

**Electrical Impedance Tomography as a monitoring tool during weaning from mechanical ventilation
an observational study during the spontaneous breathing trial**

Wisse, Jantine J.; Goos, Tom G.; Jonkman, Annemijn H.; Somhorst, Peter; Reiss, Irwin K.M.; Endeman, Henrik; Gommers, Diederik

DOI

[10.1186/s12931-024-02801-6](https://doi.org/10.1186/s12931-024-02801-6)

Publication date

2024

Document Version

Final published version

Published in

Respiratory Research

Citation (APA)

Wisse, J. J., Goos, T. G., Jonkman, A. H., Somhorst, P., Reiss, I. K. M., Endeman, H., & Gommers, D. (2024). Electrical Impedance Tomography as a monitoring tool during weaning from mechanical ventilation: an observational study during the spontaneous breathing trial. *Respiratory Research*, 25(1), Article 179. <https://doi.org/10.1186/s12931-024-02801-6>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

RESEARCH

Open Access



Electrical Impedance Tomography as a monitoring tool during weaning from mechanical ventilation: an observational study during the spontaneous breathing trial

Jantine J. Wisse^{1,2*}, Tom G. Goos^{2,3}, Annemijn H. Jonkman¹, Peter Somhorst¹, Irwin K. M. Reiss², Henrik Endeman¹ and Diederik Gommers¹

Abstract

Background Prolonged weaning from mechanical ventilation is associated with poor clinical outcome. Therefore, choosing the right moment for weaning and extubation is essential. Electrical Impedance Tomography (EIT) is a promising innovative lung monitoring technique, but its role in supporting weaning decisions is yet uncertain. We aimed to evaluate physiological trends during a T-piece spontaneous breathing trial (SBT) as measured with EIT and the relation between EIT parameters and SBT success or failure.

Methods This is an observational study in which twenty-four adult patients receiving mechanical ventilation performed an SBT. EIT monitoring was performed around the SBT. Multiple EIT parameters including the end-expiratory lung impedance (EELI), delta Tidal Impedance (ΔZ), Global Inhomogeneity index (GI), Rapid Shallow Breathing Index ($RSBI_{EIT}$), Respiratory Rate (RR_{EIT}) and Minute Ventilation (MV_{EIT}) were computed on a breath-by-breath basis from stable tidal breathing periods.

Results EELI values dropped after the start of the SBT ($p < 0.001$) and did not recover to baseline after restarting mechanical ventilation. The ΔZ dropped ($p < 0.001$) but restored to baseline within seconds after restarting mechanical ventilation. Five patients failed the SBT, the GI ($p = 0.01$) and transcutaneous CO_2 ($p < 0.001$) values significantly increased during the SBT in patients who failed the SBT compared to patients with a successful SBT.

Conclusion EIT has the potential to assess changes in ventilation distribution and quantify the inhomogeneity of the lungs during the SBT. High lung inhomogeneity was found during SBT failure. Insight into physiological trends for the individual patient can be obtained with EIT during weaning from mechanical ventilation, but its role in predicting weaning failure requires further study.

Keywords Electrical Impedance Tomography, EIT, Spontaneous breathing trial, Weaning

*Correspondence:

Jantine J. Wisse

j.j.smit@erasmusmc.nl

Full list of author information is available at the end of the article



© The Author(s) 2024. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>. The Creative Commons Public Domain Dedication waiver (<http://creativecommons.org/publicdomain/zero/1.0/>) applies to the data made available in this article, unless otherwise stated in a credit line to the data.

Background

Mechanical ventilation is one of the cornerstones in the treatment of intensive care patients. Invasive mechanical ventilation is life saving, but may cause lung injury. Prolonged weaning from mechanical ventilation is associated with increased mortality [1, 2]. Therefore, weaning and liberation from mechanical ventilation should be pursued from the initiation of invasive ventilation and choosing the right moment for extubation is essential [3–6]. A test that is widely used and integrated in clinical practice to guide clinicians in choosing the right moment for extubation is the spontaneous breathing trial (SBT). During the SBT, the patient is challenged to sustain adequate ventilation and oxygenation while the amount of support given by the ventilator is reduced or stopped. Along with the result of the SBT, the health care professional decides if the patient is ready for extubation [6]. Given the central role of weaning tests in extubation decisions, understanding their physiology is essential. However, few studies have investigated this essential point [4], likely due to the lack of simple to use and validated lung monitoring techniques.

Electrical Impedance Tomography (EIT) is a noninvasive imaging modality and a promising tool to gain physiological insight into the weaning process. EIT estimates the distribution of air inside the lungs based on changes in electrical impedance [7–9]. A belt integrated with electrodes is placed around the thorax, and small alternating currents are injected into the belt and measured between the electrodes [8]. EIT provides a dynamic image of the distribution of air in the lungs [10]. Multiple parameters can be extracted from the EIT signal providing information about the tidal volume, functional residual capacity, the center of ventilation, the (in)homogeneity of the ventilation and the percentage of collapse. Previous studies [11–14] performed with EIT around the SBT found two correlations: first, a relation between lower end-expiratory lung impedance (EELI) levels and SBT failure [11, 12] and second, a higher global inhomogeneity (GI) index was related to SBT failure [13]. A recent study investigating EIT parameters around extubation found that 2 h after extubation the GI index was higher in patients that failed extubation. Before and after extubation the amount of ventilated pixels was lower in patients that failed extubation [15].

This physiological study was conducted to determine whether EIT parameters during long term EIT measurements surrounding a T-piece weaning trial are potential predictors for SBT failure. We addressed two important topics: first, a more detailed evolution of previously described [11–15] and new EIT parameters during the SBT and second, the relation between EIT parameters and SBT success or failure. Last, we propose a novel

combination of EIT preprocessing techniques to enhance reliability of long term EIT measurements.

Methods

Study design and population

This observational physiological study was conducted in the Intensive Care Unit of the Erasmus Medical Center, Rotterdam, The Netherlands. Adults who were invasively ventilated for at least 24 h and considered ready for an SBT within the next 48 h were considered for enrollment. The protocol was approved by the local ethics review committee (MEC-2020–0521). Written informed consent was obtained from either the subject or their legal representative. Exclusion criteria were contraindications (thoracic wounds, pneumothorax, internal pacemaker or defibrillator) for an EIT measurement or transfer to another hospital before extubation.

