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Seminars in Fetal and Neonatal Medicine 27 (2022) 101333

Contents lists available at ScienceDirect

Seminars in Fetal and Neonatal Medicine

journal homepage: www.elsevier.com/locate/siny

Technology in the delivery room supporting the neonatal healthcare provider's task

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A B S T R A C T

Very preterm infants are a unique and highly vulnerable group of patients that have a narrow physiological margin within which interventions are safe and effective. The increased understanding of the foetal to neonatal transition marks the intricacy of the rapid and major physiological changes that take place, making delivery room stabilisation and resuscitation an increasingly complex and sophisticated activity for caregivers to perform. While modern, automated technologies are progressively implemented in the neonatal intensive care unit (NICU) to enhance the caregivers in providing the right care for these patients, the technology in the delivery room still lags far behind. Diligent translation of well-known and promising technological solutions from the NICU to the delivery room will allow for better support of the caregivers in performing their tasks. In this review we will discuss the current technology used for stabilisation of preterm infants in the delivery room and how this could be optimised in order to further improve care and outcomes of preterm infants in the near future.

1. Introduction

Because of their immaturity, very preterm infants are a unique and highly vulnerable group of patients that have a narrow physiological margin within which interventions are safe and effective. A large amount of scientific research along with technological innovations have improved care for preterm infants in the neonatal intensive care unit (NICU). In the NICU, infants are monitored meticulously and devices are used to provide treatment in a safe and sophisticated manner. The arrival of automated technologies, whether or not in combination with artificial intelligence (servo-controlled incubator, algorithm driven ventilators, automated oxygen titration, predictive monitoring) has decreased the manual work in the NICU and improved care and outcome in the last twenty years.

While these automated technologies are increasingly being used in the NICU, technology in the delivery room still lags far behind. Preterm infants can be difficult to manage in the intensive care unit, but this task is considerably more complex at birth due to the infant's rapidly changing physiology. Particularly at birth, automated technologies and/or artificial intelligence could be highly relevant, since the infant's physiology is undergoing large and rapid changes. We now start to understand that the transition to life after birth is an extremely critical phase of life which greatly impacts an individual's risk of death, injury [1,2] or life-long disability [3,4], particularly infants born very preterm.

Stabilisation of preterm infants in the delivery room is usually brief, but many interventions need to be performed in order to stabilise the infant's temperature, (spontaneous) ventilation and oxygenation in a time sensitive manner. It has been shown that some interventions are not as effective as caregivers assumed and that the provision of an optimal and safe treatment during this stressful moment is a major challenge for caregivers [5–8]. It also has been demonstrated that caregivers have difficulty in assimilating the complex and rapidly changing physiological information that is required to make accurate strategic decisions with regard to assisting preterm infants as they transition to newborn life [6–10].

In this review we will discuss the current technology used for stabilisation of preterm infants in the delivery room and how this could be optimised by the provision of purpose-built devices and technology that assimilates all of the physiology data and supports decision making processes.

2. Temperature management

The first step of neonatal stabilisation is the prevention of heat loss, which easily occurs in the exposed and wet infants through convection, conduction, radiation and evaporation, resulting in a decreased body temperature. Hypothermia after birth has been recognised as a significant contributor to neonatal morbidity and mortality [11,12]. Although less is known about the acute and long-term impact of hyperthermia after birth, the potential risks for both hypothermia and hyperthermia

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https://doi.org/10.1016/j.siny.2022.101333

