Effective ventilation and chest compressions during neonatal resuscitation – the role of the respiratory device

Restin, Tanja ; Hönes, Marco ; Hummler, Helmut D ; Bryant, Manuel B

Abstract: Background: The success of cardiopulmonary resuscitation (CPR) in newborns largely depends on effective lung ventilation; however, a direct randomized comparison using different available devices has not yet been performed. Methods: Thirty-six professionals were exposed to a realistic newborn CPR scenario. Ventilation with either a bag-valve mask (BVM), T-piece, or ventilator was applied in a randomized manner during CPR using a Laerdal manikin. The primary outcome was the number of unimpaired inflations, defined as the peak of the inflation occurring after chest compression and lasting at least 0.35 s before the following chest compression takes place. The secondary outcomes were tidal volume delivered and heart compression rate. To simulate potential distractions, the entire scenario was performed with or without a quiz. Statistically, a mixed model assessing fixed effects for experience, profession, device, and distraction was used to analyze the data. For direct comparison, one-way ANOVA with Bonferroni's correction was applied. Results: The number of unimpaired inflations was highest in health care professionals using the BVM with a mean ± standard deviation of 12.8 ± 2.8 (target: 15 within 30 s). However, the tidal volumes were too large in this group with a tidal volume of 42.5 ± 10.9 ml (target: 25-30 ml). The number of unimpaired breaths with the mechanical ventilator and the T-piece system were 11.6 (±3.6) and 10.1 (±3.7), respectively. Distraction did not change these outcomes, except for the significantly lower tidal volumes with the T-piece during the quiz. Conclusions: In summary, for our health care professionals, ventilation using the mechanical ventilator seemed to provide the best approach during CPR, especially in a population of preterm infants prone to volutrauma.

DOI: https://doi.org/10.1080/14767058.2023.2276042

Originally published at:
Restin, Tanja; Hönes, Marco; Hummler, Helmut D; Bryant, Manuel B (2023). Effective ventilation and chest compressions during neonatal resuscitation – the role of the respiratory device. Journal of Maternal-Fetal Neonatal Medicine, 36(2):2276042.
DOI: https://doi.org/10.1080/14767058.2023.2276042

THE JOURNAL OF MATERNAL-FETAL & NEONATAL MEDICINE
2023, VOL. 36, NO. 2, 2276042
https://doi.org/10.1080/14767058.2023.2276042

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RESEARCH ARTICLE

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Effective ventilation and chest compressions during neonatal resuscitation – the role of the respiratory device

A randomized cross-over simulation study to assess the coordination between chest compressions and breathing support

Tanja Restin[a,b], Marco Hönes[c], Helmut D. Hummler[c,d] and Manuel B. Bryant[a,c,e]

[a]Department of Neonatology, University of Zurich, Zurich, Switzerland; [b]Institute of Physiology, University of Zurich, Zurich, Switzerland; [c]Division of Neonatology and Pediatric Intensive Care, Department of Pediatrics, Ulm University, Ulm, Germany; [d]Division of Neonatology and Pediatric Intensive Care, Department of Pediatrics, Marburg University, Marburg, Germany; [e]Kantonsspital Baden, Baden, Switzerland

ABSTRACT

Background: The success of cardiopulmonary resuscitation (CPR) in newborns largely depends on effective lung ventilation; however, a direct randomized comparison using different available devices has not yet been performed.

Methods: Thirty-six professionals were exposed to a realistic newborn CPR scenario. Ventilation with either a bag-valve mask (BVM), T-piece, or ventilator was applied in a randomized manner during CPR using a Laerdal manikin. The primary outcome was the number of unimpaired inflations, defined as the peak of the inflation occurring after chest compression and lasting at least 0.35 s before the following chest compression takes place. The secondary outcomes were tidal volume delivered and heart compression rate. To simulate potential distractions, the entire scenario was performed with or without a quiz. Statistically, a mixed model assessing fixed effects for experience, profession, device, and distraction was used to analyze the data. For direct comparison, one-way ANOVA with Bonferroni's correction was applied.