Study protocol

Continuous EIT monitoring was performed with the EIT belt (LuMon™ Belt, Sentec AG, Therwil, Switzerland) applied between the 4th and 6th intercostal space. EIT data was obtained with a sampling frequency of 50.2 Hz. Ventilator data were automatically logged with a sample frequency of 1 Hz. Continuous Transcutaneous CO₂ (TcCO₂) was obtained using a dedicated sensor (SenTec OxiVent, Sentec AG, Therwil, Switzerland) applied to the skin. Measurements were conducted prior to and during the SBT and were continued until 24 h after extubation.

A T-piece SBT was performed according to the local clinical protocol. The protocolled length of the SBT was 30 min. Objective criteria for SBT failure were PaO₂ ≤ 8 kPa or SaO₂ < 90% with FiO₂ ≥ 40%, pH < 7.32, respiratory rate > 35 breaths/min or an increase in respiratory rate ≥ 50%, systolic hypertension > 180 mmHg or an increase in systolic blood pressure > 20%, systolic hypotension < 90 mmHg, and arrhythmia. Subjective criteria for SBT failure were fear and anxiety, low consciousness, heavy transpiration, cyanosis, and use of accessory respiratory muscles. Weaning failure was defined as a failed SBT or reintubation with 48 h after extubation.

EIT data preprocessing and analysis

Data preprocessing and analysis were performed in MATLAB R2021a (Mathworks, Natick, USA). First, an EIT preprocessing method was designed and applied to remove outliers, artifacts and noise components, which included automated selection of periods with stable tidal breathing (see Supplemental materials and figure A1 [16–18]). During offline processing it was noted that the reliability of prolonged EIT measurements was limited, hampering adequate comparison of post-extubation EIT signals with those measured around the SBT (see

Discussion section). Therefore, data analysis was only performed for stable measurement periods just before, during and directly after the SBT.

As the duration of the SBT trial varied from patient to patient, each SBT was divided into 5 equal stable time intervals (epochs). The number of epochs was equal for every patient but could vary in length. Data were analyzed on a breath-by-breath basis and were then averaged per epoch. The following parameters were quantified with EIT:

- delta Tidal Impedance (ΔZ)
- end-expiratory lung impedance (EELI)
- respiratory rate (RR_{EIT})
- minute volume (MV_{EIT}); with tidal volume derived from ΔZ using a point calibration between the tidal volume (ml) as measured by the mechanical ventilator and the ΔZ [AU] from EIT. The calibration factor was individualized for each patient, and one or an average of multiple calibration points were chosen from stable breathing periods before the SBT.
- rapid shallow breathing index ($RSBI_{EIT}$); based on the calibration between mechanical ventilation tidal volume and ΔZ .
- center of ventilation (CoV)
- global inhomogeneity index (GI) [19], describing the homogeneity of ventilation distribution, calculated as the sum of the absolute difference between the median value of ΔZ per pixel divided by the sum of all impedance values [19]:

$$GI = \frac{\sum_{x,y \in lung} |DI_{xy} - Median(DI_{lung})|}{\sum_{x,y \in lung} DI_{xy}} \quad (1)$$

Only pixels within the lung contour were included for this calculation. We used predefined lung contours in the LuMonTM software. Sentec selects thorax and lung models adapted to the individual patient from a set of CT-derived thorax and lung models. A GI of zero represents a perfect homogenous ventilation distribution; the larger the GI, the more inhomogeneous the tidal volume distribution within the lung area.

- Nondependent and dependent silent spaces (NSS, DSS), reflecting poorly/non-ventilated lung areas. Pixels within the lung contour with impedance changes < 10% of the maximum impedance change were quantified as silent space. Pixels below or above the CoV were considered dependent or nondependent silent spaces, respectively.
- Functional lung space (FLS), quantified as 100% minus the percentage of pixels defined as silent space.

Statistical analysis

Statistical analysis was performed using R version 2022.07.2 (RStudio, Posit Software, Boston MA, USA). Descriptive data are presented as mean $\pm$ standard deviation; the distribution of normality was checked through the Shapiro-Wilk test. Repeated measurements were compared with linear mixed-effects models with fixed effects of measurement step and random effect of subject; estimated means were compared after Tukey correction. This model was extended with fixed effect of group (to test the difference between SBT success and failure) and group by measurement step interaction to test for their interaction effect (i.e., to test if the change in repeated measurements was different between the group with successful SBT and failed SBT). Appropriate transformations were applied for those parameters in which the mixed model residuals did not fit a normal distribution. For all analyses, p -value < 0.05 was considered statistically significant.

Results

Study participants

A total of 23 patients ready for weaning were enrolled, their characteristics are presented in Table 1. Five patients failed the SBT. At baseline, the SAPSII score was higher for the patients who failed the SBT (36 vs. 53). The total ventilation duration (12 vs. 26 days), the ICU length of stay (15 vs. 32 days) were significantly higher for the SBT failure subgroup ($p < 0.05$ for all). The PaO_2 after the SBT (68 vs. 103 mmHg) was significantly lower for the SBT failure subgroup and the length of the SBT was shorter in patients that failed the SBT.

Figure 1 summarizes the weaning process of the study participants. Three patients were reintubated within 48 h after extubation, while 15 patients were successfully weaned. From the overall population, five patients were extubated directly after the SBT without restarting mechanical ventilation between the SBT and extubation.

EIT trends during the SBT for the whole group

EIT parameters during the SBT for the whole group are presented in Fig. 2. The EELI was decreased throughout the SBT, reflecting a drop in end-expiratory lung volume (Fig. 2a). After restarting mechanical ventilation, EELI did not recover to its baseline value. The delta tidal impedance (ΔZ) was decreased throughout the SBT (Fig. 2b) and quickly restored to its initial value after ventilator reconnection (within an average of 24 s). The GI increased after initiation of the SBT (Fig. 2c) and recovered to its initial value after restarting mechanical ventilation.

