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Advancing Noninvasive
Patient Monitoring

EIT applications in neonatology - A literature review

Contents

Introduction

The use of electrical impedance tomography (EIT) in neonatology has been so far limited to research, with several potential applications being described in literature. Recently SenTec has obtained CE mark registration for its new EIT system, the LuMon™ System, which appears in two separate configurations, one for adults/children and the other for neonates/infants. SenTec is now able to offer the first commercial neonatal EIT system which also includes EIT belts and contact medium specifically developed for neonates.
The scope of this document is to highlight some applications of electrical impedance tomography (EIT) in neonatology reported in literature and mention some contributions where SenTec EIT technology was used, suggesting its potential for future use.
A thorough review of the literature is out of the scope of this document. Literature reviews of EIT applications in neonatology have been published, e.g. by Frerichs et al.[1], with additional analysis in the respective online supplement 8, and by Masner et al.[2]
After each publication, the application discussed is summarized and, if an EIT technology other than SenTec was used, brief indications on how the LuMon™ System could be utilized for similar applications are given.

EIT in neonatology: a collection of publications and applications

Van der Burg et al. **CHANGES IN LUNG VOLUME AND VENTILATION FOLLOWING TRANSITION FROM INVASIVE TO NONINVASIVE RESPIRATORY SUPPORT AND PRONE POSITIONING IN PRETERM INFANTS.** Pediatr Res. 2015; 77(3):484-488. doi:10.1038/pr.2014.201

APPLICATION: ASSESS THE EFFECT OF EXTUBATION AND SUBSEQUENT PRONE POSITIONING ON LUNG VOLUMES

EIT was used in this study to assess the effect of extubation and subsequent prone positioning on lung volumes. 20 preterm infants were monitored during transition from endotracheal to nasal continuous positive airway pressure and then following prone positioning. The preterm infants were able to maintain their end expiratory lung volume (EELV) and increase their tidal volume during the transition, while placing the infants in prone position resulted in an increase in EELV and a ventral shift in tidal ventilation distribution. Indeed, to pass these transitions successfully, infants should be able to maintain an optimal EELV and normal ventilation. This is apparently the first study that has continuously monitored changes in EELV and ventilation during transition from invasive to noninvasive respiratory support.

HOW-TO IN LUMON™: LOOK AT THE TREND OF EELI AND THE DIFFERENCE BETWEEN EILI AND EELI, REPRESENTING TIDAL VOLUME. STRETCH AND SILENT SPACES IMAGES AND TRENDS GIVE INFORMATION ON TIDAL VOLUME DISTRIBUTION.

Steinmann et al. **ELECTRICAL IMPEDANCE TOMOGRAPHY FOR VERIFICATION OF CORRECT ENDOTRACHEAL TUBE PLACEMENT IN PAEDIATRIC PATIENTS: A FEASIBILITY STUDY.** Acta Anaesthesiol Scand. 2013; 57(7):881-887. doi:10.1111/aas.12143

APPLICATION: DETECT ENDOTRACHEAL TUBE MISPLACEMENT

To assess the ability of EIT to guide and confirm endotracheal tube placement, EIT measurements were recorded in 18 pediatric patients between 4 weeks of age and 18 years and then analyzed retrospectively, in particular regarding the distribution of ventilation between left and right lung. Homogeneous distribution of ventilation between left and right lung monitored with EIT correlated in each patient with correct endotracheal ETT placement. When ETT was misplaced this was also obvious from the EIT record.

HOW-TO IN LUMON™: LOOK AT THE GLOBAL DYNAMIC IMAGE SHOWING AIR DISTRIBUTION IN REAL TIME, AS WELL AS STRETCH AND SILENT SPACES IMAGES, TO CHECK FOR RELEVANT DIFFERENCES BETWEEN LEFT AND RIGHT LUNG.

[1] Frerichs et al. Chest electrical impedance tomography examination, data analysis, terminology, clinical use and recommendations: consensus statement of the TRanslational EIT development stuDy group. Thorax. 72(1), 2017, pp.83-93.
[2] Masner et al. Electrical impedance tomography for neonatal ventilation assessment: a narrative review. J. Phys.: Conf. Ser. 1272, 2019, pp.1-9.

Chatziioannidis et al. **ASSESSMENT OF LUNG VENTILATION IN INFANTS WITH RESPIRATORY DISTRESS SYNDROME USING ELECTRICAL IMPEDANCE TOMOGRAPHY.** Hippokratia. 2013; 17(2):115-119.