Results: The number of unimpaired inflations was highest in health care professionals using the BVM with a mean ± standard deviation of 12.8 ± 2.8 (target: 15 within 30 s). However, the tidal volumes were too large in this group with a tidal volume of 42.5 ± 10.9 ml (target: 25–30 ml). The number of unimpaired breaths with the mechanical ventilator and the T-piece system were 11.6 (±3.6) and 10.1 (±3.7), respectively. Distraction did not change these outcomes, except for the significantly lower tidal volumes with the T-piece during the quiz.

Conclusions: In summary, for our health care professionals, ventilation using the mechanical ventilator seemed to provide the best approach during CPR, especially in a population of preterm infants prone to volutrauma.

ARTICLE HISTORY
Received 5 April 2023
Revised 24 May 2023
Accepted 21 October 2023

KEYWORDS
Cardiopulmonary resuscitation (CPR); newborn; respiratory device (T-piece, bag-valve mask, ventilator); simulation; coordination

Introduction

The cardiovascular and respiratory systems of newborns change considerably during the transition from fetal to newborn life. Interestingly, only a small fraction of newborns requires any type of resuscitation [1]. The numbers vary depending on the population and local circumstances and range between 2 and 5 % [2,3]. However, only 1–2 in 1000 newborns require chest compressions combined with respiratory support due to persistent bradycardia (heart rate <60 beats per minute) despite adequate ventilatory support, as advised by the current resuscitation guidelines [4–7]. Although the rate of children needing chest compressions is low, rapid initiation and adequate technical performance are crucial because cardiac arrest in neonates is usually secondary to hypoxia in origin. Accordingly, an observational study in Tanzania with more than 5000 infants demonstrated that the risk of death or prolonged hospital admission increased for every 30 s delay in initiating face mask ventilation up to six minutes of life [8]. If chest compressions are necessary, coordination with lung inflations may be crucial for alveolar ventilation and successful resuscitation. In combination with noninvasive ventilation strategies, the current guidelines recommend a

CONTACT Tanja Restin tanja.restin@uzh.ch Department of Neonatology, University of Zurich, Zurich, Switzerland

synchronous approach coordinating ventilations and chest compressions [9]. Although it is clear that "high quality CPR" improves the survival rate [10,11], the best ventilation strategy is often assessed in animal studies or retrospectively as reviewed by Orso et al. [12]. In theory, airway management using a mechanical ventilator or T-piece device should be superior to the use of a bag-valve mask because the selected peak pressure and PEEP (positive end-expiratory pressure) will be more likely within the desired range [13]. However, if the coordination between respiratory and circulatory support is not guaranteed, alveolar ventilation may be less optimal and resuscitation may less likely to be successful. Recent studies have analyzed the advantages and disadvantages of different methods of respiratory support, but there has never been a direct comparison of the different available devices during chest compressions, with specific attention to the coordination of actions achieved [14–16]. In order to simulate a realistic scenario with divided attention, which often occurs by other caregivers, parents or team members and may impact on resuscitation success [17], we integrated a quiz task for standardized distraction of the caregivers.

Aim

This randomized crossover study aimed to assess the coordination of inflations with chest compressions using different devices. For this purpose, we compared a mechanical ventilator (F120, Fritz Stephan GmbH®, Gackenbach, Germany), T-piece device (Fischer & Paykel Healthcare GmbH, Schorndorf, Germany), and bag-valve mask (Laerdal Medical GmbH®, Puchheim, Germany) during newborn resuscitation.

Methods

Thirty-six health professionals, including 20 neonatologists, nine nurses, six midwives, and one obstetrician working in the neonatal intensive care unit (NICU) and delivery room of the University Hospital Ulm, participated in this study. We used a resuscitation manikin with real-time monitoring using SimPad (Resusci Baby QCPR, Laerdal Medical GmbH®, Puchheim, Germany). The manikin measured 58 cm × 26 cm × 13 cm. The manikins' chest rises during the correct inflation procedures. The finger position for chest compression was monitored by this manikin.