Table 1 Baseline characteristics in the overall population and success and failure SBT subgroups

	Total Population (n = 23)	Successful SBT (n = 18)	Failed SBT (n = 5)	p-value
Gender (M/F)	M:14, F:9	M:12, F:6	M:2 F:3	
BMI (kg/m ²)	27.8 (5.8)	26.7 (5.3)	31.6 (6.6)	0.1
Age (years)	63 [57.5 70]	62.5 [57.2 67.2]	70 [69 73]	0.26
SAPS II	39.8 (16.6)	36.2 (13.3)	52.8 (22.3)	< 0.05
SOFA at study enrolment	4.9 (2.6)	4.9 (2.9)	4.8 (1.3)	0.95
Days ventilated before study (days)	11.3 (5.8)	10.7 (5.9)	13.4 (5.0)	0.37
Total ventilation duration (days)	15.3 (8.5)	12.4 (5.9)	25.6 (8.7)	< 0.05
Pressure support ventilation before SBT (days)	3 [2 7]	3.5 [2 7]	3 [2 6]	0.51
SBT length (min)	31 [24.5 35.5]	33 [30.2 35.8]	15 [9 21]	< 0.05
ICU length-of-stay (days)	19.3 (10.7)	15.7 (7.4)	32.3 (11.8)	< 0.05
ICU mortality	2	1	1	
Admission diagnosis (n, %)				
Respiratory	10 (43%)	7 (39%)	3 (60%)	
Neurological	6 (26%)	6 (33%)	0 (0%)	
Cardiovascular	3 (13%)	2 (11%)	1 (20%)	
Trauma	3 (13%)	2 (11%)	1 (20%)	
Sepsis	1 (4%)	1 (6%)	0 (0%)	
Respiratory mechanics at study baseline (clinical settings)				
Total PEEP (cmH ₂ O)	7.5 (2.1)	7.3 (1.8)	8.4 (3.2)	0.50
dP (cmH ₂ O)	8.1 (3.2)	7.8 (3.2)	9.2 (3.5)	0.44
PaO ₂ before the SBT (mmHg)	84.8 (20.3)	86.3 (21.8)	79.6 (15.8)	0.45
PaO ₂ after the SBT (mmHg)	95.3 (36.8)	102.8 (36.8)	68.3 (23.3)	< 0.05
PaCO ₂ before the SBT (mmHg)	41.3 (5.3)	41.3 (6.0)	42.0 (3.8)	0.66
PaCO ₂ after the SBT (mmHg)	40.5 (6.0)	39.8 (5.3)	42.8 (9.0)	0.49
RSBI before the SBT	40.1 [32.1 53.9]	37.8 [31.5 48.8]	53.7 [53.3 59.5]	0.18
P/F ratio before the SBT	232 [205.5 303.5]	231 [207 318]	233 [188 279]	0.39
FiO ₂ (%)	35 [30 40]	35 [30 38.8]	35 [35 40]	0.48

Additional trends in EIT-derived parameters are a significant increase in the RR_{EIT} (Fig. 2d) and a significant decrease in the MV_{EIT} (Fig. 2e) halfway through the SBT. Both the MV_{EIT} and RR_{EIT} were restored to their baseline values after mechanical ventilation was restarted. The $RSBI_{EIT}$ (Fig. 2e) increased significantly after the start of the SBT and recovered to its baseline value after restarting the mechanical ventilation.

The other EIT parameters, including NSS, DSS, FLS, left–right and ventral–dorsal ventilation distribution, and the center of ventilation (COV_x, COV_y), did not show any significant trend from baseline (see Supplemental Figure A2).

SBT failure and success group

Differences between patients who failed ($n = 5$) or successfully passed ($n = 18$) the SBT are presented in Fig. 3. The percentual change in EELI and ΔZ were not significantly different between the two groups. No significant differences in EELI and ΔZ were found during the course of the SBT within the failure group. Therefore,

the whole group changes in EELI and ΔZ (Fig. 2a and b) were mainly driven by the successful SBT patients. The GI (Fig. 2c) was significantly different between the two groups throughout all measurements, with higher GI values in patients who failed the SBT. Within this group, GI remained stable during the SBT, while an increasing GI was found for the success group.

Another significant difference between the two groups in EIT parameters was an increase in the RR_{EIT} halfway during the SBT in the success group. The $RSBI_{EIT}$ was significantly different between the two groups at 2/5 and 4/5 of the SBT. The other EIT parameters including MV_{EIT} , FLS, NSS, DSS, left–right and ventral–dorsal ventilation distribution, COV_x and COV_y, did not show any significant changes per group or between the two groups (see Supplemental figure A3).

We explored the difference in EIT parameters between patients with a successful SBT and successful extubation and a successful SBT and reintubation. No differences in these parameters were found between the two groups but

