...,
      'cr','dc',};
   xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx', columnheader,'cpr','E1');
   xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',up_time,'cpr','E2');
   xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',upper_peak,'cpr','F2');
   xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',lp_time,'cpr','G2');
   xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',lower_peak,'cpr','H2');
   %xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',recoil_time,'cpr','I2');
   %xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',recoil,'cpr','J2');
   %xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',unrecoil_time,'cpr','K2');
   %xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',unrecoil,'cpr','L2');
   xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',tot_def,'cpr','I2');
   xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',cr,'cpr','J2');
   %xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',zero_time,'cpr','O2');
   %xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',zero_disp,'cpr','P2');
   xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',dc,'cpr','K2');
   %xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',recoil_dc,'cpr','L2');
   %results= horzcat(up_time,upper_peak,lp_time,lower_peak,recoil_time,recoil,unre-
coil_time,unrecoil);

%Calculation and Output datas

%find out the good quality cpr cycles
 %%for i=1:length(tot_def)
 %  if tot_def(i)>36 & tot_def(i)<45
   %tot_tar_ach_cy(i)=tot_def(i);

 %elseif recoil>-17.85
   %  tot_tar_ach_cy(i)=recoil(i);

 % elseif cr>100 & cr<120
     % tot_tar_ach_cy(i)=cr(i);


 % elseif dc>30 & dc<50
   %  tot_tar_ach_cy(i)=dc(i);
 %  end
```

```
%end


%duration and no of cycles
Episode_duration=time(end);

tot_cycle=length(upper_peak);
 lower_peak=lower_peak(1:end-1);
%Deflection and its quality
Average_deep=mean(tot_def);
qual_cycle=find(tot_def>35 & tot_def<43);

%%% naura

%qual_cycle=find(tot_def>=50 & tot_def<60);

%%%%%%%%%%%FOR ADULT%%%%%%%%%%%%%
%qual_cycle=find(tot_def>=50 & tot_def<60);

tot_qual_cycle=length(qual_cycle);
%un_qual_cycle=find(tot_def<36);
%un_qual_cycle2=find(tot_def>45);
%tot_un_qual_cycle=tot_cycle-tot_qual_cycle;
sec_cdqual=find(tot_def>=38 & tot_def<43);
sec_qual_cycle=length(sec_cdqual);
sec_cdqual_index=(sec_qual_cycle/tot_cycle)*100;

comp_qual_index=(tot_qual_cycle/tot_cycle)*100;

%release depth and its quality
%%% NAURA TESTING-PLASTIC STIFFNES 15.4239/MM %%%%%%%%%
%newton=lower_peak*11;

newton=lower_peak*3.63;
%kg=newton*0.10197;
kg=(newton*0.10197);
Average_recoil=mean(kg);

%recoil=find(lower_peak==0);

recoil=find(kg<2.5);
qual_recoil=length(recoil);
recoil_qual_index=(qual_recoil/tot_cycle)*100;
unrecoil=find(lower_peak>2.5);
un_qual_recoil=length(unrecoil);
unrecoil_qual_index=(un_qual_recoil/tot_cycle)*100;
```

```
sec_rf=find(lower_peak<0.5);
sec_rf_cycles=length(sec_rf);
sec_rf_index=(sec_rf_cycles/tot_cycle)*100;

%compression rate an dits quality
aver_cr=mean(cr);
q_cr=find(cr>100 & cr<120);
qual_cr=length(q_cr);
un_qual_cr=tot_cycle-qual_cr;
cr_qual_index=(qual_cr/tot_cycle)*100;

%duty cycle and its quality
mean_dc=mean(dc);
%mean_recoil_dc=mean(recoil_dc);
q_dc=find(dc>30 & dc<50);
qual_dc=length(q_dc);
dc_qual_index=(qual_dc/tot_cycle)*100;

%q_recoil_dc=find(recoil_dc>30 & recoil_dc<50);
%qual_recoil_dc=length(q_recoil_dc);
%recoildc_qual_index=(qual_recoil_dc/tot_cycle)*100;

%a=max(tot_qual_cycle,qual_recoil,qual_recoil,qual_dc)

%Calculating injury index cycles
in_cycle=find(tot_def>43);
injury_cycle=length(in_cycle);
deepc=max(tot_def);
Thoracic_injury_index=(injury_cycle/tot_cycle)*100;

%overall cpr quality index
%tot_tar_ach_cy(tot_tar_ach_cy==0)=[];
%tot_tar_ach_cycle=length(tot_tar_ach_cy);
%cpr_qual_intex=(comp_qual_index+recoil_qual_index+cr_qual_index+compdc_qual_in-
dex+recoildc_qual_index)/5;
%cpr_qual_intex=( tot_tar_ach_cycle/tot_cycle)*100;

overall_cpr_qual_1=intersect(qual_cycle,recoil);
overall_cpr_qual_2=intersect(overall_cpr_qual_1,q_cr);
overall_cpr_qual_2=overall_cpr_qual_2';
overall_cpr_qual_3=intersect(overall_cpr_qual_2,q_dc);
%overall_cpr_qual_4=intersect(overall_cpr_qual_3,q_recoil_dc);
tot_no_qual_cycles=length(overall_cpr_qual_3);
cpr_qual_intex=(tot_no_qual_cycles/tot_cycle)*100;
if isempty(cpr_qual_intex)
   cpr_qual_intex(1)=0;
end
```

```matlab
% no flow time
noflow_time=find(cycle_time>2);
noflow_count=length(noflow_time);




%%%%%%%%%%%%%%%%print re-
sults%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fprintf('%s%f\n ', 'Episode duration:', Episode_duration(:));
result(1)=Episode_duration;

fprintf('%s%f\n ', 'Total no of cycles:', tot_cycle(:));
result(2)=tot_cycle;


%compression depth

fprintf('%s%f\n ', 'Mean Compression depth (mm):', Average_deep(:));
result(3)=Average_deep;
fprintf('%s%f\n ', 'CD quality index (>=35)(%):', comp_qual_index(:));
result(4)=comp_qual_index;
fprintf('%s%f\n ', 'Secondary CD quality index(>=36mm)(%):', sec_cdqual_index(:));
result(5)=sec_cdqual_index;




columnheader = {'Episode duration:','Total no of cycles:','Mean Compression depth
(mm):',...,
    'CD quality index(>=35)(%):','Secondary CD quality index(>=36mm)(%):'};
columnheader=columnheader';
xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx', columnheader,'cpr','M1:M5');

result=result';
xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',result,'cpr','R1:R5');

result=0;


%release force

fprintf('%s%f\n ', 'mean release force (kg):', Average_recoil(:));
result(1)= Average_recoil;
fprintf('%s%f\n ', 'Release depth quality index(<2.5kg)(%):', recoil_qual_index(:));
result(2)=recoil_qual_index;
fprintf('%s%f\n ', 'Secondary complete RF index(>0.5kg)(%):', sec_rf_index(:));
result(3)=sec_rf_index;
```

```
columnheader = {'mean release force (kg):','Release depth quality index(<2.5kg)(%):','Sec-
ondary complete RF index(>0.5kg)(%):'};
columnheader=columnheader';
xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx', columnheader,'cpr','M7:M9');

result=result';
xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',result,'cpr','R7:R9');

result=0;

%compression rate

fprintf('%s%f\n ', 'Mean compression rate(cpm):', aver_cr(:));
result(1)=aver_cr;
fprintf('%s%f\n ', 'Compression rate quality index(100-120 cpm%):', cr_qual_index(:));
result(2)=cr_qual_index;

 columnheader = {'Mean compression rate(cpm):','Compression rate quality index(100-120
cpm%):'};
columnheader=columnheader';
xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx', columnheader,'cpr','M11:M12');

result=result';
xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',result,'cpr','R11:R12');

result=0;

%compression duty cycle

fprintf('%s%f\n ', 'Mean Duty cycle (%):', mean_dc(:));
result(1)=mean_dc;
fprintf('%s%f\n ', 'Duty cycle quality index(30-50%):', dc_qual_index(:));
result(2)=dc_qual_index;

 columnheader = {'Mean Duty cycle (%):','Duty cycle quality index(30-50%):'};
columnheader=columnheader';
xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx', columnheader,'cpr','M14:M15');

result=result';
xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',result,'cpr','R14:R15');

result=0;

%overall qc index

fprintf('%s%f\n ', 'Overall CPR quality index (%):', cpr_qual_intex(:));
result(1)=cpr_qual_intex;
```

```matlab
%deepest compression

fprintf('%s%f\n ', 'Deepest compression is:', deepc(:));
result(2)=deepc;

%Injury index
fprintf('%s%f\n ', 'no of injuries cycles achived:', injury_cycle(:));
result(3)=injury_cycle;
fprintf('%s%f\n ', 'Thoracic injury index (%):', Thoracic_injury_index(:));
result(4)=Thoracic_injury_index;

%No flow

fprintf('%s%f\n ', 'Number of no flow times:', noflow_count(:));
result(5)=noflow_count;

 columnheader = {'Overall CPR quality index (%):','Deepest compression is:','no of injuries
cycles achived:','Thoracic injury index (%):','Number of no flow times:'};
columnheader=columnheader';
xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx', columnheader,'cpr','M17:M21');

result=result';
xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',result,'cpr','R17:R21');

result=0;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%

fprintf('%s%f\n ', 'Total quality compression cycles(>=34mm):', tot_qual_cycle(:));
result(1)=tot_qual_cycle;

fprintf('%s%f\n ', 'Total target cycles-release force:', qual_recoil(:));
result(2)=qual_recoil;

fprintf('%s%f\n ', 'no of quality compression rate cycles:', qual_cr(:));
result(3)=qual_cr;
%fprintf('%s%f\n ', 'no of Un_quality CR cycles:', un_qual_cr(:));
%result1(6)=un_qual_cr;
fprintf('%s%f\n ', 'no of quality duty cycle:', qual_dc(:));
result(4)=qual_dc;

columnheader = {'Total quality compression cycles(>=34mm):','Total target cycles-release
force:','no of quality compression rate cycles:', 'no of quality duty cycle:'};
columnheader=columnheader';
xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx', columnheader,'cpr','M23:M26');

result=result';
```

```
xlswrite('D:\Jeyapal\PhD\results\CPR data for analysis.xlsx',result,'cpr','R23:R26');

result=0;


