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Electrical impedance tomography monitoring during spontaneous breathing trial: Physiological description and potential clinical utility

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Background: Readiness for mechanical ventilation (MecV) weaning and extubation is usually assessed clinically with the use of a spontaneous breathing trial (SBT), but its accuracy is limited, and the pathophysiology of weaning failure not completely elucidated. The purpose of the present study was to describe the physiological behavior of electrical impedance tomography parameters during SBT and to propose additional variables that could be helpful in defining weaning/extubation outcome.

Methods: From December 2015 to January 2017, all subjects who remained under MecV with an orotracheal tube for more than 24 hours and who were submitted to SBT both in pressure-support ventilation (PSV) or T-tube were included in the study. Both clinical and impedance parameters were collected immediately before as well as during SBT.

Results: Forty-two subjects were included in the final analysis. For subjects submitted to SBT in PSV, none of the impedance parameters added significant information regarding weaning outcomes. For subjects submitted to a T-tube SBT, a significant and progressive decrease in end-expiratory lung impedance (dEELI) was observed, which was more prominent in subjects who clinically failed the SBT. These subjects had a significant rapid shallow breathing index at the end of SBT.

Conclusions: dEELI was a potentially useful parameter in the evaluation of MecV weaning outcome when abrupt lung depressurization was induced during SBT in our study. The degree of dEELI decrease was probably related to the magnitude of lung derecruitment, which seems to play a key role in the MecV weaning outcome.

1 | INTRODUCTION

Mechanical ventilation (MecV) is frequently a part of the armamentarium for respiratory support in critically ill subjects. However, it is still difficult to predict which subjects will be successfully weaned and extubated. This is of major clinical relevance since reintubation is associated with higher mortality[1] and increased costs.[2]

Many clinical parameters and scores have been proposed to predict extubation success but with only mild to moderate accuracy.[3-6] More recently, electrical impedance tomography (EIT) has gained much interest as a useful bedside, noninvasive, continuous monitoring tool in mechanically ventilated subjects. It is capable of obtaining real-time, two-dimensional, cross-sectional images of the thorax, helping to evaluate the air distribution across the lungs. Its utility has been documented in many scenarios, including pneumothorax,[7,8] pulmonary edema,[9,10]positive end-expiratory pressure (PEEP) titration after recruitment maneuvers,[11-13] endotracheal tube position[14], and dynamic hyperinflation.[15]

Few previous studies have evaluated the role of EIT in predicting weaning/extubation failure in adults.[16-18] Since heterogeneous regional lung ventilation and derecruitment are frequently not accessible clinically but may be risk factors for weaning/extubation failure, we hypothesized that EIT monitoring might be an additional monitoring tool in ventilated subjects during weaning.

Hence, the aim of the present study was (a) to describe the physiological behavior of ventilation and aeration variables obtained by EIT both during T-tube and pressure-support ventilation (PSV) spontaneous breathing trials (SBTs) as well as after extubation and (b) to evaluate whether sequential monitoring of any of the measured EIT parameters might be of relevance to predict weaning and/or extubation failure.

Editorial comments

How air is distributed in the lungs in patients with ventilatory support is something that can inform clinicians. In this study, the authors demonstrate that electric impedance tomography may describe the physiological behavior of ventilation and aeration during spontaneous breathing trials as well as after extubation.

2 | METHODS

The study was approved by the Local Ethics Committee (protocol number 49489815.7.0000.0087), and written informed consent was obtained from the subjects or their relatives. From December 2015 to January 2017, the EIT device (Timpel S/A, São Paulo, Brazil) was available at our ICU for the purpose of the present study. Before the beginning of the study, all physiotherapists were trained to properly install the monitoring straps containing the electrodes, which apply a small current on the skin surface and then read the impedance change. Physiotherapists were also trained in collecting all on-time available data provided by the EIT device at its monitoring screen, including the ventilation distribution (anterior/posterior, right/left). The attending intensivists defined the moment of SBT (using classical ready-to-wean criteria), SBT duration (usually 30 minutes) and method (T-tube vs PSV) and were usually unaware of the values displayed on the EIT device although its monitoring screen was made freely accessible.

All subjects who remained at MecV with an orotracheal tube for more than 24 hours and who were submitted to a SBT were included in the study, except those who were less than 18 years old, pregnant or had a contraindication for use of the device (pacemaker or skin lesions in the area of the straps).