Available online 31 March 2022

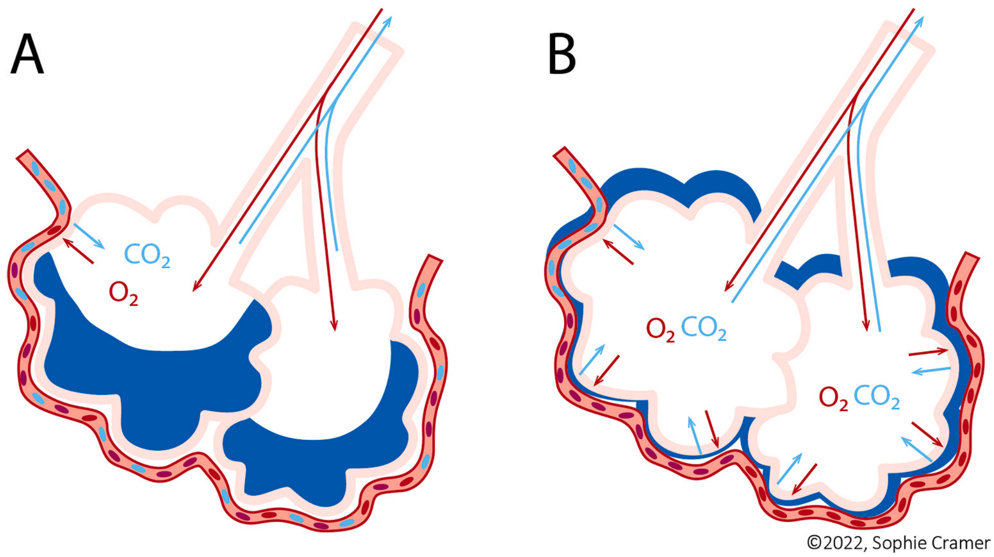

Fig. 1. Overview of the alveoli, surrounded by capillaries. A: Directly at birth, lung liquid needs to be replaced with air. The movement of liquid into the interstitial tissue causes a high airway resistance and the partially liquid-filled alveoli reduces the surface area available for gas exchange. B: As the liquid moves into the interstitial tissue surrounding the alveoli, the airway resistance decrease while the interstitial pressure and lung recoil increase. This causes alveolar collapse and liquid re-entry at end-expiration. Nevertheless, the surface area available for gas exchange increases.

are currently recognised in the international resuscitation guidelines with the advice to keep the body temperature of the infant between 36.5 and 37.5 °C [13,14]. While measures to prevent hypothermia – such as increased room temperature and the use of a head cap, a wrap, a radiant heater, a thermal mattress and heated and humidified gases - are commonly performed, keeping the body temperature within the normal range during stabilisation at birth proves to be challenging [15–18].

Currently, the temperature is often only measured at NICU admission, which does not allow us to take correcting measures until that moment. Although standardised thermoregulation protocols, training, and audits have shown to improve our temperature management [19–21], frequent or continuous measurement of temperature, in combination with a temperature dependent protocol, can further improve this [22,23]. However, temperature management based on continuous measurements requires constant attention and is more labour intensive. Technology could assist in this process by providing visual or audible cues when the recommended ranges are exceeded in order to capture the attention of the caregiver or by providing decision support on the timing and type of heat loss measures to take. Technology could even further assist caregivers by enabling automated regulation via servo-controlled mattresses and radiant warmers, which are commonly used in the NICU.

Although a recent multi-centre study reported that the use of servo-controlled radiant warmers on the delivery room showed no benefits over the use of radiant warmers on maximal output [24], studies implementing servo-controlled radiant warmers combined with a temperature dependent protocol for additional measures show the highest overall scores of normothermia at NICU admission, ranging from 74% to 100% [25–28]. As infants are much more exposed in the delivery room as compared to the NICU, full automation of thermoregulation in the delivery room probably asks for completely different closed-loop solutions minimising the effects of the environment on their temperature.

3. Tactile stimulation

As of 2005, local and international resuscitation guidelines recommend tactile stimulation in the form of warming, drying and rubbing the back or soles of the feet to evoke spontaneous breathing in newborn infants [13,14,29]. While experimental studies demonstrated tactile stimulation to increase respiratory effort [30,31], the clinical guidelines are still largely based on many years of experience and expert opinion as there is lack of data on this topic in human infants.

