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Neonatal monitoring during delivery room emergencies

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ABSTRACT

Fetal to neonatal transition after birth is a complex, well-coordinated process involving multiple organ systems. Any significant derangement in this process increases the risk of death and other adverse outcomes, underlying the importance of continuous monitoring to promptly detect and correct these derangements by effective resuscitative support. In recent years, there has been increasing efforts to move from subjective and discontinuous monitoring to more objective and continuous monitoring of different physiological parameters. Some of them like pulse oximetry for arterial oxygen saturation and electrocardiography for heart rate monitoring are now part of resuscitation guidelines whereas others like respiratory function monitoring, near infrared spectroscopy, or amplitude integrated electroencephalography are being evaluated.

In this review, we describe some of the physiological parameters that can be monitored during delivery room emergencies and review the evidence for some of the monitoring technologies currently being evaluated.

1. Introduction

Adaptation from fetal to neonatal life at birth is a well-coordinated complex physiological transition involving mainly the cardiovascular and respiratory systems. Amazingly, the majority of infants undergo this transition without much need for assistance and only about 10% of them require some degree of support. This support may vary from application of positive end expiratory pressure (PEEP), positive pressure ventilation (PPV), to chest compression and medications. Effective and timely provision of this assistance is not only critical for survival but also may significantly affect long-term outcome [1,2].Despite the importance of this critical period, neonatal resuscitation at birth has lagged behind in terms of innovation with most of the interventions performed manually with subjective and episodic monitoring of its effectiveness. This is in stark contrast to infants admitted to the neonatal intensive care unit (NICU) who benefit from continuous and objective monitoring of multiple parameters guiding clinical decision-making.

Over the last decade, there has been significant advances in the field of neonatal resuscitation in the delivery room with continuous monitoring of arterial oxygen saturation (SpO_2) by pulse oximeter, and heart rate using electrocardiography (ECG) being part of the current neonatal resuscitation program (NRP) [3]. In addition, there are increasing efforts to evaluate newer technologies including continuous monitoring of ventilation, monitoring of tissue oxygenation and function, and continuous recording of the delivery of resuscitation (Table 1). These efforts are not only critical for improving outcomes in individual patients but also for the advancement and quality improvement in the field. In this manuscript, we will discuss some of the evidence and challenges faced by these monitoring strategies.

2. Monitoring of respiratory function

The most important part of successful transition at birth is aeration of the lungs with the establishment of an air-liquid interface for gas exchange, establishment and maintenance of functional residual capacity, and change from irregular fetal breathing movements to regular inspiratory efforts. The majority of preterm infants and about 3–5% of term infants require support to establish spontaneous ventilation emphasizing the importance of providing adequate respiratory support.

2.1. Respiratory function monitor

A respiratory function monitor with a flow sensor interposed between the endotracheal tube or mask and the PPV device can provide a real time display of tidal volume, airway pressures, gas flow and leak during resuscitation.

2.1.1. Tidal volume

There is ample animal and clinical data suggesting that brief periods of ventilation with excessive tidal volumes at birth can be associated with lung and brain injury [4–6]. The current methods of monitoring the effectiveness of positive pressure ventilation (PPV) are visual

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Table 1
Neonatal monitoring technologies during delivery room emergencies.