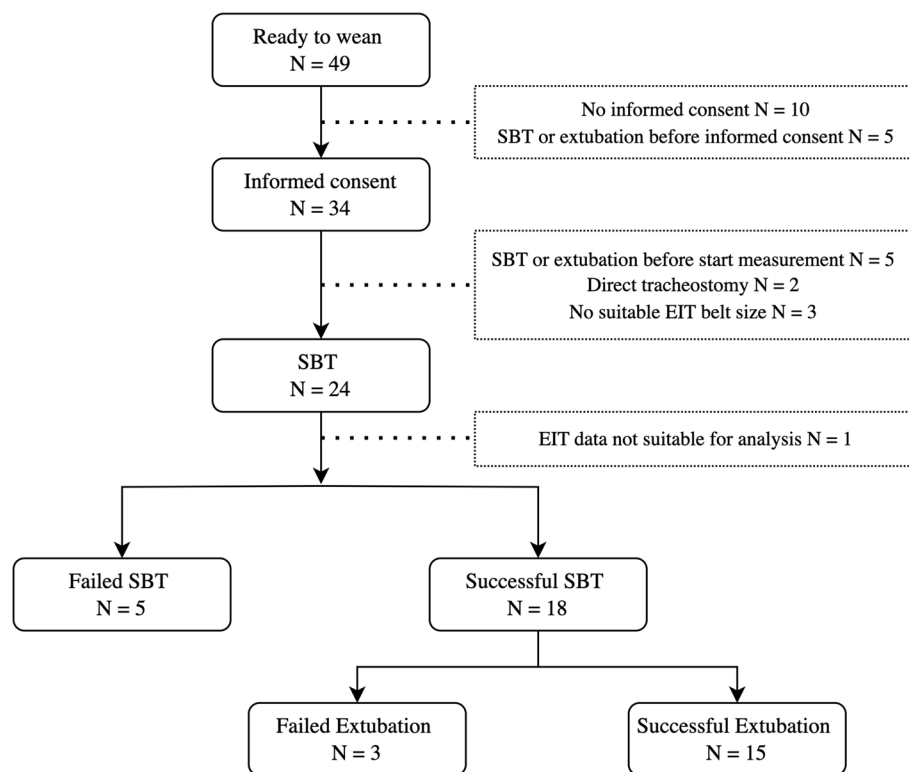


Fig. 1 The flow chart summarized the weaning process from the study participants from ready to wean to extubation

analysis is limited by the small sample size of only three patients failing extubation (supplemental figure A4).

Transcutaneous CO₂ measurements

The TcCO₂ trend (Fig. 4A) did not show any significant effects over time. However, there were significant differences between the success and failure groups (Fig. 4B): the TcCO₂ was stable during the SBT in the success group, but increased rapidly during the SBT in the failure group.

Discussion

This study provides detailed insights into the respiratory physiology during a T-piece trial as assessed by EIT and synchronized with transcutaneous CO₂ measurements. EIT parameters provide trend information of the ventilation distribution during the SBT, and findings can be summarized as follows: 1.) multiple EIT parameters showed significant changes from baseline during the SBT. The EELI, ΔZ and MV_{EIT} dropped after the start of the SBT. The respiratory rate, GI and RSBI_{EIT} increased during the SBT. After restarting mechanical ventilation, EELI did not recover to its baseline value. The other investigated EIT parameters: FLS, NSS, DSS, COV and transcutaneous CO₂ did not significantly change from baseline during the SBT. 2.) Two parameters were significantly

different between patients with a successful and failed SBT. First, the GI was significantly higher at all time points in patients failing the SBT. Second, the transcutaneous CO₂ was significantly higher at the end of the SBT in patients who failed the SBT compared to patient who successfully passed the SBT.

In addition to previous studies, we observed lung derecruitment after the SBT, as EELI values after restarting the mechanical ventilation were significantly lower than prior to the SBT. However, note that changes were only small and therefore the clinical relevance of these findings can be questioned. In contrast to EELI, the ΔZ immediately recovered to baseline, within seconds after restarting the mechanical ventilation. The combination of these results suggests derecruitment by a drop in EELI without loss of tidal volume, and that lung recruitment after resuming mechanical ventilation is a slower process. This supports the idea that resuming mechanical ventilation after a successful SBT and prior to extubation may be beneficial [20]. The drop in EELI results partially from PEEP loss during the T-piece SBT. Divergent outcomes can be anticipated during pressure-support ventilation (PSV) SBT where PEEP is (partially) retained and work of breathing is lower [12, 21]. It is also important to realize that the drop in EELI may not solely be related to reduced ventilation, but can also be caused by fluid-related