Several retrospective studies recently evaluated current practice, showing a wide variation between caregivers and between centres concerning timing, duration and method of stimulation [32–36]. In addition, stimulation turned out to be often omitted, in particular in preterm infants placed in a polyethylene bag [34–36]. A recent randomised trial showed that repetitive tactile stimulation in preterm infants increased oxygenation, while less oxygen was needed, and improved respiratory effort [37]. However, the trial also led to a high incidence of stimulation in the standard group. This effect could be attributed to the Hawthorne effect and/or the increased focus on tactile stimulation during the study, which in turn implies that omission of stimulation happens because it is simply forgotten.

Albeit the most optimal way of stimulation remains unclear, automated mechanical stimulation could ensure tactile stimulation to be provided, in a more consistent way [38]. Several closed-loop vibratory stimulation devices to treat apnoea's of preterm infants admitted to the NICU have been described in literature, but currently none of these are commercially available [39–42]. No studies have been performed in the delivery room, but mechanical vibratory stimulation in preterm infants in the NICU proved to be as effective as manual stimulation in aborting apnoeic episodes in two preliminary studies [42,43], and two other observational studies reported that their closed-loop pulsating and vibrating devices were able to terminate 90% of all apnoeas [44,45]. Applying this technique in the delivery room has the potential to replace manual intervention, eliminating the chance that stimulation will be forgotten.

4. Oxygenation

Currently, oxygen administration is guided by predefined oxygen saturation (SpO_2) target ranges [46]. Caregivers manually titrate the fraction of inspired oxygen (FiO_2) accordingly to avoid hypoxia and hyperoxia. At birth, hypoxia can lead to suppression of spontaneous breathing, and hypoxia that persists for more than 5 min after birth is associated with an increased risk of mortality and the development of intraventricular hemorrhages [47–50]. On the other hand, hyperoxia needs to be avoided as this increases the production of free radicals, but

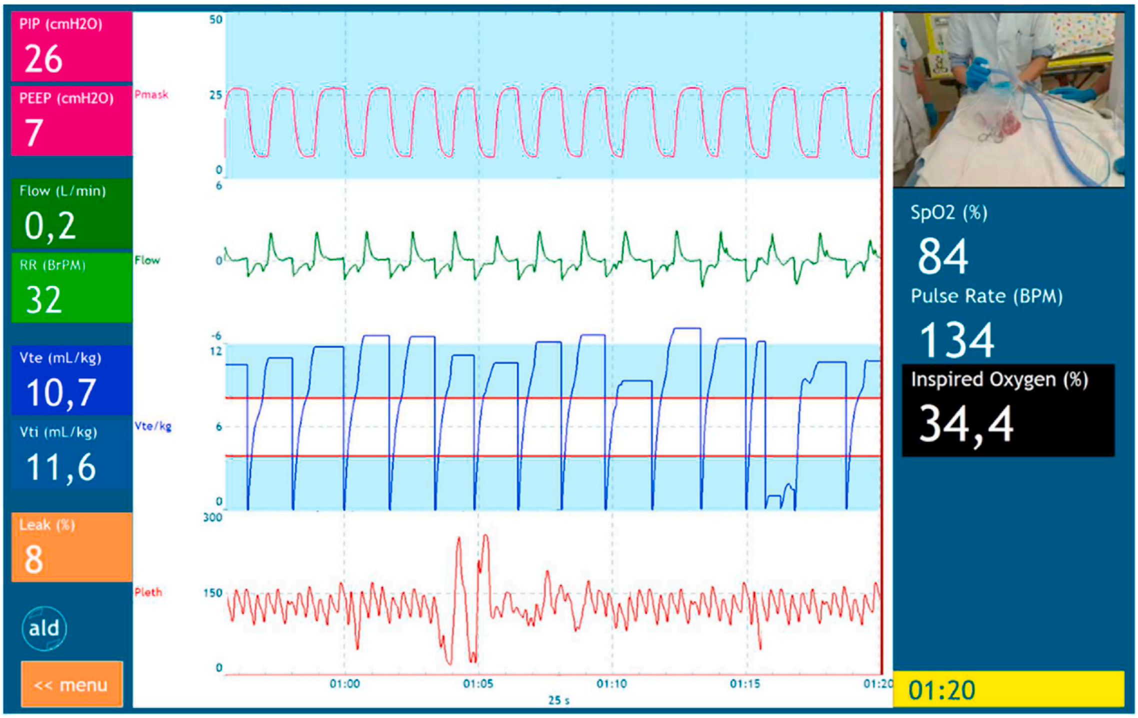

Fig. 2. Respiratory Function Monitor display.

also can inhibit the respiratory centre [51,52]. As such, it is critical to adequately control oxygenation during this period. However, this is an incredibly difficult and complex task given the fact that immediately after birth, the lung is constantly and rapidly changing.