There were teams of two caretakers and usually consisted of both a physician and a nurse, or a physician and another caretaker (midwife) working in the NICU/delivery room. Some teams ($n = 3$) consisted of two physicians. Resuscitation was performed using a two-person procedure: one person took care of the airway and the other performed chest compressions. In accordance with the current neonatal resuscitation guidelines [9], each ventilation cycle consists of one inflation followed by three chest compressions and should last 2 s. Hence, 15 ventilation cycles should take exactly 30 s. After 30 s, the two team members changed their roles: the one previously responsible for inflation, then performed the compressions and vice versa. This procedure was repeated using three different respiratory assist devices: the bag valve mask (BVM) (Laerdal Medical GmbH®, Puchheim, Germany), T-piece device Perivent (Fischer & Paykel Healthcare GmbH, Schorndorf, Germany), and infant mechanical ventilator F120 (Fritz Stephan GmbH®, Gackenbach, Germany). The order of the three devices used was randomized with the help of a random integer generator [18] to avoid any selection bias with team improvements over time. Synchrony during use of the mechanical ventilator is provided by the person doing chest compressions to give exactly 3 chest compressions after the breath was given. In other words, the person in charge for chest compressions has to adjust to the ventilator rate. During pre-study trial rounds, it became clear, that "normal" respiratory settings caused flow-generated artifacts, which were detected as small volume inflations although no inflation was performed. As the manikins' detection threshold could not be elevated, in order to detect proper inflations without artifacts, the flow had to be adjusted from 10 l/min to 4 l/min with the T-piece, but the PEEP was set to 5 cmH_2O. Furthermore, the mechanical ventilator was set to a circuit flow of 3 l/min and the PEEP was reduced to 0 cm H_2O to avoid artifacts. The peak pressure was maintained at 20 cmH_2O for both devices. The inspiration time was set to 0.5 s, while the expiration time was set at 1.5 s leading to a respiratory rate of 30 inflations/min. With these adaptations, artifacts during recording could be eliminated.

These settings chosen represent the standard care. The whole procedure with all three devices was then repeated, but during the second round, in an effort to distract the caregivers from their tasks in a standardized way, the person providing respiratory support was asked to answer simple questions using the quiz "Denk Fix!" engl. "Think fast" (J. W. Spear and Sons, Enfield, UK). Data were recorded using proprietary software of the manikin and exported to data files, which were then imported and analyzed into spreadsheet files (Microsoft Excel, Redmond, WA). One file

