Development and validation of a feedback device suitable for resuscitation of premature neonates

by
Debbie Lee Lloyd

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Supervisor:
Dr Dawie van den Heever

Co-supervisor:
Dr Kiran Hamilton Dellimore

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Declaration

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Abstract

Neonatal cardiopulmonary resuscitation (NCPR) is an important life-saving intervention. Clinicians follow the guidelines which recommend using the two-thumb (TT) or two-finger (TF) method to compress the neonates' chest to one-third of their anterior-posterior diameter (APD) at a 3:1 compression to ventilation ratio. Ineffective compressions can result in an increased mortality and morbidity rate for neonates.

Clinicians have difficulty delivering effective and consistent chest compressions (CCs) during NCPR due to the high number of actions (120 events per minute), the lack of practice due to the limited number of occurrences and poor fidelity of infant training manikins in replication of infant thoracic properties. There is therefore a need for a tool to assist the clinician in performing correct and consistent CCs.

This report presents the design, fabrication and implementation of a diagnostic tool to guide the clinician on the CC rate using a metronome and on the compression depth using LED feedback. The device is battery powered and records the depth and force during CC for post processing. The need for such a device was investigated during this project by recruiting an experienced neonatal resuscitation programme (NRP) certified clinician to perform tests on five, 6-month old white New Zealand rabbits (weight = 2.74 ± 0.27 *kg*, APD = 88.4 ± 2.7 *mm*). The fidelity of the CCs during these tests was assessed according to the target depth (one-third of the APD) and according to the estimated target depth range for 'wet' neonates (17.5 to 22.5 *mm*).

The results from the target depth fidelity analysis show that 97%, 2% and <1% of the CCs were too shallow, correct and too deep, respectively for all CCs according to target depth. The results for the target depth range for 'wet' neonates' fidelity analysis showed that 79%, 17% and 4% of all compressions were too shallow, correct and too deep, respectively. The analysis was also performed for individual CC segments which are defined as three consecutive compressions. A segment is deemed to be correct if two out of the three compressions are within the target depth range. The segment fidelity using one-third APD was 89%, 10% and <1% for too shallow, correct and too deep, respectively.

These results prove that the clinician is finding it difficult to meet the target depth and that a large percentage of the CCs are too shallow (ineffective CC) according to the APD and 'wet' neonate range. The segment analysis also shows that the CCs are inconsistent and very few consecutive CCs are correct and within the target range.

The inconsistent and ineffective compressions performed by an experienced and trained clinician validate the need for a NCPR feedback tool for 'wet' neonates.

A force-depth analysis was completed and the effect of the compression and ventilation method was examined. The mean force results showed no clear difference between compression methods, however, the mean depth for the TT method was higher than that of the TF method. The compression method used also affected the force-deformation curve. The ventilation method, however, had no effect on the measured CC depth and force or shape of the force-deformation curve.

A key finding of this study is the ineffective and inconsistent compressions performed by an experienced and trained clinician. The CCs were mostly too shallow regardless of the compression or ventilation method. It is also clear that there is no real, significant, difference between the TT and TF method with regards to fidelity or effectiveness (compression depth and force relationship).

Uittreksel

Neonatale kardiopulmonêre resussitasie (NKPR) is ’n belangrike lewensreddende intervensie. Geneeshere volg die riglyne wat aanbeveel dat die twee-duim (“two-thumb” (TT)) of twee-vinger (“two-finger” (TF)) metode gebruik word om pasgeborenes se borskas te druk tot een-derde van die anterior-posterior deursnee (APD) teen ’n 3:1 drukking tot ventilasie verhouding. Oneffektiewe drukking kan lei tot verhoogde mortaliteits- en morbiditeitskoerse vir pasgeborenes.

Geneeshere sukkel om effektiewe en konstante borsdrukke te gee tydens NKPR a.g.v. die hoë getal drukke wat gegee moet word (120 per minuut), die gebrek aan oefening a.g.v. die beperkte aantal kere wat dit nodig is en ook die swak getrouheid tot die werklikheid van baba oefenmodelle se toraks-eienskappe. Daar is dus ’n soeke na ’n manier om die geneeshere te help om borsdrukke reg en konstant toe te pas.

Hierdie verslag stel die ontwerp, vervaardiging en implementasie voor van ’n diagnostiese instrument om die geneesheer te lei deur die gebruik van ’n metronoom vir die druktempo en LED terugvoer vir die drukdiepte. Die instrument is battery-aangedrewe en registreer die diepte en krag van die drukke vir verwerking na die tyd. Die behoefte vir so ’n instrument is ondersoek tydens hierdie projek deur ’n ervare neonatale resussitasie-program (NRP) gesertifiseerde geneesheer te werf om toetse op vyf 6-maande oue wit Nieu-Seeland konyne (gewig = 2.74 ± 0.27 *kg*, APD = 88.4 ± 2.7 *mm*) uit te voer. Die getrouheid van die borsdrukke is tydens hierdie toetse geassesseer volgens die teiken-diepte (een derde APD) en ook volgens die geskatte omvang van “nat” pasgeborenes (17.5 tot 22.5 *mm*).

Die resultate van die teiken-diepte getrouheids-analise wys dat 97 %, 2% en <1% van die borsdrukke onderskeidelik te vlak, korrek en te diep was vir alle borsdrukke volgens teiken-diepte. Die resultate vir die omvang van “nat” pasgeborenes se getrouheids-analise het onderskeidelik gewys dat 79%, 17% en 4% van alle borsdrukke te vlak, korrek en te diep was. Die analise is ook uitgevoer vir individuele borsdruk-segmente wat gedefinieer is as drie agtereenvolgende drukke. ’n Segment is as korrek beskou as twee van die drie drukke binne die teiken-diepte was. Die segment-getrouheid volgens die een derde APD was onderskeidelik 89%, 10% en <1% te vlak, korrek en te diep.

Die resultate wys dat die geneesheer dit moeilik vind om die teiken-diepte te haal en dat ’n groot persentasie van die drukke te vlak is (oneffektiewe borsdrukke) volgens die APD en “nat” pasgeborenes-omvang. Die segment-analise wys ook dat die borsdrukke inkonsekwent is en dat baie min opeenvolgende borsdrukke korrek en binne die teiken-omvang is.

Die inkonsekwente en oneffektiewe borsdrukke wat uitgevoer word deur ’n ervare en opgeleide geneesheer toon dat daar ‘n behoefte is vir ’n NKPR-terugvoer instrument vir “nat” pasgeborenes.

’n Krag-diepte analise is uitgevoer en die effek van die borsdrukke en die ventilasie-metode is ondersoek. Die gemiddelde krag-resultate het geen duidelike verskil gewys tussen druk-metodes nie, maar die gemiddelde diepte van die TT-metode was hoër as dié van die TF-metode. Die druk-metode wat gebruik word beïnvloed ook die krag-vervormingskurwe. Die ventilasie-metode het egter geen effek op die krag, diepte of vorm van die krag-vervormingskurwe nie.

’n Belangrike bevinding van die projek is die oneffektiewe en inkonsekwente drukke uitgevoer deur ’n ervare en gesertifiseerde geneesheer. Die borsdrukke was meestal te vlak, ongeag die druk- of ventilasie-metode. Dit is duidelik dat daar geen werklike, beduidende verskil is tussen die TT-metode en TF-metode met betrekking tot die getrouheid of effektiwiteit (druk diepte en krag verhouding) nie.

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Nomenclature

Variables

F	Force (N)
P	Pressure (Pa)
V	Volumetric flow rate (m^3/s)
g	Gravitational acceleration (m^2/s)
h	Height (m)
k	Spring constant (N/m)
δ	Deflection (m)
ρ	Density (kg/m^3)

Abbreviations

AEC	Animal Ethics Council
AHA	American Heart Association
APD	Anterior-Posterior Diameter
BP	Blood Pressure
BPM	Beats per minute
CAD	Computer Aided Design
CC	Chest Compression
CPR	Cardiopulmonary Resuscitation
EEPROM	Electrically Erasable Programmable Read-only Memory
ERC	European Resuscitation Council
GDL	Gemeenschappelijk Dierenlaboratorium
HR	Heart Rate
IEC	International Electrotechnical Commission
IRB	Institutional Review Board
ISO	International Organization for Standardization
MV	Minute Volume

MRI	Magnetic Resonance Imaging
NLS	Neonatal Life Support™
NCPR	Neonatal Cardiopulmonary Resuscitation
NICU	Neonatal Intensive Care Unit
NRP	Neonatal Resuscitation Program
PCB	Printed Circuit Board
PEEP	Positive End-Expiratory Pressure
PIP	Peak Inspiratory Pressure
PLA	Polylactic Acid
RAM	Random-Access Memory
TF	Two-Finger
TT	Two-Thumb
UNHCR	United Nations High Commissioner for Refugees

Terms

Adult	Person after puberty
Child	Between one year and puberty
Infant	A child under one year
Neonate	A child in the first 28 days of life
Newborn	A child immediately after birth
PEEP	A method of ventilation in which airway pressure is maintained above atmospheric pressure at the end of exhalation by means of a mechanical impedance.
PIP	Highest proximal airway pressure reached during inspiration
Premature	Births before full term of 38 weeks gestation
Tidal volume	Amount of air which enters the lungs during normal inhalation at res
‘wet’ neonate	The neonate undergoing the transition from a maternally supported circulation, and ventilation to two closed circulations, pulmonary aeration and clearing the airway.

CHAPTER 1: Introduction

This thesis deals with the introduction, proof of concept and initial validation of a technical innovation. However, to fully appreciate the scope and positioning of the innovation, it is relevant that the reader be offered sufficient (medical) background: this will set the scene as it were, challenge and potentially surprise the reader, and allow the best understanding of the goals of this thesis. To this end, Chapter 1 includes a number of paragraphs geared towards this instruction.

1.1 Background

1.1.1 Neonatal cardiopulmonary resuscitation

Birth is deemed to be a natural process. However, morbidity and mortality directly prior to birth, during the birth process, or immediately after birth is a frequent occurrence [1]. These occurrences are typically traumatizing, and may in part be avoided or corrected for with relatively simple interventions, directly impacting the infant mortality rate.

South Africa has a large incidence of births before full term of 38 weeks [2]. These are termed to be ‘premature’. These neonates contribute strongly to the high infant morbidity and mortality rates in South Africa. Morbidity may be expressed as hypoxic (cerebral) damage, or pulmonary complications. Mortality results if the lungs are so underdeveloped that they cannot be inflated and diffusion of oxygen and carbon dioxide are inadequate to support life. Babies born after 28 weeks gestation age are generally accepted to be viable if medical support and suitable resources are available. An essential aspect in this care is the initial (minutes) of care given to the neonate as it makes the transition from uterine to independent life.

This transition includes the change-over from a maternally supported circulation, and ventilation (lungs not being perfused and being full of fluid) to two closed circulations, pulmonary aeration and clearing the airway. This whole process is called ‘transition’ and the neonate undergoing it, is known as a ‘wet’ neonate. The aeration of the lungs by movement of fluid into the circulation may be difficult if the birth process is protracted or the infant is depressed or premature.

Neonatal cardiopulmonary resuscitation (NCPR) is an important clinical intervention used to save the lives of newborns suffering from difficult transition and showing cardiac and respiratory insufficiency, typically demonstrated with lack of tonus, poor colour, apnea and bradycardia [3]. Pre-term infants require resuscitation more often than term neonates as a result of hypoxia as their lungs are less able to hold aeration; as a complication of the birthing process itself; as a result of insufficient clearing of the airway; non-opening of the lungs after birth,

or later, progressive cardiac failure or shock, secondary to the hypoxia, otherwise known as asphyxial arrest [4]. Once the neonate is able to breathe on its own and its heart is beating normally it is unusual for resuscitation or NCPR to be required [3].

Central to care for this group of 'wet' (premature) neonates is the knowledge that, if the threat of damage is related to transition, a relatively brief, simple, but deceptively demanding short series of manoeuvres are all that is needed to 'kick start' the neonate. The manoeuvres include assessment, clearing the airway, inflating the lungs, manual ventilation and chest compressions (CCs) to move aerated blood from the pulmonary vessels to the coronary arteries.

Surprisingly, current resuscitation techniques are still strongly based on insights, techniques, and technology from the 1960's. These heuristic methods are therefore not supported by current technologies [5]. The quality of compression during NCPR is essential to success since the heart does not store oxygen and no capability for anaerobic metabolism exists. This essential skill is often performed suboptimal, especially in the small, premature, 'wet' neonate, but also in the adult population worldwide. However, developing countries like South Africa, particularly with a higher rate of premature 'wet' neonates and limited resources, suffer more.

Innovative technologies, suitably applied could improve the quality of compression and thereby reduce the infant mortality and morbidity rate. Developing countries have a particular need for technology in this field that is robust, low-cost and easy-to-use to support clinicians in this environment.

1.1.2 Premature neonatal deaths in South Africa

The infant mortality rate is defined as the number of infant deaths between live birth and before reaching the age of one year, per 1000 live born babies. As such, it includes the deaths of neonates.

The South African infant mortality rate has decreased from 47 per 1000 births in 2009 to 34 per 1000 births in 2015 [6], [7]. There was a decline in mortality rate over the past years, however, the rate is still unacceptably high when compared to developed countries such as the Netherlands (3 per 1000 births in 2015) or United States (6 per 1000 births in 2015) and all measures should be taken to ensure that the mortality rate continues to decrease further [7]. Worldwide there are 5 million neonatal deaths that occur annually, of which 19% are due to asphyxia and finally asphyxic arrest [8].

The statistics from 2013 reveal that 35.2% of neonatal deaths in South Africa are due to respiratory and cardiovascular disorders [9]. One method of ensuring a lower mortality rate is to improve the guidelines to treat cardiac arrest in neonates

during or following transition, which does not need to be a prolonged procedure if done correctly and which could significantly reduce morbidity.

The millennium development goal four (MDG4) was implemented to reduce the under-five mortality rate by two-thirds, between 1990 and 2015. The global under-five mortality rate had decreased by more than half from 90 in 1990 to 43 deaths per 1000 live births in 2015 [10]. In 2015 the MDG4 was replaced by sustainable development goal 3 (SDG3) focussing on good health and well-being, including reducing infant mortality. This goal targets, by 2030, to end preventable deaths of newborns and children under the age of five and for all countries to reduce neonatal mortality and under five mortality to at least as low as 12 per 1000 and 25 per 1000 live births, respectively [11]. All these newborn and children under five deaths due to asphyxia would have required NCPR at some stage.

1.1.3 Current resuscitation guidelines

Cardiopulmonary Resuscitation (CPR) has become synonymous with closed-chest resuscitation as propagated by Kouwenhoven in 1960 [12]. It was seen as an advancement of the open-chest techniques which were limited to in-hospital use. It added the already accepted technique of compressions on the sternum to mouth-to-mouth ventilation, with the goal of gaining more time for further interventions. Overtime the specific technique (also known as psycho-motor skills) was expanded to recognize differences in suitable ones for adults versus children and for neonates. Central to the concepts in this thesis is that NCPR works because the heart is being compressed between the sternum and the vertebral column (cardiac pump) to move blood through both circulations.

During CPR external compressions are applied to the sternum to massage the heart (i.e. the left ventricle) and to ensure some blood circulation of about 30% of normal circulation. The compression themselves do not satisfy ventilation needs. The quality of compression (most specifically a suitable depth) during CPR is important and therefore a goal as a professional standard is that 95% of compressions should be in the correct depth range and that 95% of the time compressions should be performed to ensure the best chance of a good outcome [5]. Some other psycho-motor skills known to affect the effectiveness of compression include the rate of compression, compression to relaxation ratio, leaning (incomplete relaxation of pressure on the sternum), positioning of the compression itself and the interaction of compressions with ventilation.

Since the sternum acts like a fulcrum, the distance below the manubrium sterni is an important factor in the force-depth relationship [13]. Interestingly the European and American Resuscitation Guidelines differ slightly in this regard: an acceptable compromise is the use of the middle third of the sternum: time lost to ‘exact’ measuring is now avoided.

One of the most consistent quality indicators for CPR is correct chest compression depth, with inadequate depths causing no flow just as overly deep CCs which cause lower flows than optimal, and induce needless trauma. Getting this right is uniquely difficult.

- **Adult CPR**

According to the 2015 European Resuscitation Council (ERC) Guidelines adult CPR should be performed using a 30:2 compression to ventilation ratio [14]. When applying 30:2 compression to ventilation ratio, the duration of each ventilation is one second with a maximum pause time of five seconds. Alternatively, once an airway device such as an endotracheal tube has been placed, intermittent ventilation can be used where ventilation occurs every six seconds for a maximum of 0.5 seconds between compressions which are not paused. During this second method the clinician compressing is often distracted as it requires additional concentration to ensure the ventilations and compressions are intermittent. During adult CPR the chest compressions (CC) are on the middle to lower half of the sternum to a depth of between 5 and 6 *cm* at a rate of 100-120 min^{-1} when compressing on a hard surface [14]. To reach adequate depths forces of 500 – 800 *N* are required, with chest wall resistance behaving as non-linear springs [15].

- **Paediatric CPR**

As with other aspects in bio-mechanics, CPR in children (before puberty) is different from that in adults. First, children are a far more hybrid (i.e. heterogeneous) group than adults, as chest form alters after birth to puberty (relatively more anterior-posterior diameter changing to more elliptical), chest resistance changes from being very stiff at birth to highly compliant and then decreases again with increasing age. During paediatric CPR, after the 'wet' period during the initial 28 days of life, after 15 compressions, the head is tilted, chin lifted and two effective breaths are given. Compressions and breaths are continued with a 15:2 compression to ventilation ratio, as opposed to 30:2 [16]. During these compressions the middle of the sternum is compressed to one-third of the anterior-posterior diameter (APD) of the chest. The pressure is released completely after each compression and compressions are done at a rate of 100-120 min^{-1}.

For the infant population, the compressions should be performed on the sternum using either the two-thumb (TT) or two-finger (TF) method. The guidelines agree that the optimal compression point is just caudal of the inter-nipple line. The technique of the TT method includes encircling the clinician's hands around the patient's chest and compressing with two thumbs positioned on or next to each other [17]. The TF method is done with two fingers placed just below the inter-nipple line cranio-caudally of each other on the sternum potentially with a second hand (or arm) supporting the back of the infant [17], [18]. In both methods the compression depth should be at least one-third of the APD [16].

The TT-method is currently recommended as the preferred compression method in the 2015 European Resuscitation Council Guidelines for resuscitation [17]. According to studies the two-thumb method is more effective than the two-finger method [19]–[22], i.e. that it is easier for the caregiver to judge depth.

Compressions for children over one year of age should be done using the heel of one hand on the sternum, one finger's breadth above the Xiphisternum. With a straight arm the sternum is compressed to at least one-third the APD or by 5 *cm* [16].

- **The transition of neonates at birth**

During every birth a process known as transition occurs. The most important aspects in this process involve the right circulation and its interaction with the lungs. While oversimplified, the lungs are filled with amniotic fluid during intra-uterine life, which must be aerated, moving the fluid into the pulmonary circulation, while the alveoli must fill with air. The foramen ovale closes as well as the ductus botalli. Crying at birth is the exemplar for intra-thoracic overpressure (i.e., Positive end expiratory pressure, PEEP), driving this process.

However, if labour has been long, the surfactant in the alveoli is absent or insufficient, there has been overt blood loss, or the baby is depressed, these changes may not occur, requiring simple manoeuvres to save the baby's life. In about 1:100 to 10:100 newborns such assistance makes the difference, with typically only brief help needed [21].

The current guidelines for NCPR recommend a 3:1 chest compression (CC) to ventilation ratio for 'wet' neonates, which is a significantly higher ventilation ratio than the recommended ratio of 30:2 for adults or 15:2 for children [17], [23]. The NCPR guidelines are summarized in Appendix A. The TT or TF compression method is used for the transitional neonates with a recommended depth of at least one-third of the APD of the neonates' chest. The 'wet' neonate is a separate physiological and bio-physical entity, with the focus on the change from intra-uterine life to independent (extra-uterine) life. This thesis focusses on resuscitation around this period.

1.1.4 Brief course in neonatal resuscitation

During NCPR the chest compression to ventilation ratio of 3:1 is most commonly used and recommended for 'wet' neonates [17], [24], since during transition the respiratory function is most often the problem. Cardiac function fails or is insufficient due to hypoxia. Note that at birth the normal 'wet' neonate has an oxygen saturation of Ca. 60% (compatible with that during late intra-uterine life). Compressions are initiated when the heart rate is below 60 beats per minute (bpm) after the 'wet' neonate has been ventilated with either 21% or supplementary oxygen for 30 seconds [3], [17], [25]. The depth required during compressions for effective CC is one-third of the APD of the neonate's chest [3], [17].

The process followed prior to chest compressions during NCPR is described in Figure 1.1.

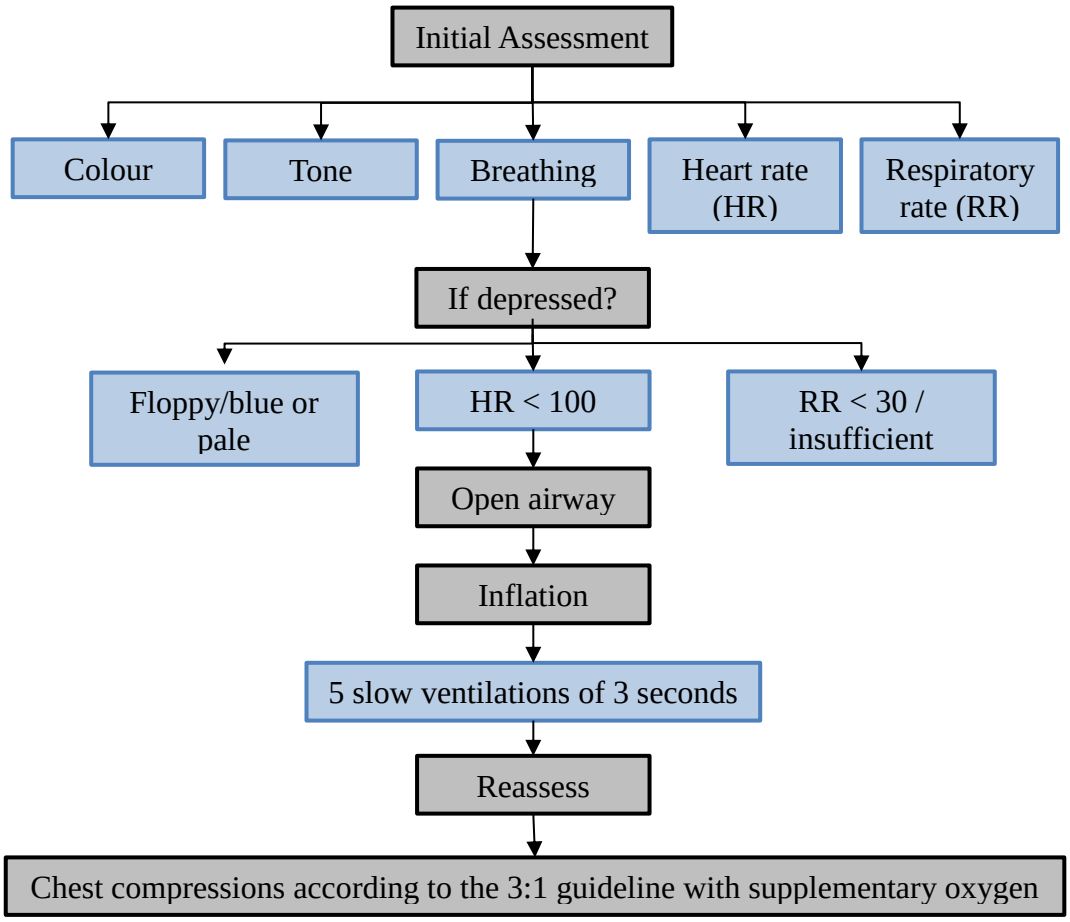

Figure 1.1: Resuscitation at birth leading up to NCPR.

Although little has been published in the literature, the quality of compressions during resuscitation of 'wet' neonates is often suboptimal, and typically too shallow. Studies have illustrated that it is difficult to do good compressions even during adult CPR [26]. It is known that NCPR is needed under stressful conditions and done at a faster rate with more activities per minute and it is therefore realistic to suppose that it is more difficult to do good quality compressions during NCPR than in adult CPR.

Ongoing research is taking place to improve neonatal resuscitation as it is often unsuccessful resulting in persisting rates of newborn deaths [27], [28]. The compression depth and the interaction with respiration is considered the main factors contributing to the quality of compressions according to adult CPR studies [29] and simple, robust and easy-to-use technical support may be very effective in reducing the length of time needed for resuscitation (and thereby post resuscitation care) as well as effectively saving (and potentially improving) the quality of life.

NCPR has had little attention in the past and there is a need for a model for NCPR in 'wet' neonates, resulting in an increased survival rate of 'wet' neonates. Good quality compressions on premature 'wet' neonates seem crucial for success in NCPR. This could be better achieved by using a feedback device for NCPR, specifically designed for (premature) neonates with small APDs.

1.1.5 Technologies and innovations to assist with good quality CPR

While different feedback devices exist for adults (e.g. CPREzy) [30], there are currently no feedback devices commercially available for neonates. The depth of compression in adult feedback is, of course, unsuitable for the highly compliant and smaller (premature) 'wet' neonates. The adult feedback devices are also designed according to the 30:2 compression to ventilation ratio recommended for adults, which is not applicable for the 3:1 compression to ventilation ratio recommended for 'wet' neonates. These devices also tend to be too large and not suitable for the neonatal anterior chest wall [30].

To date, there seems to have been initial work on two devices that have been developed for infants, not necessarily 'wet' neonates, namely the NCPR glove and the ROLA device [22], [31]. Both these devices were tested on manikin models and are currently not in clinical use.

1.2 Motivation

1.2.1 Infant mortality rate

High infant mortality rates worldwide and especially in developing countries, such as South Africa, is, and remains a concern. Reducing the infant mortality rate is the primary goal of many projects including being the project goal of the United Nations High Commissioner for Refugees (UNHCR) [32]. As far as is known, there are no projects focussing on the period of transition and the improvement of NCPR.

The infant mortality rate worldwide is high and was recorded as 32 deaths per 1000 live births in 2015 and 34 deaths per 1000 lives in 2015 in South Africa [7]. There is a high concentration of premature neonatal births in South Africa, which forms a large percentage of the infant mortality rate. NCPR on the premature 'wet' neonates is difficult and therefore the quality of compressions needs to be improved.

1.2.2 Study population

Optimization of the resuscitation of the 'wet' premature neonate, and most specifically the compressions within resuscitation, form the focus for this project as they will benefit most from the improved quality during NCPR, and are most likely to need a period of chest compressions during or just after transition.

The large numbers of this population in developing countries validates the need for a tool to support clinicians during NCPR and ensure better quality compressions are being performed, which will reduce the infant mortality rates [32]. The project set out to design and validate a tool to ensure quality chest compression focussing on the premature 'wet' neonate using an improved target depth control. This population requires NCPR frequently in South Africa and NCPR on premature 'wet' neonates is difficult and is hard to teach and perform correctly as there is no feedback / manikins are poor models of the (premature) 'wet' neonatal chest compliance [33]. A goal should be that professionals perform good quality compressions (i.e. 95% of the compressions are good, 95% of the time).

As discussed previously there are different factors contributing to the quality of compressions with the compression depth and interaction with respiration being the main factor to consider when designing a tool to assist with compression quality as proven during recent studies done on adult CPR [33].

1.2.3 Target compression depth

The target depth for NCPR according to the current guidelines is one-third of the anterior-posterior diameter (APD) of the (premature) 'wet' neonates' chest. The target depth of the tool designed during this project is based on the premature (32 to 39 week old) 'wet' neonate, with a target compression depth which corresponds to 20 *mm*. The acceptable compression depth range around this goal (i.e. acceptable error) for this population is 17.5 to 22.5 *mm*, based on 'expert opinion' of a random sample of experts/instructors of the ERC Newborn Life Support course. The magnetic resonance imaging (MRI) scan of two neonates at term gestation indicate APD heights of 85.7 *mm* (target depth = 28.6 *mm*) and 80.5 *mm* (target depth = 26.8 *mm*), respectively (Appendix B) supporting the chosen range for premature 'wet' neonates. A feedback tool was designed to give feedback to the clinician on the quality of compression depth relative to this target depth.

1.2.4 Tool to improve the quality of compressions

During this project a tool will be designed to support clinicians to improve the quality of compressions focussing on the compression depth achieved. The tool guides clinicians to achieve consistent and effective depths during NCPR on premature 'wet' neonates.

1.3 Objectives

The aims of the project are to:

i. develop an unobtrusive, robust, inexpensive, portable feedback tool that can be used to guide chest compressions (CC) depth (and qualify force) being provided during premature neonatal resuscitation.

ii. validate the use of a NCPR feedback device on an animal model for premature ‘wet’ neonates
iii. describe the force-depth relationship during NCPR on an animal model and extrapolate this to premature ‘wet’ neonates.
iv. investigate if and what the effect might be of different rhythms of compressions and ventilations, and if such a device might alleviate this.

1.4 Thesis outline

The following chapter looks at the literature and gives the relevant background information, literature review and objectives. The information learnt from this chapter can be applied in the next chapter which describes the design of the device including the components, sensors and methods used to meet the objectives of the project.

The study design follows, including ethical consent, subjects chosen and the reason for the subject choice, a priori power analysis, a detailed animal test procedure and the limitations of the study. The fidelity of chest compressions is assessed according to the target depth (one-third APD) and the chosen target depth range for ‘wet’ neonates. The methods used to assess the fidelity, the results and discussions are included in the chapter.

The results from the force-depth relationship and the force-deformation curve are given and discussed in the next few chapters. The force-depth relationship includes the depths and forces recorded during the tests. The assessment is done to compare the recorded depth and force values from the different compression and ventilation methods and for each animal.

The force-deformation curves are analysed and the shape of the curve and the peak depths and forces are investigated with regards to the compression and ventilation methods used during the test. The slope of the curve and the energy (area under the curve) is also investigated.

An overall discussion of the limitations and recommendations of the device and study and an overall conclusion including any future work.

CHAPTER 2: Literature review

This chapter summarizes the relevant literature including an overview of neonatal cardiopulmonary resuscitation (NCPR), chest compression (CC) methods, the quality of CCs and ventilation used during resuscitation.

2.1 Neonatal cardiopulmonary resuscitation

A neonate is the term used to describe an infant during the first 28 days of life. According to the World Health Organization (WHO) this is a very high risk period and responsible for a large portion of the mortality of infants in the first year of life. South Africa has a large incidence of premature births contributing to the high infant morbidity and mortality rates of 34 deaths per 1000 births in 2012. The 'wet' neonate is a well-defined subset, and describes the period from birth (i.e. extra-uterine existence) for a period of 24 hours.

A neonate undergoes a transition from 'breathing' in the fluid in the mother's womb to breathing on its own in air. This transition from fetus to neonate is a complex lung adaptation which requires coordinated clearance of the fetal fluid, surfactant secretion and the onset of consistent breathing. With the removal of the low-pressure placenta, the cardiovascular response requires striking changes in blood flow, pressures and pulmonary vasodilation. Abnormalities in this adaptation is frequent following preterm births or delivery by caesarean section at term and many of these neonates will need delivery room resuscitation to assist in this transition [34].

Resuscitation may be required in the first few minutes to weeks of postpartum if they are unable to breathe on their own due to asphyxia, depression due to the birthing process, or other medical conditions. Approximately 10% of newborns require assistance with "starting" including oxygenation at birth, however, less than 1% require intensive measures after the successful initial transition has been completed. Although the percentage is low, due to the high number of births every day, there are a significant number of infants which require resuscitation [17], [20], [21].

The first 60 second window after birth, known as "the Golden Minute" is an important time period within which certain steps need to be followed, preferentially in a structured, set, order [35]. This is the time allocated to complete the initial steps of resuscitation, which include stabilization (drying, providing warmth, assessment, initial clearing of the airway), ventilations geared to aeration of the lungs called 'rescue or resuscitative breaths', and chest compressions in combination with ventilation, are needed. Only a limited number require administration of epinephrine and/or volume expansion (typically later in the resuscitation) [17], [18], [25]. The golden minute is illustrated in Figure 2.1 with the stages indicated as follows:

A. Initial steps in stabilization (dry, provide warmth, position, clear airway, stimulate, reposition)
B. Ventilation to clear and then aerate/oxygenate the lungs
C. Chest compressions

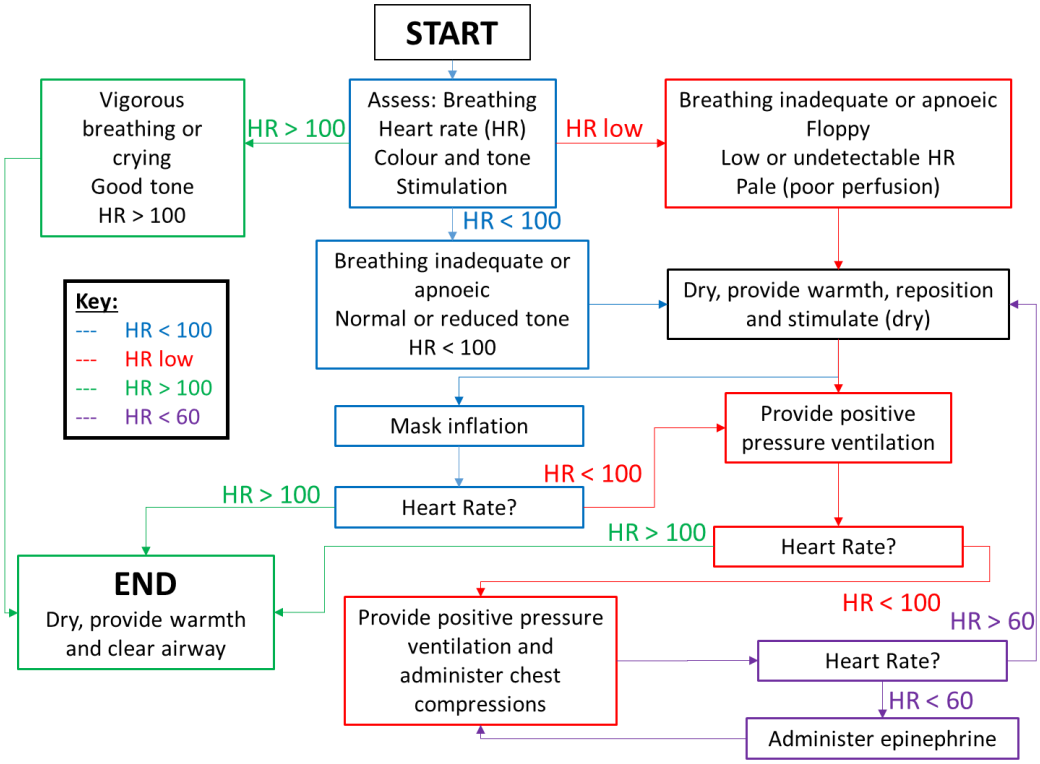

Figure 2.1: Neonatal flow algorithm. Adapted from [17], [25], [36]**.**

During initial resuscitation of the 'wet' neonate, chest compressions and (much) later epinephrine, also known as adrenaline, are only recommended in certain situations. Chest compressions are performed when the heart rate is less than 60 bpm despite adequate ventilation (i.e. confirmed chest movement and/or failure of increase in frequency after 30 seconds of regular (tidal volume) ventilations) [17].