It has been shown that maintaining SpO_2 values within a predefined target range with manual titration is extremely difficult in the delivery room as well as in the NICU [53–59]. Randomised trials demonstrated the potential of closed-loop titration of FiO_2 in the NICU, increasing the time spent within the SpO_2 target range with a decrease in extreme deviations in oxygenation, including both the duration and the number of episodes [60–69]. The use of a closed-loop oxygen controller in the delivery room has so far only been studied once in a preterm lamb model [70]. In this study, the effect of a closed-loop oxygen controller with timeout restrictions of 30s after each titration step was compared to manual titration of oxygen after evaluation of SpO_2 to be performed every 30s. Results show similar time within the SpO_2 target range and below the target range, while time above the target range was significantly shorter in the automatic titration group [70].

However, this technique cannot just simply be extrapolated to the delivery room, as there are considerable differences with regard to target ranges, physiology and devices used. In the NICU, the SpO_2 target range is static, while this is dynamic in the first minutes after birth. Oxygen exchange in the lungs is largely determined by the surface area available for gas exchange and the oxygen concentration gradient between the alveoli and adjacent capillaries. At birth, when the airways are mostly liquid-filled, the surface area available for gas exchange is small and a high oxygen concentration is required for adequate exchange (Fig. 1A). As the lungs aerate, the surface area available for gas exchange increases exponentially and as such a much lower oxygen concentration is needed for adequate oxygenation (Fig. 1B). The oxygen concentration administered after birth should thus be adjusted according to the degree of lung aeration. This would require the closed-loop titration mechanism to adjust the SpO_2 target range continuously based on the time after birth. In addition, the algorithm of the closed-loop oxygen controller should also be calibrated based on the factors present at birth which influence the position of the oxygen-haemoglobin dissociation curve.

Furthermore, titration of oxygen using a T-piece ventilator, which is commonly used for respiratory support at birth [14], can result in a delay between the moment of titration and the delivery of the corresponding FiO_2 at the face mask of the infant [71]. The algorithm used by the closed-loop oxygen controller that is used with the T-piece resuscitator should therefore reckon with this delay.

5. Continuous positive airway pressure

Although most preterm infants breathe at birth, the breathing effort is often insufficient to ensure the large pulmonary physiological changes that are needed to survive the foetal to neonatal transition. While continuous positive airway pressure (CPAP) is often used to support the infant's breathing, there is no data on the optimal pressure level. The CPAP level of 4–8 cmH_2O that is currently used is predominantly extrapolated from data from CPAP later in the NICU, while the underlying physiology during the neonatal transition is strikingly different [13,72].

Considering the physiological changes that need to occur during transition, it would be more logical to use a dynamic CPAP strategy wherein the CPAP levels suit the different phases of the transition. In the first phase of the transition (Fig. 1A), the role of CPAP is to promote lung aeration and assist movement of lung liquid across the distal airway wall into the interstitial tissue. As a result, the resistance in the airways is high due to the high viscosity of liquid (compared with air) moving across the airway epithelium requiring higher CPAP levels to overcome this [73–77]. Once the lungs become more aerated and liquid is accumulated in the interstitial tissue, the lung characteristics change quickly and the role of CPAP converts to maintaining lung aeration. During this phase of the transition (Fig. 1B), airway resistance is considerably lower (~100 fold), but lung recoil and interstitial tissue pressure increase which promote alveolar collapse and liquid re-entry at end-expiration [73–81]. Lower CPAP levels are likely sufficient to maintain aeration and support breathing, while decreasing the risk for lung overexpansion and/or adverse effect on pulmonary blood flow. This dynamic CPAP approach, following the pulmonary physiological changes during transition, has been called physiological based (PB)-CPAP.

