Bridging the clinical experience gap: – using simulation to improve ventilation performance during neonatal resuscitation in a high-resource setting

by

Joanna Haynes

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University of Stavanger
NO-4036 Stavanger
NORWAY
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‘‘We cannot accept circumstances in which asphyxial damage occurs after delivery as a result of inadequate facilities, staffing levels, or training’’ AD Milner 1991

Scientific environment and funding

This work was undertaken at Stavanger University Hospital (SUS) between 2017 and 2023. The three papers that make up the body of this work are based on studies of simulation of neonatal resuscitation performed between April 2019 and April 2021. My research forms part of Safer Births SUS, a collaboration between the hospital, University of Stavanger and Laerdal Global Health. The focus of the collaboration has been to use innovative monitoring and training techniques to gain new knowledge of normal and pathological newborn transition, improve our understanding of how best to help those failing to make a normal transition, and to enable our healthcare personnel to provide this help quickly and effectively.

The simulator used in this research was developed by Laerdal Global Health to improve neonatal resuscitation training for midwives providing newborn care in Tanzania. Indeed this applies to the monitoring technology used in Safer Births SUS, designed initially to provide insights into newborn care in the same low-resource setting. I have been the grateful recipient of an unconditional PhD grant from Laerdal Foundation, Safer Healthcare 2017-2021 number 5007. From August 2022 until May 2023 I have received 50% funding from the Department of Anaesthesia to publish paper III and write up this thesis.

I have been supported by world-class supervisors. Professor Hege Ersdal, Head of Research for Simulation and Global Health at SUS, has been my main supervisor. Professor Siren Rettedal, Principal Investigator for Safer Births SUS, and Professor Jeffrey Perlman, Chief of Newborn Medicine at Weill Cornell New York, have been my co-supervisors.

Acknowledgements

This work has been borne from the tireless input from many colleagues, friends and family. I would like to take this opportunity to acknowledge their efforts and to thank them for their valued help.

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My fantastic children Dan and Evie. I have delighted in having you in my life. Every day you do something new to make me proud. You make it all worth it.

My amazing sister-in-law Charlie. My beautiful niece and goddaughter Elli, you are missed every day, and I dedicate this work to you.

Abbreviations

AHA	American Heart Association
BL	Baby long
BS	Baby short
CLT	Cognitive load theory
CoSTR	Consensus on Science with Treatment Recommendations
CPAP	Continuous positive airway pressure
ECG	Electrocardiogram
ERC	European Resuscitation Council
eV_T	Expired tidal volume
FIB	Flow-inflating bag
FRC	Functional residual capacity
HCP	Healthcare provider
ILCOR	International Liaison Committee on Resuscitation
IQR	Interquartile range
LDHFST	Low-dose high-frequency simulation training
LNRM	Laerdal newborn resuscitation monitor
ML	Manikin long
MS	Manikin short
NE	Neonatal encephalopathy

NICU	Neonatal intensive care unit
NMR	Neonatal mortality rate
NRP	Neonatal Resuscitation Program
NRR	Norsk Resuscitasjonsråd (Norwegian Resuscitation Council)
PEEP	Positive end-expiratory pressure
PIP	Peak inflating pressure
PPV	Positive pressure ventilation
RCT	Randomised controlled trial
RFM	Respiratory function monitor
RQI	Resuscitation quality improvement
SIB	Self-inflating bag
SUS	Stavanger University Hospital
UN	United Nations
V_T	Tidal volume
WHO	World Health Organization

Definitions

Acidosis: - a process resulting in increased hydrogen ion concentration in the body, through changes in carbon dioxide (respiratory) or bicarbonate (metabolic) levels

Antepartum: - during pregnancy before the onset of labour

Apnoea (US apnea): - not breathing

Birth asphyxia: - failure to initiate or maintain regular breathing at birth

Bradycardia: -an abnormally slow heart rate; for neonates this refers to a heart rate < 100/minute

Colorimetric: - describes an analytic technique using colour changes to determine the concentration of a substance

Dystocia: - obstructed labour

Encephalopathy: - a disorder of brain structure or function caused by disease, injury, drugs or chemicals. Neonatal encephalopathy commonly results from hypoxic injury

Endotracheal tube: - a plastic tube placed in the trachea through which ventilation of the lungs may be provided

Fetal: - pertaining to the unborn baby

Functional residual capacity: - the volume of gas remaining in the lungs after a normal passive exhalation

Haptic feedback: - the use of touch to communicate with users

Hypercapnia: - an abnormally high partial pressure of carbon dioxide in the blood

Hypoxic: - having too little oxygen

Iatrogenic: - relating to injury or illness caused by medical examination or treatment

Intrapartum: - in the course of labour and delivery

Laryngeal mask: - an alternative airway to the endotracheal tube, introduced via the mouth with a cuff providing a non-leak-free seal around the larynx

Minute ventilation: - the amount of air entering the lungs per minute, the product of ventilation frequency and tidal volume

MRSOPA: - mnemonic of the corrective steps to be performed in the case of ineffective neonatal ventilation: - M- mask (tightly applied to the face); R- reposition airway (to achieve patency); S- suction (remove secretions); O- open mouth (assisting airway patency); P- pressure (increase inflating pressure); A- alternative airway (endotracheal tube or laryngeal mask)

Neonatal: - a baby in the first 28 days of life

Preload: - the amount of blood in the heart ventricles immediately prior to being pumped out, dependent on the volume of blood being returned to the heart by the venous system

Pulmonary: - pertaining to the blood circulation through the lungs

Pulse oximetry: - technology in a probe (applied around the hand in neonates, otherwise as a finger probe) which measures blood oxygen saturation by the absorption of light of different wavelengths by haemoglobin.

Systemic: - pertaining to the blood circulation of the body excluding the lungs

Term newborn: - a baby born at or after 37 weeks of gestation

Ventilation fraction: - percentage proportion of a given time period (typically 60 seconds) in which ventilation is given continuously without pauses.

Abstract

Background: Up to 10% of newborn babies need help to establish regular breathing at birth. Those who do breathe, and who are not fortunate enough to receive prompt and effective help, will die. The burden of neonatal mortality is highest in sub-Saharan Africa and Central-Southern Asia. However, the burden of morbidity in those babies who survive is proportionately a greater problem in middle-income, but also in high-income, countries. Many non-breathing babies respond to stimulation. For those who need more help, positive pressure ventilation of the lungs via a facemask is by far the most important intervention. Training midwives in low-resource settings using simulation training has led to better simulated performance, improved parameters of real-life facemask ventilation, and reduced early neonatal mortality. In high-resource settings like Norway, where paediatricians perform most neonatal facemask ventilation, infrequent simulation training does not replace the lack of clinical experience for midwives and other medical professionals working with women giving birth. It is not known if more frequent simulation training for healthcare providers (HCPs) in a high-resource setting can train and maintain ventilation skills, nor whether it has the potential to change practice in the clinical setting, or impact neonatal outcomes.

Aim: The aim of this thesis was to study methods of using simulation training to bridge the clinical experience gap in ventilation of non-breathing babies at birth in a high-resource setting. The specific aims of the individual papers were to: - 1) determine the realism of simulated ventilation using the high-fidelity manikin NeoNatalie Live; 2) evaluate the effects of a low-dose, high frequency simulation training (LDHFST) programme using NeoNatalie Live on the ventilation competence of multidisciplinary HCPs; and 3) determine the optimal simulation training load to maintain ventilation competence in these HCPs.

Method: A prospective observational study of HCPs from six different professions involved in neonatal resuscitation, with a randomised controlled study arm. Following baseline testing (T1) of simulated ventilation performance, participants attended an educational session, after which their ventilation performance was re-tested (T2). Participants were randomised to one of two training-frequency groups and asked to train independently for nine months, receiving targeted feedback from the simulator to guide their training. These groups were a) intervention group aiming for two training sessions per month and b) control group permitted to choose their own training frequency. After nine months of independent training, participants' simulated ventilation performance was re-tested a final time (T3). Parallel to the simulation study, all real neonatal ventilation was recorded using a respiratory function monitor (RFM).

To evaluate the realism of the simulated ventilation experience (study I, observational), we used panel data regression analysis of RFM data. We compared ventilation data obtained from the manikin when ventilated by paediatricians, with data obtained from real resuscitations performed by the same group of HCPs. The educational benefit of the simulation training programme (study II, randomised controlled study) was assessed by Kruskal-Wallis testing to compare T3 scores for the two training frequency groups. The same test was used to analyse the effect of the ventilation performance test scores, T1, 2 and 3, for the different professions. Finally, we used generalized linear mixed effects models to correlate ventilation competence scores, obtained by participants during their nine months of independent training, with training load (frequency and dose) (study III, observational). Estimated marginal probabilities of successful outcomes identified training loads predictive of high scores.

Results: Study I - We found similarities in three important ventilatory parameters and their inter-relationships, and the same frequency of upper airway obstruction, in the manikin and neonates, supporting the fidelity of the simulated ventilation experience. **Study II -** 187 HCPs from

paediatric, obstetric and anaesthesia services completed the simulation study. Those randomised to the intervention group trained on average 8 sessions in 9 months, while those in the control group trained 2.8 sessions. There was no difference in T3 scores between these two groups. Subgroup analysis comparing T3 scores for those performing no sessions versus those performing 9 or more sessions in 9 months showed a significant difference in favour of training. Paediatricians scored significantly higher at T1 than the other five professions. For the paediatricans, there was no difference in scores at T1, 2 or 3. Overall, scores improved significantly from T1 to T2 and to T3. At T3 there was no difference in the scores for all six professions. **Study III -** During the 9 months of independent training, 4348 simulation cases were performed. Training on average 0.6 sessions per month was predictive of high ventilation competence scores for all 187 participants.

Conclusion: NeoNatalie Live effectively simulates conditions encountered during real-life neonatal ventilation. Ventilation competence can be trained through simulation, and brief, frequent sessions maintain competence despite a lack of on-going clinical opportunities to practice this skill. For this multidisciplinary group of healthcare providers, training on average once every other month maintains competence.

List of publications

Paper I

Haynes, J., Bjorland, P., Gomo, Ø., Ushakova, A., Rettedal, S., Perlman, J., & Ersdal, H. **Novel Neonatal Simulator Provides High-Fidelity Ventilation Training Comparable to Real-Life Newborn Ventilation.** *Children*. 2021; 8(10):940. https://doi.org/10.3390/children8100940

Paper II

Haynes J., Rettedal S., Perlman J., & Ersdal H. **A Randomised Controlled Study of Low-Dose High-Frequency In-Situ Simulation Training to Improve Newborn Resuscitation.** *Children*. 2021; 8(12):1115. https://doi.org/10.3390/children8121115

Paper III

Haynes J., Rettedal S., Ushakova A., Perlman J., & Ersdal H. **How much training is enough? Low-dose, high-frequency simulation training and maintenance of competence in neonatal resuscitation.**

Manuscript submitted to Simulation in Healthcare, under review

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1 Introduction

1.1 Background

Every single day, several hundreds of thousands of babies are born around the world [1]. That day, these babies encounter the most dangerous event of their lives up until the day they die. For too many, those two days are one and the same. The neonatal transition at birth, adapting from intra- to extrauterine life, is one of the most remarkable feats of human physiology. Those newborns failing to make this transition need urgent help. The humanitarian and economic consequences of failing to provide this help cannot be overstated [2, 3].

This thesis focuses on training healthcare providers (HCPs) in a high-resource setting to provide that crucial help to newborns in need in a timely and effective manner. It builds upon vital work performed with the same goal in a low-resource setting, where the neonatal mortality burden is high [4]. Through this work, I hope to convince readers that while we cannot produce the same visible statistical improvements in neonatal outcome that Mduma [4] and many others working in Africa and Asia have demonstrated, the benefits in Norway are nonetheless both real and tangible. I would like for this potential for improved newborn care in a country with one of the lowest neonatal mortality rates (NMR) in the world to serve as inspiration for other high-resource facilities who may be resting on the laurels of an NMR just a fraction of that of the world's poorest countries.

1.2 The burden of neonatal mortality and morbidity

Globally in 2019, 2.44 million newborns died within 28 days of birth, the definition of neonatal mortality [5]. This is a substantial reduction since the introduction of Millennium Development Goal 4- Reduce child mortality, with the NMR falling from 33 to 19 deaths per 1000 live births between 2000 and 2015 [5]. However, in 2015, one million babies died

on their day of birth, and the United Nations highlighted that focus on newborns was critical in accelerating progress in child survival [5]. The World Health Organization (WHO) and United Nation's (UN) "Every Newborn Action Plan" aims to end preventable newborn deaths and reduce the global NMR to no higher than12 per 1000 live births by 2030 [6]. One of the action plans to achieve this is to ensure that a skilled health worker is present at every birth.

The majority of neonatal deaths worldwide are caused by preterm birth complications (35%), complications during labour and delivery (24%) and sepsis (23%) [6]. The burden is highest in sub-Saharan Africa (42% neonatal deaths) and Central-Southern Asia (37% neonatal deaths). Figure 1 shows the global rates of neonatal mortality in 2018 with reference to the Every Newborn Action Plan goal of 12 per 1000 live births by 2030. In Norway, the NMR for 2018 was 1.4 [7].

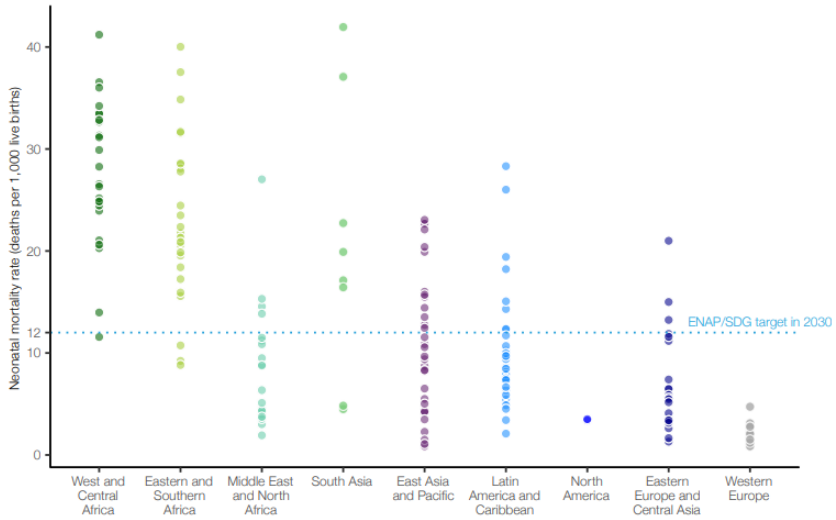


Figure 1- Disparities in global rates of newborn mortality in 2018, United Nations, Every Newborn Action Plan, ref. 6. The dotted blue horizontal line indicates the Every Newborn Action Plan (ENAP)/Sustainable Development Goal (SDG) target of ≤ 12 per 1000 live births

Many neonatal deaths could be avoided with simple, cost-effective and high-impact interventions [8, 9]. However, neonatal mortality figures do not convey the burden of morbidity. 1.3 million newborns survive each year with major disabilities, and one million with long-term disability, such as learning and behavior difficulties. Most of this disability is preventable [10]. While the NMR is substantially lower in high-resource countries like Norway, long-term impairment among survivors remains an important issue [11]. Even between and within high-resource countries, the risk of death and disability varies [12]. Figure 2 shows natural log of observed versus predicted (obtained from a regression model accounting for quality of definition of neonatal encephalopathy (NE), NE severity, and population selection bias) incidence of NE for global studies reporting NE data.

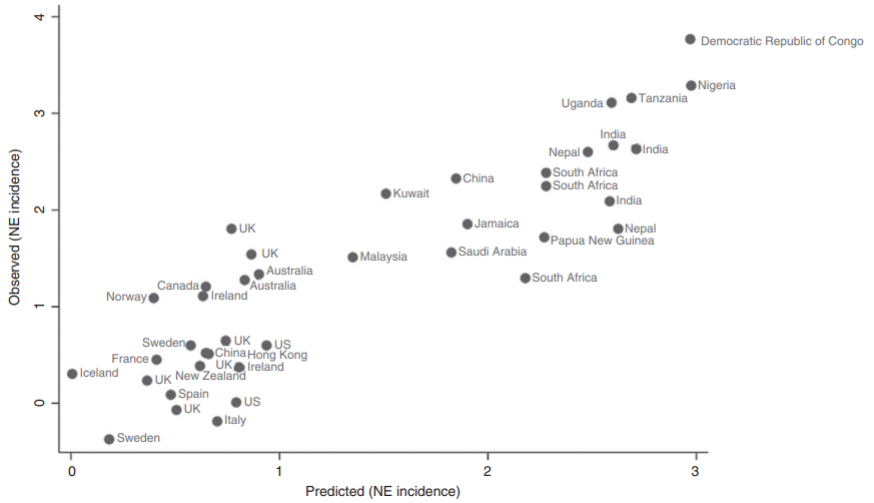


Figure 2 Observed vs predicted natural log incidence of neonatal encephalopathy (NE) in countries reporting NE data, Lee et al, ref.12

From figure 2 we can see the wide variation in reported incidences of NE in studies from North-West Europe and the USA, all with NMR < 5. This disparity in neonatal morbidity between high-income countries may be at risk of worsening in the wake of a global pandemic and war in Europe- factors known to worsen neonatal mortality figures in the most deprived areas of the world [10, 13]. All the more reason to redouble our efforts to provide the best healthcare in secondary prevention of intrapartum hypoxic events in high-resource countries.

1.3 Newborn transition-normal and abnormal

The physiological transition from intrauterine life, with fluid-filled lungs and the placenta as the organ of gas exchange, to extrauterine life with aerated lungs as the organ of gas exchange, is nothing short of remarkable.

1.3.1 The fetal circulation

Figure 3 shows a schematic representation of the fetal circulation [14].

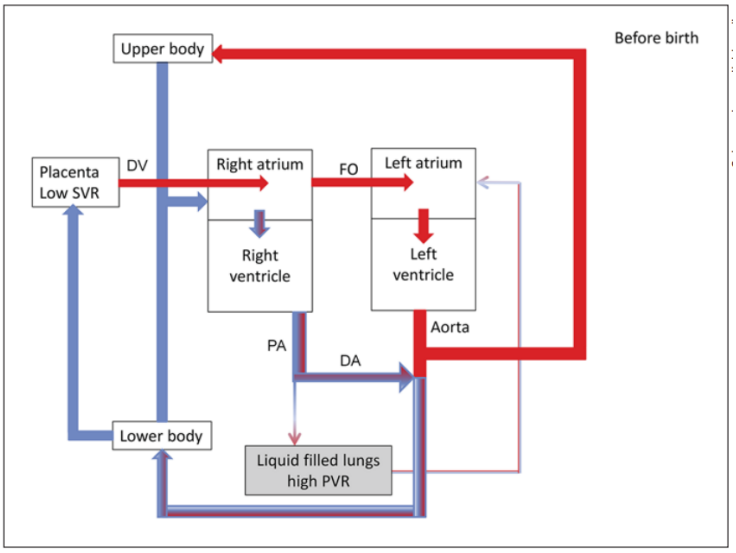


Figure 3-The fetal circulation. Red indicates blood with a high O_2 saturation and blue indicates blood with a low O_2 saturation. SVR-systemic vascular resistance; DV-ductus venosus; FO-foramen ovale; PA- pulmonary artery; DA- ductus arteriosus; PVR- pulmonary vascular resistance. From van Vonderan et al. ref. 14

Oxygenated blood enters the fetal circulation via the placenta into the inferior vena cava. It is transmitted via the ductus venosus to the right atrium where oxygenated blood is preferentially passed through the foramen ovale to the left heart (2/3) and transmitted further via the aorta to supply the heart, brain and upper body [14]. Venous return from the superior and inferior venae cavae mixes with the remainder of blood in the right atrium and is pumped out of the dominant right ventricle to the pulmonary artery. Due to high pulmonary vascular resistance, very little blood passes through the fluid-filled lungs and flows instead to the descending aorta via the ductus arteriosus, supplying the lower body before being returned to the placenta.

Figure 4 shows a schematic diagram of the neonatal circulation after birth [14].

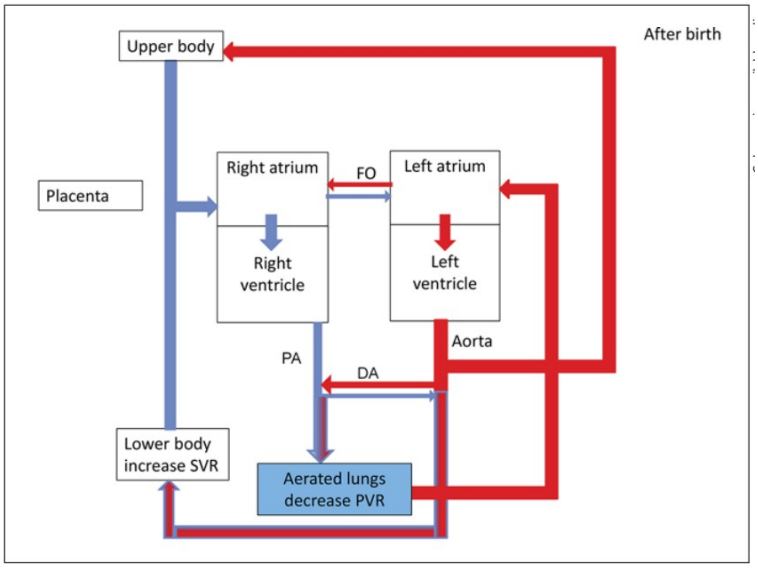


Figure 4 Neonatal circulation after birth. Red indicates blood with a high O_2 saturation and blue indicates blood with a low O_2. Saturation. FO- foramen ovale; PA- pulmonary artery; DA ductus arteriosus; SVR- systemic vascular resistance; PVR- pulmonary vascular resistance. From van Vonderan et al. ref.14

After birth, umbilical clamping results in the loss of 30–50% of total venous return along with increased systemic vascular resistance. Pulmonary resistance decreases with aeration of the lungs, as oxygen stimulates vasodilatation, causing increased blood flow through the pulmonary artery. Blood flow through the ductus arteriosus and foramen ovale becomes bidirectional. Up to 50% of the pulmonary blood flow arises from the ductus arteriosus via a left-to-right shunt [14].

1.3.2 The respiratory transition

The fetal to neonatal transition at birth starts when the newborn takes the first breaths. During the initial breaths, lung liquid is cleared and air remains in the lung at the end of expiration, providing a functional residual capacity (FRC) [15]. Hooper et al. propose that this may occur in three phases, suggesting strategies for ventilatory support in non-breathing neonates; firstly, liquid clearance principally by the movement

of liquid through the airways and across the distal airway wall; secondly, liquid leaving the airways temporarily accumulates within the interstitial space, increasing interstitial tissue pressures and the possibility of liquid re-entry into the airways, thereby compromising gas exchange; and thirdly, stable gas exchange when the liquid has been cleared from the interstitial space [16].

Although a variety of mechanisms promote lung-liquid clearance ante- and intrapartum, liquid still fills the airways after birth until the newborn takes its first breath [17]. Should the neonate fail to initiate spontaneous breathing, e.g. due to birth asphyxia, mask ventilation will be required to replicate the mechanics of lung liquid clearance and establishing FRC for gas exchange. Healthy term infants at birth may take up to 30 seconds before taking the first breath [18]. The first breaths tend to be deeper and longer than subsequent breaths and are characterised by a short deep inspiration followed by a prolonged expiratory phase, and commonly, expiratory pauses or "brakes". This can result in high positive airway pressure. This complex pattern is not easy to replicate with mask ventilation, and the required inflating pressures may be difficult to achieve with recommended settings for ventilation devices [15], making resuscitation of the newborn with completely absent respiratory effort challenging.

1.3.3 The cardiovascular transition

Soon after birth, with lung aeration and vastly reduced pulmonary vascular resistance, along with increased systemic vascular resistance after cord clamping, the circulation changes from parallel to series, where the right ventricular output equals the left ventricular output. The cardiac output nearly doubles after birth, paralleling the rise in oxygen consumption [17]. Cardiovascular stability in this situation is maintained when the newborn breathes before cord clamping, with pulmonary vasodilatation and filling of the resultant intravascular space occurring before the significant reduction in preload when the cord is clamped [16,

19, 20]. The increased pulmonary blood flow results in increased venous return to the left heart, and leads to increased left ventricular pressure, cardiac output and systemic blood pressure. [19].

1.3.4 Perinatal asphyxia

The term "asphyxia" derives from the Greek "asphuxía", meaning "stopping of the pulse". However, in common medical usage, the term "asphyxia" implies a lack of gas exchange that results in simultaneous hypoxia and hypercapnia, leading to a mixed metabolic and respiratory acidosis. In 2012, WHO defined birth asphyxia as "failing to initiate or maintain regular breathing at birth" [21]. The use of this clinical definition has been challenged [12], as the name implies that the hypoxic insult causing respiratory depression has occurred intrapartum, which may not be known, particularly in low-resource settings. However intrapartum events are a significant cause of birth asphyxia on a global basis [22], and this easy-to understand definition remains in common usage.

Impaired gas exchange can occur before, during, or after delivery. It may occur entirely during fetal life, but may also occur during labour and delivery (birth asphyxia), leading to abnormal transition. Asphyxia may also develop in the immediate neonatal period if an infant cannot support his or her own gas exchange without the placenta. During fetal life, labour and delivery, interruption of the placental blood flow is the most common final pathway leading to asphyxia [23].
The consequences of the biochemical disturbances resulting from asphyxia are progressive cellular dysfunction and death, leading to organ dysfunction and ultimately, death of the organism, if the process is not reversed. The fetus responds to asphyxia by redistributing circulation preferentially to the heart, adrenal glands and brain, to maintain haemodynamic stability and stave off brain damage (encephalopathy). Our knowledge of the response of the neonate to asphyxia is based on the original work performed by Dawes on monkeys in whom the

umbilical cord was tied and a warm bag of saline placed to prevent gas exchange via the lungs [24]. Figure 5, adapted from Dawes, visualises the respiratory and cardiovascular response to asphyxia and resuscitation.

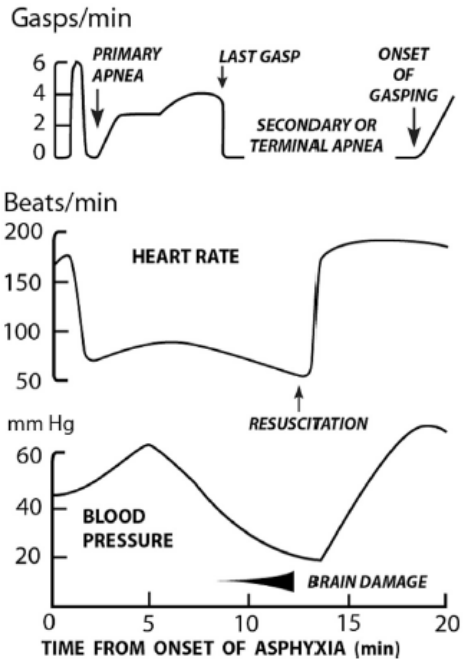


Figure 5 Respiratory and haemodynamic response to asphyxia and resuscitation, adapted from Dawes 1963, ref. 24

Within 30 seconds of the start of asphyxia, a brief period of rapid respiratory effort occurs. This culminates in primary apnoea and bradycardia. If the asphyxial process is interrupted within 30 to 90 seconds, the heart rate invariably responds to basic interventions including drying, stimulation and/or bag mask ventilation. If the asphyxial process continues, gasping occurs. Should the asphyxial process is interrupted at this point, spontaneous regular respirations may still be induced via prompt physical stimulation. Without intervention, gasping gradually becomes weaker until a terminal “last gasp” occurs. This secondary apnoea, with a profound bradycardia, is followed by

death unless resuscitation occurs [24, 25]. Delay in commencing effective ventilation progressively delays the onset of gasping and the subsequent establishment of regular respiratory effort, until such time that the damage caused by asphyxia precludes effective resuscitation.

1.4 Neonatal resuscitation

In large part, neonatal resuscitation is performed as secondary prevention in cases of birth asphyxia. It cannot undo or reverse the intrauterine pathology resulting in placental circulatory dysfunction, but can prevent or hinder further damage from occurring by re-establishing oxygenation and ensuring adequate neonatal respiratory efforts, depending upon the point at which effective gas exchange is restored.

Neonatal resuscitation is defined as the set of interventions at the time of birth to support the establishment of breathing and circulation [26]. Between 5-10% of all newborns require assistance to establish breathing at birth, and simple warming, drying, stimulation and resuscitation reduce neonatal mortality and morbidity [4].

Neonatal resuscitation in some form has been described since biblical times [27]. Many of the interventions described over the past 2000 years or so, for example, rubbing the body with spirits, swinging the infant upside-down and dilating the rectum, while lacking rigorous scientific evaluation, have the advantage of providing considerable stimulation to the newborn, a technique which remains, today, one of the central initial steps in the management of every newborn [28]. However, the need to provide assisted ventilation was also recognised, with a description of mouth-to-mouth ventilation of the newborn in 1472 and early descriptions of the use of endotracheal tubes in neonates in the 1750s [28].

Modern neonatal resuscitation can be traced back to the 1970s, following the groundbreaking work of Elam and colleagues in the 1950s, convincing the world of the effectiveness of mouth-to-mouth ventilation,

and the emergence of formal cardiopulmonary resuscitation theory in the 1960s [29, 30]. The availability of neonatal intensive care bloomed during the 1970s, providing on-going care for those babies resuscitated according to newly available guidelines [31]. Neonatal resuscitation guidelines have been subsequently produced and regularly updated by the major resuscitation councils. This work has been hampered by a paucity of high-level evidence to back up the majority of recommendations, a situation that had been appreciated many years before by Virginia Apgar, the mother of the universal scoring system used to objectively describe and document the condition of a baby at birth [32]. The International Liaison Committee on Resuscitation (ILCOR) was formed in 1992, with representatives from the major resuscitation councils around the world. ILCOR began to address the need for closer international collaboration on issues involving neonatal, paediatric, and adult cardiopulmonary resuscitation and emergency cardiovascular care [33]. Their aim was to promote evidence-based resuscitation. ILCOR regularly reviews the available evidence for, amongst many specific situations, neonatal resuscitation, and produces treatment recommendations (Consensus on Science with Treatment Recommendations- CoSTR) upon which the resuscitation councils base their guidelines [34].

Figure 6 shows the Norwegian Resuscitation Council's (Norsk Resuscitasjonsråd- NRR) most recent algorithm for neonatal resuscitation [35]. NRR published updated guidelines in 2021, based on the previous NRR guidance from 2015 [36], with input from the 2020 CoSTR recommendations [37], the 2021 European Resuscitation Council (ERC) guidelines [38] and the 2020 American Heart Association (AHA) guidelines [39]. The basic algorithm remains unchanged, with early identification of the newborn in need of stabilisation or resuscitation, maintaining body temperature and a patent upper airway, drying and stimulation, and assessment of heart rate and spontaneous respiratory efforts. Positive pressure ventilation (PPV) should be started

within 60 seconds of birth for those who are not breathing adequately and/or have a heart rate < 100 beats per minute. Effective PPV is best identified by a rapid rise in heart rate. Should this not occur, steps to ensure effective ventilation should be undertaken before consideration of more advanced resuscitation, including chest compressions, securing the airway and giving medications.

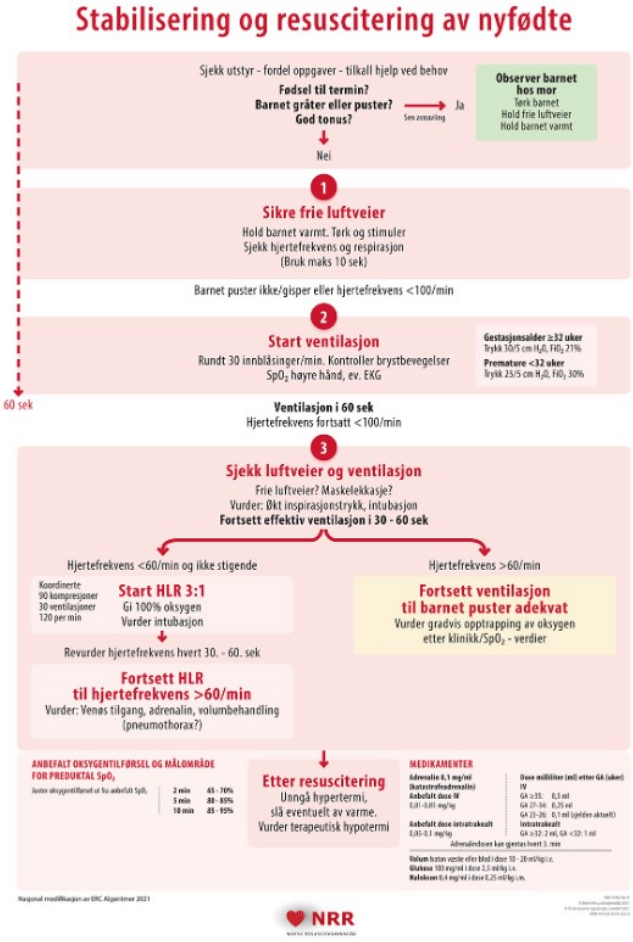


Figure 6 2022 placard of Norwegian Resuscitation Council newborn stabilisation and resuscitation algorithm

The overwhelming majority of newborns delivered globally require simple stabilisation interventions or PPV to reverse the asphyxial process and enable spontaneous respiration [40]. Figure 7 depicts the need for stabilisation and resuscitation interventions globally.

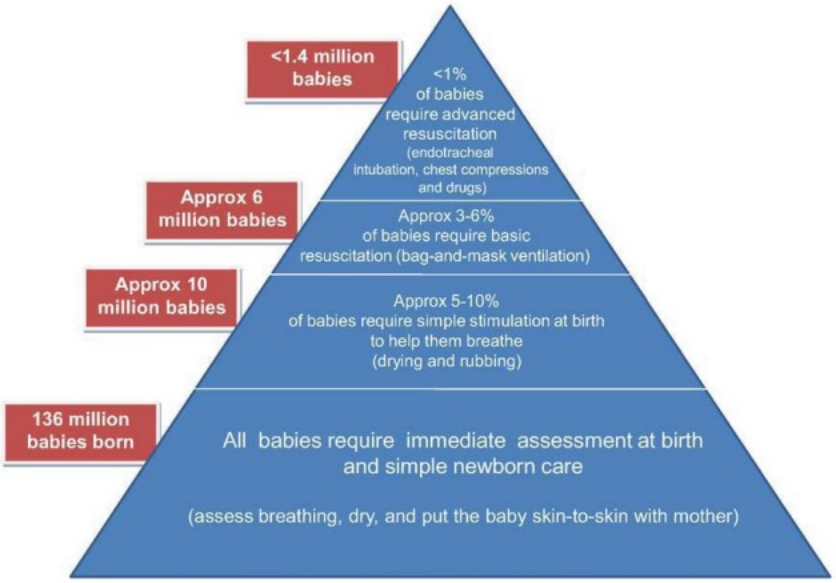


Figure 7 Global incidence of newborn stabilisation and resuscitation interventions, from Wall 2009 ref. 40

Non-breathing babies with primary apnoea will respond to simple stimulation alone, such as drying and rubbing. Basic resuscitation with a bag-and-mask is required for 3-6% of newborns, and is sufficient to resuscitate most neonates with secondary apnoea, as their bradycardia primarily results from hypoxemia. More advanced measures, including endotracheal intubation, chest compressions and medications are required in <1% of births [41, 42].

1.5 Neonatal ventilation at birth

Mask ventilation of the non-breathing newborn is the cornerstone of neonatal resuscitation. Aeration of the fluid-filled lung initiates the

process of neonatal transition at birth [43]. For those newborns who do not respond to stabilisation by breathing adequately, the caregiver must try to replicate the mechanical process of providing sufficient transpulmonary pressure to drive lung fluid into the interstitial space, establish a FRC and facilitate pulmonary gas-exchange to reverse the asphyxial process.

Studies of term neonates at birth identify that the initial spontaneous breaths generate large transpulmonary pressures, >30 cmH_2O [14]. Once fluid had been driven out of the alveolar space and FRC established, the resistance to inflating the lungs further is considerably reduced, i.e. the compliance increases. Continuing to apply the same inflating pressure will now lead to increased volume delivery. It is thought that lung fluid may be cleared in the first three to five breaths [44], and that FRC may be established after 20 breaths [45]. Ventilatory mechanics at birth are thus not static and evolve over the course of the first minutes. This means that the requirements when providing PPV at birth change rapidly [16]. Great care is needed to ensure both effective mask ventilation and avoidance of iatrogenic harm, particularly from excessive tidal volumes (V_T - the amount of air used to inflate the lungs with each ventilation), which may induce acute lung injury from over distention, and in animal models, has been shown to cause subsequent brain injury from a systemic inflammatory cascade [20].

Several methods of transmitting inflating pressure to the lungs exist. The most commonly used ventilatory device is the self-inflating bag (SIB). Figure 8 shows two forms of SIB used to provide PPV at birth. The traditional SIB comprises a 240ml silicone bag attached horizontally to the interface delivering the inflating pressure to the neonate (in this case a facemask). The newer Upright SIB (Laerdal Medical, Stavanger, Norway) has a larger silicone bag of 320ml volume, attached vertically to the facemask. In both cases, the bag is squeezed to generate pressure and gas flow through the mask. The pressures generated depend how the bag is squeezed and how tightly the mask is applied to the infant.

Inflating pressures can be increased by occluding the yellow pop-off valve, preventing the escape of gas flow via this route. The pop-off valve on both types of SIB is designed to open such that peak inflating pressure (PIP) is limited to 35cmH_2O. Gas leakage around the facemask is common, and when large, may compromise effective PPV by preventing the generation of adequate inflating pressures [46]. There is some evidence that the Upright delivers, on average, higher V_{TS} and is preferred by inexperienced operators [47].

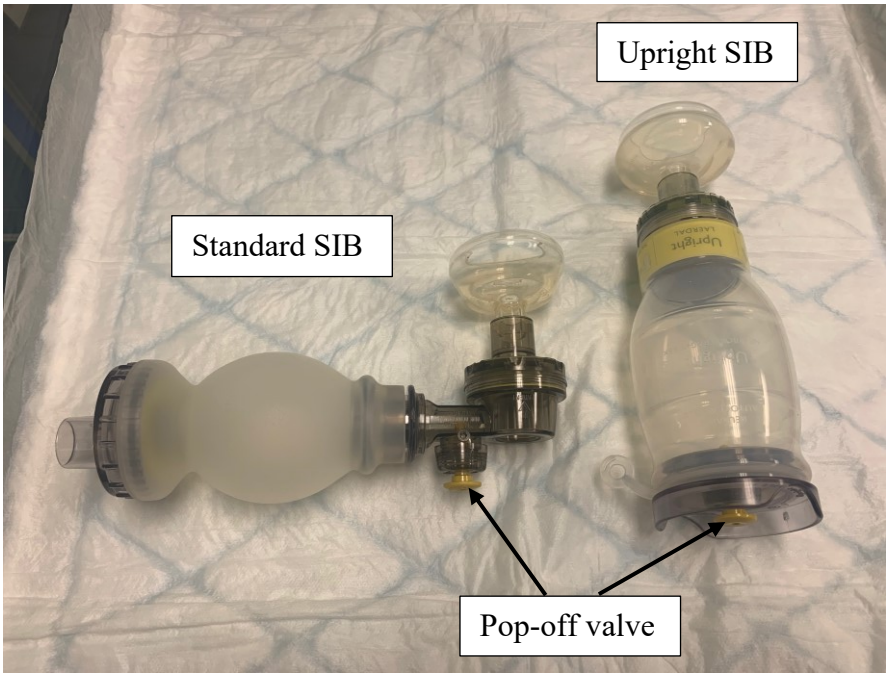


Figure 8 Two types of neonatal self-inflating bag (SIB)

The SIB is the most common device used to provide PPV at birth by virtue of its simplicity, requiring no external gas supply to generate inflating pressure and gas flow. It is cheaper to produce and maintain than other devices, and is suitable for use in low-resource settings. It remains a standard piece of ventilation equipment globally due to many decades of use [48], and the ability of the operator to rapidly increase

inflating pressure by occluding the pop-off valve [49]. Due to the rapid recoil of the bag, re-inflation happens quickly once the squeeze is released, and in comparison to flow-dependent devices, the SIB is relatively tolerant of larger mask leaks [50].