APPLICATION: DETERMINE CHANGES OF GLOBAL AND REGIONAL LUNG FUNCTION AFTER EXOGENOUS SURFACTANT ADMINISTRATION

The aim of the study was to determine changes of global and regional lung function after exogenous surfactant administration in mechanically ventilated infants with respiratory distress syndrome (RDS).
Repeated EIT measurements were performed before and after surfactant administration in 17 preterm infants suffering from RDS. These allowed to observe an improved lung function and a more homogeneous air distribution after surfactant administration. Other diagnostic techniques such as blood gas analysis were used and confirmed the improvement, however these techniques can only assess the lung function globally and may be associated with undesired side-effects.

HOW-TO IN LUMON™: LOOK AT THE TREND OF EELI AND THE DIFFERENCE BETWEEN EILI AND EELI, REPRESENTING TIDAL VOLUME. STRETCH AND SILENT SPACES IMAGES AND TRENDS GIVE INFORMATION ON TIDAL VOLUME DISTRIBUTION.

Rossi et al. **ELECTRICAL IMPEDANCE TOMOGRAPHY TO EVALUATE AIR DISTRIBUTION PRIOR TO EXTUBATION IN VERY-LOW-BIRTH-WEIGHT INFANTS: A FEASIBILITY STUDY.** Clinics (Sao Paulo). 2013; 68(3):345-350. doi:10.6061/clinics/2013(03)oa10

APPLICATION: GUIDE SETTINGS OF VENTILATION SUPPORT

This study used EIT on 14 newborns to determine the feasibility of evaluating the positive end-expiratory pressure level associated with a more homogeneous air distribution within the lungs before extubation. Ventilation was considered homogeneous when the ratio of ventilation between dependent and non-dependent lung areas was close to 1. The pressure that determined the best ventilation homogeneity was defined as the best positive end-expiratory pressure. This study showed that EIT can be safely and successfully used in patients ready for extubation to suggest the best ventilation homogeneity, which is influenced by the level of expiratory pressure applied.

HOW-TO IN LUMON™: CONSIDER THE EVOLUTION OF STRETCH AND SILENT SPACES IMAGES GIVING INFORMATION ON TIDAL VOLUME DISTRIBUTION. TRENDS OF DEPENDENT AND NON-DEPENDENT SILENT SPACES AND CENTER OF VENTILATION GIVE INFORMATION ON HOMOGENEITY WITH RESPECT TO GRAVITY TAKING INTO ACCOUNT EVENTUAL POSITION CHANGES.

Miedema et al. **EFFECT OF NASAL CONTINUOUS AND BIPHASIC POSITIVE AIRWAY PRESSURE ON LUNG VOLUME IN PRETERM INFANTS. J PEDIATR.** 2013; 162(4):691-697. doi:10.1016/j.jpeds.2012.09.027

APPLICATION: MONITOR CHANGES IN LUNG VOLUMES AND VENTILATION DISTRIBUTION WITH DIFFERENT SETTINGS OF NON-INVASIVE POSITIVE AIRWAY PRESSURE VENTILATION

Changes in EELV and tidal volumes were measured in 22 preterm infants through electrical impedance tomography and respiratory inductive plethysmography during 3 levels of nasal continuous positive airway pressure (nCPAP) and during unsynchronized nasal biphasic positive airway pressure (BiPAP).
Increasing nCPAP in the range of 2 to 6 cmH2O resulted in a homogeneous increase in EELV and an increase in tidal volume with a more physiologic ventilation distribution. Unsynchronized BiPAP did not improve tidal volume compared with nCPAP.

HOW-TO IN LUMON™: LOOK AT THE TREND OF EELI AND THE DIFFERENCE BETWEEN EILI AND EELI, REPRESENTING TIDAL VOLUME. STRETCH AND SILENT SPACES IMAGES AND TRENDS GIVE INFORMATION ON TIDAL VOLUME DISTRIBUTION.