The rescuer should ensure that effective ventilation is being delivered before compressions are initiated due to the fact that in the neonate, cardiac depression or failure is, in the absence of morphological abnormalities, always a hypoxic event. Furthermore, ensuring correct ventilation can distract the clinician and interfere with the delivery of effective CCs. Inspired oxygen fraction is increased from 21% to 40-60% with the initiation of compressions. Compressions should be continued until the spontaneous heart rate is more than 60 bpm [17], [21]. If the neonates' heart rate, however, stays below 60 bpm despite adequate ventilation with increased oxygen fraction and a cycle of 30 seconds of effective CCs, 100% oxygen is added and epinephrine may be administered [17], [21]. The

recommended dosage of epinephrine for neonates through the intravenous route is 10-30 $\mu g\ kg^{-1}$, while at least 50-100 $\mu g kg^{-1}$ is recommended when using the tracheal route. This route may achieve the same effect as the lower dosage intravenously [17], [24], although intubation is required and this activity is no longer advocated during the initial phase of resuscitation.

2.2 Chest compressions

Chest compressions (CCs) are required when the heart rate (HR) of the neonate is below 60 bpm [17]. A grey area exists between 60-100 bpm, during which some may or may not compress, depending on the situation. Compressions should be delivered just below the inter-nipple line on the lower third of the sternum with a compression depth of one-third of the anterior-posterior diameter (APD) of the neonate's chest [17], [21]. This is different from the explicit 5-6 centimetre depth goals in adult CPR. The two techniques advocated for compression include the two-thumb (TT) and two-finger (TF) method described in Section 2.2.2 and 2.2.1.

Current research indicates that the two-thumb method achieves greater compression depth and less variability with each compression as opposed to the two-finger technique when using a 3:1 compression ventilation ratio [37]. The two-thumb method also produces significantly higher systolic, diastolic, mean arterial, and pulse pressures than the two-finger method [17], [19]. In addition to the above mentioned advantages, the two-thumb method was also found to be easier to perform and thus leading to more effective compression during NCPR. [22], [37].

2.2.1 Two-thumb method

The technique of the two-thumb (TT) method includes encircling the clinician's hands around the neonate's chest and compressing with the two thumbs [17]. During this technique the thumbs of the clinician are placed together in the superior direction, on the lower third of the sternum, with the clinician's fingers spread bilaterally over the thorax [17], [19]. The encircled fingers support the neonate's back and allows for the thoracic squeeze which is included in the technique [17], [19], [38]. This method is illustrated in Figure 2.2.

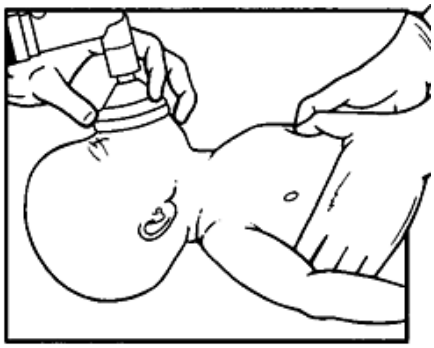

Figure 2.2: Two-thumb chest compression technique adapted from [22]**.**

The advantages of the TT method include higher systolic, diastolic and mean arterial blood pressure [19]. Higher compression forces are achieved during TT method, which results in an increase depth during chest compressions using the 3:1 ratio [22], [37]. The TT method for CCs is preferred by many clinicians as it causes less hand fatigue and correct hand positioning is easier to achieve than the alternative two finger method [19], [37]. Research has been done to support the case that the TT method is more effective in terms of CC depth [22], [37]. Due to the advantages explained and research completed in the field the TT method is recommended by the European Resuscitation Council Guidelines (ERC) for Resuscitation for newly born infants [17], [18].

2.2.2 Two-finger method

The two-finger (TF) technique was initially strongly supported by mid-wives since they had to perform compressions and ventilations by themselves. The TF method is done with two fingers placed on the lower third of the sternum potentially with a second hand (or the arm) supporting the back of the infant [17], [18]. This method is illustrated in Figure 2.3.

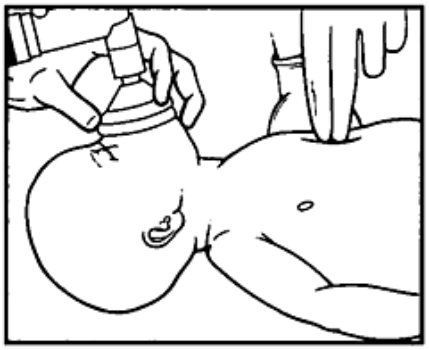

Figure 2.3: Two-finger chest compression technique adapted from [22]**.**

The TF method achieves lower systolic, diastolic and mean blood pressures during compressions [19]. TF method is however, preferred when access to the umbilicus is required when inserting an umbilical catheter [18]. The TF method is

also preferred for larger infants when the clinician is unable to perform the TT method. Additional disadvantages of this method include fatigue during resuscitation [19], lower compression depth and more variability between compressions compared to the TT method [22], [37]. This method is no longer recommended by the 2015 ERC guidelines [17].

2.3 Chest compression quality

2.3.1 Chest compression depth and force during neonatal cardiopulmonary resuscitation

One of the objectives of this study is to measure the CC depth and force during NCPR. According to the American Heart Association (AHA), European Resuscitation Council (ERC) and Neonatal Resuscitation Program (NRP) the compression depth should be approximately one-third of the anterior-posterior chest diameter (APD) [17], [20], [39]–[41]. The force required should be sufficient to reach the desired depth during each compression. There is no data on what this force might be, either in the premature, 'wet' or general neonatal population.

Aids for resuscitation training are used to teach clinicians the skills to perform effective NCPR according to the guidelines. These feedback devices, Laerdal (Norway) SkillGuide and SimPad Skill Reporter for example, give feedback during resuscitation of the manikin (i.e., in NCPR training). These devices guide the clinician not only in compression depth, but also by means of a metronome on compression rate. The feedback device is plugged into the manikin itself to measure the compression rate, depth and force. It is beneficial during training to have the feedback; however there is also a need for this type of guidance during resuscitation of neonates. There is currently no feedback device available which can be used in the clinical setting to guide clinicians during NCPR on a neonate ensuring good quality compressions.

Some previous research has been done with the goal of achieving this objective by both Stellenbosch University and other institutions. Previous work at Stellenbosch University set out to design a glove to optimize the chest compression (CC) force and depth during neonatal cardiopulmonary resuscitation by giving feedback to the clinician [22]. Technically, the glove utilizes force sensors, made from soft piezo resistive material, which is not harmful to the neonates' sensitive skin. The glove is able to measure both the CC force and depth simultaneously during NCPR. The CC depth is measured by three MEMS accelerometers placed on the dorsal (i.e. back) side of the fingers.

The performance of the glove was tested using infant manikin tests with both the TT and TF methods of applying CC during NCPR. The TT and TF methods were able to achieve the maximum CC depth and forces represented in Table 2.1.

Table 2.1: Results from the glove study using the two-thumb and two-finger method for CC during NCPR on a manikin model [22]**.**

	Two-thumb method	Two finger method
Maximum CC depth [mm]	25.7 ± 3.2	21.6 ± 2.2
Maximum CC force [N]	35.9 ± 2.2	23.7 ± 2.9

Abbreviations used: CC = chest compression

The results obtained during these manikin tests showed that the TT method was able to achieve a greater CC depth with a concomitant higher force. The greater depth therefore confirmed that TT compression are potentially more effective in depth than TF compression, however larger forces were required and a "target depth" remains unknown [22]. The device is able to measure depth and force, however, the force measurements recorded by the glove were shown not to be reliable when used in a manikin model and the NCPR glove was not able to achieve real-time feedback as originally expected. The device is currently not in clinical use.

Another study from Stellenbosch University, published in 2016, evaluated the influence of ventilation and ventilation-compression synchronization on CC force and depth during simulated neonatal resuscitation on an infant manikin. A key finding from this paper is that all of the volunteers, regardless of CC method applied, produced maximum sternal displacements that were less than one-third of the manikin chest APD, recommended by current NCPR guidelines. This suggests that meeting the guideline recommended target depth may be challenging, even for experienced NRP certified clinicians [42].

Another feedback device for resuscitation of infants is the Rhythm of Life (ROLA) device, which is an interactive audio and visual feedback device integrating a transparent foil with a pressure sensor and electroluminescent foil actuators to measure the CC pressure [31]. The prototype is not able to measure the compression depth and uses only force for the feedback. The prototype also includes an audio box to guide the clinician according to the 3:1 compression to ventilation ratio during NCPR of newborn infants. The prototype was tested on a manikin model by ten doctors and nurses from Máxima Medical Centre, Veldhoven, Netherlands, which is specialised in neonatal and premature neonatal care. The findings from these tests proved to yield a more constant rhythm and pressure during CPR on newborn infants [31]. Although the tests resulted in a more consistent rhythm and pressure, it was not stated whether these pressures generated the desired compression depth, which therefore does not illustrate good quality compressions. In the manuscript describing the ROLA, the authors

concluded that infant mortality rate, even in highly developed environments, and the lack of feedback device supports the need for the development of an easy-to-use, unobtrusive feedback device for NCPR. However, they recognize the 'resistance' of the typical caregiver to recognizing and implementing technical support.

All the previous studies mentioned or devices designed were tested on manikins which all use a linear spring. The linear spring is not an ideal model for the non-linear infant chest. The infant's chest should be modelled by a nonlinear spring due to the fact that the stiffness of the chest changes during compressions and a phenomenon namely moulding causes the chest to deform slightly and causes the stiffness to change. For an accurate model, a nonlinear spring, which also accounts for chest moulding should be used.

2.3.2 Chest compression to ventilation ratio

In certain areas of resuscitation the guidelines are based on clinical tests or extrapolated data. The chest compression (CC) to ventilation ratio of 3:1 for 'wet' neonates is one of these cases. The ratio is used for providing 90 compressions and 30 breaths per minute. This ratio is obtained by trying to match the respiratory rate to that of a normal neonate, however, there are very few studies to support this ratio [23], [39]. The 3:1 CC to ventilation ratio for 'wet' neonates is significantly lower than the ratio for infants and children of 15:2 and adults of 30:2 [14], [16], [17], [45]. The reason for the high ventilation rates during NCPR is due to the fact that even a healthy newborn demonstrates a high metabolism,, small tidal volume and thereby has a higher respiratory rate compared to that of an adult or other children, on average 20 to 25 breaths per minute [28]. The significance of ventilation in the resuscitation of infants means that this is an extremely important and clinically relevant topic.

2.4 Ventilation during resuscitation

Ventilation is one of the key initial steps during NCPR. Natural spontaneous ventilation occurs when the respiratory muscles, diaphragm and intercostal muscles pull the rib cage open, creating a negative inspiratory pressure. This negative pressure allows the lungs to expand and air is pulled into the alveoli which allows gas exchange to occur. Effective ventilation during NCPR is achieved with intermittent positive pressure mechanical ventilation, which also includes manual mechanical ventilation by bag-valve mask.

The bag-valve resuscitation is more commonly used in resource limited settings as it is a simple, easy to use ventilation method. The bag-valve mask (BVM) consists of a face mask connected to a flexible air chamber, which ventilates the infant when squeezed. The mouth piece is placed over the infants mouth/nose and when squeezed the air is forced into the infant's lungs and when released the bag inflates itself by allowing in either ambient air or low pressure oxygen from the

other end of the bag. At the same time the air exhaled by the infant is allowed to pass through the shutter valve to deflate the lungs. BVM ventilation can be used prior to other ventilation methods or as a rescue method on its own if performed correctly. The mask must not cover the infant's eyes. The mask section of the resuscitator can be replaced by an endotracheal tube, which secures the air passage. (See Figure 2.4 left)

Another ventilation strategy for mask or intubated neonates can be effectively achieved by using a flow T-piece which is designed to regulate the pressure (See Figure 2.4 right) [18], [46].

Figure 2.4: (left) Bag-valve and (right) T Piece resuscitator [46], [47]**.**

The T-piece resuscitators regulate the inflation for ventilation and are set to allow for the optimized pressure of air to flow into the infant's lungs during ventilation during NCPR. Important settings include the Peak Inspiratory Pressure (PIP) and the Positive End-Expiratory Pressure (PEEP). PIP is the point of maximum airway pressure and PEEP is the pressure maintained in airways at the end of exhalation. The difference in these two pressures is referred to as the delta pressure.

Another important parameter is the tidal volume, which is the volume of gas entering the infant's lungs during inspiration. The respiratory rate is also set on the ventilator. The ventilator during NCPR on infants can be set to administer asynchronous ventilation according to the 3:1 ratio or synchronous continuous compression ventilation. A study completed in 2013 on piglets reported that the asynchronous 3:1 CC to ventilation ratio yields similar return of spontaneous circulation, survival, and hemodynamic recovery to those of synchronous continuous compression ventilation [48]. Automatic ventilation is also often used in hospital settings.

The feasibility of using an automatic ventilation device during CPR was investigated using a porcine model [49]. Three different ventilation methods were investigated including manual ventilation using a bag (12 breaths per minute), low pressure Oxylator® (max airway pressure of 15 cmH_2O with 20 L/min constant flow in automatic mode) and high pressure Oxylator® (max airway pressure of

20 cmH_2O with 30 *L/min* constant flow in automatic mode). Both the automatic modes yielded higher PEEP than the manual ventilation and the high pressure Oxylator® resulted in lower arterial-alveolar gradient than the manual method. This study proved that an automatic ventilation device used during CPR is feasible and can supply adequate ventilation and result in comparable hemodynamic properties to manual ventilation. [49] A later study also concluded that the ventilation strategy with a tri-level pressure cycle performance is comparable to an expert, manual ventilator in an automated-CPR swine model [50]. The different ventilation ratios are investigated during recent studies.

During an observatory study using adolescent, child and infant manikins the 30:2 ratio was compared to the 15:2 compression to ventilation ratio. No difference was found for the peak compression pressure and compression rate using the two methods. The total compression cycle was however higher during the 30:2 ratio vs the 15:2 ratio. No significant difference in compression depth was observed. The heart rate during the 30:2 ratio increased, while the recovery rate and recovery time remained the same. The heart rate and respiratory rate were continuously recorded during CPR and used to determine the recovery rate and time. Another observation by the subjects performing the two techniques was that the 15:2 compression to ventilation ratio was easier to perform [51].

The literature summarized in this section further validates the need for a feedback tool for ‘wet’ neonates according to the 3:1 compression to ventilation ratio with a compression depth of one-third APD which correlates to 17.5 to 22.5 *mm*. Compressions can be done using either the TF-method or the recommended TT method, which previous research has proven to be the more effective method. The device designed to achieve the depth and force measurements, while giving the clinician depth feedback, is discussed in the following section.

CHAPTER 3: High level device design

This chapter looks at the design of the feedback tool for NCPR on 'wet' neonates and, on top of measuring the depth and force, the device is also able to give feedback to the clinician on the compression depth, and guide the clinician, with regards to the rate of compressions, using a metronome. The design of the NCPR feedback device (i.e., tool) is subject to several constraints. These include the following, in order of priority: accurate, easy-to-use, low-cost, robust, and small/unobtrusive. The design should ensure that the device does not interfere with or delay the implementation of NCPR and ventilation, therefore making it compact, small in size in relationship to both a neonatal resuscitation table and the neonate itself, and comfortable to handle. It should also be easy to clean/sterilized for use in a hospital setting. Another important design consideration is the ease of use and operation. These aspects should be taken into account during each phase of the design process to achieve the primary objective to develop and validate a portable feedback tool that can be used to measure the CC depth and force produced during premature neonatal resuscitation on an animal model.

The design must be conducive to clinical use: recall that there is a disinclination to overcome in the acceptance of clinicians in the use of feedback devices.

3.1 Overview of device

The device is to provide real-time feedback to the clinician when performing NCPR, by measuring and reporting the compression depth and measuring force. Taking the design requirements into account, with the help of advice from an experienced clinician, a patch design was envisioned. As foreseen, it would have two parts namely the patch, which was placed on the infant's chest, and the component box, which was placed next to the infant.

Communication between the two parts was achieved with a ribbon cable which was chosen for its robustness and as it would not interfere with other equipment in the hospital. Methods used by the device to measure the depth and force are discussed in Section 3.2 and 3.3, while this section provides an overview of the other components used and factors considered during the design of the device. A component list, including the manufacturers and cost of each component is found in Appendix C, where the total cost of the device is calculated as less than R5000.00. See an overview of the device in Figure 3.1.

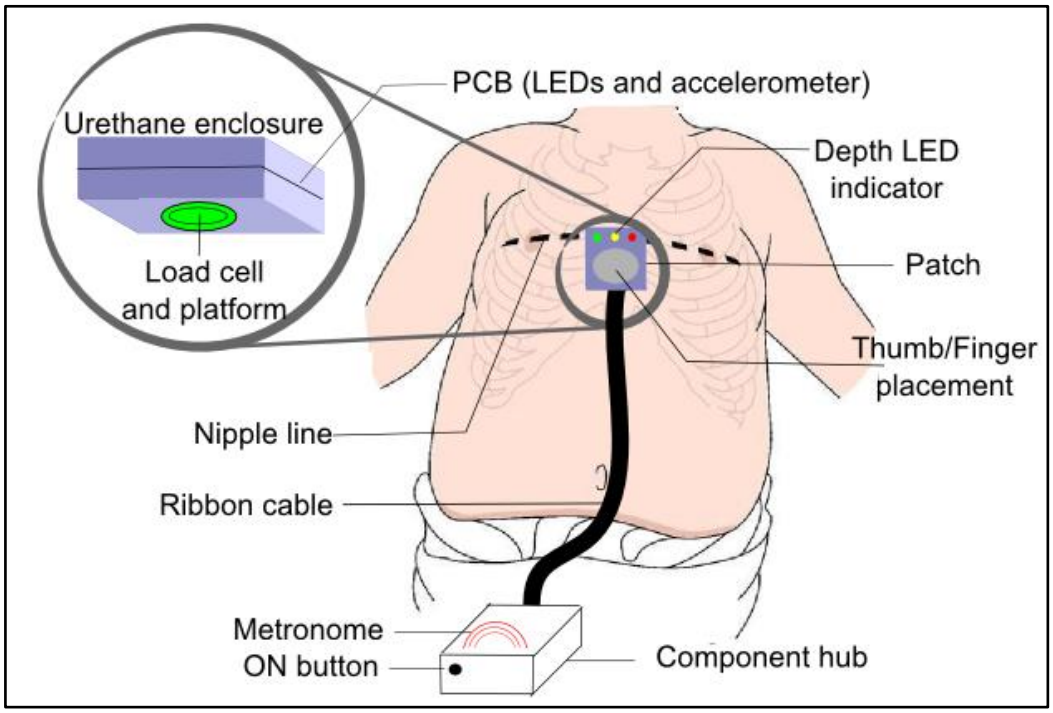

Figure 3.1: Device schematic illustrating the component hub and patch, placement of the device, depth LED indicators, load cell and additional components.

3.1.1 Microcontroller

The device needed to be portable; therefore a microcontroller was required to ensure that the measurements were recorded correctly while performing NCPR. The device is compact and the size needs to remain as small as possible, therefore the microcontroller was chosen, next to accuracy, for its physical size, while ensuring that all the necessary performance specifications were achieved.

The Tinyduino (Tinycircuits, Akron, USA) with storage and USB shield for storing data and programming the controller from Tiny Circuits was implemented in the design. The Tinyduino has an Atmel Atmega328P microcontroller chip (California, USA), which was programmed via the Arduino platform.

Detailed specifications of the Tinyduino processor are provided in Table 3.1.

Table 3.1: Specifications of the Tinyduino processor.

Specification	Value
Input/output pins	14 Digital, 6 Analog/Digital I/O
Ceramic resonator	8 *MHz*
Operating voltage	2.7 -5.5 *V*
Current	1.2 *mA* (typical) @ 3 *V*, 4 *MHz*
Memory	32KB Flash, 2KB RAM 1KB EEPROM
Physical size	20 *mm* x 20 *mm* x 2.9 *mm*

Abbreviations used: I/O = Input/Output, RAM = random access memory, EEPROM = electronically erasable programmable read-only memory.

3.1.2 Printed circuit boards

Additional electronics required were placed onto the two printed circuit boards (PCB's), one which was located inside the patch and the other inside the component box. The schematic and drawing of the layout of the PCB's are found in Appendix D. The PCB design was completed using Cadsoft EAGLE PCB Design Software 6.6.0 (Newark, USA).

3.1.3 Power source

To ensure portability of the device all of the components needed to be powered by an alternative power source. The device is connected to a 9V Ni-MH rechargeable battery, which can power the device for the duration of the testing period, which was 80 min operation time. For shorter time periods the device can be powered by two Panasonic Lithium 3V CR1632 batteries (Panasonic Electronic Components, Japan), which are mounted on the PCB in the component box. Typically, the device would need to 'run' for at least 45 minutes (preparation for a caesarean section, the transition period and potentially the resuscitation before beeping and auto-off).

3.1.4 Feedback and metronome

The most important factor which contributes to the quality of the chest compressions is the compression depth; therefore depth feedback is implemented using LEDs. There are three different colour LEDs, green, yellow and red, representing the correct depth, too shallow or too deep, respectively. The colours (green, yellow and red) are chosen as they represent general signals/warnings for correct and incorrect. The green light shows that the compression depth achieved is within the correct range (17.5 – 22.5 *mm*), while if the depth is too shallow (< 17.5 *mm*) it will have a warning colour of orange and too deep (> 22.5 *mm*) is a

more intense warning colour of red. It is dangerous for the fragile neonates if the compression depth is exceeded therefore too deep is represented by the more intense warning colour. These colours were deemed suitable by the clinician performing the tests. Clinicians will be trained in the use of the device.

The target depth should be within a close range (within 2.5 *mm*) of one-third of the APD of a neonates' chest [17]. Feedback was given every three seconds by calculating the average compression depth during the specified period. A metronome in the form of a buzzer (Sonitron SMA-13, Belgium) was also included in the design as a guide following the 3:1 compression to ventilation ratio and achieve the 120 events per minute according to the European guidelines for neonatal resuscitation [17].

3.1.5 Size of the patch

The device must be used during NCPR by a clinician applying either the TT-method or the TF-method. As the TT method covers the largest surface area and is the preferred compression method, the design of the patch was based on the average thumb size. The distance between the thumb tip and the midpoint IP flexion crease is between 26.0 and 39.7 *mm* [52], [53]. The final size of the patch including the enclosure is 43 x 35 x 15 *mm*, which is large enough to comfortably fit two average male thumbs to effectively perform the TT compression method. There are two circular stickers placed on the top of the device to indicate the finger placement during NCPR using the device.

3.1.6 Enclosure and material

The printed circuit board (PCB) in the patch is enclosed in a urethane casting (Crystal Clear 200, Smooth-on, USA) and placed onto the chest of the infant with a soft hydrogel patch (R & D Medical Products, Inc., USA) which is safe for use on sensitive skin, such as that of a neonate. The infant is thus protected from any electronic or harmful components. The urethane was moulded using a 3D printed mould, which was designed according to the rabbit chest anatomy. The bottom of the patch is arched to fit over the rabbit's chest.

The additional electronics and the battery were placed in the component box which is enclosed in a plastic housing to ensure that the device is safe to use in a hospital and near infants or animals. The dimensions of the component box are 90 x 65 x 28 *mm*.

The component box and patch PCB and the final device described in this section is illustrated in Figure 3.2.

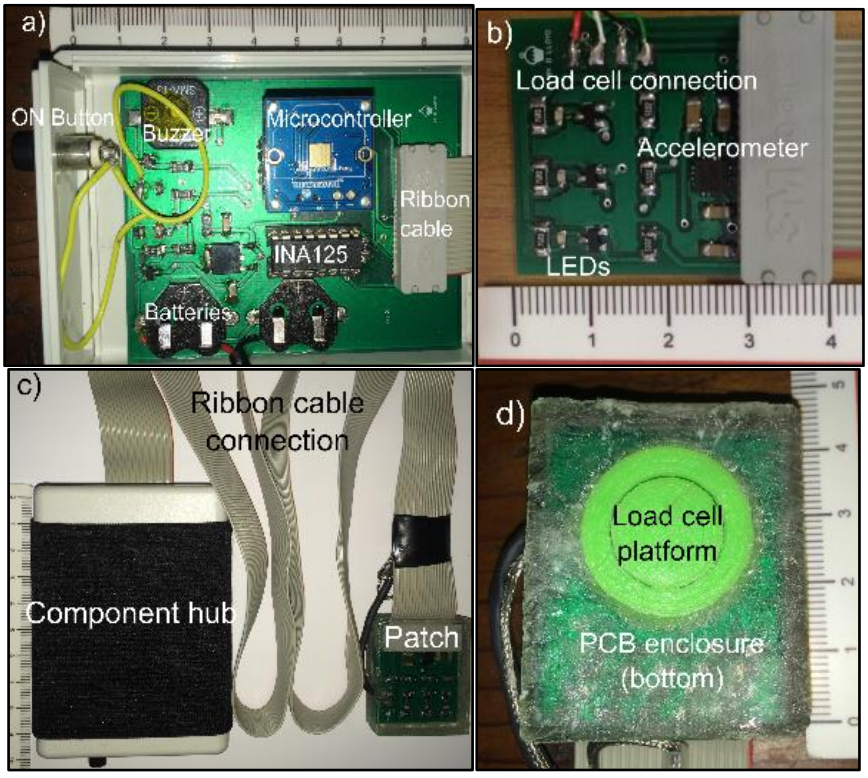

Figure 3.2: a) Component box b) Patch PCB with electronic components c) Diagnostic feedback patch and components d) Load cell platform.

3.2 Depth estimation sensor

The compression depth should be approximately one-third of the APD of the infant's chest according to the current resuscitation guidelines [17]. The device needs to accurately measure the depth during compressions and record the data for further analysis while also giving feedback on the compression depth during resuscitation. This section described the method used to estimate the depth, the design used, electronic hardware required and the calibration method applied.

3.2.1 Depth estimation method

In order to accurately estimate the depth, while ensuring all objectives of the project and device were achieved, a single accelerometer design was used. The accelerometer was placed in the centre of the PCB in the patch to ensure the correct depth was estimated during chest compressions. Many other studies use two accelerometers, one to measure the acceleration of the device and the other to measure the reference acceleration based on the mattress below the infant. The reference signal makes it easier to accurately estimate the depth, however, having

two accelerometers is not possible in this design as the infant must not be moved to place any components underneath it as this would interfere with the clinician's normal workflow and delay the start of compressions and the TT method does not allow this.

The acceleration was measured in the z-direction only as it was the axis parallel to gravity. The offset of the accelerometer is subtracted from the raw acceleration measured before converting to SI units. The signal is filtered using the weighted smoothing method with Equation 1:

$$Acc_{FIlter}(i) = (1 - \beta) * Acc(i - 1) + (\beta * Acc(i)) \quad (1)$$

The noise in the acceleration signal needs to be removed before integration to improve the accuracy as the error increases due to the integration. The signal acquired from the accelerometer can be integrated twice to determine the depth. The first integration gives the velocity signal and can be acquired using Equation 2:

$$Velocity(i) = Velocity(i - 1) + 0.004 * \frac{(Acc_{Filter}(i) + Acc(i-1))}{2} \quad (2)$$

The velocity data is filtered to emphasize the transient components of the data and remove any noise by applying Equation 3:

$$Data_{Filter}(i) = \alpha * (Data_{Filter}(i - 1) + Data + Data(i - 1)) \quad (3)$$

The same equation (Equation 3) is used to filter the depth data once the velocity has been integrated using Equation 4.

$$Depth(i) = Depth(i - 1) + 0.004 * \frac{(Velocity_{Filter}(i) + Velocity(i-1))}{2} \quad (4)$$

3.2.2 Acceleration electronic hardware

A MEMS accelerometer, ADXL362, from Analog Devices (Cambridge, Massachusetts, USA) was used in the design (Datasheet found in Appendix E). It is a small, 3-axis, low power, ±2 g accelerometer. Additional electronics required included three 0.1 μF and one 1 μF capacitor to suppress high frequency noise.

3.2.3 Accelerometer calibration

It was important for the accuracy of the results to calibrate the accelerometer prior to testing. The accelerometer was calibrated by placing it in the +z, -z, +x, -x, +y and -y direction respectively and reading the raw data measured for each orientation. The correction factors were implemented in the software to ensure that the correct acceleration was measured, which was used to estimate the CC depth. The calibration was completed prior to testing.

3.3 Force sensor

Another important factor to consider when determining the quality of CCs during resuscitation is the force exerted on the infant's chest. The force measured was also necessary to investigate the thoracic damping of the chest. The force was measured and recorded on a SD card inserted into the device. The method used to measure the force is described in this section.

3.3.1 Force measurement method

The force was measured using a Very Low Profile Button (VLPB) load cell from Load Cell Central (Milan, USA). The 10 *lbs* cell was chosen as the force exerted during neonatal resuscitation will not exceed the maximum force allowed for the specified load cell [22]. The load cell is also physically small enough to fit into the patch without affecting the size of the patch design. It was fastened onto the bottom of the printed circuit board (PCB) in the patch with clear, thin double sided adhesive Scotch tape. The surface area of the load cell is small (2.29 *mm*) and therefore a platform was designed and printed on a 3D printer to increase the surface area to 14 *mm*. This platform also ensures that the force is exerted in the axial direction only to ensure accurate load measurements and reduce the risk of damaging the load cell. The platform was placed over the load cell allowing it to make contact with the load cell pressure point and the infant's skin. This was held in place and fastened to the PCB with the spacer as seen in Figure 3.3.

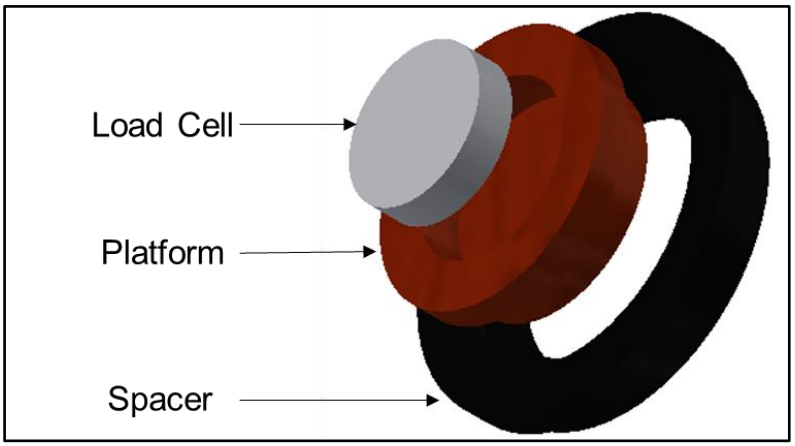

Figure 3.3: CAD drawing of the load cell platform design showing the placement of the load cell and additional components.

The 3D printed platform was printed using the BabyBot (OpenHardware, South Africa) printer running Repitier (opensource) software with Polylactic acid (PLA) material. The platform needed to be light and moulded perfectly around the load cell which is why 3D printing was used. The material of the platform is never in contact with the infant's skin due to the placement of the hydrogel patch between the device and the infant.

3.3.2 Force sensor electronic hardware

The load cell is connected through an INA125 instrumentation amplifier (Burr-Brown, USA) to the battery, ground and the analogue input port of the Tinyduino. The load cell and INA125 datasheets are found in Appendix F. The load cell has four wires connected to the Wheatstone bridge which are described in Table 3.2.

Table 3.2: Load cell wire colour description.

Wire	Colour
Red	Supply Voltage (V_S)
Black	Ground
Green	Positive voltage in (Vin^+)
White	Negative voltage in (Vin^-)

These wires are connected to the INA VREF, Vin^+ and Vin^-. The voltage output from the amplifier is connected to analogue output 0 on the Tinyduino which allows the controller to read the measured load cell readings.

The signal from the load cell is very small in amplitude. The INA125 was implemented in the design to amplify the signal. The amplification was regulated by choosing a resistor coinciding with the amplification required. For the desired gain of 54 the resistance value chosen was 1.2 $k\Omega$ using Equation 5 [54]. The desired gain was determined based on the sensitivity of the load cell specified in the datasheet.

$$Gain = 4 + \frac{60k\Omega}{R_G} \text{ where } R_G = gain\ resistor \tag{5}$$

The load applied is calculated using the calibration data acquired using the method described in Section 3.3.3 and Equation 6 and Equation 7.

$$Force = \frac{(Force_B - Force_A)}{Reading_B - Reading_A} * (Reading - Reading_A) \tag{6}$$

$$Load = Force * g \tag{7}$$

$Force_A$ and $Force_B$ are the two forces (A and B) applied during calibration, which resulted in the following load cell readings, $Reading_A$ and $Reading_B$. In Equation 6 and 7 the variables Force and Reading is the calculated force using the current load cell reading. See Appendix F for the datasheet of the load cell and INA125.

3.3.3 Force sensor calibration

The sensor was calibrated by placing known weights of between 0.1 and 4.0 kg onto the load cell and the measurements were recorded for each weight. The readings obtained were used to scale the measured value and convert it from

voltage to kilograms. The raw data was saved onto the SD card and the conversion was done during post processing to minimize the number of calculations completed by the microprocessor and in addition ensure a fast sampling rate. These measurements were repeated two times after the testing procedure to validate the calibration data.

3.4 Programming

3.4.1 Overview of the software

The programming of the device was completed on the Arduino IDE and uploaded onto the device via the USB shield and a micro USB cable. The programming was as simple as possible to ensure that the desired sampling rate is achieved. The sample rate chosen was 250 *Hz*, which is sufficient to ensure that no data is lost and the depth and force can be accurately estimated and measured during the entire compression period. The processor was programmed to be able to complete the required integration and additional processing and provide feedback to the clinician.

The device is activated by pressing the push button and it remains on for the duration of each test (two minutes). Once switched on, a new file is created on the SD card and the device is ready to record the data to a specified .csv file. The sampling, metronome and feedback are initiated and continue to run for the duration of the test. During sampling the acceleration in the z-direction and the load cell reading is stored on the SD card.

During the sampling the program also integrates the acceleration data twice to determine the depth. The depth feedback was given in the form of different coloured LED lights which were programmed to change every three seconds using the average depth measured of the maximum peaks during the specified period. The specific file was closed once the 120 seconds had elapsed and the device was switched off by making the digital pin 9 on the Tinyduino low (further explained in Section 3.4.2).

3.4.2 Arduino program flow chart

The microcontroller was programmed in the Arduino IDE and the key programming methods are further explained in this section. The programming for the Arduino is divided into the setup file (black) and the main loop (blue) with additional functions included in the main loop (See Figure 3.4).

