Electrical Impedance Tomography (EIT) in Neonatal Respiratory Care: A Curated Bibliography

Respiratory management in neonatal and adult critical care patients presents significant challenges, especially for populations with special physiological needs like neonates. Neonates have distinct physiological characteristics, such as small airway calibers, compliant chest walls, and low functional residual capacity (FRC), making ventilation management especially difficult.[1] Furthermore, the variability of respiratory problems, as well as the use of multiple invasive and noninvasive respiratory support devices, contribute to significant practice variability, which affects patient outcomes.[2] Conditions like bronchopulmonary dysplasia (BPD) and chronic lung disease (CLD) complicates neonatal respiratory care, necessitating personalized therapeutic approaches.[3] Individualized ventilatory strategies are required to effectively manage these conditions.

Electrical impedance tomography (EIT) is a radiation-free, noninvasive imaging technique that provides real-time monitoring of regional air content measuring changes in thoracic electrical conductivity. EIT provides a safe and continuous bedside monitoring solution that is particularly advantageous in neonatal and pediatric populations. It enables clinicians to evaluate the mechanical ventilation settings, ventilation distribution, and lung recruitment. This bibliography focuses exclusively on studies utilizing the Sentec's EIT System.

This document serves as a curated collection of important studies on the application of Sentec EIT in neonatal and pediatric care. It is organized by relevant clinical themes to assist clinicians and researchers in navigating the existing literature. Studies presented in this document are grouped into validation, personalized ventilation, weaning from mechanical ventilation, therapeutic interventions, and applications in resuscitation or the delivery room.

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2. Shalish, W., Anna, GMS. Respiratory Management of Newborns. 2016.
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Validation and Clinical Performance of EIT in Neonatal Care

The Sentec EIT system has been rigorously validated for use in neonatal populations. Sophocleous et al. (2018) demonstrated the clinical efficacy of Sentec's novel textile interface for neonatal EIT, addressing the unique challenges posed by its application in small, delicate patients. This advancement improved the usability and comfort of EIT monitoring for neonates.

Further validation studies have concentrated on optimizing EIT measurement techniques. Sophocleous et al. (2020) examined how the sternal electrode gap and belt rotation influence the reliability of pulmonary EIT parameters, offering insights for ideal electrode positioning in neonates. A pivotal study by Becher et al. (2021) greatly advanced the validation of EIT for extended application in neonatal and pediatric critical care. This observational study conducted across multiple centers involved 200 patients with postmenstrual ages ranging from 25 weeks to 36 months, with weights from 730 g to 12.8 kg, monitored for an average of 53+/- 20 hours each, who were at risk for or experiencing respiratory failure. The study showed that:

1. Continuous EIT monitoring for durations of up to 72 hours is both feasible and safe in neonates and young children.
2. EIT demonstrated good tolerability, with minor skin irritations (temporary redness or imprint) occurring in only 10% of patients and no instances of moderate or severe adverse events.
3. The study identified posture-dependent variations in ventilation distribution, influenced by postmenstrual age within a substantial patient cohort.

These studies have established EIT as a reliable tool for continuous regional air content monitoring in this vulnerable population.

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2. Sophocleous, L., Waldmann, A.D., Becher, T., et al. Effect of sternal electrode gap and belt rotation on the robustness of pulmonary electrical impedance tomography parameters. *Physiol Meas*. 2020.
3. Becher, T.H., Miedema, M., Kallio, M., et al. Prolonged Continuous Monitoring of Regional Lung Function in Infants with Respiratory Failure. *Ann Am Thorac Soc*. 2022.
4. Rahtu, M., Frerichs, I., Pokka, T., Becher, T., Peltoniemi, O., Kallio, M. Effect of body position on ventilation distribution in healthy newborn infants: an observational study. *Arch Dis Child Fetal Neonatal Ed*. 2024.
5. Miedema, M., Waldmann, A., McCall, K.E., Böhm, S.H., van Kaam, A.H., Tingay, D.G. Individualized Multiplanar Electrical Impedance Tomography in Infants to Optimize Lung Monitoring. *Am J Respir Crit Care Med*. 2017.
6. Janulionis, A., Sutova, V., Langiene, V., Virsilas, E., Drejeriene, V., Liubsys, A., Valiulis, A. Regional differences in lung ventilation during the early transition period in late preterm and term neonates assessed by electrical impedance tomography. *Children (Basel)*. 2024.