%fprintf('%s%f\n ', 'Release depth quality index-unrecoil(%):', unrecoil_qual_index(:));
%result1(11)=unrecoil_qual_index;


%*****

%end
```

A.5. New Duty cycle calculation-Matlab code

```matlab
%Duty cycle


% compression
comp_dc=zeros(1,length(up_time));
%if (up_time(1)-lp_time(1))>0
for i=1:length(up_time)

if i<length(up_time)
%if i<101
    j=i;

%active_t(j)=up_time(j+1)-lp_time(j);
active_t(j)=up_time(j)-lp_time(j);
  tot_t(j)=lp_time(j+1)-lp_time(j);
  comp_dc(j)=(active_t(j)/tot_t(j))*100;
 end
end
dc=comp_dc';
```

A.6. Matlab subroutine program for filter the minimum and maximum values in each compression

function varargout = peakfinder(x0, sel, thresh, extrema)%PEAKFINDER Noise tolerant fast peak finding algorithm%   INPUTS:

```
%      x0 - A real vector from the maxima will be found (required)
%      sel - The amount above surrounding data for a peak to be
%         identified (default = (max(x0)-min(x0))/4). Larger values mean
%         the algorithm is more selective in finding peaks.
%      thresh - A threshold value which peaks must be larger than to be
%         maxima or smaller than to be minima.
%      extrema - 1 if maxima are desired, -1 if minima are desired
%         (default = maxima, 1)
%  OUTPUTS:
%     peakLoc - The indicies of the identified peaks in x0
%     peakMag - The magnitude of the identified peaks
%
%  [peakLoc] = peakfinder(x0) returns the indicies of local maxima that
%      are at least 1/4 the range of the data above surrounding data.
%
%  [peakLoc] = peakfinder(x0,sel) returns the indicies of local maxima
%      that are at least sel above surrounding data.
%
%  [peakLoc] = peakfinder(x0,sel,thresh) returns the indicies of local
%      maxima that are at least sel above surrounding data and larger
%      (smaller) than thresh if you are finding maxima (minima).
%
%  [peakLoc] = peakfinder(x0,sel,thresh,extrema) returns the maxima of the
%      data if extrema > 0 and the minima of the data if extrema < 0
%
%  [peakLoc, peakMag] = peakfinder(x0,...) returns the indicies of the
%      local maxima as well as the magnitudes of those maxima
%
%  If called with no output the identified maxima will be plotted along
%      with the input data.
%
%  Note: If repeated values are found the first is identified as the peak
%
% Ex:
% t = 0:.0001:10;
% x = 12*sin(10*2*pi*t)-3*sin(.1*2*pi*t)+randn(1,numel(t));
% x(1250:1255) = max(x);
% peakfinder(x)
%
% Perform error checking and set defaults if not passed in
error(nargchk(1,4,nargin,'struct'));
error(nargoutchk(0,2,nargout,'struct'));
 s = size(x0);
```

```matlab
flipData =  s(1) < s(2);
len0 = numel(x0);
if len0 ~= s(1) && len0 ~= s(2)
    error('PEAKFINDER:Input','The input data must be a vector')
elseif isempty(x0)
    varargout = {[],[]};
    return;
end
if ~isreal(x0)
    warning('PEAKFINDER:NotReal','Absolute value of data will be used')
    x0 = abs(x0);
end

if nargin < 2 || isempty(sel)
    sel = (max(x0)-min(x0))/4;
elseif ~isnumeric(sel) || ~isreal(sel)
    sel = (max(x0)-min(x0))/4;
    warning('PEAKFINDER:InvalidSel',...
        'The selectivity must be a real scalar.  A selectivity of %.4g will be used',sel)
elseif numel(sel) > 1
    warning('PEAKFINDER:InvalidSel',...
        'The selectivity must be a scalar.  The first selectivity value in the vector will be used.')
    sel = sel(1);
end

if nargin < 3 || isempty(thresh)
    thresh = [];
elseif ~isnumeric(thresh) || ~isreal(thresh)
    thresh = [];
    warning('PEAKFINDER:InvalidThreshold',...
        'The threshold must be a real scalar. No threshold will be used.')
elseif numel(thresh) > 1
    thresh = thresh(1);
    warning('PEAKFINDER:InvalidThreshold',...
        'The threshold must be a scalar.  The first threshold value in the vector will be used.')
end

if nargin < 4 || isempty(extrema)
    extrema = 1;
else
    extrema = sign(extrema(1)); % Should only be 1 or -1 but make sure
    if extrema == 0
        error('PEAKFINDER:ZeroMaxima','Either 1 (for maxima) or -1 (for minima) must be
input for extrema');
    end
end

x0 = extrema*x0(:); % Make it so we are finding maxima regardless
```

```matlab
thresh = thresh*extrema; % Adjust threshold according to extrema.
dx0 = diff(x0); % Find derivative
dx0(dx0 == 0) = -eps; % This is so we find the first of repeated values
ind = find(dx0(1:end-1).*dx0(2:end) < 0)+1; % Find where the derivative changes sign

% Include endpoints in potential peaks and valleys
x = [x0(1);x0(ind);x0(end)];
ind = [1;ind;len0];

% x only has the peaks, valleys, and endpoints
len = numel(x);
minMag = min(x);

if len > 2 % Function with peaks and valleys

    % Set initial parameters for loop
    tempMag = minMag;
    foundPeak = false;
    leftMin = minMag;
        % Deal with first point a little differently since tacked it on
    % Calculate the sign of the derivative since we taked the first point
    %  on it does not neccessarily alternate like the rest.
    signDx = sign(diff(x(1:3)));
    if signDx(1) <= 0 % The first point is larger or equal to the second
        ii = 0;
        if signDx(1) == signDx(2) % Want alternating signs
            x(2) = [];
            ind(2) = [];
            len = len-1;
        end
    else % First point is smaller than the second
        ii = 1;
        if signDx(1) == signDx(2) % Want alternating signs
            x(1) = [];
            ind(1) = [];
            len = len-1;
        end
    end

    % Preallocate max number of maxima
    maxPeaks = ceil(len/2);
    peakLoc = zeros(maxPeaks,1);
    peakMag = zeros(maxPeaks,1);
    cInd = 1;
    % Loop through extrema which should be peaks and then valleys
    while ii < len
        ii = ii+1; % This is a peak
        % Reset peak finding if we had a peak and the next peak is bigger
```

```matlab
    %   than the last or the left min was small enough to reset.
    if foundPeak
       tempMag = minMag;
       foundPeak = false;
    end

    % Make sure we don't iterate past the length of our vector
    if ii == len
       break; % We assign the last point differently out of the loop
    end
    % Found new peak that was lager than temp mag and selectivity larger      %   than the
minimum to its left.
    if x(ii) > tempMag && x(ii) > leftMin + sel
       tempLoc = ii;
       tempMag = x(ii);        end

    ii = ii+1; % Move onto the valley
    % Come down at least sel from peak
    if ~foundPeak && tempMag > sel + x(ii)
       foundPeak = true; % We have found a peak
       leftMin = x(ii);
       peakLoc(cInd) = tempLoc; % Add peak to index
       peakMag(cInd) = tempMag;
       cInd = cInd+1;
    elseif x(ii) < leftMin % New left minima
       leftMin = x(ii);
    end
  end

  % Check end point
  if x(end) > tempMag && x(end) > leftMin + sel
     peakLoc(cInd) = len;
     peakMag(cInd) = x(end);
     cInd = cInd + 1;
  elseif ~foundPeak && tempMag > minMag % Check if we still need to add the last point
     peakLoc(cInd) = tempLoc;
     peakMag(cInd) = tempMag;
     cInd = cInd + 1;
  end

  % Create output
  peakInds = ind(peakLoc(1:cInd-1));
  peakMags = peakMag(1:cInd-1);
else % This is a monotone function where an endpoint is the only peak
  [peakMags,xInd] = max(x);
  if peakMags > minMag + sel
     peakInds = ind(xInd);
  else
```

```matlab
      peakMags = [];
      peakInds = [];
   end
end
 % Apply threshold value.  Since always finding maxima it will always be
%   larger than the thresh.
if ~isempty(thresh)
   m = peakMags>thresh;
   peakInds = peakInds(m);
   peakMags = peakMags(m);
end

% Rotate data if needed
if flipData
   peakMags = peakMags.';
   peakInds = peakInds.';
end