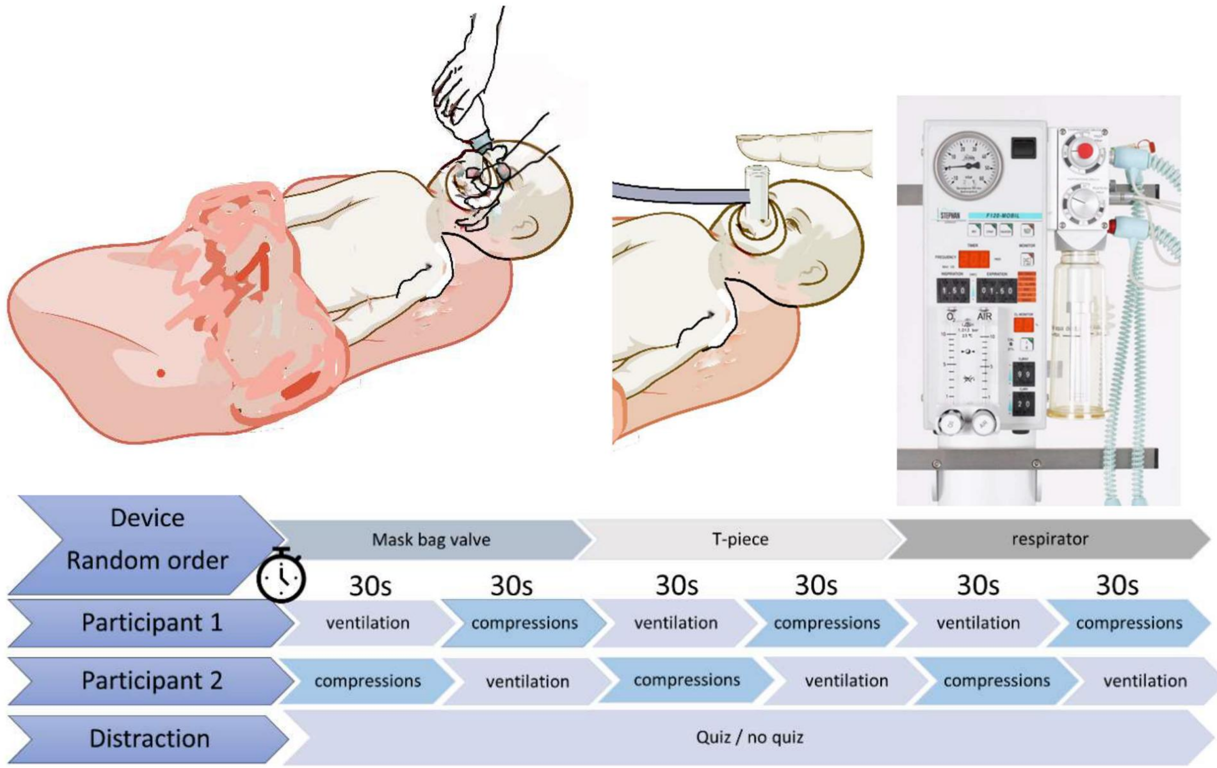

Figure 1. Sequence of test conditions during the CPR simulation procedure, graphs have been drawn with photoshop and created with BioRender. The image of the mechanical ventilator has been provided by Fritz Stephan GmbH®, Gackenbach, Germany.

was created for every 30 s resuscitation cycle. Using macros, all outcome parameters were calculated in a standardized manner (Figure 1).

Primary outcome

The primary outcome was the number of unimpaired breaths during a one 30 s cycle. Unimpaired breaths were defined as having an onset after the chest compression peak and with a duration of at least 0.35 s before the following chest compression. This decision was based 1. on physiological rationale and applied physiology and 2. the aim of a standardized analysis. First, the spontaneous inspiratory time of late preterm and full-term babies has been reported to be approximately 0.3-0.4 s (19,20), and second, we had to come up with a uniform definition.

The secondary outcomes were the number of chest compressions and inflations during a resuscitation cycle of 30 s. As in one minute, 120 actions should take place (90 compressions and 30 inflations), and the teams had to perform 15 inflations and 45 chest compressions in 30 s. Additional secondary outcomes were the tidal volume and number of breaths with correct volume (20–35 ml as suggested by the manufacturer of the resuscitation device, leading to a small rise in the chest wall). Additionally, chest compressions with the correct depth and rate were counted. Chest compression rates between 100 and 140/min were defined as correct. The compression depth was analyzed and defined as correct if it was deeper than 38 mm (as suggested by the manufacturer). The inflation rate (optimum at 30/min) was also evaluated. Because the recordings were started and stopped manually, most of them were slightly longer than 30 s in order to have a full 30 s cycle recorded. The recordings were truncated to 30 s. As potential influencing factors of professional experience in years, professional background (physician, nurse, midwife), the respiratory support device that has been used (BVM, T-piece, ventilator), and the existence of distraction (quiz) were analyzed. For the assessment of volumes applied, we used the built-in function which measures the expiratory tidal volume inside the manikin.

Statistics

In order to detect potential influencing factors on the primary outcome (number of correct inflations) and secondary outcomes (tidal volume, number of chest compressions), a linear mixed model was applied, and fixed effects for experience, profession, device, and distraction via the quiz questions were analyzed with the aid of SAS (Version 9.3, www.sas.com) at the Department of Epidemiology and Medical Biometry in Ulm. For subgroup analysis, one-way ANOVA with Bonferroni's correction was applied. The significance level was set at .05. Graphs were generated using the GraphPad Prism software (GraphPad Software, LLC, La Jolla, CA).

Results

The professional backgrounds of all the participants are shown in Figure 2. The mean number of unimpaired inflations within a 30 s period using the BVM was 12.8 ± 2.8, with the T-piece device 10.1 ± 3.7 and with the mechanical ventilator 11.6 ± 3.6 (Figure 2(B)). Thus, the BVM device performed significantly better ($p = .001$) than the T-piece (Figure 2(B)). Although the number of unimpaired inflations was slightly higher without the quiz questions, these differences were not statistically significant. Likewise, neither professional experience nor professional background significantly affected resuscitation quality during the simulation procedure.