Clinical data such as age, gender, Sequential Organ Failure Assessment (SOFA)[19] at the day of SBT, use of vasoactive drugs during SBT, method of SBT (T-tube vs PSV), maximal inspiratory and expiratory pressure, and MecV period before SBT were all analyzed. Tidal volume adjusted to predicted body weight (Vt/kg), respiratory rate (RR), minute ventilation (MinV), and rapid shallow breathing index (RSBI) were assessed 10 minutes before the beginning and at the end of the SBT. For subjects with successful SBT, extubation was followed by variable assessment again at 6 and 12 hours after extubation. More detailed EIT information that was not available at the time of monitoring was obtained later using the data recorded inside the device (offline analysis), including variations in dEELI, which is a measure of lung aeration and corresponds to the residual functional capacity of the lungs; tidal impedance variation (TIV), which is a measure of lung ventilation, and regional tidal impedance variation (%TIV), which is a measure of regional lung ventilation distribution. All these variables were obtained continuously during monitoring, and the values 10 minutes before SBT (T0), 1 minute (T1), 10 minutes (T10), and 30 minutes (T30) after the beginning of the SBT were retrieved. For subjects who failed SBT, the last registration of these variables (Tx) was determined before MecV resumption.

Weaning failure was diagnosed clinically according to the Institutional protocol using the following parameters: RR > 35/min, heart rate > 140/min, systolic blood pressure < 90 or > 180 mm Hg, arterial oxygen saturation < 90%, and/or decreased level of consciousness during SBT. No extubation was attempted in these cases. Extubation was considered successful if the subject remained extubated for the next 48 hours. Only the first SBT of each subject during the study period was considered for analysis.

Subjects were then divided into 4 main groups: pressure-support weaning failure (PSWF), pressure-support weaning success (PSWS), T-tube weaning failure (TTWF), and T-tube weaning success (TTWS). The PSWS group was then divided in 2 groups: extubation failure (PSEF) and extubation success (PSES). The TTWS group was divided equivalently: extubation failure (TTEF) and extubation success (TTES).

2.1 | Statistical analysis

General characteristics of the subjects are presented as medians and interquartile ranges for continuous variables, and the Mann-Whitney rank sum test was used for comparison of these variables between the PSV and T-tube groups. Categorical variables are presented as percentages and were compared using the Fisher's test. The assumption of homoscedasticity, which is common among linear models, was not satisfied for most of the evaluated variables; in addition, the data were longitudinally evaluated in each individual. Thus, to fit the characteristics of the data, linear mixed models considering a random effect of the intercept and parameters of distinct variances over time were adjusted, and interactions among time, SBT method, and weaning outcome were tested by ANOVA. Receiver-operating characteristic (ROC) curves were generated to test the accuracy of different variables in predicting weaning/extubation failure. SigmaPlot version 12.0 (Systat Software Inc., USA) and R 3.4.1 (R Core Team, Austria) were used for the statistical analyses. A P-value < 0.05 was considered significant.

3 | RESULTS

Of the 245 ventilated subjects in the ICU during the study period, only 42 were included in the final analysis (Figure 1). The general characteristics of the 42 subjects are presented in Table 1. Except for the patients with chronic obstructive pulmonary disease (COPD), there was no previous known lung disease in our patients. Thirty-two subjects were submitted to SBT in PSV mode and 10 subjects in T-tube mode, each one as requested by the attending physician. The 2 groups were very similar before SBT (including MecV parameters), with a significant difference only in the MecV duration (Table 1).

Five of the 32 subjects (16%) submitted to PSV-SBT failed and were not extubated (PSWF). The cause of failure was mainly attributed to increased work of breathing (2 cases), a depressed level of consciousness during SBT (2 cases), and an increased vasopressor need during SBT (1 case). Of the remaining 27 subjects (PSWS), 23 (85%) were successfully extubated (PSES). Three of the 10 subjects (30%) submitted to T-tube SBT failed and were not extubated (TTWF). All 3 failures were mainly attributed to increased work of breathing. The remaining 7 subjects (TTWS) were successfully extubated (TTES). Therefore, no patient was successfully weaned from the T-tube and subsequently failed extubation in our sample (no subjects in the TTEF group; TTWS and TTES groups correspond to the same subjects). All subjects who failed SBT in both the PSV and T-tube groups completed at least 20 minutes of SBT.

3.1 | Clinical parameters

No differences were found in Vt/kg and MinV before and at the end of SBT, for both methods (PSV and T-tube), independently of the weaning outcome (Figures 2A and 2B). RR and RSBI were also similar before and at the end of SBT, except the TTWF group had a nonsignificantly higher RR and a significantly higher RSBI at the end of SBT compared with the TTWS group (Figure 2C).