% Change sign of data if was finding minima
if extrema < 0
   peakMags = -peakMags;
   x0 = -x0;
end
% Plot if no output desired
if nargout == 0
   if isempty(peakInds)
      disp('No significant peaks found')
   else
      figure;
      plot(1:len0,x0,'.-',peakInds,peakMags,'ro','linewidth',2);
   end
else
   varargout = {peakInds,peakMags};end
```

A.7. Sample image of Matlab program generated during analysis with minimum and maximum values
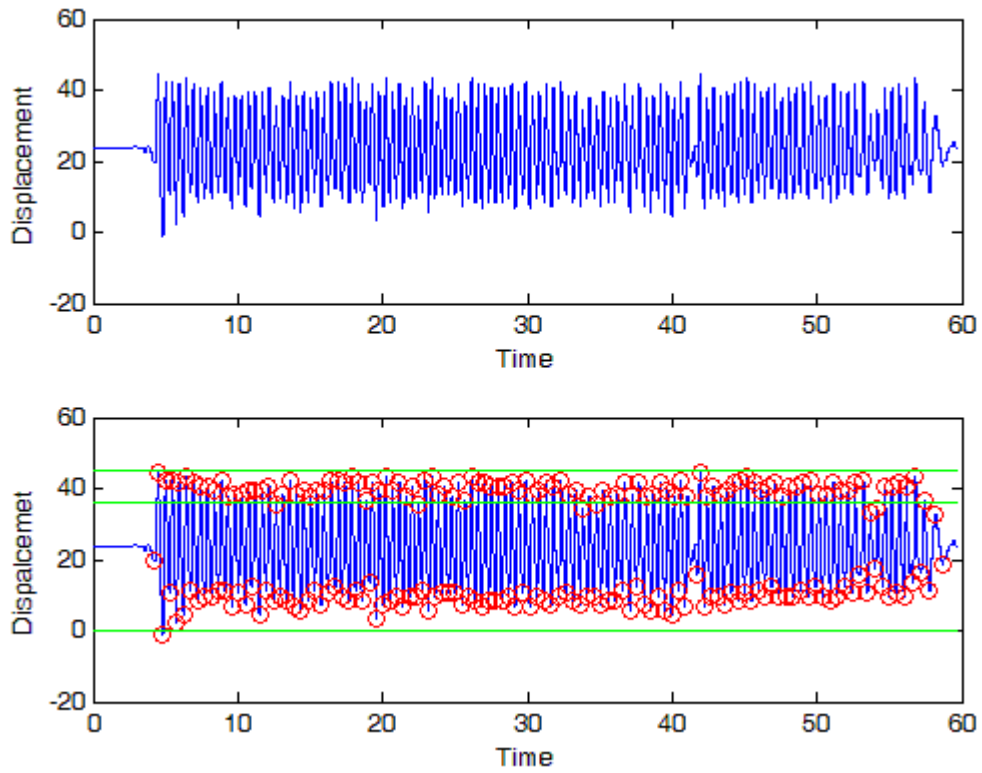
A.8. Research Protocol

Analysing CPR quality of professional healthcare people, first responders and lay persons using CPR feedback monitor

Research Protocol: Version 2 - 20/06/2015

Project ID: 1-JK-1014

Study Research Team:

Mr Jeyapal Kandasamy

Dr Peter Theobald (Co-Investigator)

Dr Michael Jones (Co-Investigator)

Study Summary

Kouwen hoven et al., 1960, first coined the external chest compression treatment for cardio-pulmonary resuscitation [201] . After that there were lots of improvement, but still the overall successful outcome rates after cardiac arrest (CA) remain poor. CC should be the primary action and the highest priority when starting CPR in victim of sudden CA to the people and continues and non-interrupted CC in CPR will continuously ensure blood flow to the heart, brain and vital organs and gives best chance to recover from CA. To improve outcomes of CA, current European and UK Resuscitation Council guidelines highlight the delivery of quality chest compressions during CPR. Infant chest compressions are recommended using the two-thumb (TT) or two-finger (TF) technique, at rates of 100-120 compressions per minute, to depths no less than one-third the external anterior-posterior (AP) chest diameter (≈40mm), with the complete release of the chest and duty cycles of 30-50%. There are many recent research studies about infant CPR efficacy, uniformly report poor quality chest compressions, with target depths, rates and duty cycles rarely achieved. Our research team previous research studies shows the real time CPR feedback monitor dramatically increased the quality of chest compression from <1% to75 to 80% [23] . So, we propose a research to exploring whether simulated infant manikin chest compression quality can be improved through real-time performance feedback.

Approximately lay persons (no experience in CPR) will be recruited over a 2 weeks period from Cardiff University. Recruited participants will be randomly assigned one of two groups such as Group 1 and Group 2. Each participant will be instructed to perform 4, 1 minute, periods of continuous TT and TF CC with ventilations on an infant CPR manikin with sensors fitted pads.

> ➤ Group 1 will perform all four CC sets with no feedback.

> ➤ Group 2 will perform all four CC sets with help of feedback

CPR feedback monitor data such as compression depths, compression rates, release forces and duty cycles will be recorded on computer hard disk for further analysis of comparing between with and without feedback monitor differences. Cardiff University School of Medicine have policies for recording data from participants which will be securely stored and then deleted after 15 years. No patients are required for this study because the CPR performance only based on baby manikin. The collected data and analysed results will be published in scientific journals and in my PhD thesis.

Introduction, Rationale, Study Background and Aims

Current CA outcomes in the infant and neonatal populations are very poor and shown undesirably high rates of both morbidity and mortality[74]. To improve the current CA survival rate, the European and UK Resuscitation Councils (ERC & UKRC) highlight the delivery of high quality chest compressions during infant CPR. However, often, the Chest compression is delivered even by well-trained rescuers very poorly [13]. Particularly for depth and compression rate does not meet as suggested guidelines targets very often [204] and recent research studies shown that trained rescuers very often fail to deliver high quality infant chest compressions during simulated CPR on instrumented CPR training manikins [22, 27, 35, 104, 197].

Similarly, chest recoil depth during the resuscitation problem of older children and adolescents can reduce by using the CPR feedback device and data also confirmed that [61]. So far, different methods have been evaluated to improve the rescuer and bystander CC performance for

adults to improve the quality of the CPR [65, 67, 68, 205]. The recent real time feedback monitors are also help the rescuer to comply with guideline recommendations to perform CPR on adult patients [204, 206].

Nevertheless, the effect of CPR real-time feedback monitor performance to improve the quality of infant CPR chest compressions has never been quantified. This was primarily due to the paucity in scientific evidence upon which to establish quality targets for infant CPR chest compressions. Some of recent studies may provide the targets of perform quality CPR for infant CA patients. The quality of chest compression is an very significant factor in CPR [65] and the five important key factors of quality of the CPR depending on following components, such as compression depth (CD), recoil or chest recoil depth (RD), duty cycle (DC), compression rate (CR), pauses in CC [130].

Investigational Plan

3(a) Infant Manikin and Feedback Program

CPR training infant manikin (Laerdal® ALS Baby, Laerdal Medical, Stavanger, Norway), which is representing a three-month-old 5kg male infant is equipped with sensors by the Institute of Medical Engineering and Medical Physics, Cardiff University for monitoring and recording chest deflection and force during simulated CPR. The maximum chest deflection depth (CDmax) of the manikin is 56mm which represents the actual physiological internal AP thorax depth of a three month old male infant [139].

The Kionix 3 axis accelerometers with evaluation board (KXPB5) are used for measuring chest deflection distance for these experiments. The operating voltage of the accelerometer is 3.3 volts. Accelerometer is an electromechanical device used for measuring the acceleration of motion. The 'g' is the unit of acceleration based on earth gravity which is 32.2 ft/sec or 9.8

m/sec. The accelerometer is calibrated and used for measure chest deflections at the lower third of the sternum. The accelerometers are placed in the rubber pads. Accelerometer sensors output voltages are collected from the rubber pads using the NI DAQ Card (National Instruments, Austin, TX, USA) at the sample rate of 200hz and the voltages are send to the LabVIEW software program (Developed by Cardiff University Medical Physics) for convert from voltage into displacement on a computer to continuously monitor and record CC sequence.

Study procedure

Information sheet about the testing will be send to all potential participants at least one-week prior through research office and standardised instructions are provided for both the investigator and participant in the Experimental Instruction Sheet. All participants will be briefed by the investigator about the experimental procedure using the experimental instruction sheet before starting testing them. If participants would have any questions will be answered by the investigator. Once they satisfied, participants will be asked to complete and sign the 'participants consent and participants detail forms'.