Monitoring technology	Potential role during delivery room emergencies	Current Evidence
Respiratory function monitor	• Tidal volume monitoring and targeting. • Monitoring of breath rate, inspiratory time, and PEEP. • Detection of gas leak around the face mask. • Assessment of endotracheal tube placement. • Detection of spontaneous breathing effort.	• Two small studies showed reduction in mask leak, intubation rates, oxygen supplementation, and number of breaths with excessive tidal volume [9,10]. • No current evidence on longer term outcomes.
Quantitative CO_2 monitoring	• Avoidance of extremes of CO_2 during resuscitation and transport	• Multiple studies reported the feasibility of quantitative CO2 monitoring during resuscitation but no effect on incidence of hypo or hypercarbia or other clinical outcomes.
Pulse oximetry	• Titration of oxygen supplementation to target arterial oxygen saturation. • Monitoring of arterial pulse wave as a surrogate for heart rate.	• No RCTs evaluating the effect of pulse oximetry during neonatal resuscitation at birth on clinical outcomes. • Some evidence that pulse oximetry could be less reliable and slower to detect heart rate when compared to ECG • No evidence of impact on clinical outcomes.
Near infra-red Spectroscopy	• Monitoring of tissue specific oxygenation with titration of oxygen supplementation to the desired targets.	• Pilot feasibility RCT enrolling 30 preterm infants showed reduction in low cerebral oxygen saturation with use of NIRS to guide respiratory support at birth with no impact on clinical outcomes [41].
Electrocardiography	• Monitoring of heart rate.	• Gold standard for heart rate assessment in newborn infants at birth. No evidence of impact on clinical outcomes.
Electrical velocimetry	• Monitoring of cardiac output during resuscitation.	• Prospective observational study showed feasibility of the technology. No current evidence of impact on outcomes.
Amplitude integrated EEG	• Monitoring of electrical activity of brain during resuscitation.	• Prospective observational study showed feasibility of the technology. No current evidence of impact on outcomes.
Video recording of resuscitation	• Auditing and quality improvement in delivery room practices. • Detection and correction of specific deficiencies in the provision of resuscitation. • Real time guidance and support during resuscitation.	• No current evidence of impact on clinical outcomes.

estimation of chest rise and improvement in heart rate. The use of chest rise as a marker of appropriate tidal volume has been shown to be often inaccurate [7,8].

A respiratory function monitor can be used to display tidal volume continuously. Expired tidal volume is a more accurate estimate of volume delivered to the lung due to the larger leaks occurring during inspiration. This data can then be used to adjust peak inspiratory pressure (PIP) or mask position to decrease leak in real time. The use of respiratory function monitor during PPV has been shown to reduce mask leak and the proportion of breaths with excessive tidal volumes [9,10].

One of the limiting factors for targeting tidal volume during PPV is the limited information on normative values for tidal volume shortly after birth. There is some evidence that spontaneously breathing, relatively mature infants generate tidal volumes between 4 and 8 ml/kg, but whether this data can be applied to sicker, extremely premature infants is not known [11,12].

2.1.2. Gas leaks

PPV using a facemask is the most frequent initial step for resuscitation in the delivery room. Adequate seal around the mask to provide effective PPV is a difficult skill to acquire with gas leaks around the mask resulting in loss of inspiratory tidal volume to the lungs. There is clear evidence that variable amount of leak is common during mask ventilation and this is difficult to estimate clinically [13,14]. This variability of leak during individual breaths increases the risk of insufficient or excessive tidal volume breaths.

The continuous trace of gas flow or tidal volume with the respiratory function monitor provides continuous visual feedback of leaks which can be used to take corrective measures to reduce them (Fig. 1). There is evidence from both simulation as well as clinical studies that the use of a respiratory function monitor results in reduced leak during PPV [9,15].

2.1.3. Other measures of ventilation

All current methods of PPV in the delivery room are prone to high variability in the breath rate and inspiratory time [16,17]. While excessively short inspiratory time may result in delivery of lower than intended tidal volumes [18], longer inspiratory times when combined with high breath rate may result in less time for expiration resulting in gas trapping. Respiratory function monitoring can help decrease these risks by providing numerical values as well as flow and volume waveforms in real time (Fig. 2).

Another use of respiratory function monitor is detection of airway obstruction, which is commonly seen in mask ventilation and is difficult to detect clinically. The use of respiratory function monitoring can help in detecting it earlier so corrective measures can be taken [19]. Similarly, detection of spontaneous breaths with adequate tidal volume can be difficult clinically. Use of a monitor can help to detect spontaneous respiratory efforts and adjust the positive pressure as necessary.