3.2 | Impedance parameters

3.2.1 | End-expiratory lung impedance variation (dEELI)

No differences were found in dEELI along the PSV-SBT, independently of the weaning outcome. However, a significant, progressive decline in total dEELI was found along the T-tube SBT from T1 until the end of SBT, independently of the weaning outcome (Figure 3). However, decreases in dEELI were significantly more pronounced in subjects who failed T-tube SBT (Figure 3). This behavior was similar in both anterior/posterior dEELI and right/left dEELI. A statistically significant decrease in dEELI already at T1 in TTWF in comparison to TTWS was also observed in posterior dEELI and left dEELI but not in anterior dEELI and right dEELI.

3.2.2 | Tidal impedance variation (TIV)

Distinct from dEELI, no significant differences were found in TIV regarding the weaning outcome, independently of the SBT method (Figure 4). The pattern was the same independently of the lung region. However, an interaction was found between time and the SBT method (lower TIV values in T-tube groups in comparison to PSV groups over time). Such an interaction was also present independently of the lung region.

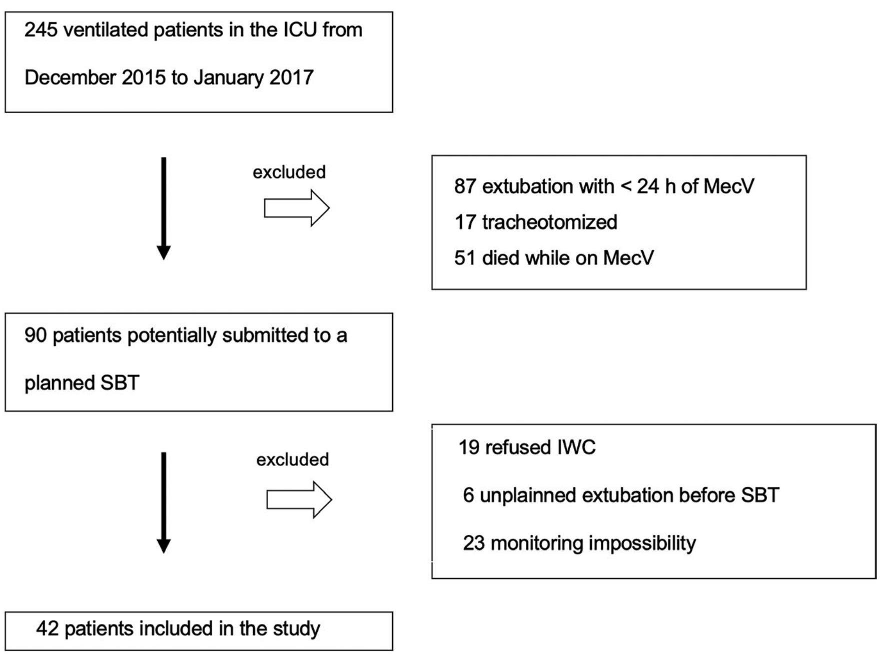

FIGURE 1 Flow chart of the study. Abbreviations: ICU, intensive care unit; MecV, mechanical ventilation; SBT, spontaneous breathing trial; IWC, informed written consent

TABLE 1 General characteristics of the 42 patients included in the study according to SBT mode