Prior to testing the instrumented baby manikin will be set up on a flat surface or table and the computer with power supply unit will be placed separately just near to the manikin. Once manikin and the computer ready for testing, each participant will be asked to perform CC on manikin sternum using both compression technique (TT and TF). Each participant in a group 1 will be instructed to perform 4 CC periods of 1-minute duration continuous TT and TF technique CC on an instrumented baby manikin (i.e. no ventilation) without CPR performance feedback monitor help. Then each participant in group will be instructed to perform the same two sets of CC with help of CPR performance feedback monitor followed by next two periods

without feedback monitor. In total, each participant will need to perform four 1-minute continuous CC on a baby manikin and approximately each participant would need to spend at least 7-8 minutes of their time.

Study Participants

Participants will be recruited from the Cardiff University. The exclusion criteria for this study will be invalid certification, incomplete acquisition of data or any health issues that the participant, training course directors or investigators feel may bias results or potentially cause injury.

Participant Approval

Participant's approval will be acquired prior to the experiments. Participant's information sheet will be made available in both electronic and paper format and circulated by the head of wales fire department to each participant at least one week prior to testing. To comply with the Research Governance Framework for Health and Social Care in Wales (2001), an option to request Welsh translated documentation will be provided. At any time, if any participants not happy to contribute the experimental study that they are free to withdraw from the study immediately which does not affect the relationship with us. Participants will be briefed on the test protocol, time and procedure with the experimental instruction sheet. After that adequate time will be provided for questions and investigator answer to their questions. Once all participants satisfied each participant need to fill and sign in the participant consent form.

Data collection

The instrumented baby manikin using the accelerometer and force sensors is powered by custom made power supply unit. Sensors output voltages will be recorded via NI DAQ on a laptop computer and voltage signals are processed for display and further analysis using the custom

LabVIEW program. The participants cannot see the laptop screen and hear any oral feedback during no feedback period.

Statistical Analysis

Chest compression quality will be calculated for each potential participant from the recorded anterior-posterior chest deflection. The CC quality based on CD, CR, RD and DC which are calculated from each participants CC performance on a manikin during testing. For each element quality index which is the proportion of the CC will be calculated. Finally, the overall quality of CC will be calculated with each participant's average of each element quality. During testing any incomplete test results will be destroyed before analysis. Then the results will statistically compare the quality of CC between the feedback and without feedback scenarios for both CC techniques (TF and TT).

Data Security and Storage

The acquired date during CC will be stored on a Cardiff University owned computer which is protected by password. All paper based documents are stored securely which can be accessed only to the investigative team members. As per the Cardiff University data production policy, all participants' data will be extremely confidential and will be stored only for maximum 15 years.

Participant Safety

The CC performance feedback chance of risk is very low and in the rare scenario if any participant injured, they must report to the team leader. Initially the team leader should manage all injuries in line with local health board policy and get back to Mr Jeyapal Kandasamy so that it may also be dealt with in line with Cardiff University policies.

Timescale

This experiment will be finished less than six months after recruiting the participants. The recorded and analysed data will be stored for further analysis only for maximum 15 years, in line Cardiff University policies.

Dissemination

The analysed results will be published in scientific journals and presented in engineering conferences. Finally, the results will be included in my PhD thesis.

The results will be published and presented in peer reviewed scientific journals, amongst scientific, medical and engineering peers at conferences, and in a PhD thesis. All participant name and recorded date during testing will remain anonymised.

Project Management

The Chief/Principal Investigator will be Mr Jeyapal Kandasamy (Institute of Medical Engineering & Medical Physics, Cardiff University, The Parade, Cardiff, Wales). The academic supervisors for Mr Jeyapal Kandasamy are Dr Peter Theobald and Dr Michael Jones (Institute of Medical Engineering & Medical Physics, Cardiff University, The Parade, Cardiff, Wales).

Reference

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A.9. Participant information Sheets

PARTICIPANT INFORMATION SHEET

Study title:

An paediatric CPR performance be improved through the provision of 'real time' feedback?

Invitation paragraph:

You are being invited to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. If you have any further questions or require more information then do not hesitate to contact us. You should take your time to decide whether or not you would like to take part in this study.

Thank you for taking the time to read this.

What is the purpose of the study?

CPR quality is an issue contributing to poor cardiac arrest survival rates, particularly when performed by untrained personnel. In an effort to improve quality of CPR in communities without access to full training, an infant CPR manikin has been developed to provide a low cost option that provides feedback on CPR quality.

To test the efficacy of the developed CPR feedback system in improving lay-persons CPR quality on infants this study will record initial quality without feedback, quality concurrent with feedback, and retention of quality post feedback in comparison to a known system. Finally this study will evaluate our new manikin design against current models via qualitative feedback.

Why have I been chosen?

A convenience sample of 30-40 participants have been selected. Eligible participants must meet the following criteria;

- No prior CPR training (i.e. lay person)

Do I have to take part?

Your involvement in this study is entirely voluntary. It is up to you to decide whether or not to take part. If you decide to take part you will be given this information sheet to keep and asked to sign a consent form. However, you are still free to withdraw at any time without giving reason and the data that has been collected will be destroyed.

What will happen to me if I take part?

If you agree to take part you will be required to attend two sessions in W1.09 in ENGIN lasting approximately 15 minutes

What about confidentiality?

At no point during the study will any personal or sensitive data be collected or stored.

What do I have to do?

To begin with you will be asked to read brief instructions from a leaflet on correct CPR practice and given 2 minutes to familiarise yourself with the CPR manikin. Then you will:

- Perform 4 minutes of CPR compressions on a manikin, where quality measures will be recorded on a computer.
- Based on the group you might do performance with or without help of feedback system.

Are there any risks?

No

What will happen to the results of the research study?

The collected data and analysed results will be published in scientific journals and in my PhD thesis.