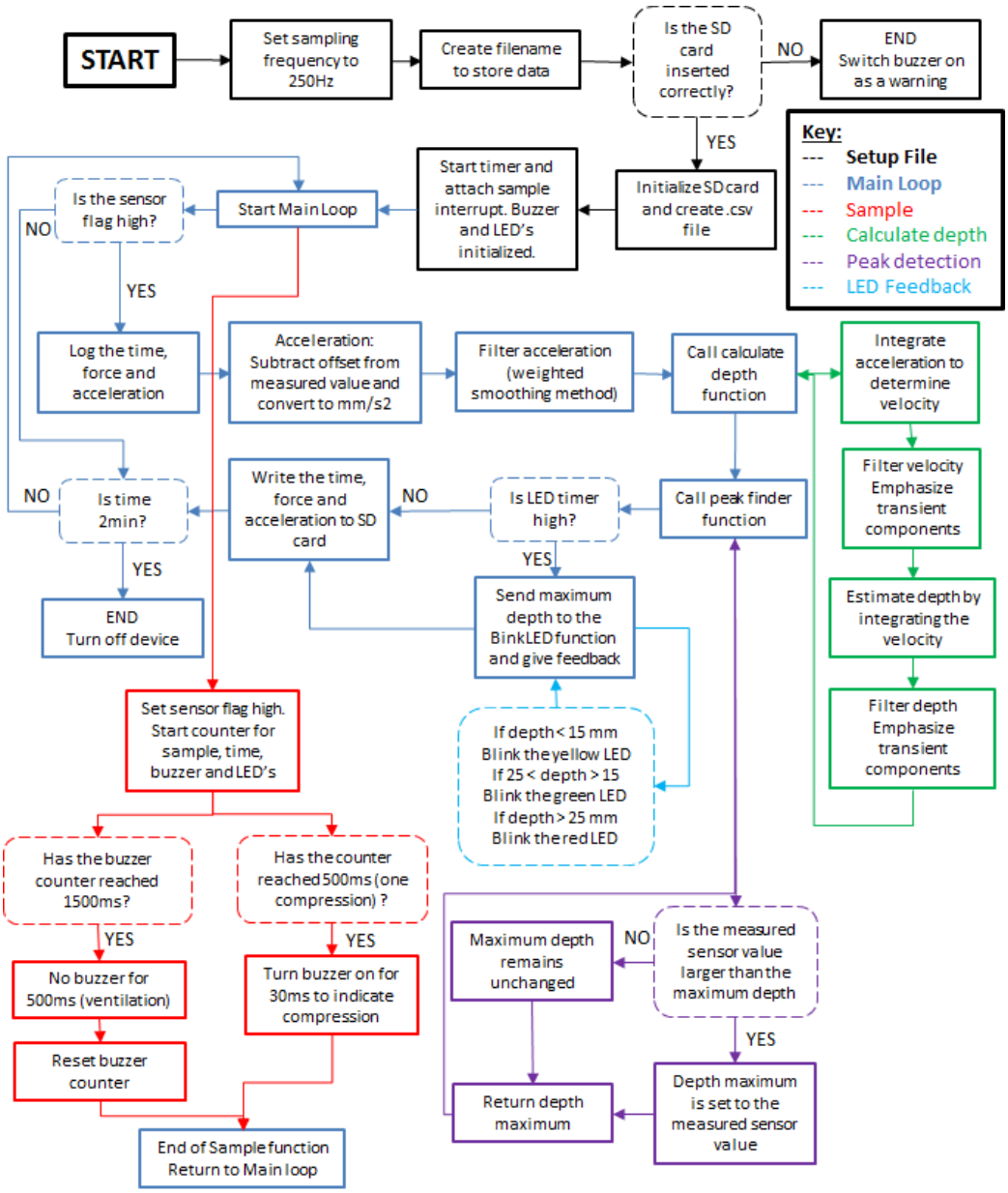

Figure 3.4: Arduino programming flow chart showing the setup file (black), main loop (dark blue), sampling code (red), depth calculation (green), peak detection (purple) and the feedback (light blue).

The setup file starts by setting the sampling frequency to 250 *Hz*, which is calculated to ensure that the sensors are sampling as fast as possible while still allowing the program to be completed, including calculations made. The device saves each dataset to a different file and the filename is set in the setup file. If a SD card is not inserted the metronome will buzz continuously to warn the user that the data is not being saved. If the SD card is present and not faulty the SD card can be initialized, timer started and all other components are initialized and the main loop starts.

The first function called is the Sample function (red) which sets the sample flag high and starts the counters for the sample, time, metronome and LEDs. This function also checks whether or not the metronome/buzzer counter has reached 1500 *ms*, which will initiate a no buzz period (ventilation period) and if the counter has reached 500 *ms* the buzzer is turned on for 30 *ms* (compression period).

Back in the main loop if the sensor flag is high, which indicates that the sensors should sample, the time, force and acceleration will be logged. The acceleration offset, determined during calibration, is subtracted and the acceleration is converted to mm/s^2 prior to filtering using the weighted smoothing method. The function to calculate depth is called (green). The acceleration signal is integrated once to determine the velocity before filtering by emphasizing the transient components. The depth is estimated by integrating the filtered velocity signal before filtering (emphasizing transient components).

Once the depth is calculated the peak finder function is called (purple), which checks if the sensor value measured is larger than the stored maximum depth. If the new measured value is not more, the maximum value remains the same and the function ends, otherwise the new value read is saved as the maximum value, which is returned to the main loop. If the timer for the LED is high then the BlinkLEDfunction (light blue) is initiated which uses the average of the depths measured during that period to give feedback by making the corresponding LED blink according to the following: yellow (too shallow), green (correct) or red (too deep). Once this is completed or if the LED timer is low the time, force and acceleration are saved to the SD card. The device is programmed so that when the time reaches 2 minutes the device switches off.

3.5 Hardware validation

Prior to commencing the animal study hardware tests were completed to ensure that the device was working correctly and to determine if it is capable of accurately measuring the depth and force during compressions. In order to determine if the depth calculation is correct a very simple ruler test was completed. The device was further validated by designing a LVDT and spring test. All of these test methods and results are described in this section.

3.5.1 Ruler test

Preliminary testing included the ruler test to qualitatively investigate the influence of chest compression (CC) frequency on depth measurement accuracy of the diagnostic feedback tool. During the ruler test the tool was placed next to a vertical ruler with marked displacements of 1, 2, 5, 10 *cm*. During the test the tool was moved up and down along the ruler by hand at various speeds (1 to 4 *Hz*) to the desired target displacement. The vertical movement was continued for

30 seconds and the data were saved to a SD card for post processing on a computer.

The ruler test determined that frequencies of 2 *Hz* and above yielded a depth accuracy of less than 15%, while the lower frequencies produced higher errors of between 20 and 30%. These results suggest that the diagnostic feedback tool is able to measure depths within a reasonable error limit (< 15%) for frequencies corresponding to CC during NCPR (1.5 to 2.0 *Hz*).

3.5.2 Linear variable displacement transducer (LVDT) and spring test

The linear variable displacement transducer (LVDT) and spring test was part of a series of hardware validation tests performed to assess the depth, force and feedback performance of the diagnostic feedback device. The LVDT-spring test used a LVDT from HBM (WA200MM-L), a CLIP amplifier (HBM, AE501) and a spring to further validate the design. Prior to commencing the LVDT-spring test the LVDT was calibrated to ensure accurate measurements (See Table 3.3).

Table 3.3: Equipment specifications used during the LVDT and spring test.

Equipment	Details
Amplifier	HBM CLIP Amplifier AE501
LVDT	HBM TypWA/2000mm K-WA-L-200W-33K-K1-D1-2-8-3
Closed end Spring (both ends ground)	D = 42 *mm* *d = 4 mm* L = 22.5 *cm* k = *N/m*
Oscilloscope	GW INSTEK GDS-1052-U

Abbreviations used: LVDT = linear variable displacement transducer, D = outer spring diameter, d = wire diameter, L = outer length of the spring, k= spring constant

The LVDT was calibrated by moving the sensor from 0 to 200 *mm* in increments of 10 *mm* on the LVDT rod. The voltage was measured and recorded at each displacement with an oscilloscope (GDS-1052-U, GW INSTEK, Taipei, Taiwan).

The results for the LVDT calibration is found in Figure 3.5.

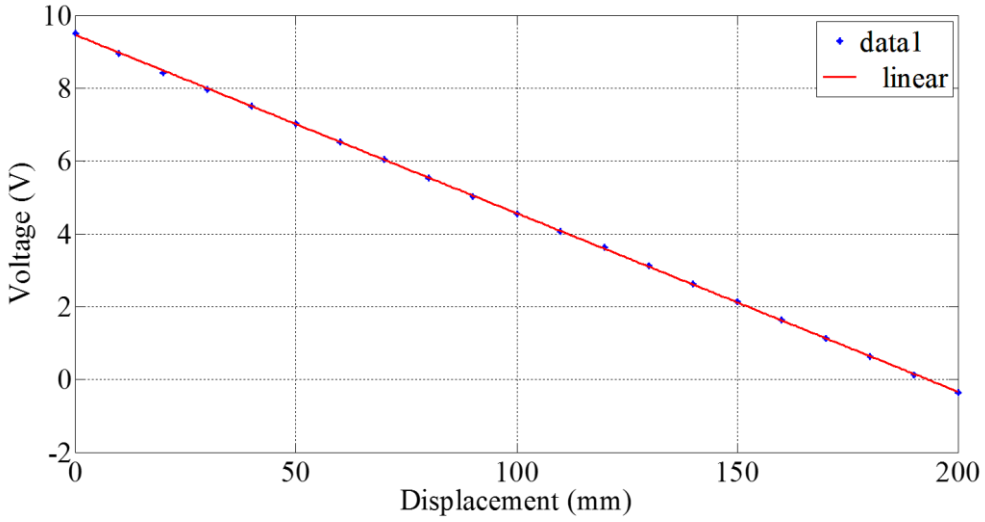

Figure 3.5: LVDT voltage measured vs displacement.

The graph in Figure 3.5 shows a linear correlation between the voltage output from the LVDT and the displacement measured. This graph is used to determine the conversion formula from voltage to displacement as seen in Equation 8.

$$\boldsymbol{Depth\ measured} = \boldsymbol{200mm} - \left(\frac{\boldsymbol{Voltage\ measured}}{\boldsymbol{9\ V}} * \boldsymbol{200mm}\right) \qquad (8)$$

The spring constant was determined by using calibration weights between 1 kg and 4 *kg*. The calibration weight is placed on the plate which is placed on the spring and the displacement is measured by the LVDT. The displacement was used to calculate the spring constant as 2.34 *N/mm* using Equation 9.

$$k = force/displacement \qquad (9)$$

During the testing of the diagnostic feedback tool, the patch was placed on a plate on top of a spring, which is placed in a pipe to minimize lateral movements. Three compressions were delivered to a pre-set target displacement (10, 15, 20 *mm*) at a frequency of approximately 2 *Hz* to simulate compression delivery in NCPR with the LVDT measuring the displacement of the spring. The force applied on the plate corresponds to the force required to achieve the desired target depth. The voltage recorded by the oscilloscope was saved onto a USB Flash drive for off-line analysis.

The LVDT was held vertically in a burette stand with the rod placed on the plate to accurately measure the displacement as seen in Figure 3.6.

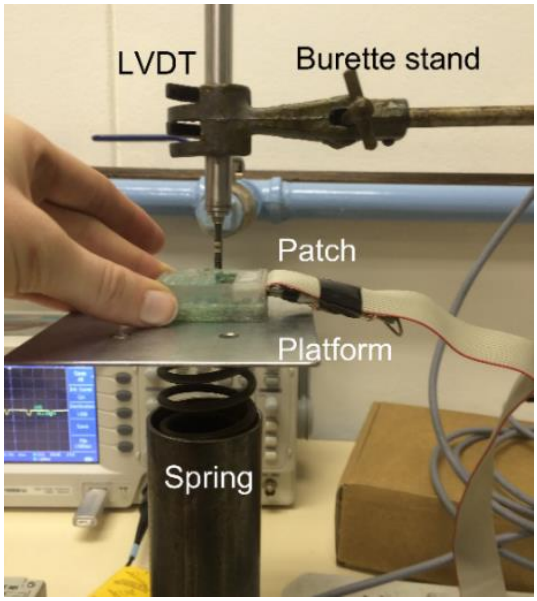

Figure 3.6: LVDT-spring test setup.

The LVDT-spring test was performed twenty-four times, with at least seven repetitions performed at each target depth, to ensure repeatability. The device measures both the depth and force during each compression, which can be compared to that measured by the LVDT-spring setup. In Table 3.4 the average depth and force measured by the device are compared to that measured by the LVDT and spring setup.

Table 3.4: LVDT-spring test results.

Target depth	Actual depth (mm)	Measured depth (mm)	Depth error (%)	Actual force (N)	Measured Force (N)	Force error (%)
20 mm	19.8(3.3)	17.2 (3.5)	13.5	46.5(7.7)	39.5(0.9)	15.5
15 mm	14.8(2.0)	13.8 (2.1)	8.8	34.6(4.7)	33.2(2.1)	12.1
10 mm	11.6(1.3)	11.0 (1.6)	9.5	27.3(3.0)	27.8(0.9)	8.6
Average	15.7(2.3)	14.2 (2.5)	10.8	37.0(5.3)	34.0(1.3)	12.4

The error percentage for the depth measurements of each LVDT test ranged between 2.2% and 20.7%, with a higher error percentage for the larger displacements. The mean error overall tests is 10.8%. The force measured by the device is compared to that calculated from the LVDT test by using the displacement measured and spring constant in Figure 3.7 bottom. The percentage errors of each individual force measurements are between 2.4% and 24.1%. The

average force error over all the tests is 12.4%. The error increases as the displacement increases as seen in Figure 3.7.

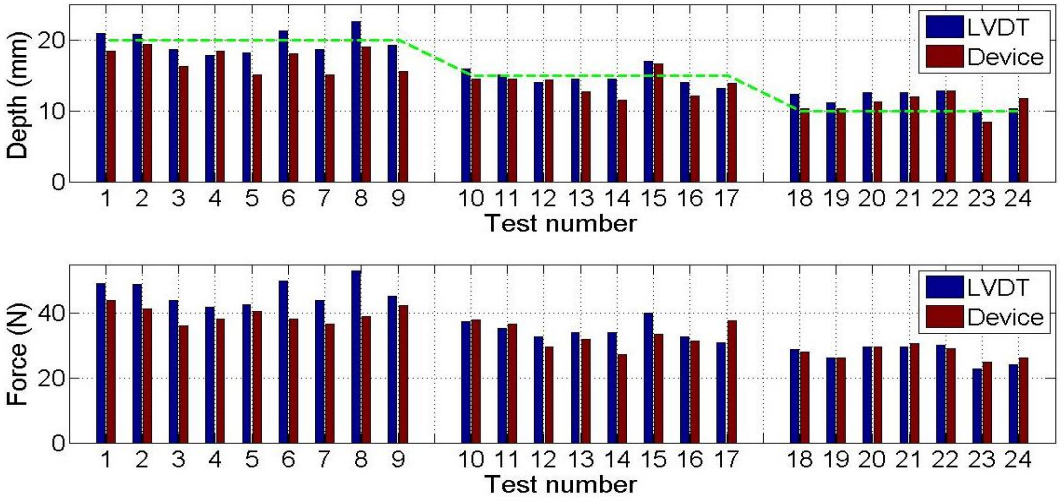

Figure 3.7: Average depth (top) and average force (bottom) measured by the device compared to that measured by the LVDT during each test grouped according to the target depth (green dashed line).

Comparing these results with the diagnostic feedback glove results indicates that lower errors were achieved in the force measured by the patch. The force measured by the diagnostic glove agreed to within 4.0-20.0 *N* of the reference measurement (a Tekscan pad) [22], while the force measured by the patch matched the applied LVDT force to within 0.02-14.10 *N*. Moreover, it is interesting note that as seen in Figure 3.7 and Table 3.4 the error in the force increases with increasing depth. This may be attributed to the spring constant and to additional lateral movement in the spring at larger displacements. The latter reason is a limitation of the current hard-ware validation tests since the placement of the patch on the spring may have resulted in the partial lateral distribution of the applied force. Given the fairly small errors encountered this effect is considered very minor

3.5.3 Feedback test

The feedback algorithm was qualitatively tested using a SkillGuide™ (Laerdal, Stavanger, Norway) as a reference. The device was attached to a Resusci Baby QCPR training manikin (Laerdal, Stavanger, Norway) with a hydrogel patch. The LEDs were observed when compressing the manikin chest and compared to the output displayed on the SkillGuide™, which was connected to the infant manikin. During the test, too deep CC, CC within the recommended range and too shallow CC were tested to see if the feedback LED light illuminated appropriately (Figure 3.8).

Figure 3.8: Feedback test showing the green LED, indicating correct depth.

The feedback test indicated that the feedback provided by the diagnostic feedback patch is consistent with that produced by the Resusci SkillGuide™ with each LED illuminating in the appropriate depth range (Figure 3.8). Manikins are linear while the neonatal chest is nonlinear; however, the feedback uses only the displacement which validates the use of a linear manikin to test the feedback indicator.

3.6 Limitations of the design

The limitations of the design are based on the objectives of the project. The device needs to be low cost, portable and easy to use, which limits the choice and number of accelerometer and controller for example. An important limitation is based on the target depth of one-third APD of the animal or neonate. A marker is required under the patient to correctly estimate the target depth for each animal or neonate; however this is not incorporated in the design. The feedback tool is programmed to a set range based on the target depth range for 'wet' neonates. A reference marker is required, however it was not incorporated in the design to ensure ease of use as the clinician does not need to place any other components below the animal or neonate.

The device was tested on animals and therefore the design needs to be adapted for the rabbit's chest which has a different arch to that of a neonate. The urethane outer of the tool is designed to fit flush on the chest of the rabbit; however it will need to be adapted for use on neonates. The positioning of the tool on the animal or neonates chest is important. If it is placed too distal on the sternum it changes the measurements taken. The size of the patch also increases the area over which the force is applied compared to the normal finger-based CC.

CHAPTER 4: Study design

The animal study used to investigate the chest compression quality during NCPR is discussed in this chapter including information regarding the ethical consent, subjects used and the priori power analysis results. This chapter also focusses on the test method used and the limitations of the study.

4.1 Ethical consent

Ethical approval for this study was obtained from the Health Research Council of Stellenbosch University (Ref: S11/10/007). Ethical approval was also obtained from the Animal Ethics Council (AEC) of Stellenbosch University (Ref: 01/11/2014). The method described in the study protocol, which was submitted to the AEC, was followed throughout the study.

4.2 Subjects

During animal testing the condition being researched was produced artificially in the animal to resemble that of the human or infant equivalent. Research over the past quarter century has revealed that the responses of the rabbit is similar to that of the human newborn in areas including the acute inflammatory response, cytokine and growth factor production and pulmonary function [55]. New Zealand white rabbits were chosen due to their chest anterior-posterior diameter (APD), compliance and the position of their heart. Rabbits are born with lungs in the early to middle alveolar stage, similar to that of a newborn human infant and they also have postnatal lung development similar to humans [55]. Adult New Zealand white rabbits were therefore selected for the study with a weight range of between 2.5 and 3.5 *kg*. The condition of the rabbit needed to be healthy with no sign of distress or physical harm.

The chest form of the animal model is slightly more curved than that of a premature neonate. The device was tested on the animal model; therefore the shape was designed according to the increased curve to ensure a flush fit. This can be adapted in the final prototype for use on premature ‘wet’ neonates.

4.3 Priori power analysis

This project is a feasibility study and thus small sample sizes are required. In order to determine the exact number of rabbits or number of test data required, a priori power analysis was completed. Due to the lack of information, the statistical parameters were based on other studies in the biomedical field. Some assumptions made were that the power required should be 0.8 with a significance level of 0.05.

The statistical analysis was completed using a two way or two tail t-test analysis as one is interested in looking at both sides of the mean. For the purpose of the priori power analysis the TT method's compression force and depth data was used from previous manikin trials at Stellenbosch University using the diagnostic glove [22]. The hypothesis is that the standard deviation will remain the same, while the forces required increase and the depth decreases when ventilation is present. The t-test is used for simple evaluation and the power analysis is completed in MATLAB®. The important assumptions are the following

- Dependent as each test is completed on the same animal (single group analysis).
- Two tail t-test is used as the effect from both sides of the mean must be evaluated.
- The effect size is defined by means of the population mean and standard deviation often based on relevant literature.
- The significance level is chosen as 0.05 for this experimental procedure as it is not very probable to find an effect that does not exist.
- A power of 0.8 is often used when minimal research has been done in the field or when no pilot study has been completed.

The power analysis was completed on MATLAB® and a sample size of 10 and 13 is calculated for force and depth, respectively. Therefore a sample size of 14 will satisfy all the indicated parameters. The tests are repeated on each animal if it is stable and therefore the 14 is the minimum number of tests per test type required. A detailed summary of the power analysis is illustrated in Appendix G.

4.4 Test method

The experimental setup, apparatus required and test method used during the study are explained in this section (See Figure 4.1).

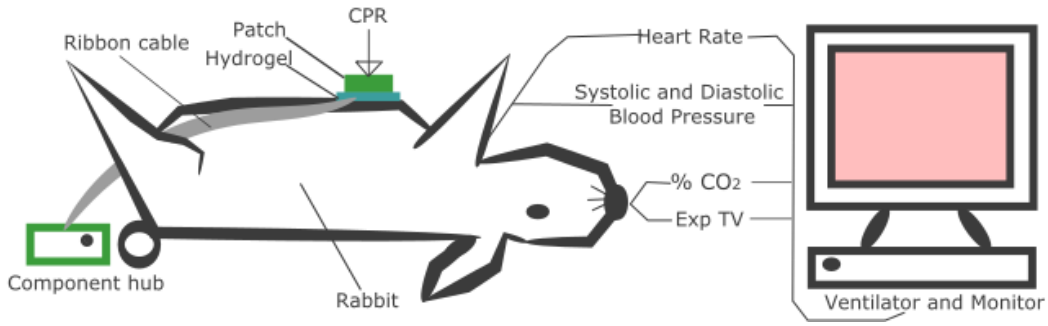

Figure 4.1: Animal testing setup.

4.4.1 Experimental setup

NCPR was performed by an experienced and trained clinician on five sedated, adult New Zealand white rabbits (weight = 2.74 ± 0.27 *kg*, APD = 88.4 ± 2.7 *mm*) at Stellenbosch University medical School Tygerberg Campus Animal Research Laboratory. The experimental setup included the hospital bed on which the subject will be placed for preparation and testing, the ventilator and anaesthesia machine, surgical light and consumables, e.g., gloves, needles, medication, etc.

4.4.2 Apparatus

The main medical apparatus required to complete the animal testing included the Anaesthesia System Gencare (CREST®, Crest Healthcare Technology), Datex-Ohmeda M-ESTPR ventilator (USA) and Datex Engstrom monitor (USA). The respective settings are explained in Table 4.1, which correspond to the guidelines.

Table 4.1: Ventilator and Anaesthesia system settings.

Setting	Dosage	Fixed/ change as required
Breathing rate	35 breaths/min	Fixed
Inspiratory: Expiratory ratio	1:2	Fixed
PEEP	2 *cm H20*	Fixed
Anaesthesia: Isoflurane	0.7-1.8% with 100% O2	
PIP		As required to deliver minute volume.
Minute ventilation	350-400 *ml/min*	

Abbreviations used: PEEP = positive end-expiratory pressure, PIP = peak inspiratory pressure.

The properties displayed and recorded on the monitor are explained in Table 4.2. These values were monitored throughout the testing procedure and video recorded for further analysis.

Table 4.2: Monitor properties description and units.

Property	Description	Unit
CO_2	End-tidal CO_2	kPa
P_{peak}	ventilator peak inspiratory pressure	cmH_2O
MV	Minute volume	L/min
Compl	Respiratory (Lung and chest wall) compliance	ml/cmH_2O
PEEP	Volume/pressure (P_{peak})	cmH_2O
Art BP	Systolic/Diastolic BP (mean BP)	mmHg

Abbreviations used: Art = arterial, Compl = compliance, BP = blood pressure.

4.4.3 Testing procedure

The procedure followed is explained in detail in this section focussing on the aspects highlighted in the study flow diagram in Figure 4.2.

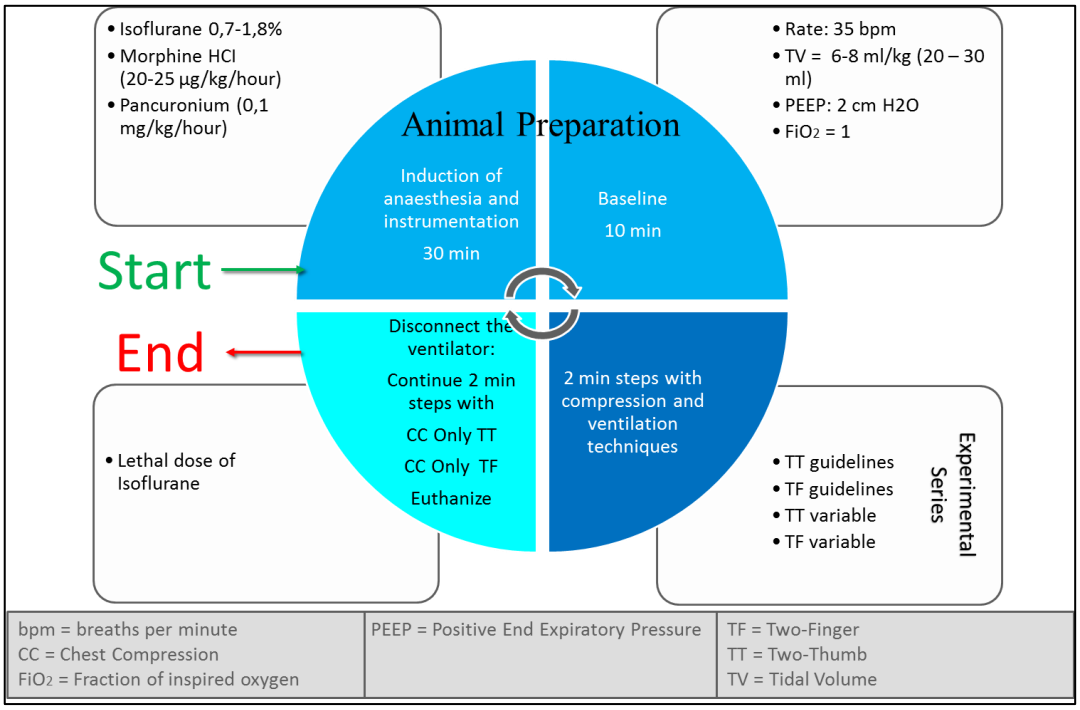

Figure 4.2: Study flow diagram showing the procedure followed during the animal testing.

The test procedure was divided into four main functions namely preparation, ventilation and stabilization, CPR methods and euthanasia. These functions were completed for each subject or phase of the study.

- **Preparation**

For the surgical preparation, each rabbit was anaesthetized with 0.7 - 1.8% of Isoflurane (intubated). The subject was placed in a supine position and a peripheral venous catheter was placed in a vena auricularis and an infusion of 5% dextrose in Ringer's lactate begins at a rate of 5ml kg^{-1} h^{-1}. The catheter used was the Vasofix 22G B/Braun catheter connected to Art-Line™ Biometrix (Breda, Netherlands) with a pressure transducer connected to a Datex Engstrom monitor (Datex-Ohmeda Division, Helsinki, Finland). Arterial oxygenation status was continuously monitored throughout the experiment with a pulse oximeter with the probe affixed to one of the rabbit's hind legs (Ohmeda Biox 3700e, Louisville, KY). The Isoflurane concentration was increased if the animal showed signs of distress or restlessness. Under local anaesthetic a longitudinal mid-line incision was made along the shaved neck and a tracheostomy was performed. After the tracheostomy, the trachea was intubated with an uncuffed 3.5 *mm* (internal

diameter) endotracheal tube. The endotracheal tube was advanced to the mid-trachea and secured by ligature to avoid leakage around the tube. Anaesthesia was maintained during the entire test procedure and pancuronium bromide (0.1 mg kg^{-1} h^{-1}) was used for muscle paralysis. [56] The left carotid artery was cannulated for continuous monitoring of blood pressure (Datex Cardiocap, CCI 104, Helsinki) and for intermittent determination of arterial blood gases [56]. The APD of the animal was measured at the Xiphoid using a Vernier calliper. The fur height was estimated by measuring the distance from the skin to the fur while compressing the fur to the point that the hairs are flush with the measurement tool.

- **Ventilation and stabilization during preparation**

The subjects were artificially ventilated using the time-cycled pressure-limited mode (Datex-Ohmeda ventilator module), with 100% oxygen, a peak inspiratory pressure (PIP) sufficient to ensure a tidal volume of 8–12 *ml/kg* body weight at a rate of 40 *breaths per minute* and an inspiration:expiration ratio of 1:2 and a positive end-expiratory pressure (PEEP) of 4 *cm* H^2O. A tidal volume (V_t) in the range 8–12 *ml/kg* was selected, since this setting results in a partial arterial pressure of carbon dioxide ($PaCO_2$) between 4.5 and 5.3 *kPa* [57]–[59].

Different ventilation methods were introduced and tested during this study using a M_ESTR ventilator module from Datex Ohmeda (Datex-Ohmeda Division, Helsinki, Finland) to investigate the effect of ventilation on CC performance during NCPR, which has a higher ventilation to compression ratio than adult CPR. The two ventilation methods namely guidelines and variable ventilation are compared to the Chest Compression (CC) only tests to determine if the ventilation has an effect on the compression depth and force (See Figure 4.3).

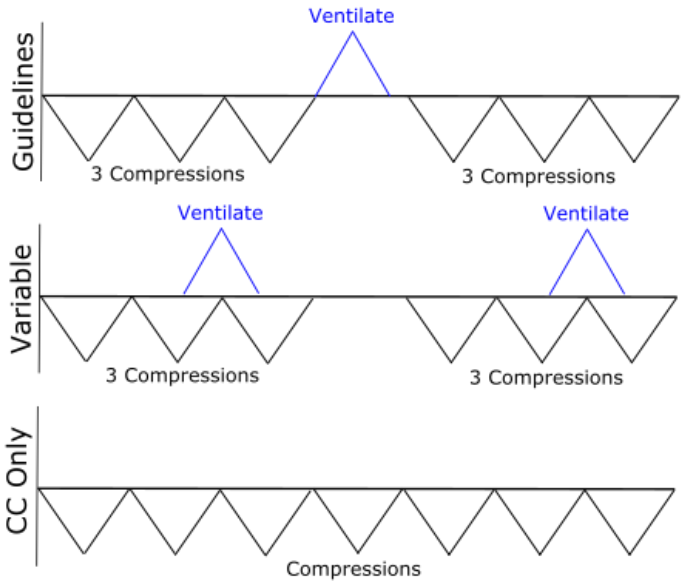

Figure 4.3: Guidelines, variable ventilation and CC only methods described.

- Guidelines ventilation - the ventilator was set to deliver breaths at the desired PIP and is synchronised with the compressions according to the 3:1 compression to ventilation guidelines [17]. After each set of three compressions the ventilator delivered a breath. This continued for the entire duration of compression.
- Variable ventilation - the ventilator was set for the same desired PIP and respiratory rate as during the guideline ventilation. The CCs were delivered in sets of three which are defined as a segment and the breaths were timed independently of the compressions. The clinician ensured that the compressions were consistent and timed correctly throughout the duration of the test.
- CC only - there was no ventilation present and continuous compressions were delivered to the infant or animal. (See Figure 4.3)

- **CPR methods**

Twelve experimental series were performed on five different rabbits by a trained and experienced clinician recruited from the Tygerberg Children's Hospital Neonatal Intensive Care Unit (NICU). The clinician is Neonatal Resuscitation Program (NRP) certified in neonatal resuscitation. During each phase the different ventilation and chest compression methods were completed according to the flow diagram in Figure 4.2. The clinician was instructed to perform NCPR as usual and the CC depth should not be affected by the feedback of the device as his CC depth and force for different methods will be evaluated during the study. The first step in the experimental series was the guidelines ventilation using TT method with a 3:1 compression to ventilation ratio. Thereafter the second step was the same guideline ventilation using the TF method.

Once the guideline ventilation tests were completed, both the TT (step 3) and TF (step 4) method were performed according to variable ventilation, which included three CCs and single ventilation, however the ventilation was administered in a compression series without pauses (asynchronously). Each step was performed for a two minute duration with a resting period of two minutes between each step. The TT and TF method were performed as shown in Figure 4.4.

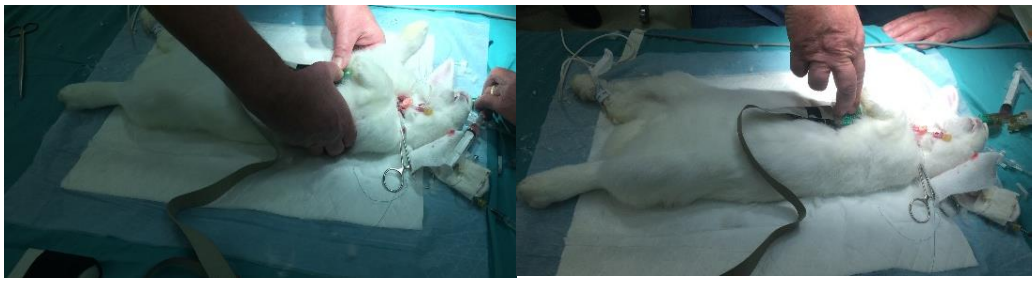

Figure 4.4: (left) TT method (right) TF method on an animal model using the prototype feedback device.

The following steps were performed during each test:

1. The baseline data was recorded, which includes the weight, anterior posterior diameter (APD) of the animal chest, heart rate and blood pressure of the animal.
2. The data acquisition (DAQ) system or device was switched on and placed on the subject's chest with a hydrogel patch.
3. Chest compressions were delivered for 120 seconds at the AHA recommended rate of 90 (-120) CC's per minute with a target sternal displacement of 1/3rd of the APD of the animal's chest.
4. Chest compressions were initiated using the appropriate compression method (TT or TF compression method).
5. The CC depth and force were measured and stored to the SD card.
6. The HR and blood pressure were recorded once the tests are completed.
7. The feedback device was removed and the DAQ system was switched off.

Once the experimental series has been completed the animal could be assessed to determine if another experimental series could be initiated or if the animal was too unstable to continue. In this latter case then CC only tests were performed (i.e. with no ventilation). Before the ventilator was disconnected the thoracic stiffness test was completed where the device was placed on the rabbit's chest and pressed down while recording the depth and force. The chest was allowed to return to its original position after pressing on the device and this was repeated at least three times. Thereafter the ventilator was disconnected and the CC only test was done using both the TT and TF compression method. The CC only test could only be performed at the end of the phase; else the animal may not survive the testing period. Once all of the tests were completed the data were extracted for computer analysis and post processing.