	All patients (n = 42)	PSV SBT (n = 32)	T-tube SBT (n = 10)	*P*-value*
Age (years)	68 [44,80]	69 [48,81]	56 [41,74]	0.308
Gender (m/f)	24/18	18/14	6/4	1.000
Ideal body weight (kg)	64 [55,71]	64 [55,71]	66 [52,73]	0.745
SOFA at the day of SBT	3 [2,4]	3 [2,4]	4 [1,5]	0.631
MV period before SBT (hours)	74 [45,127]	66 [42,108]	137 [72,221]	**0.030**
ΔP before SBT (cmH_2O)	9 [8,10]	8 [8,10]	9 [8,10]	0.964
PEEP before SBT (cmH_2O)	6 [5,6]	6 [5,7]	6 [5,7]	0.912
Pimax during SBT (cmH_2O)	−45 [−50,−35]	−47 [−50,−35]	−40 [−45,−33]	0.266
Pemax during SBT (cmH_2O)	40 [24,50]	40 [24,50]	30 [3,43]	0.370
Vasoactive drugs during SBT—n (%)	14 (33.3)	12 (37.5)	2 (20.0)	0.451
Weaning success—n (%)	34 (81.0)	27 (84.4)	7 (70.0)	0.369
Extubation success—n (%)	30 (71.4)	23 (71.9)	7 (70.0)	1.000
Main reason for intubation				
Major surgery n (%)	15 (35.7)	12 (37.5)	3 (30.0)	1.000
Abdominal	6	4	2	
Neurosurgery	4	4	0	
Thoracic	2	1	1	
Gynecologic	2	2	0	
Cardiac	1	1	0	
Respiratory failure n (%)	14 (33.3)	10 (31.3)	4 (40.0)	0.707
ARDS	3	3	0	
COPD	3	3	0	
Neuromuscular disease	2	0	2	
Pneumonia	2	2	0	
Pulmonary embolism	1	1	0	
Diabetic ketoacidosis	1	0	1	
Hypervolemia	1	0	1	
Aspiration	1	1	0	
Septic shock n (%)	11 (26.2)	9 (28.1)	2 (20.0)	0.705
Lung	5	4	1	
Soft tissue	4	3	1	
Abdominal	2	2	0	
Coma n (%)	2 (4.8)	1 (3.1)	1 (10.0)	0.424
Meningitis	1	1	0	
Hepatic encephalopathy	1	0	1	

Abbreviations: ΔP, driving pressure; Pimax, maximum inspiratory pressure; Pemax, maximum expiratory pressure; PEEP, positive end-expiratory pressure; PSV, pressure-support ventilation; SBT, spontaneous breathing trial.
*Comparison between PSV SBT and T-tube SBT groups.
Bold indicates statistically significant value (< 0.05).

3.2.3 | Regional tidal impedance variation (%TIV)

The %TIVs between right and left lungs as well as between anterior and posterior regions were similar, independently of the SBT method, time, or outcome (Figures 5A and 5B).

3.2.4 | Rapid shallow breathing index—impedance equivalent (RR/TIV)

Since the RSBI includes only *total* Vt and is a clinical parameter, we also assessed an impedance equivalent of this parameter using RR

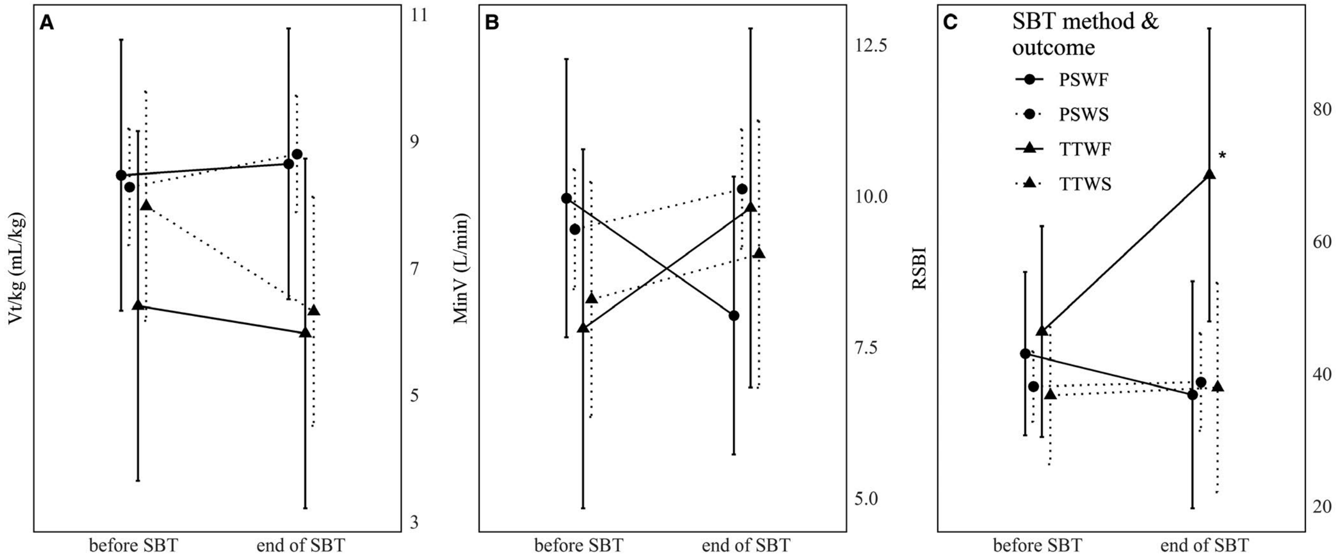

FIGURE 2 (A) Tidal volume adjusted to ideal body weight (Vt/kg), (B) minute ventilation (MinV), and (C) rapid shallow breathing index (RSBI) before and at the end of the spontaneous breathing trial (SBT) in PSV or T-tube, according to weaning outcome. Abbreviations: PSWF, pressure-support weaning failure; PSWS, pressure-support weaning success; TTWF, T-tube weaning failure; TTWS, T-tube weaning success. *$P < 0.05$ in comparison to the same time in TTWS