However, the most common criticism of the SIB is the lack of any monitoring of the ventilation provided, with the operator unaware of pressures applied and V_{TS} achieved [51]. SIBs in general provide higher PIPs than flow-dependent devices [49, 52] and PIP generated may be higher than that intended, particularly with the Upright SIB [53]. Standard SIBs used in many countries lack a valve to generate positive end-expiratory pressure (PEEP), although it is possible to add in a PEEP valve on newer models. PEEP is believed to be beneficial in maintaining alveolar aeration on expiration, particularly prior to clearance of lung fluid from the interstitial space, when re-flooding with fluid may occur [43].

When a pressurised gas source is available, a flow-dependent device may be used to provide PPV in the delivery room. As such, these devices are not suitable for use in resource-limited settings. Two types of flow-dependent device are recommended [54]. Of these, the T-piece resuscitator is most widely used as the first choice for neonatal PPV in high-resource settings [55]. Figure 9 shows a commonly used T-piece resuscitator, the NeoPuff™ (Fisher and Paykel, Auckland, New Zealand). In contrast to the SIB, there is no bag to squeeze to provide lung inflation. Instead, the operator must intermittently occlude the PEEP valve located at the distal end of the T-piece to direct gas flow through the facemask to the infant. Figure 10 shows a close-up of the PEEP valve on the T-piece. When uncovered, the PEEP valve allows sufficient gas flow to escape to maintain the desired end-expiratory pressure. By holding the mask applied to the infant's face without providing PPV, continuous positive airway pressure (CPAP) is given. A manometer displays the pressure delivered. T-pieces deliver consistent pressures in line with the device's settings [56], irrespective of operator

experience [57], and can limit PIP, thereby potentially avoiding dangerously large V_{TS}. This has made them particularly valuable in avoiding iatrogenic harm when ventilating premature neonates [58].

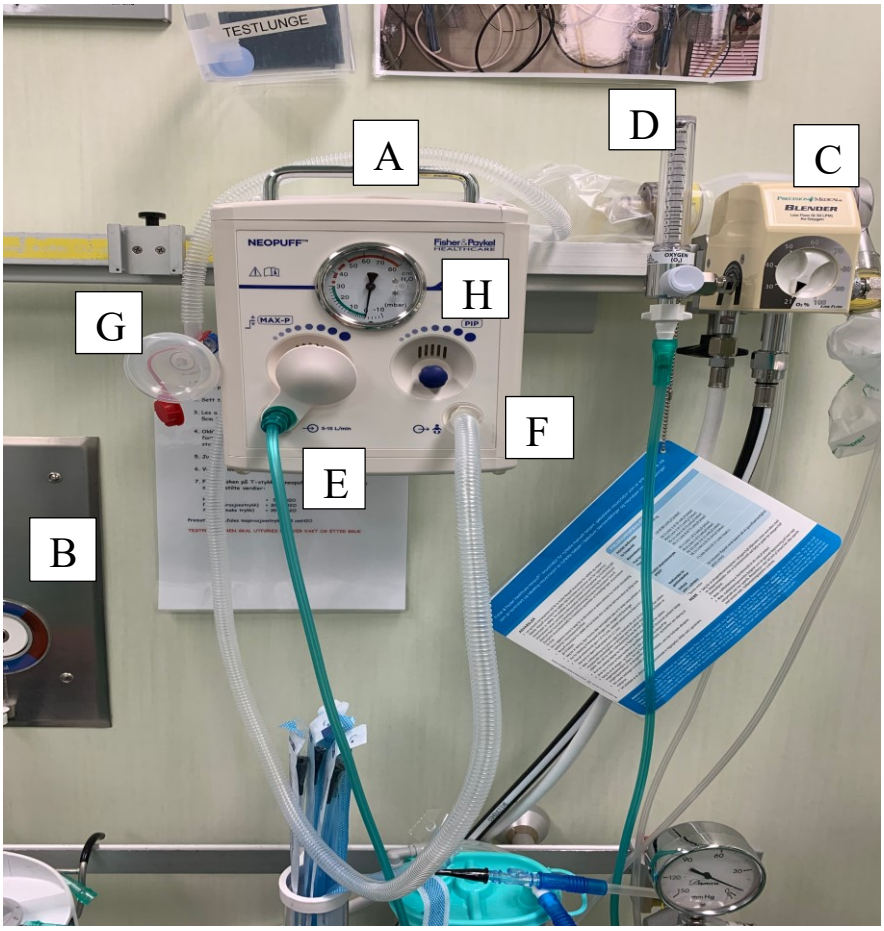


Figure 9 Neopuff™ T-piece infant resuscitator. A- NeoPuff™ unit, B- pressurised gas source, C- gas mixer determining oxygen concentration, D- flowmeter regulating gas flow, E- plastic tubing introducing gas flow into NeoPuff™ unit, F- proximal T-piece directing gas flow from unit to facemask, G- facemask at distal end of T-piece, H- manometer displaying pressures

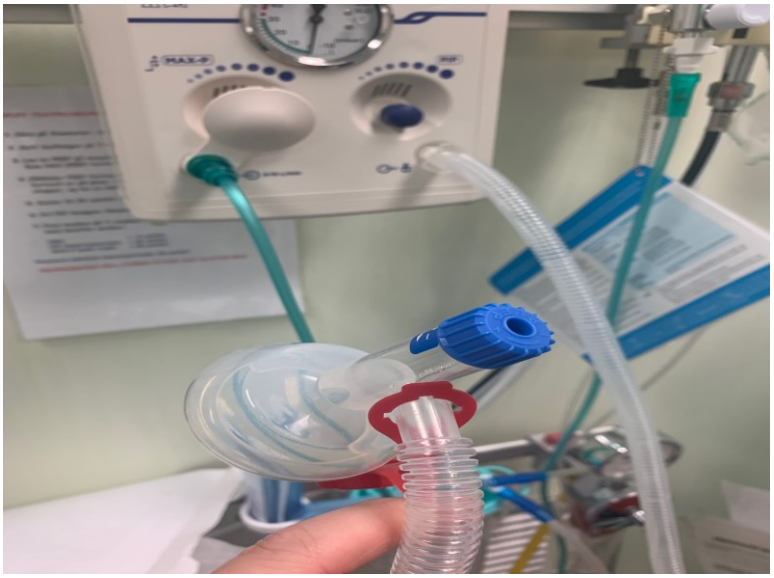


Figure 10 Distal end of T-piece showing the blue PEEP valve with its opening which is occluded to cycle from PEEP to PIP in order to inflate the lungs. PEEP – positive end-expiratory pressure PIP- peak inflating pressure

The flow inflating anaesthesia bag (FIB-figure 11) is less frequently used. This system also requires a pressurised gas source to create flow, but changing pressure from PEEP to PIP is performed by the operator squeezing the flow-inflating bag. It is more difficult to provide successful PPV with a FIB, particularly for inexperienced operators [59]. It also provides less stable PIP and PEEP than the T-piece resuscitator [60]. The main advantages of the FIB are the possibility to read the pressure delivered from a manometer and the ability of the operator to assess the lung compliance through the feel of the bag.

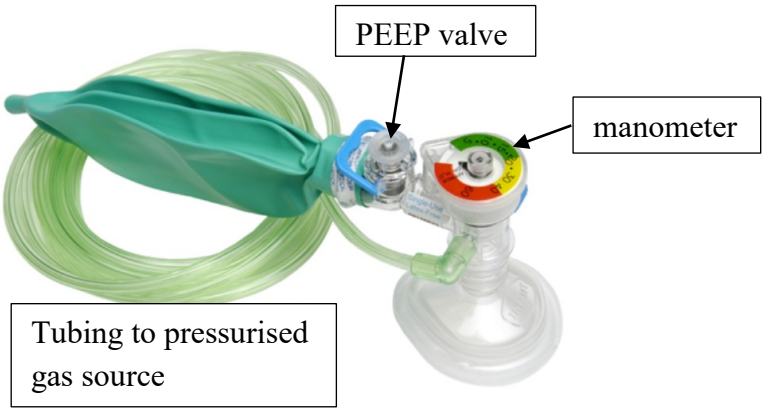


Figure 11 A flow-inflating bag with integral manometer

While all three ventilation devices have their benefits and limitations, with respect to PPV in term neonates, no one device is clearly superior to any other [61]. The most important factor in choice of device is that the operator has been appropriately trained and is aware of the particular hazards and limitations.

European and American guidelines suggest targets for ventilation of the non-breathing newborn. ERC recommend that if the newborn is apnoeic, gasping or not breathing effectively, aim to start PPV as soon as possible, ideally within 60 seconds of birth. Check for response to PPV by observing a rapidly increasing heart rate and chest rise. If there is a positive response, continue uninterrupted ventilation until the infant begins to breathe adequately and the heart rate is above 100/minute, aiming for about 30 breaths/minute. If there is no heart rate response and the chest is not moving with inflations, check if the equipment is working properly; recheck the head-position; check mask size, position and seal; consider inspection of the pharynx and suction under direct vision to remove obstructing foreign matter; consider a gradual increase in inflation pressure [38]. AHA recommends that most term newborns can be resuscitated using peak inflation pressures of 30 cm H_2O, delivered without PEEP; occasionally, higher peak pressures are required. Further, the AHA states that it is reasonable to initiate PPV at a rate of 40 to

60/minute and that term and late preterm newborns have lower short-term mortality when respiratory support during resuscitation is started with 21% oxygen (air) versus 100% oxygen [39].

Optimal V_Ts during PPV in the delivery room remain unclear, and, for the most part, are not monitored during neonatal resuscitation. As a result, both ERC and AHA make no specific recommendation for V_Ts during neonatal resuscitation [38, 39]. It is known that spontaneously breathing newborns increase their V_Ts over the first minutes of life, reaching on average 5 to 7ml/kg after two to three minutes [62, 63]. Animal studies indicate harm with larger V_Ts between 8 to 15ml/kg [64]. A clinical study has shown greater risk for brain injury when ventilating preterm infants with V_Ts >6ml/kg [65]. Traditional advice is to aim for 4 to 8ml/kg when providing PPV, although this is data extrapolated from intubated infants [66]. Interestingly, a study of term newborns in Tanzania found that V_Ts of 9.3 ml/kg produced the largest increase in heart rate during PPV [67]. The ERC recommend a target of 4 to 8ml/kg in cases where a RFM is used during neonatal resuscitation [38].

1.6 Monitoring ventilation

Adequate PPV is the key to successful neonatal resuscitation. However, current recommendations are to assess the effectiveness of PPV by looking for heart rate rise and chest wall movement [38, 39]. While a rapid rise in heart rate is the surest sign of effective PPV, indicating that FRC, increased pulmonary blood flow and gas exchange have been achieved [16], the absence of this sign only indicates the likely inadequacy of PPV. It will not provide clues as to the cause of this. Guidelines suggest remedial actions [38], which should be performed sequentially to try to identify the problem [68]. Assessment of chest wall movement is known to be difficult, and correlates poorly with the V_T delivered [69, 70].

As adjuncts to clinical monitoring during stabilisation in the delivery room, the 2015 ILCOR recommendations advised the use of two

objective assessment tools: (1) pulse oximetry (with or without electrocardiogram - ECG) to regulate oxygen delivery and (2) exhaled carbon dioxide (CO_2) detectors for confirmation of correct endotracheal tube placement [71]. However, there are other potential uses for CO_2 detection in the delivery room. Colorimetric CO_2 detection during mask PPV in neonatal resuscitation precedes a significant increase in heart rate and oxygen saturation and may be a useful, simple tool early in resuscitation [72]. Finer et al. have also reported on the use of colorimetric exhaled CO_2 in identifying airway obstruction during mask ventilation, and have highlighted how commonly this occurs [73, 74].

This contrasts with evidence that optimal ventilation in the Neonatal Intensive Care Unit (NICU) should be guided by a continuous display of airway pressure, gas flow, V_T and gas leak at the endotracheal tube [75]. This information, when combined with clinical evaluation and other clinical testing, has been described as allowing "informed judgment" regarding PPV in neonates [76]. The relative lack of monitoring options in the delivery room is both a reflection of the difficulties in acquiring the information and interpreting these data for decision-making in real-time [77].

The RFM measures flow, pressure and CO_2. Volumes are calculated by integrating flow signals. Leak is also a derived value, given as the fraction of inspired minus expired volume by inspired volume, expressed as a percentage [78]. In many cases, the monitor can be set to continuously display pressure, flow and V_T waves. It can display numerical values for PIP, PEEP or CPAP, expired tidal volume (eV_T), respiratory rate, expiratory minute ventilation and the leak between mask and face or around the endotracheal tube. Leak may be graphically presented as the difference in area under the flow curves above (inflation) and below (deflation) zero flow [79].

A RFM can aid training and resuscitations by adding objectivity to the assessment. RFMs can be used during manikin-based training to teach

correct mask hold and positioning techniques [79]. O'Currain found that addition of a RFM to teach newborn facemask ventilation on a manikin reduced facemask leak and increased delivered volume, with less variability in both [80]. In a similar clinical study, using a RFM was associated with significantly less mask leak, more mask adjustments, and a lower rate of excessive V_T. However, when ventilating newborns, median eV_T was similar in RFM visible and RFM masked groups [81]. This was confirmed in a multicentre randomised controlled trial of respiratory function monitoring during stabilisation of preterm infants at birth, with no differences between the RFM and no RFM groups in the percentage of inflations within a predefined eV_T target range (MONitoR trial) [82]. RFM graphical output data has also been used to identify airway obstruction, where appropriate PIP delivery is associated with little or no flow or V_T, indicating obstruction to gas flow [83, 84].
Figure 12 shows a RFM graphical output displaying airway obstruction.

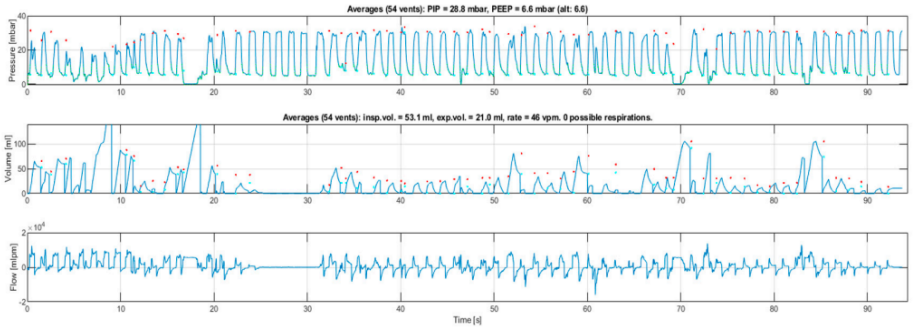


Figure 12 Pressure, volume and flow curves obtained from a respiratory function monitor during positive pressure ventilation of a term neonate. Between 25 and 30 seconds, pressure is maintained while volume and flow curves disappear, indicated no gas flow due to airway obstruction.

However, a RFM only displays the waves and data to aid the HCP, and does not provide interpretation of the signals or a diagnosis [79]. Indeed, the issue of interpretation has been used as an argument against the widespread rollout of RFMs in the delivery room. Milner et al found that although many trainee doctors found the information provided by a RFM

whilst ventilating preterm newborns useful, with 58% making PIP adjustments to achieve the desired eV_T, many of the adjustments made were not evidence-based [85]. Kuypers found in a follow-up study to the MONitoR trial that many trial participants considered the RFM to be helpful to guide neonatal resuscitation, but sufficient training was required to achieve the maximum benefit [86].
A 2010 Cochrane review found that there is insufficient evidence to determine the efficacy and safety of a RFM in addition to clinical assessment during PPV at neonatal resuscitation [87]. The 2015 ILCOR review on the use of RFMs to reduce morbidity, mortality and time to heart rate >100 states "Although a feasible technique, we suggest against the routine use of flow and volume monitoring for babies who receive PPV at birth, until more evidence becomes available (weak recommendation, low-quality evidence)" [61]. The use of respiratory function monitors in the delivery room remains rare, and is currently not recommended by ILCOR [34].

1.7 From theory to practice: - neonatal resuscitation training

With the growth of Neonatology as a subspecialty during the 1960s and 70s, the need for specific training for clinicians in managing newborns during transition rapidly became a priority. The first specific course in neonatal resuscitation originated in the United States. The Neonatal Resuscitation Program (NRP) of the American Academy of Pediatrics has set a US national standard and international example for training in the resuscitation of the newborn. The course manual has been translated into 25 different languages and the course taught in 124 countries. The concept of a standardised approach to neonatal resuscitation, based on the best available evidence, was revolutionary in 1987 when the NRP was officially launched. The goal of the NRP is to have a trained provider in neonatal resuscitation at every delivery [33].

The educational structure and delivery of the course are based on evidence and educational theory. In 1987, the emphasis was on

assimilation of content knowledge and demonstration of the technical skills necessary for neonatal resuscitation. However, knowledge and technical skills alone are insufficient for the delivery of optimal care while working as a team under intense time pressure. Behavioral skills, such as effective communication, teamwork, and leadership, also are important. Successive revisions of the course have led to an increasing emphasis on the learner adopting responsibility for their own learning, with assessment of content knowledge completed on-line, freeing up valuable contact time with instructors for skills training. As simulation became more accepted in medical education, and evidence was accumulated suggesting its benefit, the NRP officially added simulation into its courses in 2010. Simulation- based medical education is now an integral part of NRP courses, both in teaching psychomotor skills, as well as the teamwork skills needed for effective newborn resuscitation [88].
Participation in NRP currently is recommended on a biennial basis as a single isolated training experience. Renewal of NRP provider status, or recertification, consists of several hours of training, taking the NRP written examination, technical skills stations, and a «megacode» in which trainees are required to demonstrate integration of knowledge and skills. The NRP Steering Committee recognises that even though a single training experience once every two years facilitates compliance with institutional policies, it often is not consistent with achieving optimal educational outcomes [33]. While the main emphasis of ILCOR reviews is on the clinical aspects of resuscitation, there are also questions concerned with how best to conduct training [88]. Recommendations from ILCOR published in 2015 included a review of the frequency of resuscitation training [61].

The two curriculum levels, NRP Essentials and NRP Advanced, provide individualised content based on the provider's role, access to personnel, and resources during newborn resuscitation. Individual provider organisations decide who should be an Essentials provider or Advanced provider. The NRP Essentials curriculum (lessons 1-4) is for those

assigned responsibility for the newborn at birth when there are no apparent perinatal/neonatal risk factors and who will not participate in resuscitation beyond PPV. It includes skills training for facemask ventilation and laryngeal mask insertion. The NRP Advanced curriculum (lessons 1-11) is for those who attend births and are responsible for anticipated resuscitation of the newborn with known risk factors and for those who participate in newborn resuscitation beyond PPV, including alternative airway placement, chest compressions, vascular access and medication administration [89]. In addition to the traditional instructor-led course, the 8th edition can also be delivered through Resuscitation Quality Improvement (RQI) for NRP, a new self-directed, simulation-based option. RQI for NRP offers the NRP Essentials course and uses low-dose, high-frequency quarterly learning and skill sessions to verify competence in PPV performance on a neonatal simulator. The programme is available in hospitals that already use RQI solutions for life support education.

In the UK, the first course incorporating neonatal resuscitation was the Advanced Paediatric Life Support Course (APLS), developed and piloted in 1992. While the course mainly focuses on teaching the skills and knowledge required to treat children with life-threatening illness or injury, in the early years of the course, treatment of newborns was covered in the first day focusing on resuscitation [90]. All content related to newborns has now been removed and is covered in separate courses.

The UK Resuscitation Council administers the Neonatal Life Support Course (NLS), a one-day course exclusively covering neonatal resuscitation launched in 1999. Its mandate is to teach the knowledge and skills to manage the first 10-20 minutes of life for a newborn requiring assistance [90]. This course is thus appropriate for any practitioner involved in the care of a newborn. A specialised neonatal course available from 2014, the Advanced Resuscitation of the Newborn Infant course (ARNI), provided training for paediatricians and neonatologists who required highly specialised skills in the care of

neonates with life-threatening illness, including advanced airway management and chest drain insertion. Knowledge and skills for the management of the premature newborn and those with congenital anomalies are also a feature.

ERC administers a neonatal resuscitation course, along the lines of the Neonatal Life Support Course of UK Resuscitation Council, and carries the same name.

1.8 The theory of adult learning

The Cambridge English dictionary describes learning as « the process of getting an understanding of something by studying it or by experience » [91]. There are a number of different, but overlapping, theories of adult learning. The Association for Medical Education in Europe (AMEE) published an overview of these, dividing the learning theories into six main categories: - 1) Instrumental learning, which includes experiential, behavioral and cognitive learning theories; 2) Humanistic theories which are learner-centred and promote individual development 3) Transformative learning theory, using critical reflection; 4) Social theories of learning which assume that learning and thinking are social activities; 5) Motivational models involving motivation and reflection; 6) Reflective models in which reflection leads to action and then change [92].

Although any one single model likely does not explain all elements of adult learning, Kolb's experiential learning has been the basis of many current medical pedagogical principles. His theory states that learning is a continuous process grounded in experience. Kolb's emphasis on the process of learning as opposed to the behavioural outcomes distinguishes experiential learning from the idealist approaches of traditional education and the behavioural theories of learning. In this model, knowledge is continually created or recreated through experience, and is not an independent entity to be acquired or transmitted [93].

Whichever learning model one subscribes to, cognitive load theory (CLT) is an important element to consider. CLT relates to the fact that working memory has a limited capacity and duration when dealing with novel information. When the capacity of the working memory is surpassed, learning is impaired. In contrast, working memory has no known limits when dealing with previously organised information that is retrieved from long-term memory. Immensely complex bodies of information can be dealt with by working memory providing it first has been organised and stored in long-term memory. Accordingly, expertise and skill result from the storage of large amounts of knowledge in the long-term memory [94].

Learning complex procedural skills through simulation training imposes a high cognitive load on novices [95]. As complex skills require the coordination and integration of many interacting information elements and actions, they place heavy demands on a novice's working memory, which may hamper learning [95]. One approach to dealing with high intrinsic cognitive load is through segmentation of information. By reducing tasks into manageable chunks and practicing each chunk until it is effectively stored in long-term memory, a large amount of information can eventually be manipulated and incorporated into the long-term memory [94].

Commonly, learners begin with relatively simple tasks and progress to more complex tasks. Complex performances are broken down into simpler parts that are trained separately, and are gradually combined into whole-task performance [96].

CLT emphasizes the need to integrate support for novice learners with the task environment, otherwise, split-attention effects increase extrinsic cognitive load [96].

Sawyer described a six-step pedagogical framework for procedural skills: - Learn, See, Practice, Prove, Do, and Maintain (LSPPDM). In this framework, procedural skill training begins with the learner acquiring cognitive knowledge through didactic education (Learn) and observation

of the procedure (See). The learner then progresses to the stage of psychomotor skill acquisition and is allowed to deliberately practice the procedure on a simulator (Practice). Simulation-based mastery learning is employed to allow the trainee to prove competency prior to performing the procedure on a patient (Prove). Once competency is demonstrated on a simulator, the trainee is allowed to perform the procedure on patients with direct supervision, until he or she can be entrusted to perform the procedure independently (Do). Maintenance of the skill is ensured through continued clinical practice, supplemented by simulation-based training as needed (Maintain) [97]. Within several pedagogical revisions, the NRP course has come to embrace the LSPPDM paradigm as a tried and tested educational model.

The concept of deliberate practice in the acquisition of expert skill-performance came to prominence with the work of Ericsson [98]. He states "*deliberate practice is a highly structured activity, the explicit goal of which is to improve performance".* The starting point for the pedagogy of deliberate practice is that humans are not born with specific skills, and that expert performance is within the grasp of all. The main features of deliberate practice described by Ericsson include (1) motivated learners, (2) well-defined learning objectives, (3) focused and repetitive practice, (4) precise measurements of performance, and (5) informative feedback on performance. Deliberate practice can be expanded upon in the concept of mastery learning. This paradigm states that expert level performance can be expected of all practitioners, given the correct learning environment, and further, that no differences in outcome should be expected, irrespective of the practitioner involved [99]. In a WHO paper, McGagie summarised the evolution of medical education thus: - *The clinical medical education paradigm has been shifting slowly from a time-based model grounded principally in exposure to patients and much variation in learning outcomes to a competency-based model involving mastery learning where educational outcomes are uniform and learning time varies* [100].

1.9 The principles of medical simulation training

Medical education has traditionally relied on an apprenticeship model to educate learners. The well-known Halstedian mantra "see one, do one, teach one" is the traditional method for teaching procedural skills in medicine [101]. In this paradigm, skill training is accomplished through direct patient care, with trainees practicing on patients as part of an apprenticeship model. This training method has been brought under scrutiny more recently because of patient safety concerns [102, 103], particularly in the light of the increasing diversity of medical procedures [104], and the paradigm does not mesh with modern principals of adult learning. An end to the apprenticeship model era, through the use of simulation-based medical education, is becoming a reality [97].

Simulations are scenarios or environments designed to closely approximate real-world situations, usually for the purposes of training. While much of the literature documenting the use and benefits of simulation stems from recent times, simulation has been used for centuries, from medieval knight training for jousts using quintains as mock opponents, to the early flight simulators used to train fighter pilots in World War II. Simulation continues to play a large role in high-risk industries in which there are inherent risks of catastrophic error, and where training in the real world is not feasible, or would be too costly or dangerous. These industries include commercial aviation, nuclear power, the military and NASA. Medicine has been relatively slow in embracing simulation. However, the era of modern medical simulation has its roots in the mid-20th century with the development of the 'Resusci Annie' manikin by Åsmund Lærdal, and the first high-fidelity simulator designed by Denson and Abrahamson, appropriately named 'Sim One'. Although the 'Sim One' project was short lived, the medical simulation industry has grown substantially since then [105]. Reasons for the hesitancy in wide-spread adoption of simulation in medicine include financial outlays in an era of increasing cost containment, limits to accurately modeling complex human pathophysiology, demands for

rigorous scientific evidence of effectiveness, and resistance to change from a strong professional culture. However, as summarized by Gaba: - "*no other industry in which human lives depend upon the skilled performance of responsible operators has waited for unequivocal proof of the effect of simulation training before embracing it*" [106]. A more receptive atmosphere for expanding the use of simulators in medical training seems to now exist [103].

Various types of simulators exist, ranging from simple models to highly advanced, computer-driven systems. Fidelity is the extent to which the appearance and behaviour of the simulator or simulation match the appearance and behaviour of the simulated system. Simulator fidelity ranges from low-fidelity models including static mannequins and partial task-trainers (designed to teach one specific skill such as intubation), to high-fidelity simulators with life-like manikins connected to computer systems designed to control the manikin's physical and physiological responses [105]. Although debate continues regarding the comparative benefits and educational value of low- versus high-fidelity simulators [107], to maximize their value and potential, medical educators should aim to match the amount of realism to the desired educational objectives of the simulation session [105].

Initially, much of the enthusiasm for healthcare simulation was related to its grounding in adult learning theory and, in particular, Kolb's cycle of experiential learning [93]. Simulation-based medical education seems to provide a perfect medium in which to use deliberate practice. Deliberate practice in neonatal resuscitation using simulation allows the participant to actively experience a simulated neonatal resuscitation ("do") and the facilitated debriefing allows participants to reflect on their actions ("observe"). Allowing an interval of time to pass between training sessions allows the participant to conceptualise what they have learned ("think") and to consider any needed changes in their performance ("plan") [108]. This aligns with Peyton's four-step technique of demonstration, deconstruction, comprehension and

performance, which has been shown to a more efficient way of teaching medical procedural skills, including those of neonatal resuscitation, compared to the traditional apprenticeship model[109, 110]. It is now well established that simulation-based training techniques are effective and its use has been associated with better patient care and improved patient safety [97]. The research agenda has shifted to one of how to best apply this educational technique. [94].

A systematic review of simulation-based training determined that repetitive practice is one of the most important features of simulation-based training, second only to feedback [111]. Another recent review showed a strong association between hours of practice and learning outcomes, indicating that increased time spent in simulation training resulted in improved performance [112].

1.10 A history of neonatal resuscitation simulation training

While many other areas of medicine have only recently adopted simulation training, manikins (referred to as "phantoms") were developed as early as the 16th century to teach obstetrical skills and reduce high maternal and infant mortality rates [113].

One of the earliest uses of simulation training for neonatal resuscitation was reported by Halmek et al. in 2000. They developed a simulation-based training program in neonatal resuscitation (NeoSim) to bridge the gap between textbook descriptions and real life. The subjects expressed high levels of satisfaction with nearly all aspects of this novel program. Responses to open-ended questions were particularly positive in describing the realistic nature of simulation-based training. The major limitation of the program was the lack of fidelity of the neonatal manikin compared to a human neonate, with only one-half of the participants describing the neonatal manikin as providing a real-life experience [114]. Since this time, Halamek has investigated widely and commented on this

topic, and stated that simulation-based training is becoming the standard method of teaching neonatal resuscitation [115].

Early research on simulation-based training in NRP showed it to be feasible and well received by participants [108]. However, there is limited data on the effectiveness of simulation-based training on NRP performance. Studies reporting outcomes after a single simulation-based training session have failed to demonstrate statistically significant improvements in NRP performance. Participation in repeated simulation-based training may be more effective at improving NRP performance than a single-session training [108].

Mastery of the technical skills required for successful resuscitation of the newborn requires not only an understanding of when those skills should be used but also the ability to interpret visual, auditory, and tactile cues to perform the appropriate manual tasks in the correct sequence. Simulators used to train resuscitation skills should ideally possess a level of fidelity similar enough to a real human newborn that the important cues are presented to the provider. To date, most human neonatal models have had a low level of anatomic fidelity and little or no ability to represent the physiologic alterations intrinsic to the neonate in distress. To stimulate interest in development of a realistic human neonatal patient simulator, a list of characteristics was drawn up and vetted by the NRP Steering Committee and published online in 2005 as a request for proposals to the simulation industry. This was the first time that development of a highly realistic patient simulator was driven by the learning objectives put forth by a professional body rather than by the internal marketing imperatives of industry [33].

Using a pretest-posttest design, Sawyer et al. studied teams of residents participating in a series of three NRP simulations followed by a facilitated debriefing. Objective measures of NRP performance and time to complete critical tasks were evaluated on the first (pretest) and the third (posttest) simulations. Their results suggest that deliberate practice

using simulation is associated with improvements in NRP performance and supports its use in NRP training. Sawyer also found significant improvements in positive-pressure ventilation scores. Improvements in performance were not associated with clinical experience gained during the course of the study, suggesting that the performance improvements were the result of the simulation training, rather than natural skills acquisition from clinical exposure [108]. They state that future studies should work to define the optimal training interval for repetitive simulation-based training. Research should also be directed at combining deliberate practice with a mastery learning model in an effort to determine the average amount of time, or simulation sessions, required for trainees of different educational levels to become proficient at NRP [108].

1.11 Impacting neonatal morbidity and mortality

The ultimate goal of this research, and indeed any initiative focusing on the quality of newborn resuscitation, is to improve neonatal outcome. Globally, considerable progress has been made towards the WHO's goal of ending preventable newborn deaths by 2035 [116]. Since 2009, the Helping Babies Breathe program has led to impressive reductions in neonatal mortality in low- and middle-income countries [117, 118]. However, NMR is a blunt instrument with which to measure the effect of simulation training in a high-resource setting like Norway, where NMR is already well below the 2035 target of 10 per 1000 live births. Morbidity may be a more appropriate end-point to measure impact of training, but numbers of neonatal encephalopathy are also rather low in Norway, and large, multicentre studies are required to demonstrate any significant change in the incidence.

Additionally, any improvement in patient outcomes may also be difficult to ascribe to simulation training, which is seldom initiated in isolation, but is more commonly part of a multifaceted intervention. In principle this may not matter- if neonatal outcomes improve, is it important which

element of treatment had the greatest impact? In practice, it may be essential to understand the nuanced impact of an intervention in order to adapt it appropriately to tackle neonatal mortality in the huge variety of settings around the globe.

Further adding to the problem of demonstrating the effect of any training intervention is that we know very little about how we perform neonatal resuscitation in real life. We measure little of what we do in the delivery room, and it is correspondingly difficult to assess whether change has occurred. What we do know is that evidence-based guidelines for neonatal resuscitation exist, but we struggle to adhere to these [119, 120]. As a starting point for improving neonatal outcome in high-resource countries, translation of evidence based guidelines into evidence based practice is a valid aim. As research furthers our understanding of how the compromised newborn responds to resuscitation, and through translation of this knowledge into guidelines, improved monitoring during resuscitation may allow us to adapt our treatments to those providing greatest benefit towards improved neonatal outcome.

1.12 Implementation science and outcomes research

Knowing which strategies and treatments work to improve neonatal mortality is essential, but it is not enough to reduce, let alone end, avoidable newborn deaths.

The 2014 document «Every Newborn – An Action Plan To End Preventable Deaths» [116] states *"Although remarkable progress has been made in recent decades to reduce the number of child deaths worldwide, too many newborns continue to die each year despite the availability of feasible, evidence-based solutions. Nearly 3 million lives could be saved each year if the actions in the plan are implemented and its goals and targets achieved"*.

Implementation science and outcomes research are concerned with how things work in real-life settings, with the ultimate goal of improving

health care. Implementation science often starts by identifying under-utilisation of evidence-based practice. Outcomes research starts by identifying a specific clinical problem within a healthcare system.

Implementation research acknowledges the challenge of taking evidence-based practice, knowledge often assimilated through research controlling for factors commonly found in the clinical situation, and implementing it into real world settings. This requires research on the implementation process itself- what, why, and how interventions work in real world settings [121]. In the case of neonatal resuscitation to address preventable newborn deaths, adoption of potential solutions on a wide-scale, global basis, and addressing vital sustainability of interventions, rely heavily on implementation research to achieve the goals set. As such, implementation research is especially concerned with the users of the research and not purely the production of knowledge, and is sensitive to the social, cultural, economic, political, legal and physical contexts [121].

Outcome research aims to bridge the divide between the capabilities of the medical profession and the best interests of patients and society. It identifies and measures links between interventions and the actual outcomes achieved, with a broad focus on safety, effectiveness, equity, efficiency, timeliness and patient-centeredness [122].

The Helping Babies Breathe programme is an example highlighting the essential role of implementation science and outcomes research in maximizing the impact of evidence-based interventions. An early impact on newborn mortality was seen following the programmes introduction but reduction in NMR did not match expectations, with gaps in implementation a significant road block to further progress [123].

1.13 Translational simulation

The well-known simulation enthusiast David Gaba wrote: - *"Simulation has the potential to revolutionize health care and address the patient safety issues if appropriately used and integrated into the educational and organizational improvement process"* [124].
Implementation science and outcomes research in simulation-based education must bridge the gap between the considerable weight of evidence of benefit identified by research and the transfer of skills to the clinical setting, and ultimately, improved patient outcomes [125]. Such research may be termed "translational", referring to "bench-to-bedside" transfer and implementation of knowledge [126]. McGaghie identified simulation as an ideal medium with which to engage in translational science [127].

The term "translational simulation" was coined more recently, describing simulation activities that are directly focused on improving healthcare processes and patient outcomes [128]. This concept moves away from describing simulation by its methodology, e.g. high-fidelity, or in-situ, but rather promotes simulation design with focus on targeted healthcare outcomes. In this way, simulation is performed to directly address implementation issues and desired outcomes, moving away from an assumption that any given form of simulation training will necessarily lead to improved patient outcomes. This is especially valuable for areas such as newborn resuscitation, in which outcomes may be difficult to measure in order to prove the value of simulation training [129]. Lowe and colleagues describe the effective use of translational simulation to prepare for obstetric emergencies in the context of the Covid 19 pandemic, allowing for favourable outcomes in conditions widely reported to negatively impact healthcare outcomes [130].

A variation in the alignment of simulation training and implementation science was described by Dubrowski and colleagues in 2018. They

proposed the Adapted Implementation Model for Simulation (AIM-SIM) [131]. The AIM-SIM concept provides a practical implementation guide and starting point for using implementation science in simulation-based education. Its three phases are: - 1) stakeholder engagement and context exploration, 2) pre-implementation planning, and 3) programme implementation with monitoring and ongoing evaluation.

1.14 Summary: - what will this thesis address?

Throughout this introduction, I have explored the global extent of the problem of non-breathing babies at birth, the physiological background for the recommendations for management of these newborns, the educational theory underpinning how this management is taught to HCPs, in particular the role simulation training, and how implementation science can make the improvement of neonatal outcomes a reality. Through the studies making up this thesis, I will explore the role of simulation training in a high-resource setting, an arena where relatively little evidence exists, in ensuring competence in neonatal ventilation. Our goal is to provide evidence of pedagogical strategies that are effective in this setting, in response for calls to fill knowledge gaps [34, 61], and to guide implementation strategies.

2 Aims of this thesis

The overall aim of this thesis was to study methods of using simulation training to bridge the clinical experience gap in ventilation of non-breathing babies at birth in a high-resource setting.

The specific objectives of the individual papers were as follows:-

Paper I:-To determine the realism of the high-fidelity manikin NeoNatalie Live in simulating actual clinical conditions of PPV during neonatal resuscitation.

Paper II: - To evaluate the effect of a programme of low-dose, high frequency simulation training using NeoNatalie Live on the ventilation competence of multidisciplinary healthcare providers involved in newborn resuscitation during their work.

Paper III: - To determine the optimal simulation training load to maintain ventilation competence in these healthcare providers.

3 Methodology

3.1 Setting

Stavanger University Hospital has a catchment area of 330 000 in south-west Norway. It has a level III Obstetric and Paediatric department and serves as a tertiary referral centre for high-risk pregnancies from a nearby district hospital, Helse Fonna. Neonates from gestational age 23 weeks are cared for, excluding those with antenatally-diagnosed severe cerebrospinal, cardiac- or gastrointestinal malformations requiring surgery immediately after birth, who are delivered at the national competence centre for neonatal surgery.

Babies are delivered in one of three sites in the hospital. Low-risk mothers may choose to give birth on the midwife-run unit on the seventh floor. Women with more complicated pregnancies, or who desire epidural analgesia, deliver on the labour ward situated in close proximity to the operating theatre suite on the first floor. Cesarean deliveries, both planned and emergency, take place in one of two theatres assigned to this function, approximately two minutes walking distance from the labour ward. Resuscitation facilities for babies at birth are found in all three locations. There is a dedicated neonatal resuscitation room on both labour ward and the midwife-run low-risk unit, serving all delivery rooms in these two locations. In the operation suite, the resuscitation equipment is found in the anterooms immediately adjacent to the cesarean section operating theatres.

A neonatal resuscitation team can be rapidly summoned via the hospital's alarm system whenever this is needed. The team consists of a consultant neonatologist, a junior paediatrician, a NICU nurse, two anaesthetists and an anaesthesia nurse. The team assumes responsibility for the resuscitation started by a midwife and paediatric nurse assistant, and on occasion, obstetrician, who attended the delivery. The consultant

neonatologist leads the resuscitation. Paediatric medical staff will usually assume responsibility for the airway and ventilation, supported as needed by anaesthesia personnel. In deliveries where the need for resuscitation is anticipated, for example emergent assisted vaginal deliveries or emergency cesarean section, the junior paediatrician will be called ahead of time, and is thus available immediately. The midwife will assist the paediatrician, however, for more complex resuscitations, this doctor may call on the consultant neonatologist for assistance.