Personalization of Ventilation Strategies

The use of EIT has demonstrated its efficacy as a valuable tool for personalizing ventilation in neonatal care. Becher et al. (2022) showed feasibility of prolonged continuous monitoring of regional lung function in infants with respiratory failure, enabling real-time adjustment of ventilation. This is important due to variability in neonatal lung conditions and the need for individualized care. Rahtu et al. (2024) further explored the impact of body positioning on ventilation distribution in healthy newborns, providing insights for optimizing positioning during mechanical ventilation. Together, these findings highlight EIT's role in guiding personalized interventions to optimize ventilation and reduce ventilator-related lung complications.

1. Becher, T.H., Miedema, M., Kallio, M., et al. Prolonged Continuous Monitoring of Regional Lung Function in Infants with Respiratory Failure. *Ann Am Thorac Soc*. 2022.
2. Onland, W., Hutten, J., Miedema, M., et al. Precision Medicine in Neonates: Future Perspectives for the Lung. *Front Pediatr*. 2020;8:586061. 2020.
3. Rahtu, M., Frerichs, I., Pokka, T., Becher, T., Peltoniemi, O., Kallio, M. Effect of body position on ventilation distribution in healthy newborn infants: an observational study. *Arch Dis Child Fetal Neonatal Ed*. 2024.
4. Kallio, M., Rahtu, M., van Kaam, A.H., Bayford, R., Rimensberger, P.C., Frerichs, I. Electrical impedance tomography reveals pathophysiology of neonatal pneumothorax during NAVA. *Clin Case Rep*. 2020.
5. Tingay, D.G., Waldmann, A.D., Frerichs, I., Ranganathan, S., Adler, A.. Electrical Impedance Tomography Can Identify Ventilation and Perfusion Defects: A Neonatal Case. *Am J Respir Crit Care Med*. 2019.

Weaning from Mechanical Ventilation

Weaning preterm infants from mechanical ventilation is essential, as prolonged ventilation and unsuccessful extubation increase morbidity rates.* EIT facilitates real-time monitoring, offering insights into ventilation distribution to support the weaning process.

In the 2021 DELUX study, Plastina et al. utilized EIT to monitor changes in end-expiratory lung impedance (EELI) during extubation in preterm infants.

Key Findings

1. *Significant FRC Loss:* A 40% decline in FRC occurred during extubation, mainly attributed to the removal of adhesive tape securing the endotracheal tube.
2. *Rapid Recovery:* About 40% of the lost FRC was restored within the initial ten breaths post-extubation, highlighting the importance of prompt noninvasive ventilation.
3. *Optimal Positioning:* Positioning infants in a prone orientation post-extubation markedly enhanced FRC, surpassing levels observed prior to extubation.
4. *Clinical Correlation:* Changes in FRC exhibited a strong correlation with oxygen saturation (SpO_2) levels, underscoring the clinical significance of EIT.

Clinical Implications

- *FRC Loss Prevention:* Minimizing FRC loss during extubation, particularly during tape removal, may enhance patient outcomes.
- *Seamless Transition:* Immediate noninvasive support following extubation is essential for the prompt recovery of lung volume.
- *Optimal Positioning:* Prone positioning can enhance respiratory stability post-extubation.
- *Individualized Monitoring:* EIT allows real-time, tailored monitoring to identify extubation risks and optimize interventions.

Future Directions

Additional research is required to establish standardized EIT protocols for extubation, develop predictive models for extubation success, and assess the effects of noninvasive support modes on lung recovery. In summary, EIT provides essential insights into lung function during the weaning process, thereby improving the management of preterm infants and potentially enhancing their outcomes.

1. Plastina, L., Gaertner, V.D., Waldmann, A.D., Thomann, J., Bassler, D., Rüegger, C.M. The DELUX study: development of lung volumes during extubation of preterm infants. *Pediatr Res.* 2022.

*Fischer, et al. *Pediatrics.* 2013.; Choi, et al. *The Journal of Pediatrics.* 2017.

Evaluation of Therapeutic Interventions

EIT has become an effective tool for assessing the impact of various therapeutic strategies in neonatal respiratory care. Its ability to continuously and noninvasively monitor regional lung function in real-time makes it particularly suited for assessing the effectiveness of different treatments and support interventions.