2.1.4. Detection of endotracheal tube position

Endotracheal intubation in the delivery room is a critical step in neonatal resuscitation. It is a difficult skill to acquire and maintain [20] and many infants require a prolonged time or more than one attempt for intubation. Both problems have been associated with worse outcomes [21–23]. The most common methods to confirm correct placement of the endotracheal tube, including detection of chest rise and auscultation of breath sounds are subjective and intermittent, increasing the risk of a late detection of wrong placement of the endotracheal tube. Colorimetric detection of carbon dioxide (CO_2) in the expired gas is one of the methods commonly used to confirm endotracheal tube placement. This test is dependent on adequate pulmonary blood flow for CO_2 to be exhaled, and may incorrectly suggest tube misplacement [24].

Observation of the flow curve on a respiratory function monitor can detect correct placement of the endotracheal tube and has been shown to be more accurate as well as quicker in detecting the correct tube position when compared to colorimetric CO_2 detector [25]. In addition, the continuous monitoring data from a respiratory function monitor can be used to detect potential complications such as abrupt reduction in tidal volume suggesting misplacement of the tube into a bronchus, or increase in leak suggesting proximal displacement of the tube.

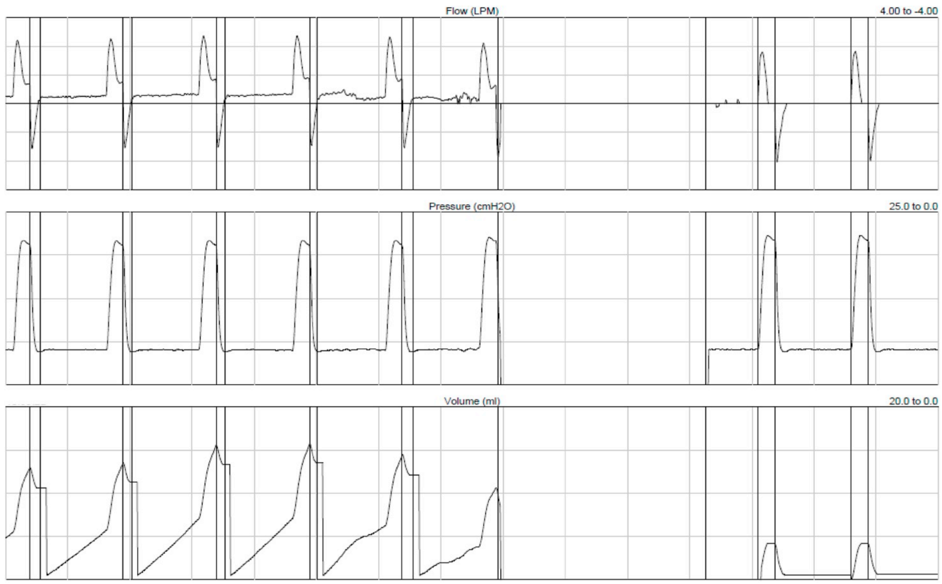

Fig. 1. Representative tracing of flow, pressure and volume during PPV with mask ventilation. There is both inspiratory and expiratory leak with flow above the baseline. There is no inspiratory or expiratory leak in last two positive pressure breaths after mask repositioning.

2.2. Challenges of respiratory function monitoring

Like many other technologies used in patient care, it is critical that respiratory function monitoring be used with clear evidence of improved clinically relevant outcomes. There is an urgent need for large randomized controlled trials evaluating the use of respiratory function monitor, with some efforts currently underway to accomplish this. Another concern for the use of respiratory function monitoring during neonatal resuscitation is finding a balance between use of the monitoring data and the clinical assessment of the patient to avoid over reliance on the monitor data. There is a need to optimize these monitors for use during neonatal resuscitation making their use simple and reliable [26,27].