Who is organising and funding the research?

Cardiff University

Contact for further information.

If you require further information, please contact either;

Dr. Peter Theobald
Project Supervisor
Email: TheobaldPS@cardiff.ac.uk

Jeyapal Kandasamy
PhD student
Email: Kandasamyj@cardiff.ac.uk

A.10. Participant Consent form

PARTICIPANT CONSENT FORM

Quantitative assessment of the effects of real-time performance feedback on chest compression quality during simulated infant CPR

Please tick as appropriate

1. I can confirm that I have read and understood the Participant Information Form for the above study (Project ID: 1-JK-1014). I have had the opportunity to ask questions and have had them answered to my satisfaction.

2. I can confirm that I have completed the Participant Details Form for the above study (Study Number: 1-JK-1014).

3. I can confirm that I have been instructed in and understand the testing procedure for the above study (Study Number: 1-JK-1014). I feel that I know how to, and am able to, perform both infant CPR techniques over the required periods of time. I have had the opportunity to ask questions and have had them answered to my satisfaction.

4. I understand that I am being observed and that my experimental data will be used for research purposes. I can further confirm I understand my details will not be used to identify experimental data when disseminated in the public domain.

5. I understand that my participation is voluntary and I am free to withdraw at any time, with no need to give reason, without my legal rights being affected.

6. Would you like to receive feedback via your training course director?
    ☐ Yes ☐ No

I agree to participate in the above study (Study Number: 1-JK-014).

_____   _____   _____

Participant Name (BLOCK CAPITALS)   **Signature**
Date

_____   _____   _____

Investigator Name (BLOCK CAPITALS)   Signature   Date

A.11. Participant details form

PARTICIPANT DETAILS FORM

Participant Code: _____

Quantitative assessment of the effects of real-time performance feedback on chest compression quality during simulated infant CPR

The below information is recorded to provide an appreciation of the overall study demographics. It will in no way be used to identify experimental data or be used for any other purpose than that which has been outlined in the Participant Information form. You will be asked to confirm that you have completed this form on the Participant Consent form to allow data anonymization.

Please fill as appropriate:

1. Gender (tick as applicable):   2. Hand grip (Dynamometer): _____kg

    ☐ Male

    ☐ Female

3.   Age: _____   4. Weight: _____Kg   5. Height: _____Cm

6.   Field of expertise (tick as applicable):

    a. Registered nurse

    b. Resuscitation Practitioner/Officer

    c. Operating Department Practitioner (ODP)

    d. Doctor: Grade _____

    e. Other (please specify) _____

7.   Clinical experience (years) _____

8.   Current certification (tick as applicable):

    a. APLS

    b. EPLS

    c. PLS

    d. PILS

    e. Other equivalent (please specify) _____

9.   Time since last certification (years) _____

10.   Number of times infant CPR performed professionally (tick as applicable):

    a. None

b. <5

c. 6-10

d. 11-19

e. >20

A.12. Ethical Approval from School of Engineering, Cardiff University Ethical Review Application

AR

Aderyn Reid

Thu 20/08/2015, 16:47
Jeyapal Kandasamy;
Peter Theobald
Inbox

Dear Jeypal,

I am pleased to inform you that your Ethical Review application: "Can paediatric CPR performance be improved through the provision of real time feedback" has been approved today (20/08/2015) by Chair's action, on recommendations made by the School's Ethical Review Panel.

Regards
Aderyn

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A.13 Air flow sensor-Omron-D6F-A1-Data sheet

A Compact, High-accuracy Sensor That Measures Low Flow Rates.

- **High accuracy of ±3% FS.**
- **Flow rates can be measured without being affected by temperature or pressure.**

| RoHS Compliant |

Refer to the *Safety Precautions* on page 3.

Ordering Information

Model	Applicable fluid	Flow rate range	Minimum order
D6F-01A1-110	Air	0 to 1 L/min	1
D6F-02A1-110		0 to 2 L/min.	1

Output Voltage Characteristics
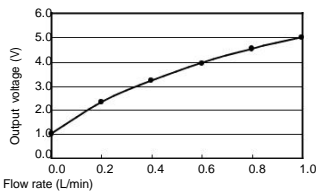
D6F-01A1-110   **D6F-02A1-110**
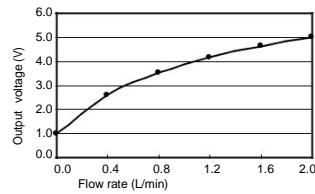
D6F-01A1-110

Flow rate L/min (normal)	0	0.2	0.4	0.6	0.8	1.0
Output voltage V	1.00 ±0.12	2.31 ±0.12	3.21 ±0.12	3.93 ±0.12	4.51 ±0.12	5.00 ±0.12

D6F-02A1-110

Flow rate L/min (normal)	0	0.4	0.8	1.2	1.6	2.0
Output voltage V	1.00 ±0.12	2.59 ±0.12	3.53 ±0.12	4.18 ±}0.12	4.65 ±0.12	5.00 ±0.12

Measurement conditions: Power supply voltage of 12±0.1 VDC, ambient temperature of 25±5°C, and ambient humidity of 35% to 75%.

Connections

D6F-01A1-110
D6F-02A1-110

Pin No.	1: Vcc
	2: Vout
	3: GND
Connector	53398 (Made by Molex Japan)

Use the following connectors for connections to the D6F:

Housing	51021 (Made by Molex Japan)
Terminals	50079 (Made by Molex Japan)
Wires	AWG28 to AWG26

Tubes   Install tubes made of materials such as rubber or urethane so that they will not come out.
For urethane tubes, tubes with an outer diameter of 12 mm and an inner diameter of 8 mm are recommended.

2: Vout
1: Vcc   3: GND

Enlarged View

D6F @-A1

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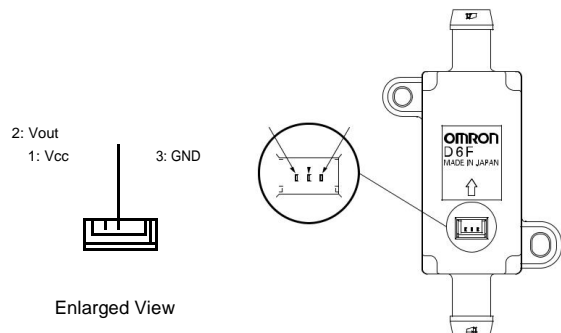
D6F-@A1

MEMS Flow Sensor

Characteristics/Performance

Model	D6F-01A1-110	D6F-02A1-110
Flow Range (See note 1.)	0 to 1 L/min	0 to 2 L/min.
Calibration Gas (See note 2.)	Air	
Flow Port Type	Barb joint Maximum outside diameter: 8.6 mm, Minimum outside diameter: 7.4 mm	
Electrical Connection	Three-pin connector	
Power Supply	10.8 to 26.4 VDC	
Current Consumption	15 mA max with no load, with a Vcc of 12 to 24 VDC, and at 25°C	
Output Voltage	1 to 5 VDC (non-linear output, load resistance of 10 kΩ)	
Accuracy	±3% FS (25°C characteristic)	
Repeatability (See note 3.)	±0.3% FS	
Output Voltage (Max.)	5.7 VDC (Load resistance: 10 kΩ)	
Output Voltage (Min.)	0 VDC (Load resistance: 10 kΩ)	
Rated Power Supply Voltage	26.4 VDC	
Rated Output Voltage	6 VDC	
Case	PPS	
Degree of Protection	IEC IP40	
Withstand Pressure	200 kPa	
Pressure Drop (See note 3.)	0.42 kPa	1.06 kPa
Operating Temperature	−10 to 60°C (with no condensation or icing)	
Operating Humidity	35% to 85% (with no condensation or icing)	
Storage Temperature	−40 to 80°C (with no condensation or icing)	
Storage Humidity	35% to 85% (with no condensation or icing)	
Temperature Characteristics	±3% FS for 25°C characteristic at an ambient temperature of −10 to 60°C	
Insulation Resistance	Between Sensor outer cover and lead terminals: 20 MΩ min. (at 500 VDC)	
Dielectric Strength	Between Sensor outer cover and lead terminals: 500 VAC, 50/60 Hz min. for 1 min (leakage current: 1 mA max.)	
Weight	12.8 g	

Note: 1. A 0 to 1 L/min. (normal) volumetric flow rate at 0°C, 101.3 kPa.
Note: 2. Dry gas. (must not contain large particles, e.g., dust, oil, or mist.)
Note: 3. Reference (typical)

Dimensions (Unit: mm)

D6F-01A1-110
D6F-02A1-110
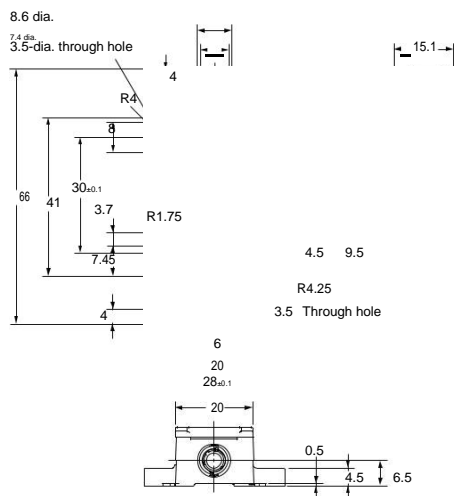
Mounting Hole Dimensions
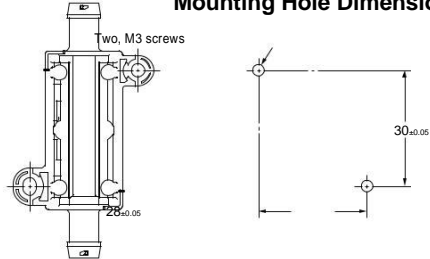
Lead Wire (included): D6F-CABLE1
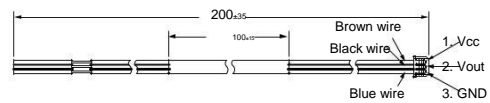
D6F-@A1

Safety Precautions

⚠ WARNING .

The D6F is built for use with general-purpose devices. In cases such as those described below, where safety is required, imple-ment measures to ensure the safety of the system and all devices, such as fail-safe designs, redundancy designs, and reg-ular maintenance.