3.2 Equipment and data sources

3.2.1 Neonatal reuscitation set-up and equipment

Newborns requiring resuscitation are placed on the resuscitaire, a purpose-built unit providing a height-adjustable surface on which to treat the baby, with integrated heating, lighting and clock. This is stocked with towels for drying and stimulating the baby. Suction, powered by a wall-integrated vacuum, is available to clear airway secretions. 3-lead ECG and pulse oximetry monitoring is integral to the resuscitaire. Figure 13 shows the type of resuscitaire used at SUS at the time of these studies.

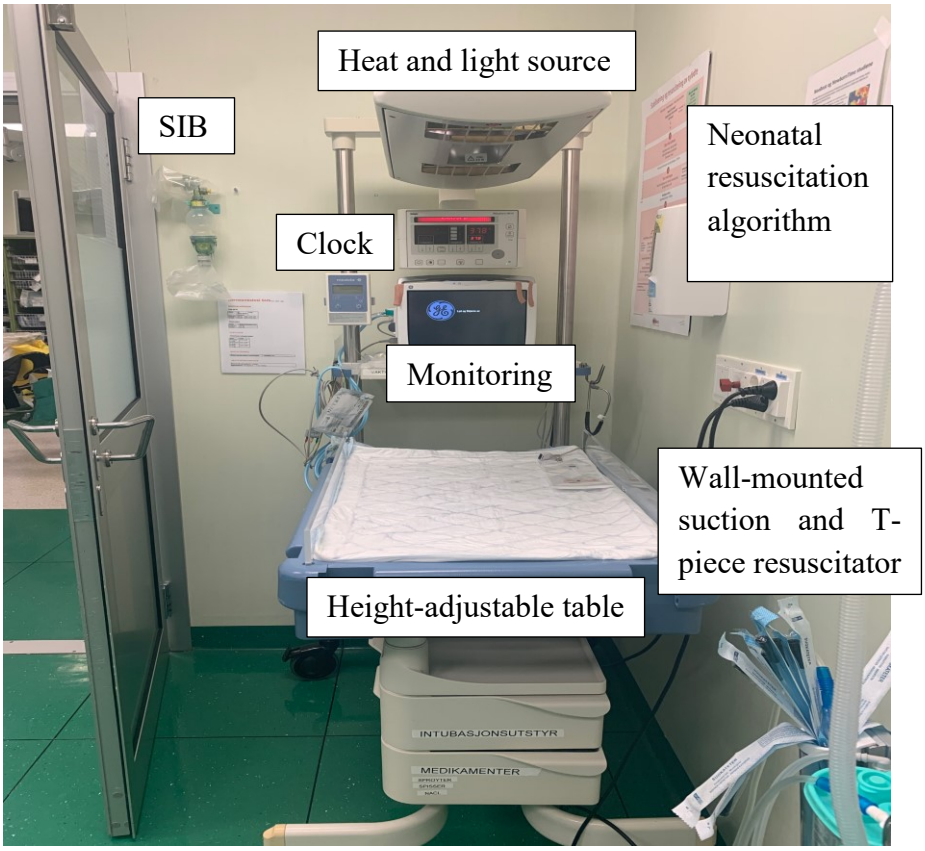


Figure 13 A resuscitaire of the type used at the time of the studies in this thesis. This is a reserve unit for the back-up cesarean section operating theatre, and when required, is turned clockwise through 90˚ to allow healthcare providers to stand on three sides of the unit during resuscitation. SIB – self-inflating bag

Mounted on the wall adjacent to the resuscitaire is a flowmeter and oxygen blender to provide a continuous gas source with the desired oxygen concentration for PPV. Such a pressurised gas source is essential to drive the T-piece resuscitator, NeoPuff™, but can also be attached to the self-inflating bag to provide titrated oxygen during ventilation. A range of facemasks is available, to ensure a tight fit for babies of all gestational ages.

PPV is primarily provided using the T-piece resuscitator, NeoPuff™. Standard initial settings for term newborns are flow 10L/minute, PIP 30 cmH_2O, PEEP 5 cmH_20, and inspired oxygen 21%. Alternatively, a standard 0.25L neonatal SIB and the newer Upright 0.32L SIB are available.

A standardised cart containing equipment for advanced resuscitation (intravenous cannulas, umbilical vein catheters, intubation equipment, drugs) are situated in all three resuscitation locations. An A5 placard of the current Norwegian neonatal resuscitation algorithm is hung on the wall in all three sites.

A NeoBeat is available in all resuscitation locations. NeoBeat is a novel neonatal heart rate meter, using dry electrodes in place of gel electrodes. This makes skin drying prior to use unnecessary. The dry electrodes are incorporated in a C-shaped plastic arch, which can be easily applied around the newborns torso or abdomen. It rapidly and reliably measures the newborns heart rate and displays it on the arch [132]. Heart rate data are stored in the NeoBeat and can be downloaded as required. Additionally, this data can be transferred via Bluetooth to the Liveborn application installed on an iPad used by the attending paediatric nurse assistant during resuscitation. The nurse assistant uses Liveborn to record time of birth and umbilical cord clamping, producing a timeline of events and neonatal heart rate during resuscitation. Figure 14 shows a newborn with NeoBeat applied and an example of a Liveborn timeline.

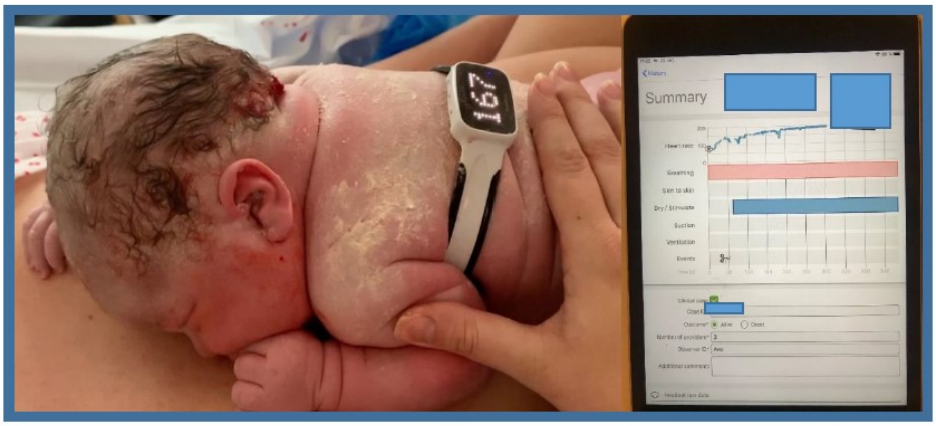


Figure 14 A newborn baby with NeoBeat applied, displaying the baby's heart rate. A screen shot from the Liveborn application (unrelated to the baby shown), documenting heart rate transferred from NeoBeat, spontaneous respiratory efforts and management provided by the resuscitation team. Photo S. Rettedal, reproduced with parental permission

Due to on-going studies in the Safer Births research group, many newborns arrive at the resuscitaire with a NeoBeat already placed on their torso or abdomen.

All ventilation provided using NeoPuff™ is automatically recorded using Laerdal Neonatal Resuscitation Monitor (LNRM). The LNRM is a patient monitor designed by Laerdal Global Health (Stavanger, Norway) for research purposes [133]. Three LNRMs are wall-mounted behind the resuscitaires, and record airway pressures and gas flow. Sensors are placed between the T-piece and the facemask. The LNRM has a lever formed to hold the T-piece and mask when not in use, and lifting up the T-piece will initiate recording. Events are stored the LRNM`s internal memory as reports that are tagged with the date and time of recording. The reports can be uploaded to a computer through a USB-port.

Air pressure is measured using a piezoresistive sensor (MPXV5010, Freescale Semiconductor Inc., Austin, TX, USA). The flow sensor (MIM Gmbh, Krugzell, Germany) has negligible resistance and dead space (1

mL), and measures airflow using hot wire anemometer technology. V_T is calculated as flow integrated over time. The flow sensor measures both the inflated and expired gas. Expired volume is used as an estimate for V_T since mask leak is reported to primarily occur during inflation [78]. Face mask leak is calculated as a percentage of inspired V_T from the formula $((V_{Tinspired} - V_{Texpired})/V_{Tinspired}) \times 100$.

Downloaded raw data is presented in numerical format, giving values for PIP, PEEP, eV_T, leak, dynamic compliance, inflation time and instant inflation rate for each individual ventilation. PIP and PEEP are measured in mbar, where one mbar equals 1.02 cmH_2O. The dynamic lung compliance is calculated as the inflated volume divided by PIP. Instant inflation rate is defined as 60 divided by the time interval between current and previous inflation. Raw data can be processed using the programme Mathlab (MathWorks, Natric, MA) to produce pressure, volume and flow graphical representations. Figure 15 shows such a graphical output.

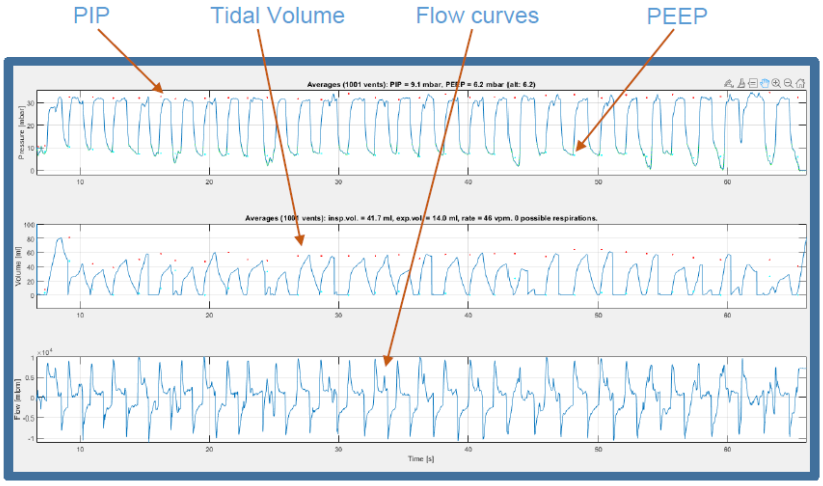


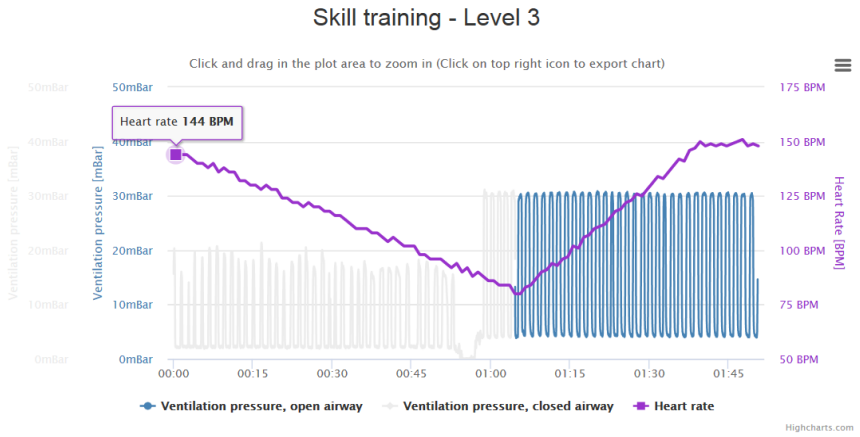
Figure 15 Graphical representation of pressure, volume and flow curves using data from Laerdal Neonatal Resuscitation Monitor recorded during a real resuscitation. PIP – peak inflating pressure, PEEP – positive end-expiratory volume. Figure prepared by P. Bjorland

3.2.2 NeoNatalie Live

NeoNatalie Live is a low-cost, high fidelity manikin designed specifically to train ventilation proficiency. Based on the original Laerdal low-fidelity manikin, NeoNatalie, it has the size and shape of a term newborn. The manikin is modified to provide a realistic experience of PPV at birth. Head position detection determines if the upper airway is patent. Air pressure during PPV is measured in the upper airway. Ventilation frequency and continuity of ventilation are measured. A closed valve simulates conditions of low lung compliance. Successful PPV (adequate PIP applied via a patent upper airway) results in the value opening, simulating improved compliance, and PPV then results in visible chest-rise. An active electrocardiogram allows monitoring of heart rate using NeoBeat, replicating recommended assessment of the adequacy of ventilation. Real resuscitation data derived from 1237 newborns informs the algorithm guiding the realistic heart rate response according to PPV provided [134]. On successful resuscitation, a cry sound indicates spontaneous breathing. Figure 16 shows the manikin with a NeoBeat attached.

Figure 16. A NeoNatalie manikin with an attached NeoBeat heart rate meter

Four scenarios of increasing difficulty are pre-programmed. Scenarios 1 and 2 involve normal initial lung compliance. Scenarios 3 and 4 begin with low lung compliance that improves as the scenario progresses. The initial heart rate is progressively lower as case difficulty increases, and requires correspondingly longer periods of optimal PPV to progress to successful conclusion of the scenario. In skills-training mode, where the provider selects a scenario and purely trains ventilation, a random option allows for not knowing the allocated difficulty level. In scenario-training mode, two or more providers may work together and a specific scenario must be chosen by one of them. Here the scenario begins at the birth of the baby and the newborn resuscitation algorithm guides when PPV should begin. On conclusion of the scenario, providers can access the ventilation and heart rate curves, along with targeted feedback on an aspect of performance that could be improved. Feedback is provided on the element of performance that is highest up on the priority list of corrections. For example, problems with holding a patent airway rank higher than deviation from the recommended ventilation frequency. If all elements of ventilation are within the algorithms tolerances, “well done” feedback is given. Figure 17 shows a ventilation and heart rate curve for a skills training scenario 3, in which the initial PIP is too low to aerate low-compliant lungs and heart rate first rises once delivered PIP is increased. The feedback indicates that the initial PIP was too low.



Start with a few ventilations with more air/higher pressure until you see the chest rise.

Figure 17. Feedback and ventilation/heart rate curves following a difficulty-level 3 skill training with NeoNatalie Live.

Study participants were issued with a personal training number, and used this number to log on to the iPad containing the NeoNatalie Live application. The app communicates with the manikin via Bluetooth. It is used to select training mode (skills or scenario) and scenario difficulty, and was the platform by which immediate feedback was given at the conclusion of the case. The data from each scenario performed is uploaded automatically to a weblog, along with the participant's personal number. Figure 18 shows the set up between manikin, iPad and weblog.

Figure 18 The manikin and NeoNatalie Live app communicate via Bluetooth. Training data from the iPad is automatically uploaded to a weblog.

3.3 Participants, study design and timeline

3.3.1 Study participants

Approximately 300 HCPs from six different professions may be involved in neonatal resuscitation at SUS. They include 120 midwives, 18 paediatric nursing assistants, 25 obstetricians, 60 doctors and 70 nurses from the anaesthesia department, 10 non-specialist doctors from the paediatric department and 10 consultants from the neonatal department. We designed a prospective observational study, with a randomised controlled arm allocating training frequency, to assess the educational benefits of implementing a low-dose, high-frequency simulation training (LDHFST) programme using NeoNatalie Live on the ventilation competency of these HCPs.

Any of the approximately 300 HCPs working in greater than 50% employment was eligible to participate in the study. This stipulation was made to limit the effect of absence form work affecting training frequency. They were invited to give informed, written consent to participation. Beyond the percentage employment stipulation, there were no exclusion criteria.

3.3.2 Overall study design

HCPs enrolled received a pre-participation questionnaire (Appendix 1) designed to collect baseline data on their employment history, how much training in neonatal resuscitation they received on a regular basis, previous clinical experience with neonatal resuscitation, and their own self-assessed confidence and competence in neonatal resuscitation. Participants were asked to complete baseline testing of their PPV competence by performing two observed simulated resuscitations in test 1. The test composed of the least and the most challenging cases of NeoNatalie Live (levels 1 and 4 respectively), performed without any instruction regarding neonatal resuscitation in general, nor specific

instruction in the use of the manikin. Each scenario in test one was observed and scored by one investigator (Joanna Haynes) using a matrix developed by this investigator along with Siren Rettedal and Hege Ersdal, and validated in a pilot study (unreported data). Each scenario was scored out of a maximum of 40 points, 12 of which related to observed completion of the initial steps in the resuscitation algorithm and 28 related to objective measures of ventilation quality from the simulator.

Each participant subsequently took part in a personalised 120-180 minute education session, mostly individually or in pairs. A small fraction of the education was delivered to small groups of a maximum of five participants. The educational session involved study of the national neonatal resuscitation algorithm [35], with particular focus on ventilation, followed by practice with the simulator until such time as the participant could demonstrate providing appropriate and effective PPV, and was confident in their ability to train independently.

At the conclusion of the educational session, participants were immediately re-tested using the same two simulation cases, providing two post-education scores in test 2. They were then randomised into one of two groups and asked to train independently with NeoNatalie Live for nine months. Randomisation was performed using a binary randomisation application, RandomOrg (RANDOM.ORG, Dublin, Ireland), and was undertaken concurrently for all HCPs attending the educational session. One group (twice monthly) were asked to aim for two training sessions per month. The other group (self-guided) were allowed to train as often or as little as desired. For both groups, no stipulation was made regarding the duration of a training session. All independent training was logged and the individual cases performed were scored by the same investigator (Joanna Haynes), with a scoring matrix using only ventilation data obtained form the weblog, to a maximum of 30 points per case.

After nine months of independent training, each participant was tested a third time with the same two cases, giving two final scores. At this time, they completed a second, post-participation questionnaire (Appendix 2), asking about their experience with training with NeoNatlie Live and how their self-reported confidence and competence had changed.

Parallel to the stimulation study, the LNRM was used to collect ventilation data from real resuscitations.

Figure 19 shows a flow chart of the different elements of the study. Four study questions were proposed, and colour coding shows which data were used to answer the different questions.

The four study questions were:-

1. Do HCPs like and use NeoNatalie Live?
2. How realistic is NeoNatalie Live in simulating conditions encountered in real neonatal reuscitation?
3. Does LDHFST with NeoNatalie Live improve simulated ventilation performance?
4. How often do HCPs need to train to maintain ventilation competence?

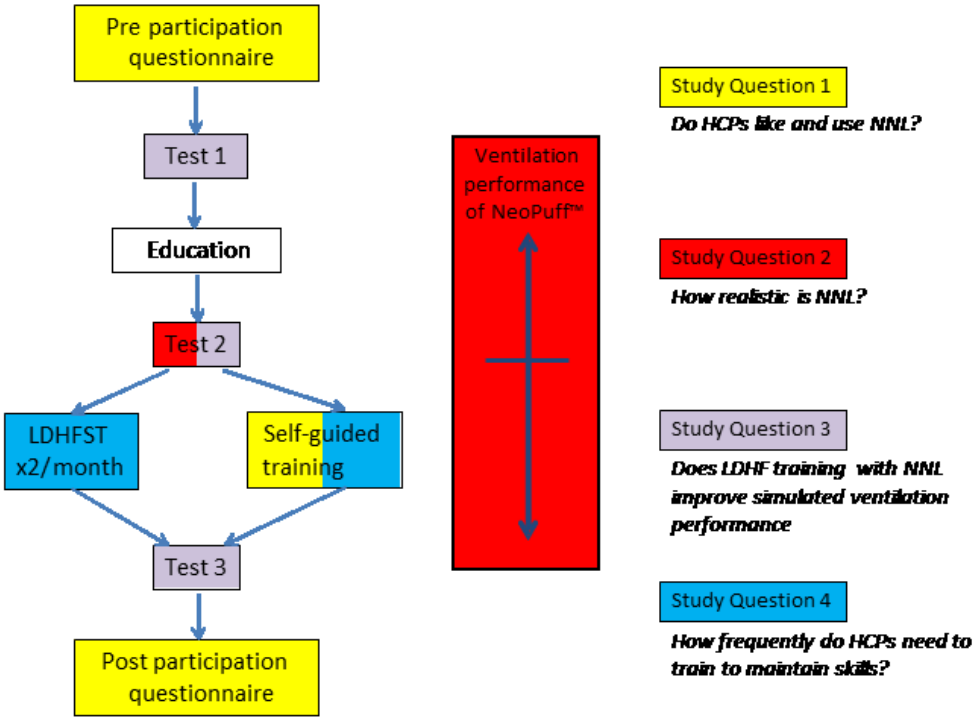


Figure 19. Flow chart of the study and study questions. HCP – healthcare provider, LDHF – low-dose, high-frequency NNL- NeoNatalie Live

3.3.3 Data collection

Data collected for the four proposed research questions were as follows:-

1. Do HCPs like and use NeoNatalie Live? (Yellow) Data from pre- and post-participation questionnaires, along with training frequency observed in the self-guided randomisation group (web log of independent training).
2. How realistic is NeoNatalie Live? (Red) Simulated ventilation data from LNRM when participating paediatricians ventilated the manikin in test 2, paired with LNRM data from real neonatal resuscitations.

3. Does LDHFST with NeoNatalie Live improve simulated ventilation performance? (Purple) Comparison of test 1 (baseline), test 2 (post-education) and test 3 (post independent training) scores.
4. How frequently do HCPs need to train to maintain ventilation competence? (Blue) Analysis of participants' independent training data from the weblog, and how scores relate to the amount of training performed.

Figure 20 shows the scoring matrix used for tests 1, 2, and 3.

Points	0	1	2	3	4	5	6	7
Action								
Preparation	none	check O2 OR equipment	check O2 AND equipment					
open/position airway	none		adequate					
dry/stimulate	none	dry OR stimulate	dry AND stimulate					
check heartrate	none	inadequate	yes					
check breathing	no	inadequate	yes					
position mask	poor		adequate					
start ventilation	> 2 min/not done	> 1.5 min	> 1min	60 sec or <				
ventilation fraction	< 50%	51-60%	61-70%	71-80%	81-90%	>90%		
frequency	< 20/min	< 30/min	>60/min	30-60/min				
valid ventilations	<50%	>50%	>60%	>70%	>80%	>90%		
visual chest rise/MRSOPA	none	adjust mask + 1 point	reposition airway + 1 pt	suction + 1pt	openmouth/jaw thrust + 1pt	increase pressure + 1 pt	alternative airway + 1 pt	yes
time to baby cry	time out	> x 2.5	> X2	> x 1.5	> x 1	x 1		

Figure 20 Scoring matrix used for tests 1, 2 and 3

Figure 21 shows the scoring matrix used to score participants' independent training data.

Action point	0	1	2	3	4	5
% valid ventilations	< 50%	< 60%	>/= 60%	> 70%	> 85%	> 90%
ventilation frequency	< 30	> 60	30 - 60			
VF % total ventilation time	< 70%	< 80%	< 90%	< 95%	>/= 95%	
Time to baby cry	Time out	> X 2	> X 1.5	> X 1.25	> X 1	X 1
% too low pressure ventilations	> 40%	> 30%	> 20%	> 10%	> 5%	< 5%
% too high pressure ventilations	> 30%	> 20%	> 10%	> 5%	< 5%	
% ventilations no headtilt	> 25%	< 25%	< 20%	< 15%	< 10%	< 5%

Figure 21 Scoring matrix used for cases performed by study participants during nine months of independent training. VF – ventilation fraction

3.3.4 Timeline

HCPs were enrolled and received the educational intervention from 01.04.19. This was a rolling enrolment, and test1, education, test 2 and randomisation were carried out as soon as practically possible. All education was provided at the place of work during the working period, including at night for those working exclusively night shifts. All education and testing was performed by the author of this thesis. On conclusion of test 2, participants were randomised and began their nine months of independent training immediately. After nine months, test 3 was scheduled at the participants' earliest convenience. Thus, education continued until the last enrolments in July 2020, with completion of independent training and test 3 carried out by 30.04.21.

As a result of the study design, it was only possible to begin data analysis for one of the four study questions (number 2) before all participants completed the entire study. This analysis was undertaken in the second half of 2020 and resulted in study/paper I. Analysis of test score data (study question 3) began in April 2021 and resulted in study/paper II. Analysis of participants' own training data (study question 4) began in October 2021, and resulted in study/paper III. No formal analysis of questionnaire data (study question 1) was undertaken during this PhD.

3.3.5 Individual study design and statistical analysis

Study I

Design: prospective observational study.

Hypothesis: When experienced paediatricians ventilate NeoNatalie Live with NeoPuff™ T-piece resuscitator using standard settings for ventilation of term neonates, parameters of ventilation will be similar to those observed when this same group of HCPs ventilate real newborns. Episodes of upper airway obstruction will occur with a similar frequency in the simulator and real newborns.

Subjects: all paediatricians participating in the study; neonates requiring PPV.

Data collection: LNRM data from test 2 performed by participating paediatricians and LNRM data from real neonatal resuscitations. Two test 2 ventilation episodes from 18 paediatricians (36 ventilation episodes) paired with 36 real neonatal ventilation episodes of similar (± 15%) duration of ventilation.

Outcomes: Per-inflation PIP, PEEP, eV_T and mask leak, and number of episodes of upper airway obstruction, as assessed from graphical LNRM output.

Data analysis: No power calculations were performed. The 72 ventilation episodes (36 simulated, 36 real) were divided into one of four groups for the purposes of comparison. The groups were formed according to whether the data came from the manikin (M) or a real newborn baby (B), and whether the ventilation episode was short (S-corresponding to scenario 1 for the simulator) or long (L- corresponding to scenario 4 for the simulator). The four groups, MS, BS, ML and BL, each contained 18 ventilation sequences. For each group, continuous data for the ventilatory parameters PIP, PEEP, eV_T and leak were summarised using median and interquartile range (IQR). To compare the dynamics of

ventilatory parameters between the groups, we used panel data regression analysis. Comparisons were done separately for short and long ventilation sequences. Dynamics of the ventilatory parameters between manikin and baby groups were then formally compared using the method of dynamical correlation for multivariate longitudinal data. Chi-Square testing was used to compare the occurrence of airway obstruction between the combined manikin (MS and ML) and combined baby (BS and BL) groups.

Paper II

Design: A randomised controlled intervention study.

Hypotheses: Following an educational initiative, twice monthly LDHFST will result in superior newborn ventilation competence compared to self-guided independent training. Subgroups of HCPs may derive greater benefit than others.

Subjects: All HCPs who may be required to provide PPV during neonatal resuscitation and who consent to participate

Data collection: Ventilation competence of participating HCPs as assessed through two simulation scenarios using NeoNatalie Live. Testing occurred prior to (test 1), and immediately after (test 2), completion of the educational initiative, and following completion of nine months of independent training (test 3). Participants were randomised to two groups for independent training: - twice monthly or self-guided. A scoring matrix (figure 19, page 51) was competed for each test.

Primary outcome: T3 scores of the twice monthly group and self-guided group.

Secondary outcomes: T3 scores of those performing no training and those performing at least monthly training; progression of T1-T2-T3 scores for the individual professions participating in the study.

Data analysis: No power calculations were performed. We used a convenience sample of all those eligible and consenting to participate. The primary outcome of test 3 scores according to randomisation group was analysed using Kruskal-Wallis test. The secondary outcomes of T3 scores according to actual training frequency and T1-2-3 score by profession were also analysed using Kruskal-Wallis tests.

Paper III

Study design: Prospective observational study.

Hypotheses: A greater simulation training load will better promote ventilation skill retention better than a lower training load; subgroups of HCPs may benefit from different training regimes.

Subjects: All HCPs participating in the simulation study who completed it through to T3.

Data collection: Each simulated case performed over nine months of independent training was consecutively logged for each individual participant, and scored according to a matrix (figure 20, page 52). The matrix consisted of seven individual skill elements. Each participant's scores (global and individual skill elements) were registered, providing data on the number of months out of nine in which training was performed (frequency data), the number of training sessions undertaken each month (frequency data) and the number of cases per session (dose or time spent in session).

Outcomes: Global competency scores and individual skill element scores

Data analysis: Global competency scores and individual skill element scores were analysed by generalized linear mixed effects models (GLME), using number of months where training occurred, number of training sessions (both frequency measures), and number of cases (dose or time spent training) as predictors. We used profession as a random

effect (intercept) and participant-specific random slopes. In addition, the models included the ventilation device used (self-inflating bag, T-piece ventilator, or both) and the case difficulty, both as random intercepts. If the estimated variance of a random effect was negligibly small ($<10^{-5}$), the corresponding random effect was removed. Estimated marginal probabilities of successful outcomes identified training loads predictive of high scores.

3.4 Consent and ethical/data protection approvals

The research offered increased levels of in-work training to all involved HCPs and the intervention involved was not considered to cause any ethical concerns. As there is no standard for using simulation-based testing to assess employee competence and all data are de-identified at the individual level, no concerns regarding the potential employment consequences of performance at testing were raised.

No ethical concerns regarding the management of neonates requiring PPV were raised as enhanced training of HCPs is unlikely to result in poorer clinical management and may improve care given to these babies.

The study was approved by the Regional Committee for Medical and Healthcare Research Ethics, Region West, reference numbers 2018/330/REK vest and 2018/338/REK vest, and also by the local data protection officer.

All HCP participants provided informed, written consent to participation. Informed written consent was obtained from all parents of neonates whose ventilation data was studied.

4 Summary of the results

4.1 Progression of participants through the study

A total of 220 participants from six different professions were recruited. 191 completed the education session and were randomised to one of the two training groups. 187 remained in the study and completed the final test 3. Table 1 shows the numbers from each profession completing the various stages of the study.

Table 1 Numbers of participants recruited and progressing through the study from the six professions

		Total Recruited and Completed Test 1	Educated and Completed Test 2	Randomised to Twice a Month (of Which x Did not Complete Test 3)	Randomised to as often as Desired (of Which x did not Complete Test 3)	Final Total Completing Study and Analysed after Test 3
Profession	Anaesthesia nurse	54	46	20 (0)	26 (0)	46
	Anaesthetist	38	34	19 (0)	15 (0)	34
	Midwife	72	62	28 (0)	34 (2)	60
	Paediatric nurse assistant	17	17	6 (0)	11 (0)	17
	Paediatrician	18	18	7 (1)	11 (0)	17
	Obstetrician	21	14	5 (1)	9 (0)	13
Total		220	191	85 (2)	106 (2)	187

The 187 HCPs who completed the study performed 4384 simulation cases during nine months of independent training. Table 2 shows how these cases were distributed across the six professions in the nine months of training; the number of months training, sessions and simulation cases performed by the six professions; and the number of sessions performed by the randomisation groups in nine months.

Table 2 Distribution of the 4348 cases performed during independent training by the six professions in the nine months of training; the number of months training, sessions and simulation cases performed by the six professions; and the number of sessions performed by the randomisation groups in nine months.

Profession	Cases performed by goup in 9 months	Median (range) number months in which training occurred	Median (range) number sessions per month	Median (range) cases per session	Median (range) sessions in 9 months by randomization
Anesthesia nurse	1604	5 (0-9)	1 (1-4)	4 (1-29)	
Anesthetist	537	5 (0-9)	1 (1-11)	2 (1-15)	
Midwide	1365	5 (1-9)	1 (1-5)	2 (1-10)	
Pediatric Nurse Assistant	456	4 (0-9)	1 (1-3)	3 (1-10)	
Pediatrician	212	4 (1-9)	1 (1-3)	3 (1-12)	
Obstetrician	174	4 (0-9)	1 (1-4)	3 (1-11)	
Totals	4348				
Randomization group					
Twice a month					8 (0-19)
As often as desired					2 (0-19)

4.2 Paper I - Novel Neonatal Simulator Provides High-Fidelity Ventilation Training Comparable to Real-Life Newborn Ventilation

Four groups of 18 ventilation sequences were compared. A total of 3256 ventilations were analysed, distributed among the four groups as follows: Manikin Short (MS) 443, Baby Short (BS) 475, Manikin Long (ML) 1160, Baby Long (BL) 1178.

Table 3 shows the median (interquartile range –IQR) PIP, PEEP, eV_T and leak for these four groups.

Table 3 Median (interquartile range) of the four ventilatory parameters measured in short and long manikin and baby ventilation

Group	Median (IQR)			
	PIP (mbar)	**PEEP (mbar)**	**eV_T (mL/kg)**	**Leak (%)**
Manikin Short	30 (1)	3.9 (2.3)	3.5 (3.2)	33.5 (81)
Baby Short	30 (4)	4.9 (2.9)	3.3 (4.6)	50 (80)
Manikin Long	30 (1)	3.7 (2.3)	4.1 (3.2)	20 (57)
Baby Long	30 (4)	4.8 (2.1)	5.0 (4.9)	36 (73)

PIP = peak inflating pressure, PEEP = positive end-expiratory pressure, eV_T = expiratory tidal volume.

Figure 22 shows the box plots for PIP, PEEP, eV_T and leak for all four groups, along with the dynamical curves comparing manikin and baby ventilation for short and long sequences

We found identical median PIP and PEEP in the short ventilation groups, MS and BS. PIP and PEEP were clinically similar in the long groups, ML and BL, although statistically different. PIP was higher in the ML group, as expected due to an intentional increase in PIP in a number of these sequences to overcome low simulated lung compliance. eV_Ts, while lower in the manikin groups, and statistically different from the baby groups, all fell within the recommended clinical range of 4 to 8ml/kg. The dynamical plots also showed a trend towards increasing eV_T the longer the ventilation sequence lasted. Similarly, no difference in leak was identified between the short groups and similar, widely varying leak was observed in the long groups. The dynamical plots for both manikin and baby showed decreasing leak as the duration of the ventilation sequence increased.

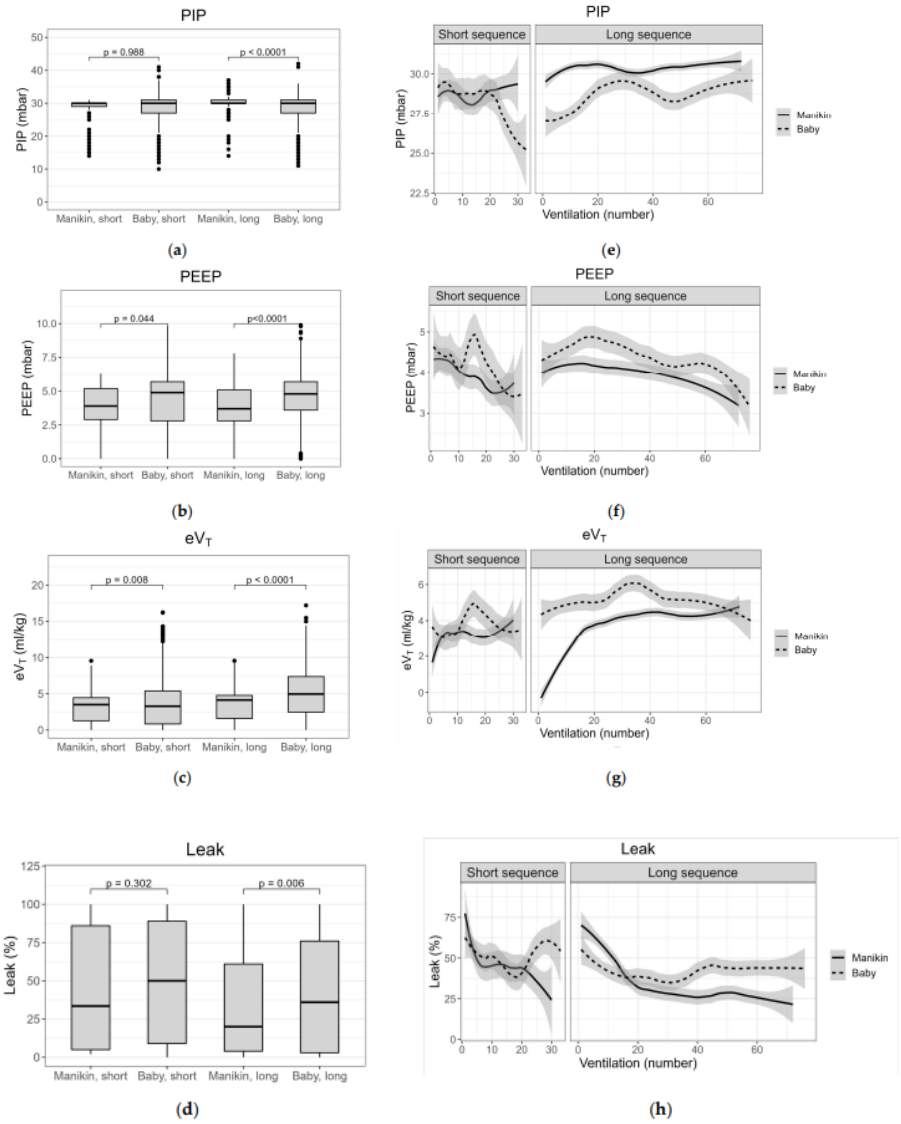


Figure 22 Box plots of median (interquartile range; range) PIP (peak inflating pressure), PEEP (positive end-expiratory pressure, eVT (expiratory tidal volume) and leak for groups Manikin Short (MS), Baby Short (BS), Manikin Long (ML) and Baby Long (BL); (e–h) Dynamical smoothed mean (standard error) plots of PIP, PEEP, eVT and leak for groups MS, BS, ML and BL

We found similar relationships between PIP and eV_T, PIP and leak, and leak and eV_T for both manikin and baby groups. The only significant correlation existed between leak and eV_T, where decreasing leak was associated with increasing eV_T for both manikin and baby ventilation.

Figure 23 shows the pairwise correlations between PIP, eV_T and leak for combined manikin and baby groups.

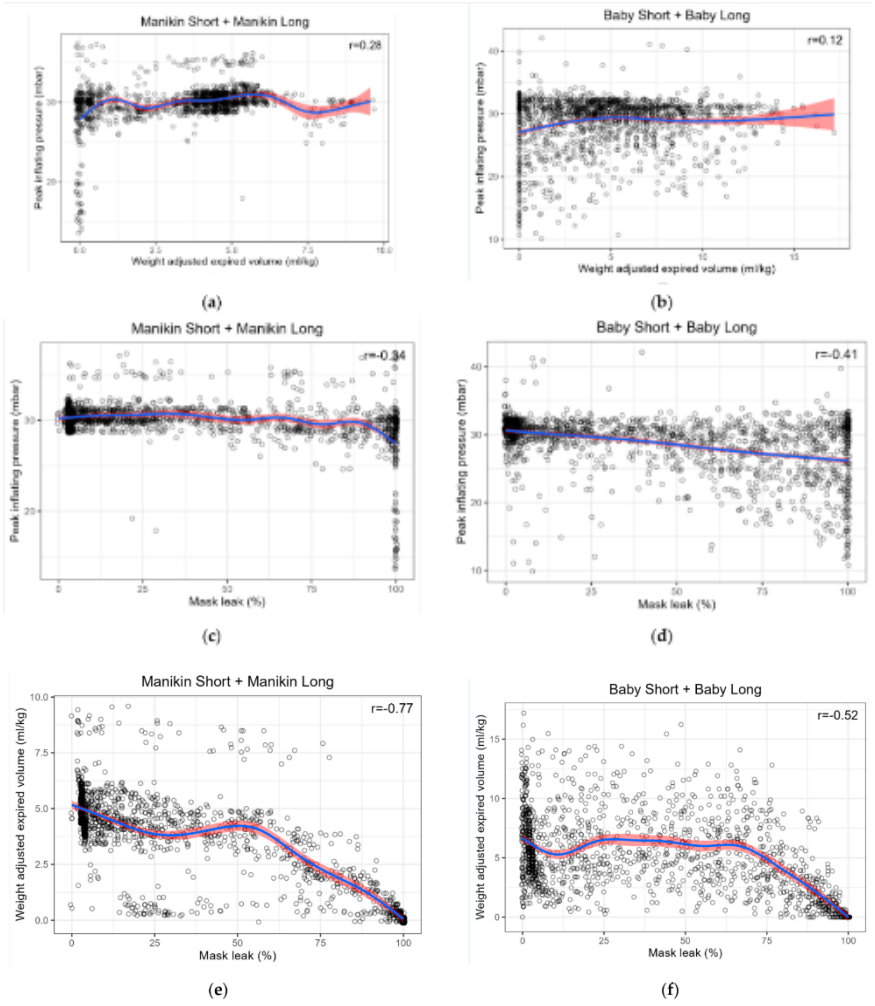


Figure 23 plots of correlation between (a) Peak inflating pressure (PIP) and expired tidal volume (eVT) for combined Manikin Short + Manikin Long (MS + ML); (b) PIP and eVT for combined Baby Short + Baby Long (BS + BL); (c) PIP and leak for combined MS + ML; (d) PIP and leak for combined BS + BL; (e) leak and eVT for combined MS + ML; (f) leak and eVT for combined BS + BL. Pearson's r for each correlation is given in the corresponding box

There was no difference in the occurrence of upper airway obstruction between manikin and babies.