3. Monitoring of effectiveness of ventilation

The goal of respiratory support is adequate gas exchange with oxygenation and CO_2 removal. In recent years, continuous monitoring of oxygenation with use of oxygen saturation has become standard of care in neonatal units. In addition, there have been some efforts to evaluate the role of continuous CO_2 monitoring in the delivery room for effectiveness of ventilation.

3.1. Monitoring of oxygenation

Oxygen is the most common drug used during neonatal resuscitation after birth. In addition to being required for aerobic metabolism and cellular function, oxygen plays a critical role in pulmonary vasodilatation with increased left ventricular preload and closure of intra – and extra cardiac shunts during fetal to neonatal transition. On the other hand, excessive oxygen supplementation can result in oxidative stress and cellular injury [28]. There is some evidence suggesting that excessive oxygen supplementation during resuscitation is associated with adverse outcomes including higher mortality, thereby stressing the importance for continuous monitoring of oxygenation during this critical period [29,30].

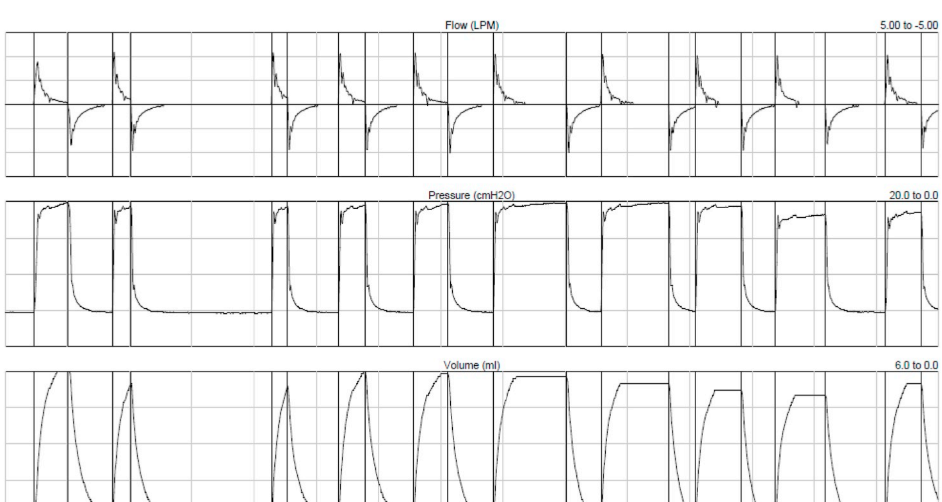

Fig. 2. Representative tracing of flow, pressure and volume during PPV. Darker vertical line represent start and end of inspiration and lighter vertical lines represent time. There is considerable variability in inspiratory time and breath rate.

3.1.1. Pulse oximetry

Pulse oximetry is the most common method to continuously monitor arterial oxygen saturation (SpO_2) by measuring differential absorption of light at two wavelengths by oxyhemoglobin and reduced hemoglobin. This data has been calibrated against direct measurements of arterial oxygen saturation to provide an accurate value of SpO_2. The advantages of pulse oximetry are ease of use, continuous noninvasive measurement, as well as quite accurate correlation with true arterial oxygen saturation in normoxemic and mildly hypoxemic conditions.

Even though pulse oximetry is the best available tool for monitoring of oxygenation, one should be aware of potential limitations of the technology. One of the limitation is the disagreement between pulse oximetry values and true arterial oxygen saturation with pulse oximetry underestimating arterial oxygen saturations in many situations [31,32]. This limitation is more pronounced in hypoxemic conditions, something which is commonly encountered during transition at birth [33]. In recent years, there has been development of newer pulse oximetry sensors with some improvement in accuracy [34]. Other technological limitations include time delay in signal processing, artifact due to limb movement or low perfusion, all of which limit the accuracy of data when used during resuscitation at birth.