 • Safety devices for ensuring safety for persons
 • Transportation equipment control (such as applications to stop operation)
 • Aviation and space equipment
 • Nuclear power equipment

Do not use the D6F for applications in which D6F operation would directly affect human life.

⚠ Caution .

Make sure that the power to all equipment is turned OFF before you install the Sensor. Installing the Sensor while the power sup-ply is ON may result in electrical shock or abnormal operation.

Precautions for Correct Use

● **Fluids,Tubes, and Sensor Installation**

All Models

(1) Use clean fluids. Dust and mist can affect the characteristics of the Sensor or damage the Sensor. Install a filter and mist separator on the upstream tube. (Not required for the D6F-W@A1, D6F-V, D6F-P or D6F-PH.)

(2) Do not use combustible gases (e.g., hydrogen), corrosive gases (e.g., chlorine, sulfur, acidic, or alkali gas), or other non-approved fluids. They may damage the Sensor.

(3) The performance specifications that are given for the G6F do not apply if any fluids other than the specified applicable fluid are used.

(4) Foreign matter in the tubes that are connected to the Sensor may damage the Sensor. Prevent any foreign matter from entering the tubes after the Sensor is removed from its packaging.

(5) Attach the tubes so that fluid flows only in the direction des-ignated by the arrows on the Sensor. Correct measurements cannot be obtained if the fluid flows in the wrong direction.

(6) We recommend that you install the tubes horizontally. If the tubes are not installed horizontally, an error of $\pm 1\%$ FS or higher may result. (This does not apply to the D6F-03A3.)

(7) Install the Sensor on a flat surface. Incorrect installation may damage the Sensor and make it impossible to obtain correct measurements.

(8) After the Sensor is installed, check to confirm that it oper-ates correctly.

(9) Do not drop the Sensor, remove the cover, or attempt to dis-assemble the Sensor in any way.

D6F-01A1/02A1

(1) Make sure that the tube connections to the barb joints are airtight. Any leaks from these joints will result in incorrect measure-ments.

(2) Use M3 panhead screws to install the Sensor, and tighten them to a maximum torque of 0.59 N·m.

● **Operating Environment**

Do not use the Sensor in the following locations:

 • Locations directly subject to heat radiated from heating equip-ment
 • Locations subject to water or oil
 • Locations subject to direct sunlight
 • Locations subject to intense temperature changes
 • Locations subject to icing or condensation

• Locations subject to excessive vibration or shock

● Countermeasures against Noise

Noise may make it impossible to obtain correct measurements. Consider the following countermeasures.

 • Allow as much space as possible between the Sensor and devices that generates high frequencies (such as high-fre-quency welders and high-frequency sewing machines) or surges.

 • Attach surge absorbers or noise filters to noise-generating devices that are near the Sensor (in particular, equipment with inductance, such as motors, transformers, solenoids, and magnetic coils).

(It also helps to separate pipes and ducts, and to use shielded cables.)

● Power Supply

 • Do not directly solder power supply leads to the connector terminals. Use only the appropriate connectors.

 • Wire with the correct terminal names and polarities. Incorrect wiring will cause failure of internal components.

 • When using a commercially available switching regulator, ground the FG (frame ground) and G (ground) terminals.

RoHS Directive

D6F @-A1

The RoHS mark is displayed on the packing of products for which the six substances banned by the RoHS Directive have been abolished (both in processing and in the electronic components

mounted to the PCBs).

*   RoHS marking may be terminated if it is later determined that parts that were previously treated as RoHS compliant are not compliant due to circum-stances at the supplier of the parts.

● RoHS Compliance Criteria

The following standards are used to determine RoHS compliance for the six banned substances.

(Items to which the RoHS Directive is not applicable are not given.)

 • Lead: 1,000 ppm max.

 • Hexavalent chromium: 1,000 ppm max.

 • Mercury: 1,000 ppm max.

 • PBB: 1,000 ppm max.

 • Cadmium: 100 ppm max.

 • PBDE: 1,000 ppm max.

A.14. Accelerometer- Kionix Evaluation board-KXPB5-2050-Data sheet
Product Description

The KXPB5-2050 is a Tri-axis, silicon micromachined accelerometer with a full-scale output range of +/-2g (19.6 m/s/s).   The sense element is fabricated using Kionix's proprietary plasma micromachining process technology. Acceleration sensing is based on the principle of a differential capacitance arising from acceleration-induced motion of the sense element, which further utilizes common mode cancellation to decrease errors from process variation, temperature, and environmental stress. The sense element is hermetically sealed at the wafer level by bonding a second silicon lid wafer to the device using a glass frit. A separate ASIC device packaged with the sense element provides signal conditioning and self-test. The accelerometer is delivered in a 5 x 3 x 0.9 mm LGA plastic package operating from a 2.5 – 5.25V DC supply.

There are 4 factory programmable modes of operation for the KXPB5:

Mode 00 – The three outputs (X, Y, Z) are read through the **digital** SPI interface, which is also used to command Selftest and Standby Mode. The digital I/O pads are powered from a separate power pin, and will interface to 1.8V logic.

Mode 01 – The three outputs (X, Y, Z) are provided on three **analog** output pins. The KXPB5 also features an integrated **3-channel multiplexer** (X, Y, Z). The Enable pin must be **high** for normal operation and **low** for power shutdown.

Mode 10 – The three outputs (X, Y, Z) are provided on three **analog** output pins. The KXPB5 also features an integrated **4-channel multiplexer** (X, Y, Z, Aux In). The Enable pin must be **high** for normal operation and **low** for power shutdown.

Mode 11 – The three outputs (X, Y, Z) are provided on three **analog** output pins. The KXPB5 also features an integrated **4-channel multiplexer** (X, Y, Z, Aux In). The Enable pin must be **low** for normal operation and **high** for power shutdown.

The KXPB5-2050 is factory programmed to be in MODE 11.

Functional Diagram

Mode 11
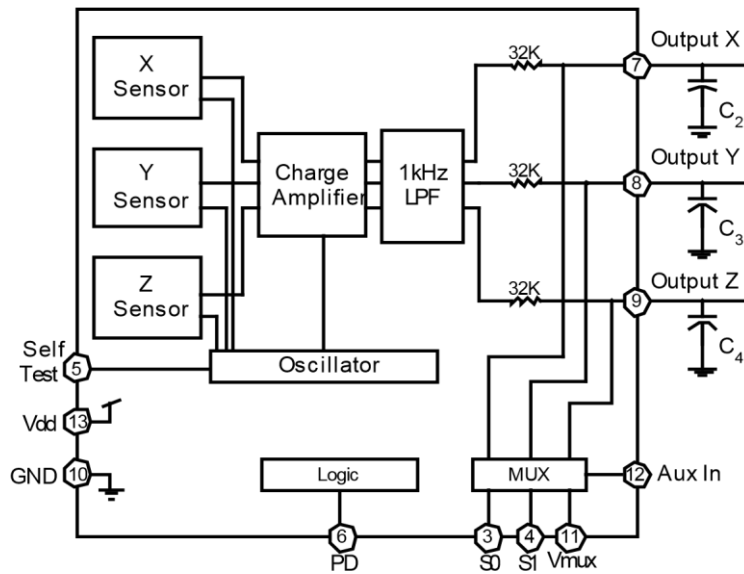
Product Specifications

Table 1. Mechanical

Analog (specifications are for operation at 3.3V and T = 25C unless stated otherwise)

Parameters	Units	Min	Typical	Max
Operating Temperature Range	ºC	-40	-	85
Zero-g Offset	V	1.559	1.65	1.741
Zero-g Offset Variation from RT over Temp.	mg/ºC		0.6	
Sensitivity	mV/g	640	660	680
Sensitivity Variation from RT over Temp.	%/ºC		0.005	
Offset Ratiometric Error (V_{dd} = 3.3V ± 5%)	%		0.3	1.5
Sensitivity Ratiometric Error (V_{dd} = 3.3V ± 5%)	%		0.4	1.5
Self-Test Output change on Activation	g	2.2 0.7	2.7 (xy) 1.1 (z)	3.2 1.6
Non-Linearity	% of FS		0.1	
Cross Axis Sensitivity	%		2	
Noise Density (on filter pins)	µg / √Hz		175	

Table 2. Electrical

Analog

(specifications are for operation at 3.3V and T = 25C unless stated otherwise)

Parameters		Units	Min	Typical	Max
Supply Voltage (V_{dd})	Operating	V	2.5	3.3	5.25
Current Consumption	Operating (full power)	µA	300	500	700
	Standby	µA	-	0.0012	
Input Low Voltage		V			0.2 * V_{dd}
Input High Voltage		V	0.8 * V_{dd}		
Analog Output Resistance(R_{out})		kΩ	24	32	40
Power Up Time[1]		ms		1	
Bandwidth (-3dB)[2]		Hz	800	1000	1200

Notes:

1. Power up time can also be determined by 5 times the RC time constant of the optional user defined low pass filter.

2. Internal 1 kHz low pass filter. Lower frequencies are user definable with external capacitors.

Table 3. Environmental

Parameters		Units	Min	Typical	Max
Supply Voltage (V_{dd})	Absolute Limits	V	-0.3	-	7.0
Operating Temperature Range		ºC	-40	-	85
Storage Temperature Range		ºC	-55	-	150
Mech. Shock (powered and unpowered)		g	-	-	5000 for 0.5ms
ESD	HBM	V	-	-	3000

Caution: ESD Sensitive and Mechanical Shock Sensitive Component, improper handling can cause permanent damage to the device.

This product conforms to Directive 2002/95/EC of the European Parliament and of the Council of the European Union (RoHS). Specifically, this product does not contain lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB), or polybrominated diphenyl ethers (PBDE) above the maximum concentration values (MCV) by weight in any of its homogenous materials. Homogenous materials are "of uniform composition throughout."

This product is halogen-free per IEC 61249-2-21. Specifically, the materials used in this product

HF contain a maximum total halogen content of 1500 ppm with less than 900-ppm bromine and less than 900-ppm chlorine.

Soldering

Soldering recommendations available upon request or from www.kionix.com.

Application Schematic
Mode 11
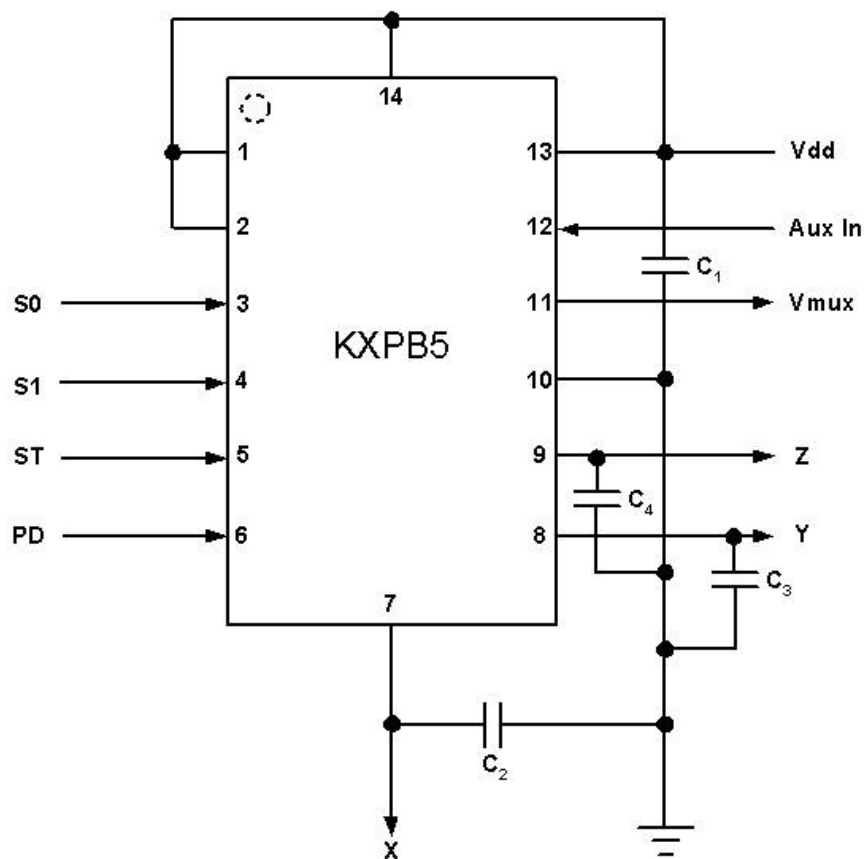
Table 4. KXPB5 Pad Descriptions

Pad	Name	Description
1	Vdd	The power supply input. Decouple this pin to ground with a 0.1uF ceramic capacitor (C_1).
2	NC	Not Connected Internally (can be connected to Vdd)
3	S0	MUX selector 0 (See Output Select Table). Connect to Vdd or Ground if not used.
4	S1	MUX selector 1 (See Output Select Table). Connect to Vdd or Ground if not used.
5	ST	Self Test: **High** - Device is in self-test mode; **Low** - Normal operation
6	PD	Power shutdown: **Low** - Normal operation; **High** - Device is in standby, power down mode
7	X Output	Analog output of the x-channel. Optionally, a capacitor (C_2) placed between this pin and ground will form a low pass filter.

8	Y Output	Analog output of the y-channel. Optionally, a capacitor (C_3) placed between this pin and ground will form a low pass filter.
9	Z Output	Analog output of the z-channel. Optionally, a capacitor (C_4) placed between this pin and ground will form a low pass filter.
10	GND	Ground
11	Vmux	Multiplexed analog output. Float if the multiplexer is not used.
12	Aux In	Auxiliary input for multiplexer. Connect to Vdd or Ground if not used.
13	Vdd	The power supply input. Decouple this pin to ground with a 0.1uF ceramic capacitor (C_1).
14	Vdd	The power supply input. Decouple this pin to ground with a 0.1uF ceramic capacitor (C_1).

USING THE MULTIPLEXED OUTPUT OF THE KXPB5

Multiplexer Data Select

The KXPB5 features an integrated 4-channel multiplexer. This feature reduces system MCU requirements to only 1 ADC and 2 digital I/O's. The KXPB5 uses two select inputs (S0, S1) to control the data flow from Vmux. When a microprocessor toggles the select inputs, the desired output is attained based on the select table. Note that logic 0 is GND and logic 1 is Vdd.

S1	S0	Vmux
0	0	X Output
0	1	Y Output
1	0	Z Output
1	1	Aux In

Output Select   Table

Data Sampling Rate

When operating in its multiplexed mode, the KXPB5 has the ability to achieve very high data sampling rates. Internally, the sensor elements (X, Y, and Z) are sequentially sampled in a "round robin" fashion at a rate of 32 kHz per axis. Note that this is a differential capacitance sampling of each sensor element, which stores an analog voltage on the filter cap for each axis. Combine this high sensor element sampling rate with the short 5 µs settling time of the integrated multiplexer, and the user can achieve a performance very close to that of the 3 separate analog outputs. This is more than sufficient to eliminate any aliasing in the final application since the KXPB5 will be operating with a typical bandwidth of ~50Hz and a maximum of 1000Hz.

Test Specifications

! *Special Characteristics:*

These characteristics have been identified as being critical to the customer. Every part is tested to verify its conformance to specification prior to shipment

.

Table 5. Test Specifications

Parameter	Specification	Test Conditions
Zero-g Offset @ RT	1.65 +/- 0.0911 V	25C, Vdd = 3.3 V
Sensitivity @ RT	660 +/- 20 mV/g	25C, Vdd = 3.3 V
Current Consumption -- Operating	300 <= Idd <= 700 uA	25C, Vdd = 3.3 V

Package Dimensions and Orientation

3 x 5 x 0.9 mm LGA
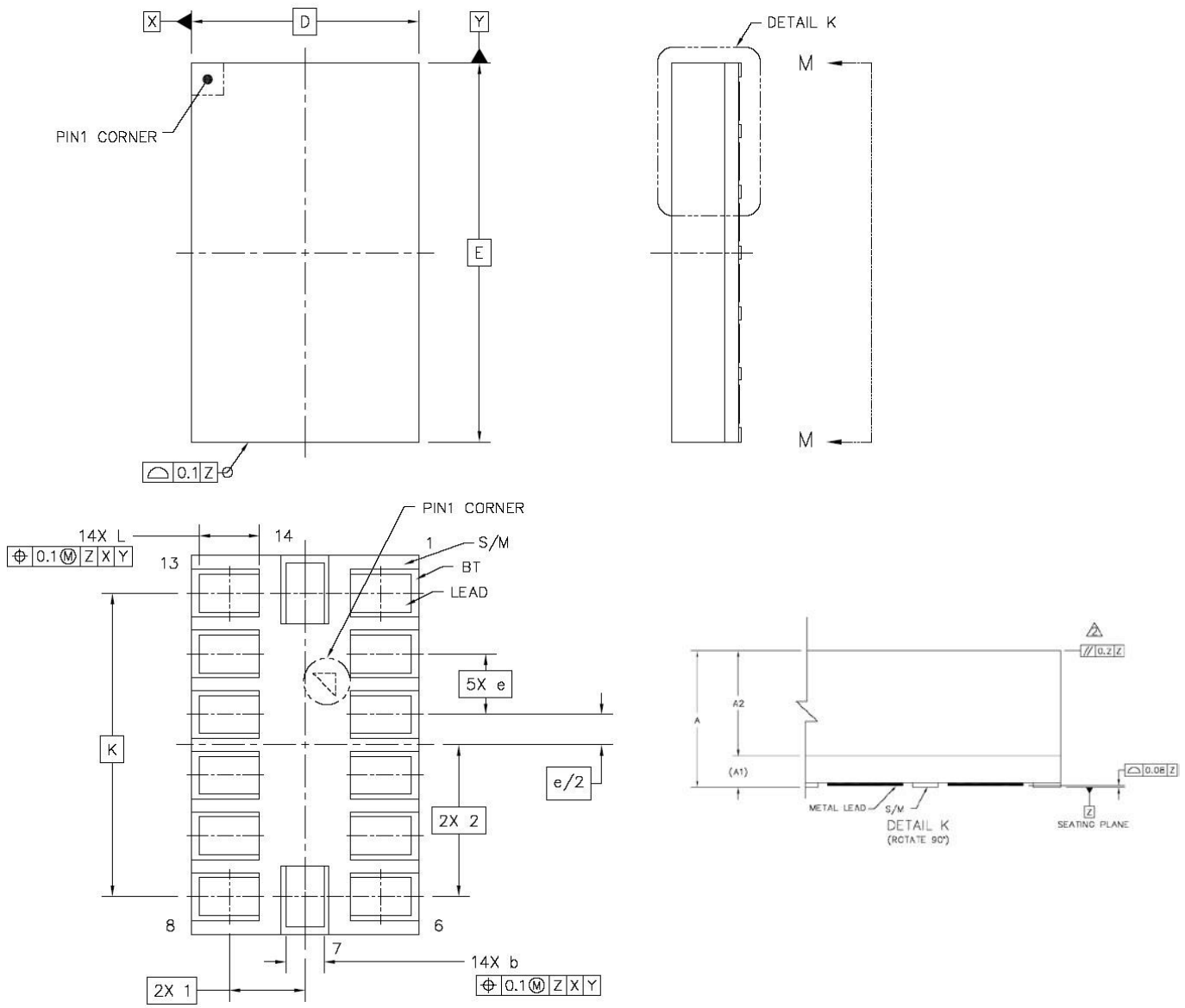
Dimension	mm			inch		
	Min	Nom	Max	Min	Nom	Max
A	---	0.91	1.0	---	0.036	0.039
A1		0.21 REF			0.008 REF	

A2	0.66	0.7	0.74	0.026	0.028	0.029
b	0.45	0.5	0.55	0.018	0.020	0.022
D	2.8	3.0	3.2	0.110	0.118	0.126
E	4.8	5.0	5.2	0.189	0.197	0.205
K	3.9	4.0	4.1	0.153	0.157	0.161
e	0.78	0.8	0.82	0.030	0.031	0.032
L	0.75	0.8	0.85	0.029	0.031	0.033

All dimensions and tolerances conform to ASME Y14.5M-1994

Orientation
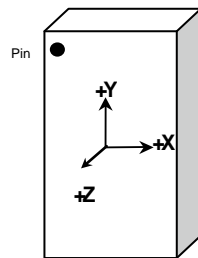
When device is accelerated in +X, +Y or +Z direction, the corresponding output will increase.

Static X/Y/Z Output Response versus Orientation to Earth's surface (1-g):

Position	1	2	3	4	5	6
Diagram					Top / Bottom	Bottom / Top
X	1.65 V	2.31 V	1.65 V	0.99 V	1.65 V	1.65 V
Y	2.31 V	1.65 V	0.99 V	1.65 V	1.65 V	1.65 V
Z	1.65 V	1.65 V	1.65 V	1.65 V	2.31 V	0.99 V
X-Polarity	**0**	**+**	**0**	**-**	**0**	**0**
Y-Polarity	**+**	**0**	**-**	**0**	**0**	**0**
Z-Polarity	**0**	**0**	**0**	**0**	**+**	**-**

(1-g)
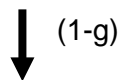
Earth's Surface

Revision History

REVISION	DESCRIPTION	DATE
1	Initial release	27-Oct-2006
2	Revised standby current spec and pin descriptions	19-Mar-2007
3	Changed to new format & revisioning.	09-Sep-2009

A.15. BLS rescuers CPR simulated performances quality measures and quality indices between the no-feedback and feedback groups for two thumb technique chest compression at the study and experiment stage

Table 1:BLS rescuers CPR simulated performances quality measures and quality indices between the no-feedback and feedback groups for two thumb technique chest compression at the study and experiment stage

CPR Quality Measures	Continous Chest Compression only				5 Initial rescue breaths and CC only				5 Initial rescue breaths and 15:2			
	No Feedback Group	Feedback Group	Mean Difference	P-value	No-Feedback Group	Feedback Group	Mean Difference	P-value	No-Feedback Group	Feedback Group	Mean Difference	P-value
Chest Compression Depths												
Mean Compression depth (mm)	40±4.7	41±1.2	-1	0.4	40.4±4.3	40±1.5	0.4	0.32	40±3.8	40.6±1.4	0.6	0.67
Median Compression depth (mm)	42.4 [37, 44]	40.8 [40, 42]		0.36	41.2 [38, 43]	40 [40, 41]		0.37	40.5 [39, 44]	40 [39, 42]		0.68
Compression Depth quality index (>=35-43 mm)/(%)	38.1 [10, 60]	85.4 [78, 90]		<0.0001	43.4 [29, 65]	81.4 [76, 88]		<0.0001	45.1 [35, 71]	80.1 [78, 85]		<0.0001
Under compression (<35 mm)/(%)	38.2	12.8		<0.0001	36	17.2		<0.0001	30.9	16.3		<0.0001
Over compression (>43mm)/(%)	23.7	1.8		<0.0001	20.6	1.4		<0.0001	24	3.6		<0.01
Chest Release Forces												
Mean release force (kg)	2.2±0.8	1.3±0.7	1.1	<0.001	2.1±0.9	1.4±0.7	0.7	<0.01	2±0.9	1.45±0.7	0.55	<0.05
Median release force (kg)	2.07 [1.7, 2.8]	1.0 [0.9, 2]		<0.01	2.5 [1.5, 2.7]	1.3 [1, 2]		<0.001	2.1 [1.7, 2.5]	1.4 [1.2, 2.2]		<0.05
Release force quality index (<2.5kg)/(%)	45.4 [0.9, 2]	89.6 [80, 97]		<0.001	56.1 [43, 91]	87.1 [78, 96]		<0.001	58.1 [56, 84]	77.7 [72, 88]		<0.001
Complete Release force index (<0.5kg)/(%)	4.2	24		<0.0001	7.9	29		<0.0001	9.8	18.9		<0.0001
Chest Compression Rates												