The number of unimpaired inflations was significantly higher using the BVM or mechanical ventilator than using the T-piece device. The tidal volume using a BVM was 42.5 ml on average (SD ± 11.7 ml) and therefore significantly higher than with the mechanical ventilator or T-piece, and also 7.5–22.5 ml higher than recommended, indicating a relevant risk of overinflation. Again, there was no significant difference between doing a quiz (distraction) and not doing so during this procedure. The correct tidal volume was achieved best using the mechanical ventilator, resulting in the highest number of inflations with correct tidal volume (12.1 ± 4.9 breaths). The BVM predominantly applied larger volumes and only 3.8 ± 5.5 correct breaths. The T-piece device was better than the BVM, but with 8.1 ± 5.0 still off the target in nearly half of the possible inflations. The chance of delivering tidal volumes below the optimal threshold was high with the T-piece, particularly during the quiz. With the T-piece, the participants applied significantly lower volumes when distracted during the quiz compared to the situation without the quiz questions.

Interestingly, the frequency of chest compressions increased when distracted, and this change was shown to be significant during BVM and T-piece ventilation.

Discussion

Successful neonatal resuscitation is crucial for intact patient survival and largely depends on effective and timely coordinated techniques that have to be trained by healthcare workers working according to the best available evidence [21]. Since 1958, resuscitation techniques have been developed using manikins to train and expose healthcare professionals in resuscitation simulation settings as realistically as possible [22]. Since then, the manikins have improved technically, and in our setup, the anatomic and elastic properties of the thorax of the manikin seemed to be fairly realistic, as judged by the more experienced health care professionals participating in this study.

Unlike adults, where the major focus is currently on heart compressions [23], newborn survival largely depends on successful positive pressure ventilation of the infants' lungs, which usually precedes a normalization in heart rate [24]. Cardiac arrest in neonatal patients is usually caused by hypoxia, which explains the importance of effective lung ventilation. The ventilation strategy is challenging because newborn airways are often filled with liquid, leading to a high surface tension and increased frictional forces, as reviewed by others [25] and the functional residual capacity is often decreased [26]. In addition, the oxygen consumption rate of newborns has been reported to be approximately twice as high as that of adults (4.2–9.7 ml/kg/min) [27,28]. Consequently, effective ventilation of the lungs is particularly important for the successful return of spontaneous circulation [29]. However, while the self-inflating BVM, a flow-generating device is widely used for resuscitation worldwide, the use of T-piece devices is largely dependent on regional preferences and the infrastructure of the delivery room [30]. The T-piece respirator requires an external flow source but has the advantage of providing a defined PEEP and peak inspiratory pressure (PIP) or continuous positive airway pressure (CPAP), as chosen by the operator. Using targeted PIP and PEEP is probably associated with a lower risk of unintended overinflation of the lung, avoiding acute barotrauma such as pneumothorax and/or other types of lung injury. Moreover, unintended overinflation and provision of oxygen excess does not only bear the risk of permanent long-term lung-injury due to volutrauma, atelectotrauma, or oxygen toxicity [31] but has been shown to be associated with long-term brain-damage as reviewed by Cannavo et al. [32,33]. Although overinflation is avoided, ventilation via the T-piece may be associated with higher expiratory resistance [34] and some risk of inadvertent PEEP [35,36].