- **Lung hemodynamic data**

The hemodynamic data was recorded during some of the tests by taking a video of the monitor. The data is extracted after testing during the post processing and the results for systolic and diastolic blood pressure, percentage CO_2, tidal volume and lung compliance are included in Appendix H. There is currently no clear understanding of the hemodynamic results and further analysis is required to determine any trends in the results.

- **Euthanasia**

The subject was euthanized once all testing on the specific subject were completed by administering a lethal dose of Isoflurane. The rabbit was then disposed of according to the prescribed humane methods and regulations.

4.4.4 ISO 13485, IEC 60601

The ISO 13485 standard ensures a quality management system that is suitable for medical devices, demonstrates the ability to supply medical equipment that meets the specifications and regulatory requirements and evaluates how well the organization meets these specified requirements. The standard is divided into three classes. Class 1, a non-invasive, minimal risk medical device, is important for this study [60]. The ISO 13485 is not a requirement for the prototype, but expert advice will be sought regarding the standard to ensure that a safe, risk free prototype is developed. As the device is an electronic device, International Electrotechnical Commission (IEC) 60601, which is an international standard for electrical medical devices, is also advised and used as a guideline. (See Appendix I)

4.5 Limitations of the study

The CPR was performed on the subject without inducing hypoxia or circulatory arrest as the animals are too fragile and they may not have survive the procedure if hypoxia is induced. The compression depth and force measured were not affected and the effect of ventilation can still be determined by comparing the results recorded. The force-depth relationship should also not be affected by this limitation of the study. The tests were performed on an animal with a beating heart and the circulation is disrupted by the arterial blood pressure line, which can affect the hemodynamic data obtained.

The APD height of the animals was not measured on the day of testing. A group of animals from Gemeenschappelijk Dierenlaboratorium (GDL), Utrecht University were measured and the APD for the test animals was estimated using a linear fit. When measuring the APD of the control group the rabbit was distressed and placed on its side, which could lead to a slightly higher measurement than the sedated rabbits on their back. Another limitation is that the animal's chest height is different to that of a 'wet' neonate.

The animal was also used for multiple tests to reduce the number of animals sacrificed during the study, which could affect the thoracic stiffness of the chest. This is taken into account when analysing the data.

CHAPTER 5: Fidelity analysis

The fidelity of chest compression (CC) is defined according to a target CC depth. A high fidelity is when the CC depth for all compressions, within a segment and between segments, has a high degree of exactness and can be reproduced, while a low fidelity has a low degree of exactness and cannot be reproduced. A segment is defined as three consecutive compressions separated by a pause. Examples of high and low fidelity CCs are illustrated in Figure 5.1.

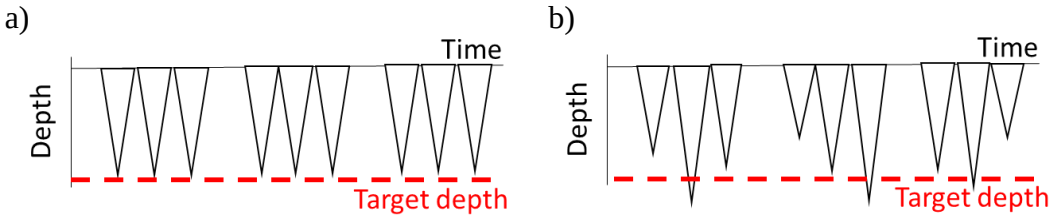

Figure 5.1: a) High fidelity and b) low fidelity chest compressions.

In the context of this study the fidelity is assessed, between compressions and within a segment, by determining the percentage of too shallow, correct and too deep compressions according to a chosen depth range. The depth ranges chosen are the target depth and the target depth range for 'wet' neonates. The target depth, according to the current NCPR guidelines, is one-third of the anterior-posterior diameter (APD) of the animal or neonate's chest. The target depth range for a 'wet' neonate (the population of this study) is based on one-third APD, which is defined as 17.5 to 22.5 *mm*.

5.1 Introduction

During the animal testing the fidelity of chest compressions is calculated to determine the degree of consistency and reproducibility with which the compressions were delivered. The raw depth data in Figure 5.2 shows that the compressions performed were inconsistent as the clinician was unable to reach the same depth during the entire test period and within a segment.

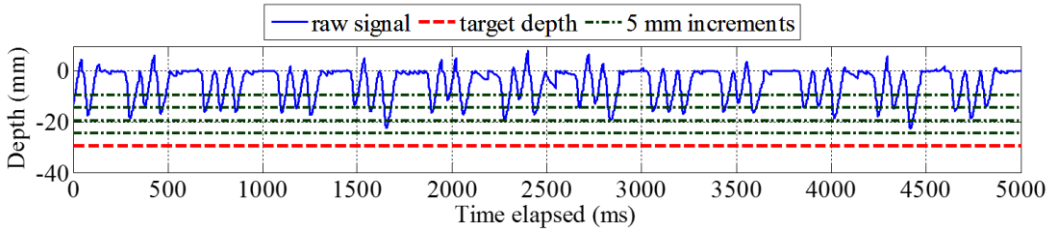

Figure 5.2: Raw depth data from a TT guideline test on Animal B.

The green lines in Figure 5.2 are increments of 5 *mm* to indicate the inconsistency in depth within segments and between all compressions. The depth of compression within a segment varies with up to 10 *mm*. This inconsistency is regardless of the target depth (indicated in red on the graph). When taking the target depth (one-third APD) into account the tests can be analysed to determine how many compressions are within 10%, 20% and 30% of the target depth (See Figure 5.3).

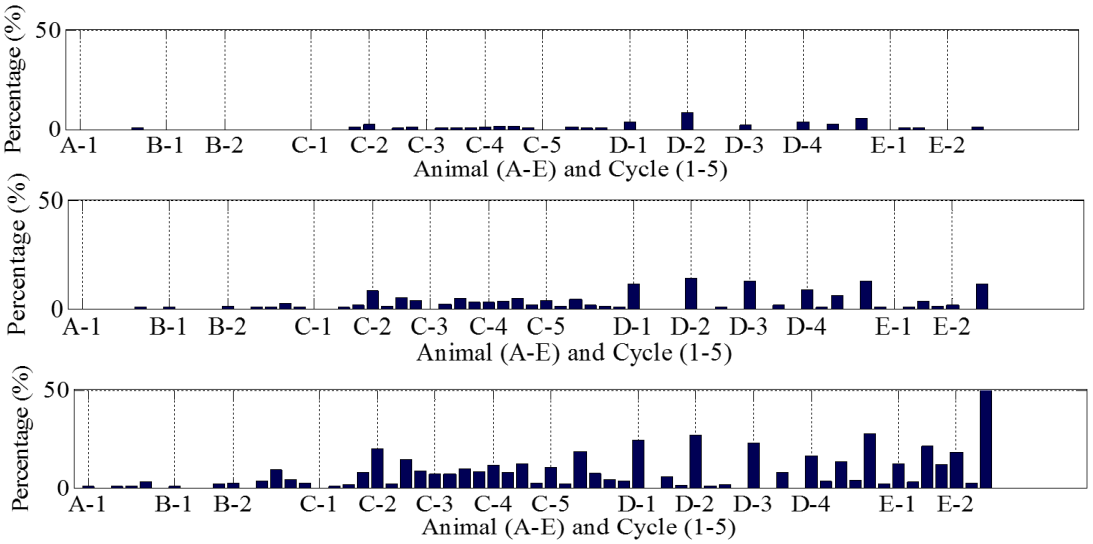

Figure 5.3: The number of compressions within 10% (top), 20% (middle) and 30% (bottom) of the target depth (one-third of the APD).

The 10% and 20% graphs show that many tests have zero percent within the specified range with a maximum percentage for a test being 8% and 15%, respectively. The percentage of compressions within the specified range increase to a maximum percentage of more than 50% when using 30% of the target depth range. This range will be used during further analyses when determining the fidelity according to the target depth.

The device is designed for 'wet' neonates for whom the APD range is specified as 17.5 to 22.5 *mm*, therefore the fidelity analysis is also completed using this range. See Figure 5.4 for the percentage of compressions within this range for each test.

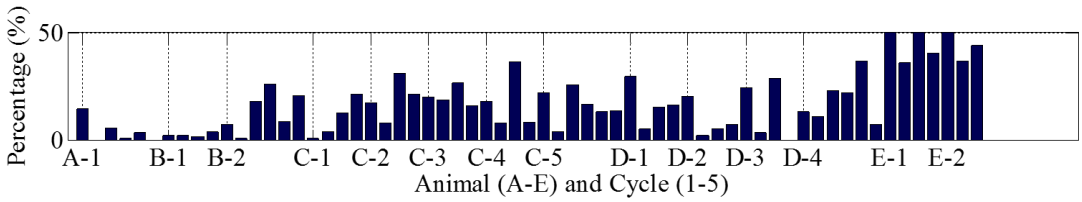

Figure 5.4: The number of compressions within the target depth range for 'wet' neonates (17.5 to 22.5 *mm*).

There is an increased number of compressions within the target depth range for ‘wet’ neonates than within 30% of the target depth (one-third APD). The fidelity is assessed further for both the 30% of target depth and the target depth range for ‘wet’ neonates. The methods for the fidelity analysis are described in this section.

5.2 Methods

The fidelity of each test is determined by examining both the number of individual compressions and the number of compression segments (three consecutive compressions as seen in Figure 4.3) that were within the correct depth range according to the target depth range for ‘wet’ neonates (17.5 to 22.5 *mm*) and the target depth range. A segment within range is defined in this study as a segment with two out of three compressions within the target depth range. The target depth for effective NCPR is calculated as one-third of the animal’s anterior-posterior diameter (APD). The weight and APD height of four New Zealand white rabbits at the Gemeenschappelijk Dierenlaboratorium, Utrecht University, were measured a minimum of three times. An additional eight rabbits were measured at Tygerberg animal laboratory and a linear fit was used to estimate the corresponding APDs for the specific weight of each animal tested on. The results from these measurements are illustrated in Figure 5.5.

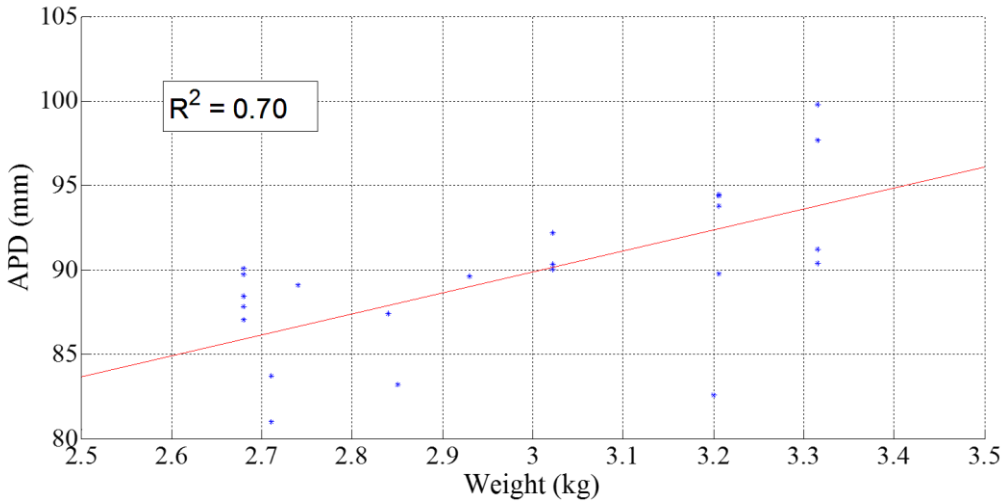

Figure 5.5: Animal weight vs APD of twelve rabbits with a linear fit to estimate the APD height of the tested animals corresponding to their weight.

A linear fit on the graph in Figure 5.5 is used to estimate the APD for the rabbits used in the study. The correlation coefficient of the linear fit is 0.7. The estimated APD for the rabbits tested on are summarized in Figure 5.1.

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Table 5.1: Animal weight and average APD information.

Animal	Weight (kg)	APD (mm)	APD without fur (mm)
Animal A	2.7	93	88
Animal B	2.7	93	88
Animal C	2.6	92	87
Animal D	2.5	91	86
Animal E	3.2	98	93

The target compression depth for each animal is calculated as one-third of the APD using the APD dimensions summarized in Table 5.1. The APD height without fur is also included in the table. The fur was estimated during the measurements, as explained in the study procedure, as 5 *mm*, which is subtracted from the estimated APD. The fur is subtracted due to the fact that the animals tested on were shaved during the tests, while the rabbits measured for the APD had fur. The APD without fur for each animal is used as the APD in further calculations.

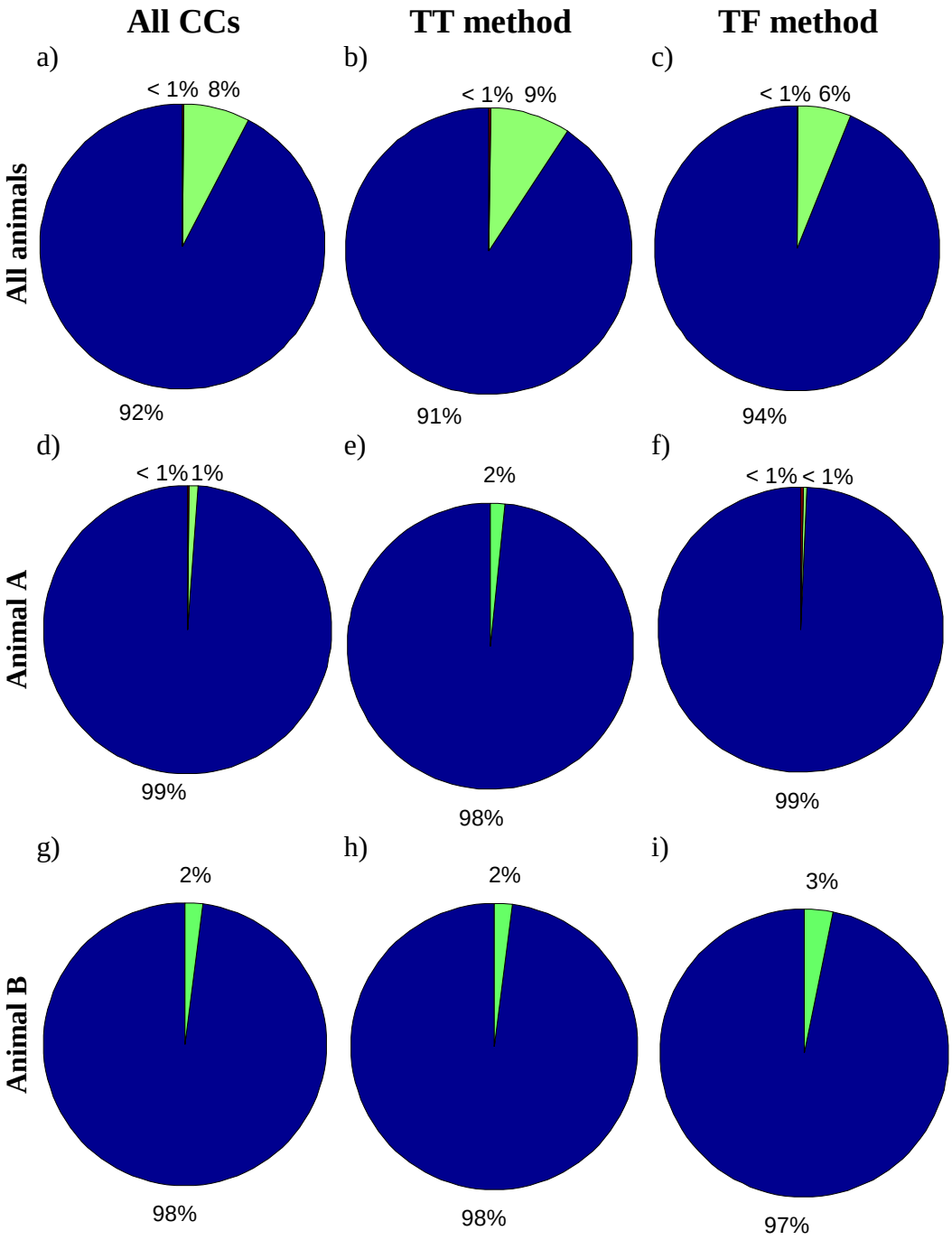
The target depth is an estimation and therefore a range of 30% of the target depth is used to determine whether a compression depth is correct. Using this interval the fidelity of each test can be checked by determining the number of compressions and/or segments that are within the target range, or how many are too shallow or too deep. These graphs, including the fidelity according to the target depth range for 'wet' neonates of 17.5 to 22.5 *mm*, are summarized in this section for all tests per animal and divided into different compression (TT and TF method) and ventilation methods (guideline, variable and CC only).

5.3 Results

The fidelity is assessed according to the target depth range for 'wet' neonates and within a 30% range of the target depth. This analysis is done for all compressions and segments (three consecutive compressions) for all of the tests. The overall compressions per animal was analysed before dividing them into compression and ventilation methods.

5.3.1 Fidelity according to 30% of the target depth for all compressions by animal

All of the tests are analysed by animal to determine the fidelity, consistency and accuracy of the compressions according to 30% of the target depth (one-third of the APD).



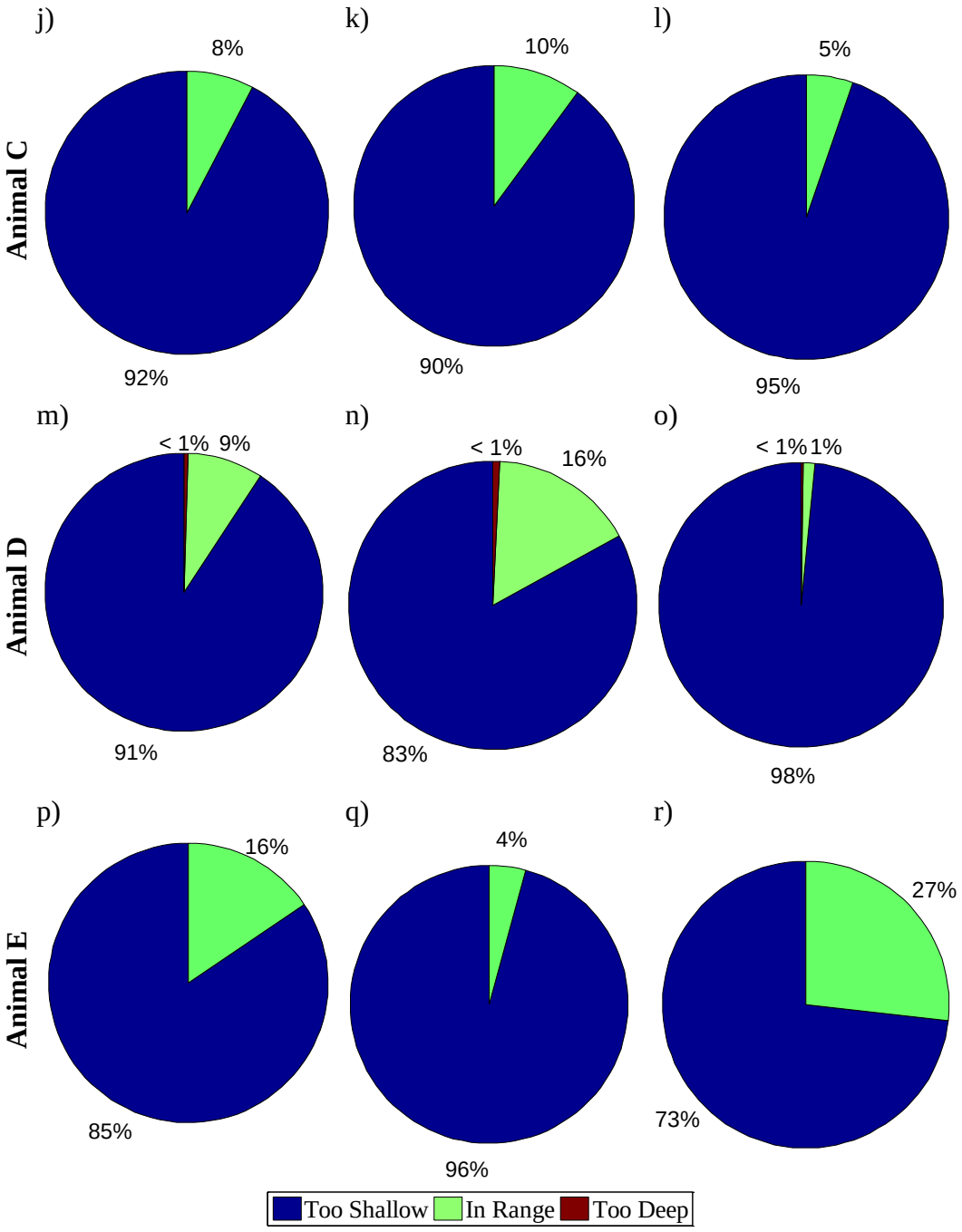


Figure 5.6: Fidelity of compressions within 30% of the target depth (one-third of the APD) for all compressions, TT and TF method, by animal.

The fidelity of all compressions, including TT and TF method, within 30% of the target depth is illustrated in Figure 5.6 a) to c). The mean for all compressions is 92%, 8% and <1% for too shallow, correct and too deep, respectively. When looking at the TT method only, the findings are similar with the majority of all compressions too shallow. The overall mean for all TT method compressions is 91%, 9% and <1% for too shallow, correct and too deep, respectively. During the

TF method test the mean percentage of compressions is 94%, 6% and <1% for too shallow, correct and too deep, respectively. The percentage of compressions correct is larger for the TT method than the TF method. When looking at ventilation types the majority of the compressions are too shallow with 92%, 92% and 94% too shallow for guideline, variable and CC only, respectively.

Figure 5.6 d) to r) illustrates the fidelity of all compressions, TT and TF method, for each animal (Animal A to Animal E). The majority of compressions are too shallow for each animal according to 30% of the target depth. The highest percentage of correct compressions is for TF method on Animal E, which is 27%. The TF method yielded larger mean correct percentages for Animal B and E when compared to the TT method. The percentage correct compression is higher for the TT method than the TF method for Animal A, C and D. The fidelity of all compressions per animal is summarized in Table 5.2.

Table 5.2: Mean percentage of compressions too shallow, within range and too deep for each animal for 30% of the target depth per animal.

	All CCs			TT method			TF method		
	Too Shallow	Correct	Too Deep	Too Shallow	Correct	Too Deep	Too Shallow	Correct	Too Deep
Animal A	99%	1%	<1%	98%	2%	0%	99%	<1%	<1%
Animal B	98%	2%	0%	98%	2%	0%	97%	3%	0%
Animal C	92%	8%	0%	90%	10%	0%	95%	5%	0%
Animal D	91%	9%	<1%	83%	16%	<1%	98%	1%	<1%
Animal E	85%	16%	0%	96%	4%	0%	73%	27%	0%

The compressions are separated into individual tests according to animal to assess the consistency and accuracy of compressions. The fidelity is assessed according to the target depth (one-third APD) per test divided into animal in Figure 5.7.

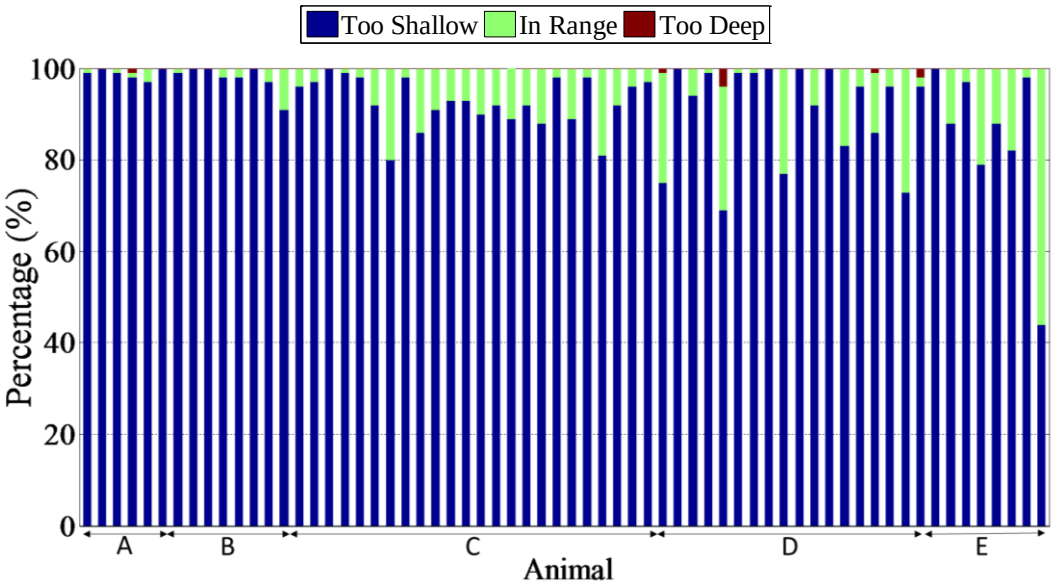
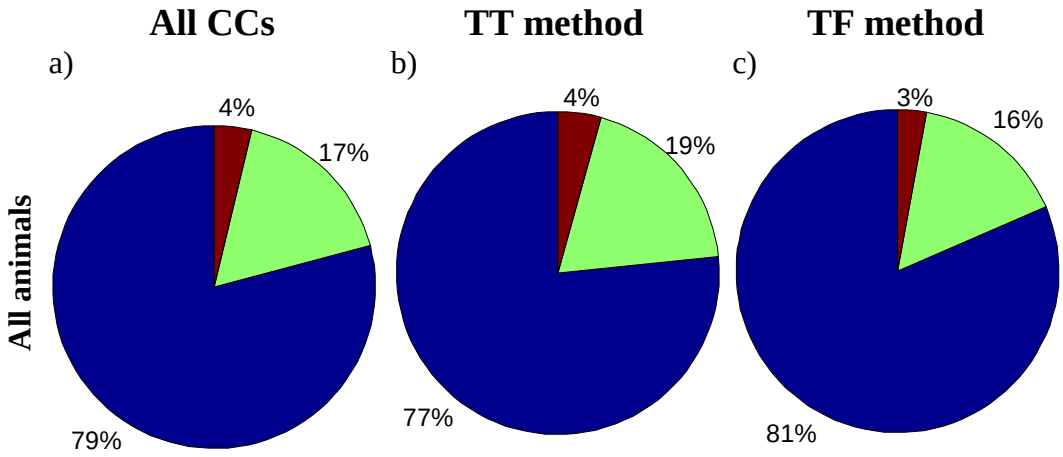


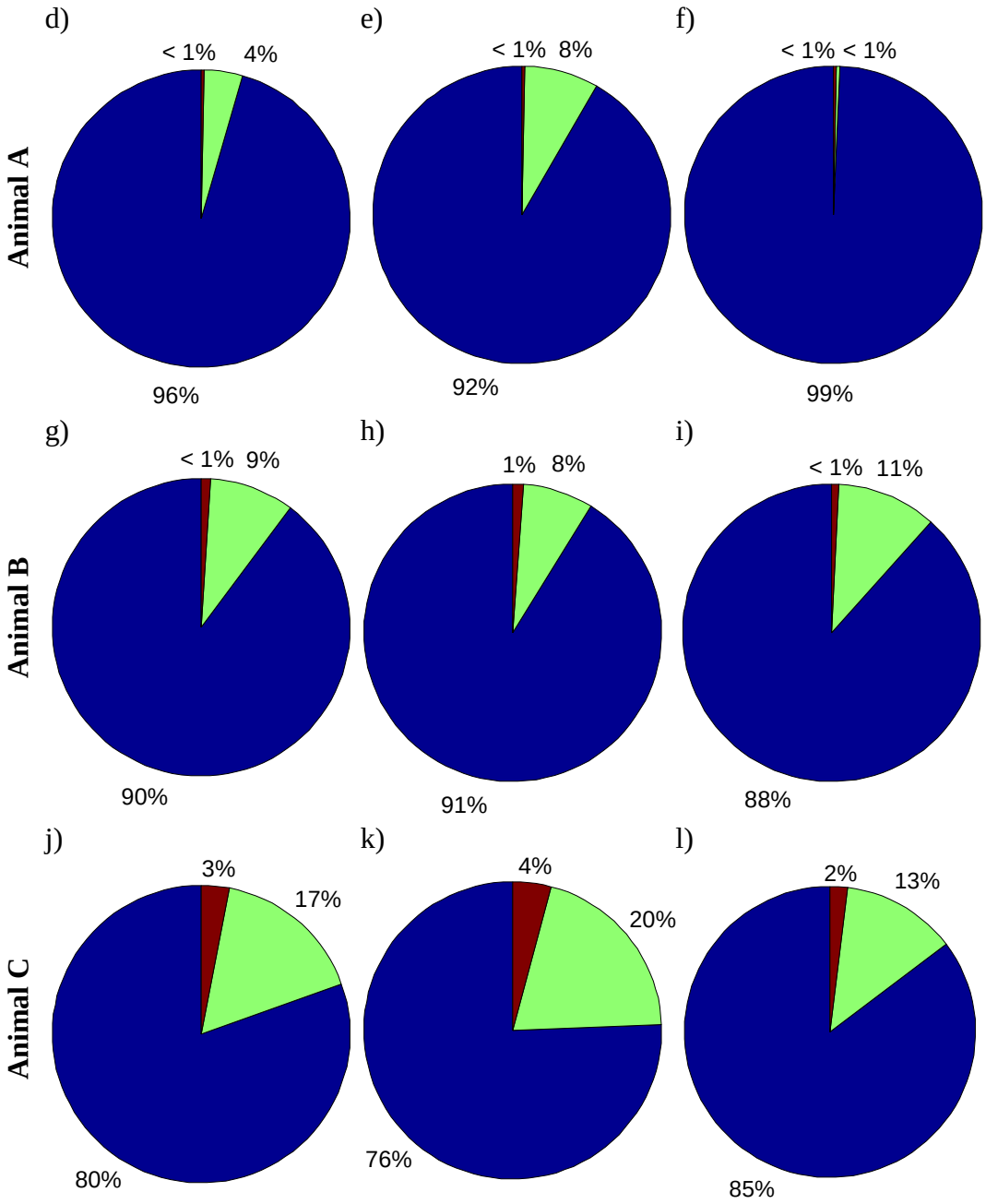
Figure 5.7: Fidelity of all compressions within a 30% range of the target depth (one-third APD).

The fidelity analysis of all individual tests indicates that the majority of compressions are too shallow for all animals according to the 30% of the target depth. This analysis is repeated for the target depth range for 'wet' neonates.

5.3.2 Fidelity according to the target depth range for 'wet' neonates for all compressions by animal

All the compressions, during all of the tests, are assessed according to the target range for 'wet' neonates, which is defined as 17.5 to 22.5 *mm*. The fidelity of all compressions, TT and TF method is illustrated in Figure 5.8.





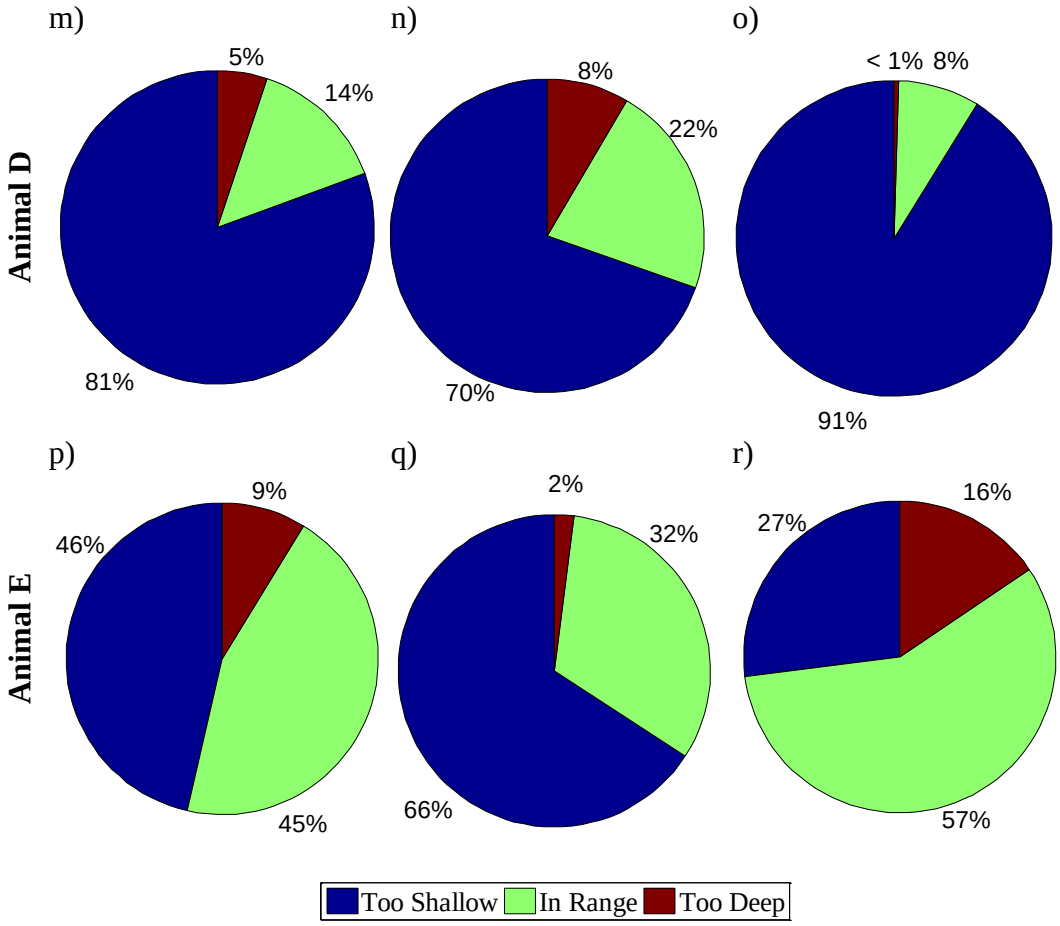


Figure 5.8: Fidelity of compressions within the 'wet' neonate range for all compressions, TT and TF method by animal.

The majority of all compressions are too shallow (< 17.5 *mm*) and a very small percentage in each case is too deep (> 22.5 *mm*). The overall mean for all compressions, including TT and TF method, is 79%, 17% and 4% for too shallow, correct and too deep, respectively.

When looking at only the TT method, the findings are similar with the majority of compressions being too shallow. The overall mean for all TT method compressions is 77%, 19% and 4% for too shallow, correct and too deep, respectively. During the TF method, the mean percentage of compressions is 81%, 16% and 3% for too shallow, correct and too deep, respectively. There is a larger percentage correct compressions for the TT method compared to the TF method.

Figure 5.8 d) to r) illustrates the fidelity of all compressions, TT and TF method for each animal (Animal A to Animal E). The majority of compressions are too shallow for each animal according to the target depth range for 'wet' neonates. The percentage of all compressions too shallow, correct and too deep for each animal are summarized in Table 5.3.

Table 5.3: Mean percentage of compressions too shallow, within range and too deep for each animal using the target depth range for 'wet' neonates.