Noninvasive Ventilation Strategies

1. *HFNC vs. nCPAP:* Gaertner et al. (2022) used EIT to analyze lung volume distribution in preterm infants receiving noninvasive high-frequency ventilation (nHFOV) compared to nasal continuous positive airway pressure (nCPAP). Although nCPAP resulted in higher tidal volumes, the overall distribution of tidal volumes throughout the lungs was comparable between the two methods. nHFOV significantly enhanced lung aeration, especially in non-gravity-dependent regions, facilitating a more uniform air distribution.

2. *Nasal High-Frequency Oscillatory High-Flow Therapy ("Osciflow"):* Thomann et al. (2023) investigated the application of osciflow in preterm infants. This therapy did not significantly decrease desaturation or bradycardia events relative to conventional high-flow therapy; however, EIT data indicated the presence of oscillations at the lung level. These oscillations constituted approximately 9% of the total tidal volume, suggesting a limited impact.

3. *Positioning Effects:* Schinckel et al. (2020) used EIT to explore the impact of skin-to-skin care (SSC) on regional lung ventilation in stable infants. The findings indicated that SSC resulted in a unique ventilation pattern, characterized by increased airflow directed toward the dorsal regions of the lung in comparison to prone positioning in a crib.

4. *Transitioning from nCPAP to High-Flow:* Büchler et al. (2024) used EIT to investigate lung volume changes in stable preterm infants as they transitioned from nasal continuous positive airway pressure (nCPAP) to high-flow nasal cannula therapy. The transition was associated with a steady reduction in end-expiratory lung volume (EELI). Despite gradual escalation back to pre-weaning flow levels, high-flow treatment did not fully restore lung volume to baseline. Only switching back to nCPAP improved EELV, but not to pre-intervention levels. These changes in lung aeration were followed by physiological responses, such as increased heart rate and decreased oxygenation (SpO_2/FiO_2). The findings suggest that pressures higher than those generated by high-flow may be required to maintain alveolar stability and recover lung capacity in preterm infants weaned from nCPAP.

Surfactant Administration

Gaertner et al. (2023) showed slight increases in lung aeration after prophylactic surfactant nebulization in preterm infants, particularly in central lung areas.

Suctioning Procedures

Händel et al. (2023) used EIT to examine the impacts of routine endotracheal suctioning in neonates and young infants. Suctioning resulted in EIT-detectable, though minor, alterations in ventilation distribution, characterized by a slight dorsal shift in the center of ventilation and a 7% reduction in tidal impedance variation. Regional time constants, indicative of respiratory system mechanics, displayed no significant change following suctioning.

Clinical Implications

1. *Personalized Respiratory Support:* EIT allows for real-time evaluation of the effects of different interventions on individual patients, enabling clinicians to tailor respiratory support strategies.
2. *Optimization of Noninvasive Ventilation:* Comparing different modes of noninvasive support (e.g., HFNC, nCPAP, nHFOV) using EIT can help in selecting the most effective strategy for individual patient.
3. *Surfactant Administration Guidance:* EIT can potentially guide the timing and assessment of surfactant therapy.
4. *Suctioning Protocols:* The findings on suctioning effects suggest that routine suctioning may have limited impact on lung mechanics in many cases, potentially leading to more targeted use of this procedure.
5. *Positioning Strategies:* EIT data on the effects of different positions (including skin-to-skin care) can inform optimal positioning for ventilation distribution.

In conclusion, EIT supports the evaluation of therapeutic interventions in neonatal care, providing unique insights into lung function that can help guide personalized respiratory support.

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3. Händel, C., Becher, T., Miedema, M., et al. Effect of routine suction on lung aeration in critically ill neonates and young infants measured with electrical impedance tomography. *Sci Rep*. 2023.
4. Thomann, J., Gaertner, V.D., Waldmann, A.D., Plastina, L., Bassler, D., Rüegger, C.M. Nasal high frequency oscillatory highflow therapy in preterm infants: A randomized crossover trial. *Pediatr Pulmonol*. 2024.
5. Gaertner, V.D., Minocchieri, S., Waldmann, A.D., et al. Prophylactic surfactant nebulisation for the early aeration of the preterm lung: a randomised clinical trial. *Arch Dis Child Fetal Neonatal Ed*. 2023.
6. Belting, C., Rüegger, C.M., Waldmann, A.D., Bassler, D., Gaertner, V.D. Rescue nasopharyngeal tube for preterm infants non-responsive to initial ventilation after birth. *Pediatr Res*. 2024.