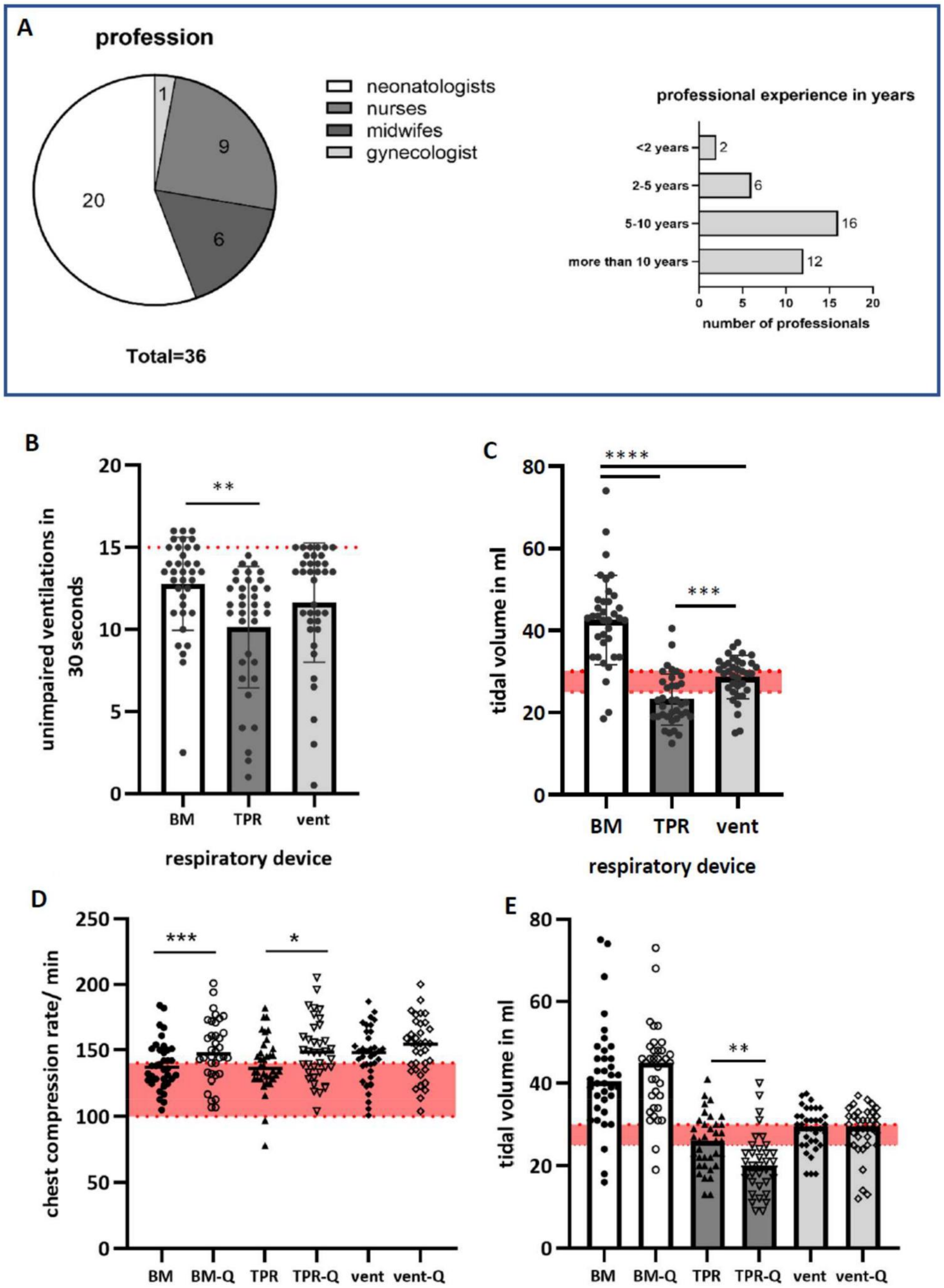

Figure 2. (A) Characteristics of the involved participants. (B–E) Performance achieved with the different respiratory devices (bag-valve mask (BVM), T-piece resuscitator (TPR), and ventilator (vent) during a simulation scenario of mechanical cardiopulmonary resuscitation). (B) Analysis of the number of unimpaired inflations in 30 s. Each dot represents the mean of two independent measurements of the same health care professional over a 30 s time period. The red line indicates the optimal number of inflations (15/30 s). (C) Analysis of the tidal volume achieved with each device during the resuscitation procedure. Each dot represents the mean tidal volume applied during a 30 s period. The red line demonstrates the optimal tidal volume, which should be between 25 and 30 ml. (D) Chest compression rate per minute with the different respiratory devices BVM, TPR, or vent with or without quiz (Q). Each dot represents the mean compression rate of each participant during the scenario. The red line indicates the optimal rate (range between 100 and 140/min). (E) Mean tidal volumes applied by each participant during the simulation scenario depending on the device. The optimal tidal volume is indicated by the red line (25–30 ml). $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$, and $^{****}p < .0001$.