4.3 Paper II - A Randomised Controlled Study of Low-Dose High-Frequency In-Situ Simulation Training to Improve Newborn Resuscitation

4.3.1 Primary outcome

T3 scores for the randomised groups showed no difference in scores between those in the twice monthly versus those in the self-guided groups. Figure 24 shows the box plots of T3 scores for these groups for the easier simulation scenario 1 and the more challenging scenario 4.

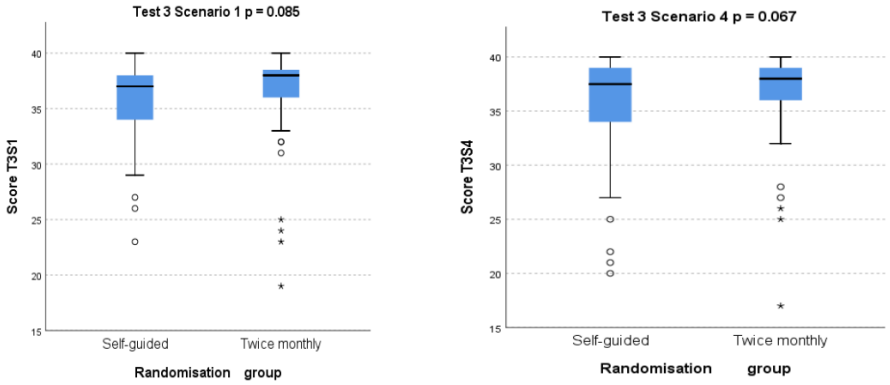


Figure 24 Box plots of test T3 scores for scenario 1 (a) and scenario 4 (b) by randomisation group

However, the twice monthly group did not train as often as expected, achieving a mean (standard deviation -SD) of 8 (5.2) sessions in nine months. The self-guided group also trained, performing a mean (SD) of 2.8 (3.8) sessions in nine months. We consider it possible that the fact that both groups trained more frequently that they usually do to result in the lack of difference in competence scores between the two groups.

4.3.2 Secondary outcomes

(i) T3 scores by training frequency: Comparing those HCPs performing no independent training in 9 months with those who trained on average a minimum of once a month (at least 9 sessions), we found a borderline statistically significant difference in competence scores for the easier scenario 1, and a highly significant difference for the more challenging scenario 4. Figure 25 shows the box plots for these comparisons.

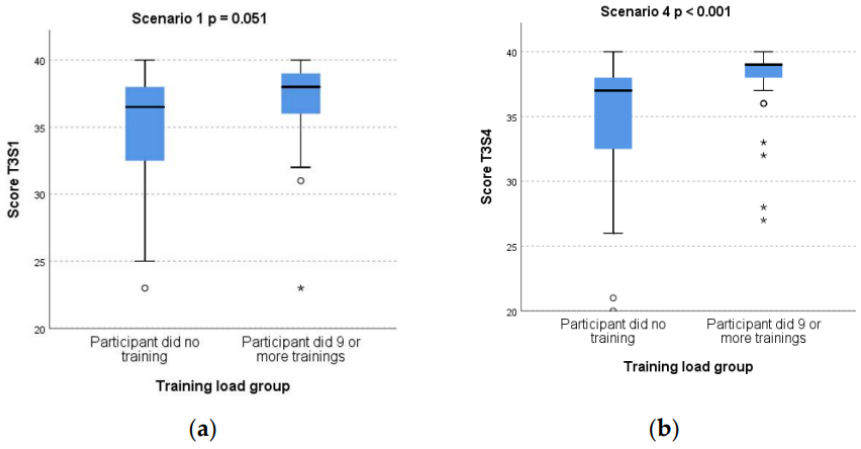


Figure 25 Box plots of test T3 scores for scenario 1 (a) and scenario 4 (b) by training load group

(ii) Progression of T1-T2-T3 scores by profession

We found that there was a significant improvement in ventilation competence scores from T1 to T2 and T3 for all HCPs apart from the paediatricians, who scored highly from baseline. The other five professions maintained the improvement seen after education, which was the same level of competence observed in the paediatricians through to T3 with independent simulation training.

Figure 26 shows a line graph of the mean scores within each professional group over the three testing points.

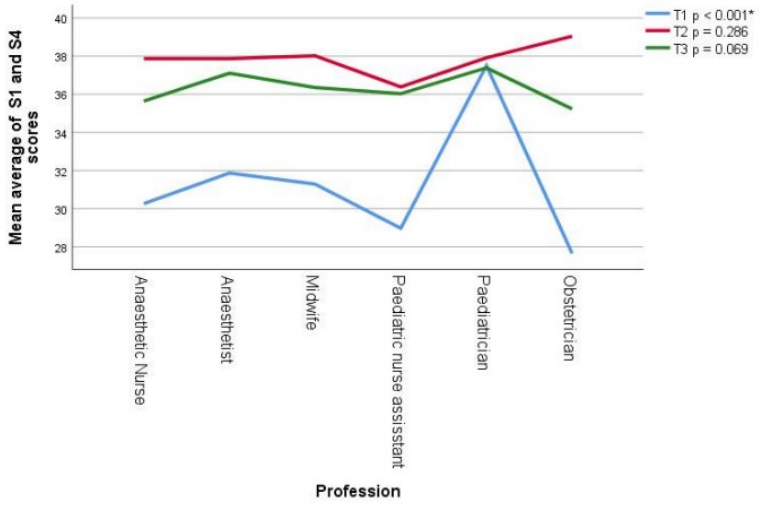


Figure 26 Line graph of the professional-group mean of averaged scenario 1 (S1) and scenario 4 (S4) scores at each test (T)-point. Blue line connects mean T1 scores of the six professional groups, the red and green lines T2 and T3 scores, respectively. HCP = healthcare provider; LDHF = low-dose high-frequency; * = significant difference in scores at the 0.05 level

4.4 Paper III - How much training is enough? Low-dose, high-frequency simulation training and maintenance of competence in neonatal resuscitation

The best predictor of global competence scores was the number of sessions performed, i.e. scores were more dependent on training frequency than dose. Estimated marginal probabilities of successful outcomes identified a threshold of 5 or more sessions in 9 months to achieve global ventilation competence scores > 28/30. This translates as training on average 0.6 sessions per month to maintain ventilation competency. While frequency was also the best predictor for some of the seven individual skill elements, e.g. achieving adequate mask seal and avoiding dangerously high inflating pressures, those assessing global performance, such as time to baby cry, were dose dependent. The only outcome for which profession was not a negligibly small random effect was ventilation frequency. For this outcome, profession specific

training-load cut-offs are given. Table 4 shows the training loads predictive of success for the individual skill elements and global competence score.

Table 4 Training load thresholds predictive of competence for the different skill elements and global competency score. For each, the average estimated marginal probability of a successful outcome with its 95% confidence intervals is given

Score or skill element	Predictive training load:- months/sessions/cases	Minimum number to achieve competence	Average marginal predicted probability of successful outcome with 95% CI*
Ventilation frequency 30-60	cases	Anesthesia nurse……6 Anesthetist……36 Midwife……N/A Pediatric nurse assistant…10 Pediatrician……N/A Obstetrician……9	0.89 (0.8 – 0.95) 0.91 (0.8 – 0.96) 0.9 (0.8 – 0.95) 0.91 (0.81 – 0.96) 0.93 (0.82 – 0.97) 0.93 (0.8 – 0.98)
Maintaining airway patency in > 95% ventilations	months	2**	0.88 (0.77 – 0.94)
Adequate mask seal to generate sufficient inflating pressure for valid ventilation in > 95% ventilations	sessions	6	0.85 (0.72 – 0.92)
Avoiding dangerously high inflating pressures (<45 cmH_20) in >95% ventilations	sessions	5	0.99 (0.88 – 1.0)
≥ 95% ventilation fraction	months	3	0.85 (0.58 – 0.96)
Baby cry (successful resuscitation) in shortest time possible	cases	18	0.73 (0.49 – 0.89)
>90% valid ventilations	cases	35	0.65 (0.44 – 0.81)
Global competency score > 28	sessions	5	0.66 (0.6 – 0.72)

* Predicated at the minimum required training load

** The regression analysis identified that the best predictor of success (months, sessions or cases) was different for different skill elements. For maintaining airway patency, it identifies that training in 2 out of 9 months (average of once every 4.5 months) maintains competence.

4.5 Summary of the findings of this thesis

NeoNatalie Live facilitates realistic simulation training, providing comparable conditions during PPV to those found during ventilation of

term newborns in need of the same duration of PPV to promote spontaneous breathing.

HCPs with less experience in real newborn ventilation achieved and maintained the same level of competence as those who regularly provide PPV at neonatal resuscitations through simulation training with NeoNatalie Live. Training at least once a month compared to no maintenance training promoted retention of competence.

Looking more closely at the training load necessary to maintain ventilation competence in this group of multidisciplinary HCPs, training on average 0.6 sessions per month, roughly equivalent to one session every other month, predicted high global competence scores.

5. Discussion

5.1 Methodological considerations

5.1.1 Study design

This thesis comprises three papers investigating the use of a neonatal simulator in a high resource setting and the ventilation competence of HCPs in that setting. The overall aim was to study methods of using simulation training to bridge the clinical experience gap in ventilation of non-breathing babies at birth. As such the overall study design employed an intervention (simulation training) and measured an outcome (ventilation performance).

The randomised controlled trial (RCT) is widely considered the gold standard in study design in order to attribute the outcome to the intervention employed, in as much as it controls for confounding factors found in real life which may have a relationship with both intervention and outcome, thus blurring the assignment of causality. In a number of situations, an RCT is not feasible, practicable or ethical. This is certainly the case for much research in the field of neonatal resuscitation. The observational study is an alternative methodology which may overcome many of the barriers to RCTs. Although observational studies are widely regarded as inferior to the RCT, in particular due to their susceptibility to bias, real-life treatment effects may in fact be better identified and quantified by observational research [135, 136]. Bias may result from inappropriate selection of participants (selection bias), failure to reliably measure the outcome of interest (information bias) and unaccounted-for factors relating both to intervention and outcome (confounding). Decision-making in modern medicine is increasingly supported by combining data from RCTs, observational studies and meta-analyses, a methodology which synthesizes results of multiple studies to provide a more accurate estimate of treatment effects [137].

5.1.2 Paper II

Paper II forms the backbone of this thesis. We designed a randomised controlled study with the hypothesis that the intervention (simulation training twice a month) would result in improved ventilation competence compared to the control (simulation training as often as desired). Integral to this hypothesis was the assumption that the control group would train less frequently than twice per month. A significant flaw in this design is that in order to prove the effect of the intervention, the control group would ideally not be exposed to the intervention. We considered it unethical to provide simulation training for some HCPs and not for others. Therefore our control group was a double compromise, in as much as it resulted in a simulation training frequency over which we had no control. However, this compromise allowed us to use the robust RCT design, allowing for the confounders of participant profession, prior job and education experience, and real-life resuscitation experience, to be equally distributed between the intervention and control groups. Each participant was consecutively randomised following participation in the education session and test 2. Despite using a binary randomisation application, this process resulted in an imbalance, with more participants in the control group (104) than the intervention group (83) (table 1, page 58). This imbalance held true within all six profession-groups except the anaesthetists, for whom a greater number were randomised to the intervention than the control group. It is impossible to be sure how this may have affected the outcome, but it is possible that both the large number of participants and the nature of the control (performing some, rather than no, simulation) may mitigate any influence of the uneven groups.

Other concerns with our methodology for paper II regard the possibility for bias. Selection bias is always a concern for any interventional study. Participation was voluntary, but all of the approximately 300 HCPs potentially involved in neonatal resuscitation, and working in over 50% employment, were invited to participate. 220 (>70%) were recruited, and

unsurprisingly, some were lost underway. The majority of dropouts occurred after test 1. Table 5 shows the number of dropouts after test 1 for the four professions in which this occurred, along with average test 1 scores for the dropouts compared to those completing the study.

Table 5 Numbers (No) of study dropouts from the four relevant profession-groups and the test (T) 1 scores of the dropouts compared to those completing the study

Profession	No dropout after T1 (% of all recruited)	No completing study	Ave T1 score dropout	Ave T1 score completed	Score dfference
Anaesthetist	4 (10.5)	34	29	31.87	-2.87
Anaesthesia nurse	8 (14.8)	46	27.75	30.26	-2.5
Midwife	10 (13.9)	60	32.9	33.75	-0.85
Obstetrician	7(33.3)	13	28,79	27.67	1.12

It is appropriate to consider whether these dropouts may have affected the outcome. One might postulate that participants not progressing beyond test 1 may have performed less well and were discouraged from further participation due to performance anxiety. This could bias the outcome. We can see that from table 5, the profession from which the greatest percentage proportion of dropouts occurred, the obstetricians, that there was about a one-point difference (in favour of those dropping out) in how those lost from the study scored compared to those completing it. It is unlikely, therefore, that this affected the study's outcome. The anaesthetic staff lost from the study did, in fact, score less well than those remaining in the study, but as the percentage loss from these two groups is less than half of that of the obstetricians, this may have had little impact on the overall results. The midwives, representing the largest profession-group numerically, were the highest scorers at test 1 of these four professions, and showed a minimal difference in score between those leaving the study and those completing the study. Overall, we believe that the outcome is unlikely to have been biased by the loss of 29 out of 220 participants (13.2%) after test 1. Subsequently, only 4 more participants were lost after test 2 (equally divided between the intervention and control groups, and shown in table 1, page 58). This is also unlikely to have influenced the study's outcome.

The other selection bias issue is that of initial recruitment. Only around 10 of approximately 300 HCPs were ineligible to participate due to working in a 50% or lower employment-time position. Was there any systematic bias hindering participation of the approximately 70 HCPs who were not recruited to the study? It may be that performance anxiety, a dislike of simulation, or a concern that poor performance might have consequences, prompted some to not participate. Others may have felt they didn't have time to participate in the course of a hectic shift. This we cannot know with any degree of certainty. However, these 70 represent less than a quarter (23.3%) of the total number of participants, and adding in the 10 who were ineligible (due to < 50% employment), only 26.7% of the target population relevant for our study aims did not take part. Overall, we feel it likely that our findings are valid for the whole population of interest.

Information, or measurement, bias is another issue to be addressed for this study. All tests were scored by the author of this thesis, using a scoring matrix assessing completion of the initial steps of resuscitation according to the neonatal resuscitation algorithm [35], and performance of ventilation using data from the simulator. Figure 20 (page 52) shows the scoring matrix used. The first six actions allocate a maximum of 12 points from observed performance, and are therefore subjective. Keeping points per action low, this both minimizes subjective variation and allows weighting of the ventilation data. The final six actions all use data recorded by the simulator and are therefore entirely objective. These elements generate potentially higher scores than the first six, being a direct assessment of ventilation competence. Within the final six, elements measuring global performance, e.g. time to baby cry, or those essential to success, e.g. achieving visible chest rise, were weighted more heavily than for example, ventilation frequency. The penultimate element, visible chest rise/MRSOPA, awarded seven points if chest rise was achieved, and if not, rewarded performance of corrective steps-MRSOPA- with one point per step. In this way, demonstration of the

knowledge of, and ability to perform, corrective manoeuvres in case of unsuccessful ventilation was acknowledged. It should be noted that the final step- alternative airway- is part of MRSOPA, but cannot be performed on the manikin. A point was awarded if the participant mentioned that they would consider this in case of unsuccessful ventilation.

It was necessary to create a scoring system for this study. Previously used and validated scoring systems for neonatal ventilation are not adaptable for use with this simulator, and are in large part based on subjective assessment [138, 139]. Many established scoring systems are, in the main, based on checklists. To the best of our knowledge, no other scoring system rating neonatal ventilation by using objective data has been published.

In producing the scoring matrix, the author worked with supervisor Hege Ersdal and co-supervisor Siren Rettedal. We decided to score the initial elements of the neonatal resuscitation algorithm up to the point of starting ventilation, and use the data available from the simulator to score ventilation performance. We reviewed the data available from the simulator and reached a consensus on how the different elements should be weighted. Through the consensus process, content validity of the matrix was assured. Prior to starting the study, it was successfully trialed for usability. The matrix was used in paper II. In the first test, the paediatricians scored highly, which we believe provides evidence of face validity, correctly identifying those with high competence at the outset of the study.

5.1.3 Paper I

Paper I was an observational study. A much-debated element of simulation training – fidelity - is an important issue for this study. We believed that a certain degree of fidelity in the manikin was likely to be necessary in order to effectively train competence in a technically difficult and multifaceted procedure. The unique design of the study

allowed us to make a direct comparison of manikin ventilation with real-life neonatal ventilation. As an observational study, no power calculations were performed. We wished to minimize the variability of performance of manikin ventilation, and chose, therefore, to use data obtained when the paediatricians ventilated the manikin. This was also an appropriate choice in terms of comparing ventilation data produced by the same providers, as the paediatricians perform most of the neonatal ventilation during resuscitation. Due to anonymity of participants in neonatal resuscitation, it was not possible to pair manikin and real newborn ventilation episodes by individual provider. However, we considered it valid to compare manikin ventilation provided by the 18 paediatricians in the study with real life ventilation provided by approximately 20 paediatricians regularly attending newborn resuscitations. Thus there was only an approximately 10% chance that any given real life ventilation episode had been generated by a paediatrician who did not also provide manikin ventilation data.

Appropriate statistical analysis of ventilation data in this study required discussion and reflection. A number of studies have used RFMs to record both real [45, 69, 83] and simulated [46, 60, 140, 141] ventilation data. Almost all of these papers report central tendencies over the whole ventilation episode for ventilatory parameters such as PIP, PEEP, eV_T and leak. While these statistics provide a snapshot of what is being achieved, they provide no insight into the dynamical evolution over the course of a ventilation episode, something of particular relevance for PPV during neonatal resuscitation. We employed panel data regression analysis to allow us to compare the ventilation dynamics over the course of a ventilation episode between simulated (manikin) and real (baby) PPV. Time-series data such as these are strongly auto-correlated, and it was necessary to correct for this [142]. The smoothed trajectories of the four parameters PIP, PEEP, eV_T and leak were presented visually, comparing manikin and baby ventilation in short and long ventilation episodes separately. Smoothing was performed using the LOESS

(Locally Weighted Scatterplot Smoothing) method with a span of 0.5, which equally balances the level of noise in the data against the identification of trends in the data. The p-values associated with these comparisons were displayed along with the more traditionally used box and whisker plots for the four parameters (figure 22 page 61).

As well as comparing the dynamical evolution of individual ventilatory parameters between simulated and real ventilation, we thought it relevant to consider how these parameters vary as a function of one another during ventilation. This has been done before for both simulated [60] and real [45] ventilation data, using linear regression. This method poses challenges in the analysis of ventilation data; as a repeated measure, the assumption of independence is violated. We therefore chose to use a method of dynamical correlation for multivariate longitudinal data [143]. In order to facilitate comparison with studies using linear regression, we present the Pearson's correlation coefficient of linear correlation along with the dynamical correlation coefficients (figure 23 page 63).

5.1.4 Paper III

Paper III is also an observational study. The aim of this study was to identify the optimal simulation training load (frequency and/or dose) to maintain ventilation competence in the whole group of participants. Large amounts of data were collected; over 4300 simulation cases were performed and recorded. Linear regression was not a suitable technique to identify patterns of training ensuring high competency scores. To identify how training load predicted global competency scores, we used generalized linear mixed effects models (GLME). GLME was used to model two outcome variables based on global competence score and individual skill element scores. GLME is an extension of the regression model that makes it possible to incorporate subject-specific differences in the model definition, thus giving potential to assess the effect of, for example, profession.

The issues of selection bias are in large part very similar to those discussed for paper II.

A scoring system was also required for this study. None of the cases were observed directly, and this scoring system was based entirely on ventilation data from the simulator. Of necessity, this meant adapting the scoring system as used in paper II. Figure 21, page 53, shows the scoring matrix used.

The maximum possible score was 30 points. The seven individual elements that made up this score had potential maximum scores of between three and five points, weighted according to clinical importance in terms of achieving effective ventilation. We wished to consider the effect of training load on the overall competence score out of 30, and also the individual skill elements. As these elements had differing maximum scores, these seven elements were logged in terms of points lacking to attain the maximum, i.e. a score of zero is best, with increasingly negative points indicating steadily poorer performance. In terms of modelling these scores in the regression analysis, it was necessary to define a cut-off indicating successful performance. For the global competence score, this was defined as >28 points, and for the seven skill elements, success = zero points, with > zero points indicating failure. These are strict definitions of competence, and the relationship of success or failure to clinically relevant changes in ventilation performance can be debated. However, setting the success bar high does allow us to be confident that personnel achieving the minimum training loads predictive of success are performing to a very high level.

5.2 Discussion of the results

5.2.1 Paper I Novel Neonatal Simulator Provides High-Fidelity Ventilation Training Comparable to Real-Life Newborn Ventilation

This is perhaps the most unique of all the three papers comprising this thesis. Simulation training in neonatal resuscitation has reached, arguably, universal acceptance as a teaching and training tool for healthcare providers of all levels of experience. However, a commonly cited limitation of simulation in the setting of neonatal resuscitation is the lack of recreation of the changing lung compliance over the course of the first few minutes of life [61, 140]. This change has implications for the provision of PPV.

PPV is a very tactile procedure, and haptic feedback is an important part of the process. While many simulators allow for learning the individual steps that make up procedure, the element of haptic feedback facilitating appropriate adjustments is a technical step too far for most.

Previously published literature assessing the fidelity of neonatal simulators is largely based on objective assessments by users of the simulator [144]. To our knowledge, no published study directly compares simulated and real neonatal ventilation as a means to address the simulator's fidelity. The unique study design using RFMs during real and simulated resuscitation allowed us to do just that.

In addition to being able to directly compare real and simulated neonatal ventilation, this study made use of dynamical data. This provides a unique insight into what is occurring over the course of a ventilation episode. Many studies reporting on ventilation parameters report median values for PIP, PEEP, eV_T and leak over the course of a ventilation episode. Table 3, page 60, summarizes these values for manikin and baby ventilation in both short and long ventilation episodes.

The box plot is commonly used to visualize this data, and is shown in figure 22, page 61. This figure also shows the dynamical data for the corresponding comparisons of manikin and real baby data.

From the PIP box plots in figure 22, it seems that the comparisons between manikin and baby are very similar for both long and short sequences. However the p-values, which are calculated for the dynamical data, identify no difference in PIP between manikin and baby for short sequences, but a highly significant difference in the long sequences. This difference becomes very clear when looking at the dynamical plots, where the manikin data is consistently higher than the baby data, and is accounted for by the fact that the paediatricians, whose data was used, commonly increased PIP from 30 to 35 cmH_20 when ventilating the manikin.

Looking at the eV_T data in figure 22, the median values appear similar, and there is considerable overlap of the box plots, but the p-values demonstrate the differences that are clear from the dynamical plots. At the outset of this study, it was felt unlikely that tidal volumes in the manikin would compare favourably with the real data. The median values are similar for manikin and baby in short and long sequences, and, in the case of the long sequences, are within commonly reported values during newborn resuscitation [81, 83]. While this is interesting, it is also notable that the trends visible in the dynamic plots are also similar for manikin and baby. In both cases, longer ventilation episodes are associated with higher eV_Ts. Increasing V_Ts during the first minutes of neonatal ventilation is commonly ascribed to improved compliance [45]. While this is not what is really happening in the manikin long sequences, there is nonetheless a rapid increase in eV_T as a consequence of a very abrupt removal of total obstruction to gas flow, mimicking the improved compliance. These similarities in tidal volumes and the dynamics of these are noteworthy, but it seems unlikely that achieving these similarities in themselves is an important feature of the simulator. V_Ts are not measured by the simulator; rather, evolution of the heartrate in

the simulator is driven by applying appropriate pressures via a patent upper airway, and what the provider is looking for it to achieve visible chest rise. What is, therefore, relevant is that the similar tidal volumes in manikin ventilation are producing a degree of chest rise that, along with the rising heart rate, provide HCPs with the confidence that they are providing effective ventilation.

The leak data is also interesting in the similarities between manikin and baby ventilation. It confirms previous reports of large and variable leaks in real life [69] and simulation [145]. It is also interesting that over the course of longer ventilation episodes, leak is reduced in both manikin and baby, and mirrors the increase in tidal volume. The relationship between leak and volume was very similar for manikin and baby, and is seen in figure 23, page 63.

These scatterplots highlight another feature seen throughout this paper, namely that the variation in data is much greater for the baby than for the manikin, something which might intuitively be understood due to the uniformity of the manikin, and also the multiple providers present, performing different tasks concurrently in real resuscitation. But despite this uniformity in the manikin ventilation situation, some common factor appears to be present in terms of adjustments made to reduce mask leak.

The data in this study suggest that similar PIP is being generated in the manikin and baby, and that this generates similar tidal volumes which increase over time as mask leak diminishes. Additionally, airway obstruction is an issue occurring with similar frequency in both. A reasonable conclusion might be that manipulations made to ensure a patent airway and adequate mask seal are performed in a comparable way in the manikin and baby. The logical extension of this is that there is both anatomical and functional fidelity that leads the paediatricians to perform PPV in a similar way in the manikin as they do in real life.

The concept of fidelity is frequently discussed in simulation literature. No universal definition of fidelity exists, but it is usually refers to the

degree to which a simulator looks, feels and acts like the human subject it is replacing [146]. Typically, simulators are described as low- or high-fidelity, depending on to what degree the simulator replicates the conditions encountered in real life. High-fidelity usually indicates considerable replication of real life in most or all aspects of simulator design and is often computer-driven, while low-fidelity achieves this to a lesser degree and is usually instructor-driven [147]. Again, there are no universal definitions to identify high-versus low-fidelity, and the literature uses these terms variably. There is a general assumption that the higher the fidelity, the greater the learning effect, However, there is limited data to support this, and in many studies comparing high- and low-fidelity simulators, there is no difference in learning outcomes [148, 149]. This clearly has implications considering the cost of increasing the level of technology required for high-fidelity simulators.

There are a number of theories concerning the apparent lack of superiority of high-fidelity simulation training over lower-fidelity. It is generally believed that novices have different learning needs compared to experienced personnel. The relationship between simulator fidelity and learning effect is not linear, and may be more dependent on experience levels and the stage of training [148]. Integral to both these paradigms is cognitive load theory (CLT). This is an intuitive factor that goes against the notion of high-fidelity being superior in all situations, and increasing fidelity may lead to negative learning experiences [148].

What may be more useful approach is to consider the different types of fidelity and how this influences learning goals, and further the design of the most appropriate simulator, for any given learning outcome. Modern medical simulation is in large part adopted from aviation safety principles. In aviation, simulator fidelity is typically divided into two domains- engineering or environmental fidelity (does the simulation look realistic) and psychological fidelity (does the simulator contain the critical elements to accurately stimulate the behaviours required to complete the task in real life) [150]. Fidelity in medicine may sometimes

be divided into three or more domains [115,151], but essentially, all can be placed under one of the two headings- environmental or psychological. Environmental fidelity refers to the physical replication of the human subject, the immediate surroundings and the equipment used. Psychological fidelity refers to the degree to which the trainee can "suspend disbelief" and engage cognitively with the simulator. Psychological fidelity is commonly associated with increased stress levels which would naturally be present in the clinical environment. Simulation may allow learners to learn to manage this stress to the benefit of their performance in real life [150]. Psychological fidelity also encompasses the element of realistic haptic feedback which the simulator achieves. This type of fidelity is often referred to as functional fidelity and relates to the degree the skill(s) needed in real life is (are) captured in the simulation [150]. This element may be may be particularly important for some skills, for example simulation training for laparoscopic surgery [152]. However, the simulator does not necessarily need to have high environmental fidelity to possess high psychological feedback. For example, a piece of animal tissue may provide high psychological fidelity when learning suturing techniques despite being of low environmental fidelity.

It is widely agreed that of these two types of fidelity, psychological fidelity is the more important [148, 153, 154]. This holds true for many skills but may also be relevant for teamwork, an area where environmental fidelity is also considered important.

The simulator NeoNatalie Live may be considered of moderate environmental fidelity. The manikin realistically replicates the size and form of a term newborn, and is anatomically correct in its head shape and in its facial features. Interestingly, these physical features may in fact contribute to the psychological fidelity due to the need to appropriately position the manikin to maintain a patent upper airway, and to place and hold the facemask in a way that corresponds with the real life situation, in order to obtain sufficient seal to enable effective PPV. It is this

psychological fidelity that can truly be considered high in NeoNatalie Live. In addition to the described physical features which contribute to the haptic feedback of the process of ventilating a newborn, the design features of changing lung compliance and heartrate response according to the quality of PPV provided truly allow the trainee to engage with the simulator. Realistic cues are provided to the trainee to allow them to adapt their management as they would do in the clinical situation.

Does maximum fidelity equate to maximum skill transfer to the clinical situation? It seems intuitive that a simulator with a high degree of psychological fidelity would likely be more effective in promoting skills transferable to the clinical situation than a simulator low in psychological fidelity. But is there any evidence for this? There is some data to support this idea coming from areas other than neonatal resuscitation. Draycott and colleagues showed that obstetric staff training to manage shoulder dystocia benefited more from a high fidelity simulator which included haptic feedback on pressure applied, compared to a low fidelity simulator [155]. Additionally this research showed that shoulder dystocia training improved outcome for the babies, irrespective of the fidelity of the simulator [156]. However, rates of successful delivery were statistically higher in the high-fidelity group, providing a valid argument for the fidelity having an important impact. Research involving high-fidelity neonatal simulators is in its infancy, and earlier work suggests no advantage of high- over low-fidelity [147, 157]. A more recent systematic review suggests a moderate benefit of high- over low-fidelity in neonatal resuscitation simulation training [107]. There are also data to suggest that fidelity in this field may make a difference in the clinical situation. Størdal and colleagues found that regular NeoNatalie Live training was associated with improved delivered V_Ts during ventilation [158]. Vadla et al showed that NeoNatalie Live training resulted in reduced time to initiate PPV in real life, with fewer pauses in ventilation [159].

For optimal learning efficiency, the learning objectives and the learners themselves must be the prime consideration [149, 150]. From this starting point, the level of simulator fidelity needed to match these criteria should follow naturally. Although NeoNatalie Live is described as high fidelity, it seems that this level of fidelity is not a hindrance to learners from a wide variety of backgrounds. Our goal was PPV competence in simulated neonatal resuscitation for a diverse group of HCPs, and it appears that the level of fidelity is appropriate.

NeoNatalie Live was designed in response to feedback from midwives in Tanzania, who described that lack of realistic interaction with her predecessor, NeoNatalie, as a hindrance to effective learning i.e. the "adrenaline gap" [150]. One might reasonably suspect that a simulator designed for the needs of midwives in a low-resource country might not address the needs of healthcare providers working in a high-resource country. However, the learning effect was clearly demonstrable for all except the pediatricians. From the questionnaires, the paediatricians felt that the training was useful, in particular the possibility to train using a self-inflating bag which they use rarely in clinical practice, and if they do, in difficult cases. However, they also stated the desire for a greater variety of cases and the possibility to train other skills such as intubation and umbilical vein catheterisation (unpublished data). It is likely that increasing the complexity of the simulator in this manner will lead to deterioration of learning effect for other personnel in line with CLT.

Limitations in the fidelity of NeoNatalie Live have been identified in paper I. These are the disconnect in extremely low lung compliance and the too rapid increase in heartrate seen in the most difficult scenario, and the abrupt transition from non-breathing to breathing in all scenarios. In terms of learning effect, it may that the first limitation has limited impact on learning outcomes. It is the very fact that very low "compliance" prevents heart rate increase and visible chest rise that encourages the appropriate interventions that are necessary to achieve effective PPV in real life. For many HCPs training with the manikin, the complex scenario

of judging when a neonate is breathing adequately, and when PPV can be discontinued, is beyond the trainees' needs and would be both technologically advanced and costly to achieve. Realistically, producing such a simulator for the pediatricians, for whom it would be anticipated that there is a potential benefit, the return in learning effect seems unlikely to justify the outlay [148].

5.2.2 Paper II A Randomised Controlled Study of Low-Dose High-Frequency In-Situ Simulation Training to Improve Newborn Resuscitation

The primary hypothesis in paper II was rejected; there was no significant difference in test 3 scores between the intervention (train twice monthly) and the control (self-guided training) groups. This is shown by the box plots for this analysis, figure 24, page 64. Whilst this was a disappointing result, it is not proof of the lack of benefit of frequent simulation training. We have interpreted this result in the light of the control group compromise: - this group did train, performing on average one third of the number of training sessions as the intervention group. To compound the issue, the intervention group performed, on average, just short of half the planned number of training sessions. This means that the intended comparison for the hypothesis was not actualised. However, our assumption that the control group would perform less training than the intervention group was accurate. Indeed one third of this group performed no training. Comparing test 3 scores of all those performing no training with those training on average at least once a month did show a benefit of training, with a highly significantly higher score in the more difficult case 4.This is shown in the box plots for this analysis, figure 25, page 65. This sub-group analysis allowed us to conclude an advantage of low-dose, high-frequency simulation training in maintaining ventilation competence. This advantage was particularly clear for the more difficult case four. This feels intuitively correct; one would predict the need for more training to manage more complicated situations. However, this analysis was undertaken irrespective of the randomisation

groups. As a result, the finding of this sub-group analysis is a secondary outcome. 90% of those in the no-training sub-group had been randomised to self-guided training, and 81% of those performing nine or more trainings had been randomised to twice monthly training. Figure 27 shows how the training frequency sub-groups were distributed by profession.

Participants performing no sessions during nine months of independent training

	Number	Percent
Anaesthetist	10	32,3
Anaesthesia nurse	8	25,8
Paediatrician	4	12,9
Paediatric nurse assistant	2	6,5
Obstetrician	7	22,6
Total	31	100,0

Participants performing nine or more sessions during nine months of independent training

	Number	Percent
Anaesthetist	7	16,3
Anaesthesia nurse	10	23,3
Paediatrician	1	2,3
Paediatric nurse assistant	6	14,0
Obstetrician	1	2,3
Midwife	18	41,9
Total	43	100,0

Figure 27 Numbers of participants from each profession-group performing no independent training (left), and performing nine or more sessions of independent training (right)

Figure 27 shows that there was far from an even intra-professional distribution in the two training frequency sub-groups. However, there was also an uneven distribution in the randomisation groups (table 1, page 58). This, along with a very high percentage of the sub-group participants also belonging to the corresponding randomisation group (no training and self-guided; nine or more trainings and twice monthly), provides more confidence that a real effect has been demonstrated.

The other secondary outcome in this study, the progression of T1-T2-T3 scores by profession, provides evidence of the potential of simulation training to ensure high levels of competence in HCPs who are not regularly exposed to real-life neonatal ventilation. From figure 26 on page 66, we can see that all the non-paediatrician profession-groups improved their test scores to the same level as the paediatricians following the educational initiative (T2), and equally importantly, were all able to maintain their performance at this level through nine months of independent training (T3). Although a secondary outcome, this

important finding is of utmost relevance for the overall aim of this thesis, to use simulation training to bridge the clinical experience gap

The theme of this study, demonstrating improved neonatal ventilation performance using simulation, may not be new, but this paper is novel in taking a large, diverse group of HCPs, comprising the majority of those actually involved in neonatal resuscitation, and using an objective method of assessment of their ventilation performance.

A number of studies have demonstrated improved simulated ventilation performance in low- and middle-income settings [160, 161]. These papers also describe the involvement of a large proportion of the staff who are also responsible for newborn resuscitation in those settings. However, the organisation of neonatal services, and the scope of newborn resuscitation which is appropriate in these settings, usually deviates considerably from that which is standard and expected in high-resource countries. In contrast, studies of simulation training to improve ventilation performance in high-income countries often focus on a small number of personnel and may not be representative of those performing resuscitation in real life [162].

This paper's findings have real relevance for the improvement of performance of neonatal resuscitation in the department in which the research was carried out. It provides a real-world example of quality improvement in healthcare. Not only does this quality improvement involve the majority of the personnel who are targets for the initiative, it also describes improvement occurring in a working clinical environment with real-life limitations on the amount of training that can be achieved. As such, the results of paper II may have transfer value to other institutions with similar clinical resources and set-ups.

A criticism of including such a wide variety of HCPs in a study whose aim is to improve neonatal ventilation competence, is that many of the study participants do not regularly perform newborn PPV. This can be seen from data presented in paper III. Figure 28 shows pie charts

describing when the six profession-groups last ventilated a newborn, as reported at entrance into the study, taken from pre-participation questionnaires (shown in paper III, submitted manuscript, and therefore reproduced here). We can see from this figure that while the vast majority of paediatricians had last performed PPV within the preceding month, this was far from the experience of the other professions, and, indeed, over 50% of paediatric nursing assistants and nurse anesthetists had never performed neonatal PPV.

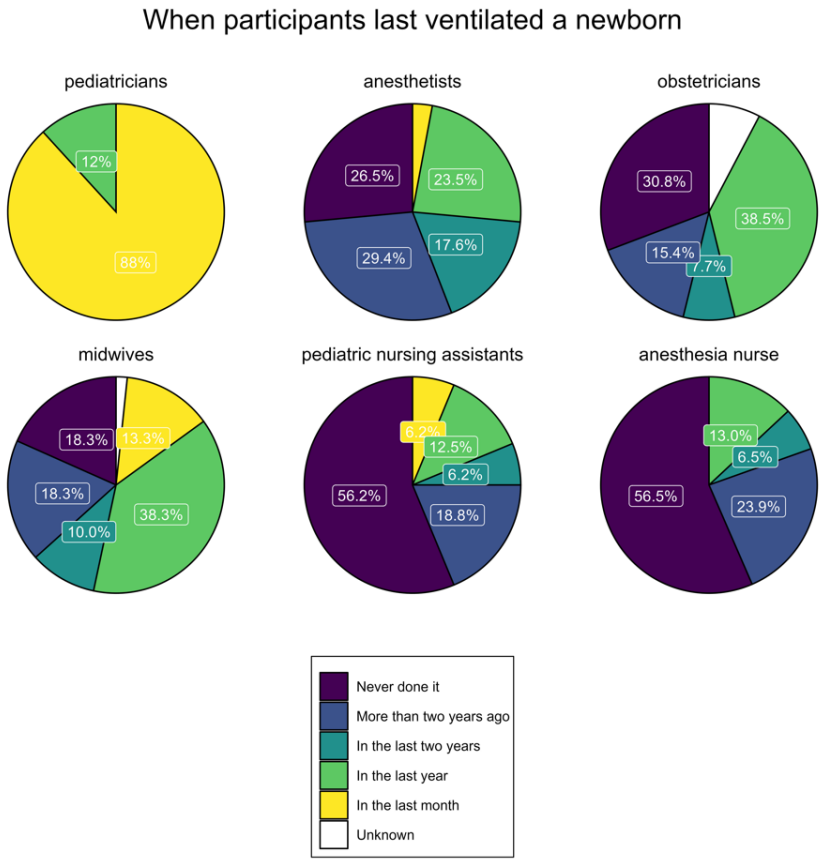


Figure 28 Pie charts describing how recently each of the six profession-groups had ventilated a newborn on entering the study

Is it important to ensure ventilation competence in everyone working in labour and delivery services, when most neonatal ventilation is performed by the paediatricians? Any of the HCPs involved in the study might find themselves unexpectedly called-upon to start newborn resuscitation. In 2021 and 2022 at SUS, 41 and 35, respectively, newborn resuscitation alarms were issued, indicating the birth of a neonate in unexpectedly poor condition, and where a paediatrician had not been summoned in anticipation of the need for resuscitation. The neonatal intensive care unit is in another building to the labour ward and operating theatres, and it may take a number of minutes for a paediatrician or neonatologist to arrive. Those staff immediately available on delivery ward or in the operating theatres have the potential to provide high-quality care in the first vital minutes of a newborn's life. Although the quality of clinical care the study participants are capable of providing cannot be inferred from this study, the ground-work to facilitate high-quality, effective neonatal ventilation has been laid; competence in the simulated situation can be assured, and this training has undoubtedly led to improved confidence among the participants, as shown in figure 29. Figure 29 shows responses to four statements from the post-participation questionnaire (unpublished data). From the entire group of participants, around four-fifths and two-thirds, respectively, agreed that knowledge and ability to ventilate the manikin had improved through study participation. Approximately three-quarters felt more confident in real resuscitation situations. However, two-thirds replied that they did not know, or it was not relevant to them, in response to the statement that they were more successful in ventilating a real newborn. This is unsurprising given the low exposure to real-life ventilation amongst the group as a whole.