One of the critiques for using SpO_2 for titrating oxygen supplementation is the lack of good quality evidence supporting target SpO_2 ranges during transition. The current target ranges of SpO_2 as advised by NRP are based on healthy neonates with very small number of infants being of extremely low gestational age [35]. In the majority of extremely preterm infants requiring respiratory support, these targets are not easily achieved [36]. There is an urgent need for studies evaluating different ranges of SpO_2 after birth and the effects on clinically relevant outcomes.

3.1.2. Near infrared spectroscopy

While arterial oxygen saturation is a surrogate of oxygen content in the blood, it does not provide a complete picture of oxygen delivery, which is dependent on multiple factors including cardiac output, hemoglobin content and changes in end organ blood supply. These factors are likely to play a more prominent role at birth during the time of cardiovascular transition with changes in cardiac output and regional blood flow. In addition, tissues also have the ability to increase the extraction of oxygen in the face of decreased oxygen delivery or increased metabolic demand [37]. These factors have led to increasing efforts to evaluate different ways to monitor tissue oxygenation and extraction.

Near infrared spectroscopy (NIRS) is one of the methods to monitor tissue oxygenation by measuring differential absorption of light according to tissue content of deoxygenated and oxygenated hemoglobin to provide oxygen saturation of underlying tissue. Unlike pulse oximetry, NIRS provides a venous weighted saturation of underlying tissue [38]. There has been increasing interest in monitoring cerebral tissue oxygenation ($CrSO_2$) during transition with increasing amount of normative data in neonates [39]. In a small observational study, Baik et al. showed an association between IVH and low $CrSO_2$ during transition suggesting the potential utility of $CrSO_2$ monitoring during resuscitation [40]. In a feasibility trial in preterm infants, Pichler et al. showed reduction in cerebral hypoxia with use of NIRS guided oxygen supplementation during resuscitation, when compared to controls but there was no significant difference in outcomes [41]. Based on these results, a multicentric randomized trial is currently underway to evaluate NIRS guided oxygen supplementation during resuscitation in preterm infants [42].

Despite early promising results, many questions still remain regarding use of NIRS during resuscitation. These include variability in values according to the device, limited data on normative values in different gestation age groups, as well as definitive evidence on its effect on outcomes.

3.2. Monitoring CO_2 elimination

One of the markers of adequacy of respiratory support during resuscitation is arterial CO_2 levels. Increased CO_2 level not only reflect inadequate ventilation but also may affect cerebral blood flow. One of the methods for CO_2 monitoring is end tidal CO_2 ($ETCO_2$) which uses a CO_2 sensor interposed between the facemask or ET tube and the PPV device. Obtained values have been shown to correlate well with arterial CO_2 [43].

There is limited data on the use of continuous quantitative $ETCO_2$ monitoring during neonatal resuscitation with studies showing feasibility of the method but no effect on proportion of infants with CO_2 outside of a pre-specified range [44]. There is a need for further studies to evaluate the effect on clinical outcome before this technology can be recommended for routine use.

4. Cardiovascular monitoring

The complex physiologic changes that occur in the cardiovascular system after birth are an integral part of successful fetal to neonatal transition. Establishment of effective ventilation and oxygenation results in a reduction in pulmonary vascular resistance thereby increasing pulmonary blood flow, venous return to the left side of the heart, and an increase in left ventricular output. All these changes are critical for adequate systemic blood flow and any significant perturbation may affect outcome.

Evaluation of heart rate is a critical part of current NRP guidelines, not only as an important marker for the need for resuscitation, but also increase in heart rate is considered as the most reliable indicator of effective ventilation. Despite the importance of accurate heart rate detection, the methods to assess it have been subjective and prone to error until recently. Some of the common methods include palpation of brachial or femoral artery, umbilical cord pulsation, or auscultation of heart rate. All these methods are subjective, provide discontinuous observation, and may interfere with critical components of resuscitation such as ventilation and chest compression [45].