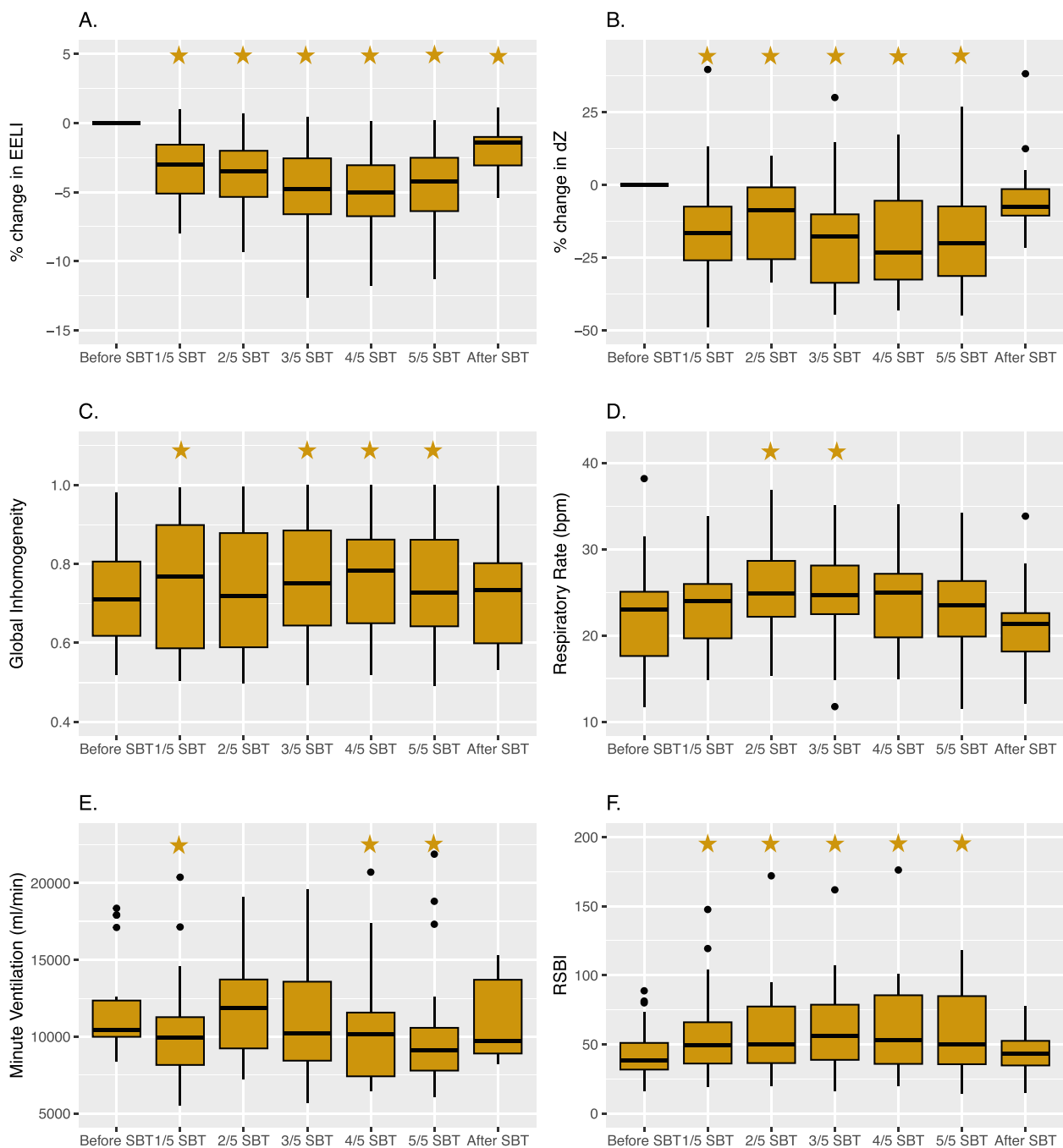


Fig. 2 EIT parameters trends during the SBT extracted from stable tidal breathing periods before the SBT at 1/5th, 2/5th, 3/5th, 4/5th, 5/5th and after the SBT. **A** Percentual change of EELI during the SBT. **B** Percentual change of delta tidal impedance (ΔZ) during the SBT. **C** The Global Inhomogeneity (GI) during the SBT. **D** Respiratory Rate (RR_{EIT}) during the SBT. **E** Minute ventilation (MV_{EIT}) during the SBT. **F** Rapid shallow breathing Index ($RSBI_{EIT}$) during the SBT. – Significant difference from the baseline measurement is indicated with a star

changes in thoracic impedance. We did not screen for weaning induced pulmonary oedema during the SBT [22] and could therefore not discriminate between the two potential causes of reduced impedance measurements.

We found the GI index to be significantly different between those patients with a successful SBT and those with a failed SBT. The GI index for patients failing the SBT was higher compared to patients with a successful SBT, and this difference already existed prior to the SBT.

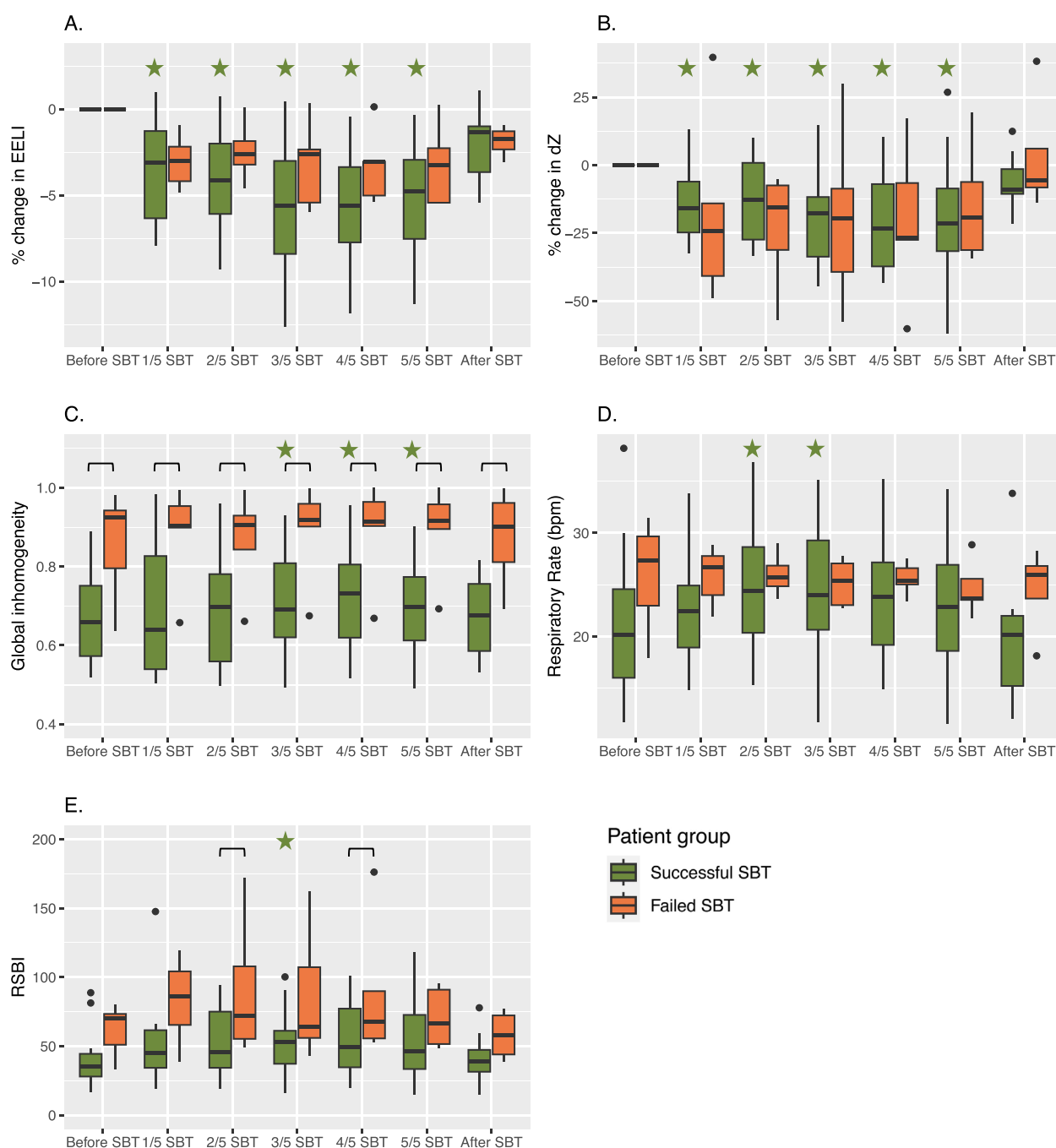


Fig. 3 EIT parameters trends during the SBT extracted from stable tidal breathing periods before the SBT at 1/5th, 2/5th, 3/5th, 4/5th, 5/5th and after the SBT. The group is divided between patients with a successful SBT (green) and a failed SBT (orange). **A** Percentual change in the EELI during the SBT. **B** Percentual change of delta tidal impedance (ΔZ) during the SBT. **C** The Global Inhomogeneity (GI) during the SBT. **D** RR_{EIT} during the SBT. **E** Rapid shallow breathing Index ($RSBI_{EIT}$) during the SBT. — Significant differences ($p < 0.05$) between the two groups are indicated with a horizontal bar (—), significant differences from the baseline measurement ($p < 0.05$) successful SBT is indicated with a green star. Significant differences from the baseline measurement ($p < 0.05$) for the failed SBT is indicated with an orange star