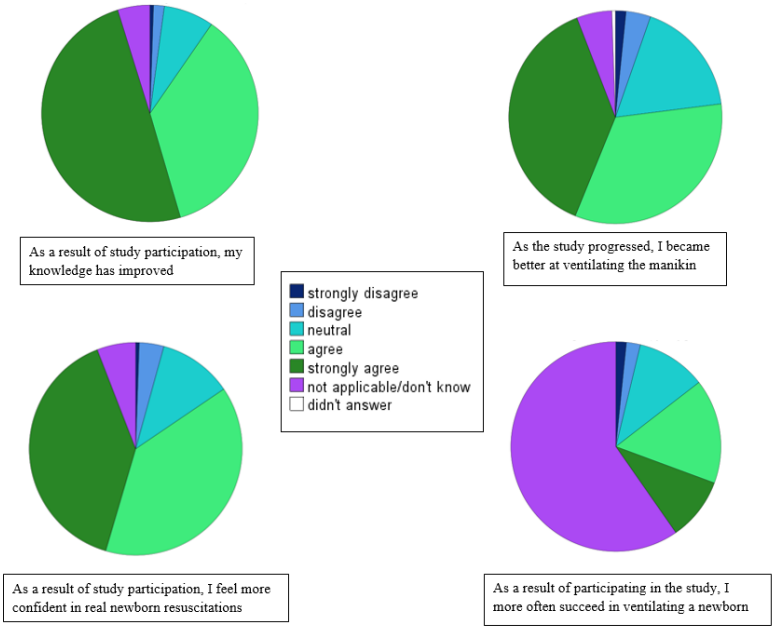


Figure 29 Pie charts of self-reported knowledge, confidence and skill as a result of study participation for all healthcare providers

Paper II uses a novel method of assessing ventilation competence, as described in the methodology section. We believe this to be a valid and objective assessment of ventilation performance. Such an assessment has not been described in the literature previously. Although the scoring matrix used is designed around, and thus is unique to, the simulator NeoNatalie Live, the principles used may potentially be adapted to other objective scoring systems.

The major strength of this scoring system is the objective measurement of parameters important to the success of PPV, for example, maintaining a patent upper airway and generating sufficient inflating pressure to deliver appropriate tidal volumes. To the best of our knowledge, no other published ventilation scoring system makes use of such objective data.

Recently, Whalen et al published a validated paediatric bag-mask ventilation assessment tool [163]. Building on a checklist-based neonatal

ventilation assessment tool, a thorough consensus process was used to find appropriate modifications for the paediatric setting. This was combined with a global assessment tool, in which experienced physicians, trained as raters, assessed performance according to descriptions of novice, advanced beginner, competent, proficient and expert performance. The outcomes of these two assessments allows a judgment on so-called entrustable professional activities, i.e. a statement of entrustment to competently perform paediatric ventilation in real life. This performance assessment tool moves towards evaluating competency and translating this into a statement of readiness to be entrusted with this task in the clinical situation.

Despite a robust validation process, this tool remains reliant on subjective assessment by expert providers, rather than objective measurement of performance. This may not necessarily detract from the relevance of the result of the global assessment tool. Expert providers are able to make experience-based, nuanced global assessments of ventilation performance that is very different from, for example, a black-and white evaluation of whether a specific inflating pressure is achieved. However, it may be difficult to progress to a universal evaluation process applicable in all settings and which has the potential to be used by certifying bodies to declare clinical competence. As such, it is likely that such evaluation tools will likely play a local role in performance assessment.

Paper I in this thesis describes the use of a RFM to measure both real and simulated data. Indeed this formed the basis of that paper, identifying similarities in these data as an indication of the realism of the simulated experience. While RFM data does not form part of the assessment process of performance in simulated ventilation in these studies, it seems appropriate to consider that if we can use RFMs to evaluate how we provide PPV in real-life, we can likely do the same for simulated PPV. Indeed this has been done in both situations [56, 80]. The studies presented in this thesis are unique in using a RFM in both real-life and

simulation together, and show how closely these two situations can mirror each other. This lends credibility to the use of RFMs to objectively evaluate simulated PPV performance.

The role of evaluating simulated performance in assessment of healthcare providers' competence remains a topic of debate. Valid concerns exist as to whether performance in simulation can be representative of what any given HCP can achieve in a pressurised clinical setting. In a climate of reduced clinical exposure through improved (reduced!) hours of working, and a changing landscape of medical education, it seems likely that such assessments are inevitable in the future. This paper adds to the literature documenting that this indeed might be the future of HCP performance assessment.

Why is it that the studies using a high-fidelity simulator in this thesis show a positive learning effect, when other research suggests that there is no learning advantage in high- over low-fidelity neonatal simulators [157]? Might there be some relationship to the methods used to assess learning effect? Research suggesting no advantage of high- over low-fidelity neonatal simulators and resuscitation skills commonly uses check-list based assessment [147, 157]. These same assessment methods of neonatal resuscitation skills are also used in the studies comparing low- and high- fidelity training in Huang et al.'s meta-analysis, which suggests a moderate benefit in favour of high-fidelity simulation [107]. It may be that these check-list based assessments lack the sensitivity to differentiate changes in skills in low- versus high-fidelity situations. The very objective nature of evaluating ventilation performance in this study may strengthen the data supporting the advantage of high-fidelity simulation training for this particular competency of neonatal PPV.

5.2.3 Paper III How much training is enough? Low-dose, high-frequency simulation training and maintenance of competence in neonatal resuscitation

Having established that we can use simulation training to improve neonatal ventilation competence, this final paper deals with the issue of training frequency. How often should on-going simulation training occur to prevent the well-documented skill decay that occurs without regular practice [164-166]? We analysed over 4000 simulation cases performed by the study participants during nine months of independent training after an educational initiative. Considering the amount of training performed, both in terms of frequency (number of months in which training occurred and number of sessions performed) and dose (number of cases performed, reflecting the amount of time spent training), we used regression analysis to correlate training load to the competency scores achieved. Performing five or more training sessions in nine months predicted global competency scores of ≥ 28 out of a maximum of 30 points. Success in the individual skill elements making up the global competency score was best predicted by various training loads, as shown in table 4 on page 67.

Some published studies have tried to address the question of training frequency [167-170]. These studies are heterogeneous in their design, and perhaps, therefore, heterogeneous in their results. Some identify as infrequently as six-monthly as adequate, others as often as monthly. This has clear implications for service provision in the busy healthcare sector. However, with such varied estimates, can we rely on the results?

This paper is unique in describing real-life training frequencies actually obtainable in a high-resource setting, rather than prescribed training frequencies often employed in studies. In itself, this may lend credibility to this study's findings; this is what can actually be achieved in the real-world, rather than an isolated study situation. It is perhaps also credible that that these findings suggest an optimal training frequency in between

that of the highest identified training frequency (monthly) and arguably the most commonly identified training frequency:- three-monthly or quarterly. However, in this paper we argue for a limitation in the robustness of our data, in the multi-disciplinary nature of our study participants with varied real-life experience. It is intuitive to presume that HCPs from different professions, with different lengths of service and varied real-life exposure to opportunities to perform neonatal PPV, will have different training needs. A weakness of this study was the inability to evaluate training loads by profession. Our regression model, identifying training loads predictive of high global competence scores for all HCPs from six different professions, had a marginal probability of success of 0.66 (95% CI 0.6-0.72) for the identified cut-off of five training sessions in nine months (table 4, page 67). This moderate marginal probability likely reflects the precision of the cut-off when making this calculation for such a diverse group of HCPs. The moderate precision of training thresholds predictive of success in the two skill elements assessing performance globally, % valid ventilations and time to baby cry, can also be seen in table 4.

It may be that should we have calculated the training load cut-off for global competence scores by profession, a more precise estimate could be obtained. Only for one score, that of achieving ventilation frequency within recommended limits, was it possibly to assess training loads predictive of success by profession. This analysis identified that those with the most recent real-life experience of providing PPV at study start, the paediatricians and the midwives (figure 28, page 87), were predicted to succeed in this skill element with no training, i.e. were successful from the start. While this is not proof that different professions, or participants with varying real-life experience, do indeed have varying training needs, this finding is compatible with the notion. Moving forward with future research on this topic, it may be that designing studies assessing training loads on an individualised basis will allow for more robust results.

How can we provide a more individualised answer to this problem? One clear solution is to analyse data by profession, perhaps the easiest way to achieve data quantities allowing such analysis. Other possible targets are frequency of exposure to real-life neonatal PPV or length of service, or indeed, the interaction of these two. Data on these for this group of HCPs is shown in figures 30 and 31, taken from pre-participation questionnaires (unpublished data).

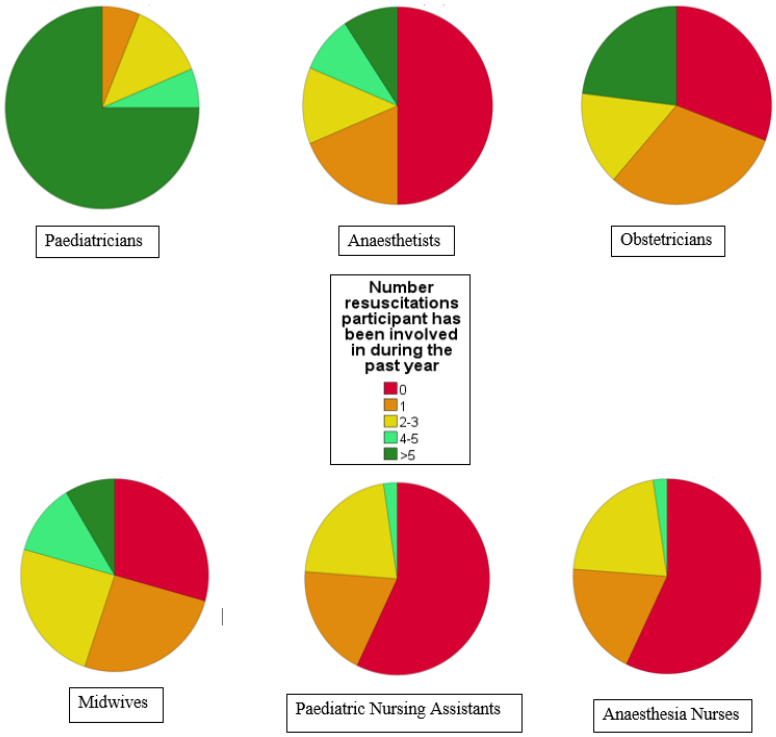


Figure 30 Pie charts showing how many neonatal resuscitations the six professions were involved in in the year preceding study inclusion

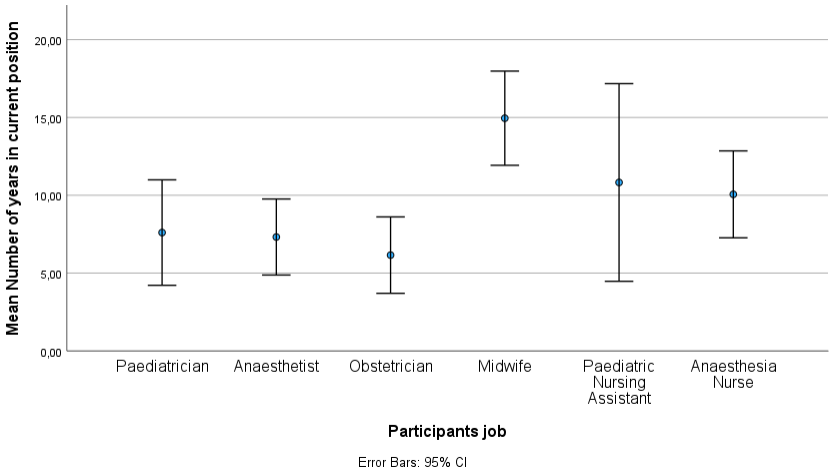


Figure 31 Error bars of average length of service for the six profession groups

While the midwives are less frequently involved in neonatal resuscitation than the paediatricians, they have more clinical experience than all other groups except the obstetricians. However, their length of service is on average longer than the paediatricians, such that cumulatively over their careers, they may have equivalent, and potentially more, experience compared to the paediatricians.

This study also collected, and made use of, data on the difficulty level of the simulation cases performed and the ventilation device used. The training load outputs were averaged across both these, such that information on how case difficulty or use of a self-inflating bag rather than a T-piece resuscitator influences the predicted thresholds for competence is not known. One might well presume the result if training load were to be analysed by case difficulty- a more difficult scenario would require greater training load to maintain competence. It is interesting to look back at the subgroup analysis of test 3 scores in paper II (figure 25, page 65). The score improvement for the easiest case 1 was borderline different, comparing those performing no training versus those training at least monthly. However, the same comparison for the

most difficult case 4 showed a highly significant difference in scores. As noted previously, this aligns with the prediction of the need for more training to maintain competence in more difficult situations.

However, there may well be merit in considering differences occurring as a result of the ventilation device used. Table 6 shows the distribution of the 4348 cases performed by case difficulty and ventilation device (unpublished data).

Table 6 Distribution of cases by case difficulty and ventilation device

Case level	Neopuff only	Self-inflating bag only	Both devices	Total number cases
1	769	353	21	1143
2	729	302	33	1064
3	689	472	126	1287
4	457	299	98	854
Total number cases	2644	1426	278	4348

Almost twice as many cases were performed with NeoPuff™ alone than with SIB alone. Relatively few cases were performed using a combination of devices. It is not known why both Neopuff™ and SIB were used in the same case, but modifying the analysis to show training loads by device may provide some insights. Figure 32 (unpublished data) shows the marginal probabilities with 95% confidence intervals of success for the skill of adequate mask seal to provide sufficient inflating pressures according to device used. The marginal probabilities for use of Neopuff™ are higher than for SIB, although there is considerable overlap of the confidence intervals. However, the marginal probabilities for the combined use of devices in the same case are much lower. This suggests that problems in establishing effective ventilation with the first device chosen prompt the provider to switch devices. The order of the use of devices is not known.

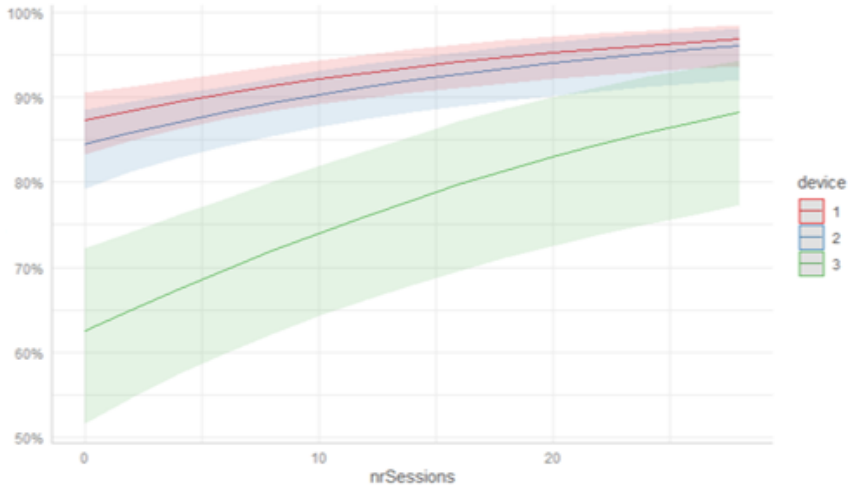


Figure 32 Marginal probability with 95% CI of successfully creating adequate mask seal with device 1 = Neopuff™, device 2 = self-inflating bag and device 3 = both

This paper identifies that training on average once every other month maintains ventilation competence in this group of HCPs. Is this training load achievable for all HCPs involved in newborn resuscitation? Some insights can be gleaned from the post-participation questionnaire data. Several statements enquired about facilitators and barriers to training. Figure 33 shows responses of those who were in the «train twice monthly» group to statements regarding training frequency (unpublished data).

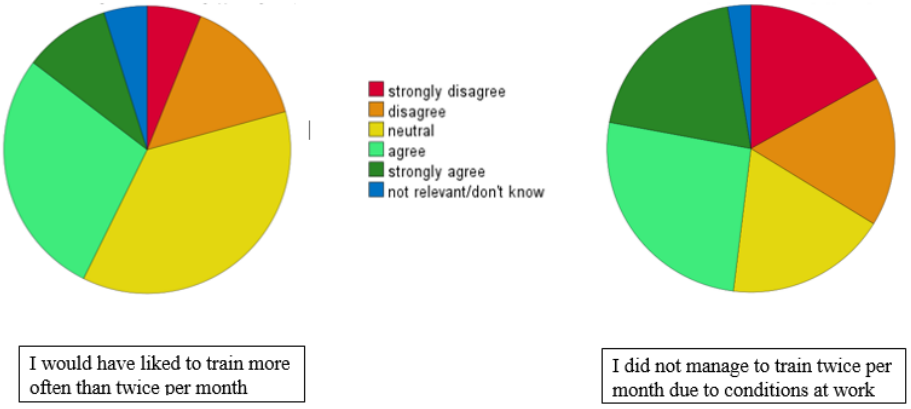


Figure 33 Pie charts describing results from HCPs in the train twice per month group to two post-participation questionnaire statements regarding training frequency

Around one third of HCPs in the «train twice per month» group stated they would have liked to train more often than the prescribed frequency. However, only around one-fifth disagreed with this statement. This group did not achieve the aimed-for frequency, training on average eight sessions in nine months. From figure 32 we can see that just under half of the group were in disagreement that conditions at work prevented them from achieving two sessions per month.

Those HCPs in the «train as often as you wish» group were asked for open-ended responses to either the statement "I trained often because….." or "I trained infrequently because…..". Three themes recurred in answers regarding frequent training: - 1) simulation equipment being readily available in the place of work; 2) a perception of benefit to training or of increased competence; and 3) cooperation within the department such that several participants working together on a particular shift all managed to train. Three themes were also recurrent in relation to reasons for training infrequently: - 1) a busy shift with little time available to train or the need to prioritize clinical activities; 2) the Covid-19 pandemic affecting both work and the possibility to train; and 3) forgetting to train.

While these questionnaire responses provide only limited insights into facilitators and barriers to training, there are clear trends that cooperation within a department encourages training for those working together, and that having some sort of obligation to train is important, as the lack of this may lead to forgetting about performing this activity, especially during a busy working shift. It remains unclear what the barriers to achieving the prescribed training load were for those in the train twice per month group.

5.3 Final comments on the studies in this thesis

Over the two-year period of performing studies in this PhD, a large amount of data has been collected. The three papers presented in this thesis demonstrate the fidelity of the simulated experience using NeoNatalie Live, the improved ventilation performance in simulated resuscitation through training with the manikin, and the need to train every other month to ensure this competence endures despite a lack of regular clinical experience. This is possible for a wide range of healthcare providers with this simulator demonstrating moderate environmental fidelity, but high psychological fidelity.

These three studies provide evidence on pedagogical strategies that are effective in ensuring that HCPs in a high-resource setting gain and maintain the competence to perform PPV at birth. The educational methodology used incorporates elements of Kolb's cycle of experiential learning [93], Ericsson's concept of deliberate practice [98], and McGaghie's paradigm of mastery learning [99], whilst also taking heed of cognitive load theory [94].

The final goal of this work is to enable skill transfer to the clinical situation, and ultimately improve outcomes for the babies who are born not breathing. While it is nice to believe that future analysis of the real PPV data collected during this study period might provide some insights, the realities of a small data set, of the lack of evidence as to what is the most appropriate method of providing PPV in this situation, and the

difficulties of defining and following –up suitable end-points for this environment, may lead to disappointment.

If we look towards the low-resource setting for inspiration, where absolute numbers of non-breathing newborns are higher, and the all-too-visible end-point of neonatal mortality makes change easier to identify, we remember that knowing what works in terms of HCP training is only half the story; widespread implementation is needed to make changes that count [123]. What might a future implementation strategy look like in this high-resource setting? Engaging stakeholders, both at SUS and beyond, to accept that we can and must train our HCPs to perform PPV with high levels of competence is a great starting point. We believe that the findings in this thesis add to the literature highlighting this vital issue and suggest sustainable ways to implement change.

Engaging HCPs themselves is equally important. Anecdotally, participants have reported that their performance in real life has benefitted from their participation in the study. Increased self-efficacy is commonly noted in favour of high-fidelity simulation training [171], and future analysis of data from the questionnaires may highlight this important step towards improving real-life ventilation performance.

6. Conclusions

- Similarities in ventilatory parameters and their inter-relationships, along with upper airway obstruction occurring with the same frequency in the manikin and babies, support the fidelity of the simulated ventilation experience when using NeoNatalie Live
- Neonatal ventilation competence can be trained and maintained through simulation training, irrespective of a provider's background or real-life experience with this skill
- Maintenance of this level of performance requires a short training session approximately once every other month
- Different elements that make up overall competency to perform neonatal ventilation vary in the frequency or dose of training need to predict success, and providers may benefit from individualised training programmes
- Those with limited real-life exposure to neonatal facemask ventilation at birth performed as well as those with most experience after training with NeoNatalie Live
- The fidelity demonstrated when these same experienced providers ventilated the manikin gives confidence that NeoNatalie Live training can foster ventilation skills that have the potential to translate into competence in the clinical situation

7. Clinical implications and future perspectives

Through this PhD work, we have shown that despite lacking frequent real-life opportunities to perform neonatal ventilation, all healthcare providers working with women giving birth can train to provide high-quality ventilation to a newborn in need. This need occurs frequently and often unpredictably, such that all personnel working in this environment need to be ready at a moment's notice. We have demonstrated how a training programme to meet this need in our environment can be set up to ensure that this is the case at Stavanger University Hospital. Using a novel and objective way to reliably measure ventilation performance, these studies may serve as inspiration to other high-resource settings wishing to train their staff to deliver excellence in the care of the newborn who fails to initiate adequate spontaneous breathing at birth. Despite low neonatal mortality in such settings, starting effective facemask ventilation promptly is the key to reducing morbidity, which is relevant wherever in the world a baby is born.

This PhD has been undertaken within a clinical-research collaboration in which the focus is to provide new insights into newborn transition, identify the best ways to support transition, and train healthcare providers to quickly and effectively resuscitate babies who have been exposed to intrauterine asphyxia. Commonly cited issues in neonatal resuscitation are the lack of scientifically-derived knowledge underpinning recommendations for care, and the on-going need to work towards the translation of simulation-based skills into bedside competence. This PhD has provided insights into the latter. We have seen the value of objectively measuring simulated performance and of individualising training. In future research we will combine multifaceted monitoring of real-life newborn resuscitations to provide data-driven simulation-based training and feedback. The aim is to provide

translational simulation training that is relevant for the department in which our providers work, the whole resuscitation team, and for the individual provider. Scaling up this initiative to involve other centres in Norway, the data collected will be large enough to consider the ultimate outcome of simulation-based training: - that of the newborn baby.

8. References

1. How many babies were born in 2021? UNICEF. How many babies were born in 2021? - UNICEF Data Accessed 16.12.22
2. Ending preventable newborn deaths and stillbirths by 2030. July 2020. World Health Organization. Ending-preventable-newborn-deaths-stillbirths-English_2020.pdf. Accessed 16.12.22
3. Blencowe H, Lee ACC, Cousens S, Bahalim A, Narwal R, Zhong N, Chou D, Say L, Modi N, Katz J, Vos T, Marlow N, Lawn JE. Preterm birth–associated neurodevelopmental impairment estimates at regional and global levels for 2010. Pediatr Res 2013 Dec;74(1):17-34. doi: 10.1038/pr.2013.204.
4. Mduma E, Ersdal H, Svensen E, Kidanto H, Auestad B, Perlman J. Frequent brief on-site simulation training and reduction in 24-h neonatal mortality—An educational intervention study. Resuscitation 2015;93:1-7. doi: 10.1016/j.resuscitation.2015.04.019
5. The Millennium Goals Development Report 2015. United Nations. MDG 2015 rev (July 1).pdf (un.org) Accessed 16.12.22
6. Every newborn progress report 2019. Geneva: World Health Organization and the United Nations Children's Fund (UNICEF), 2020. Licence: CCBY-NC-SA3.0IGOFinal-Every-Newborn-Report-2019-web-05-11-20.pdf (healthynewbornnetwork.org) Accessed 17.12.22
7. UNICEF Data Warehouse Norway Neonatal mortality rate. UNICEF. Data Warehouse - UNICEF DATA Accessed 25.04.23
8. Ersdal HL, Mduma E, Svensen E, Perlman JM. Early initiation of basic resuscitation interventions including face mask ventilation may reduce birth asphyxia related mortality in low-income countries: a prospective descriptive observational study. Resuscitation 2012;83:869-73. doi:10.1016/j.resuscitation.2011.12.011
9. Kamath-Rayne BD, Griffin JB, Moran K, et al. Resuscitation and obstetrical care to reduce intrapartum-related neonatal deaths: a MANDATE study. Matern Child Health J 2015;19:1853–63.
10. Survive and Thrive. Transforming care for every small and sick newborn 2018. World Health Organization. WHO-FWC-MCA-18.11-eng.pdf Accessed 17.12.22

11. Lawn JE, Blencowe H, Darmstadt GL, Bhutta ZA. Beyond newborn survival: the world you are born into determines your risk of disability-free survival. Pediatr Res. 2013;74(1):1-3. doi: 10.1038/pr.2013.202
12. Lee AC, Kozuki N, Blencowe H, et al. Intrapartum-related neonatal encephalopathy incidence and impairment at a regional and global level for 2010 and trends from 1990. Pediatr Res 2013;74(1):50-72. doi:10.1038/pr.2013.206
13. The Sustainable Development Goals Report 2022. United Nations. The-Sustainable-Development-Goals-Report-2022.pdf (un.org) Accessed 21.12.22
14. van Vonderen JJ, Roest AA, Siew ML, Walther FJ, Hooper SB, te Pas AB. Measuring physiological changes during the transition to life after birth. Neonatology 2014;105(3):230-242. doi:10.1159/000356704
15. te Pas AB, Davis PG, Hooper SB, Morley CJ. From Liquid to Air: Breathing after Birth. The Journal of Pediatrics 2008;152(5):607-611. doi: 10.1016/j.jpeds.2007.10.041
16. Hooper SB, Te Pas AB, Kitchen MJ. Respiratory transition in the newborn: a three-phase process. Arch Dis Child Fetal Neonatal Ed. 2016;101(3):F266-F271. doi:10.1136/archdischild-2013-305704
17. Hillman NH, Kallapur SG, Jobe AH. Physiology of transition from intrauterine to extrauterine life. Clin Perinatol. 2012;39(4):769-783. doi:10.1016/j.clp.2012.09.009
18. Karlberg P, Cherry RB, Escardo FE, Koch G. Pulmonary ventilation and mechanics of breathing in the first minutes of life, including the onset of respiration. Acta Paediatr Scand 1962;51:121-36
19. Ersdal HL, Linde J, Mduma E, Auestad B, Perlman J. Neonatal outcome following cord clamping after onset of spontaneous respiration. Pediatrics 2014;134(2):265-272. doi:10.1542/peds.2014-0467
20. Polglase GR, Dawson JA, Kluckow M, Gill AW, Davis PG, te Pas AB, Crossley KJ, McDougall A, Wallace EM, & Hooper SB. Ventilation onset prior to umbilical cord clamping (physiological-based cord clamping) improves systemic and cerebral oxygenation in preterm lambs. PloS one 2015;10(2), e0117504. doi:10.1371/journal.pone.0117504
21. World Health Organization. Basic Newborn Resuscitation: A Practical Guide. Geneva, Switzerland: World Health Organization, 1997

22. Lawn J, Shibuya K, Stein C. No cry at birth: global estimates of intrapartum stillbirths and intrapartum-related neonatal deaths. Bull World Health Organ. 2005 Jun;83(6):409-17
23. Rainaldi MA, Perlman JM. Pathophysiology of Birth Asphyxia. Clin Perinatol. 2016;43(3):409-422. doi:10.1016/j.clp.2016.04.002
24. Dawes GS, Jacobson HN, Mott JC, Shelley HJ, Staffort A. The treatment of asphyxiated, mature foetal lambs and rhesus monkeys with intravenous glucose and sodium carbonate. J. Physiol 1963;169:167-184
25. Moshiro R, Mdoe P, Perlman JM. A Global View of Neonatal Asphyxia and Resuscitation. Frontiers in Pediatrics 2019;7: 489. doi: 10.3389/fped.2019.00489
26. Lee ACC, Cousens S, Wall SN, Niermeyer S, Darmstadt GL, Carlo WA, Keenan WJ, Bhutta ZA, Gill C, Lawn JE. Neonatal resuscitation and immediate newborn assessment and stimulation for the prevention of neonatal deaths: a systematic review, meta-analysis and Delphi estimation of mortality effect. BMC Public Health 2011; 11(3):S12 http://www.biomedcentral.com/1471-2458/11/S3/S12
27. The Bible (King James Version). II Kings. Chapter 4, verse 32–36
28. O'Donnell CP, Gibson AT, Davis PG. Pinching, electrocution, ravens' beaks, and positive pressure ventilation: a brief history of neonatal resuscitation. Arch Dis Child Fetal Neonatal Ed. 2006;91(5):F369-73. doi: 10.1136/adc.2005.089029. PMID: 16923936;
29. Elam JO, Brown ES, Elder Jr JD. Artificial respiration by mouth-to-mask method. A study of the respiratory gas exchange of paralyzed patients ventilated by operator's exhaled air. New England Journal of Medicine 250:749, 1954
30. History of CPR. American Heart Association. History of CPR | American Heart Association CPR & First Aid Accessed 21.12.22
31. Neonatal resuscitation program (NRP) 20th Anniversary 1987-2007. American Academy of Pediatrics. nrp_20thanniversary.pdf (aap.org). Accessed 21.12.22
32. Apgar V. A proposal for a new method of evaluation of the newborn infant. Anesth Analg 1953;32:260–7
33. Halamek LP. Educational Perspectives: The Genesis, Adaptation, and Evolution of the Neonatal Resuscitation Program. Neoreviews 2008;9:e142-e149. doi: 10.1542/neo.9-4-e142
34. Wyckoff MH, Greif R, Morley PT et al. 2022 International Consensus on Cardiopulmonary Resuscitation and Emergency

Cardiovascular Care Science With Treatment Recommendations: Summary From the Basic Life Support; Advanced Life Support; Pediatric Life Support; Neonatal Life Support; Education, Implementation, and Teams; and First Aid Task Forces. Resuscitation 2022;181:08-88. doi: 10.1016/j.resuscitation.2022.10.005

35. NRR retningslinjer for gjenoppliving av nyfødte, barn og voksne 2021 Stabilisering og resuscitering av nyfødte. NRR_Guidelines_2021_Stabilisering_og_resuscitering_av_nyfodte.pdf Accessed 21.12.22
36. Norsk Resuscitasjonsråd Retningslinjer 2015 Resuscitering av nyfødte. NRR retningslinjer for resuscitering 2005 Accessed 21.12.22
37. Wyckoff MH, Wyllie J, Aziz K et al on behalf of the Neonatal Life Support Collaborators. Neonatal Life Support: 2020 International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science With Treatment Recommendations. Circulation 2020;142(16):S185-S221 doi:10.1161/CIR.0000000000000895
38. European Resuscitation Council Guidelines 2021: Newborn resuscitation and support of transition of infants at birth. Madar J, Roehr CC, Ainsworth S et al. Resuscitation 2021;161:291-326. doi:10.1016/j.resuscitation.2021.02.014
39. 2020 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Part 5: Neonatal Resuscitation. Aziz K, Lee HC, Escobedo MC et al. Circulation 2020;142:S524–S550. doi: 10.1161/CIR.0000000000000902
40. Wall SN, Lee AC, Niermeyer S, et al. Neonatal resuscitation in low-resource settings: what, who, and how to overcome challenges to scale up? Int J Gynaecol Obstet. 2009;107(1):S47-S64. doi:10.1016/j.ijgo.2009.07.013
41. Lee AC, Cousens S, Wall SN, et al. Neonatal resuscitation and immediate newborn assessment and stimulation for the prevention of neonatal deaths: a systematic review, meta-analysis and Delphi estimation of mortality effect. BMC Public Health 2011;11(3):S12. doi: 10.1186/1471-2458-11-S3-S12
42. Bjorland PA, Øymar K, Ersdal HL, Rettedal SI: Incidence of newborn resuscitative interventions at birth and short-term outcomes: a regional population-based study. BMJ Paediatr. Open 2019; 3e000592. doi.org/10.1136/bmjpo-2019-000592

43. Foglia EE, te Pas AB. Effective ventilation: The most critical intervention for successful delivery room resuscitation. Seminars in Fetal and Neonatal Medicine 2018;23:340–46. doi : 10.1016/j.siny.2018.04.001
44. Hooper SB, Kitchen MJ, Wallace MJ, et al. Imaging lung aeration and lung liquid clearance at birth. FASEB J 2007;21(12):3329-3337. doi:10.1096/fj.07-8208com
45. Ersdal HL, Eilevstjonn J, Perlman J, Gomo Ø, Moshiro R, Mdoe P, Kidanto H, Hooper SB, Linde JE. Establishment of functional residual capacity at birth: Observational study of 821 neonatal resuscitations. Resuscitation 2020;153:71-78. doi :10.1016/j.resuscitation.2020.05.033
46. O'Donnell CP, Davis PG, Lau R, Dargaville PA, Doyle LW, Morley CJ. Neonatal resuscitation 2: an evaluation of manual ventilation devices and face masks. Arch Dis Child Fetal Neonatal Ed. 2005 Sep;90(5):F392-6. doi: 10.1136/adc.2004.064691
47. Thallinger M, Ersdal HL, Francis F, Yeconia A, Mduma E, Kidanto H, Linde JE, Eilevstjønn J, Gunnes N, Størdal K. Born not breathing: A randomised trial comparing two self-inflating bag-masks during newborn resuscitation in Tanzania. Resuscitation 2017;116:66-72. doi: 10.1016/j.resuscitation.2017.04.012
48. H. Breivik. A safe multipurpose pediatric ventilation bag. Crit Care Med 1976;4(1):32-39
49. Bennett S, Finer NN, Rich W, Vaucher Y.A comparison of three neonatal resuscitation devices. Resuscitation 2005;67(1):113-118. doi: 10.1016/j.resuscitation.2005.02.016
50. The Airway Jedi 2017 Difference in Manual Ventilation: Self-Inflating Ventilation Bag vs. a Free Flow Inflating Bag - The Airway Jedi Accessed 28.12.22
51. Tracy MB, Klimek J, Coughtrey H, et al. Ventilator-delivered mask ventilation compared with three standard methods of mask ventilation in a manikin model. Arch Dis Child Fetal Neonatal Ed. 2011;96(3):F201-F205. doi:10.1136/adc.2009.169730
52. Tracy M, Maheshwari R, Shah D, Hinder M. Can Ambu self-inflating bag and Neopuff infant resuscitator provide adequate and safe manual inflations for infants up to 10kg weight? Arch Dis Child Fetal Neonatal Ed. 2017;102(4):F333-F338. doi:10.1136/archdischild-2016-311830
53. Coffey PS, Saxon EA, Narayanan I, DiBlasi RM. Performance and Acceptability of Two Self-Inflating Bag-Mask Neonatal

Resuscitator Designs. Respiratory Care 2015;60(9):1227-37. doi: 10.4187/respcare.03867

54. Wyckoff MH, Aziz K, Escobedo MB, Kapadia VS, Kattwinkel J, Perlman JM, Simon WM, Weiner GM, Zaichkin JG. Part 13: Neonatal Resuscitation: 2015 American Heart Association Guidelines Update for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care (Reprint*).* Pediatrics 2015;136 (2):S196–S218. 10.1542/peds.2015-3373G
55. Hinder M, Tracy M. Newborn resuscitation devices: The known unknowns and the unknown unknowns. Seminars in Fetal and Neonatal Medicine 2021;26(2):101233. doi: 10.1016/j.siny.2021.101233
56. Bjorland PA, Ersdal HL, Haynes J, Ushakova A, Øymar K, Rettedal SI. Tidal volumes and pressures delivered by the NeoPuff T-piece resuscitator during resuscitation of term newborns. Resuscitation 2021;170:222-29. doi:10.1016/j.resuscitation.2021.12.006
57. Roehr CC, Kelm M, Fischer HS, Bührer C, Schmalisch G, Proquitté H. Manual ventilation devices in neonatal resuscitation: Tidal volume and positive pressure-provision. Resuscitation 2010;81(2):202-205, doi:10.1016/j.resuscitation.2009.10.008
58. Guinsburg R, de Almeida MFB, de Castro JS, et al. T-piece versus self-inflating bag ventilation in preterm neonates at birth. Arch Dis Child Fetal Neonatal Ed 2018;103:F49– F54
59. Kanter RK. Evaluation of mask-bag ventilation in resuscitation of infants. Am J Dis Child 1987;141(7):761-763
60. Tracy MB, Klimek J, Coughtrey JH, et al. Ventilator-delivered mask ventilation compared with three standard methods of mask ventilation in a manikin model. Arch Dis Child Fetal Neonatal Ed 2011;96(3):F201-F205
61. Perlman JM, Wyllie J, Kattwinkel J, et al*.* Part 7: neonatal resuscitation: 2015 international consensus on cardiopulmonary resuscitation and emergency cardiovascular care science with treatment recommendations (reprint) Pediatrics 2015;136(2):S120-S166
62. Blank DA, Gaertner VD, Kamlin COF, et al. Respiratory changes in term infants immediately after birth. Resuscitation 2018;130:105-110.
63. te Pas AB, Wong C, Kamlin CO, Dawson JA, Morley CJ, Davis PG. Breathing patterns in preterm and term infants immediately after birth. Pediatr Res. 2009;65(3):352–6.