Pulse oximetry and electrocardiography (ECG) are two methods which have been evaluated the most for continuous noninvasive measurement of heart rate during resuscitation at birth. Since pulse oximetry is dependent on propagation of pulse wave in the artery being monitored, it may provide inaccurate values during conditions of low perfusion, commonly seen during transition after birth. In addition, limitations of pulse oximeter include effect of motion, and the delay in getting accurate data. On the other hand, using pulse oximeter for heart rate detection avoids the need for another monitor or leads placement needed for ECG. The current NRP guidelines recommend ECG as the preferred method for evaluation of heart rate. Both, pulse oximeter and ECG are more reliable and accurate than palpation or auscultation, but there is increasing evidence that ECG may detect heart rate quicker and more accurately than pulse oximeter in certain conditions [46,47]. Some of the rare limitation of using ECG could be in cases of significant subcutaneous edema or pulseless electrical activity with ECG providing inaccurate information underlying the need for not relying on single monitoring technology [48]. Other emerging technologies for heart rate monitoring in the delivery room include doppler ultrasound, auscultation with digital stethoscope, and photoplethysmography.

While heart rate monitoring is commonly used during resuscitation, cardiac output is likely to be a better marker of tissue perfusion. Noninvasive continuous monitoring of cardiac output using electrical velocimetry has been evaluated in the NICU and has been shown to have good correlation with cardiac output measured by echocardiography. There are early reports of its use during transition at birth but further work is needed to validate the technology, generate normative values and learn how this information can be used in clinical management [49].

5. Monitoring brain function

The brain is one of the organs at highest risk of injury during resuscitation at birth and there is an increasing effort to monitor its function continuously. While NIRS monitoring provides some information on brain oxygenation and perfusion, amplitude-integrated electroencephalography (aEEG) is a potential tool to continuously monitor cerebral activity during resuscitation. Two recent studies have described the use of aEEG during early transition at birth showing its feasibility and an association between aEEG activity, cerebral oxygenation and the need for resuscitation [50,51]. Advantages of this technology include continuous noninvasive monitoring but some of the limitations are the need for additional equipment and space, motion artefacts, and interpretation of the signal. Significant work needs to be done to define normal and abnormal brain activity during transition, effects of different resuscitation measures, as well as the impact of this type of monitoring on neurological outcomes.

6. Monitoring effectiveness of resuscitation

All neonatal resuscitation guidelines are based on a set sequence of observations and actions to be performed at set time periods in a highly stressful condition. Currently, there is no mechanism to objectively collect data on deviations from NRP, both in terms of sequence as well as timing. In most conditions, the information is recorded as a summary by the clinical team after the event. This lack of objective monitoring of delivery of resuscitation when combined with the limitations of APGAR scores as marker of infant's condition during resuscitation, makes this critical period of transition at birth relatively inaccessible to critical evaluation. Some of the consequences of this include difficulty in quality improvement, training and advancement of resuscitation providers, developing evidence-based guidelines or objective evaluation of any changes in the guidelines. This is reflected in the current resuscitation guidelines where most of the recommendations are based on no or very limited objective evidence.

One of the methods for monitoring the resuscitation process includes video recording of the procedure. In one such study, Finer et al. used video recordings and showed deviation from NRP guidelines in more than half of the cases [52]. Video recording when used in combination with other physiological monitoring data can be used to analyze different steps of resuscitation to analyze specific deficiencies [53]. One of the important deficiencies of current neonatal resuscitation training is reliance on simulation for training which despite significant recent improvements, does not match real life scenarios. Video recording of actual resuscitation can be extremely useful in the training of providers.

Some of the potential challenges for its use includes concerns for privacy for both patient and clinicians, medico-legal issues, as well as the psychological effect on the resuscitation providers. In addition to robust cost benefit evaluation, studies showing positive impact of video recording on clinical outcomes needs to be performed before it can be recommended in routine clinical practice.