These results are in accordance with previous literature where the GI was described as a potential identifier for patients at risk for weaning failure, but no clear cutoff

values were proposed [11, 23, 24]. GI values were found higher after extubation in patients with extubation failure, however the GI index was not significantly different

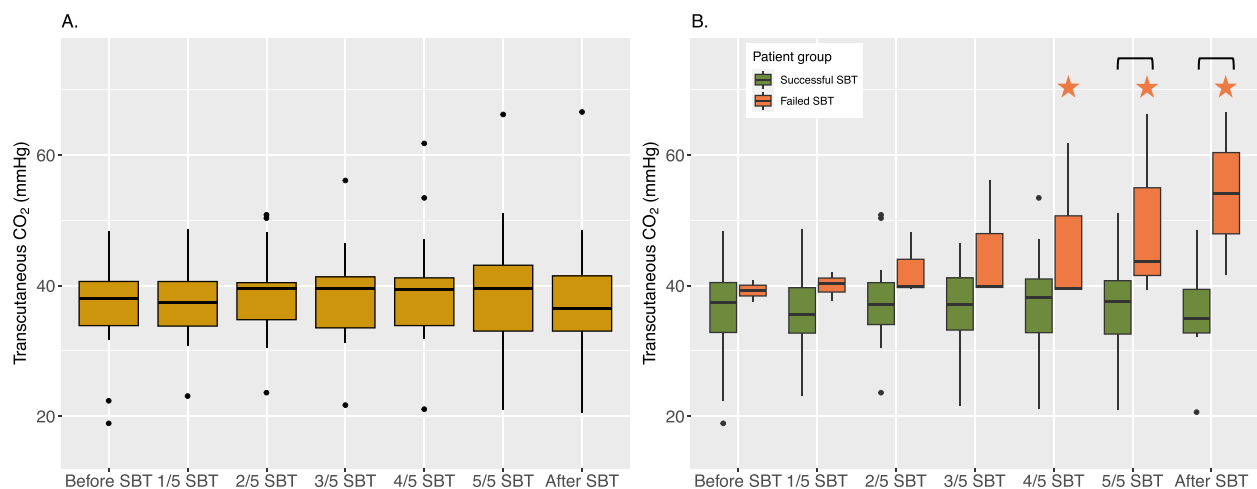


Fig. 4 **A** Transcutaneous CO₂ values of all patients during the SBT. **B** Transcutaneous CO₂ measurements divided between patients with a successful SBT (green) and a failed SBT (orange). – Significant differences ($p < 0.05$) between the two groups are indicated with a horizontal bar —, significant differences from the baseline measurement ($p < 0.05$) successful SBT is indicated with a green star. Significant differences from the baseline measurement ($p < 0.05$) for the failed SBT is indicated with an orange star

before extubation. Jousselin et al. argue that mechanical ventilation before extubation could help for homogenization of the distribution of the ventilation [15]. However, we found higher GI values before the start of the SBT on pressure support ventilation in patients failing the SBT. We explored the difference in GI after extubation in our cohort. No differences in these parameters were found between patients with successful or failed extubation but analysis is limited by the small sample size of only three patients failing extubation (supplemental figure A5). The GI is a feasible index to summarize the complex pulmonary impedance distribution pattern into a single number [25]. A higher GI implies more regional differences in lung mechanics, which could be caused by e.g., ventilation-perfusion mismatch, atelectasis or inflammation. The role of GI in predicting patients at risk for SBT failure, including optimal cutoff values, requires further study.

The RSBI has been used as a predictor of weaning success where Yan and Tobin proposed that patients with an RSBI of < 105 were more likely to be successfully extubated [26, 27]. We found RSBI values < 105 throughout the SBT in all but one patient, meaning that this threshold was not discriminative for predicting weaning success in our cohort. However, it should be noted that the RSBI was calculated from ΔZ converted to tidal volumes instead of tidal volumes (ml). ΔZ derived tidal volumes were calculated by utilizing the relationship between the two during the pre-SBT period and applying a one point calibration [28]. This relationship, however, may change with altered lung conditions as airways may open or collapse during the SBT or after extubation. Therefore,

whether the same threshold of 105 can be applied reliably to our data is questionable. However, during the SBT the RSBI was significantly higher at two time points in the failure group compared to the successfully weaned patients. Looking at EIT-derived changes from baseline may therefore provide more clinical guidance than a threshold value solely.

The transcutaneous CO₂ increased in patients with a failed SBT. This could imply that SBT failure was mostly related to weak spontaneous breathing effort leading to carbon dioxide retention. Indeed, while the respiratory rate did not increase, minute ventilation decreased throughout the course of the SBT.

Strengths and limitations

This was the first study aiming to perform long-term continuous EIT measurements (up to 24 h before and after extubation) during weaning, and where EIT measurements were combined with transcutaneous CO₂ recordings. The reliability of long-term EIT measurements, however, posed an important challenge and could only be partially utilized in our analysis. To address this, we developed a novel combination of preprocessing techniques to filter out cardiovascular artifacts and identify stable tidal breathing periods, applicable to both ventilated and spontaneously breathing patients. Furthermore, we utilized the LuMon™ EIT device, featuring an oblique belt shape and lung contours for extraction of EIT parameters. The use of this device complements previous studies that used EIT devices from other manufacturers during the SBT, and also provides novel parameters (i.e., silent spaces) that were not previously investigated.