64. Hillman NH, Moss TJ, Kallapur SG, et al. Brief, large tidal volume ventilation initiates lung injury and a systemic response in fetal sheep. American journal of respiratory and critical care medicine. 2007;176(6):575-581
65. Klingenberg C, Wheeler KI, McCallion N, Morley CJ, Davis PG. Volume-targeted versus pressure-limited ventilation in neonates. Cochrane Database Syst Rev. 2017;10:CD003666
66. Mian Q, Cheung PY, O'Reilly M, Barton SK, Polglase GR, Schmölzer GM. Impact of delivered tidal volume on the occurrence of intraventricular haemorrhage in preterm infants during positive pressure ventilation in the delivery room. Arch Dis Child Fetal Neonatal Ed. 2019;104(1):F57–62
67. Linde JE, Schulz J, Perlman JM, et al. The relation between given volume and heart rate during newborn resuscitation. Resuscitation. 2017;117:80-86.
68. Sawyer T, Umoren RA, Gray MM. Neonatal resuscitation: advances in training and practice. Adv Med Educ Pract. 2017;8:11-19 doi:10.2147/AMEP.S109099
69. Schmölzer GM, Kamlin OC, O'Donnell CP, Dawson JA, Morley CJ, Davis PG. Assessment of tidal volume and gas leak during mask ventilation of preterm infants in the delivery room. Arch Dis Child Fetal Neonatal Ed. 2010;95(6):F393-F397. doi:10.1136/adc.2009.174003
70. Poulton DA, Schmolzer GM, Morley CJ, Davis PG. Assessment of chest rise during mask ventilation of preterm infants in the delivery room. Resuscitation (2011) 82(2):175–9. doi:10.1016/j.resuscitation.2010.10.012 63
71. Wyllie J, Bruinenberg J, Roehr CC, Rudiger M, Trevisanuto D, Urlesberger B. European resuscitation council guidelines for resuscitation 2015: section 7. Resuscitation and support of transition of babies at birth. Resuscitation 2015;95:249–63. doi:10.1016/j.resuscitation.2015.07.029
72. Blank D, Rich W, Leone T, Garey D, Finer N. Pedi-cap color change precedes a significant increase in heart rate during neonatal resuscitation. Resuscitation. 2014;85:1568-1572.
73. Leone TA, Lange A, Rich W, Finer NN. Disposable colorimetric carbon dioxide detector use as an indicator of a patent airway during noninvasive mask ventilation. Pediatrics. 2006;118(1)
74. Finer NN, Rich W, Wang C, Leone T. Airway obstruction during mask ventilation of very low birth weight infants during neonatal

resuscitation. Pediatrics. 2009;123(3):865-869. doi:10.1542/peds.2008-0560

75. Klimek J, Morley CJ, Lau R, et al. Does measuring respiratory function improve neonatal ventilation? J Paediatr Child Health 2006;42:140–2
76. Bhutani VK. Clinical applications of pulmonary function and graphics. Semin Neonatol. 2002;7(5):391-399. doi:10.1053/siny.2002.0133
77. Finn D, Boylan GB, Ryan CA and Dempsey EM. Enhanced Monitoring of the Preterm Infant during Stabilization in the Delivery Room. Front. Pediatr. 2016;4:30. doi: 10.3389/fped.2016.00030
78. O'Donnell CP, Kamlin CO, Davis PG, et al. Neonatal resuscitation 1: a model to measure inspired and expired tidal volumes and assess leakage at the face mask. Arch Dis Child Fetal Neonatal Ed 2005;90:F388–91
79. Schmölzer GM, Kamlin CO, Dawson JA, te Pas AB, Morley CJ, Davis PG. Respiratory monitoring of neonatal resuscitation. Arch Dis Child Fetal Neonatal Ed 2010;95:F295-303.
80. O'Currain E, Thio M, Dawson JA, Donath SM, Davis PG. Respiratory monitors to teach newborn facemask ventilation: a randomised trial. Arch Dis Child Fetal Neonatal Ed. 2019;104(6):F582-F586. doi:10.1136/archdischild-2018-316118
81. Schmölzer GM, Morley CJ, Wong C, Dawson JA, Kamlin COF, Donath SM, et al. Respiratory function monitor guidance of mask ventilation: a feasibility study. J Pediatr 2012;160:377-81
82. van Zanten HA, Kuypers K, van Zwet EW, et al. A multi-Centre randomised controlled trial of respiratory function monitoring during stabilisation of very preterm infants at birth. Resuscitation. 2021;167:317-325
83. Schmölzer GM, Dawson JA, Kamlin CO, O'Donnell CP, Morley CJ, Davis PG. Airway obstruction and gas leak during mask ventilation of preterm infants in the delivery room. Arch Dis Child Fetal Neonatal Ed. 2011;96(4):F254-F257. doi:10.1136/adc.2010.191171
84. Kaufman J, Schmölzer GM, Kamlin CO, Davis PG. Mask ventilation of preterm infants in the delivery room. Arch Dis Child Fetal Neonatal Ed. 2013;98(5):F405-F410. doi:10.1136/archdischild-2012-303313
85. Milner A, Murthy V, Bhat P, et al. Evaluation of respiratory function monitoring at the resuscitation of prematurely born infants. Eur J Pediatr. 2015;174(2):205-208. doi:10.1007/s00431-014-2379-2

86. Kuypers KLAM, van Zanten HA, Heesters V, et al. Resuscitators' opinions on using a respiratory function monitor during neonatal resuscitation. Acta Paediatr. 2023;112(1):63-68. doi:10.1111/apa.16559
87. Schmölzer GM, Morley CJ, Davis PG. Respiratory function monitoring to reduce mortality and morbidity in newborn infants receiving resuscitation. Cochrane Database of Systematic Reviews 2010, Issue 9. Art. No.: CD008437. doi: 10.1002/14651858.CD008437
88. Ades A, Lee HC. Update on simulation for the Neonatal Resuscitation Program. Semin Perinatol. 2016;40(7):447-454. doi:10.1053/j.semperi.2016.08.005
89. Korioth T. Updated NRP materials include 2 curriculum levels, 2 methods to deliver content. AAP News June 1 2021.Updated NRP materials include 2 curriculum levels, 2 methods to deliver content | AAP News | American Academy of Pediatrics Accessed 29.04.23
90. Jewkes F, Phillips B. Resuscitation training of paediatricians. Arch Dis Child. 2003 Feb;88(2):118-21. doi: 10.1136/adc.88.2.118
91. Cambridge Dictionary LEARNING | English meaning - Cambridge Dictionary accessed 27.01.23
92. Taylor DCM, Hamdy H. Adult learning theories: Implications for learning and teaching in medical education: AMEE Guide No. 83. Med Teach. 2013;35:e1561-e72.
93. Kolb, DA. Experiential Learning: Experience as the Source of Learning and Development. 1984 Englewood Cliffs, NJ: Prentice Hall. http://academic.regis.edu/ed205/Kolb.pdf Accessed 27.01.23
94. Fraser KL, Ayres P, Sweller J. Cognitive load theory for the design of medical simulations. Simul Healthc. 2015;10(5): 295–307
95. Bjerrum AS, Hilberg O, van Gog T, Charles P, Eika B. Effects of modelling examples in complex procedural skills training: a randomised study. Med Educ. 2013;47(9):888–898
96. van Merrienboer JJG, Kirschner PA & Kester L. Taking the Load Off a Learner's Mind: Instructional Design for Complex Learning, Educational Psychologist 2003;38(1):5-13. doi: 10.1207/S15326985EP3801_2
97. Sawyer T, White M, Zaveri P, Chang T, Ades A, French H, et al. Learn, see, practice, prove, do, maintain: an evidence-based pedagogical framework for procedural skill training in medicine. Acad Med. 2015;90(8):1025–1033
98. Ericsson KA. The Role of Deliberate Practice in the Acquisition of Expert Performance. Psychol Rev. 1993;100:363-406

99. McGaghie WC. Mastery learning: it is time for medical education to join the 21st century. Acad Med. 2015;90(11):1438-1441. doi:10.1097/ACM.0000000000000911
100. McGaghie WC, Miller GE, Sajid A, Telder TV. Competency-Based Curriculum Development in Medical Education. Geneva, Switzerland: World Health Organization; 1978. Public Health Paper no. 68
101. Halsted WS. The training of the surgeon. Bull Johns Hopkins Hosp. 1904;15:267–275.
102. Kohn LT, Corrigan JM, Donaldson MS. To Err is Human: Building a Safer Health System. Washington DC: National Academy Press, 1999
103. Ziv A, Wolpe PR, Small SD, Glick S. Simulation-Based Medical Education: An Ethical Imperative. Simulation In Healthcare: The Journal of the Society for Simulation in Healthcare 2006;1(4):252-256. doi:10.1097/01.SIH.0000242724.08501.63
104. Kotsis SV, Chung KC. 2013. Application of see one, do one, teach one concept in surgical training. Plastic and Reconstructive Surgery 131:1194–1201 DOI 10.1097/PRS.0b013e318287a0b3
105. Cheng A, Duff J, Grant E, Kissoon N, Grant VJ. Simulation in paediatrics: An educational revolution. Paediatr Child Health 2007;12(6):465-468.
106. Gaba DM. Improving anesthesiologists' performance by simulating reality. Anesthesiology 1992;76:491-4
107. Huang J, Tang Y, Tang J, et al. Educational efficacy of high-fidelity simulation in neonatal resuscitation training: a systematic review and meta-analysis. BMC Med Educ. 2019;19(1):323. Published 2019 Aug 29. doi:10.1186/s12909-019-1763-z
108. Sawyer T, Sierocka-Castaneda A, Chan D, Berg B, Lustik M, Thompson M. Deliberate practice using simulation improves neonatal resuscitation performance. Simul Healthc. 2011;6 (6):327–336
109. Nourkami-Tutdibi N, Hilleke AB, Zemlin M, Wagenpfeil G, Tutdibi E. Novel modified Peyton's approach for knowledge retention on newborn life support training in medical students. Acta Paediatr. 2020;109(8):1570-1579. doi:10.1111/apa.15198
110. Giacomino K, Caliesch R, Sattelmayer KM. The effectiveness of the Peyton's 4-step teaching approach on skill acquisition of procedures in health professions education: A systematic review and meta-

analysis with integrated meta-regression. PeerJ. 2020;8:e10129. doi:10.7717/peerj.10129

111. Issenberg SB, McGaghie WC, Petrusa E, Gordon DL, Sales RJ. Features and uses of high-fidelity medial simulation that lead to effective learning: a BEME systematic review. Med Teach 2005;27:10 –28.
112. McGaghie WC, Issenberg SB, Petrusa ER, Scalese RJ. Effect of practice on standardized learning outcomes in simulation-based medical education. Med Educ 2006;40:792–797
113. Buck GH. Development of simulators in medical education. Gesnerus. 1991;48 Pt 1:7-28
114. Halamek LP, Kaegi DM, Gaba DM, et al. Time for a new paradigm in pediatric medical education: teaching neonatal resuscitation in a simulated delivery room environment. Pediatrics. 2000;106(4):E45. doi:10.1542/peds.106.4.e45
115. Halamek LP. The simulated delivery-room environment as the future modality for acquiring and maintaining skills in fetal and neonatal resuscitation. Semin Fetal Neonatal Med 2008;13:448 –453
116. EVERY NEWBORN An Action Plan to End Preventable Newborn Deaths. WHO 2014 every-new-born-action-plan-(enap).pdf (who.int) Accessed 20.03.23
117. Msemo G, Massawe A, Mmbando D, Rusibamayila N, Manji K, Kidanto HL, Mwizamuholya D, Ringia P, Ersdal HL, Perlman J. Newborn Mortality and Fresh Stillbirth Rates in Tanzania After Helping Babies Breathe Training. Pediatrics 2013;131(2): e353–e360. doi: 10.1542/peds.2012-1795
118. Agudelo-Pérez S, Cifuentes-Serrano A, Ávila-Celis P, Oliveros H. Effect of the Helping Babies Breathe Program on Newborn Outcomes: Systematic Review and Meta-Analysis. Medicina 2022; 58:1567. https://doi.org/10.3390/ medicina58111567
119. Skåre C, Boldingh AM, Nakstad B, et al. Ventilation fraction during the first 30s of neonatal resuscitation. Resuscitation 2016;107:25-30. doi:10.1016/j.resuscitation.2016.07.231
120. Bjorland PA, Ersdal HL, Øymar K, Rettedal SI. Compliance with Guidelines and Efficacy of Heart Rate Monitoring during Newborn Resuscitation: A Prospective Video Study. Neonatology 2020;117(2):175-181. doi:10.1159/000506772

121. Peters DH, Adam T, Alonge O, Agyepong IA, Tran N. Implementation research: what it is and how to do it. BMJ. 2013;347:f6753. doi:10.1136/bmj.f6753
122. Krumholz HM. Outcomes research: generating evidence for best practice and policies. Circulation 2008;118(3):309-318. doi:10.1161/CIRCULATIONAHA.107.690917
123. Ehret DEY, Patterson JK, Kc A, Worku B, Kamath-Rayne BD, Bose CL. Helping Babies Survive Programs as an Impetus for Quality Improvement. Pediatrics 2020;146(2):S183-S193. doi:10.1542/peds.2020-016915J
124. Gaba DM. The future vision of simulation in health care. Qual Saf Health Care. 2004;13(1):i2–i10
125. Dubrowski R, Dubrowski A. Why Should Implementation Science Matter in Simulation-based Health Professions Education? Cureus 10(12): e3754. doi:10.7759/cureus.3754
126. Woolf SH. The meaning of translational research and why it matters. JAMA 2008;299(2):211-213. doi:10.1001/jama.2007.26
127. McGaghie WC, Issenberg SB, Cohen ER, Barsuk JH, Wayne DB. Translational educational research: a necessity for effective health-care improvement. Chest 2012;142(5):1097-1103. doi: 10.1378/chest.12-0148
128. Brazil V. Translational simulation: not 'where?' but 'why?' A functional view of in situ simulation. Adv Simul (Lond) 2017;2:20. doi:10.1186/s41077-017-0052-3
129. Brazil V, Purdy EI, Bajaj K. Connecting simulation and quality improvement: how can healthcare simulation really improve patient care? BMJ Qual Saf. 2019;28(11):862-865. doi:10.1136/bmjqs-2019-009767
130. Lowe B, De Araujo V, Haughton H, Schweitzer J, Brazil V. Preparing maternity for COVID-19: A translational simulation approach. Aust N Z J Obstet Gynaecol. 2020;60(4):628-632. doi:10.1111/ajo.13185
131. Dubrowski R, Barwick M, Dubrowski A. I Wish I Knew This Before…an Implementation Science Primer and Model to Guide Implementation of Simulation Programs in Medical Education. In: Safir O, Sonnadara R, Mironova P, Rambani R, eds. Boot Camp Approach to Surgical Training.Cham, Switzerland: Springer 2018:103–121

132. Pike H, Eilevstjønn J, Bjorland P, Linde J, Ersdal H, Rettedal S. Heart rate detection properties of dry-electrode ECG compared to conventional 3-lead gel-electrode ECG in newborns. BMC Res Notes. 2021;14(1):166. doi:10.1186/s13104-021-05576-x
133. Linde JE, Eilevstjønn J, Øymar K, Ersdal HL. Feasibility of a prototype newborn resuscitation monitor to study transition at birth, measuring heart rate and ventilator parameters, an animal experimental study. BMC Res Notes 2017;10(1):235-235
134. Eilevstjønn J, Linde JE, Blacy L, Kidanto H, Ersdal HL: Distribution of heart rate and responses to resuscitation among 1237 apnoeic newborns at birth. Resuscitation 2020;152:69–76. doi:10.1016/j.resuscitation.2020.04.037
135. Black N. Why we need observational studies to evaluate the effectiveness of health care. BMJ. 1996 May 11;312(7040):1215-8. doi: 10.1136/bmj.312.7040.1215
136. Benson K, Hartz AJ. A comparison of observational studies and randomized, controlled trials. N Engl J Med. 2000;342(25):1878-1886. doi:10.1056/NEJM200006223422506
137. Dreyer NA. Making observational studies count: shaping the future of comparative effectiveness research. Epidemiology. 2011;22(3):295–7
138. van der Heide PA, van Toledo-Eppinga L, van der Heide M, van der Lee JH. Assessment of neonatal resuscitation skills: A reliable and valid scoring system. Resuscitation 2006;71:212–221. doi: 10.1016/j.resuscitation.2006.04.009
139. Kane SK, Lorant DE. Creation and Validation of Tool to Assess Resident Competence in Neonatal Resuscitation. Acad Pediatr. 2019, 19, 394–398
140. te Pas, A.; Schilleman, K.; Klein, M.; Witlox, R.S.; Morley, C.J.; Walther, F. Low versus High Gas Flow Rate for Respiratory Support of Infants at Birth: A Manikin Study. Neonatology 2011;99:266–271DOI: 10.1159/000318663
141. Schilleman K, Schmölzer GM, Kamlin OC, Morley CJ, te Pas AB, Davis PG. Changing gas flow during neonatal resuscitation: a manikin study. Resuscitation. 2011;82(7):920-924. doi:10.1016/j.resuscitation.2011.02.029

142. Newey WK, West KD. A Simple, Positive Semi-Definite, Heteroskedasticity and Autocorrelation Consistent Covariance Matrix. Econometrica 1987;55:703
143. Dubin JA, Müller HG. Dynamical Correlation for Multivariate Longitudinal Data. J. Am. Stat. Assoc.2005;100:872–881
144. Sawyer T, Strandjord TP, Johnson K, Löw D. Neonatal airway simulators, how good are they? A comparative study of physical and functional fidelity. J. Perinatol. 2015;36:151–156
145. Wood FE, Morley C, Dawson J, Kamlin COF, Owen LS, Donath S, Davis PG. Assessing the effectiveness of two round neonatal resuscitation masks: Study 1. Arch. Dis. Child. Fetal Neonatal Ed. 2008, 93, F235–F237
146. Hamstra SJ, Brydges R, Hatala R, Zendejas B, Cook DA. Reconsidering fidelity in simulation-based training. Acad Med. 2014;89(3):387-392. doi:10.1097/ACM.0000000000000130
147. Curran V, Fleet L, White S, et al. A randomized controlled study of manikin simulator fidelity on neonatal resuscitation program learning outcomes. Adv Health Sci Educ Theory Pract. 2015;20(1):205-218. doi:10.1007/s10459-014-9522-8
148. Norman G, Dore K, Grierson L. The minimal relationship between simulation fidelity and transfer of learning. Med Educ. 2012;46(7):636-647. doi:10.1111/j.1365-2923.2012.04243.x
149. Munshi F, Lababidi H, Alyousef S. Low- versus high-fidelity simulations in teaching and assessing clinical skills-Journal of Taibah University Medical Sciences 2015;10(1):12-15. 10.1016/j.jtumed.2015.01.008
150. Maran NJ, Glavin RJ. Low- to high-fidelity simulation - a continuum of medical education? Med Educ. 2003;37(1):22-28. doi:10.1046/j.1365-2923.37.s1.9.x
151. Beaubien JM, Baker DP. The use of simulation for training teamwork skills in health care: how low can you go? Qual Saf Health Care 2004;13(1):i51-6. doi: 10.1136/qhc.13.suppl_1.i51
152. Kneebone R. Simulation in surgical training: educational issues and practical training. Med Educ 2003;37:267–77
153. Brydges R, Carnahan H, Rose D, Rose L, Dubrowski A. Coordinating progressive levels of simulation fidelity to maximise educational benefit. Acad Med 2010;85 (5):806–12

154. Finan E, Bismilla Z, Whyte HE, Leblanc V, McNamara PJ. High-fidelity simulator technology may not be superior to traditional low-fidelity equipment for neonatal resuscitation training. J Perinatol. 2012;32(4):287-292. doi:10.1038/jp.2011.96
155. Crofts JF, Bartlett C, Ellis D, Hunt LP, Fox R, Draycott TJ. Training for shoulder dystocia: a trial of simulation using low-fidelity and high-fidelity mannequins. Obstet Gynecol. 2006;108(6):1477-1485. doi:10.1097/01.AOG.0000246801.45977.c8
156. Draycott TJ, Crofts JF, Ash JP, et al. Improving neonatal outcome through practical shoulder dystocia training. Obstet Gynecol. 2008;112(1):14-20. doi:10.1097/AOG.0b013e31817bbc61
157. Nimbalkar A, Patel D, Kungwani A, Phatak A, Vasa R, Nimbalkar S. Randomized control trial of high fidelity vs low fidelity simulation for training undergraduate students in neonatal resuscitation. BMC Res Notes. 2015;8:636. doi:10.1186/s13104-015-1623-9
158. Størdal K, Eilevstjønn J, Mduma E, Holte K, Thallinger M, Linde J, et al. Increased perinatal survival and improved ventilation skills over a five-year period: An observational study. PLoS ONE 2020;15(10):e0240520. doi 10.1371/journal.pone.0240520
159. Vadla MS, Moshiro R, Mdoe P, Eilevstjønn J, Kvaløy JT, Hhoki BH, Ersdal H. Newborn resuscitation simulation training and changes in clinical performance and perinatal outcomes: a clinical observational study of 10,481 births. Adv Simul (Lond). 2022 Nov 5;7(1):38. doi: 10.1186/s41077-022-00234-z
160. Gurung R, Gurung A, Sunny AK, et al. Effect of skill drills on neonatal ventilation performance in a simulated setting- observation study in Nepal. BMC Pediatr. 2019;19(1):387. doi:10.1186/s12887-019-1723-0
161. Vadla MS, Mdoe P, Moshiro R, Haug IA, Gomo Ø, Kvaløy JT, Oftedal B, Ersdal H. Neonatal Resuscitation Skill-Training Using a New Neonatal Simulator, Facilitated by Local Motivators: Two-Year Prospective Observational Study of 9000 Trainings. Children. 2022; 9(2):134. doi 10.3390/children9020134
162. Rubio-Gurung S; Putet G, Touzet S, Gauthier-Moulinier H, Jordan I, Beissel A, Labaune JM, Blanc S, Amamra N, Balandras C, et al. In Situ Simulation Training for Neonatal Resuscitation: An RCT. Pediatrics 2014;134:e790

163. Whalen AM, Merves MH, Kharayat P, Barry JS, Glass KM, Berg RA, et al. Validity evidence for a novel, comprehensive bag-mask ventilation assessment tool. J Pediatr 2022;245:165-71.e13
164. Kaczorowski, J.; Levitt, C.; Hammond, M.; Outerbridge, E.; Grad, R.; Rothman, A.; Graves, L. Retention of Neonatal Resuscitation Skills and Knowledge: A Randomised Controlled Trial. Fam. Med. 1998, 30, 705–711
165. Sutton RM, Niles D, Meaney PA, Aplenc R, French B, Abella BS, Lengetti EL, Berg RA, Helfaer MA, Nadkarni V: Low-dose high-frequency CPR training improves skill retention of in-hospital pediatric providers. Pediatrics. 2011;128:e145-151. doi:10.1542/peds.2010-2105
166. Cusack J, Fawke J. Neonatal resuscitation: are your trainees performing as you think they are? A retrospective review of a structured resuscitation assessment for neonatal medical trainees over an 8-year period. Arch Dis Child Fetal Neonatal Ed 2012;97:F246–F248. doi:10.1136/archdischild-F246 2011-300548
167. Ciurzynski SM, Gottfried JA, Pietraszewski J, Zalewski M: Impact of Training Frequency on Nurses' Pediatric Resuscitation Skills. Journal Nurses Prof Dev 2017;33(5):E1-E7. doi: 10.1097/NND.0000000000000386
168. Dudzik LR, Heard DG, Griffin RE, Vercellino M, Hunt A, Cates A; Rebholz M: Implementation of a Low-Dose, High-Frequency Cardiac Resuscitation Quality Improvement Program in a Community Hospital. Jt Comm J Qual Patient Saf 2019;45:789–797. doi: 10.1016/j.jcjq.2019.08.010
169. Anderson R, Sebaldt A, Lin Y, Cheng A. Optimal training frequency for acquisition and retention of high-quality CPR skills: A randomized trial. Resucitation 2019; 135:153-61. doi.org/10.1016/j.resuscitation.2018.10.033
170. Oermann MH, Krusmark MA, Kardong-Egren S, Jastrzembski TS, Gluck KA: Personalized Training Schedules for Retention and Sustainment of Cardiopulmonary Resuscitation Skills Sim Healthcare 2022;17:e59–e67
171. Rodgers DL, Securro S Jr, Pauley RD. The effect of high-fidelity simulation on educational outcomes in an advanced cardiovascular life support course. Simul Healthc. 2009;4(4):200-206. doi:10.1097/SIH.0b013e3181b1b877

9. Appendices

Appendix 1- Questionnaire 1 before participation in the study «Simulation training to ensure competence in neonatal resuscitation»

Questionnaire 1 before participation in the study «Simulation training to ensure competence in neonatal resuscitation»

About you: circle the response that fits best

(1) Neonatologist / Paediatrician / Anaesthetist / Obstetrician / Midwife / Paediatric nursing assistant / Anaesthesia nurse	
(2) How many years have you worked in your current job?	……years

Experience with neonatal resuscitation and teaching/training: circle the response that fits best

(3) How many neonatal resuscitations have you been involved in in the last year?	0	1	2-3	4-5	>5
(4) When was the last time you gave facemask ventilation to a newborn at birth?	Never done it	In the last month	In the last year	In the last two years	> two years ago
(5) How often do you receive teaching in neonatal resuscitation?	Never had	< once per year	Once per year	Once per six months	> once per six months
(6) How often do you participate in simulation training of neonatal resuscitation?	Never done	< once per year	Once per year	Once per six months	> once per six months

Your experience of confidence and competence in neonatal resuscitation: circle the response that fits best (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree, 6 = not applicable

(7) I am confident about what my role in neonatal resuscitation involves	1	2	3	4	5	6
(8) I know the instructions contained in the neonatal resuscitation algorithm	1	2	3	4	5	6
(9) It is easy to see when a newborn needs help with their breathing	1	2	3	4	5	6
(10) It is rare that I am not successful in ventilating a newborn	1	2	3	4	5	6
(11) In my experience, a newborn who needs ventilation receives this within 60 seconds of birth	1	2	3	4	5	6
(12) I am worried about harming the newborn during ventilation	1	2	3	4	5	6
(13) Regular teaching on neonatal resuscitation increases/maintains my knowledge	1	2	3	4	5	6
(14) It is easy to forget information given during teaching on neonatal resuscitation	1	2	3	4	5	6
(15) Even though I know what to do, it is not easy to perform resuscitation according to the algorithm	1	2	3	4	5	6
(16) Simulation training in neonatal resuscitation results in better technical competence which helps in real situations	1	2	3	4	5	6
(17) My technical competence becomes noticeably worse between simulation training sessions	1	2	3	4	5	6
(18) Simulation training is important for good team work during acute situations	1	2	3	4	5	6
(19) I would like more frequent teaching on neonatal reuscitation	1	2	3	4	5	6
(20) I would like more frequent simulation training in neonatal reuscitation	1	2	3	4	5	6
(21) I would like to be able to practice neonatal resuscitation myself when the opportunity arises at work	1	2	3	4	5	6

(22) I know where to find equipment to perform simulation training at work	1	2	3	4	5	6
(23) The neonatal simulation training equipment available gives a realistic representation of what it is like to perform real resuscitation	1	2	3	4	5	6

Comments regarding my experience of, and my need for, neonatal resuscitation simulation training:-

Thank you for participating in the study. You will now perform two test simulation scenarios to document baseline knowledge and ventilation skills.

Study nr_____

Date of test scenario 1_____

Appendix 2- Questionnaire 2 after participation in the study «Simulation training to ensure competence in neonatal resuscitation»

Questionnaire after participation in the study «Simulation training to ensure competence in neonatal resuscitation» **STUDY NUMBER_____**

Thank you for participating in the study. I would like to ask about your experience of the study and what was useful for you. Read the following statements and circle the response that fits best: -

1=strongly disagree 2=disagree 3= neutral 4=agree 5= strongly agree 6= not applicable/don't know

As a result of participation, my knowledge has increased. 1 2 3 4 5 6

As the study progressed, I became better at ventilating the manikin. 1 2 3 4 5 6

I could train often enough that I didn't experience any deterioration of my skills between sessions. 1 2 3 4 5 6

As a result of participation, I feel more confident in real neonatal resuscitations.

1 2 3 4 5 6

As a result of participation, I find that I am more often successful in ventilating a newborn who needs help. 1 2 3 4 5 6

As a result of participation, I can more easily give advice to a colleague who is ventilating a newborn. 1 2 3 4 5 6

After the study started, I believe that we more often start ventilation within 60 seconds of birth than we managed before the study. 1 2 3 4 5 6

Because of the study, I think that the number of newborns being ventilated has increased. 1 2 3 4 5 6

Because of the study, I think that some newborns not being ventilated should have been.

1 2 3 4 5 6

Because of the study, I think that some newborns are ventilated but don't need to be.

1 2 3 4 5 6

The new simulator, NeoNatalie Live (NNL), gives a realistic experience of what it is like to ventilate a real newborn 1 2 3 4 5 6

I think that the NNL cases (1-4) are realistic. 1 2 3 4 5 6

It is useful to train with the different cases. 1 2 3 4 5 6

The simulation training equipment was readily available such that it was not a problem to train when the opportunity arose. 1 2 3 4 5 6

I experienced that I had many opportunities to train during a shift 1 2 3 4 5 6

I would have liked to train more often that I had the opportunity to. 1 2 3 4 5 6

The manikin and iPad were easy to use. 1 2 3 4 5 6

Feedback was relevant and helped me to perform better next time. 1 2 3 4 5 6

After the study, I am confident in the use of both NeoPuff and self-inflating bag.

1 2 3 4 5 6

NNL simulator covers my requirements for neonatal resuscitation training.

1 2 3 4 5 6

I would like some more advanced cases. 1 2 3 4 5 6

I would like to train for additional skills such as chest compressions, intubation.

1 2 3 4 5 6

I would like the possibility to perform team training. 1 2 3 4 5 6

I would like to continue training with NNL after the study is completed.

1 2 3 4 5 6

My requirements for teaching in neonatal resuscitation go beyond that which is covered in this study. 1 2 3 4 5 6

This sort of training should be obligatory for everyone who takes part in neonatal resuscitation. 1 2 3 4 5 6

I was in the train twice per month group, but wanted to train more than this.

1 2 3 4 5 6

I was in the train twice per month group but didn't manage to do this due to work obligations. 1 2 3 4 5 6

I was in the train as often as you want group and I trained often because_____
_____

I was in the train as often as you want group and I trained infrequently because_____
_____

Other comments irrespective of group_____
_____
_____
_____
_____
_____

10. Reprint of publications

children

MDPI

Article

Novel Neonatal Simulator Provides High-Fidelity Ventilation Training Comparable to Real-Life Newborn Ventilation

Joanna Haynes [1,2,*], Peder Bjorland [3,4], Øystein Gomo [5], Anastasia Ushakova [6], Siren Rettedal [2,3], Jeffrey Perlman [7] and Hege Ersdal [1,2]

[1] Department of Anaesthesia, Stavanger University Hospital, 4011 Stavanger, Norway; hege.ersdal@safer.net
[2] Faculty of Health Sciences, University of Stavanger, 4021 Stavanger, Norway; siren.irene.rettedal@sus.no
[3] Department of Paediatrics, Stavanger University Hospital, 4011 Stavanger, Norway; peder.aleksander.bjorland@sus.no
[4] Department of Clinical Science, University of Bergen, 5007 Bergen, Norway
[5] Research and Development Department, Laerdal Medical, 4002 Stavanger, Norway; Oystein.Gomo@laerdal.com
[6] Department of Research, Section of Biostatistics, Stavanger University Hospital, 4011 Stavanger, Norway; anastasia.ushakova@sus.no
[7] Department of Pediatrics, Weill Cornell Medicine, New York, NY 10065, USA; jmp2007@med.cornell.edu
* Correspondence: joanna.claire.haynes@sus.no

Abstract: Face mask ventilation of apnoeic neonates is an essential skill. However, many non-paediatric healthcare personnel (HCP) in high-resource childbirth facilities receive little hands-on real-life practice. Simulation training aims to bridge this gap by enabling skill acquisition and maintenance. Success may rely on how closely a simulator mimics the clinical conditions faced by HCPs during neonatal resuscitation. Using a novel, low-cost, high-fidelity simulator designed to train newborn ventilation skills, we compared objective measures of ventilation derived from the new manikin and from real newborns, both ventilated by the same group of experienced paediatricians. Simulated and clinical ventilation sequences were paired according to similar duration of ventilation required to achieve success. We found consistencies between manikin and neonatal positive pressure ventilation (PPV) in generated peak inflating pressure (PIP), mask leak and comparable expired tidal volume (eV_T), but positive end-expiratory pressure (PEEP) was lower in manikin ventilation. Correlations between PIP, eV_T and leak followed a consistent pattern for manikin and neonatal PPV, with a negative relationship between eV_T and leak being the only significant correlation. Airway obstruction occurred with the same frequency in the manikin and newborns. These findings support the fidelity of the manikin in simulating clinical conditions encountered during real newborn ventilation. Two limitations of the simulator provide focus for further improvements.

Keywords: neonatal resuscitation; positive pressure ventilation; respiratory function monitor; deliberate practice; in-situ simulation training; perinatal mortality

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1. Introduction

The need for neonatal resuscitation is ubiquitous and often unpredictable. Positive pressure ventilation (PPV) of the non-breathing newborn is the cornerstone of resuscitation. In-situ simulation training is widely used to prepare healthcare personnel (HCP) to manage this stressful and time-critical event. Simulation training has shown the potential to change clinical management of babies; however, data to support improved outcomes are limited [1].

PPV is a seemingly simple intervention, which belies the complex interplay of elements necessary for success. Fundamental to ventilation in the non-breathing newborn is the establishment of functional residual capacity (FRC). That can usually be achieved by PPV coupled with positive end-expiratory pressure (PEEP). Mitigating factors that may influence establishing FRC include mask leak and obstruction of the upper airways.

Studies of neonatal PPV, using respiratory function monitors (RFMs) to evaluate ventilatory mechanics, highlight the challenges faced by HCPs, with large leaks around the face mask and obstructed upper airways resulting in widely-varying tidal volume (V_T) delivery [2,3]. Other studies have reviewed the role of RFMs in teaching effective PPV during simulated resuscitation [4–6]. Research suggests that HCPs face the same obstacles to effective mask-ventilation as they do in real life [7–10].

Newer simulators aim for fidelity of approximating clinical conditions. Despite improvements, valid concerns exist regarding the extent to which learning on a simulator can translate into clinical competence [6,11,12]. Specifically, the changing neonatal lung conditions encountered during newborn resuscitation are not replicated by commonly used simulators [13,14]. To be effective, a simulator should closely replicate the clinical situation, in both form and function, and promote management of known hindrances to effective PPV in a way that corresponds to that practised in the clinical environment.

Previous attempts to identify the functional fidelity of neonatal simulators have relied on subjective user feedback rather than measured respiratory parameters [15]. To our knowledge, no existing study has examined the ventilatory mechanics of a neonatal simulator and directly compared them to clinical data from real resuscitations. This study aims to do just that, using the novel high-fidelity manikin NeoNatalie Live™ (Laerdal Medical, Stavanger, Norway). The manikin aims to simulate changing lung compliance encountered during neonatal PPV by using a valve mechanism to alter the physical resistance to lung inflation. Coupling heart rate changes to ventilation performance provides a realistic experience of assessing the effectiveness of PPV. By comparing ventilation parameters and their inter-relationships, along with the occurrence of upper airway obstruction between the manikin and real resuscitations, we aim to demonstrate the functional fidelity of this new simulator.

2. Materials and Methods

2.1. Study Setting

This prospective, observational study was conducted at Stavanger University Hospital (SUS), Norway. It is the only hospital in the region with both delivery and newborn services, managing approximately 4500 births per annum and providing care for newborns $\geq$ 23 weeks' gestational age (GA). Rate of PPV provision at birth is 3.7%, and most neonates are resuscitated by a paediatrician [16]. In some unforeseen resuscitations, PPV is initiated by midwifery or anaesthetic staff. All HCPs receive neonatal resuscitation training according to national resuscitation guidelines. Most PPV is provided using a flow-driven T-piece resuscitator (NeoPuff™, Fischer and Paykel, Auckland, New Zealand).

2.2. The Neonatal Simulator

NeoNatalie Live is a newborn simulator, produced with the specific aim of training competence in PPV. Simulated, changing lung compliance and variable heart rate linked to ventilation performance allow HCPs to practise management of newborns with differing degrees of birth asphyxia. Real resuscitation data derived from 1237 newborns informs the algorithm guiding the realistic heart rate response according to PPV provided [17]. An active electrocardiogram allows monitoring of heart rate using the dry-electrode technology NeoBeat™ (Laerdal Medical), replicating the clinical situation. A sensor measures air pressure in the upper airway. Head-tilt detection identifies upper airway closure due to poor positioning. A cry-sound indicates spontaneous respiration and successful resuscitation. Communication with a training application (NeoNatalie Live, Laerdal Medical) allows HCPs to review their performance and gives targeted feedback in any of four scenarios (1–4) of increasing difficulty. Bluetooth® technology allows for the collection of training data in a web log. Figure 1 shows a participant ventilating NeoNatalie Live.

The single NeoNatalie Live manikin used in this study was identified as leak-free internally. Details of this process are available from the corresponding author. Any leak measured by the RFM during mask ventilation was thus attributed to leak at the face mask.

Figure 1. Study participant ventilates NeoNatalie Live with a NeoPuff T-piece resuscitator. The heart rate is clearly visible on both the NeoBeat sensor applied to the manikin and the tablet-device with the training application open.

2.3. The Respiratory Function Monitor

Each resuscitation bay was equipped with a Newborn Resuscitation Monitor (Laerdal Medical) that recorded airway pressures and gas flow. Sensors were placed between the T-piece and the face mask. Air pressure was measured using a piezoresistive sensor (MPXV5010, Freescale Semiconductor Inc., Austin, TX, USA). The flow sensor (MIM Gmbh, Krugzell, Germany) has negligible resistance and dead space (1 mL), and measures airflow using hot wire anemometer technology. V_T is calculated as flow integrated over time. The flow sensor measures both the inflated and expired gas. Expired volume is used as an estimate for V_T since mask leak is reported to primarily occur during inflation [9]. Face mask leak is calculated as a percentage of inspired V_T from the formula $((V_{Tinspired} - V_{Texpired})/V_{Tinspired}) \times 100$ [9]. The resuscitation monitor has been further described previously [18].

2.4. Study Design

This study is part of a comprehensive research set-up at SUS, called Safer Births Bundle [19]. Resuscitation and ventilation data are continuously recorded for newborns of consenting parents, and who are GA $\geq$ 37 weeks without innate cardiorespiratory anomalies.

Eighteen paediatricians were recruited to this study. Following an individual teaching session with NeoNatalie Live, the paediatricians performed two simulated resuscitation scenarios. The first and easiest scenario (S1—apnoea, normal lung compliance, compen-

sated heart rate) and the most difficult scenario (S4—apnoea, low initial lung compliance and decompensated heart rate), required 30 and 90 s, respectively, of optimal PPV to achieve baby-cry (suboptimal PPV resulted in longer scenario times). The RFM recorded ventilatory parameters during simulated PPV.

Each of these 36 simulated ventilation episodes was paired with a real ventilation episode of similar duration of PPV (±15%), allocated consecutively from the clinical data-pool. This manikin-baby ventilation pairing was made according to the premise that the duration of PPV required to initiate adequate spontaneous respiration is a proxy for the clinical condition at birth. Thus a further 36 clinical ventilation episodes also recorded by the RFM were included. Nineteen neonates received continuous positive airway pressure (CPAP) immediately following cessation of PPV for up to two minutes. No neonate required transfer to the Neonatal Intensive Care Unit for continued CPAP, and none were intubated.

All ventilation was performed with the NeoPuff T-piece resuscitator with standard settings of 8 L/min gas flow and initial 30 cmH_2O PIP and PEEP of 5 cmH_2O. PIP could be increased to 35cmH_2O at the discretion of the HCP. A standard silicone facemask size 0/1 (Laerdal Medical) or the newer snap-design silicone mask size 1 (Laerdal Medical) was used on both babies and manikin.

The 72 ventilation episodes were allocated to one of four groups of 18 PPV sequences (=total PPV time, excluding any pauses > 5 s), according to the recipient of PPV (manikin-M, or baby-B) and the duration of ventilation (≈30 s = short-S, or ≈90 s = long-L).