7. Future advances in monitoring in the delivery room

One of the critical components of fetal to neonatal transition at birth is homogenous lung aeration and establishment of functional residual capacity. As opposed to provision of standard respiratory support to all neonates at birth, provision of respiratory support tailored to the specific needs of each infant may potentially results in less lung injury and better outcome. One way to achieve this is by real time monitoring of lung aeration using electrical impedance tomography (EIT) and optimizing the respiratory support accordingly during transition. In one study in preterm lambs, Tingay et al. showed that the individualized lung recruitment strategies using EIT may reduce lung injury [54].

There has been increasing use of closed loop technologies like automated adjustment of inspired oxygen according to measured SpO_2, or adjustment of peak inspiratory pressure according to exhaled and target tidal volume in volume targeted ventilation in the neonatal intensive care unit. The next step for continuous monitoring in the field of neonatal resuscitation is evaluation of these technologies. Before these new systems can be used clinically, there is a need to develop evidence based normative ranges for these measures and interventions at different stages of transition along with critical evaluation of their impact on clinically relevant outcomes.

As neonatal resuscitation at birth becomes more complex and requires highly skilled clinicians, provision of these services on every birth is a great challenge not only in developing countries but also in the more advanced settings. As the majority of infants do not require much support at birth, low volume and unpredictability of the need for neonatal resuscitation makes availability of skilled personnel and retention of their skills very challenging. One of the potential ways to overcome this challenge is the use of telemedicine with both simulation training of the staff as well as real time support during resuscitation [55,56].

One of the advantages of monitoring neonatal resuscitation is the collection of various parameters of oxygenation and ventilation along with the degree and timing of support provided during fetal to neonatal transition. If these data are collected in a large number of infants of different gestational ages, and requiring different respiratory support and correlated with clinical outcomes, these can not only be used to develop evidence-based guidelines but also can be used to develop automated systems with machine learning capabilities. In addition, these data can be used in combination with cellular and molecular markers of tissue injury to understand the pathways of various perinatal disease processes and develop newer treatment strategies.

8. Conclusion

The transition from a placenta dependent fetus to a self-sustained neonate after birth is a complex process requiring aeration of lungs, improving oxygenation with resultant cardiovascular changes. A minority of infants need support during this transition but when needed, timing and effectiveness of these efforts are not only lifesaving but also may have long-term benefits. There are concerted efforts to objectively evaluate the effects of support during this transition. So far, most of the currently recommended monitoring strategies are simple technologies routinely used in NICU, like pulse oximetry for SpO_2 or ECG for heart rate monitoring.

There is increasing interest in bringing other technologies currently used in NICU, like ventilation parameter monitoring with RFM, or monitoring of brain oxygenation with NIRS to the delivery room. Some of the obstacles for using these or any other monitoring technology in the delivery room include the lack of normative values, cost and space limitations, as well as limited information on their impact on the patients and on the clinical team. There is a need for well conducted large randomized controlled trials evaluating relevant outcomes before any of these monitoring strategies can be recommended for routine use.

As in other fields of medicine, increasing use of objective, continuous monitoring is likely to become an integral part of neonatal resuscitation at birth. Whether these changes will improve long term health will need to be closely evaluated.

Practice points

- Pulse oximetry for arterial oxygen saturation and ECG for heart rate detection are more accurate than subjective assessment, but their impact on clinical outcome is not known.
- Respiratory function monitoring has been shown to reduce mask leak and decrease high tidal volumes with studies on their impact on clinical outcomes currently underway.
- There is limited normative data for infants of different gestational ages for currently used monitoring parameters in the delivery room.

Research directions

- Role of tissue oxygenation monitoring after birth and its effect on clinical outcomes.
- Use of respiratory function monitor data to adjust respiratory support and its impact on clinical outcomes.
- Development of tools for continuous monitoring of regional perfusion and effect of different management strategies on outcomes.

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