During the realistic simulation resuscitation scenario used in our study, our study participants had more difficulties with the T-piece to provide ventilation within the targeted limits of rate, synchrony, and tidal volume during cardiopulmonary respiration compared to the mechanical ventilator or the BVM. We speculate that timing of the breath was less perfect using the T-piece as the person in charge for the airway is more prone to distraction. As respiratory support using the BVM is far more complex than simply placing one finger to occlude the outward flow, it might be that healthcare professionals undertaking this procedure are more concentrated, but may have the disadvantage of providing too much force during bagging, which could explain the higher tidal volumes observed. The problem that neither the leakage of the face mask nor the applied air volume can be reliably estimated in clinical emergency settings [37,38] leads to the problem that positive pressure might be inadvertently increased during BVM ventilation. Similarly, leakage of the mask leading to impaired ventilation with the T-piece or ventilator might be unrecognized, which correlates with the findings of our simulation (Figure 2). We had to use lower flow rates compared to those typically used in real-life situations, which may have contributed to smaller tidal volumes because of poorer leak compensation. However, the tidal volumes achieved with the mechanical ventilator were higher than those of the T-piece device, despite lower flow rates on the mechanical ventilator. Depending on the design (i.e. acoustic and visual properties of the ventilator and available graphic displays), the ventilator can be used as a metronome and/or provide feedback on the properties of the inflation achieved. Audio guidance during resuscitation improves performance [39–41]. Poorer perception of the counterparts' action potentially leads to worse coordination of the team, which has been shown to be decisive for resuscitation outcomes as reviewed by Fernandez Castelao et al. [42]. With regard to tidal volumes, the mechanical ventilator has a clear benefit because the target volumes are standardized, and the target volume can be achieved significantly more often than with the other devices. However, the resuscitation manikin lacks a stomach, which is a clear disadvantage in our study setting. With the T-piece, significantly lower volumes were given when distracted during the quiz. We speculate that duration and/or timing of valve closure was too short/not ideal. Furthermore, there is no "low pressure alarm" with the T-piece, which may result in low tidal volumes (secondary to lower peak pressure) being underrecognized compared to the use of a ventilator device.

This study has the strength of a realistic scenario, including healthcare professionals who are used to performing cardiopulmonary resuscitation (CPR) in newborns. Randomization of the techniques limits the potential bias by eliminating period effects. The limitations are the changes to flow (for the T-piece device and ventilator) and PEEP (for the ventilator) that needed to be applied in order to avoid artifacts. With a typical bias flow of 10 l/min and regular PEEP levels, the release after each chest compression led to the recording of a small tidal volume inflation, resulting in a very high number of ventilations, a very low mean tidal volume, and an almost universal percentage of uncoordinated ventilation. Manikin software does not elevate the threshold for inflation detection. While choosing a lower bias flow was the only option to avoid this artifact, it may have reduced the ability to compensate for mask leakage, and thus may have led to lower tidal volumes. Other differences to a real-life setting are that the skin of the manikin is not as wet and thus slippery as in newborns immediately after birth. Consequently, potential distracting factors such as drying the skin and temperature management can be simulated only to a limited degree, whereas the positioning and procedures of obtaining vascular access may be simulated as well. We only used three different devices for respiratory support and one manikin, which means that the individual differences between patients of different providers are not taken into account, but potentially play a role [34]. However, the finding that the T-piece resuscitator was less effective suggests that the quality of ventilation has to be reassessed during resuscitation procedures and that, especially in larger-term babies, it might be necessary to increase the PIP of the device. On the other hand, it underlines the importance of being aware of ventilatory volumes applied by the bag valve, which has to be considered critically, especially in preterm babies with smaller lung capacities. Our study points out again how important the coordination between the involved healthcare providers is, and that the ventilation procedure should be pointed out loudly to be used as a joint metronome.

In summary, although the mechanical ventilator provided approximately 2–3 unimpaired breaths less per minute compared to the BVM, this difference was not significant from a statistical point of view. However, with tidal volumes more commonly within the target range with the mechanical ventilator, the mechanical ventilator may be the device of choice for respiratory support, since it may reduce volutrauma, which is particularly important in preterm infants. However, we acknowledge that use of a mechanical ventilator device may not be feasible in settings, where resources are limited or training with more complicated devices may be an issue.

Acknowledgements

We thank Laerdal Medical GmbH® (Puchheim, Germany) for providing the resuscitation manikin for this study. We thank all participants in this resuscitation simulation study. We would like to thank Prof. Benjamin Mayer, Medical Biometry, Ulm University, for his help with statistical analysis of our data. The publication costs are kindly covered by Short Grant 2023__SG_027 provided by the University of Zurich.

Disclosure statement

None of the authors has any conflict of interest to declare.

Funding

The publication costs are kindly covered by Short Grant 2023__SG_027 provided by the University of Zurich.

Data availability statement

Data will be available upon request.

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