2.5. Data Collection

For each PPV sequence, per individual inflation values of PIP, PEEP, expired tidal volume (eV_T) expressed as ml/kg and mask leak % were recorded. For manikin V_T data, the median birth weight of the 1237 newborns contributing data to the simulation algorithm was used [18]. Additionally, we assessed whether upper airway obstruction occurred. This was defined as minimal inspiratory/expiratory gas flow and V_T for three or more consecutive ventilations, despite achieving target PIP, identified from the graphical output of the RFM. The inflations immediately preceding, and/or following, obstruction achieved flows and volumes typical of the whole sequence. This is likely to represent failure of positioning to maintain an open airway [3,20]. Figure 2 shows PIP, eV_T and flow curves for one of the clinical ventilation episodes, demonstrating airway obstruction occurring between 25 and 30 s.

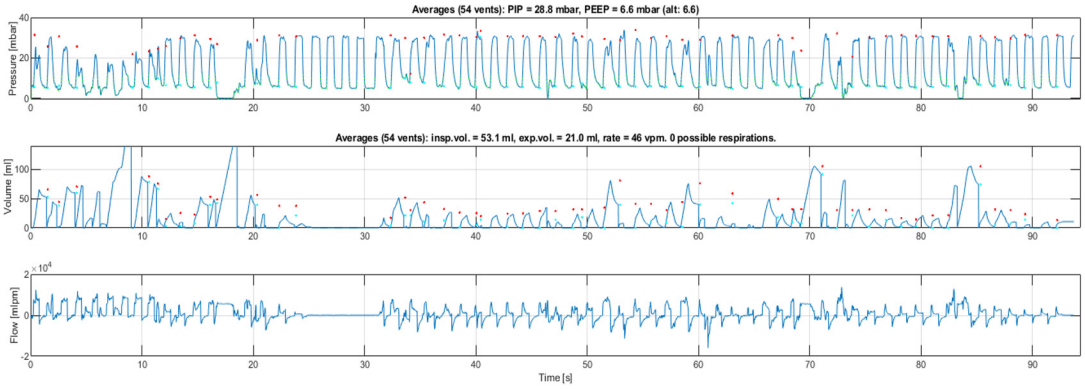


Figure 2. Graphical respiratory function monitor output from a clinical ventilation sequence. The upper curve shows peak inflating pressure, generally maintained around 30 mbar (1 mbar = 1.02 cmH_2O and the units are used interchangeably in this article). The second curve shows tidal volume (mL); the discrepancy between inflated and expired volumes is due to mask leak. The third curve shows gas flow (mL/min), with positive values indicating flow towards the neonate and negative values indicating flow away. The volume and flow curves disappear while pressure is maintained between 25–30 s, indicating obstruction to gas flow which is rapidly corrected.

2.6. Data Analysis

Data analysis was undertaken using SPSS (IBM SPSS Statistics for Windows, Version 26.0. Armonk, NY, USA: IBM Corp) and R project for statistical computing (https://www.r-project.org, accessed on 1 September 2021) version 4.0.4. R package plm version 2.4-1 was used to estimate linear panel models and package dynCorr version 1.1.0. was used to evaluate dynamical correlation. Scatterplots were produced using R package ggplot2 version 3.3.5.

First, continuous data for the ventilatory parameters PIP, PEEP, eV_T and leak were summarised using median and interquartile range (IQR) for each of the four groups (manikin short-MS, baby short-BS, manikin long-ML and baby long-BL) and presented using boxplots.

To compare the dynamics of ventilatory parameters between the groups, we used panel data regression analysis with one-way random effects models with a temporal error component. Comparisons were done separately for short and long ventilation sequences. The use of each model was justified by unit root test for stationarity [21]. A Newey and West variance estimator was used to correct for the serial correlation and heteroscedasticity in the residuals [22]. The *p*-values of these comparisons are presented together with the corresponding box plots. For each ventilatory parameter, we present their smoothed trajectories obtained using the LOESS method with a smoothing span of 0.5. Individual ventilations with data from at least five of the 18 ventilated subjects in each group were used for these dynamic trend plots.

Dynamics of the ventilatory parameters between manikin and baby groups were then formally compared using the method of dynamical correlation for multivariate longitudinal data [23]. Pearson correlation analysis is unsuited to this repeated-measures data because the data has a high degree of autocorrelation [24], but in order to place our findings in the context of other research, Pearson correlation coefficients are given, along with scatter plots depicting these correlations. P-values and 95% confidence intervals (CI) for dynamical correlation were calculated using the bootstrap method with 1000 samples.

Chi-Square testing was used to compare the occurrence of airway obstruction between the combined manikin and combined baby groups. A p-value < 0.05 was considered statistically significant.

3. Results

3.1. Ventilations Analysed

Each group (MS, BS, ML and BL) consisted of 18 PPV sequences of a varying number of ventilations. A total of 3256 ventilations were analysed, and distributed as follows: MS 443, BS 475, ML 1160, BL 1178.

3.2. Ventilatory Parameters

Median (IQR) values for PIP, PEEP, eV_T and leak in the four groups are presented in Table 1.

Table 1. Median (interquartile range) ventilatory parameters for the four groups.

Group	Median (IQR)			
	PIP (mbar)	PEEP (mbar)	eV_T (mL/kg)	Leak (%)
Manikin Short	30 (1)	3.9 (2.3)	3.5 (3.2)	33.5 (81)
Baby Short	30 (4)	4.9 (2.9)	3.3 (4.6)	50 (80)
Manikin Long	30 (1)	3.7 (2.3)	4.1 (3.2)	20 (57)
Baby Long	30 (4)	4.8 (2.1)	5.0 (4.9)	36 (73)

PIP = peak inflating pressure, PEEP = positive end-expiratory pressure, eV_T = expiratory tidal volume.

Figure 3 shows these data as box plots along with the corresponding trend lines estimated as smoothed mean (standard error) for the parameters PIP, PEEP, eV_T and leak.

PIP was higher in ML compared to BL and greater variation around the central tendencies was seen in the baby-compared to the manikin-groups (Figure 3a,e). Overall, PEEP was lower in manikin ventilation but with a similar variation compared to baby ventilation (Figure 3b,f). eV_T was generally lower for the manikin, but values converged towards those observed in the babies at the end of short and long sequences. As with PIP, eV_T variation is lower for the manikin than for babies (Figure 3c,g). Median eV_T was greater in long sequences compared to short sequences for both manikin and babies. A large variation in leak was observed in all ventilation sequences; variation between short and long sequences for manikin and babies reversed the pattern seen for $eV_{T,}$ with lower median leak in longer sequences (Figure 3d,h).

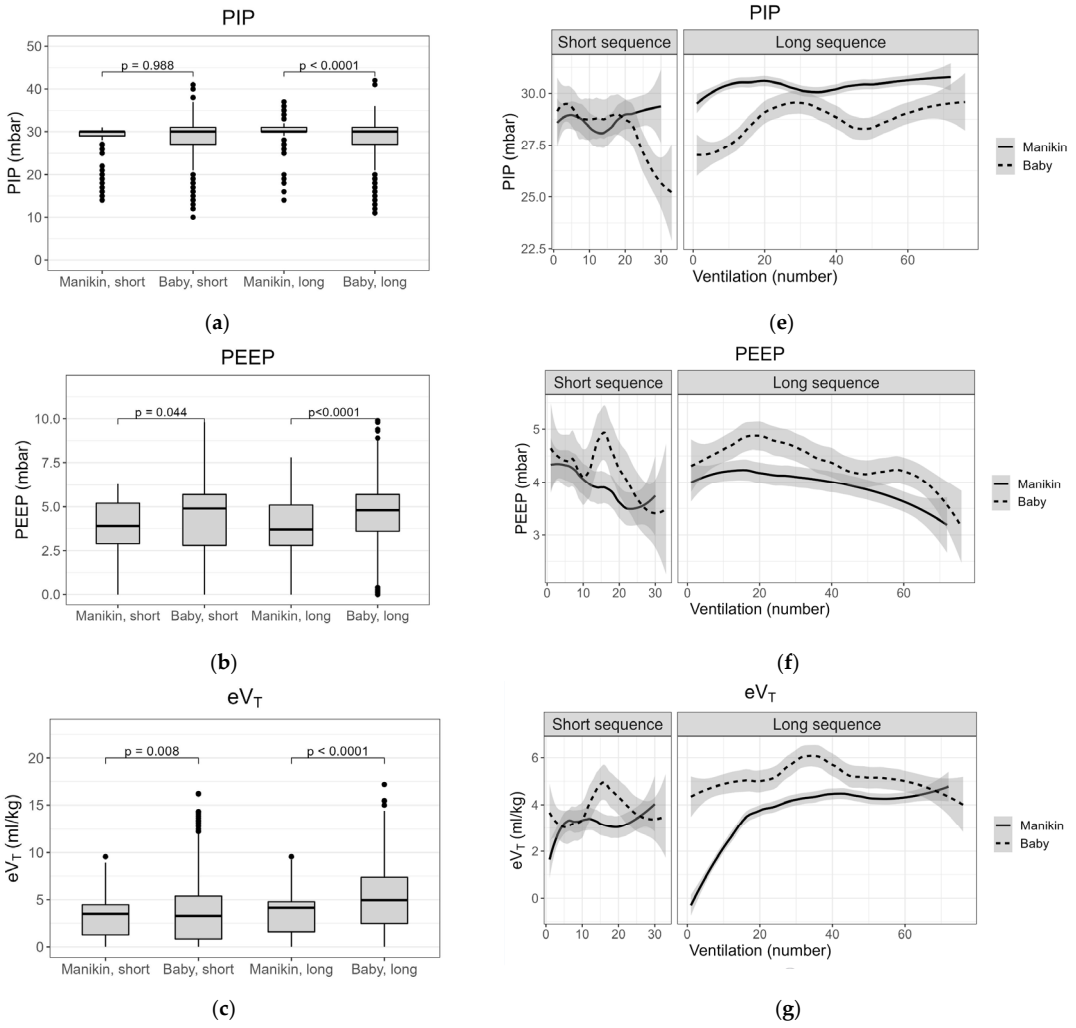
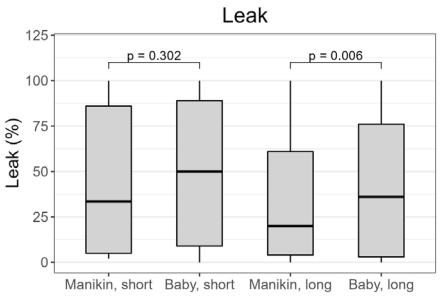
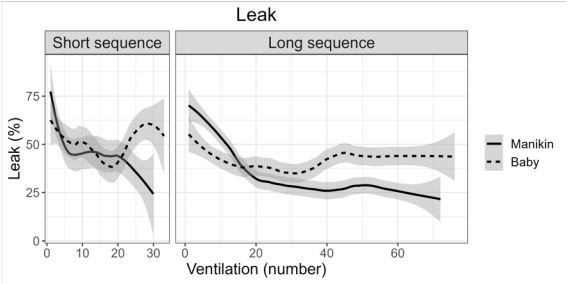


Figure 3. *Cont.*



(**d**)



(**h**)

Figure 3. (**a**–**d**) Box plots of median (interquartile range; range) PIP (peak inflating pressure), PEEP (positive end-expiratory pressure, eV_T (expiratory tidal volume) and leak for groups Manikin Short (MS), Baby Short (BS), Manikin Long (ML) and Baby Long (BL); (**e**–**h**) Dynamical smoothed mean (standard error) plots of PIP, PEEP, eV_T and leak for groups MS, BS, ML and BL.

3.3. Dynamical Correlation between Ventilatory Parameters

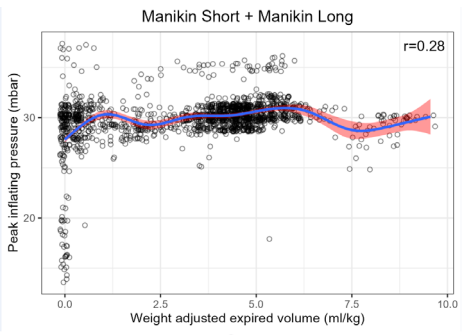
For all four groups, dynamical correlation between PIP and eV_T, PIP and leak, and leak and eV_T are shown in Table 2. Pearson's correlation coefficient, r, is given under the corresponding dynamical correlation coefficient, ρ.

Table 2. Dynamical correlation and Pearson correlation coefficients for pairwise relationships of PIP-eV_T-leak for the four groups.

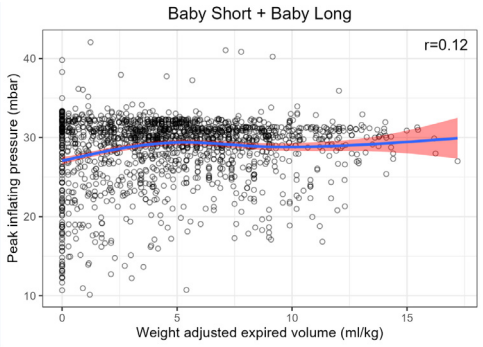
Correlation	Coefficients	Manikin Short	Baby Short	Manikin Long	Baby Long
PIP- eV_T	Dynamic ρ (95% CI); *p*-value	−0.22 (−0.55;0.34); 0.530	0.27 (−0.31;0.39); 0.866	−0.27 (−0.42;0.16); 0.334	0.14 (−0.16;0.66); 0.262
	Pearson's r	0.47	0.14	0.14	0.12
PIP-Leak	Dynamic ρ (95% CI); *p*-value	−0.23 (−0.61;0.12); 0.176	−0.22 (−0.47;0.27); 0.702	−0.15 (−0.56;0.18); 0.296	−0.42 (−0.74;0.02); 0.054
	Pearson's r	−0.51	−0.23	−0.19	−0.49
Leak-eV_T	Dynamic ρ (95% CI); *p*-value	−0.51 (−0.80;−0.09); 0.020 *	−0.65 (−0.61;0.09); 0.150	−0.47 (−0.61;−0.07); 0.016 *	−0.41 (−0.7;−0.02); 0.032 *
	Pearson's r	−0.84	−0.58	−0.74	−0.48

* = significantly different from zero at the 0.05 level.

To give a visual impression of these correlations, scatter plots are shown in Figure 4. Within the manikin and baby groups, each correlation was either positive or negative. Therefore, to simplify the figure, data for combined groups are shown, i.e., MS + ML and BS + BL.



(**a**)



(**b**)

Figure 4. *Cont.*

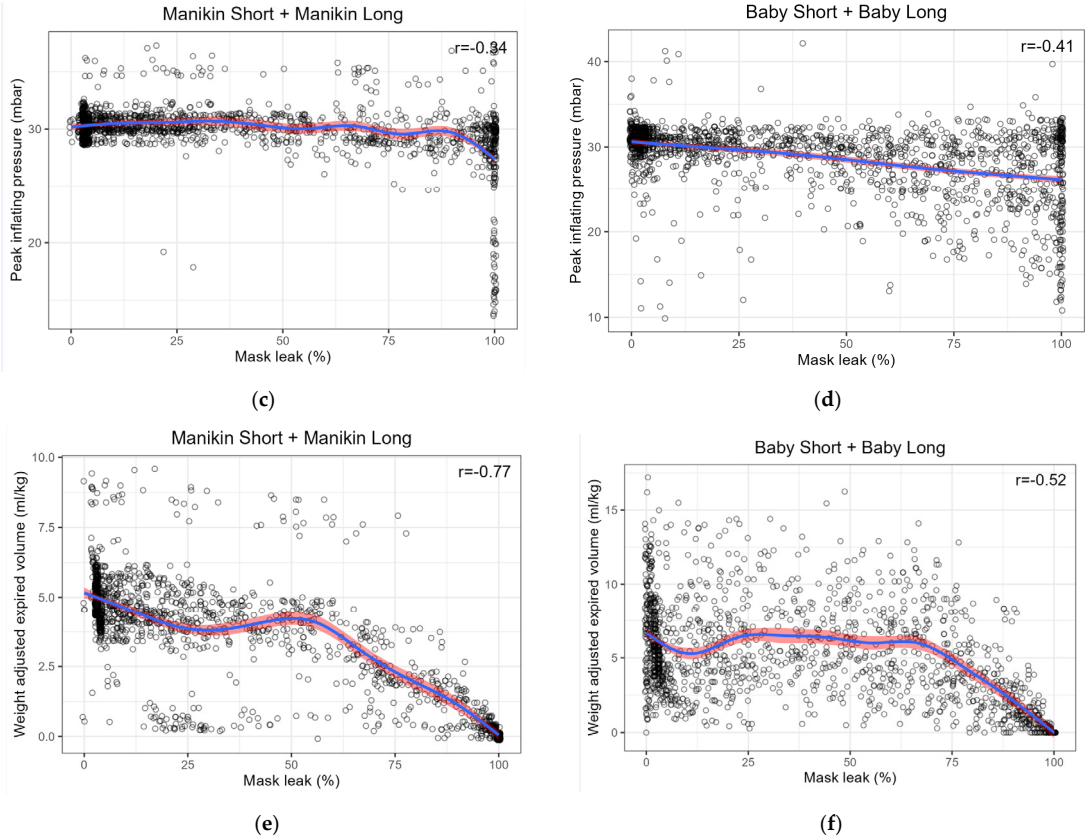


Figure 4. Scatter plots of correlation between (**a**) Peak inflating pressure (PIP) and expired tidal volume (eV_T) for combined Manikin Short + Manikin Long (MS + ML); (**b**) PIP and eV_T for combined Baby Short + Baby Long (BS + BL); (**c**) PIP and leak for combined MS + ML; (**d**) PIP and leak for combined BS + BL; (**e**) leak and eV_T for combined MS + ML; (**f**) leak and eV_T for combined BS + BL. Note that Pearson's r given in the figures differs from those quoted in Table 2 as a result of the combination of manikin and baby groups.

3.4. Obstruction

There was no difference in the occurrence of upper airway obstruction between manikin and babies, with four and seven ventilation sequences, respectively, in which obstruction occurred, $p = 0.33$.

4. Discussion

This study compared ventilation of a high-fidelity term neonatal simulator with ventilation of term newborns, matched by a proxy for clinical condition. We aimed to assess the degree to which NeoNatalie Live provides a realistic representation of the experience of ventilating a non-breathing newborn. Our findings of comparable values of four ventilatory parameters, similar inter-relationships between these parameters, and the occurrence of upper airway obstruction to the same degree in manikin and newborn ventilation support the fidelity of the simulated experience of neonatal PPV.

4.1. Ventilatory Parameters

Similar median PIP, corresponding to the set value, was generated in all four groups, consistent with previous clinical [10,20] and simulation studies [25,26]. The higher smoothed-

mean in ML compared to BL, reflected in the significant p value of the boxplots, was expected, as PIP was sometimes intentionally increased from 30 to 35 cmH_2O in this group to overcome low lung compliance and achieve visual chest rise. The greater variability of delivered PIP in the baby groups, seen in Figure 3a,e, may result from variation in the clinical condition not being replicated in the simulated setting- for example spontaneous movement of the baby, neonatal respiratory efforts [27,28], or continued stimulation.

Wide variation in PEEP was seen in all groups, and delivered PEEP was lower in the manikin groups. This is consistent with previous clinical [10,20] and simulation data [25].

Using eV_T corrected for birth weight for manikin data is unusual and, to our knowledge, has not been described previously. This approach was essential in this study in order to compare simulated and clinical data. The actual weight of the manikin used is 1.54 kg, however, the manikin's size (length and head circumference) simulates a newborn of around 3 kg birth weight. Therefore, we chose to use the median weight (3.14 kg) of newborns in the study supplying heartrate data [17]. Manikin studies quoting actual eV_T [5,11] are difficult to compare to clinical studies quoting eV_T/kg. We found comparable manikin and neonatal eV_Ts/kg, below and at the lower end of recommended ranges [29] and in line with other reports of neonatal PPV with NeoPuff at standard settings [3,10]. This is a novel and important finding, particularly in light of concerns regarding the unphysiological compliance curves of typical neonatal manikins [14].

We found that higher median volumes were achieved in both manikin and babies when longer ventilation is required. A recent study described a progressive increase in eV_T over the first 20 ventilations in term neonates requiring PPV at birth [30]. The authors relate this to the establishment of FRC. Our clinical data may support this. Interestingly, a sharp increase in mean eV_T is seen in the dynamic MS plot (Figure 3g, short sequence) and is due to the initially flat and empty manikin lung being filled with air during the first few ventilations before reaching the "air in = air out" stage.

Mask-leak was similar in the short ventilation groups. However, our study confirms previously published data showing both large and highly variable mask leaks during both manikin and neonatal PPV [2,7]. Even experienced HCPs are reported to have large, and often unappreciated, leaks during PPV [12,31,32]. There is, however, a trend towards lower leak in both manikin and baby groups in long sequences versus short. This might imply more successful leak-reducing manipulations given more time to make adjustments.

4.2. Correlations between Ventilatory Parameters

Significant dynamical correlations were found between leak and eV_T for MS, ML and BL groups. For the other relationships (i.e., PIP and eVT, PIP and leak), no clear correlation was found. This is in contrast to published data where linear or the Pearson correlation are typically used, and thus comparisons with our dynamical data, which compare slopes of the trend lines, are difficult to interpret. A weak, but unquantified, relationship between PIP and eV_T has been reported in preterm neonates [2] and a term manikin [31]. A simulation study using a different manikin and a lower set PIP found a strong correlation between PIP and eV_T and a moderate negative correlation between PIP and leak [11]. The Pearson's r for our scatter plots in Figure 4 shows a weak to moderate correlation for PIP/eV_T and moderate correlation for PIP/leak. The scatter plots highlight the similar relationships in both manikin and neonatal ventilation, again with a distinct greater variability in the clinical compared to simulation data.

The lack of correlation between PIP and either eV_T or leak using a more robust, non-parametric method is perhaps predictable. eV_T varies widely in studies using set PIPs [2,10,32]. Similarly, it has been demonstrated that at high gas flows, a set PIP is consistently achieved, independent of mask-leak, unless the latter is very large [13,31]. We did find a strong, significant correlation between eV_T and leak:- eV_T increases as leak decreases. This is inevitable, given that leak is calculated as the fraction of the difference between inspired and expired V_T and inspired V_T. However, we believe that this does not

detract from the probability of a real effect. The consistency of this relationship has been demonstrated in other studies [3,13,30,33].

4.3. Obstruction

Defining upper airway obstruction as occurring in ventilations with minimal flow/V_T despite adequate PIP likely represents inadequate head positioning to open the airway [2,3]. Our finding of no difference in the occurrence of obstruction in the manikin or babies when experienced paediatricians provide PPV suggests that airway patency is being maintained in similar ways in both groups, with potential for skills learned on the manikin to translate to the clinical scenario.

4.4. Limitations in the Fidelity of Simulated Neonatal Ventilation

Despite the similarities, this study highlights two main limitations of NeoNatalie Live. First, the transition between "non-breathing" and "breathing adequately" is very abrupt for the manikin compared to a more gradual change in the babies. This is represented visually in the MS and BS dynamical smoothed-mean PIP and PEEP plots (Figure 3e,f), where both pressures are maintained to the last ventilation for the manikin, whereas for the babies, these values fall. We believe this is due to ventilations with a less tightly applied face mask when evaluating the adequacy of spontaneous efforts in the babies. This pressure fall is mirrored by a simultaneous, considerable increase in leak (Figure 3h).

Secondly, the most difficult scenario 4 in NeoNatalie Live likely combines a low lung compliance derived from severely asphyxiated neonates, with a too rapid increase in heartrate and too short ventilation than that which would be needed to achieve adequate spontaneous ventilation in real life. Additionally, the low manikin compliance is achieved by a closed valve, resulting initially in little or no V_T along with no visible chest rise. The valve opens relatively abruptly once sufficient adequate ventilations have been given. The very rapid rise in manikin eV_T seen on the trend plot, Figure 3g, for long sequences is clearly different to the neonates in our study, despite the ventilation sequences being paired by duration, and thus, indirectly, by heartrate evolution. Although manikin scenario 4 permits crucial skill training for low-compliant lungs [34,35], there is a disconnect (in heartrate response, ventilation duration and abrupt change in chest rise) with the typical clinical scenario in which these conditions of low lung compliance would likely be encountered.

4.5. Strengths and Limitations of the Study

The strengths of this study include the unique design, addressing an issue commonly cited as a limitation to the interpretation of manikin studies [5,6,8,13,33]. The use of experienced paediatricians to ventilate the manikin, and who are also responsible for most real-life PPV, reduces variation which might affect differences between simulated and clinical PPV.

Weaknesses of our study design include the single site setting, limiting generalisability to other institutions. In particular, our use of a flow-driven T-piece resuscitator, rather than a self-expanding bag most commonly employed on a global basis, limits generalisability to other settings.

4.6. Future Studies

Future research should focus on addressing the limitations of our study, involving other healthcare settings and looking at simulator fidelity when using a self-inflating bag for PPV. Follow-up studies investigating the training effect of NeoNatalie Live for personnel in different professions, and focusing on training load, have been undertaken and will be reported.

5. Conclusions

We compared T-piece PPV of term neonates and a novel, term manikin, paired by a proxy for clinical condition. Our findings of the generation of comparable ventilatory pa-

rameters PIP, PEEP, eV_T and leak, a consistent inter-relationship between these parameters, and a similar occurrence of upper airway obstruction support the functional fidelity of the simulator. We believe this allows confidence in the ability of NeoNatalie training to foster and maintain PPV skills that can translate into competence in the clinical setting.

Author Contributions: Conceptualization, J.H., S.R. and H.E.; methodology, J.H., S.R. and H.E.; software, P.B., Ø.G. and A.U.; validation, J.H., P.B., Ø.G. and A.U.; formal analysis, J.H. and A.U.; investigation, J.H.; resources, Ø.G.; data curation, J.H., P.B. and A.U.; writing—original draft preparation, J.H.; writing—review and editing, J.H., P.B., Ø.G., A.U., S.R., J.P. and H.E.; visualization, J.H., S.R. and H.E.; supervision, S.R., J.P. and H.E.; project administration, J.H., S.R. and H.E.; funding acquisition, H.E. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and was approved by the Regional Committee for Medical and Healthcare Research Ethics, Region West (REK), reference numbers 2018/330/REK (approved date is 23 March 2018) vest and 2018/338/REK vest (approved date is 27 April 2018).

Informed Consent Statement: Informed written consent was obtained from all parents of neonates whose ventilation data was studied. Informed written consent was obtained from healthcare personnel participating in this study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy statements made in informed consent obtained from both participating healthcare personnel and parents of studied neonates.

Conflicts of Interest: Joanna Haynes and Peder Bjorland have received unconditional PhD scholarships from Laerdal Foundation, Stavanger, Norway. Siren Rettedal has received an unconditional Post Doc grant from Laerdal Foundation. Laerdal Medical and Laerdal Global Health provided simulation and monitoring equipment used in this study. Laerdal Foundation, Laerdal Medical and Laerdal Global Health played no part in the design or performance of the study, nor in the analysis or interpretation of results. Øystein Gomo is a senior research and development scientist employed by Laerdal Medical and provided technical assistance in the collection of simulation data.

References

1. Mduma, E.; Ersdal, H.; Svensen, E.; Kidanto, H.; Auestad, B.; Perlman, J. Frequent brief on-site simulation training and reduction in 24-h neonatal mortality—An educational intervention study. *Resuscitation* **2015**, *93*, 20–26. [CrossRef] [PubMed]
2. Schmölzer, G.M.; Kamlin, O.C.O.F.; O'Donnell, C.; Dawson, J.; Morley, C.; Davis, P.G. Assessment of tidal volume and gas leak during mask ventilation of preterm infants in the delivery room. *Arch. Dis. Child. Fetal Neonatal Ed.* **2010**, *95*, F393–F397. [CrossRef] [PubMed]
3. Schmölzer, G.M.; Dawson, J.; Kamlin, C.O.F.; O'Donnell, C.; Morley, C.; Davis, P.G. Airway obstruction and gas leak during mask ventilation of preterm infants in the delivery room. *Arch. Dis. Child. Fetal Neonatal Ed.* **2010**, *96*, F254–F257. [CrossRef]
4. Schmölzer, G.M.; Roehr, C.C. Use of Respiratory Function Monitors during Simulated Neonatal Resuscitation. *Klinische Pädiatrie* **2011**, *223*, 261–266. [CrossRef] [PubMed]
5. O'Currain, E.; Thio, M.; Dawson, J.A.; Donath, S.M.; Davis, P.G. Respiratory monitors to teach newborn facemask ventilation: A randomised trial. *Arch. Dis. Child. Fetal Neonatal Ed.* **2019**, *104*, F582–F586. [CrossRef]
6. Schilleman, K.; Witlox, R.; Lopriore, E.; Morley, C.; Walther, F.; te Pas, A. Leak and obstruction with mask ventilation during simulated neonatal resuscitation. *Arch. Dis. Child. Fetal Neonatal Ed.* **2010**, *95*, F398–F402. [CrossRef] [PubMed]
7. Wood, F.E.; Morley, C.; Dawson, J.; Kamlin, C.O.F.; Owen, L.S.; Donath, S.; Davis, P.G. Assessing the effectiveness of two round neonatal resuscitation masks: Study 1. *Arch. Dis. Child. Fetal Neonatal Ed.* **2008**, *93*, F235–F237. [CrossRef] [PubMed]
8. Wood, F.E.; Morley, C.; Dawson, J.; Kamlin, C.O.F.; Owen, L.S.; Donath, S.; Davis, P.G. Improved techniques reduce face mask leak during simulated neonatal resuscitation: Study 2. *Arch. Dis. Child. Fetal Neonatal Ed.* **2008**, *93*, F230–F234. [CrossRef]
9. O'Donnell, C.; Kamlin, C.O.F.; Davis, P.G.; Morley, C. Neonatal resuscitation 1: A model to measure inspired and expired tidal volumes and assess leakage at the face mask. *Arch. Dis. Child. Fetal Neonatal Ed.* **2005**, *90*, F388–F391. [CrossRef]

10. Schmölzer, G.M.; Morley, C.; Wong, C.; Dawson, J.; Kamlin, C.O.F.; Donath, S.; Hooper, S.B.; Davis, P.G. Respiratory Function Monitor Guidance of Mask Ventilation in the Delivery Room: A Feasibility Study. *J. Pediatr.* **2012**, *160*, 377–381.e2. [CrossRef]
11. Tracy, M.; Klimek, J.; Shingde, V.; Hinder, M.; Maheshwari, R.; Tracy, S. Neopuff T-piece mask resuscitator: Is mask leak related to watching the pressure dial? *Acta Paediatr.* **2010**, *99*, 1314–1318. [CrossRef] [PubMed]
12. Wilson, E.V.; O'Shea, J.E.; Thio, M.; Dawson, J.; Boland, R.A.; Davis, P.G. A comparison of different mask holds for positive pressure ventilation in a neonatal manikin. *Arch. Dis. Child. Fetal Neonatal Ed.* **2013**, *99*, F169–F171. [CrossRef] [PubMed]
13. te Pas, A.; Schilleman, K.; Klein, M.; Witlox, R.S.; Morley, C.J.; Walther, F. Low versus High Gas Flow Rate for Respiratory Support of Infants at Birth: A Manikin Study. *Neonatology* **2011**, *99*, 266–271. [CrossRef] [PubMed]
14. Pearlman, S.A.; Zern, S.C.; Blackson, T.; Ciarlo, J.A.; Mackley, A.B.; Locke, R.G. Use of neonatal simulation models to assess competency in bag-mask ventilation. *J. Perinatol.* **2015**, *36*, 242–246. [CrossRef]
15. Sawyer, T.; Strandjord, T.P.; Johnson, K.; Löw, D. Neonatal airway simulators, how good are they? A comparative study of physical and functional fidelity. *J. Perinatol.* **2015**, *36*, 151–156. [CrossRef]
16. Bjorland, P.A.; Øymar, K.; Ersdal, H.L.; Rettedal, S.I. Incidence of newborn resuscitative interventions at birth and short-term outcomes: A regional population-based study. *BMJ Paediatr. Open* **2019**, *3*, e000592. [CrossRef]
17. Eilevstjønn, J.; Linde, J.E.; Blacy, L.; Kidanto, H.; Ersdal, H.L. Distribution of heart rate and responses to resuscitation among 1237 apnoeic newborns at birth. *Resuscitation* **2020**, *152*, 69–76. [CrossRef]
18. Linde, J.E.; Eilevstjønn, J.; Øymar, K.; Ersdal, H.L. Feasibility of a prototype newborn resuscitation monitor to study transition at birth, measuring heart rate and ventilator parameters, an animal experimental study. *BMC Res Notes* **2017**, *10*, 235. [CrossRef]
19. Bjorland, P.A.; Ersdal, H.L.; Eilevstjønn, J.; Øymar, K.; Davis, P.G.; Rettedal, S.I. Changes in heart rate from 5 s to 5 min after birth in vaginally delivered term newborns with delayed cord clamping. *Arch. Dis. Child. Fetal Neonatal Ed.* **2021**, *106*, 311–315. [CrossRef]
20. Kaufman, J.; Schmölzer, G.; Kamlin, C.O.F.; Davis, P.G. Mask ventilation of preterm infants in the delivery room. *Arch. Dis. Child. Fetal Neonatal Ed.* **2013**, *98*, F405–F410. [CrossRef]
21. Maddala, G.S.; Wu, S. A Comparative Study of Unit Root Tests with Panel Data and a New Simple Test. *Oxf. Bull. Econ. Stat.* **1999**, *61*, 631–652. [CrossRef]
22. Newey, W.K.; West, K.D. A Simple, Positive Semi-Definite, Heteroskedasticity and Autocorrelation Consistent Covariance Matrix. *Econometrica* **1987**, *55*, 703. [CrossRef]
23. Dubin, J.A.; Müller, H.-G. Dynamical Correlation for Multivariate Longitudinal Data. *J. Am. Stat. Assoc.* **2005**, *100*, 872–881. [CrossRef]
24. Bakdash, J.Z.; Marusich, L. Repeated Measures Correlation. *Front. Psychol.* **2017**, *8*, 456. [CrossRef]
25. Tracy, M.; Klimek, J.; Coughtrey, H.; Shingde, V.; Ponnampalam, G.; Hinder, M.; Maheshwari, R.; Tracy, S.K. Mask leak in one-person mask ventilation compared to two-person in newborn infant manikin study. *Arch. Dis. Child. Fetal Neonatal Ed.* **2010**, *96*, F195–F200. [CrossRef] [PubMed]
26. Tracy, M.; Maheshwari, R.; Shah, D.; Hinder, M. Can Ambu self-inflating bag and Neopuff infant resuscitator provide adequate and safe manual inflations for infants up to 10 kg weight? *Arch. Dis. Child. Fetal Neonatal Ed.* **2017**, *102*, F333–F338. [CrossRef]
27. Boon, A.; Milner, A.; Hopkin, I. Lung expansion, tidal exchange, and formation of the functional residual capacity during resuscitation of asphyxiated neonates. *J. Pediatr.* **1979**, *95*, 1031–1036. [CrossRef]
28. Murthy, V.; Dattani, N.; Peacock, J.L.; Fox, G.F.; Campbell, M.E.; Milner, A.D.; Greenough, A. The first five inflations during resuscitation of prematurely born infants. *Arch. Dis. Child. Fetal Neonatal Ed.* **2011**, *97*, F249–F253. [CrossRef]
29. Madar, J.; Roehr, C.C.; Ainsworth, S.; Ersdal, H.; Morley, C.; Rüdiger, M.; Skåre, C.; Szczapa, T.; te Pas, A.; Trevisanuto, D.; et al. European Resuscitation Council Guidelines 2021: Newborn resuscitation and support of transition of infants at birth. *Resuscitation* **2021**, *161*, 291–326. [CrossRef] [PubMed]
30. Ersdal, H.; Eilevstjonn, J.; Perlman, J.; Gomo, Ø.; Moshiro, R.; Mdoe, P.; Kidanto, H.; Hooper, S.; Linde, J. Establishment of functional residual capacity at birth: Observational study of 821 neonatal resuscitations. *Resuscitation* **2020**, *153*, 71–78. [CrossRef] [PubMed]
31. O'Donnell, C.P.F.; Davis, P.G.; Lau, R.; Dargaville, P.; Doyle, L.; Morley, C. Neonatal resuscitation 2: An evaluation of manual ventilation devices and face masks. *Arch. Dis. Child. Fetal Neonatal Ed.* **2005**, *90*, F392–F396. [CrossRef] [PubMed]
32. Schmölzer, G.M.; Kamlin, O.C.O.F.; Dawson, J.; te Pas, A.; Morley, C.; Davis, P.G. Respiratory monitoring of neonatal resuscitation. *Arch. Dis. Child. Fetal Neonatal Ed.* **2009**, *95*, F295–F303. [CrossRef] [PubMed]
33. Schilleman, K.; Schmölzer, G.M.; Kamlin, O.C.; Morley, C.J.; te Pas, A.; Davis, P.G. Changing gas flow during neonatal resuscitation: A manikin study. *Resuscitation* **2011**, *82*, 920–924. [CrossRef] [PubMed]
34. McGaghie, W.C.; Issenberg, S.B.; Cohen, E.R.; Barsuk, J.; Wayne, D.B. Does Simulation-Based Medical Education With Deliberate Practice Yield Better Results Than Traditional Clinical Education? A Meta-Analytic Comparative Review of the Evidence. *Acad. Med.* **2011**, *86*, 706–711. [CrossRef] [PubMed]
35. Sawyer, T.; Sierocka-Castaneda, A.; Chan, D.; Berg, B.; Lustik, M.; Thompson, M. Deliberate Practice Using Simulation Improves Neonatal Resuscitation Performance. *Simul. Health J. Soc. Simul. Health* **2011**, *6*, 327–336. [CrossRef]

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A Randomised Controlled Study of Low-Dose High-Frequency In-Situ Simulation Training to Improve Newborn Resuscitation

Joanna Haynes [1,2,*], Siren Rettedal [2,3], Jeffrey Perlman [4] and Hege Ersdal [1,2]

[1] Department of Anaesthesia, Stavanger University Hospital, 4011 Stavanger, Norway; hege.ersdal@safer.net
[2] Faculty of Health Sciences, University of Stavanger, 4021 Stavanger, Norway; siren.irene.rettedal@sus.no
[3] Department of Paediatrics, Stavanger University Hospital, 4011 Stavanger, Norway
[4] Department of Pediatrics, Weill Cornell Medicine, New York, NY 10065, USA; jmp2007@med.cornell.edu
* Correspondence: joanna.claire.haynes@sus.no

Abstract: Positive pressure ventilation of the non-breathing newborn is a critical and time-sensitive intervention, considered to be the cornerstone of resuscitation. Many healthcare providers working in delivery units in high-resource settings have little opportunity to practise this skill in real life, affecting their performance when called upon to resuscitate a newborn. Low-dose, high-frequency simulation training has shown promise in low-resource settings, improving ventilation performance and changing practice in the clinical situation. We performed a randomised controlled study of low-dose, high-frequency simulation training for maintenance of ventilation competence in a multidisciplinary staff in a busy teaching hospital in Norway. We hypothesised that participants training according to a low-dose, high-frequency protocol would perform better than those training as they wished. Our results did not support this, although the majority of protocol participants were unable to achieve training targets. Subgroup analysis comparing no training to at least monthly training did identify a clear benefit to regular simulation practice. Simulated ventilation competence improved significantly for all participants over the course of the study. We conclude that frequent, short, simulation-based training can foster and maintain newborn ventilation skills in a multidisciplinary delivery unit staff in a high-resource setting.