Our study had also several limitations. First, this observational study was performed in a small group with heterogeneous patients. Since EIT parameters during long term measurements around the weaning phase were unknown during the design of the study, a convenience sample was chosen. Although SBTs are protocolized in our ICU, differences were present in terms of the length of the SBT, mode and use of additional respiratory support after extubation, and also the flow of oxygen support during the SBT. Second, EIT signals are prone to several artifacts that could influence the reliability of parameters, including disturbances from alternating pressure relief mattresses which may have affected EELI calculations (but likely not other parameters) [29]. However, the effect was minimized by selection of stable tidal breathing periods.

Third, as mentioned earlier the reliability of comparing EIT parameters over a long time period was limited, for multiple reasons, including patient and belt movements, reapplication of contact agent on the EIT-belt (which was deemed necessary every several hours to obtain sufficient belt to skin contact), and noise and artifacts. The combination of these reasons affects the EIT signal and therefore reliable comparison of EIT parameters for prolonged recordings (supplemental figure A6). EIT researchers should be aware of these acquisition-related challenges when designing future studies with prolonged recordings. Therefore, recruitment/derecruitment after extubation could not be reliably assessed. As a result, we focused solely on EIT parameters directly around the SBT which were measured in a shorter and more stable period. Nevertheless, we explored the ventilation inhomogeneity for patients with a successful SBT and failed/successful extubation. These parameters are not affected by changes in EIT baseline and therefore can be adequately compared prior and after extubation.

Clinical implications

Although the prediction of extubation failure is limited with EIT, EIT is a feasible non-invasive bedside measurement to obtain insight into the patient's individual ventilation distribution and homogeneity of aeration. The ability to predict SBT failure based on EIT should be evaluated in further larger studies, and could have several clinical utilities. First, EIT is likely to be useful in signaling a patient's ability to tolerate discontinuation of mechanical ventilation. If EIT parameters can predict SBT failure, they can help to identify patients at higher risk of failure early on. This allows clinicians to take appropriate actions promptly, adjust ventilation strategies, optimize respiratory support or consider alternative weaning approaches. Second, it facilitates individualized weaning strategies based on the underlying physiological factors identified by EIT that contribute to weaning difficulties. Third, it might help to avoid

unnecessary extubation attempts which ensures patient safety and minimizes potential complications. Overall, the evaluation of EIT parameters during the SBT could support the clinicians' decision-making process and might improve patient care during the weaning process from mechanical ventilation.

Conclusions

Insight into physiological trends for the individual patient can be obtained with EIT during weaning from mechanical ventilation. Derecruitment after the SBT is common, observed by a drop in EELI without loss of tidal volume. The higher GI observed in patients failing to wean from mechanical ventilation can be attributed to regional differences in lung function. EIT has the potential to assess changes in ventilation distribution and quantify the inhomogeneity in electrical properties during the SBT, providing insights into the underlying physiological factors contributing to weaning failure.

Abbreviations

COV _y	Center of Ventilation y-direction
COV _x	Center of Ventilation x-direction
DSS	Dependent Silent Space
ΔZ	Delta Tidal Impedance
EIT	Electrical Impedance Tomography
EELI	End expiratory lung impedance
EILI	End inspiratory lung impedance
FLS	Functional Lung Space
GI	Global Inhomogeneity
ICU	Intensive Care Unit
MVeit	Minute Volume derived from EIT
NSS	Non-dependent Silent Space
PaCO ₂	Partial pressure of carbon dioxide
PaO ₂	Partial pressure of arterial oxygen
PEEP	Positive end-expiratory pressure
P/F	Partial pressure of oxygen to the fraction of inspired oxygen
RR	Respiratory Rate
RSBI _{EIT}	Rapid Shallow Breathing Index derived from EIT
SAPS	Simplified Acute Physiology Score
SOFA	Sequential Organ Failure Assessment
SBT	Spontaneous Breathing Trial
TcCO ₂	Transcutaneous CO ₂

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s12931-024-02801-6>.

Supplementary Material 1.

Acknowledgements

We thank the ICU staff for help during the study and thank the patients for their participation in the study.

Authors' contributions

Concept and design: JW, TG, PS, IR, DG. Data acquisition: JW. Data analysis: JW, AJ, TG. Data interpretation: all authors. Manuscript drafting: JW, AJ, TG, HE. Manuscript revising for intellectual contact and final approval: all authors.

Funding

This study was funded by an unrestricted grant by Sentec AG (Therwil, Switzerland).

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The ethics board approved the study (MEC-2020–0521) and informed consent was obtained. The study has been carried out in accordance with the Helsinki declaration for medical research involving humans.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

¹Department of Adult Intensive Care, Erasmus Medical Centre, Rotterdam, the Netherlands. ²Department of Neonatal and Pediatric Intensive Care, Erasmus Medical Centre – Sophia Children's Hospital, Rotterdam, The Netherlands. ³Department of Biomechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Delft, The Netherlands.