	All CCs			TT method			TF method		
	Too Shallow	Correct	Too Deep	Too Shallow	Correct	Too Deep	Too Shallow	Correct	Too Deep
Animal A	96%	4%	<1%	92%	8%	<1%	99%	<1%	<1%
Animal B	90%	10%	<1%	91%	8%	1%	88%	11%	<1%
Animal C	80%	17%	3%	76%	20%	4%	85%	13%	2%
Animal D	81%	14%	5%	70%	22%	8%	91%	8%	<1%
Animal E	46%	45%	9%	56%	32%	2%	27%	57%	16%

The largest percentage of too shallow overall compressions (96%) was during the tests on Animal A, while Animal E had the largest percentage of overall correct compressions (45%). The compressions were divided into TT and TF method and the highest percentage of correct compressions was for TF method on Animal E, which is 57%. For Animal B and E the percentage of correct compressions is larger for the TF method. The percentage correct compression is higher for the TT method than the TF method for Animal A, C and D.

Animal E had the largest percentage of correct compressions for all CCs, TT and TF method. The compressions on Animal E were therefore more effective and this animal was chosen for further analysis in Section 5.4.3.

The fidelity according to the target depth range for 'wet' neonates for all compressions divided into guideline, variable and CC only ventilation, which is described in Section 2.4, is illustrated in Figure 5.9.

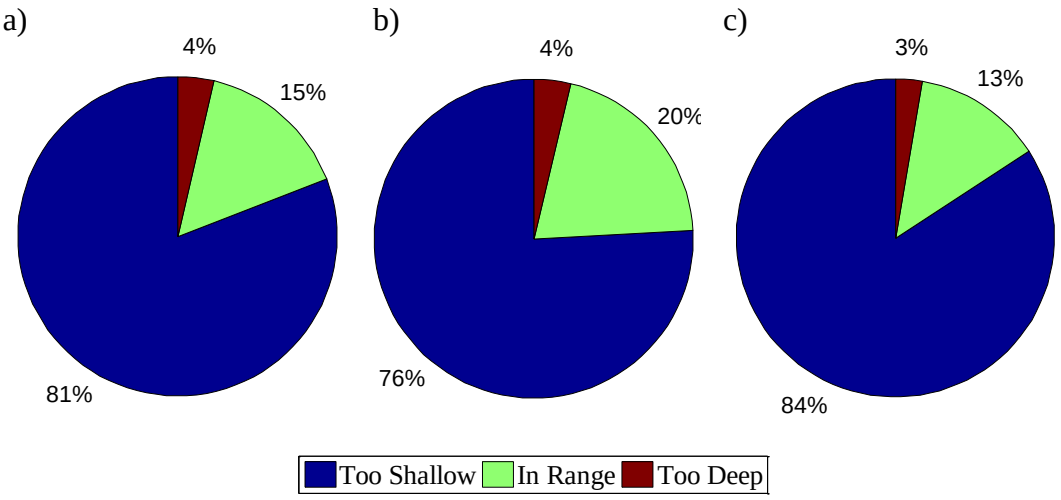


Figure 5.9: Fidelity of compressions within the 'wet' neonate range for a) guideline, b) variable and c) CC only ventilation.

The guideline ventilation method yields an overall percentage of 81%, 15% and 4% for too shallow, correct and too deep, respectively. The percentage of correct compressions is higher with the variable method where the overall percentages are 76%, 20% and 4% for too shallow, correct and too deep, respectively. The CC only tests resulted in the lowest percentage of correct compressions with percentages of 84%, 13% and 3% for too shallow, correct and too deep, respectively.

The fidelity of the TT and TF method can further be divided into the different ventilation methods to determine a correlation between the compression and ventilation methods and the percentage of correct compressions (See Table 5.4).

Table 5.4: Fidelity according to the 'wet' neonate range divided into TT and TF method and further into the guideline, variable and CC only ventilation.

	Guideline			Variable			CC Only		
	Too Shallow	Correct	Too Deep	Too Shallow	Correct	Too Deep	Too Shallow	Correct	Too Deep
TT	76%	18%	6%	76%	22%	2%	80%	15%	4%
TF	85%	13%	1%	76%	19%	5%	88%	11%	<1%

The results from this analysis show that the TT method for all ventilation types has a larger percentage of correct compressions compared to that of the TF method. The higher percentage of correct compressions is during variable ventilation for both TT and TF method. The compression segments will be analysed to further investigate the consistency of the compressions within a segment.

The compressions are separated into individual tests according to animal to assess the consistency and accuracy of compressions, which is illustrated in Figure 5.10.

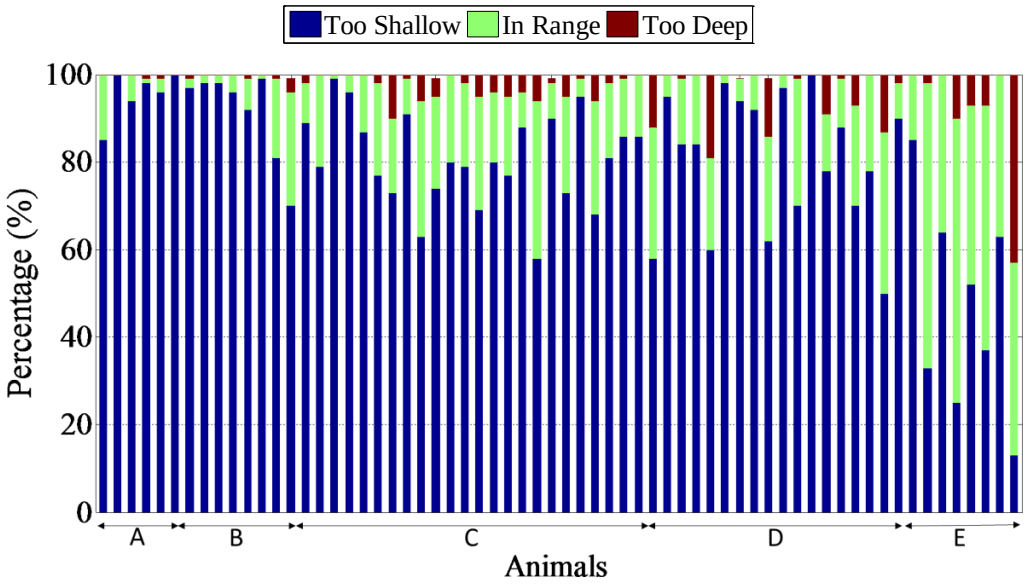


Figure 5.10: Fidelity of all compressions within the target depth range for 'wet' neonates.

The fidelity analysis according to the target depth range for 'wet' neonates shows that the majority of compressions are too shallow for Animal A, B, C and D for each individual test. The clinician was finding it difficult to get the compression depth within the specified range for all tests, regardless of the compression method and ventilation. The clinician was therefore finding it difficult to perform consistent and effective NCPR on the animal model.

5.3.3 Fidelity according to the target depth range for 'wet' neonates for Animal E

The animal with the largest percentage of correct compressions is chosen for further analysis. The data for animal E are therefore divided into different compression methods and ventilation to determine if there are any trends or correlation between the fidelity and compression method or ventilation. A breakdown of all of the tests performed on Animal E is illustrated in Figure 5.11 indicating a large percent of correct compressions during these tests. The increased number of correct compressions within range indicates that more consistent and effective NCPR was being performed.

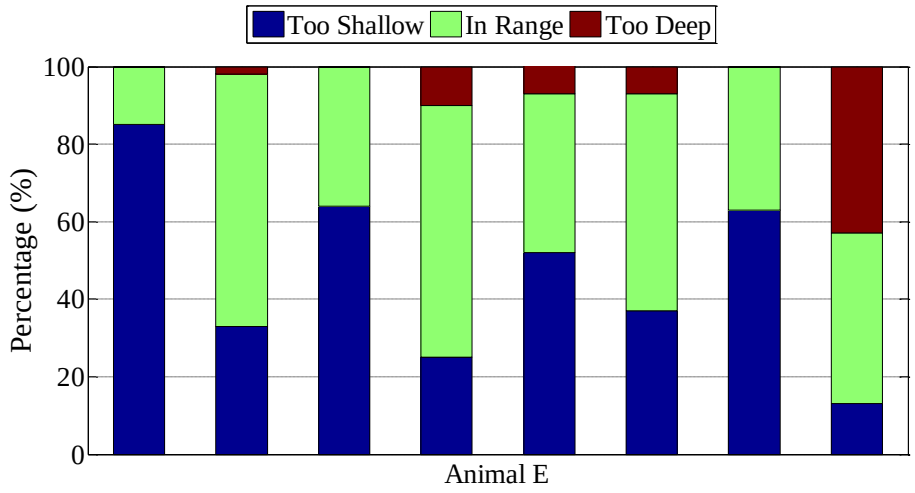


Figure 5.11: Breakdown of the fidelity for the different tests performed on Animal E according to the 'wet' neonate range.

The tests on Animal E result in overall percentages of 46%, 45% and 9% too shallow, correct and too deep, respectively. The compressions can further be separated into TT and TF method, which is illustrated in Figure 5.7 q) and r), respectively.

These results show that the percentage of compressions within range is significantly higher for the TF method with a percentage of 57% correct compressions compared to the 32% correct compressions during the TT method. During the TT method a large percentage (66%) of compressions were too shallow, while 2% of compressions were too deep. For the TF method 27% of compressions were too shallow and 16% were too deep. The TT and TF compression method results are further divided into guideline and variable ventilation in Figure 5.12 and Figure 5.13.

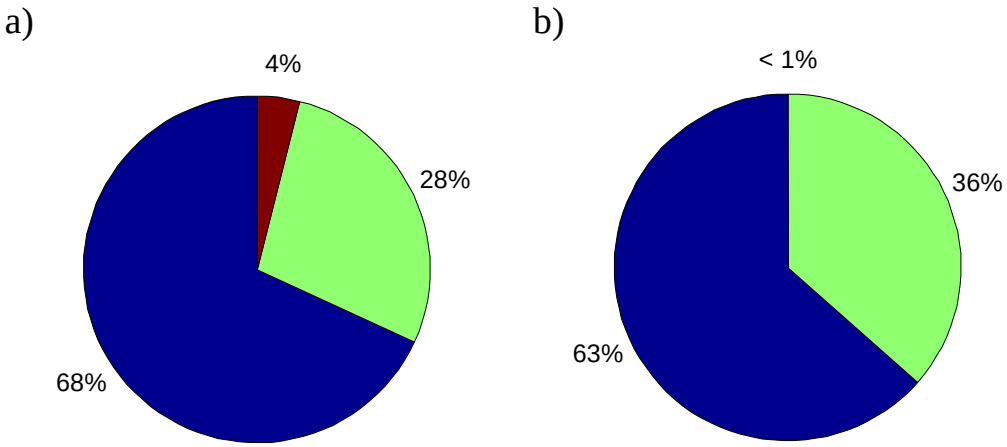


Figure 5.12: TT method fidelity of all compressions for a) guideline and b) variable ventilation for Animal E.

During the TT method there is a larger percentage correct compressions with the variable ventilation of 36% than for the guideline ventilation which has 28% correct compressions. The TT guideline method results in 68% of compressions too shallow and 4% too deep, while the TT variable method results in 63% compressions too shallow and <1% too deep.

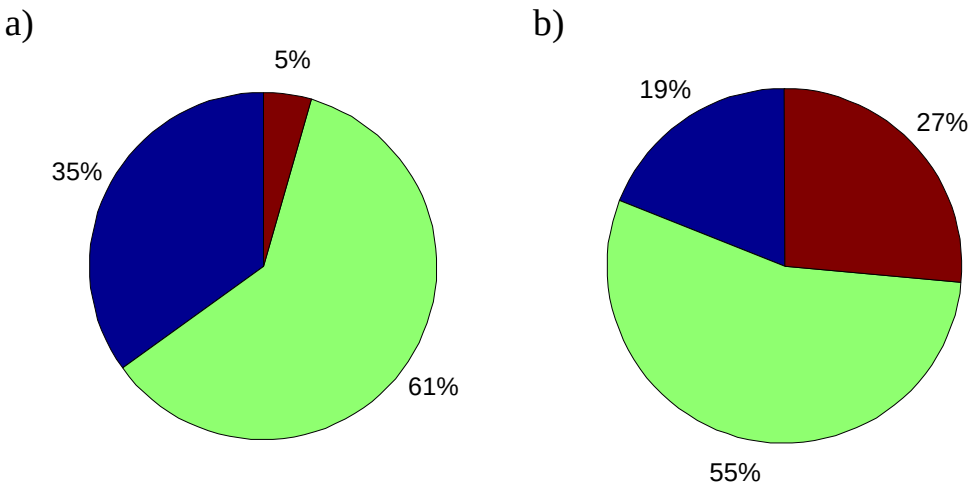


Figure 5.13: TF method fidelity of all compressions with a) guideline and b) variable.

The percentage compressions using TF guideline method is 35%, 61% and 5% too shallow, correct and too deep, respectively. The percentage compressions using TF variable method is 19%, 55% and 27% too shallow, correct and too deep, respectively. A larger percentage of compressions are correct during the TF method than the TT method.

The fidelity of the chest compression segments was also assessed according to the target depth range for 'wet' neonates in the following section.

5.3.4 Fidelity according to the target depth range for 'wet' neonates for all chest compression segments

For a segment to be correct, two out of three compressions need to be correct. If more than two out of three compressions within a segment are too shallow or too deep, the segment is classified as too shallow or too deep, respectively. The segment results for the analysis using the 'wet' neonate range is illustrated in Figure 5.14.

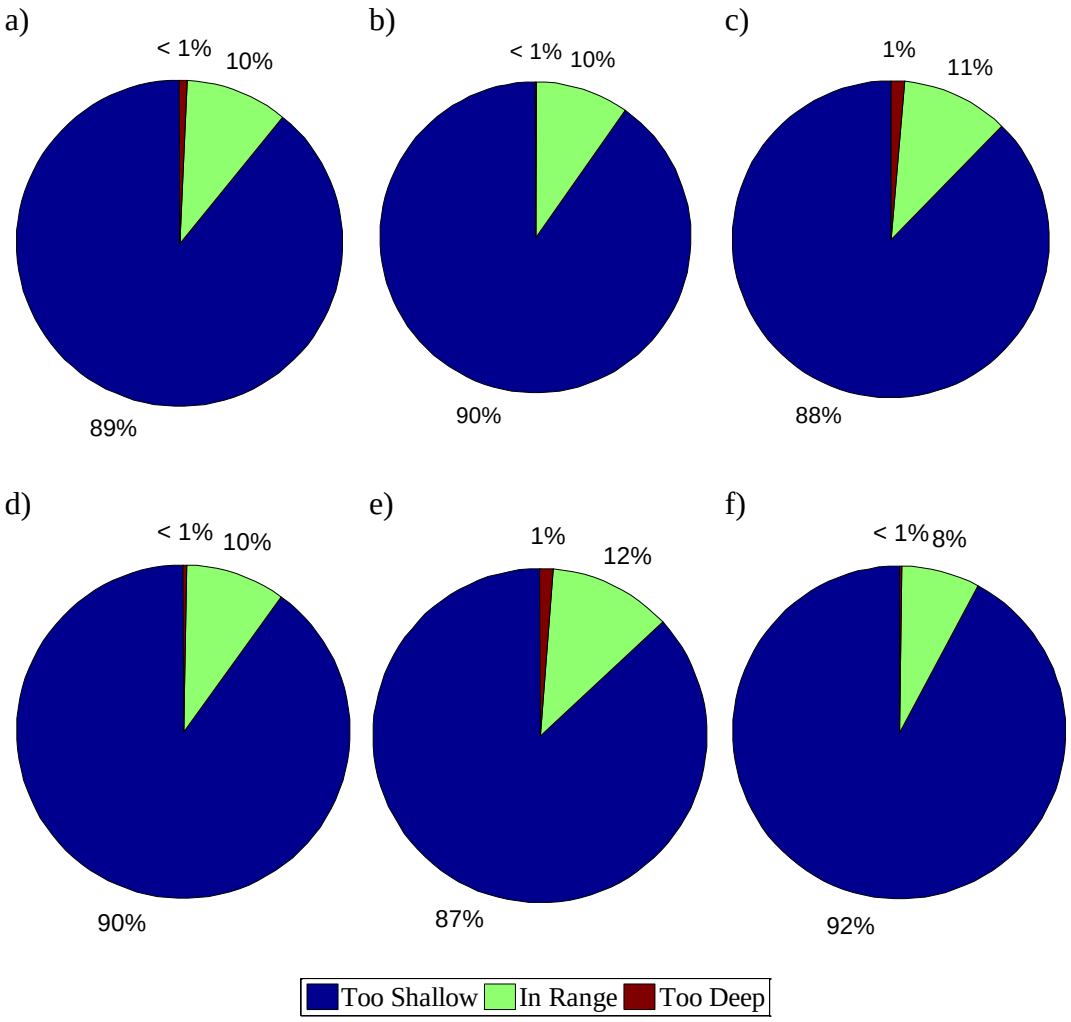


Figure 5.14: Fidelity according to the 'wet' neonate range for a) all segments, b) TT method, c) TF method, d) guideline, e) variation and f) CC only ventilation.

The majority of all segments are too shallow (< 17.5 *mm*) and a very small percentage in each case is too deep (> 22.5 *mm*). The overall mean for all compressions, including TT and TF method, is 89%, 10% and <1% for too shallow, correct and too deep, respectively. Overall mean for all TT method compressions is 90%, 10% and <1% for too shallow, correct and too deep, respectively. During the TF method test the mean percentage of compressions is 88%, 11% and <1% for too shallow, correct and too deep, respectively.

The guideline ventilation yields an overall percentage of 90%, 10% and <1% for too shallow, correct and too deep, respectively. The percentages for variable ventilation are 87%, 12% and 1% for too shallow, correct and too deep, respectively. The CC only percentages are 92%, 8% and <1% for too shallow, correct and too deep, respectively. It is clear that the clinician is finding it difficult to perform consistent compressions on an animal model.

5.4 Discussion of fidelity analysis

The fidelity graphs illustrate a difficulty to achieve consistent and effective CCs in a clinical setting. There is inconsistency between tests, within segments and within compressions. The results also show that the majority of chest compressions (CCs) are too shallow according to 30% of the target depth and the target depth range for 'wet' neonates of 17.5 to 22.5 *mm*. The fidelity according to these two target depth ranges were assessed further to determine whether there was an effect on the fidelity due to different CC methods and ventilation.

5.4.1 Fidelity according to 30% of the target depth

The fidelity is assessed according to the target depth range, which resulted in the majority of CCs being too shallow. The actual target depth is one-third of the APD, however a range around the target depth was chosen to assess the fidelity. The range for 10%, 20% and 30% from the target depth was assessed and the 30% range was chosen for further calculation. The fidelity results using this range yielded the majority of the CCs for all tests, TT and TF method, guideline, variable and CC only tests, too shallow. The overall mean percentages for all CCs were 92%, 8% and <1% for too shallow, correct and too deep, respectively.

The mean overall percentages for the TT method was 91%, 9% and <1% for too shallow, correct and too deep, respectively, which was larger than the mean overall percentages for TF method of 94%, 6% and <1% for too shallow, correct and too deep, respectively. The TT method had a larger overall percentage correct CCs compared to the TF method. The mean overall percentage of shallow CCs for guideline, variable and CC only was 92%, 92% and 94% respectively.

The overall compressions were also analysed according to animal. The majority of compressions are too shallow for each animal according to 30% of the target depth. Animal B and E showed a larger mean percentage of correct compressions for the TT method compared to the TF method. The percentage correct compression is, however, higher for the TT method than the TF method for Animal A, C and D. Animal E using the TT method had the largest percentage of correct compressions recorded. The animal was larger than the other animals that were tested on, possibly making it easier to estimate the APD height and the CC depth is therefore in a more familiar range. Research also shows that the TF method is more effective when the infant is larger, which explains the larger mean percentage of correct compressions for the TF method for this animal.

5.4.2 Fidelity according to the target depth range for 'wet' neonates for all compressions

The fidelity is analysed according to the target depth range for 'wet' neonates of 17.5 to 22.5 *mm*, modelled by an animal model. The mean percentages for all CCs were 79%, 17% and 4% for too shallow, correct and too deep, respectively. This

analysis resulted in a higher percentage of correct CCs compared to the analysis according to 30% of the target depth. The overall percentage of correct CCs using TT method was 3% higher than the TF method, which support the NCPR guideline's recommendation to use the TT method. The overall compressions were further analysed according to ventilation.

The guideline ventilation yields an overall percentage of 81%, 15% and 4% for too shallow, correct and too deep, respectively. The percentage of correct compressions is higher with the variable ventilation where the overall percentages are 76%, 20% and 4% for too shallow, correct and too deep, respectively. The CC only tests resulted in the lowest percentage of correct compressions with percentages of 84%, 13% and 3% for too shallow, correct and too deep, respectively. The results, when divided into ventilation, show that the TT method has a larger percentage of correct compressions compared to the TF method regardless of the ventilation used. The fidelity was also assessed according to animal for the overall compressions, TT and TF method.

The highest percentage of correct compressions for Animal E of 57%, was for TF method. Animal B also showed a larger percentage of correct compressions using the TF method. The percentage correct compression was higher for the TT method than the TF method for Animal A, C and D. These results are similar to the results found when assessing the fidelity according to target depth, which can be explained by the difference in size of the animals.

The fidelity using the target depth range for 'wet' neonates was also divided into a segment analysis which resulted in similar percentages, with the number of correct CCs for TF method being slightly more than TT method by 1% for all compressions. The fidelity within segments and between segments is therefore better using the TF method. The ventilation fidelity showed that the variable ventilation resulted in the largest percentage of correct segments, with guidelines being the second highest and the CC only method being the lowest. This analysis of segments supports the findings from the fidelity analysis for CCs.

5.4.3 Fidelity for Animal E according to the target depth range for 'wet' neonates

The largest percentage of correct CCs were for the tests performed on Animal E. This percentage for Animal E indicates that the CCs were the most effective and these results were therefore analysed further. When looking at the results for Animal E, it is not clear whether there is a correlation between CC method and ventilation with regards to the fidelity of compression depth. The percentage of CCs within range is significantly higher for the TF method with 57% correct compared to that of the TT method of 32%.

5.4.4 Possible reasons for the high percentage of shallow compressions

The fidelity results indicate that the majority of the compressions were too shallow, illustrating that the clinician was finding it difficult to deliver good quality CCs. This section discussed possible reasons for the too shallow CCs.

For guideline ventilation, the clinician was rushed to achieve the 120 events per second as indicated by the NCPR guidelines and to ensure that three CCs were delivered between the short ventilation pause. The rushed CCs could result in too shallow CC depth. The rate of performing the TT and TF method could affect the CC depth, depending on the time and effort required to perform each method.

Another possible reason for too shallow CCs could be the incorrect estimation of the APD of the animal. It is difficult for a clinician to estimate the APD during NCPR. A recommendation for the feedback tool is to include a method to accurately estimate the APD of the animal or neonate, which eliminates the need for the clinician to estimate the depth resulting in an improved CC fidelity.

5.4.5 Fidelity findings and the current NCPR guidelines

NCPR guidelines indicate that CCs are more likely to be too shallow than too deep and that clinicians find it difficult to estimate the target depth during NCPR. The results support the NCPR guidelines by indicating the majority of compressions being too shallow and highlight the difficulty to estimate and achieve the compression depth. The NCPR guidelines also indicate the preference for the TT method over the TF method. When analysing al of the data according to the target depth and target depth range for ‘wet’ neonates, the TT method had a larger percentage of correct compressions. This supports the ERC’s recommendation to perform the TT method instead of the TF method.

These results are, however, contradicted when analysing the segments only or when isolating Animal E, which resulted in a larger percentage of correct compressions when using the TF method. During the segment analysis the percentage of correct CCs were similar for TT and TF method, while the analysis of Animal E showed a significantly higher mean percentage using the TF method than the TT method. Animal E was the largest animal tested with the largest APD height. The size of the animal could affect the compression depth as the target depth is easier to estimate for larger animals and the TF method is also recommended for larger APD heights, which could explain the increased fidelity using this more suited CC method.

5.4.6 Limitations of the test

The main limitation of these tests is that the APD height used was not measured on the day of testing and it was estimated using a linear correlation by using data obtained from similar animals. The target depth is based on the APD height, which is an important parameter used during the fidelity analysis.

CHAPTER 6: Force-depth analysis

This chapter investigates the force-depth relationship of the compressions performed on an animal model.

6.1 Introduction

The compression depth is a key indication of the quality of chest compressions (CCs) during NCPR. The feedback device measures and stores the depth data and gives depth feedback to the clinician using LEDs over the duration of the test. The depth range for NCPR on a 'wet' neonate is between 17.5 and 22.5 *mm*, which is based on the guideline of a target depth of one-third of the anterior-posterior diameter (APD) of the premature 'wet' neonate. The small range makes the compression depth during NCPR very important as too shallow compressions are insufficient to save the infant and reduces the flow, while too deep compressions can harm the infant and also restrict the flow.

The force applied to achieve this depth during CC is also an important factor. This section describes the force-depth relationship during NCPR on an animal model and investigates any trends between ventilation and/or CC methods. This section includes the methods used, results and discussions.

6.2 Methods

The method for measuring the compression depth and force are described in Section 3.2 and 3.3, respectively. The current section describes the post processing methods used to analyse the raw data extracted from the SD card after testing was completed. The data was post processed offline using mathematical software MATLAB® (Natick, MA, USA). The time, acceleration and force data were recorded by the feedback tool after being imported for post processing. The force-depth analysis is explained in this section.

6.2.1 Depth

The depth was estimated by double integrating the acceleration signal. The acceleration signal was filtered through a low-pass filter to remove the noise before converting it to mm/s^2 and before integration. The acceleration signal was integrated to calculate the velocity signal and filtered with a high pass filter to emphasize the transient components. The depth signal was determined by integrating the velocity signal and filtering it with a high pass filter. For each test the maxima in the CC depth were determined using a peak detection algorithm and then averaged over the entire CC period.

6.2.2 Force

The raw force data was converted to SI units and the offset was removed before the peak detection algorithm was applied to the signal to determine the minimum and maximum peaks, which were used to calculate the peak force by subtracting the absolute minimum from the absolute maximum. These values were used to calculate the mean force and the standard deviation. The post processing methods are indicated in Figure 6.1, including the depth and force algorithms.

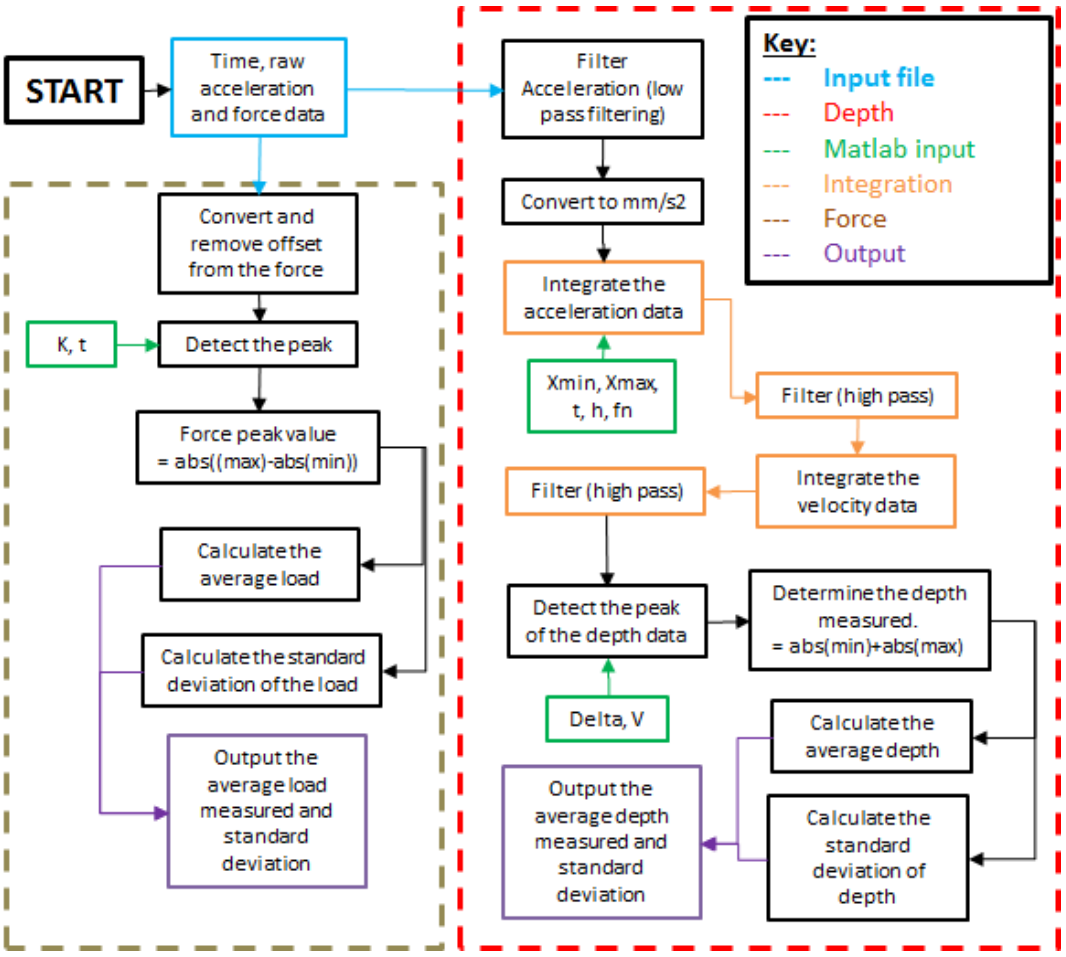


Figure 6.1: Post processing flow diagram for depth and force.

The post processing algorithm described in this section and illustrated in Figure 6.1 was used to investigate the force-depth relationship. An ANOVA analysis was completed on the depth and force results to determine the variance within and between different groups of data.

6.3 Results

The measured and calculated results for the force-depth analysis and the calculated statistical variance are included in this section.

6.3.1 Force-depth relationship for each animal

The force and depth is analysed per animal in this section to determine if there is a trend or correlation between the force and depth results and the CC method and ventilation used during the animal tests. The force is indicated on the left hand axis of each graph for Animal A, B, C, D and E in Figure 6.2, while the normalized depth (depth/APD) is indicated on the right hand axis with the target depth of one-third APD/APD indicated by a red dotted line on each graph.

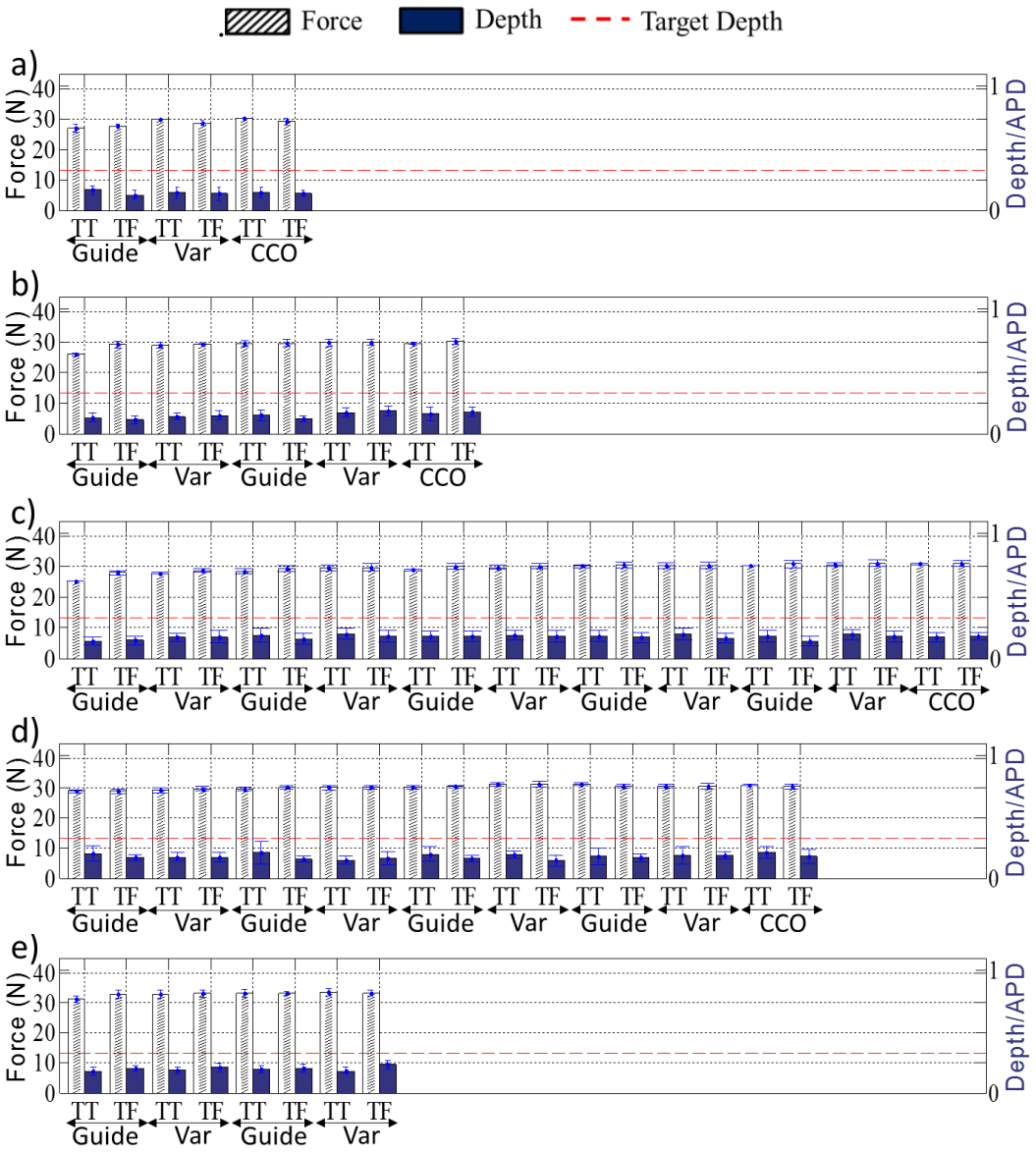


Figure 6.2: Force-depth analysis for all tests on Animal A, B, C, D and E (target depth of one-third APD/APD = red dotted line).

The force-depth results illustrated in Figure 6.2 show that the forces applied are similar for all tests, while the depths vary between the tests and within a specific

test (larger calculated standard deviations). The results are analysed according to CC method and the overall mean depth and force for each animal using the TT and TF method are summarized in Table 6.1.

Table 6.1: Mean depth and force per animal using the TT and TF method.