Keywords: in-situ simulation training; low-dose; high-frequency training; booster training; neonatal resuscitation; positive pressure ventilation; skill mastery; neonatal mortality

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1. Introduction

The need for neonatal resuscitation is ubiquitous and often unpredictable. Positive pressure ventilation (PPV) of the non-breathing newborn is the cornerstone of resuscitation. Studies in both high- and low-resource settings suggest that PPV skills are often suboptimal [1,2]. Simulation training is widely used to prepare healthcare personnel (HCP) to manage this stressful and time-critical event, and is now an integral part of formal neonatal resuscitation programmes [3,4]. Infrequent training (once a year or less) results in deterioration of knowledge and resuscitation skills in particular [5,6]. Simulation-based booster training may maintain skills acquired in formal training programmes [7]. However, optimal training strategies remain unclear, and studies elucidating this issue are urgently required [8].

Low-dose, high-frequency simulation training (LDHFST) training shows promise in promoting retention of acquired skills [9,10]. Studies from low-resource countries have identified LDHFST as an effective means of not only increasing competence in the simulated situation, but also improving skills and changing practice in the clinical situation [11,12].

The extent to which these findings are transferable to a high-resource situation is less well studied, and it may be that training needs of HCPs in this setting differ from those in studies undertaken in low-resource settings. Using a novel neonatal manikin, we randomised HCPs from six different professions allied to the delivery unit in a busy

teaching hospital in Norway to train according to a LDHFST protocol or to train as they wished over a nine-month period following an initial educational session.

2. Materials and Methods

2.1. Study Setting

This study was conducted at Stavanger University Hospital (SUS), Norway. It is the only hospital in the region with both delivery and newborn services, managing approximately 4500 births per annum and providing care for newborns ≥23 weeks' gestational age (GA). Resuscitation of babies at birth occurs at three sites: the newborn resuscitation room on labour ward, the cesarean section operating theatre and the midwife-run delivery unit. Most HCPs allied to the delivery unit undergo yearly off-site neonatal resuscitation training according to the national guidelines. Additionally, a fortnightly in-situ multidisciplinary team training session is offered to HCPs working on the delivery unit on the day.

Rate of PPV provision at birth is 3.6%, and most neonates are resuscitated by a paediatrician called to attend the delivery [13]. In some unforeseen resuscitations, PPV is initiated by midwifery or anaesthetic staff. Most PPV is provided using a flow-driven T-piece resuscitator (NeoPuff™, Fischer and Paykel, Auckland, New Zealand).

An ongoing research collaboration, Safer Births Bundle SUS, aims to contribute new knowledge on newborn transition and improve the care of newborns on the day of birth. Initiatives include rapid monitoring of newborns' heart rate using NeoBeat™ (Laerdal Medical, Stavanger, Norway) [14], recording all PPV provided at birth using Laerdal Resuscitation Monitor (Laerdal Medical, Stavanger, Norway) [15], and multidisciplinary ventilation training with a novel neonatal simulator, NeoNatalie Live™ (Laerdal Medical, Stavanger, Norway) [16].

2.2. The Neonatal Simulator

NeoNatalie Live is a low-cost newborn simulator, produced with the specific aim of training competence in PPV. Changing simulated lung compliance and variable heart rate linked to ventilation performance allow HCPs to practise management of newborns with differing degrees of birth asphyxia. Real resuscitation data derived from 1237 newborns informs the algorithm guiding the realistic heart rate response according to PPV provided [17]. An active electrocardiogram allows monitoring of heart rate using the dry-electrode technology NeoBeat, replicating practice in the clinical situation. A sensor measures air pressure in the upper airway. Head-tilt detection identifies upper airway closure due to poor positioning. A cry-sound indicates spontaneous respiration and successful resuscitation. Communication with a training application (NeoNatalie Live, Laerdal Global Health, Stavanger, Norway) allows HCPs to review their performance and the App gives targeted feedback to improve skills in any of four scenarios of increasing difficulty. Bluetooth® technology allows collection of training data in a web-log.

2.3. The Study

A prospective, randomised controlled study of the effects of LDHFST on competence in neonatal PPV was performed between April 2019 and April 2021. Approximately 300 HCPs may potentially be involved in neonatal resuscitation. All those working in >50% employment were eligible to participate and invited to give informed, written consent. On enrolment, baseline knowledge and simulated performance of resuscitation (test 1 = T1) were documented using NeoNatalie Live scenario 1 (S1; apnoea, normal lung compliance and compensated heart rate) and scenario 4 (S4; apnoea with low initial lung compliance and decompensated heart rate). Participants were invited to attend a 120- to 180-min personalised education session, including PPV training according to Norwegian neonatal resuscitation guidelines and instruction in the use of the simulator [18]. Sessions were concluded when each individual participant had demonstrated providing effective PPV and felt confident in their ability to train independently with NeoNatalie Live. On completing the educational session, a second documentation of performance (test 2 = T2)

was undertaken, repeating S1 and S4. Participants were then immediately randomised into one of two groups, (1) train twice a month or (2) train as often as desired, over a nine-month period. Randomisation was performed using a binary randomisation application, RandomOrg (RANDOM.ORG, Dublin, Ireland), and was undertaken concurrently for all HCPs attending the educational session. These participants then trained on their own using any of three NeoNatalie Live simulators, placed in-situ where resuscitation takes place, receiving immediate performance feedback via the application. Each training session was logged, including timelines and objective ventilation data. Knowledge and simulated performance were tested again after nine months (test 3 = T3) using S1 and S4.

2.4. Data Collection

Study participants were observed performing S1 and S4 at each of the three test time-points by the same investigator (JH), and scored according to a protocol developed and evaluated in a pilot study. Demonstration of knowledge (by performance) of the initial steps of resuscitation [18] (with potentially 10 points gained) and ventilation skills assessed objectively by the simulator (potentially gaining a further 30 points) gave a maximum of 40 points for each simulation. Skill points were allocated according to achieving adequate face mask seal, generating sufficient but not excessive inflation pressures, appropriate ventilation rate, % valid ventilations, % ventilation fraction, achieving visible chest rise and time to successfully complete the scenario (with better performance resulting in a shorter time to baby-cry).

2.5. Data Analysis

Data analysis was undertaken using SPSS (IBM SPSS Statistics for Windows, Version 26.0. Armonk, NY, USA: IBM Corp).

Test scores are summarised for all participants or for subgroups of participants as mean (standard deviation = sd). T3 scores are presented as boxplots. The number of LDHFSTs performed over nine months is presented as a population pyramid. Points lost at T3 are presented as bar charts.

The primary outcome of T3 scores according to randomisation group was analysed using Kruskal-Wallis test, also used for subsequent subgroup analysis according to training frequency.

Secondary outcomes were analysed as follows: comparison of individual test (T1, 2 or 3) scores across professional groups using Kruskal-Wallis tests; all participants' score change pair-wise from T1 to T3 (reflecting the effect of study participation), from T1 to T2, (the effect of the education session), and from T2 to T3, (the effect of training) using Wilcoxon signed-rank test; analysis of differences in scenario S1 and S4 scores at each test-point (1–3) using Wilcoxon signed-rank test; progression of test scores from T1 to T2 and T3 according to professional group using Friedman's Anova.

A p value < 0.05 was considered statistically significant.

3. Results

3.1. Participants and CONSORT Flow Chart

220 HCPs were recruited to the study and performed baseline testing, T1. 191 progressed to the education session, performed post-teaching T2, and were randomised. 187 completed nine months of training and performed post-training T3 with four being lost to follow-up (did not meet to test 3). Figure 1 shows the CONSORT flow chart. Table 1 shows the distribution of participants from the six professional groups.

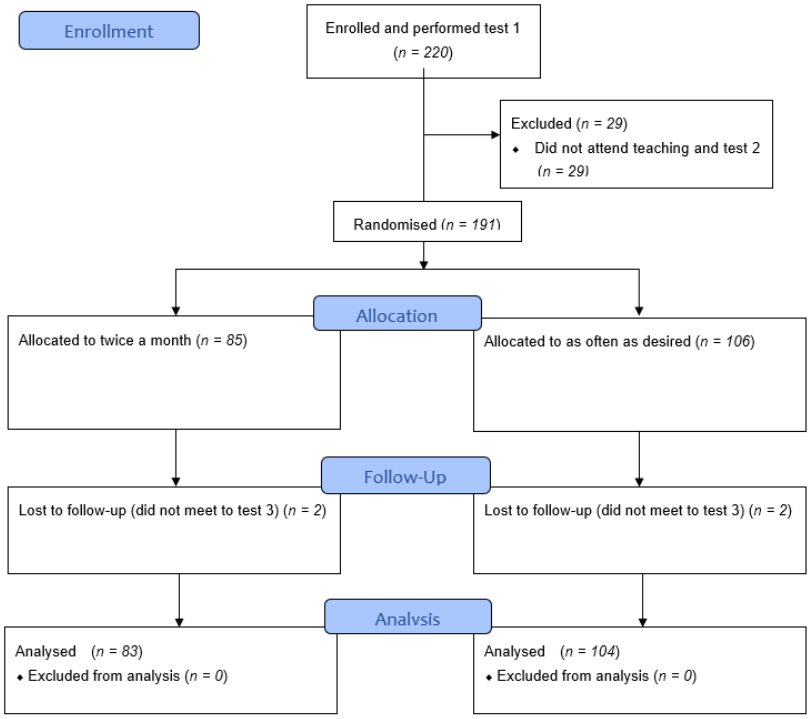


Figure 1. CONSORT flow chart for participants in the randomised controlled study.

Table 1. Participants from six professional groups and their progression through the study.

		Total Recruited and Completed Test 1	Educated and Completed Test 2	Randomised to Twice a Month (of Which x Did not Complete Test 3)	Randomised to as often as Desired (of Which x did not Complete Test 3)	Final Total Completing Study and Analysed after Test 3
Profession	Anaesthesia nurse	54	46	20 (0)	26 (0)	46
	Anaesthetist	38	34	19 (0)	15 (0)	34
	Midwife	72	62	28 (0)	34 (2)	60
	Paediatric nurse assistant	17	17	6 (0)	11 (0)	17
	Paediatrician	18	18	7 (1)	11 (0)	17
	Obstetrician	21	14	5 (1)	9 (0)	13
Total		220	191	85 (2)	106 (2)	187

3.2. Primary Outcome: Effect of Randomisation Group on Test 3 Scores

Those randomised to train twice a month performed a mean (sd) of 8 (5.2) trainings in nine months while those in the as often as desired (self-guided) trained 2.8 (3.8) times in nine months. Figure 2 shows a population pyramid of training frequencies in the two randomisation groups.

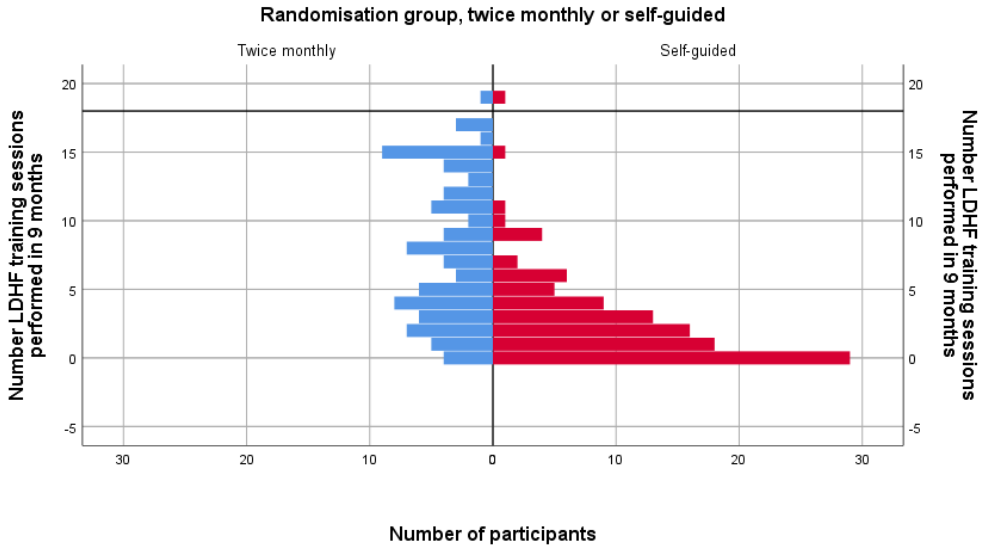
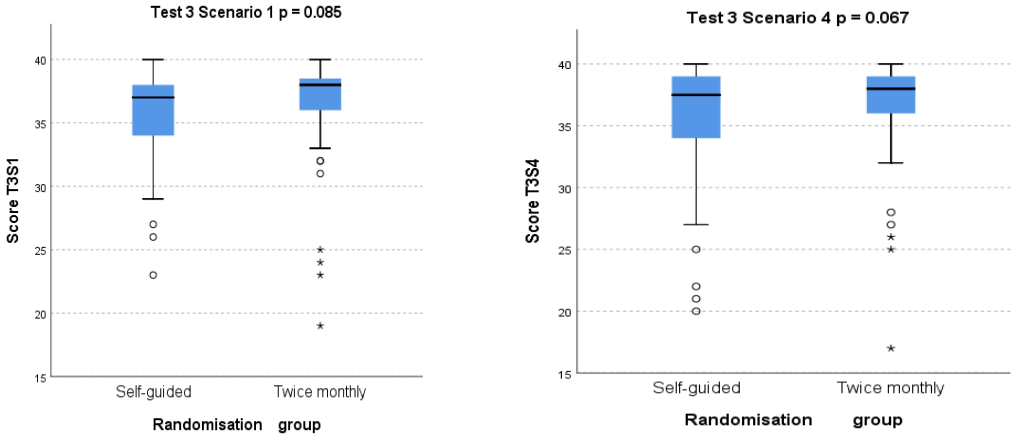


Figure 2. Population pyramid of training frequencies in the two randomisation groups. The black horizontal line indicates 18 trainings (=twice a month). LDHF = low-dose, high-frequency.

T3 scores were not higher in those allocated to train twice a month compared to those training as often as desired, for either S1 ($p = 0.085$) or S4 ($p = 0.067$). Figure 3 show boxplots of T3 scores for both scenarios by training group.



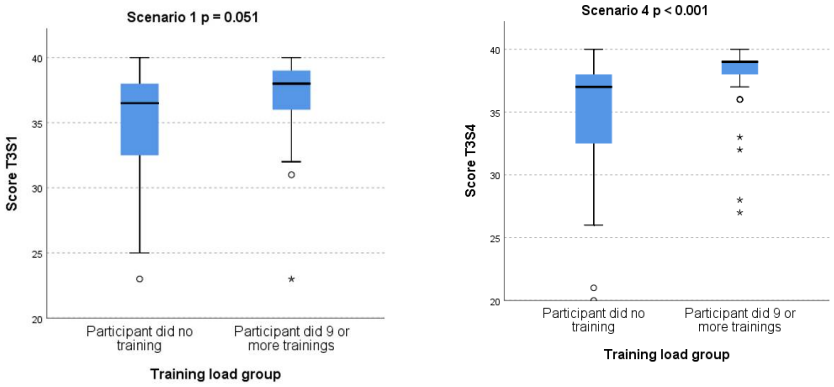
(**a**) (**b**)

Figure 3. Box plots of test T3 scores for scenario S1 (**a**) and scenario S4 (**b**) according to randomisation group.

3.3. Subgroup Analysis of Test 3 Scores by Training Load

Subgroup analysis comparing T3 scores for participants performing no training sessions ($n = 32$) and those who performed nine or more trainings ($n = 43$) showed borderline higher S1 score ($p = 0.051$), and significantly higher S4 score, ($p < 0.001$) for those training

nine or more times in nine months. Figure 4 shows boxplots of T3 scores for both scenarios by training-load group.



(**a**) (**b**)

Figure 4. Box plots of test T3 scores for scenario S1 (**a**) and scenario S4 (**b**) according to training-load group.

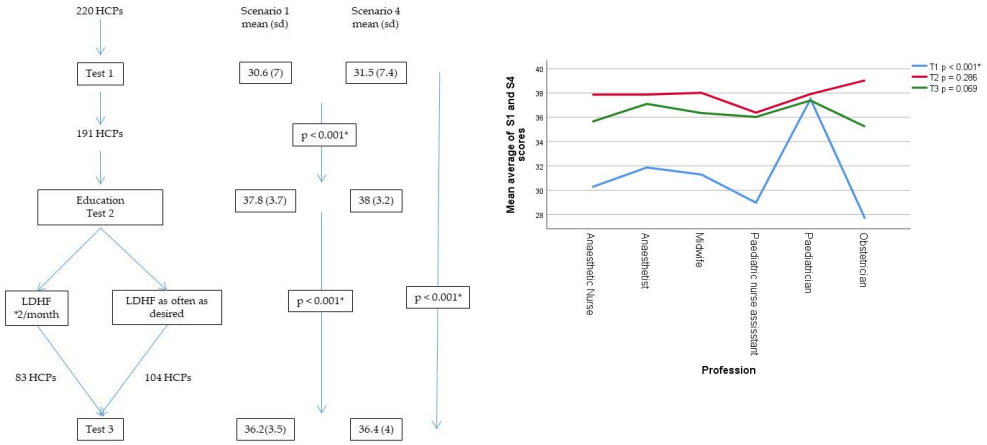
3.4. Secondary Outcomes: Effect of Study Participation on Test Scores and Comparison across Professional Groups

Comparing the average score of both scenarios for all participants, there was an increase in scores from T1 baseline to T2 post-teaching, $p < 0.001$. Following nine months' training, the mean scores at T3 post-training were lower than T2, $p < 0.001$. Study participation improved mean test scores from T1 to T3, $p < 0.001$. Figure 5a shows the flow diagram of participants through the study along with mean (sd) test scores for all participants performing each test. Analysing this same progression of scores from T1 to T2 to T3 according to profession, this pattern remained the same and the changes were significant for all groups ($p < 0.001$) except the paediatricians ($p = 0.819$). Follow-up analysis of separate scenario scores for all participants at the three test-points demonstrates a higher score for S4 compared to S1 at baseline T1, $p = 0.014$. This was not seen at T2 or T3 where scores for both scenarios were similar.

Analysis of the average score of S1 and S4 at each test 1, 2 and 3 by professional group showed a significant difference only for test 1, in which paediatricians scored higher than other groups; T1 $p < 0.001$, T2 $p = 0.286$, T3 $p = 0.069$. Figure 5b shows these results as a line diagram.

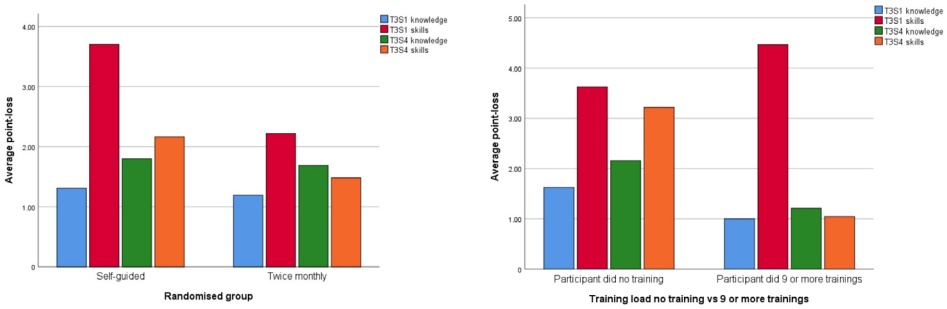
3.5. Knowledge and Skills Points Lost at Test 3 by Randomisation and by Training Load

Figure 6 shows bar charts of points lost for knowledge and skills in both scenarios at T3 (a) for randomisation groups and (b) training-load groups (subgroups ≥ 9 vs. 0 training). For both comparisons (randomisation and training load), there is a reduction in both knowledge- and skill-point loss when more training is compared to less training, with the exception of S1 skill-points in the nine or more training-load group.



(**a**) (**b**)

Figure 5. (**a**) Flow diagram of participants through the study with mean (sd) scores for scenario (S)1 and scenario (S)4 of all participants performing each of the three tests; and (**b**) line graph of the professional-group mean of averaged S1 and S4 scores at each test-point. Blue line connects mean T1 scores of the six professional groups, the red and green lines T2 and T3 scores, respectively. HCP = healthcare personnel; LDHF = low-dose high-frequency; * = significant difference in scores at the 0.05 level.



(**a**) (**b**)

Figure 6. Bar charts of knowledge and skills points lost at test 3 scenarios 1 and 4 (**a**) according to group randomised to and (**b**) according to training-load group. T = test, S = scenario.

4. Discussion

Our randomised controlled study of LDHFST for maintenance of competence in neonatal PPV did not identify improved post-nine months' training T3 scores compared to participants who trained as desired. However, the twice-monthly group did not achieve the 18 trainings specified in the protocol, performing on average less than 50% of this target in nine months. Subgroup analysis comparing T3 scores of those performing no training with those training at least monthly did identify an advantage to frequent, short simulation training. Competence scores improved significantly over the course of the study for all participants, with analysis by profession identifying the paediatricians as the only group not following this pattern. The paediatricians scored highly from baseline T1. Participation in the study resulted in the scores of all other professional groups improving to the level of the paediatricians at T2 and T3. Regular simulation training improved both knowledge and skills scores.

We studied HCPs coming from six different professional groups. Only one group, the paediatricians, have regular hands-on experience of ventilating newborns at birth. It is unsurprising, therefore, that this group scored significantly higher than the other five at baseline testing T1 on study inclusion. An interesting finding was that a clear learning effect existed on first use of NeoNatalie Live. For all participants, scores for the more demanding S4 were higher than those for S1, which was the first to be performed. This might at first glance seem counter-intuitive. We speculate this reflects the culture for using simulation training in teaching neonatal resuscitation at our institution, with previous experience allowing a rapid adjustment to a new simulator on the first encounter.

Simulation training for enhancing neonatal resuscitation skills has been established as an effective teaching modality [19,20]. Studies investigating simulation training as part of a formal neonatal resuscitation programme have identified learning benefits for birth attendants in low-resource settings and for multi-disciplinary participants in high-resource settings [21–23]. Our study findings of improved PPV competence scores at T2 after the educational session echo this. Whilst a limited number of these studies evaluate differences in training benefit between professional groups, our findings highlight the potential for HCPs with little real-life hands-on experience of neonatal PPV to attain knowledge and skills-scores comparable to those with greater experience.

The issue of deterioration of knowledge, and in particular, skills, following formal education programmes is widely acknowledged [6,24,25]. Studies have identified skill deterioration as early as two to three months post-education [26–28]. Additionally, the very heterogeneous literature on the effect of booster training strategies to mitigate this deterioration provides conflicting results. A recent systematic review of spaced learning, including booster training, compared to massed learning in resuscitation supported improved performance with spaced learning, but noted that the evidence base was weak and study heterogeneity prevented any meta-analysis [29]. Guideline-issuing authorities have identified the need for studies increasing the knowledge pool on which strategies are effective as a priority [30].

We chose to evaluate a LDHFST strategy, the pedagogical principles of which are established [31,32]. This approach has been shown to maintain simulated skills, contribute to improved clinical performance and to maintain PPV skills in real life in low-resource settings [12,33,34]. One study identifies reduced neonatal mortality in such a setting [11], while another projects reduced mortality with on-going simulation-based performance improvements [35]. The literature on LDHFST and neonatal resuscitation in high-resource settings is sparse by comparison.

Our study participants were randomised consecutively following completion of the education session and performance of test two. This method resulted in an uneven split of participants between the two randomisation groups, although the split by professional group is quite consistent, with only the anaesthetists having more in the <twice monthly> group. Loss to follow up prior to T3 was evenly split between the two groups.

We found that despite the simulator being readily available in the place of work, and clear instructions regarding a non-prescriptive approach to time spent versus validity of training sessions, almost all those in the twice monthly group were unable to achieve this aim. Reasons for this were identified as a heavy clinical workload and the occurrence of a global pandemic during the study period, resulting in a leadership-led de-prioritisation of simulation training for staff. Additionally, those in the <self-guided> group performed on average approximately a third of the number of training sessions achieved by the <twice a month> group. We speculate that our results indicating lack of benefit of our LDHFST protocol result from the fact that we compared two groups who both did some training, where the break point for optimal training load is, as yet, unclear. Subgroup analysis comparing <some> training with <no> training did demonstrate a benefit. This benefit was highly significant for the more complex and demanding scenario 4 (Figure 4b). Another randomised simulation study conducted in the United States found maintained neonatal ventilation skills in those performing booster training monthly or every three months

compared to none, but with no difference between the two booster training frequencies [36]. It remains to be determined at what training frequency or training load benefit arises

Whilst study participation did improve competence scores between T1 and T3, the greatest benefits were seen after the educational session, as identified by T2 scores (Figure 5a). It is interesting to consider that one educational initiative is able to improve the performance of HCPs with widely differing backgrounds and clinical experience to the same level. We believe this relates to the personalised approach to teaching, given for the most singly or in pairs, and never exceeding five participants, often from the same professional group. This allowed tailoring of education to the specific needs and clinical role of the participant. For the participants as a whole, scores deteriorated between T2 and T3, although the reduction was modest (Figure 5a). Despite this small score reduction between T2 and T3, we believe our results suggest that a regime of frequent, short, feedback-guided simulation sessions maintain competence gained in education, particularly in light of the fact that T3 scores were not different between the professional groups despite wide variation in real-life PPV experience (Figure 5b). We can, however, only comment on this effect up to nine months post education. We consider it probable that instructor-led, formal education sessions will be necessary at certain longer-term intervals to prevent deterioration that might otherwise occur with prolonged self-guided training.

Previous studies have highlighted that skills deteriorate more quickly than knowledge [36]. Comparing loss of knowledge- and skill-points at T3 shown in Figure 6, there was a reduction in point loss (and thus improved scores) for both knowledge and skills with increased training frequency, both when comparing by randomization and by training-load. The scoring system used in this study is heavily weighted towards objective measures of ventilation skill, and knowledge retention in our data is not comparable to the often extensive testing of knowledge performed in studies using assessments based on the Neonatal Resuscitation Program [37]. On the other hand, our highly objective and detailed assessment of ventilation skills may be a more reliable and valid measurement of PPV competence than that obtained from check-list assessments commonly employed [38]. We hypothesise that the rather unexpected finding of greater skills point-loss at T3 S1 for <nine or more trainings> compared to <no training> reflects the detailed nature of our skills evaluation.

The strengths of this study include the randomised controlled design, allowing comparison of differing training frequencies. Our method of assessment provides an objective and detailed evaluation of ventilation competence. We also studied multidisciplinary HCPs, constituting a majority of the target group for improved training strategies. Weaknesses include an uneven randomisation to the two groups, and the failure of most twice-monthly-randomised participants to achieve the protocol training frequency.

Future studies will use the considerable volume of training data (>2600 simulations) to try to answer the question of optimum LDHFST frequencies to maintain PPV competency, including stratification according to profession. We will also evaluate the details of which aspects of the skill of PPV resulted in greatest point-loss in order to promote targeted training strategies.

5. Conclusions

Simulation training with NeoNatalie Live improves PPV competence in multidisciplinary HCPs working in our delivery unit. LDHFST as a booster training strategy after formal instructor-led education successfully prevents skill deterioration. The optimal LDHFST frequency and the optimal interval between formal instructor-led education sessions remain unclear.

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Informed Consent Statement: Informed written consent was obtained from healthcare personnel participating in this study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy statements made in informed consent obtained from participating healthcare personnel.

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References

1. Yamada, N.K.; Yaeger, K.A.; Halamek, L.P. Analysis and classification of errors made by teams during neonatal resuscitation. *Resuscitation* **2015**, *96*, 109–113. [CrossRef]
2. Cavicchiolo, M.E.; Cavallin, F.; Bertuola, F.; Pizzol, D.; Segafredo, G.; Manzungu Wingi, O.; Da Dalt, L.; Putoto, G.; Trevisanuto, D. Effect of a Low-Dose/High-Frequency Training on Real-Life Neonatal Resuscitation in a Low-Resource Setting. *Neonatology* **2018**, *114*, 294–302. [CrossRef]
3. Johnson, L.; Mu, T.; Sawyer, T. Use of medical simulation in neonatal-perinatal fellowship training programs. *J. Neonatal Perinat. Med.* **2012**, *5*, 339–345. [CrossRef]
4. Sawyer, T.; Ades, A.; Ernst, K.; Colby, C. Simulation and the Neonatal Resuscitation Program 7th Edition Curriculum. *NeoReviews* **2016**, *17*, e447. [CrossRef]
5. Levitt, C.; Kaczorowski, J.; Outerbridge, E.; Connolly, B.; Jimenez, V.; Slapcoff, B. Knowledge gained during Neonatal Resuscitation Program courses. *Fam. Med.* **1996**, *28*, 403–406. [PubMed]
6. Kaczorowski, J.; Levitt, C.; Hammond, M.; Outerbridge, E.; Grad, R.; Rothman, A.; Graves, L. Retention of Neonatal Resuscitation Skills and Knowledge: A Randomised Controlled Trial. *Fam. Med.* **1998**, *30*, 705–711.
7. Bender, J.; Kennally, K.; Shields, R.; Overly, F. Does simulation booster impact retention of resuscitation procedural skills and teamwork? *J. Perinatol.* **2014**, *34*, 664–668. [CrossRef]
8. Mileder, L.; Urlesberger, B.; Szyld, E.G.; Roehr, C.C.; Schmölzer, G.M. Simulation-Based Neonatal and Infant Resuscitation Teaching: A Systematic Review of Randomised Controlled Trials. *Klin. Padiatr.* **2014**, *226*, 259–267. [CrossRef] [PubMed]
9. Gurung, R.; Gurung, A.; Sunny, A.K.; Basnet, O.; Shrestha, S.K.; Gomo, Ø.H.; Myklebust, H.; Girnary, S.; Ashish, K.C. Effect of skill drills on neonatal ventilation performance in a simulated setting—Observation study in Nepal. *BMC Pediatrics* **2019**, *19*, 387. [CrossRef] [PubMed]
10. Kamath-Rayne, B.D.; Tabangin, M.E.; Taylor, R.G.; Geis, G.L. Retention of Basic Neonatal Resuscitation Skills and Bag-Mask Ventilation in Pediatric Residents Using Just-in-Place Simulation of Varying Frequency and Intensity: A Pilot Randomized Controlled Study. *Hosp. Pediatr.* **2019**, *9*, 681–689. [CrossRef]
11. Mduma, E.; Ersdal, H.; Svensen, E.; Kidanto, H.L.; Auestad, B.; Perlman, J. Frequent brief on-site simulation training and reduction in 24-h neonatal mortality—An educational intervention study. *Resuscitation* **2015**, *93*, 1–7. [CrossRef] [PubMed]

12. Størdal, K.; Eilevstjønn, J.; Mduma, E.; Holte, K.; Thallinger, M.; Linde, J.; Mdoe, P.; Kidanto, H.; Ersdal, H. Increased perinatal survival and improved ventilation skills over a five-year period: An observational study. *PLoS ONE* **2020**, *15*, e0240520. [CrossRef] [PubMed]
13. Bjorland, P.A.; Øymar, K.; Ersdal, H.L.; Rettedal, S.I. Incidence of newborn resuscitative interventions at birth and short-term outcomes: A regional population-based study. *BMJ Paediatr. Open* **2019**, *3*, e000592. [CrossRef]
14. Bjorland, P.A.; Ersdal, H.L.; Eilevstjønn, J.; Øymar, K.; Davis, P.G.; Rettedal, S.I. Changes in heart rate from 5 s to 5 min after birth in vaginally delivered term newborns with delayed cord clamping. *Arch. Dis. Child Fetal Neonatal Ed.* **2021**, *106*, F311–F315. [CrossRef]
15. Linde, J.E.; Eilevstjønn, J.; Øymar, K.; Ersdal, H.L. Feasibility of a prototype newborn resuscitation monitor to study transition at birth, measuring heart rate and ventilator parameters, an animal experimental study. *BMC Res. Notes* **2017**, *10*, 235. [CrossRef]
16. Haynes, J.; Bjorland, P.; Gomo, Ø.; Ushakova, A.; Rettedal, S.; Perlman, J.; Ersdal, H. Novel Neonatal Simulator Provides High-Fidelity Ventilation Training Comparable to Real-Life Newborn Ventilation. *Children* **2021**, *8*, 940. [CrossRef]
17. Eilevstjønn, J.; Linde, J.E.; Blacy, L.; Kidanto, H.; Ersdal, H.L. Distribution of heart rate and responses to resuscitation among 1237 apnoeic newborns at birth. *Resuscitation* **2020**, *152*, 69–76. [CrossRef] [PubMed]
18. Available online: https://nrr.org/images/nedlasting/pdf/NRR_Guidelines_2021_Stabilisering_og_resuscitering_av_nyfodte.pdf (accessed on 10 October 2021).
19. Rubio-Gurung, S.; Putet, G.; Touzet, S.; Gauthier-Moulinier, H.; Jordan, I.; Beissel, A.; Labaune, J.M.; Blanc, S.; Amamra, N.; Balandras, C.; et al. In Situ Simulation Training for Neonatal Resuscitation: An RCT. *Pediatrics* **2014**, *134*, e790. [CrossRef]
20. O'Currain, E.; Davis, P.G.; Thio, M. Educational Perspectives: Toward More Effective Neonatal Resuscitation: Assessing and Improving Clinical Skills. *NeoReviews* **2019**, *20*, e248. [CrossRef] [PubMed]
21. Budhathoki, S.S.; Gurung, R.; Ewald, U.; Thapa, J.; Ashish, K.C. Does the Helping Babies Breathe Programme impact on neonatal resuscitation care practices? Results from systematic review and meta-analysis. *Acta Pædiatr.* **2019**, *108*, 806–813. [CrossRef]
22. Lee, M.O.; Brown, L.L.; Bender, J.; Machan, J.T.; Overly, F.L. A Medical Simulation-based Educational Intervention for Emergency Medicine Residents in Neonatal Resuscitation. *Acad. Emerg. Med.* **2012**, *19*, 577–585. [CrossRef]
23. Mileder, L.P.; Gressl, J.; Urlesberger, B.; Raith, W. Paramedics' Newborn Life Support Knowledge and Skills before and after a Targeted Simulation-Based Educational Intervention. *Front. Pediatr.* **2019**, *7*, 132. [CrossRef]
24. Skidmore, M.B.; Urquhart, H. Retention of skills in neonatal resuscitation. *Paediatr. Child Health* **2001**, *6*, 31–35. [CrossRef] [PubMed]
25. Roy, K.M.; Miller, M.P.; Schmidt, K.; Sagy, M. Pediatric residents experience a significant decline in their response capabilities to simulated life-threatening events as their training frequency in cardiopulmonary resuscitation decreases. *Pediatr. Crit. Care Med.* **2011**, *12*, e141–e144. [CrossRef] [PubMed]
26. Patel, J.; Posencheg, M.; Ades, A. Proficiency and Retention of Neonatal Resuscitation Skills by Pediatric Residents. *Pediatrics* **2012**, *130*, 515–521. [CrossRef] [PubMed]
27. Mosley, C.M.J.; Shaw, B.N.J. A longitudinal cohort study to investigate the retention of knowledge and skills following attendance on the Newborn Life support course. *Arch. Dis. Child.* **2013**, *98*, 582–586. [CrossRef]
28. Matterson, H.H.; Szyld, D.; Green, B.R.; Howell, H.B.; Pusic, M.V.; Mally, P.V.; Bailey, S.M. Neonatal resuscitation experience curves: Simulation based mastery learning booster sessions and skill decay patterns among pediatric residents. *J. Perinat. Med.* **2018**, *46*, 934–941. [CrossRef] [PubMed]
29. Yeung, J.; Djarv, T.; Hsieh, M.J.; Sawyer, T.; Lockey, A.; Finn, J.; Greif, R.; on behalf of the Education, Implementation and Team Task Force and Neonatal Life Support Task Force of the International Liaison Committee on Resuscitation (ILCOR). Spaced learning versus massed learning in resuscitation—A systematic review. *Resuscitation* **2020**, *156*, 61–71. [CrossRef]
30. Wyckoff, M.H.; Aziz, K.; Escobedo, M.B.; Kapadia, V.S.; Kattwinkel, J.; Perlman, J.M.; Simon, W.M.; Weiner, G.M.; Zaichkin, J.G. Part 13: Neonatal Resuscitation 2015 American Heart Association Guidelines Update for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care. *Circulation* **2015**, *132*, S543–S560. [CrossRef] [PubMed]
31. McGaghie, W.C.; Issenberg, S.B.; Petrusa, E.R.; Scalese, R.J. Effect of practice on standardized learning outcomes in simulation-based medical education. *Med. Educ.* **2006**, *40*, 792–797. [CrossRef] [PubMed]
32. Ericsson, K.A. Deliberate practice and the acquisition and maintenance of expert performance in medicine and related domains. *Acad. Med.* **2008**, *15*, 988–994. [CrossRef]
33. Ashish, K.C.; Wrammert, J.; Nelin, V.; Clark, R.B.; Ewald, U.; Peterson, S.; Målqvist, M. Evaluation of Helping Babies Breathe Quality Improvement Cycle (HBB-QIC) on retention of neonatal resuscitation skills six months after training in Nepal. *BMC Pediatrics* **2017**, *17*, 103. [CrossRef]
34. Tabangin, M.E.; Josyula, S.; Taylor, K.K.; Vasquez, J.C.; Kamath-Rayne, B.D. Resuscitation skills after Helping Babies Breathe training: A comparison of varying practice frequency and impact on retention of skills in different types of providers. *Int. Health* **2018**, *10*, 163–171. [CrossRef]
35. Mduma, E.; Kvaløy, J.T.; Søreide, E.; Svensen, E.; Mdoe, P.; Perlman, J.; Johnson, C.; Kidanto, H.L.; Ersdal, H.L. Frequent refresher training on newborn resuscitation and potential impact on perinatal outcome over time in a rural Tanzanian hospital: An observational study. *BMJ Open* **2019**, *9*, e030572. [CrossRef] [PubMed]
36. Nourkami-Tutdibi, N.; Hilleke, A.B.; Zemlin, M.; Wagenpfeil, G.; Tutdibi, E. Novel modified Peyton's approach for knowledge retention on newborn life support training in medical students. *Acta Paediatr.* **2020**, *109*, 1570–1579. [CrossRef] [PubMed]

37. Dunn, S.; Niday, P.; Watters, N.E.; McGrath, P.; Alcock, D. The provision and evaluation of a neonatal resuscitation program. *J. Contin. Educ. Nurs.* **1992**, *23*, 118–126. [CrossRef]
38. van der Heide, P.A.; van Toledo-Eppinga, L.; van der Heide, M.; van der Lee, J.H. Assessment of neonatal resuscitation skills: A reliable and valid scoring system. *Resuscitation* **2006**, *71*, 212–221. [CrossRef]

How much training is enough? Low-dose, high-frequency simulation training and maintenance of competence in neonatal resuscitation

Joanna C Haynes MD[1*,2]; Siren I Rettedal PhD, Associate Professor[2,3]; Anastasia Ushakova PhD[4]; Jeffrey M Perlman MB Ch B, Professor[5] and Hege L Ersdal PhD, Professor[1,2]

1. Department of Anaesthesia, Stavanger University Hospital, Stavanger, Norway; joanna.claire.haynes@sus.no
2. Faculty of Health Sciences, University of Stavanger, Stavanger, Norway; hege.ersdal@safer.net
3. Department of Paediatrics, Stavanger University Hospital, Stavanger, Norway; siren.irene.rettedal@sus.no
4. Department of Biostatistics, Stavanger University Hospital, Stavanger, Norway; anastasia.ushakova@sus.no
5. Department of Pediatrics, Weill Cornell Medicine, New York; jmp2007@med.cornell.edu

*Correspondence to joanna.claire.haynes@sus.no; tel 0047 95447338; Department of Anaesthesia, Stavanger University Hospital, Gerd-Ragna Bloch Thorsens gate 8, Stavanger, Rogaland 4011, Norway