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van Veenendaal et al. **EFFECT OF CLOSED ENDOTRACHEAL SUCTION IN HIGH-FREQUENCY VENTILATED PREMATURE INFANTS MEASURED WITH ELECTRICAL IMPEDANCE TOMOGRAPHY.** Intensive Care Med. 2009; 35(12):2130-2134. doi:10.1007/s00134-009-1663-5

APPLICATION: MONITOR GLOBAL AND REGIONAL CHANGES IN LUNG VOLUME DURING AND AFTER CLOSED ENDOTRACHEAL TUBE SUCTION

Endotracheal tube (ETT) suction is essential in ventilated patients to maintain airway patency. However, ETT suction may also lead to transient hypoxia and cardiovascular instability, side effects generally attributed to loss of lung volume due to negative pressure and atelectasis. The effect of ETT on lung volumes was monitored on 11 non-muscle relaxed preterm infants with RDS ventilated with open lung high-frequency ventilation (HFV). ETT suction resulted in an acute loss of lung volume followed by spontaneous recovery, while at the regional level the lung volume changes during and after ETT suction were heterogeneous in nature with no consistent pattern.

HOW-TO IN LUMON™: LOOK AT THE TREND OF EELI OR THAT OF AERATION, REPRESENTING MEAN LUNG VOLUME. STRETCH AND SILENT SPACES IMAGES AND TRENDS GIVE INFORMATION ON TIDAL VOLUME DISTRIBUTION.

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van der Burg et al. **UNILATERAL ATELECTASIS IN A PRETERM INFANT MONITORED WITH ELECTRICAL IMPEDANCE TOMOGRAPHY: A CASE REPORT.** Eur J Pediatr. 2014;173(12):1715-1717. doi:10.1007/s00431-014-2399-y

APPLICATION: DETECT ADVERSE EVENTS OR COMPLICATIONS SUCH AS ATELECTASIS

A unilateral atelectasis in an extremely low birth weight infant resulted in a loss of regional ventilation measured by EIT in the affected lung. By monitoring regional lung aeration continuously at the bedside, EIT appears the most promising technique to detect such adverse events in infants.

HOW-TO IN LUMON™: LOOK AT THE STRETCH AND IN PARTICULAR THE SILENT SPACES IMAGES.

SenTec EIT in neonatology

Becher et al. **FEASIBILITY AND SAFETY OF PROLONGED CONTINUOUS MONITORING WITH ELECTRICAL IMPEDANCE TOMOGRAPHY IN NEONATES AND INFANTS WITH RESPIRATORY FAILURE.** Intensive Care Medicine Experimental 2019, 7(3):55.

APPLICATION: MONITOR VENTILATION IN NEONATES

The feasibility and safety of continuous EIT monitoring for up to 72 hours in 200 neonates and preterm infants at risk for respiratory failure was confirmed within the multicenter ´Continuous Regional Analysis Device for neonate Lungs´ (CRADL) study (clinicaltrials.gov NCT02962505). No moderate or severe study-related adverse events were recorded. Minor study-related adverse events included reversible redness of skin or imprint of EIT belt on the skin.

Rahtu et al. **EARLY RECOGNITION OF PNEUMOTHORAX IN NEONATAL RESPIRATORY DISTRESS SYNDROME WITH ELECTRICAL IMPEDANCE TOMOGRAPHY.** Am J Respir Crit Care Med. 2019; 200(8):1060-1061. doi:10.1164/rccm.201810-1999IM

APPLICATION: DETECT ADVERSE EVENTS OR COMPLICATIONS SUCH AS PNEUMOTHORAX

This is a case report of a female infant suffering from respiratory distress syndrome where EIT was able to identify a pattern of parameters indicating a potential pneumothorax which was then confirmed by the gold standard chest X-ray a few hours later. The clinicians were blinded for EIT during recording and the retrospective EIT analysis identified a progressive pattern of EIT parameters that indicated a potential pneumothorax by 1) increased end-expiratory lung impedance and 2) decreased tidal EIT signal variation, both at the affected side, resulting from regionally increased air content and reduced ventilation, as well as by 3) decreased end-expiratory

lung impedance at the contralateral side, possibly due to a mediastinal shift and compression of the lung. This was visible in the EIT waveforms of the plethysmogram, while the tidal volume distribution images at different points in time were highly indicative of the different distributions in the two lungs. Prompt diagnosis in such a life-threatening condition is paramount.