	TT method				TF method			
	Mean Depth (mm)	**SD (mm)**	**Mean Force (N)**	**SD (N)**	**Mean Depth (mm)**	**SD (mm)**	**Mean Force (N)**	**SD (N)**
Animal A	13.3	3.5	29.2	1.7	11.8	3.3	28.7	1.0
Animal B	12.8	3.3	28.6	1.8	11.6	3.3	29.0	1.0
Animal C	14.2	3.8	29.2	1.6	13.1	4.3	29.0	1.1
Animal D	12.1	3.7	28.7	1.6	13.8	3.8	29.1	1.5
Animal E	13.1	3.11	29.2	1.5	11.9	3.7	28.4	1.7
Average	14.6	4.6	30.1	1.9	15.0	4.4	30.2	1.6

Abbreviations: TT = two-thumb, TF = two-finger, SD = standard deviation

The mean forces over all the tests are similar irrespective of the CC method used. The mean depth recorded for each animal, except Animal D, is larger for the TT method than the TF method. Surprisingly the overall mean depth is also higher during the TF method compared to the TT method. The force values are similar, with Animal A, C and E higher mean forces when using TT method and Animal B and D when using TF method. There is no clear correlation between CC force and compression method. The CC depth and force are analysed according to ventilation in Table 6.2.

Table 6.2: Mean depth and force according to CC method and ventilation.

		Mean Depth (mm)	**SD (mm)**	**Mean Force (N)**	**SD (N)**
Guideline	All CCs	14.6	5.2	29.7	2.0
	TT method	14.6	5.5	29.6	2.3
	TF method	14.6	4.9	29.8	1.6
Variable	All CCs	15.1	3.8	30.4	1.6
	TT method	14.8	3.6	30.4	1.6
	TF method	15.3	4.0	30.5	1.7
CC Only	All CCs	14.4	4.5	30.5	1.0
	TT method	12.4	5.3	30.6	0.9
	TF method	15.2	3.9	30.5	1.0

Abbreviations: CC = chest compression, TT = two-thumb, TF = two-finger, SD = standard deviation

The highest mean depth values for all compressions, TT and TF method, are during the variable ventilation, while the lowest depth is during CC only ventilation. The force values are similar, irrespective of the ventilation used, with slightly lower forces when using guideline ventilation. All the mean depths recorded are, however, below the target depth, with relatively large standard deviations, which supports the finding during the fidelity analysis that the compressions are inconsistent and ineffective during NCPR performed by a trained clinician.

6.3.2 Two tailed t-test

The CC depth and force data for the TT and TF method were analysed using a two-tailed t-test. This test was used due to the fact that both sides of the mean should be evaluated. Both CC methods were tested on the same animal and therefore the test is dependent (one group for all tests). The results for the t-test indicated a p value of 0.232 and 0.003 for depth and force, respectively.

Die p value indicates the level of statistical significance. For a p-value of <0.05 it with 95% certainty that the means are different, and they are therefore significantly different.

6.3.3 ANOVA

The one way ANOVA was performed on the depth and force data obtained during the animal tests. The CC depth and force was compared for different compression methods, different ventilation (guideline, variable and CC only) and per animal. These results are described in Table 6.3.

Table 6.3: ANOVA results for depth and force according to CC method, ventilation and per animal

	Parameter	F statistic	P value
Compression method	Depth	10.65	0.0018
	Force	20.42	3.10919E-5
Ventilation	Depth	33.84	1.3452E-11
	Force	367.58	3.70276E-43
Animal	Depth	56.53	1.16348E-28
	Force	3115.82	1.832E-139

The large F statistic value and low p value (< 0.05) indicates that there is more variation between the tested groups than within the group itself. If a p value is less than 0.001 then it is sure (more than 99%) that there is a difference between the two means, which is true for different compression methods and ventilation and per animal for force and depth. The compression method depth value is slightly higher, however it is still below 0.05.

6.4 Discussion of force-depth analysis

The mean recorded CC depth during the animal tests are higher for the TT method than the TF method for Animal A, B, C and E. The mean forces were similar for TT and TF method. The TT method is therefore more effective according to the force-depth analysis, as larger depths are achieved (closer to the target depth), with similar applied forces. This supports the guidelines' recommendation to use the TT method over the TF method.

The mean CC depth and force are further analysed according to different ventilation. The variable ventilation has the largest mean CC depths, followed by guideline and then CC only ventilation. All mean CC depths are, however, below the target depth The CC depth standard deviation is between 3.3 and 5.5 *mm*, which supports the low fidelity in CC depth found during the fidelity analysis performed during this study. The ventilation analysis indicates a slightly lower mean force with a low standard deviation, between 0.9 and 2.3 *N*, recorded for guideline ventilation than variable and CC only ventilation.

The force-depth results are compared to that obtained using the NCPR glove during a manikin study [22]. The TT method yielded maximum CC depths and forces of as much as 25.7 ± 3.2 *mm* and 35.9 ± 2.2 *N* while the TF method produced CC depths and forces of as much as 21.6 ± 2.2 *mm* and 23.7 ± 2.9 *N*. The current study yielded overall lower depths than the glove project. The APD of the animal is however, smaller than that of the manikin, which results in a lower target depth. The TT method, however, yielded larger depths and forces during both studies. The difference in force measurement is significantly smaller than that observed during the glove project, which could be due to the difference in chest stiffness of the animal and manikin. The manikin is also a linear model, which is not a good representation of an infant's chest.

A two tailed t-test was performed on the CC depth and force to compare the TT and TF method, which investigates whether there is a significant (or only random) difference in the average depth or force between the TT and TF method. The low p-value (< 0.05) for depth indicates that there is a significant difference between the depth during TT and TF method. It is therefore likely to get a result similar to these and it is not different from what was expected. The p-value larger than 0.05 for the force results indicates that there is no difference between the force means for TT and TF methods. If one was to say that there was a difference there is a 23.2% probability that the depth was influenced by the compression method

The variance within and between different ventilation and animals was determined using a one-way ANOVA, which is used when more than two groups are compared and a parametric test is applicable. The large F statistic value and low p value (< 0.05) for all groups (CC method, ventilation and according to animal) indicates that the variance is not significant and that there is more variation between the tested groups than within the groups themselves.

CHAPTER 7: Force-deformation curve

This chapter includes the methods, results and discussions of force-deformation curves obtained from chest compressions (CCs) performed on an animal model.

7.1 Introduction

The force-deformation curve obtained during CC was investigated to gain deeper insight into the influence of different CC methods and ventilation on the CC mechanics.

7.2 Methods

The force-deformation curve was completed for a section of six consecutive compressions for each test type on Animal C and Animal D. These two animals were chosen for the force-deformation analysis, because the fidelity analysis showed larger percentage correct compressions for each test type. Animal E, with the largest percentage correct compressions, could not be used for the force-deformation curves as there were no CC only tests performed on this animal. A mean force-deformation curve is determined for each test type, which is used during further analysis to compare different CC methods and ventilation. The shape of the force-deformation curve, the gradient, as well as the energy required to perform the compression, was investigated. The energy required is determined by calculating the area under the mean curve for each test type.

The slope of the tangent line to the curve in the initial, middle and final section was analysed to investigate the rate of the CC depth and force (See Figure 7.1).

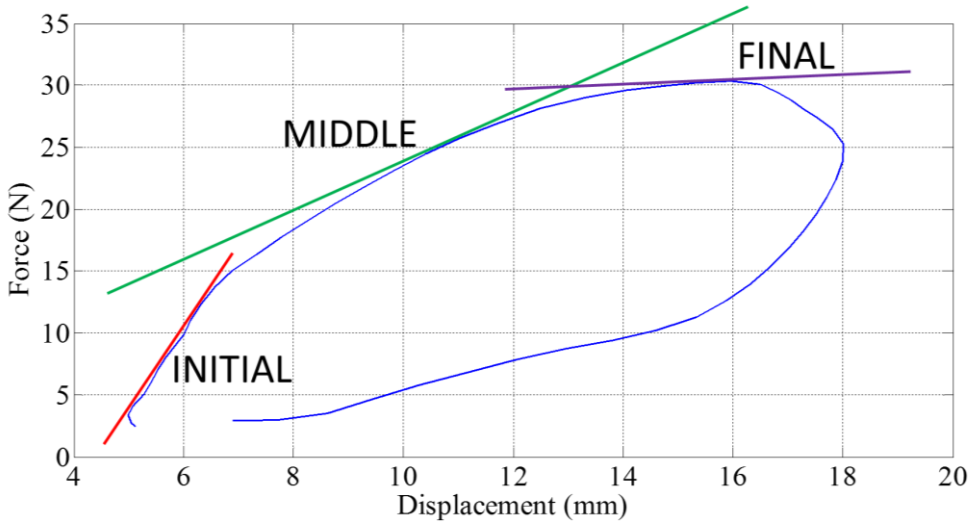


Figure 7.1: Initial, middle and final slope of the force-deformation curve.

The initial slope gives insight into the force, depth and rate required to initiate the compression, while the final slope gives insight into the force, depth and rate required at the final stage of the compression, approaching the target depth range. The middle slope is the slope of the tangent line to the curve between the initial and final section. The shape of the decompression curve is also investigated during this study. The compression and decompression curve of a force-deformation curve, in the context of this study, is illustrated in Figure 7.2.

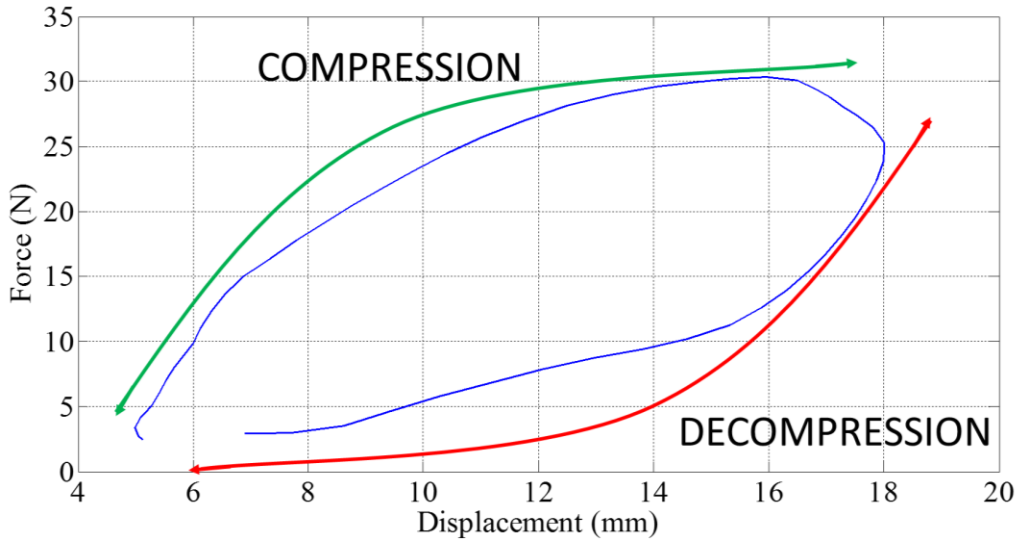


Figure 7.2: Compression and decompression of the force-deformation curve.

7.3 Results

Each test type for Animal C and D is assessed and six compressions are used to determine a mean force-deformation curve (see Appendix I and Appendix K). The calculated mean curve is used to determine the effect of the different CC methods and ventilation on the force-deformation curve.

7.3.1 Force-deformation curves for Animal C

The force deformation curve for the TT method using guideline, variable and CC only are investigated on Animal C. The shape of these curves are similar for all ventilation when using the TT method as seen in in Figure 7.3.

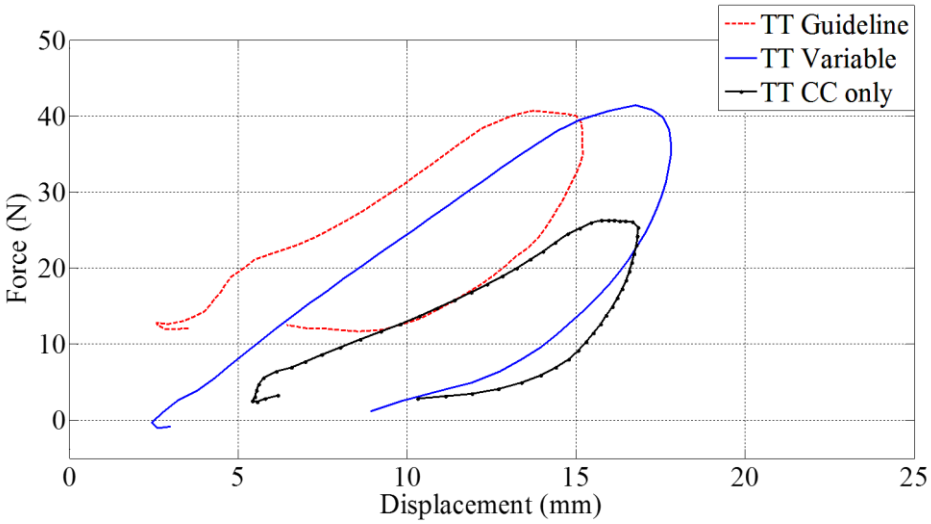


Figure 7.3: Force-deformation curve using TT method only for Animal C.

The curves increases to a mean depth and force of 16.4 *mm* and 35.3 *N* for TT method. The maximum peak depth and force was measured during variable ventilation and the minimum peaks were measured during CC only. The ventilation is compared for the TF method in Figure 7.4.

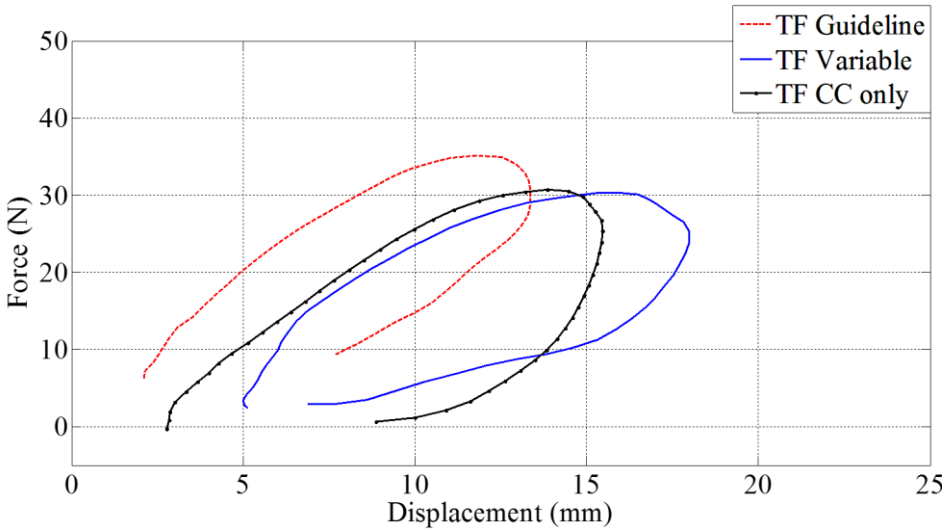


Figure 7.4: Force-deformation curve using TF method only for Animal C.

The shape of the force-deformation curve for the TF method is similar, irrespective of the ventilation. The force-deformation curve increases to a mean maximum peak depth and force of 15.1 *mm* and 30.3 *N*, respectively. The maximum peak CC depth using the TF method is for variable ventilation, while the minimum peak CC depth is for guideline ventilation. The maximum peak force is for guideline ventilation, while the minimum peak force is for variable ventilation. The shape of the compression is rounder (an inverse log graph) for the

TF method than the TT method. The TT and TF method are compared for constant ventilation methods to compare the shape of the compression and decompression curves. Guideline ventilation for TT and TF method is compared in Figure 7.5.

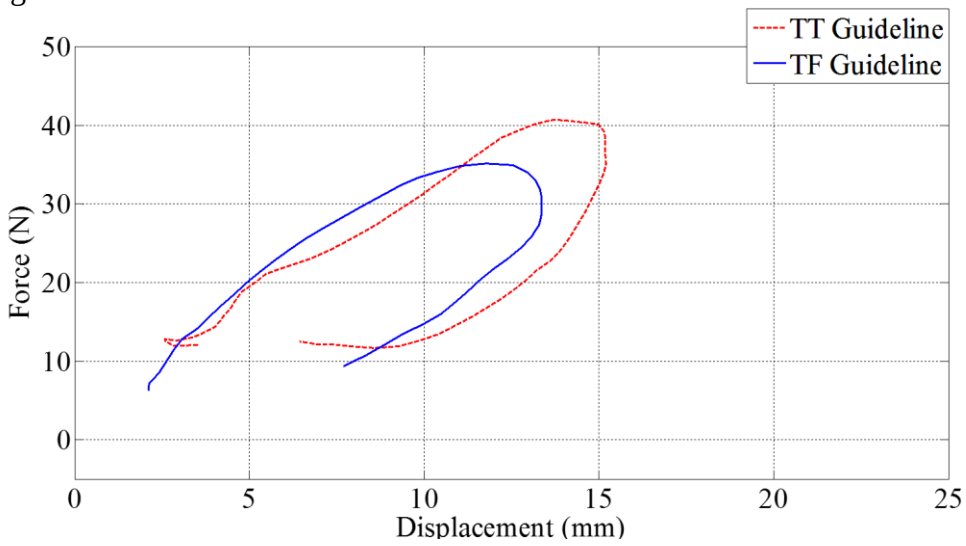


Figure 7.5: Force-deformation curve using guideline ventilation for Animal C.

The force-deformation curve for guideline ventilation increases to a mean depth and force of 14.1 *mm* and 36.5 *N*, respectively. The maximum peak CC depth and force is measured for TT method. The shape of the TF method compression curve is rounder than the TT method. The shape of the force-deformation curve affects the required energy for compressing to the target depth. The force-deformation curve for TT and TF method is compared with constant variable ventilation in Figure 7.6.

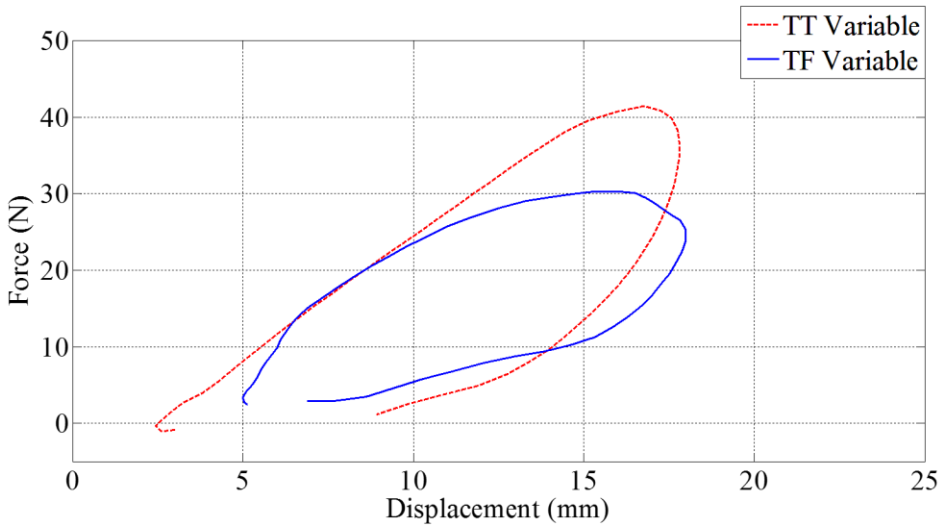


Figure 7.6: Force-deformation curve using variable ventilation for Animal C.

The force-deformation curve for variable ventilation increases to a mean maximum peak depth and force of 17.7 *mm* and 33.1 *N*, respectively. The maximum peak depth was measured for TF method and the maximum peak force was measured for TT method. The maximum depth for both compression methods is similar, with a higher force for the TT method, indicating less effective compressions. The shape of the compression curve is straighter and more linear for TT and rounder for the TF method, which is similar to the compression curve for CC only ventilation seen in Figure 7.7.

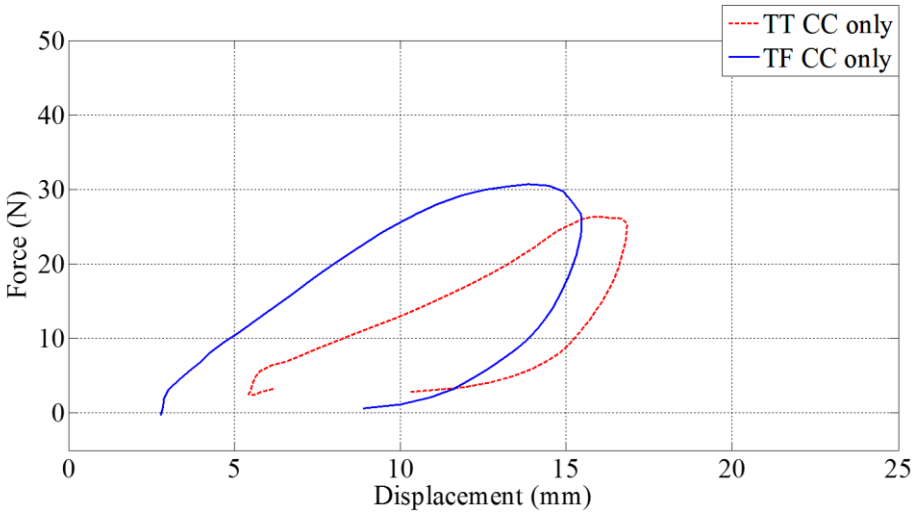


Figure 7.7: Force-deformation curve using CC only method for Animal C.

The force-deformation curve for CC only increased to a mean peak depth and force of 16.0 *mm* and 27.1 *N*, respectively. The maximum peak depth is for TT method, while the maximum peak force is for TF method. The TT method is therefore the more effective method when no ventilation is present as the larger depths were achieved using less force.

The difference in the shape of the compression curve indicates a difference in energy required to perform the NCPR and the difference in slope of the curve. The energy is determined by calculating the area under the graph and the results for these calculations are summarized in Table 7.1 for different compression methods and ventilation.

Table 7.1: The peak depth and force, mean slope and mean energy for the force-deformation curves of Animal C.

	Guideline		Variable		CC Only	
	TT	**TF**	**TT**	**TF**	**TT**	**TF**
Peak depth (mm)	15.2	13.0	17.6	17.5	16.8	15.0
Peak force (N)	39.6	34.0	39.8	27.4	25.4	28.8
Energy (J)	161	163	271	201	119	225
Initial slope	2.9	4.9	3.1	6.9	7.8	7.9
Middle slope	1.7	2.6	3.2	2.5	2.1	3.1
Final slope	0.6	0.1	1.1	0.3	0.8	0.7

Abbreviations: CC = chest compression, TT = two-thumb, TF = two-finger

The minimum peak CC depth was recorded for the TF guideline method, while the maximum was for TT variable method. The minimum peak force was recorded for TT CC only method, while the maximum was recorded for TT variable method. The peak depth of the TT method is always slightly higher than the TF method for Animal C. The peak forces are higher for the TT method during guideline and variable ventilation, but lower during the CC only tests.

There seems to be no correlation between the CC or ventilation method used and the energy required (area under the graph). The guideline method, however, shows more consistency in energy required than the variable or CC only ventilation, which have large discrepancies. The higher energy required for some methods could be due to the chest being less compliant, possibly due to the lack of ventilation.

The initial slope is higher for the TF method than the TT method, while the final slope is lower for the TF method. The middle slope is higher for the TF method than TT method during guideline and CC only method, however it is lower for variable ventilation. The initial slope is the highest for the CC only method, then the variable method and the lowest for the guideline method when using the same CC only method.

7.3.2 Force deformation curves for Animal D

The force-deformation curve for the different compression methods and ventilation for Animal D are discussed in this section. The TT method force-deformation curves are compared in Figure 7.8.

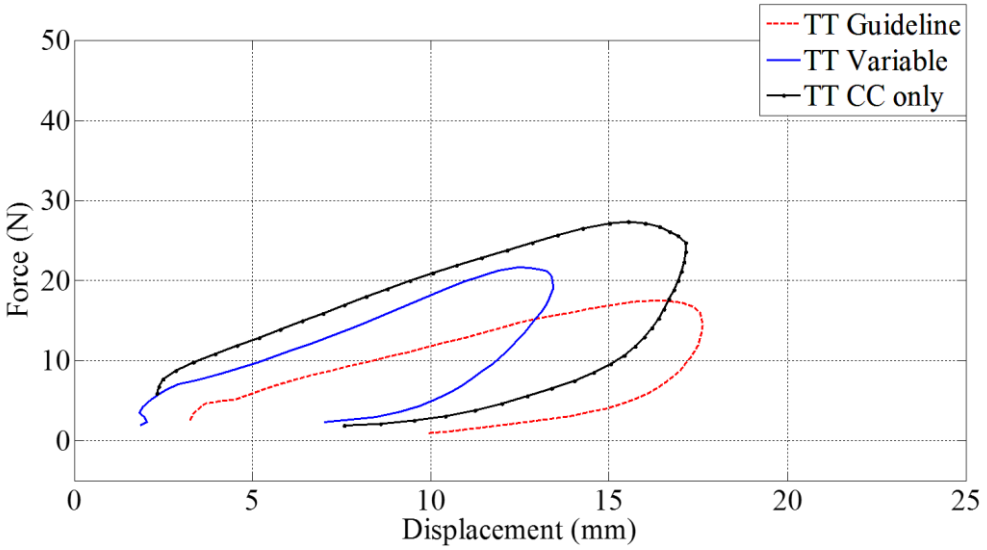


Figure 7.8: Force-deformation curve using TT method only for Animal D.

The shape of the force deformation curves obtained for TT method is similar, regardless of the ventilation method used. The curve increases to a mean maximum peak CC depth and force of 18.0 *mm* and 20.6 *N*, respectively. The maximum peak CC depth for the TT method is for guideline ventilation, while the maximum peak force is for CC only. The shape of the compression curve is linear, while the decompression curve is rounder. The shape of these curves are similar to that found for Animal C. The force-deformation curve for the TF method on Animal D is illustrated in Figure 7.9.

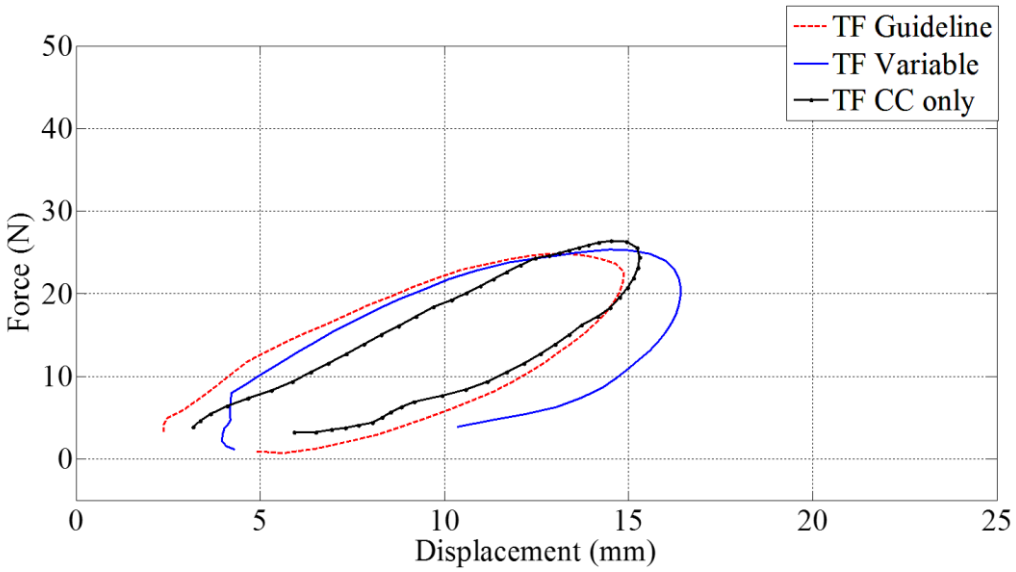


Figure 7.9: Force-deformation curve using TF method only for Animal D.

The force deformation curves for TF method increases to a mean maximum peak depth and force of 14.8 *mm* and 22.6 *N*, respectively. The maximum peak depth for the TF method is for variable ventilation, while the maximum peak force is for CC only. The compression curve is in the shape of an inverse log curve, which is rounder than the compression curve for TT method. The force-deformation curves are also investigated for the TT and TF method, while keeping the ventilation method constant. The TT and TF method for guideline ventilation is illustrated in Figure 7.10.

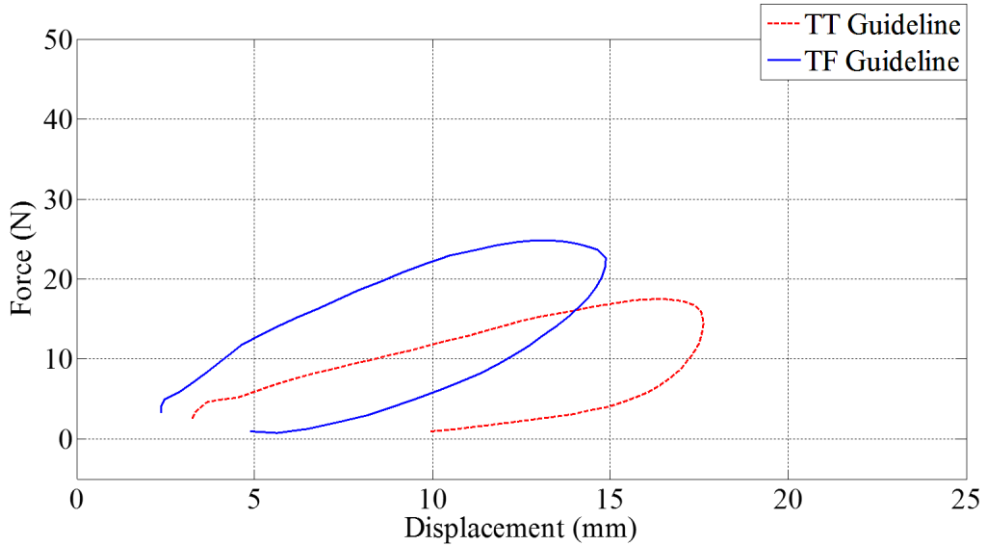


Figure 7.10: Force-deformation curve using guideline ventilation for Animal D.

The force-deformation curves for guideline ventilation increases to a mean maximum peak depth and force of 16.2 *mm* and 19.3 *N*, respectively. The maximum peak depth for the guideline ventilation is for TT method, while the maximum peak force is for TF method. The TT method compression curve is linear, while the TF method compression curve is rounder. The decompression curve is similar regardless of the compression method, however, the area of the TT method force-deformation curve is larger than the TF method. The TT and TF method for variable ventilation is illustrated in Figure 7.11.

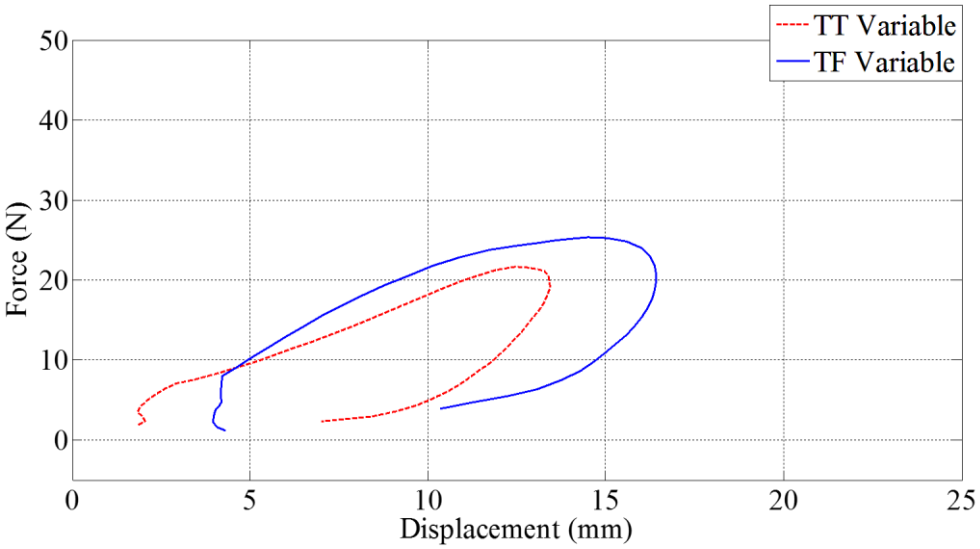


Figure 7.11: Force-deformation curve using variable ventilation for Animal D.

The force-deformation curves for variable ventilation increases to a mean maximum peak depth and force of 14.8 *mm* and 21.7 *N*, respectively. The maximum peak depth and maximum peak force for guideline ventilation is for TF method. The TT method compression curve is linear and straight, while the TF method compression curve is rounder. The decompression curve is similar regardless of the compression method, however, the area of the curve is larger for the TF method than the TT method. The TT and TF method for CC only is illustrated in Figure 7.12.

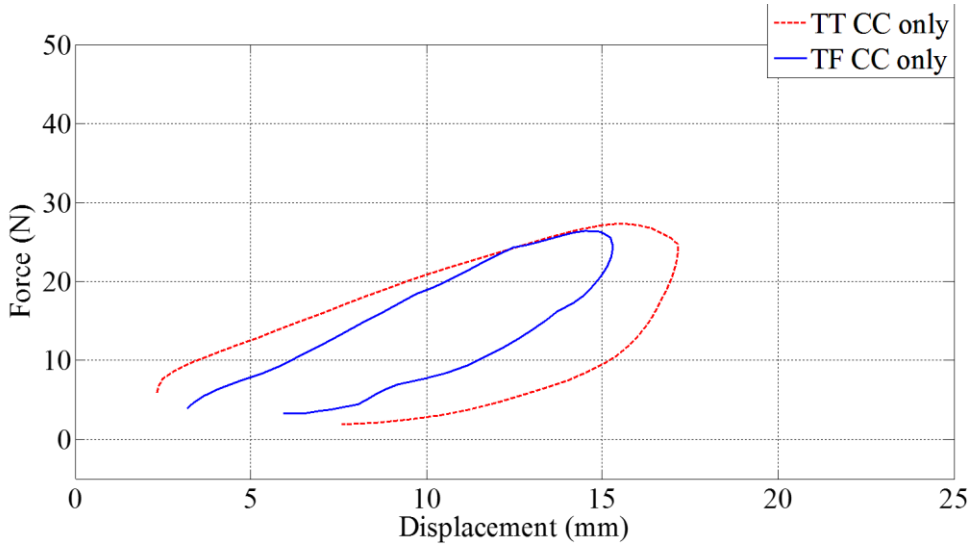


Figure 7.12: Force-deformation curve using CC only ventilation for Animal D.

The force-deformation curves for the CC only method increases to a mean maximum peak depth and force of 16.2 *mm* and 25.1 *N*, respectively. The maximum peak depth for the CC only is for TT method, while the maximum peak force is for TF method. The differences in the shape of the compression and decompression curves for CC only ventilation is also linear for TT method and slightly rounder for TF method.

All the force-deformation curve results for the tests performed on Animal D are summarized in Table 7.2

Table 7.2: The peak depth and force, mean slope and area under the graph for the force-deformation curves from Animal D.

	Guideline		Variable		CC Only	
	TT	**TF**	**TT**	**TF**	**TT**	**TF**
Peak depth (mm)	17.6	14.9	13.5	16.2	18.9	15.2
Peak force (N)	15.7	22.6	20.5	22.9	25.5	25.5
Energy (J)	136	155	104	179	215	101
Initial slope	4.9	3.9	3.9	2.7	3.5	2.4
Middle slope	1.1	2.2	1.6	1.9	1.5	2.2
Final slope	0.1	0.8	0.3	0.5	0.4	0.5

Abbreviations: CC = chest compression, TT = two-thumb, TF = two-finger

The maximum peak CC depth is for TT CC only method, while the minimum peak CC depth was for TT variable method. The minimum peak force was for TT guideline method, while the maximum peal force was for both the TT CC only and TF CC only method. The peak depth of the TT method is higher than the TF method using guideline and CC only. The peak forces are larger for the TF method during guideline and variable ventilation, but the same during the CC only tests.