Experimental studies in spontaneously breathing preterm animal models demonstrated that PB-CPAP should ideally start with CPAP of 15 cmH_2O which is stepwise decreased to 8 cmH_2O. These studies also showed that PB-CPAP promotes lung aeration (functional residual capacity; FRC)), breathing effort and pulmonary blood flow, without causing bulging of the lungs or pneumothoraxes [82,83]. These results were translated into a small randomised controlled trial wherein PB-CPAP was compared to 5–8 cmH_2O CPAP. This feasibility study demonstrated that PB-CPAP led to a quicker restoration of heart rate and shorter duration of mask ventilation, likely reflecting lung aeration. Nevertheless, post-trial evaluations indicated that caregivers found it difficult to combine standard care with a CPAP protocol that requires constant evaluations and changes in CPAP levels [84].

This is where technological innovation could help the caregiver in assimilating complex physiological changes and fine-tuning and optimising the respiratory support. Mathematical modelling with currently available physiological data could be used to create algorithms, which will allow us to develop a decision or even automated pressure support system in the delivery room.

6. Positive pressure ventilation

If preterm infants fail to clear their lung liquid, establish FRC and initiate spontaneous breathing to facilitate gas exchange [85], manual non-invasive positive pressure ventilation (NIPPV) is provided by occluding the aperture of a T-piece resuscitator with a thumb or finger. The sufficiency of the provided tidal volumes is confirmed by adequate chest rise, auscultation or, indirectly, by an increase in heart rate [86]. However, due to rapidly changing pulmonary physiology and inconsistent respiratory drive of infants at birth, variable tidal volume are administered that might be inadequate or excessive. Large tidal volumes could overstretch the delicate alveoli and airways (volutrauma), while small tidal volumes could lead to loss of lung volume or cycling between collapse and recruitment (atelectotrauma) thereby injuring the lungs [87,88]. A recent multicentre trial evaluating tidal volume monitoring during manual ventilation reported that, despite using a respiratory function monitor (RFM) (Fig. 2), ineffective ventilation <4 mL/kg and potentially harmful ventilation >8 mL/kg was provided 40.7% and 20.0% of the time, respectively [89].

The high percentage of ineffective manual ventilation could be caused by pharyngeal ventilation as the glottis is predominantly closed after birth and only opens when a spontaneous breath is taken [90]. When ventilation is provided to a closed glottis, no air is able to enter into the lungs [90]. Providing inflations which coincides with spontaneous breaths would be more effective, but also increases the risks of high tidal volumes and thus the risk of lung and/or cerebral injury [91]. As it is difficult for caregivers to evaluate the presence and quality of spontaneous breathing at birth [8], especially during manual ventilation [7], this hampers safe and effective ventilation at birth.

Again, automation can offer a solution. In this case, several solutions already exist and are being applied as features of a neonatal ventilator. Replacing the T-piece resuscitator for a regular neonatal ventilator in the delivery room therefore brings several opportunities to prevent inappropriate ventilation. The first solution is automated synchronised NIPPV (sNIPPV). Caregivers can only detect breathing after a breath has been taken, while a ventilator can detect the start of a breath. This enables ventilators to synchronise their ventilation. In addition, caregivers have to keep overview of the clinical condition of the infant and are, therefore, not able to continuously focus on the infant's breathing while a ventilator can. Although there is no evidence for the effectiveness of synchronised ventilation in the delivery room, it has shortened the duration and improved the effectiveness of ventilation in the NICU [92,93].