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8. Schinckel, N.F., Hickey, L., Perkins, E.J., et al. Skin-to-skin care alters regional ventilation in stable neonates. *Arch Dis Child Fetal Neonatal Ed*. 2021.
9. Thomson, J., Rüegger, C.M., Perkins, E.J., et al. Regional ventilation characteristics during non-invasive respiratory support in preterm infants. *Arch Dis Child Fetal Neonatal Ed*. 2021.
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12. Strodthoff, C., Kähkönen, T., Bayford, R.H., Becher, T., Frerichs, I., Kallio, M. Bronchodilator effect on regional lung function in pediatric viral lower respiratory tract infections. *Physiol Meas*. 2022.
13. Gaertner, V.D., Waldmann, A.D., Davis, P.G., et al. Lung volume changes during apnoeas in preterm infants. *Arch Dis Child Fetal Neonatal Ed*. 2023.

Delivery Room Applications and Early Interventions

EIT has been used in the delivery room and early therapies for preterm newborns to gain understanding of the physiological changes that take place during the crucial transition from fetal to neonatal life. These investigations have not only improved our understanding of lung aeration and ventilation strategies, but they have also created new opportunities for individualized respiratory care in the immediate postnatal period.

Respiratory Transition and Breathing Patterns

Tingay et al. (2021) conducted a complementary investigation that used EIT to image the respiratory transition in term infants born via elective cesarean surgery. Their findings provide further insights into the intricacies of the first breaths of life.

1. *Rapid lung aeration*: The majority of lung aeration occurred shortly after birth, with an exponential pattern.
2. *Spatiotemporal heterogeneity*: Initially, ventilation favored the right lung and gravity-dependent regions before transitioning to a more anatomical ventrodorsal pattern.
3. *Crying as a physiological mechanism*: Crying, which was prevalent in the first two minutes, resulted in distinct flow characteristics, including quicker inspiratory flow and complex expiratory patterns, such as expiratory braking and pendelluft flows.
4. *FRC preservation*: Expiratory braking, particularly during crying helped to preserve FRC and permitted gas redistribution within the lungs.

These findings highlight the complexities of respiratory transition in both preterm and term newborns, suggesting that different breathing patterns play distinct roles in establishing FRC and optimizing ventilation soon following birth. The findings all underline the relevance of crying and expiratory braking mechanisms in aiding a successful transition to air breathing.

Following these observations, Gaertner et al. (2024) conducted a study analyzing EIT data from very preterm infants (26-32 weeks gestational age) during the first ten minutes after birth. They identified three distinct breathing patterns:

1. Tidal breathing (44% of breaths): Sinusoidal breathing without expiratory disruption.
2. Braking (50% of breaths): Expiratory brake with a short duration.
3. Holding (6% of breaths): Expiratory brake with a long duration.

Importantly, only the act of holding breaths was linked to an increase in the end-expiratory lung volume, contributing to the initial expansion of the lungs. This phenomenon was made possible by the redistribution of air within the chest, specifically towards the left side and the regions of the lung that are not affected by gravity, which occurred during braking or holding maneuvers. This redistribution is likely caused by the movement of gas known as pendelluft. These findings emphasize the intricate nature of respiratory transition in premature newborns and indicate that various breathing patterns may have distinct functions in building FRC immediately after birth.

EIT provides real-time insight into regional and time dynamics of the resuscitation process enabling more comprehensive evaluation of the pulmonary to establish FRC and ventilation during this critical period.

Rescue Interventions in Non-Responsive Infants

Belting et al. (2024) investigated the use of a rescue nasopharyngeal tube (NPT) in very preterm infants who were non-responsive to initial facemask ventilation after birth. Using EIT, they found that:

1. Insertion of an NPT resulted in a considerable increase in end-expiratory lung impedance (EELI), corresponding to an increase in FRC.
2. While the increase in lung volume was not significantly larger than during facemask ventilation, NPT insertion was associated with significant improvements in heart rate and oxygenation.
3. The use of an NPT as a rescue airway may prevent intubation in some non-responsive infants.

This study demonstrates the potential of EIT to help guide clinical decision-making in challenging resuscitation scenarios and supports the consideration of NPT as an alternative airway in specific situations.

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6. Gaertner, V.D., Restin, T., Bassler, D., Fauchère, J.C., Rüegger, C.M. Case report: Intrapulmonary tidal volumes in a preterm infant with chest wall rigidity. *Front Pediatr*. 2022.

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