Kallio et al. **INITIAL OBSERVATIONS ON THE EFFECT OF REPEATED SURFACTANT DOSE ON LUNG VOLUME AND VENTILATION IN NEONATAL RESPIRATORY DISTRESS SYNDROME.** Neonatology. 2019; 116(4):385-389. doi:10.1159/000502612

APPLICATION: ASSESS EFFECTS OF SURFACTANT ADMINISTRATION

EIT was used to assess surfactant dosing in 9 invasively ventilated neonates. Preterm infants requiring invasive ventilation and repeated surfactant treatment, were included in this analysis. Ventilation distribution, end-expiratory lung impedance and tidal impedance variation were determined by electrical impedance tomography together with clinical parameters before and after repeated endotracheal surfactant treatment. The analysis shows that repeated surfactant dosing can improve oxygenation without affecting significantly the ventilation distribution. This information is important to assess whether adjustments of ventilator settings are required after the repeated surfactant dosing as after the initial dose. To note, clinicians were blinded to the EIT findings during the recording, and treatment decisions were done by clinical assessment only. Ventilator settings were adjusted as part of daily routine without any study-related protocol.

Gaertner et al. **TRANSMISSION OF OSCILLATORY VOLUMES INTO THE PRETERM LUNG DURING NONINVASIVE HIGH-FREQUENCY VENTILATION.** . Am J Respir Crit Care Med. 2020 Oct 23. doi: 10.1164/rccm.202007-2701OC.

APPLICATION: ASSESS EFFECTS OF HIGH FREQUENCY OSCILLATION VENTILATION

The study investigated noninvasive high-frequency oscillatory ventilation (nHFOV) in 30 preterm infants compared to nasal continuous positive airway pressure in a randomized crossover trial. It could be shown that the generated oscillations are effectively transmitted to the alveoli. Compared with the regional distribution of tidal breaths, oscillations preferentially reached the right and non-gravity-dependent lung. These data increase understanding of the physiological processes underpinning nHFOV and may lead to further refinement of this novel technique.

Dowse et al. **SYNCHRONIZED INFLATIONS GENERATE GREATER GRAVITY-DEPENDENT LUNG VENTILATION IN NEONATES.** J Pediatr. 2020: S0022-3476(20)31029-5. doi: 10.1016/j.jpeds.2020.08.043.

APPLICATION: ASSESS EFFECTS OF INFLATION STRATEGIES

The aim of this study was to compare mechanical ventilation that is either synchronous or asynchronous with an infant's own breathing effort by describing the regional distribution patterns of tidal ventilation within the lung. 2749 inflations were analyzed in 19 infants. Synchronous lung inflations generated more gravity dependent lung ventilation and more uniform right to left ventilation than asynchronous inflations.

Schinckel et al. **SKIN-TO-SKIN CARE ALTERS REGIONAL VENTILATION IN STABLE NEONATES.** Arch Dis Child Fetal Neonatal Ed. 2020: fetalneonatal-2020-319136. doi: 10.1136/archdischild-2020-319136..

APPLICATION: ASSESS EFFECTS OF A THERAPEUTIC INTERVENTION OR A CARE PROTOCOL

This study aimed to study physiological effects and in particular compare regional ventilation indices and other cardiorespiratory parameters during skin-to-skin care with supine and prone position cot-nursing in 20 infants. The findings provide evidence of general clinical stability for the infant during skin-to-skin care and show an effect on respiratory patterns, in particular, greater dorsal ventilation.

Khodadad et al. **OPTIMIZED BREATH DETECTION ALGORITHM IN ELECTRICAL IMPEDANCE TOMOGRAPHY.** Physiol Meas. 2018; 39(9):094001. Published 2018 Sep 6. doi:10.1088/1361-6579/aad7e6

APPLICATION: DETECT BREATHS AND MEASURE RESPIRATORY RATE

This study investigates the breath detection algorithms that use the trend data derived from EIT. The identification of the breath phases is important for a better patient monitoring and evaluation and for generating tidal impedance variation images. The optimization of these breath detection algorithms is particularly important in neonatal care since the existing breath detectors developed for adults may give insufficient reliability in neonates due to their very irregular breathing pattern. The proposed algorithms, featuring SenTec methodology and variants thereof, were tested in 10 neonatal patients and confirm the reliability of SenTec breath detection methodology.

Sophocleous et al. **CLINICAL PERFORMANCE OF A NOVEL TEXTILE INTERFACE FOR NEONATAL CHEST ELECTRICAL IMPEDANCE TOMOGRAPHY.** Physiol Meas. 2018 Apr 26; 39(4):044004. doi: 10.1088/1361-6579/aab513. PubMed PMID: 29516865.