Even with sNIPPV, it remains difficult to provide tidal volumes in a safe target range. To date, caregivers are only able to apply pressure-limited manual ventilation in the delivery room due to the lack of appropriate technology. However, a recent neonatal resuscitation simulation study showed it is feasible to use a ventilator with RFM in the delivery room as it increased the proportion of tidal volumes within the target range and reduced the number of large tidal volumes during different simulated scenarios of changing pulmonary mechanics commonly encountered at birth [86]. Also, the delivery of consistent tidal volumes during changing pulmonary mechanics could be improved by implementing volume-targeted ventilation. While, this ventilation mode showed to improve outcome and is a widely accepted in the NICU, there is no data on using this mode in preterm infants at birth [87,94,95]. This effect might even be increased when using a ventilator with synchronised ventilation and/or volume-targeted ventilation.

7. Monitoring

Regular feedback on the patient's physiological state is a pivotal element of neonatal stabilisation after birth, guiding corrective actions and clinical decision making of the caregivers. Despite its importance, monitoring in this critical period is still relatively basic compared to the continuous and extensive monitoring techniques used in the NICU.

The current guidelines recommend the use of pulse oximetry and/or ECG for physiological feedback instead of rudimentary methods such as auscultation, palpation of the umbilical cord and assessment of skin color, as these methods proved to be prone to subjectivity [96,97]. The same applies to the assessment of administered tidal volumes by observing chest excursions [98] but the evidence for using a RFM instead remains conflicting. Although manikin studies demonstrated that providing continuous feedback on ventilation pressures, tidal volumes, mask leak, SpO 2, heart rate and FiO2 via a RFM improved the performance of the caregiver during PPV [86,99–101], a recent multicenter randomised controlled trial showed no difference between neonatal resuscitation with or without integrated feedback by RFM [89]. This result might be explained by previous findings that the use and interpretation of a RFM in the delivery room is experienced as challenging and therefore not helpful to all caregivers in critical decision making [7,102].

Although continuous, objective and accurate data acquisition is necessary to further implement modern technological innovations such as closed-loop interventions and prediction models, the question is whether presenting all this data directly to the caregivers is always useful. Future research should also be focused on which data to present, and in particular in what manner, to facilitate quick assimilation and easy interpretation by caregivers so that they can recognize and act upon abnormalities or changes in physiology. In other words, in the design or development of monitoring methods, one should consider carefully whether the data is processed by algorithms or a human brain.

8. Man and machines

Our understanding of the foetal to neonatal transition and the underlying physiological changes has evidently increased in the recent decades, facilitating clear opportunities aiming to improve clinical outcome. However, these insights also underscore the eminent complexity of the transition process, especially in ill or preterm infants who cannot meet the required physiological challenges on their own.

Whilst the expansion of monitoring solutions and intervention strategies and the finetuning of protocols and target ranges can definitely aid caregivers in providing the right support, it makes the resuscitation process increasingly sophisticated. As of today, caregivers continuously have to assimilate and interpret many physiological parameters from different devices in order to decide if, when and which intervention is required, in just a small-time window. The more difficult, dynamic and versatile the process, the more prone it becomes to human errors such as forgetfulness and lack of continued focus.

Over the last decades the development and adoption of automated medical technology has tremendously increased and accordingly