There seems to be no correlation between the CC method or ventilation and the energy required (area under the graph). The guideline method, however, shows more consistency (a smaller discrepancy) in energy required than the variable or CC only method, which have large discrepancies.

The initial slope is higher for the TT method than the TF method for all ventilation methods and the middle slope is higher for the TF method using all ventilation methods. The initial slope is, however, the highest for guideline, then the variable method and the lowest for CC only method.

7.4 Discussion of force-deformation curve

The results from the force-deformation analysis for Animal C and Animal D are compared in this section and the findings are discussed briefly.

The maximum peak CC depth is higher for the TT method than the TF method for both Animal C and Animal D for guideline and CC only. The maximum peak CC depth of variable ventilation is higher for TT method for Animal D, however it is higher for TF method for Animal C. The maximum peak depths for TT method compression is higher than that of the TF method for the force-deformation curves.

The maximum peak force is higher for guideline and variable ventilation for Animal C for TT method. The maximum peak force is higher for CC only for Animal C and guideline and variable for Animal D for TF method. The maximum peak force is the same for CC only using TT and TF method. No conclusions can be made with regards to the maximum peak force of the force-deformation curves.

There is no correlation or trend with regards to the amount of energy required for the compression for different compression methods or ventilation. There is a large discrepancy with regards to the energy for the different methods. The smallest discrepancy, within a ventilation method, is for guideline ventilation, while the largest discrepancy is CC only for both Animal C and Animal D. There is therefore a correlation with regards to the energy discrepancy between ventilation.

There is no trend and conclusions that can be drawn from the calculated slope of the tangent line to the initial, middle and final section of the compression. The differences with regards to the slope results could also be due a difference in thoracic stiffness between the two animals analysed.

The shape of the force-deformation curves and the differences and similarities between compression and decompression curves for different compression methods and ventilation are constant for Animal C and D. The compression curve of the TT method has a linear shape, while the TF method compression curve rounded and similar to an inverse log graph. The linear shape could be due to the fact that the CC depth was insufficient and the curve is still in the linear range and no deformation has occurred. The decompression curve remains the same with regards to the compression method and ventilation. The ventilation also has no effect on the shape of the compression curve.

CHAPTER 8: Discussion

Good quality compressions is a key part in saving the lives of premature 'wet' neonates. Transitional neonatal cardiopulmonary resuscitation (NCPR) is difficult to perform due to the high number of actions (120 events per minute), the lack of practice due to the limited number of occurrences and poor fidelity of infant training manikins in replication of infant thoracic properties. The chest compression (CC) depth is a key parameter of good compressions and was further investigated during this study. This chapter includes a critical overview of the feedback tool, recommendations and a summary of the key findings.

8.1 Critical overview of the feedback tool

The feedback tool was designed to measure the CC depth and force as well as give real-time feedback to the clinician during NCPR. The feedback tool must be low cost, portable and easy to use.

Advantages: The feedback tool is able to accurately measure the depth (derived from the acceleration) and raw force data as well as store the data on a SD card for post processing. The tool is also able to guide the clinician in real-time during NCPR with a metronome to deliver the guideline recommended rate of compression and LED feedback lights to indicate to the clinician whether the compression depth is within a target range. The depth feedback is based on the mean depth over a three second period. There is an indicator on the device of where to place the two thumbs or two fingers during resuscitation.

Disadvantages: The device does not include a guide to assist in pacing the device in the correct position on the animal or neonate's chest. The depth feedback is programmed using a set target depth range, which does not take into account the exact anterior-posterior diameter (APD) of the animal or neonate being resuscitated. The device should be able to measure the APD of the animal to give accurate depth feedback to the clinician. The feedback LEDs only indicate whether the compressions are too shallow, correct or too deep, however, they should also indicate how far the compression depth is from the target depth.

8.2 Recommendations for future versions

Some improvements can be made to the feedback tool to improve the design and to better achieve the objectives. A line or arrows should be added to the device to indicate the inter-nipple line to assist with the placement of the device on the animal or neonate's chest. The depth feedback should be indicated as a percentage or range from the target depth. This can be achieved by including an array of LEDs indicating different percentages (e.g. 10%, 20% and 30%) from the target depth in both directions (too shallow and too deep). The depth feedback should be based on the target depth, one-third of the APD, and the device should be able

to estimate the APD of the animal or neonate. Further research is required to determine how to estimate it without using an additional sensor-equipped device, but rather using a known distance/angle as a reference or an additional on-board sensor. The placement of the LED's should also be along the centre of the device with space for the clinicians fingers next to it.

8.3 Recommendations for future studies

During the testing procedure the APD height of the animal should be measured in order to ensure accuracy in the assessment of the compression fidelity during post processing. The order of the test should also be randomized to ensure that there are no artefacts or findings, which could be influenced by the order of the tests. Multiple clinicians should also be tested to prove that the results are based on a larger group, which makes it a better representation of all clinicians and further validates the need for a feedback tool. The hemodynamic data (blood pressure, percentage CO_2, tidal volume and lung compliance) should be recorded continuously during the tests for all animals. Also, hemodynamic data should be acquired when the animals is in the terminal phase of the clinical protocol (i.e., with a weak beating heart) as this is when the influence of the CCs on the survival of the animal can be best assessed. The effectiveness of the depth feedback of the feedback tool should also be tested in a clinical setting by structuring a series of tests where the clinician is instructed to resuscitate according to the feedback only, without taking his/her own judgement into account.

8.4 Summary of the key findings

The fidelity of CCs was analysed according to the target depth recommended by current NCPR guidelines of one-third of the APD and according to the specified target depth range for 'wet' neonates. The main finding was that the CCs performed on an animal model by an experienced clinician were mostly too shallow regardless of the compression method and ventilation used. There is therefore a clear need for a feedback tool to guide clinicians in performing consistent and effective CCs to perform good quality resuscitation.

The CC depth and force relationship was also investigated and the results show that there is no real clear, significant difference between the TT method and the TF method. The NCPR guidelines recommend the TT method, however the reason for this is not clear when analysing the force-depth relationship. The CC depth and force of the two methods is similar. The force-deformation curve, however, indicated a difference in the shape of the compression curve when comparing the two CC methods. The TF method compression curve is in the shape of an inverse log graph, while the TT method compression shape is more linear. The decompression curves are similar for both CC methods.

CHAPTER 9: Conclusion

The study included the design, fabrication and implementation of an unobtrusive, robust, inexpensive, portable diagnostic feedback tool to guide experienced clinicians on the CC rate using a metronome and on the compression depth using LED feedback while performing NCPR on premature 'wet' neonates. The feedback tool was put through a series of hardware validation tests to ensure accurate depth and force measurements were recorded and effective depth feedback was given to the clinician. Once validated, the feedback tool was used to measure the compression depth and force during animal tests and the fidelity of the compressions was assessed according to the target depth, which is one-third anterior-posterior diameter (APD), and the chosen target depth range for 'wet' neonates, which is 17.5 to 22.5 *mm*. The results from these fidelity tests validate the need for a feedback tool due to the ineffective and inconsistent chest compressions (CCs) performed by a trained and experienced clinician with the majority of CCs being too shallow for all compression methods and ventilation.

A force-depth analysis was completed to determine the effect of the compression methods and ventilation on the depths and forces measured during NCPR on an animal model. The mean CC depth was higher for TT method than the TF method, with slightly higher measured forces. The mean results show that the TT method was more effective during the tests resulting in a larger CC depth using similar forces, which supports the current NCPR guideline recommendation to use the TT method instead of the TF method. There is no trend or correlation according to ventilation type found during the force-depth analysis, however, lower mean CC depths were recorded for guideline ventilation.

The force-deformation curves of Animal C and Animal D were analysed for the different compression and ventilation methods. The TT and TF method force-deformation curves showed distinct differences in the compression shape. The TT method yielded a more linear compression curve, while the TF method yielded an inverse log graph (more rounded), which is similar to what one would expect. The decompression curve is similar for both compression methods. There was also no difference in curve shape for different ventilation.

The findings of this study validate the need for a feedback device for premature 'wet' neonates. Future work in this field could include additional tests performed by multiple clinicians to investigate the fidelity and effectiveness of CCs to further validate the need for a feedback tool. The APD of the animal being tested should be measured on the day of testing in the correct supine position to accurately calculate the target depth of one-third of the APD. Further investigations into this field could contribute to changing the current NCPR guidelines and in time reducing the infant mortality and morbidity rates.

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18, pp. 918–923, 1994.
[60] International Standard, “ISO 13485,” vol. 2003, 2003.

Appendices

A. Neonatal resuscitation guidelines

Neonatal cardiac arrest is predominantly due to asphyxia, so initiation of ventilation remains the focus of initial resuscitation. The following are the key points:

The guidelines include a section on the anticipation of resuscitation need, which specifies that for every birth at least one person should be present who can perform initial steps of newborn resuscitation. The initial steps of resuscitation include maintaining normal temperature in the delivery room, clear the airway, assess the heart rate and assess the oxygen need and administer the oxygen.

Immediately after birth the newborn's heart rate is assessed to evaluate the effectiveness of spontaneous respiratory effort and determine the need for subsequent interventions. During resuscitation an increase in heart rate is a sensitive indicator of a successful response to intervention.

Assisted ventilation should be delivered at a rate of 40 to 60 breaths per minute to promptly achieve or maintain a heart rate >100 per minute. When the heart rate is less than 60 per minute despite adequate ventilation, chest compressions are indicated. Ventilation is the most effective action in neonatal resuscitation and the chest compressions can compete with effective ventilation. The chest compressions can compete with effective ventilation, therefore ensure that the assisted ventilation is delivered optimally before starting chest compressions. The compressions are delivered on the lower third of the sternum to a depth approximately one-third of the anterior-posterior diameter of the chest.

The two techniques described for chest compression with two-thumbs with the fingers encircling the chest and supporting the back or the two-finger method with a second hand supporting the back. The two thumb method is recommended due to the higher blood pressures and coronary perfusion pressure generated and less rescuer fatigue.

The compression to ventilation should be coordinated with a compression to ventilation ratio of 3:1, with 90 compressions and 30 breaths to achieve approximately 120 events per minute to maximize ventilation. If the arrest is believed to be of cardiac origin higher ratios (e.g. 15:2) may be considered.

Respirations, heart rate and oxygenation should be reassessed periodically and the chest compression and ventilation should be continued until the heart rate is more than 60 beats per minute.

B. MRI scans of neonates at full term gestation

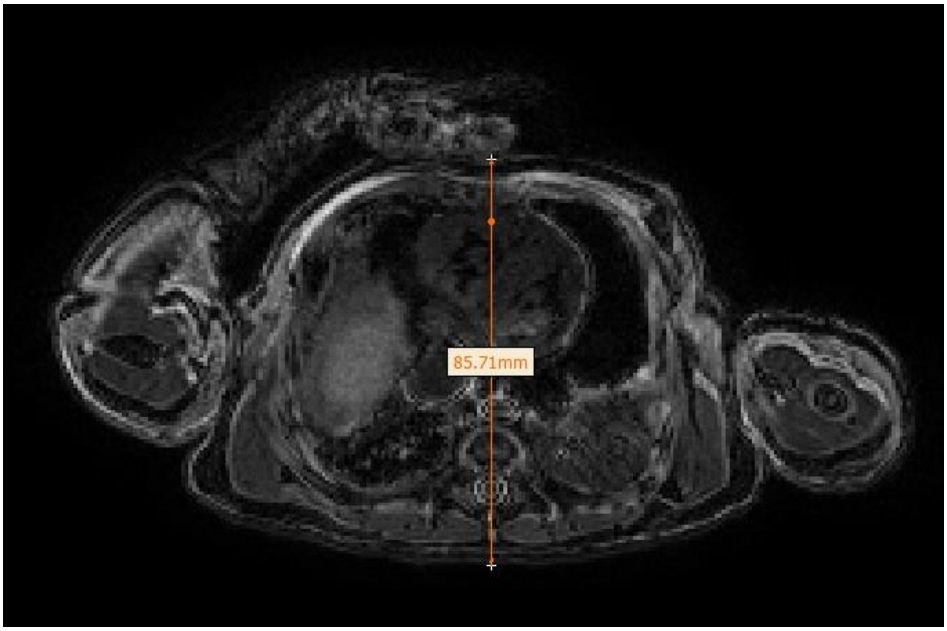


Figure B.1: MRI scan of a neonate of 40 weeks gestation. (APD = 85.7 mm)

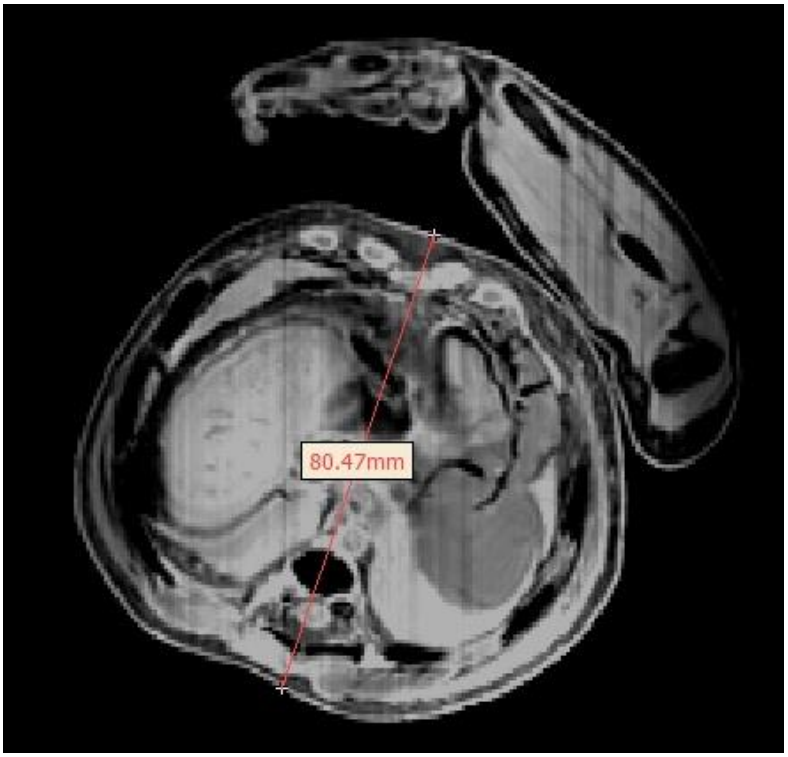


Figure B.2: MRI scan of a neonate at term gestation (37 to 42 weeks). (APD = 80.5 mm)

C. Component list

Table C.1: Component list including cost and manufacturer.

Component	**Manufacturer/ Company**	**Cost**
VLPB Load cell	Load cell central	R852.00
ADXL362 accelerometer	Mouser electronics	R90.00
Tinyduino Microprocessor	Tiny Circuits	R900.00
Battery	RS Components	R50.00
Component box	RS Components	R70.00
PCBs	Trax	R2740.00
Sonitron Buzzer	Mantech electronics	R80.00
LEDs, resistors, capacitors and transistors.	RS Components	R120.00
Total		**R4902.00**

D. PCB schematic and layout

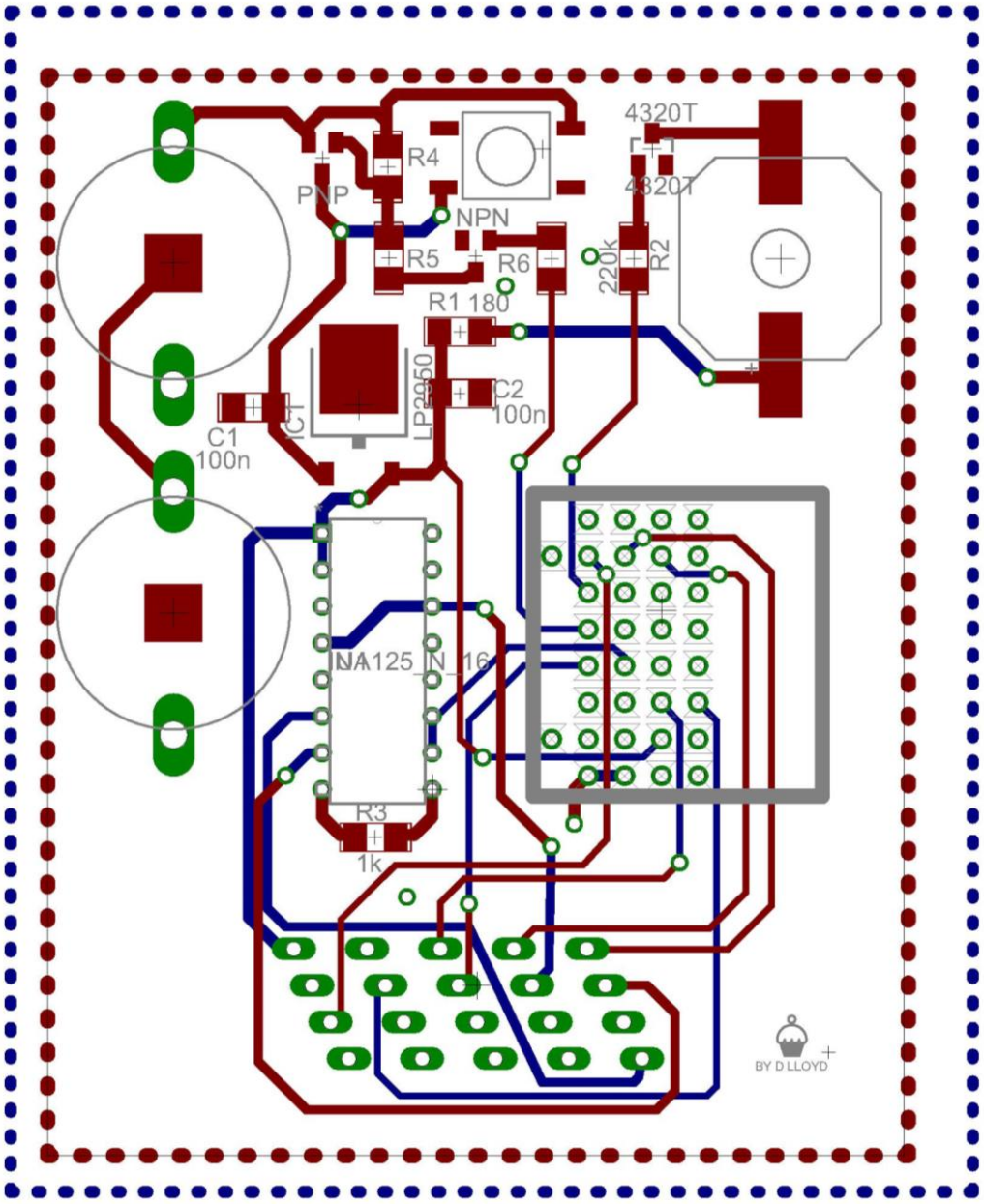


Figure D.1: Component box PCB layout.

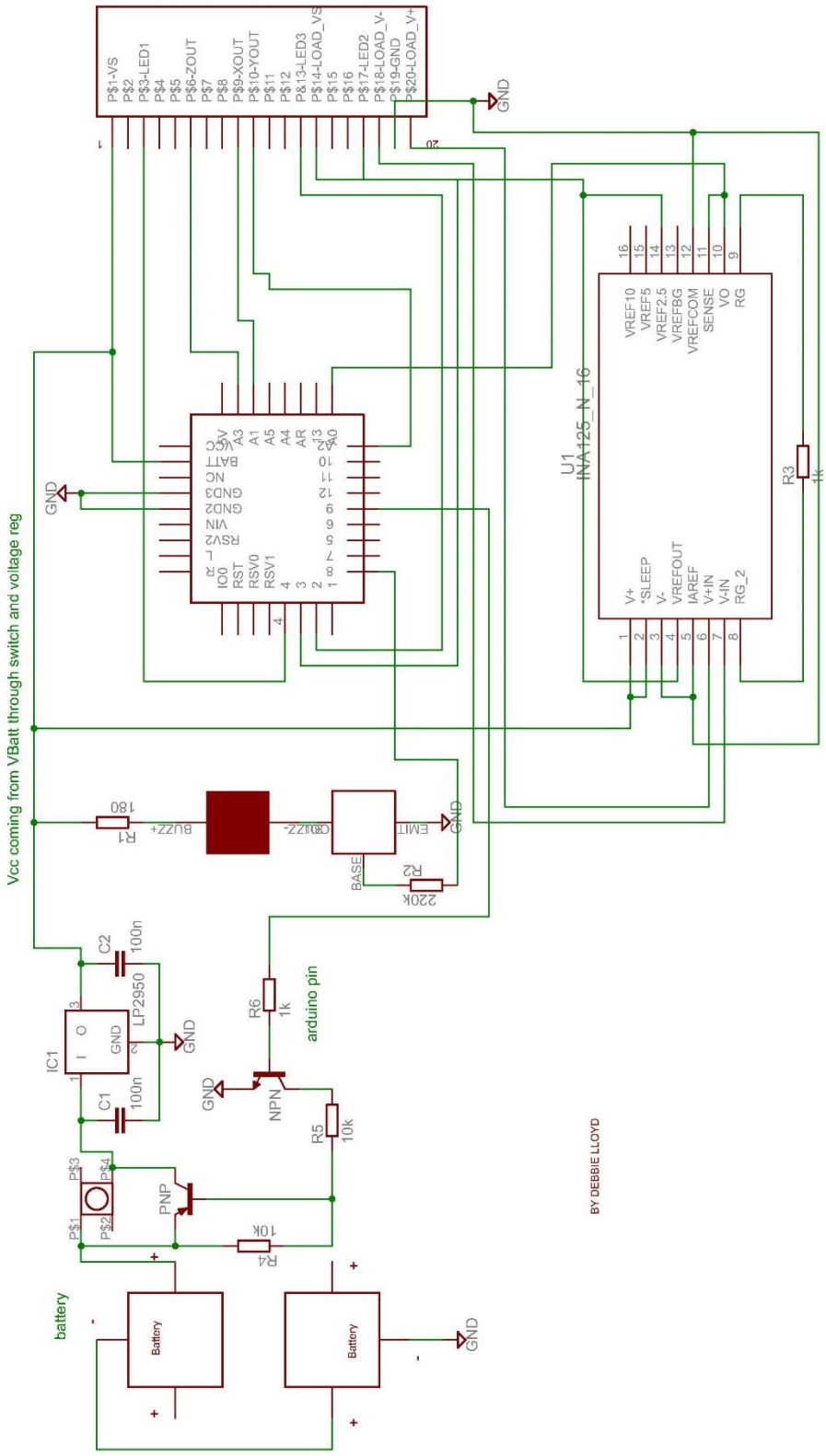


Figure D.2: Component box PCB schematic.

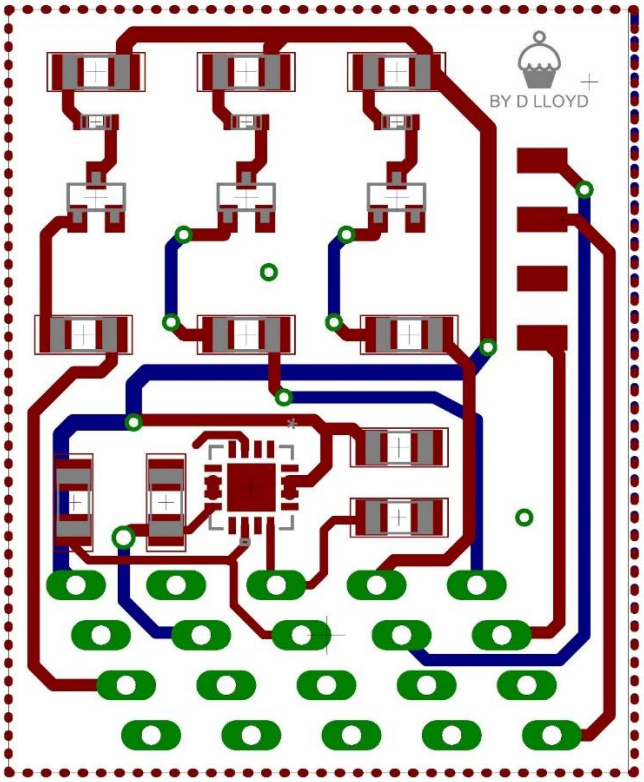


Figure D.3: Patch PCB layout.

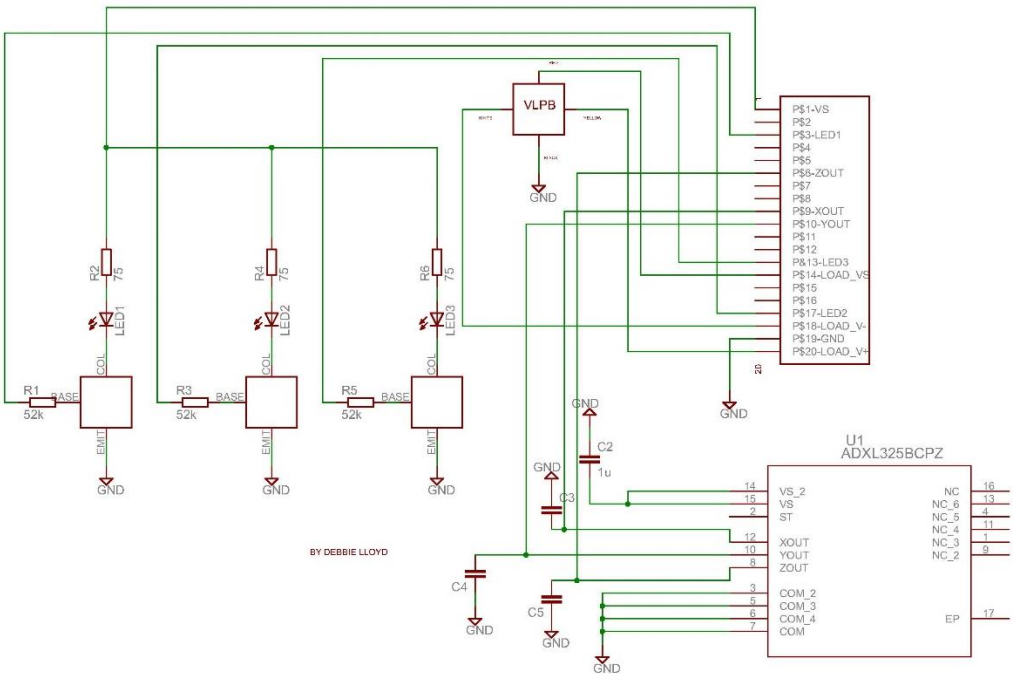


Figure D.4: Patch PCB schematic.

E. Datasheet: ADXL362 accelerometer

ANALOG DEVICES

Micropower, 3-Axis, ±2 *g*/±4 *g*/±8 *g* Digital Output MEMS Accelerometer

Data Sheet **ADXL362**

FEATURES

- Ultralow power
  - Power can be derived from coin cell battery
  - 1.8 µA @ 100 Hz ODR, 2.0 V supply
  - 3.0 µA @ 400 Hz ODR, 2.0 V supply
  - 270 nA motion activated wake-up mode
  - 10 nA standby current
- High resolution: 1 mg/LSB
- Built-in features for system-level power savings:
  - Adjustable threshold sleep/wake modes for motion activation
  - Autonomous interrupt processing, without need for microcontroller intervention, to allow the rest of the system to be turned off completely
  - Deep embedded FIFO minimizes host processor load
  - Awake state output enables implementation of standalone, motion activated switch
- Low noise down to 175 µg/√Hz
- Wide supply and I/O voltage ranges: 1.6 V to 3.5 V
  - Operates off 1.8 V to 3.3 V rails
- Acceleration sample synchronization via external trigger
- On-chip temperature sensor
- SPI digital interface
- Measurement ranges selectable via SPI command
- Small and thin 3 mm × 3.25 mm × 1.06 mm package

APPLICATIONS

- Hearing aids
- Home healthcare devices
- Motion enabled power save switches
- Wireless sensors
- Motion enabled metering devices

GENERAL DESCRIPTION

The ADXL362 is an ultralow power, 3-axis MEMS accelerometer that consumes less than 2 µA at a 100 Hz output data rate and 270 nA when in motion triggered wake-up mode. Unlike accelerometers that use power duty cycling to achieve low power consumption, the ADXL362 does not alias input signals by undersampling; it samples the full bandwidth of the sensor at all data rates.

The ADXL362 always provides 12-bit output resolution; 8-bit formatted data is also provided for more efficient single-byte transfers when a lower resolution is sufficient. Measurement ranges of ±2 *g*, ±4 *g*, and ±8 *g* are available, with a resolution of 1 mg/LSB on the ±2 *g* range. For applications where a noise level lower than the normal 550 µg/√Hz of the ADXL362 is desired, either of two lower noise modes (down to 175 µg/√Hz typical) can be selected at minimal increase in supply current.

In addition to its ultralow power consumption, the ADXL362 has many features to enable true system level power reduction. It includes a deep multimode output FIFO, a built-in micropower temperature sensor, and several activity detection modes including adjustable threshold sleep and wake-up operation that can run as low as 270 nA at a 6 Hz (approximate) measurement rate. A pin output is provided to directly control an external switch when activity is detected, if desired. In addition, the ADXL362 has provisions for external control of sampling time and/or an external clock.

The ADXL362 operates on a wide 1.6 V to 3.5 V supply range, and can interface, if necessary, to a host operating on a separate, lower supply voltage. The ADXL362 is available in a 3 mm × 3.25 mm × 1.06 mm package.

FUNCTIONAL BLOCK DIAGRAM

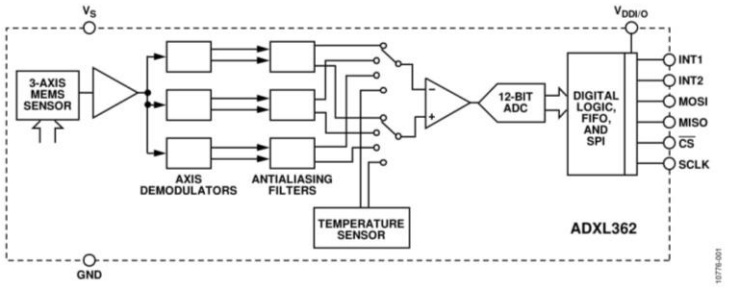


Figure 1.

Rev. B Document Feedback

One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
Tel: 781.329.4700
Technical Support www.analog.com

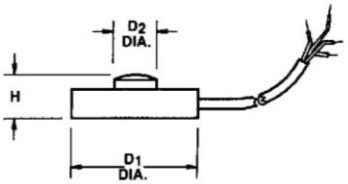
F. Datasheet: load cell and INA125

Load Cell Central
1-800-LOADCEL

VLPB

Very Low-Profile "Button" Load Cell

CAPACITY	D1"	D2"	H"
150, 250, 500, 1000 grams	.38	.09	.13
5, 10, 25, 50 lbs.	.38	.09	.13
100, 250 lbs	.50	.12	.15
500, 1000 lbs	.75	.25	.25



Load Cell Central's Model VLPB (compression only) low-profile load cell is designed to measure load ranges from 150 grams to 1000 lbs. With subminiature dimensions, including diameters from .38" to 0.75" and heights of .13" to 0.25", these units are easily incorporated into systems having limited space. Both models achieve a combined non-linearity and hysteresis of +/- 0.5% full scale. A small (1.0" long x .08" thick) circuit board is included in the load cell's lead wire cable for temperature compensation, and should not be removed.

Standard Semiconductor Capacities : 150, 250, 500 grams
Standard Foil Gage Capacities : **1Kg**; 5, **10**, **25**, **50**, **100**, **250**, **500**, **1000** lbs.
(**Boldfaced** are typically stock items for fast delivery)

Output 150g to 500g	15mV/V Nominal
Output 1Kg to 1000 lb	2mV/V Nominal
Non-Linearity	±0.5%
Hysteresis	±0.5%
Non-Repeatability	±0.1%
Thermal Sensitivity Shift	0.02% Rdg/°F
Thermal Zero Shift	0.01% FS/°F
Comp.Temp. Range	+60°F to +160°F
Operating Temp. Range	-65°F to +250°F

Foil Bridge Resistance	350Ω
Semiconductor Bridge Resistance	500Ω
Insulation Resistance	> 5000 MΩ
Recommended Excitation	5V
FS Deflection Foil	0.0005-0.0015"
FS Deflection Semi	0.001-0.003"
Weight	< 2 oz
Safe Overload	150% FS
Casing Material	Stainless Steel
Cable Length	5 ft.

Load Cell Central
28175 Route 220
Milan, PA 18831

Web: www.800loadcel.com
Email: sales@800loadcel.com

Toll Free: 1-800-562-3235
Ph: 1-570-731-7048
Fax: 1-570-731-7054

BURR-BROWN®

INA125

INSTRUMENTATION AMPLIFIER
With Precision Voltage Reference

FEATURES

- LOW QUIESCENT CURRENT: 460µA
- PRECISION VOLTAGE REFERENCE: 1.24V, 2.5V, 5V or 10V
- SLEEP MODE
- LOW OFFSET VOLTAGE: 250µV max
- LOW OFFSET DRIFT: 2µV/°C max
- LOW INPUT BIAS CURRENT: 20nA max
- HIGH CMR: 100dB min
- LOW NOISE: 38nV/√Hz at f = 1kHz
- INPUT PROTECTION TO ±40V
- WIDE SUPPLY RANGE
  Single Supply: 2.7V to 36V
  Dual Supply: ±1.35V to ±18V
- 16-PIN DIP AND SO-16 SOIC PACKAGES

APPLICATIONS

- PRESSURE AND TEMPERATURE BRIDGE AMPLIFIERS
- INDUSTRIAL PROCESS CONTROL
- FACTORY AUTOMATION
- MULTI-CHANNEL DATA ACQUISITION
- BATTERY OPERATED SYSTEMS
- GENERAL PURPOSE INSTRUMENTATION

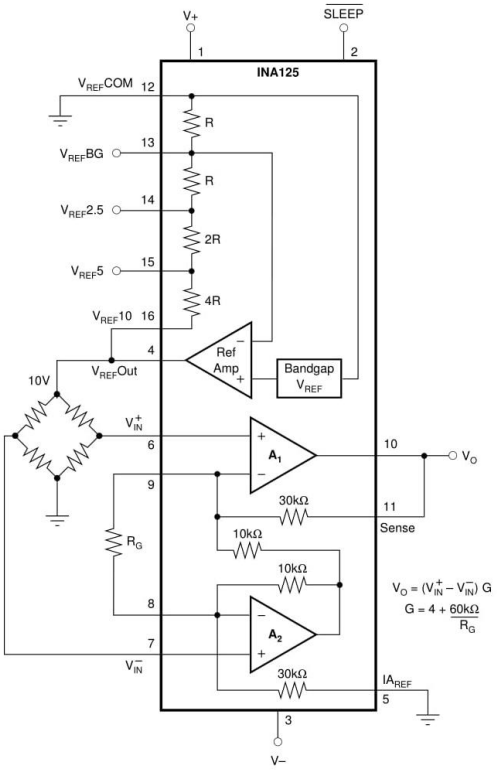
DESCRIPTION

The INA125 is a low power, high accuracy instrumentation amplifier with a precision voltage reference. It provides complete bridge excitation and precision differential-input amplification on a single integrated circuit.