Received: 21 December 2023 Accepted: 2 April 2024

Published online: 25 April 2024

References

- Beduneau G, Pham T, Schortgen F, Piquilloud L, Zogheib E, Jonas M, et al. Epidemiology of weaning outcome according to a new definition the WIND study. *Am J Respir Crit Care Med*. 2017;195(6):772–83.
- Pham T, Heunks L, Bellani G, Madotto F, Aragao I, Beduneau G, et al. Weaning from mechanical ventilation in intensive care units across 50 countries (WEAN SAFE): a multicentre, prospective, observational cohort study. *Lancet Respir Med*. 2023;11(5):465–76.
- Hall JB, Wood LDH. Liberation of the patient from mechanical ventilation. *JAMA J Am Med Assoc*. 1987;257(12):1621–8.
- Thille AW, Richard JCM, Brochard L. The decision to extubate in the intensive care unit. *Am J Respir Crit Care Med*. 2013;187(12):1294–302.
- Boles JM, Bion J, Connors A, Herridge M, Marsh B, Melot C, et al. Weaning from mechanical ventilation. *Eur Respir J*. 2007;29(5):1033–56.
- Thille AW, Gacouin A, Coudroy R, Ehrmann S, Quenot J-P, Nay M-A, et al. Spontaneous-breathing trials with pressure-support ventilation or a T-piece. *N Engl J Med*. 2022;387(20):1843–54.
- Barber DC, Brown BH. Applied potential tomography. *J Phys E Sci Instrum*. 1984;17(9):723. [cited 2022 Oct 3]. Available from: <https://iopscience.iop.org/article/10.1088/0022-3735/17/9/002>.
- Frerichs I, Amato MBP, Van Kaam AH, Tingay DG, Zhao Z, Grychtol B, et al. Chest electrical impedance tomography examination, data analysis, terminology, clinical use and recommendations: Consensus statement of the Translational EIT development study group. *Thorax*. 2017;72(1):83–93.
- Tomicic V, Cornejo R. Lung monitoring with electrical impedance tomography: technical considerations and clinical applications. *J Thorac Dis*. 2019;11(7):3122–35. Available from: <http://jtd.amegroups.com/article/view/30075/21816>
- Wolf GK, Arnold JH. Noninvasive assessment of lung volume: Respiratory inductance plethysmography and electrical impedance tomography. *Crit Care Med*. 2005;33(3 SUPPL):163–9.
- Longhini F, Maugeri J, Andreoni C, Ronco C, Bruni A, Garofalo E, et al. Electrical impedance tomography during spontaneous breathing trials and after extubation in critically ill patients at high risk for extubation failure: a multicenter observational study. *Ann Intensive Care*. 2019;9(1). <https://doi.org/10.1186/s13613-019-0565-0>
- Lima JNG, Fontes MS, Szmuszkowicz T, Isola AM, Maciel AT. Electrical impedance tomography monitoring during spontaneous breathing trial: Physiological description and potential clinical utility. *Acta Anaesthesiol Scand*. 2019;63(8):1019–27.
- Li J, Zeng F, Yang F, Luo X, Liu R, Ren Y, et al. Electrical impedance tomography predicts weaning success in adult patients with delayed upper abdominal surgery: a single-center retrospective study. *Front Med*. 2021;8:748493.
- Wang D, Ning Y, He L, Pan K, Xiong X, Jing S, et al. Pendelluft as a predictor of weaning in critically ill patients: An observational cohort study. *Front Physiol*. 2023;14(March):1–8.
- Joussellin V, Bonny V, Spadaro S, Clerc S, Parfait M, Ferioli M, et al. Lung aeration estimated by chest electrical impedance tomography and lung ultrasound during extubation. *Ann Intensive Care*. 2023;13(1). <https://doi.org/10.1186/s13613-023-01180-3>
- Addison PS. Wavelet transforms and the ECG: a review. *Physiol Meas*. 2005;26(5):R155. <https://doi.org/10.1088/0967-3334/26/5/R01>.
- Ten DI. Lectures on Wavelets. Society for Industrial and Applied Mathematics: Society for industrial and applied mathematics; 1992.
- Haris K, Vogt B, Strodtzoff C, Pessoa D, Cheimariotis GA, Rocha B, et al. Identification and analysis of stable breathing periods in electrical impedance tomography recordings. *Physiol Meas*. 2021;42(6):064003.
- Zhao Z, Möller K, Steinmann D, Frerichs I, Guttman J. Evaluation of an electrical impedance tomography-based global inhomogeneity index for pulmonary ventilation distribution. *Intensive Care Med*. 2009;35(11):1900–6.
- Mar Fernandez M, González-Castro A, Magret M, Bouza MT, Ibañez M, García C, et al. Reconnection to mechanical ventilation for 1 h after a successful spontaneous breathing trial reduces reintubation in critically ill patients: a multicenter randomized controlled trial. *Intensive Care Med*. 2017;43:1660–7.
- Sklar MC, Burns K, Rittayamai N, Lanys A, Rauseo M, Chen L, et al. Effort to breathe with various spontaneous breathing trial techniques. *Am J Respir Crit Care Med*. 2017;195(11):1477–85.
- Trepte CJC, Phillips CR, Solà J, Adler A, Haas SA, Rapin M, et al. Electrical impedance tomography (EIT) for quantification of pulmonary edema in acute lung injury. *Crit Care*. 2016;20(1):6. <https://doi.org/10.1186/s13054-015-1173-5>.
- Zhao Z, Peng S-Y, Chang M-Y, Hsu Y-L, Frerichs I, Chang H-T, et al. Spontaneous breathing trials after prolonged mechanical ventilation monitored by electrical impedance tomography: an observational study. *Acta Anaesthesiol Scand*. 2017;61(9):1166–75. [cited 2020 Oct 27]. Available from <http://doi.wiley.com/10.1111/aas.12959>.
- Bickenbach J, Czaplik M, Polier M, Marx G, Marx N, Dreher M. Electrical impedance tomography for predicting failure of spontaneous breathing trials in patients with prolonged weaning. *Crit Care*. 2017;21(1):1–8.
- Zhao Z, Pullett S, Frerichs I, Müller-Lisse U, Möller K. The EIT-based global inhomogeneity index is highly correlated with regional lung opening in patients with acute respiratory distress syndrome. *BMC Res Notes*. 2014;7(1):1–7.
- Yang KL, Tobin MJ. A Prospective Study of Indexes Predicting the Outcome of Trials of Weaning from Mechanical Ventilation. *N Engl J Med*. 1991;324(21):1445–50. <https://doi.org/10.1056/NEJM199105233242101>.
- Trivedi V, Chaudhuri D, Jinah R, Piticar J, Agarwal A, Liu K, et al. The Usefulness of the Rapid Shallow Breathing Index in Predicting Successful Extubation: A Systematic Review and Meta-analysis. *Chest*. 2022;161(1):97–111. <https://doi.org/10.1016/j.chest.2021.06.030>.
- Mosing M, Cheong JM, Müller B, Böhm SH, Hosgood G, Raisis A. Determination of tidal volume by electrical impedance tomography (EIT) after indirect two-point calibration. *Physiol Meas*. 2022;43(3):035005. [cited 2023 Feb 8]. Available from: <https://iopscience.iop.org/article/10.1088/1361-6579/ac604a>.
- Piraino T. Lung expansion therapy: Please, (visually) show me the value! *Respir Care*. 2019;64(10):1314–8.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.