Mean compression rate/min	136±38	110±6	26	<0.01	135±35	109±6	26	<0.01	142±38	107±6.4	35	<0.0001
Median compression rate/min	140 [100, 171]	108 [104, 116]		<0.001	131 [99, 165]	107 [105, 116]		<0.001	155 [99, 176]	105 [102, 112]		<0.0001
Compression rate quality index(100-120/min)/%	9.3 [0, 35]	80.5 [74, 88]		<0.001	10.9 [0, 24]	80.5 [67, 83]		<0.001	13.7 [0, 36]	77.6 [64, 80]		<0.0001
Compression rate-Too fast (>120/min)/%	66.4	4.8		<0.0001	63.6	3.2		<0.0001	52.7	13.3		<0.0001
Compression rate-Too slow (<100/min)/%	24.3	14.7		0.36	25.5	16.3		0.24	33.6	9.1		<0.001
Compression Duty Cycles												
Mean Duty cycle (%)	55±5.6	44.7±3.5	10.3	<0.0001	56.3±5.9	45.4±3.9	10.9	<0.0001	55.7±5.2	46.5±3.5	9.2	<0.0001
Median Duty cycle (%)	53 [52, 57]	42.9 [42, 45]		<0.0001	55.3 [53, 59]	43.6 [42, 46]		<0.0001	54 [51, 60]	44.9 [43, 49]		<0.0001
Duty cycle quality index (30-50%)/%	15.5 [2, 33]	87.4 [68, 97]		<0.0001	16.4 [2, 28]	85.1 [66, 98]		<0.0001	18.5 [3, 31]	79.2 [67, 94]		<0.0001
Prolonged DC (>50%)/%	84.4	12.6		<0.0001	83.6	14.9		<0.0001	81.4	20.8		<0.0001
Rescue breath mean	0±0	0±0	0	1	0.88±0.33	1±0	0.12	0.13	4.2±1.6	6.1±1.5	1.9	<0.001

CPR mean quality measures are presented as mean ± standard deviation. Median and quality indices are presented as median measures (interquartile range).

Difference between feedback and no feedback groups are presented as mean difference (95% confidence interval). P-values are calculated using two-sided independent samples Student's T test.

A.16. CPR performance changes in simulated chest compression duty cycle quality by 'new method' measures and quality indices of between the BLS no-feedback and feedback groups

Table 2:CPR performance changes in simulated chest compression compression duty cycle quality by 'new method' measures and quality indices of between the no-feedback and feedback groups for two thumb technique chest compression at the study and experiement stage-experiment stage-BLS resusciators

CPR Quality Measures	Continous Chest Compression only				5 Initial rescue breaths and CC only				5 Initial rescue breaths and 15:2			
	No Feedback Group	Feedback Group	Mean Difference	P-value	No-Feedback Group	Feedback Group	Mean Difference	P-value	No-Feedback Group	Feedback Group	Mean Difference	P-value
Compression Duty Cycles												
Mean Duty cycle (%)	47.6±8.7	44.6±4.9	3	0.22	47±7	44.5±4.4	2.5	0.21	46.2±7.9	42.5±5.3	3.7	0.11
Median Duty cycle (%)	49.4[46, 52]	46.9[42, 48]		0.35	48.5[48, 51]	46.2[40, 49]		0.27	48.4[44, 50]	48.4[40, 47]		0.14
Duty cycle quality index (30-50%)/%	38.4[23, 73]	84.9[78, 91]		<0.0001	41.9[29, 66]	86.4[60, 86]		<0.0001	32.4[18, 65]	84.3[62, 85]		<0.0001
Prolonged DC (>50%)/%	61.6	15.1		<0.0001	58.5	13.6		<0.0001	67.6	15.7		<0.0001

CPR mean quality measures are presented as mean ± standard deviation. Median and quality indices are presented as median measures (interquartile range). P-values are calculated using two-sided independent samples Student's T test.

Difference between feedback and no feedback groups are presented as mean difference (95% confidence interval).

 A.17. Lay rescuers CPR simulated performances quality measures and quality indices between the no-feedback and feedback groups for two thumb technique chest compression at the study and experiment stage

Table 3: Lay rescuers CPR simulated performances quality measures and quality indices between the no-feedback and feedback groups for two thumb technique chest compression at the study and experiment stage

CPR Quality Measures	Continous Chest Compression only				5 Initial rescue breaths and CC only				5 Initial rescue breaths and 15:2			
	No Feedback Group	Feedback Group	Mean Difference	P-value	No-Feedback Group	Feedback Group	Mean Difference	P-value	No-Feedback Group	Feedback Group	Mean Difference	P-value
Chest Compression Depths												
Mean Compression depth (mm)	40±3.5	41±1.5	1	0.26	40.5±4	41±1	0.5	0.52	41±4	42±1	1	0.29
Median Compression depth (mm)	40 [38, 42]	41 [40, 42]		0.33	42 [39, 43]	41 [40, 42]		0.33	42 [40, 44]	42 [42, 43]		0.41
Compression Depth quality index (>=35-43 mm)/(%)	42.3 [41, 85]	88 [84, 98]		<0.001	39 [41, 48]	91.7 [86, 96]		<0.0001	36.8 [34, 81]	84.9 [74, 91]		<0.001
Under compression (< 35 mm)/(%)	37.5	9.7		<0.0001	41	5.7		<0.0001	39.9	10.1		<0.0001
Over compression (>43mm)/(%)	20.2	2.3		<0.001	20	2.6		<0.0001	23.3	5		<0.0001
Chest Release Forces												
Mean release force (kg)	3.6±0.7	2±0.4	1.6	<0.0001	4±4	2.1±0.4	2.9	<0.05	3.7±2.1	2.1±0.5	1.6	<0.001
Median release force (kg)	3.7 [3.1, 4]	2.1 [2, 2.4]		<0.0001	3.4 [3.1, 4.7]	2.2 [2.1, 2.5]		<0.01	3.4 [3.1, 4.2]	2.1 [1.9, 2.4]		<0.001
Release force quality index (<2.5kg)/(%)	20.1 [14, 28]	74.9 [59, 76]		<0.05	32.1 [21, 45]	73 [66, 78]		<0.05	28.6 [2, 30]	80.9 [64, 88]		<0.01
Complete Release force index (<0.5kg)/(%)	1.4	47		<0.0001	2.1	46		<0.0001	2.4	41		<0.0001
Chest Compression Rates												
Mean compression rate/min	101±46	107±11.5	6	0.58	106±51	107±10	1	0.93	98±40	105±11	7	0.46
Median compression rate/min	86 [64, 124]	101 [101, 114]		0.41	83 [69, 145]	102 [101, 114]		0.34	96 [72, 118]	100 [97, 115]		0.79
Compression rate quality index(100-120/min)/%	12.2 [4, 17]	75.2 [63, 81]		<0.01	13 [4, 24]	77 [61, 79]		<0.01	11.6 [6, 15]	81 [55, 87]		<0.001
Compression rate-Too fast (>120/min) /%	42	23.3		<0.01	47	18.5		<0.01	45.4	12		<0.001
Compression rate-Too slow (<100/min)/%	45.8	1.5		<0.001	40	4.5		<0.01	43	7		<0.0001
Compression Duty Cycles												
Mean Duty cycle (%)	73±6	60±5	13	<0.0001	72±6	60±4	12	<0.0001	69±4	59±5	10	<0.0001
Median Duty cycle (%)	77 [68, 78]	62 [56, 63]		<0.0001	73 [68, 76]	61 [57, 63]		<0.0001	69 [67, 71]	61 [55, 63]		<0.0001
Duty cycle quality index (30-50%)/%	16.1 [0, 5]	36.8 [18, 28]		<0.001	12.8 [8, 34]	34.7 [10, 31]		<0.001	22 [0, 10]	40.8 [14, 39]		<0.001
Prolonged DC (>50%)/%	83.9	63.1		<0.01	87.2	65.3		<0.001	78	59.1		<0.001
Rescue breath mean	0±0	0±0		1	1±0	1±0	0	1	3.9±1.4	5.6±0.9	1.7	<0.01

CPR mean quality measures are presented as mean ± standard deviation. Median and quality indices are presented as median measures (interquartile range).

Difference between feedback and no feedback groups are presented as mean difference (95% confidence interval). P-values are calculated using two-sided independent samples Student's T test.

A.18. CPR performance changes in simulated chest compression duty cycle quality by 'new method' measures and quality indices of between the lay no-feedback and feedback groups

Table 4:CPR performance changes in simulated chest compression compression duty cycle quality by 'new method' measures and quality indices of between the no-feedback and feedback groups for two thumb technique chest compression at the study and experiement stage-Lay resuscitators

CPR Quality Measures	Continous Chest Compression only				5 Initial rescue breaths and CC only				5 Initial rescue breaths and 15:2			
	No-Feedback Group	Feedback Group	Mean Difference	P-value	No-Feedback Group	Feedback Group	Mean Difference	P-value	No-Feedback Group	Feedback Group	Mean Difference	P-value
Compression Duty Cycles												
Mean Duty cycle (%)	53.7±8.4	46±6	7.7	<0.0001	52.9±10	46.5±6.5	6.4	<0.05	52.7±7.7	47±7.6	5.7	<0.05
Median Duty cycle (%)	52.9 [50,56]	45.2 [43,49]		<0.0001	51.5 [50,55]	42.2 [42,52]		<0.05	51.2 [48,55]	46 [42,53]		<0.05
Duty cycle quality index (30-50%) %	42.1 [21,51]	81.6 [72,91]		<0.0001	32.7 [7,57]	82.5 [73,93]		<0.0001	37.7 [33,66]	77.2 [71,86]		<0.0001
Prolonged DC (>50%) %	57.9	18.4		<0.0001	67.3	17.5		<0.0001	62.3	22.8		<0.0001

CPR mean quality measures are presented as mean ± standard deviation. Median and quality indices are presented as median measures (interquartile range).