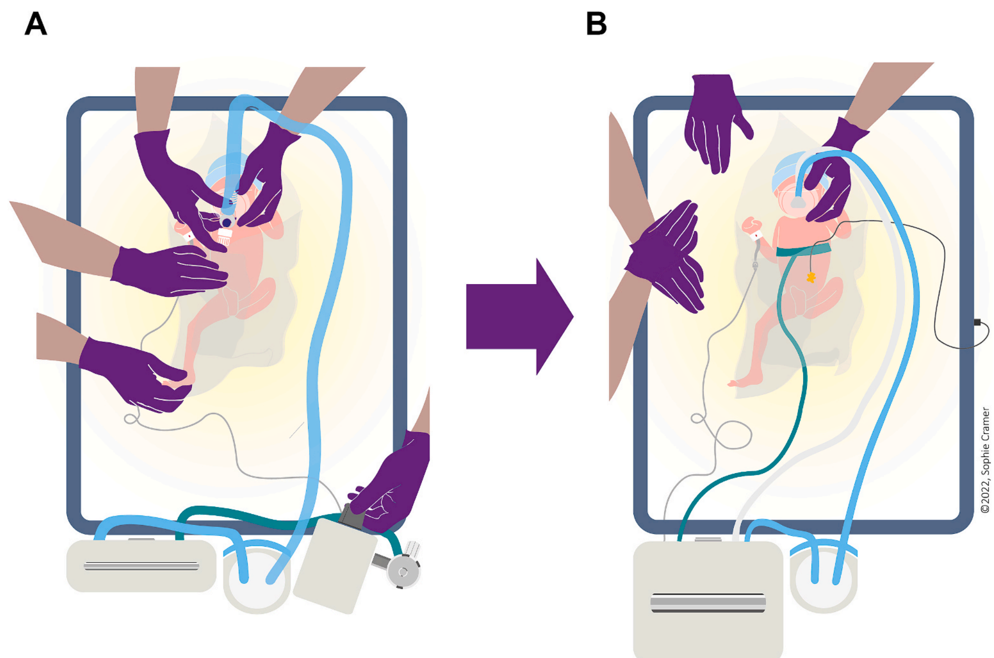

Fig. 3. Visualisation of evolving technologies for use in the delivery room. From providing manual heat loss measures, manual tactile stimulation, manual supplemental oxygen control and manual CPAP and NIPPV with a T-piece resuscitator (A) to automated thermoregulation, automated tactile stimulation, automated oxygen control and automated ventilation using a ventilator (B).

revolutionised medical practice, but not yet in the delivery room. We argue that the development and implementation of automation, closed-loop systems and artificial intelligence could serve as a next iteration in improving resuscitation management by reducing human error and unwanted variability in human behaviour. However, this can only be achieved if we critically validate the added value using a holistic approach; not only taking into account the patient but also the caregivers. This means that we should not blindly use existing solutions for new problems but find new ones fitting the entire context. We should not use or implement innovations because it is technically feasible, but because it is desirable and we should not endlessly extend and expand existing solutions but come up with solutions that replace a bundle of existing ones.

Although some might dream, and others fear, a completely automated transition support system, it is more likely that technology will take on an integral part of resuscitation management, resulting in an increased caregiver-machine interaction. Given the growing complexity of automated systems, the poor explainability of artificial intelligence and the consequences of possible erroneous automated interventions, a paradigm shift is necessary. Caregivers should not only be clinically aware, understanding the status of the patient with regard to the interlinked physiological changes, but be situational aware, also understanding the status of all automated devices, systems and software during the transition process. Shaping this role is however not the sole responsibility of the caregivers. To make the most out of it, designers and developers should indeed focus on the explainability and interpretability of automated systems and error prone interfaces including clear user feedback. Managers and medical engineers should moreover ensure that caregivers are trained like pilots; focussing on the capabilities to identify and respond to system errors or failure. As it is utopian to think that capitalising some strength of computers will fully replace human weaknesses, caregivers have to accept that improvement of care will always remain an iterative process.

9. Conclusion

Although the complexity of stabilisation after birth increases by our growing understanding of the complex physiology, the development and implementation of technology to assist in this process lags behind. Implementing state-of-the-art technology during the neonatal stabilisation would enable us to i) prevent hypo- and hyperthermia through closed-loop temperature management, ii) stimulate spontaneous breathing by providing automatic repetitive tactile stimulation to all infants, iii) control oxygenation in relation to neonatal transition through closed-loop oxygenation, iv) support spontaneous breathing during neonatal transition by automated PB-CPAP algorithms and v) provide safe and effective ventilation by using synchronised volume targeted ventilation (Fig. 3). By using technology to assist caregivers to provide the optimal care, caregivers would be able to comprehend an overview of the infant's clinical condition more easily and finetune the stabilisation where appropriate.

Although most of the technology discussed in this review is already used in the NICU, it cannot simply be extrapolated to the delivery room because of the difference in physiology, environment and situation. The adoption of automation has great potential to improve the care we provide in the delivery room, as long as we put humans, not technology, first. Above all, we must realise that technology does not make man superfluous: the clinical view remains necessary.

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