A single external resistor sets any gain from 4 to 10,000. The INA125 is laser-trimmed for low offset voltage (250µV), low offset drift (2µV/°C), and high common-mode rejection (100dB at G = 100). It operates on single (+2.7V to +36V) or dual (±1.35V to ±18V) supplies.

The voltage reference is externally adjustable with pin-selectable voltages of 2.5V, 5V, or 10V, allowing use with a variety of transducers. The reference voltage is accurate to ±0.5% (max) with ±35ppm/°C drift (max). Sleep mode allows shutdown and duty cycle operation to save power.

The INA125 is available in 16-pin plastic DIP and SO-16 surface-mount packages and is specified for the –40°C to +85°C industrial temperature range.



International Airport Industrial Park • Mailing Address: PO Box 11400, Tucson, AZ 85734 • Street Address: 6730 S. Tucson Blvd., Tucson, AZ 85706 • Tel: (520) 746-1111 • Twx: 910-952-1111
Internet: http://www.burr-brown.com/ • FAXLine: (800) 548-6133 (US/Canada Only) • Cable: BBRCORP • Telex: 066-6491 • FAX: (520) 889-1510 • Immediate Product Info: (800) 548-6132

PDS-1361B
Printed in U.S.A., February, 1998

G. Priori power analysis

Table G.1: Power Analysis results using a two tailed dependent means t-test in MATLAB®.

		A priori: Compute required sample size using the compression force data	A priori: Compute required sample size using the compression depth data
Input:	Tail(s)	Two	Two
	Mean1	25.7 *N*	35.9 *mm*
	Mean2	29 *N*	34 *mm*
	Standard deviation	3.2 *N*	2.2 *mm*
	alpha	0.05	0.05
	Power	0.8	0.8
Output:	Total sample size	10	13
	Actual power (N=14)	0.9453	0.8474

H. Hemodynamic data

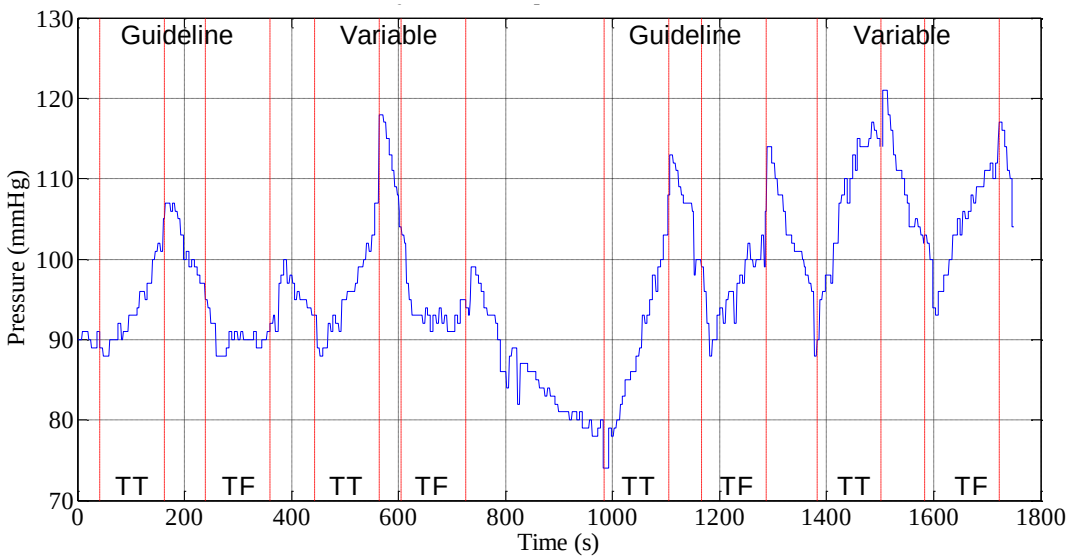


Figure H.1: Systolic blood pressure during animal test.

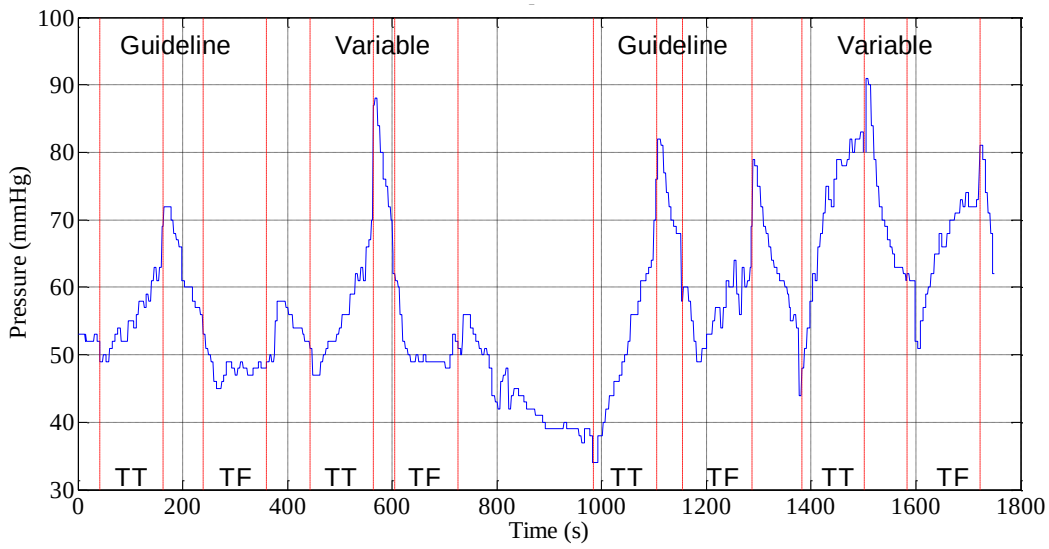


Figure H.2: Diastolic blood pressure during animal test.

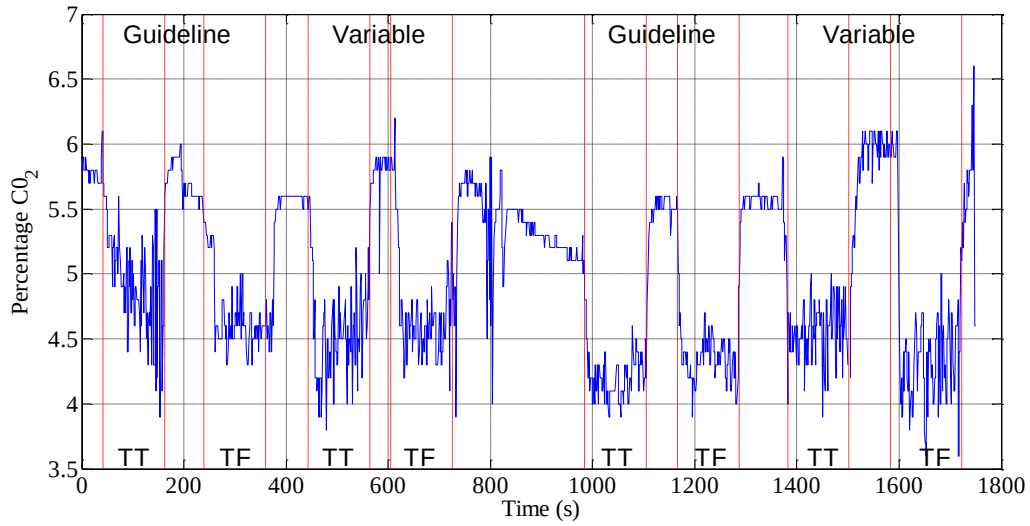


Figure H.3: Percentage CO2 during animal test.

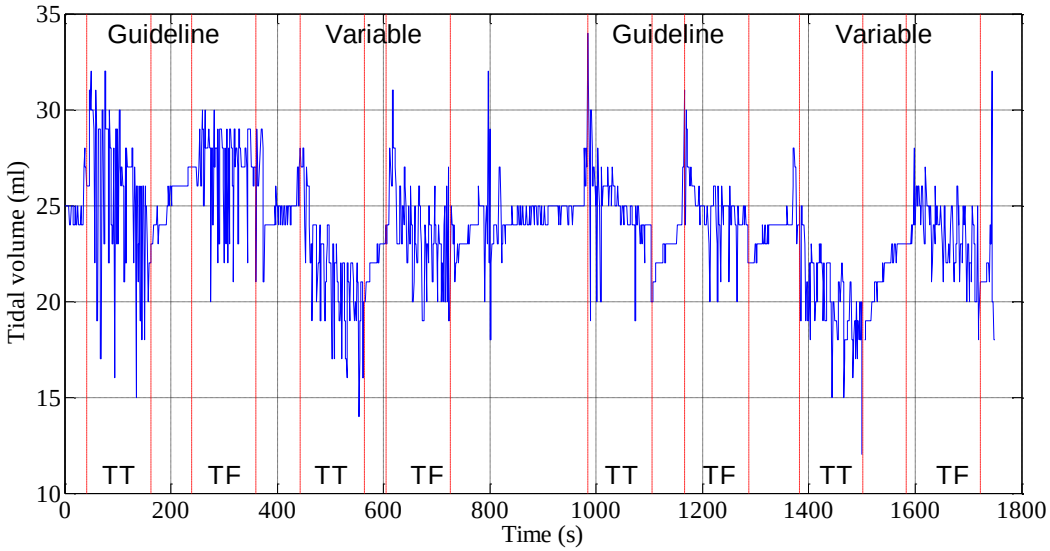


Figure H.4: Expiratory tidal volume during animal test.

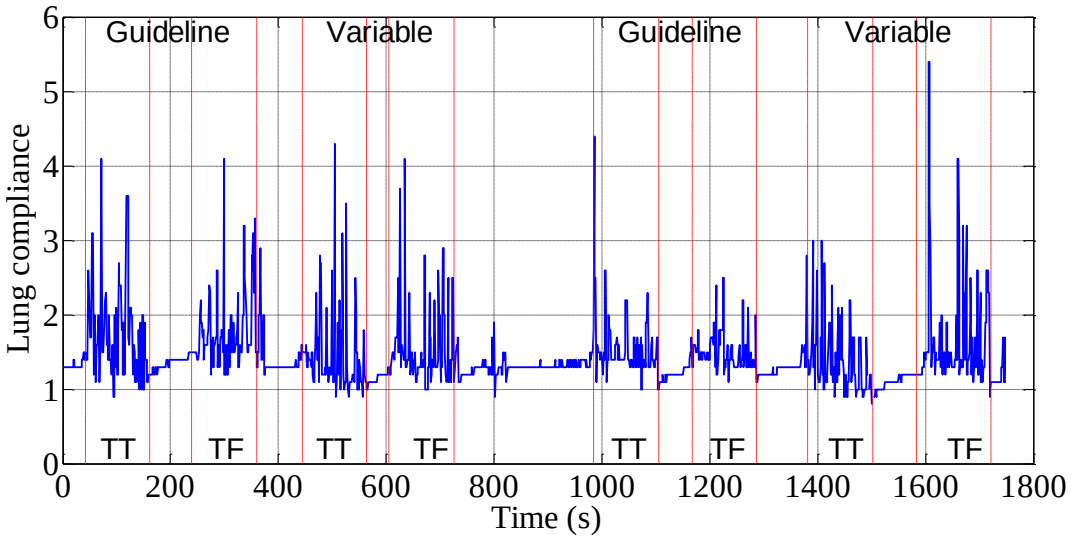


Figure H.5: Lung compliance during animal test.

I. ISO and IEC standards

ISO 13485

ISO 13485:2016 specifies the requirements for a quality management system where an organization needs to demonstrate its ability to provide medical devices and related services that constantly meet customer and applicable regulatory requirements. ISO 13485 is a regulatory standard whose focus is meeting customer requirements, including regulatory requirements, and maintaining the effectiveness of the quality management systems.

ISO 13485 Section 4 gives the general requirements, which include identifying specific processes and how they interact, and responsibility for processes that are outsourced. A quality manual, policy and objectives and the requirements of control of documents and records are given in this section of the standard. Document control includes review and approval of documents before use, control of changes, and making sure that current versions of controlled documents are available where needed for use.

IEC 60601

IEC 60601 is a series of technical standards for the safety and effectiveness of medical electrical equipment. Compliance with this standard is a requirement to bring a new medical device to the market in many countries. This standard becomes involved in the product-development process. The product is often complex, therefore a more involved process is required. This can often not only be assessed in the final design alone.

The third edition of this standard requires that the overall means of protection be a combination of one or more means of operator protection and means of patient protection. This is satisfied with basic safety insulation, use of protective earth ground, and isolation barriers. If a particular circuit or function falls under one of these categories; the manufacturer needs to assess this and record it in the risk management file. This edition covers both the hardware and software design of the product.

J. Force-deformation curves: Animal C

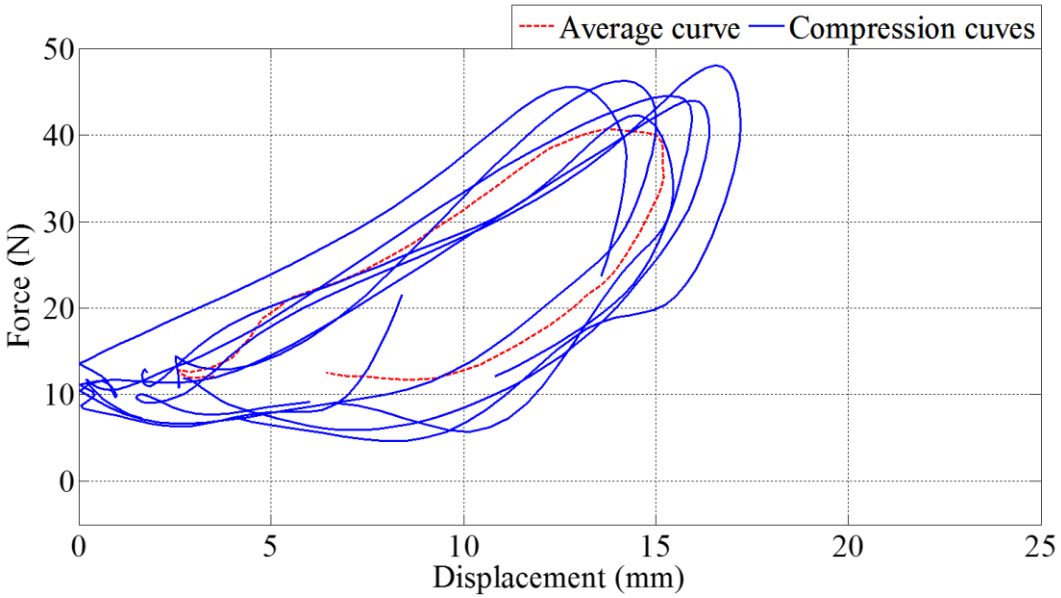


Figure J.1: TT guideline force deformation curve.

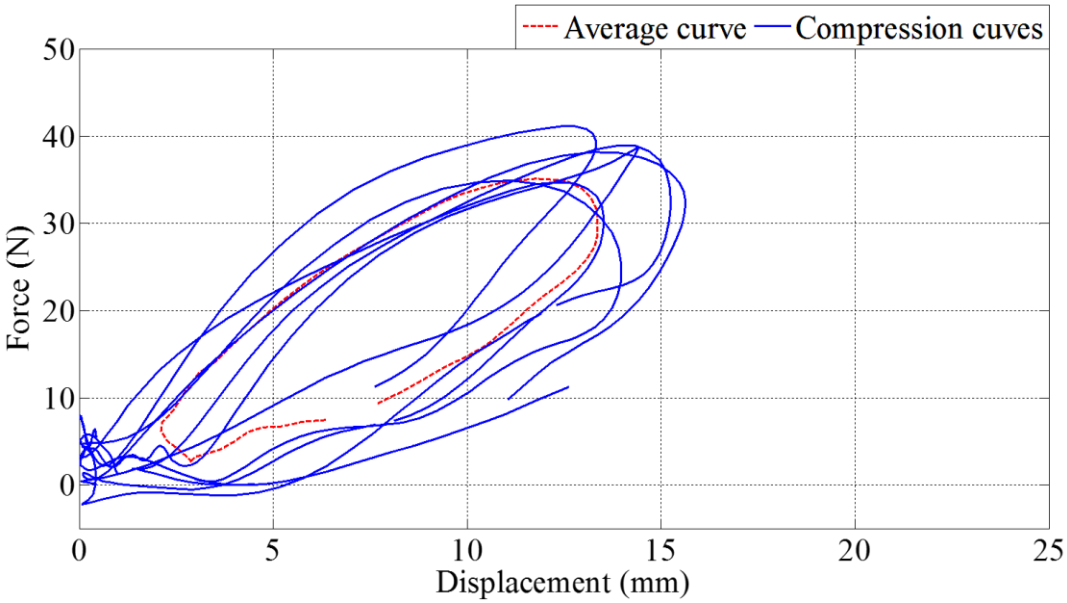


Figure J.2: TF guideline force deformation curve.

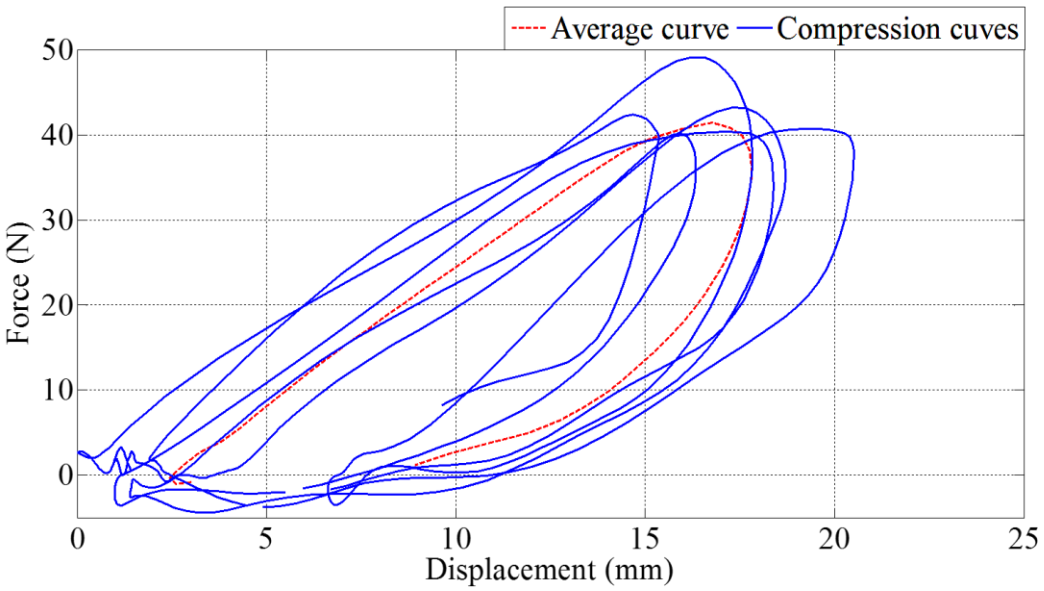


Figure J.3: TT variable force deformation curve.

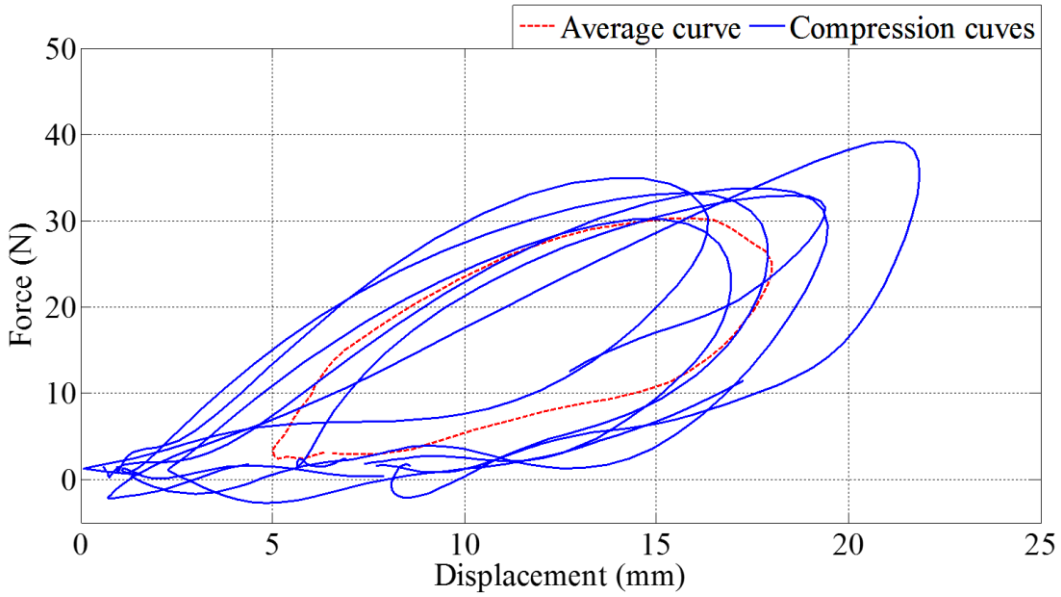


Figure J.4: TF variable force deformation curve.

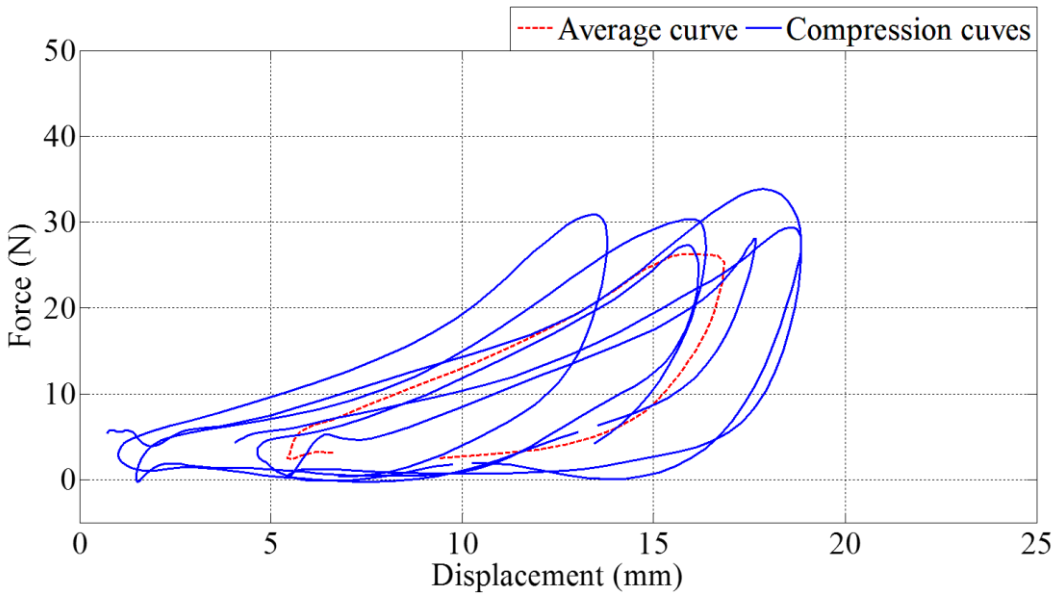


Figure J.5: TT CC only force deformation curve.

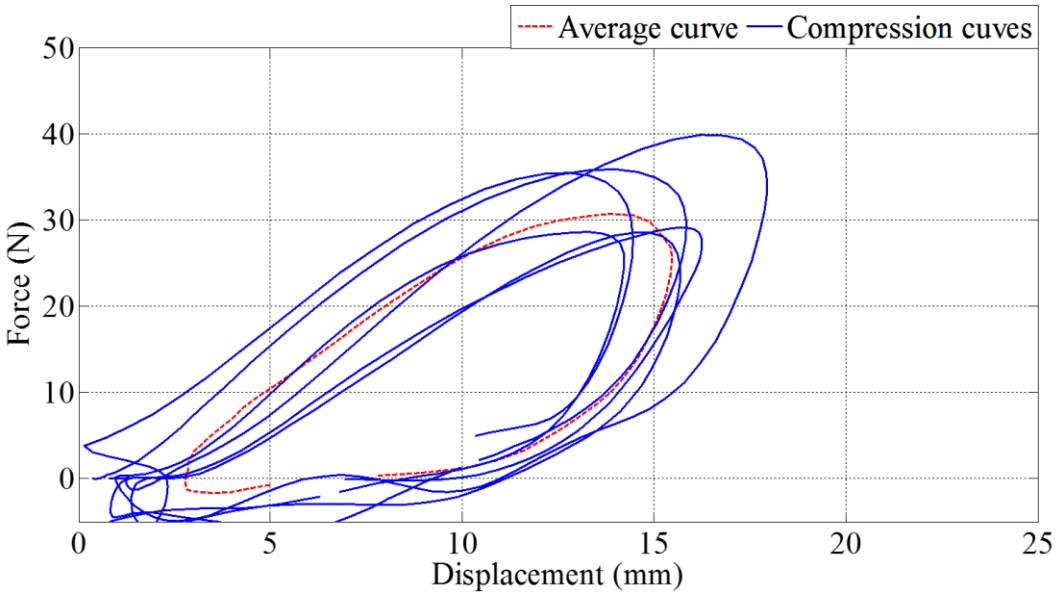


Figure J.6: TF CC only force deformation curve.

K. Force-deformation curves: Animal D

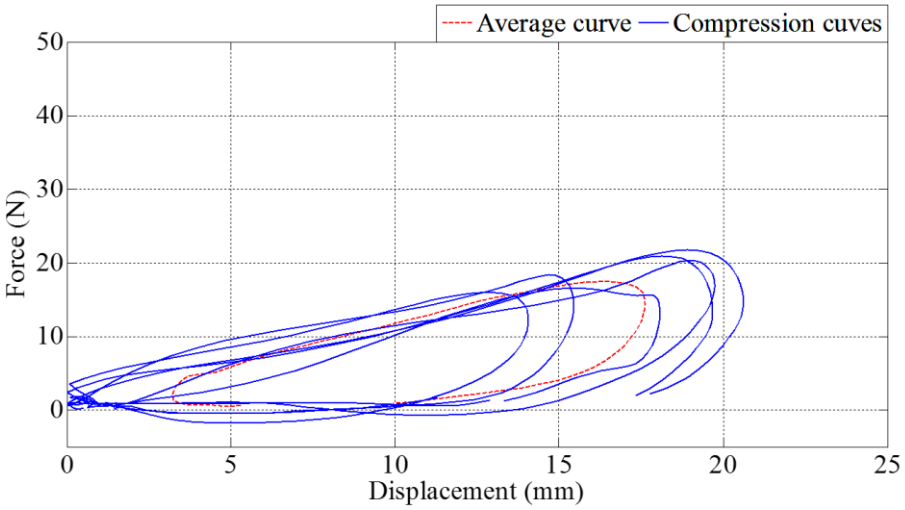


Figure K.1: TT guideline force deformation curve.

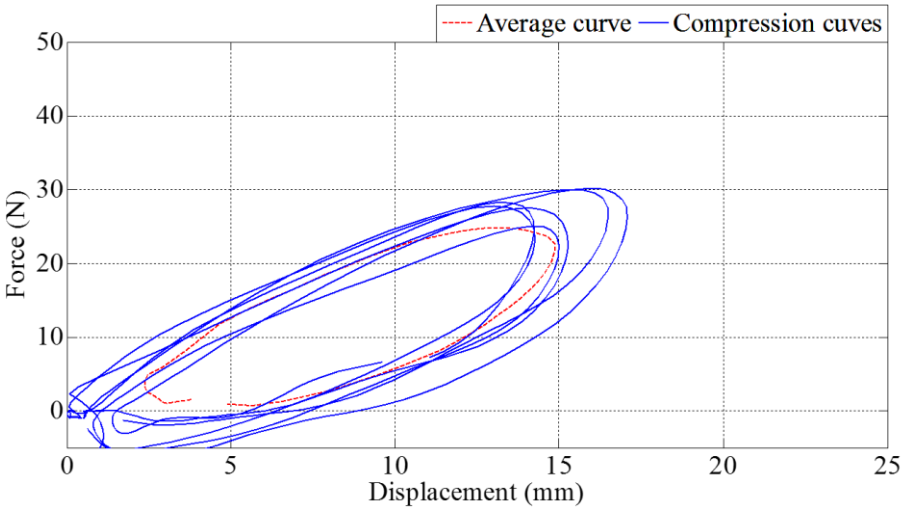


Figure K.2: TF guideline force deformation curve.

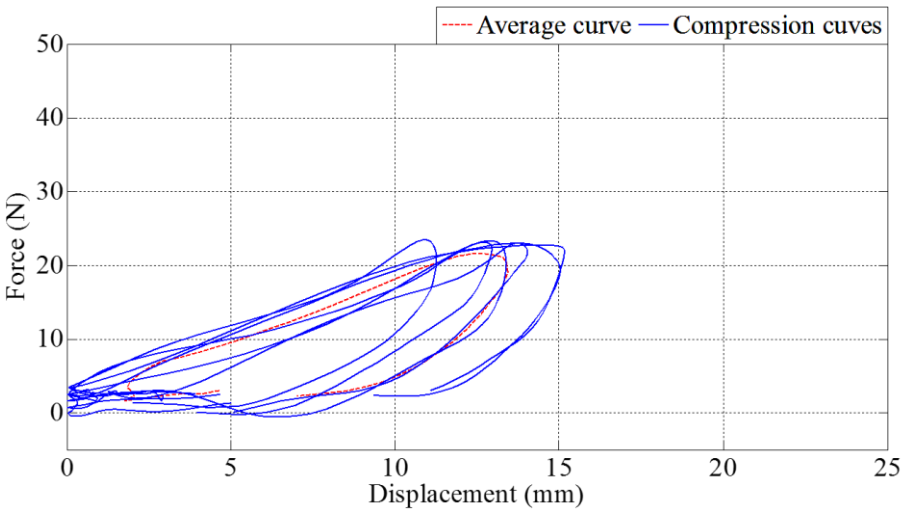


Figure K.3: TT variable force deformation curve.

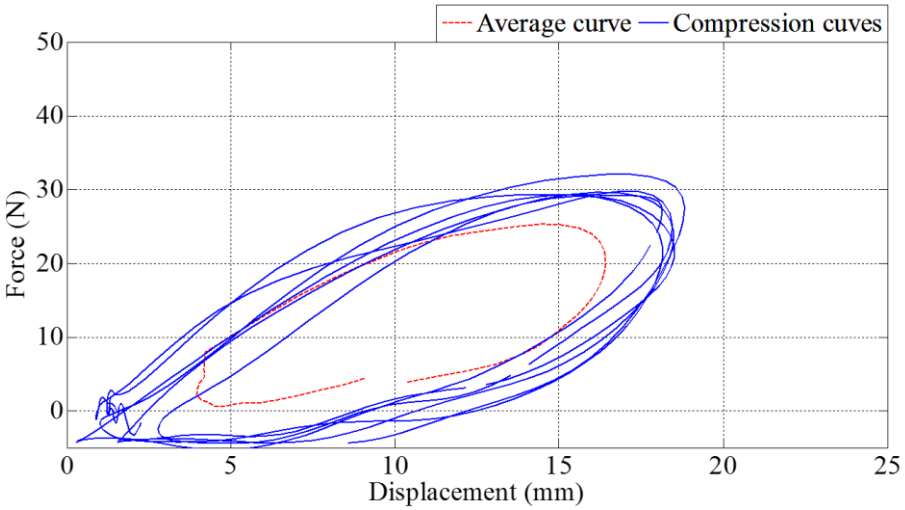


Figure K.4: TF variable force deformation curve.

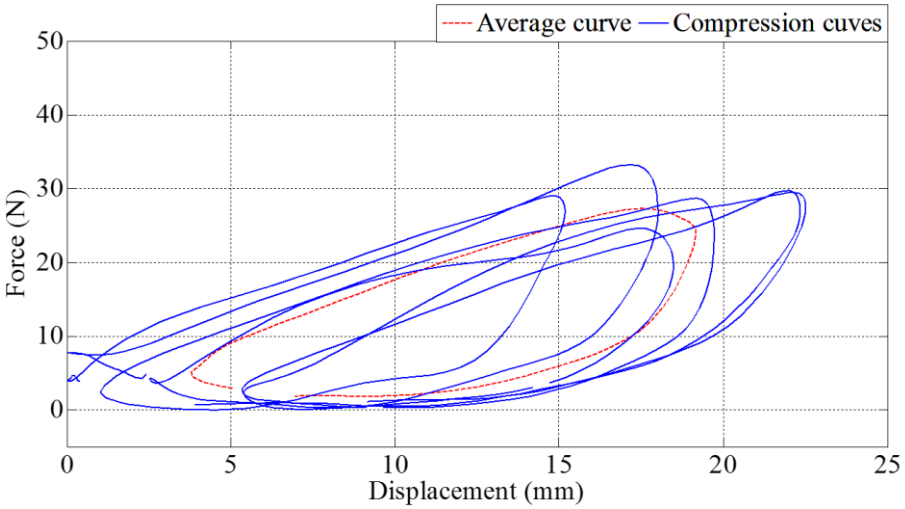


Figure K.5: TT CC only force deformation curve.

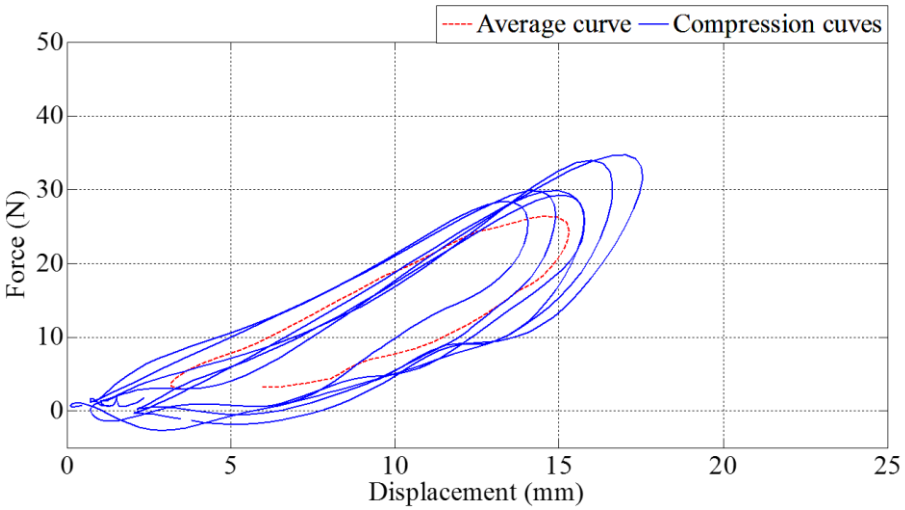


Figure K.6: TF CC only force deformation curve.