APPLICATION: MONITOR VENTILATION IN NEONATES

This study is about the performance of the LuMon™ Belt during 3 days of continuous recording in 30 neonatal patients. In this multicenter clinical study (CRADL) the attending clinicians were instructed to report observed skin irritations or suspected restriction of breathing caused by the neonatal belt during a maximal period of 72h. The belt was found to be skin friendly and there was no evidence of any distress or discomfort for the neonatal patients. The placement of the belt was considered simple, fast and reproducible opening promising applications in neonatology.

Miedema et al. **INDIVIDUALIZED MULTIPLANAR ELECTRICAL IMPEDANCE TOMOGRAPHY IN INFANTS TO OPTIMIZE LUNG MONITORING.** Am J Respir Crit Care Med. 2017 Feb 15; 195(4):536-538. doi: 10.1164/rccm.201607-1370LE. PubMed PMID: 28199154.

APPLICATION: DETECT VENTILATION INHOMOGENEITY

This case report is about an infant with a known congenital left upper lobe lesion. The EIT images showed varying degrees of ventilation inhomogeneity that correlated with the findings of chest X-ray and high resolution CT. The image reconstruction was shown to be feasible at different levels of the thorax and was able to profit from a chest model approach optimized through the CT data.

SenTec EIT in neonatal preclinical models

McCall et al. **TIME TO LUNG AERATION DURING A SUSTAINED INFLATION AT BIRTH IS INFLUENCED BY GESTATION IN LAMBS.** Pediatr Res. 2017; 82(4):712-720. doi:10.1038/pr.2017.141

APPLICATION: UNDERSTAND PHYSIOLOGICAL CHANGES AT BIRTH

This is an experimental study in lambs, used as a neonatal animal model. This study was performed in 49 lambs with different gestational ages. The results showed that mechanical and developmental differences related to the gestational age affect the time required to achieve optimal lung aeration during sustained inflation delivery at birth.

Miedema et al. **ELECTRICAL IMPEDANCE TOMOGRAPHY IDENTIFIES A DISTINCT CHANGE IN REGIONAL PHASE ANGLE DELAY PATTERN IN VENTILATION FILLING IMMEDIATELY PRIOR TO A SPONTANEOUS PNEUMOTHORAX.** J Appl Physiol (1985). 2019; 127(3):707-712. doi:10.1152/japplphysiol.00973.2018

APPLICATION: DETECT ADVERSE EVENTS OR COMPLICATIONS SUCH AS PNEUMOTHORAX

The study revealed predictive changes in EIT derived parameters such as end expiratory lung impedance and phase angle before the onset of a one-sided pneumothorax in 6 preterm lambs ventilated with high-frequency oscillatory ventilation. It is postulated that EIT monitoring can give clinicians bedside information to change treatment of preterm infants and prevent a life-threatening pneumothorax from happening.

Tingay et al. **Gradual Aeration at Birth Is More Lung Protective Than a Sustained Inflation in Preterm Lambs.** Am J Respir Crit Care Med. 2019; 200(5):608-616. doi:10.1164/rccm.201807-1397OC

Application: Assess lung aeration strategy at birth

The aim of the study was to examine the effects of gradual and rapid aeration at birth on lung volumes and lung injury. To this aim 87 preterm lambs were randomized to different aeration strategies. Rapidly aerating the preterm lung at birth created heterogeneous volume states, producing distinct regional injury patterns that affected subsequent tidal ventilation. Gradual aeration supporting tidal ventilation with adequate PEEP produced the least lung injury.

Miedema et al. **Lung Recruitment Strategies During High Frequency Oscillatory Ventilation in Preterm Lambs.** Front Pediatr. 2018; 6: 436. Published online 2019 Jan 22. doi: 10.3389/fped.2018.00436

Application: Assess effect of lung recruitment strategies

This study allocated 36 lambs to different recruitment strategies, a low, a medium and a high lung volume strategy. It showed that lung recruitment during high frequency oscillatory ventilation optimizes gas exchange but has only modest effects on lung injury. In the high lung volume group aiming at a more extensive lung recruitment gas exchange was better without affecting lung injury. The intended EELV response could be directly related to the target oxygen level during lung recruitment.

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2ST800-400 Rev.000 | December 2020