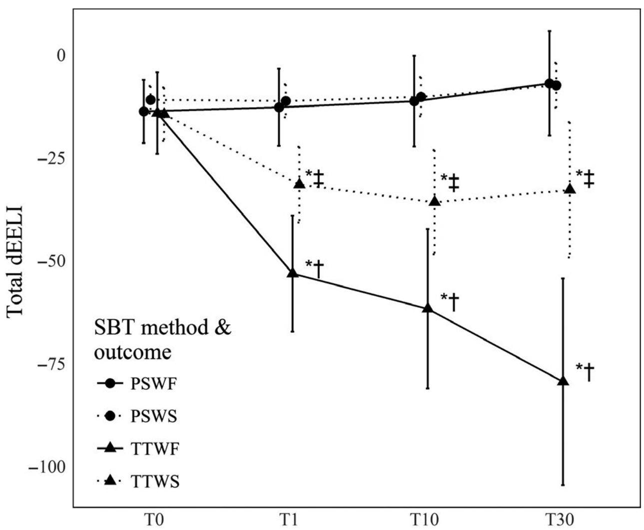

FIGURE 3 Time course of variations in total dEELI immediately before (T0) and after 1 (T1), 10 (T10), and 30 (T30) minutes of spontaneous breathing trial (SBT) initiation according to the SBT method and weaning outcome. Abbreviations: PSWF, pressure-support weaning failure; PSWS, pressure-support weaning success; TTWF, T-tube weaning failure; TTWS, T-tube weaning success. *$P < 0.01$ in comparison to T0 (within group); ‡$P < 0.01$ in comparison to the same time in PSWS (between groups); †$P < 0.05$ in comparison to the same time in TTWS (between groups)

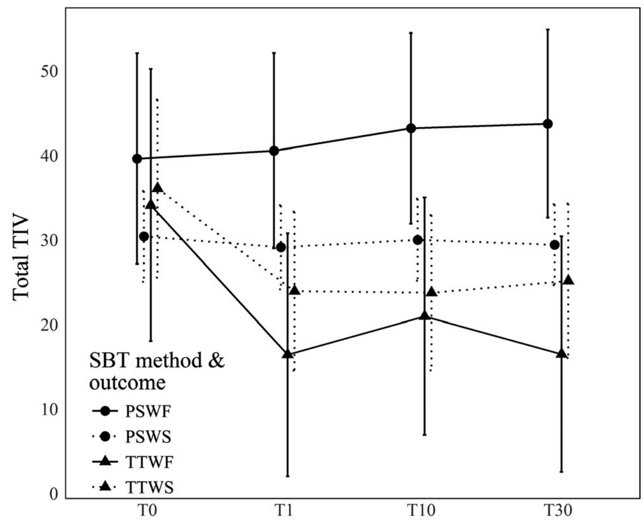

FIGURE 4 Time course of tidal impedance variation (TIV) immediately before (T0) and after 1 (T1), 10 (T10), and 30 (T30) minutes of spontaneous breathing trial (SBT) initiation according to the SBT method and weaning outcome. Abbreviations: PSWF, pressure-support weaning failure; PSWS, pressure-support weaning success; TTWF, T-tube weaning failure; TTWS, T-tube weaning success

and TIV (total and separated by regions: right/left, anterior/posterior) at T0 and T30, corresponding to before and at the end of SBT (same points of RSBI assessment). RR/total TIV was also significantly higher at T30 in the TTWF group in comparison to TTWS. The results were similar using any of the regional TIVs instead of the total TIV, except for RR/left TIV, in which the increase at T30 in the TTWF group was not statistically significant.

3.2.5 | dEELI accuracy in predicting T-tube SBT failure

To evaluate the accuracy of decreases in total dEELI to predict weaning failure, 2 ROC curves using total dEELI at T10 and T30 (or Tx in cases of SBT failure) minus total dEELI before SBT were constructed (Figure 6). The accuracy using total dEELI at T10 was excellent but with marginal statistical significance ($P = 0.05$). Using total dEELI at T30/Tx, there was a significant improvement in accuracy.

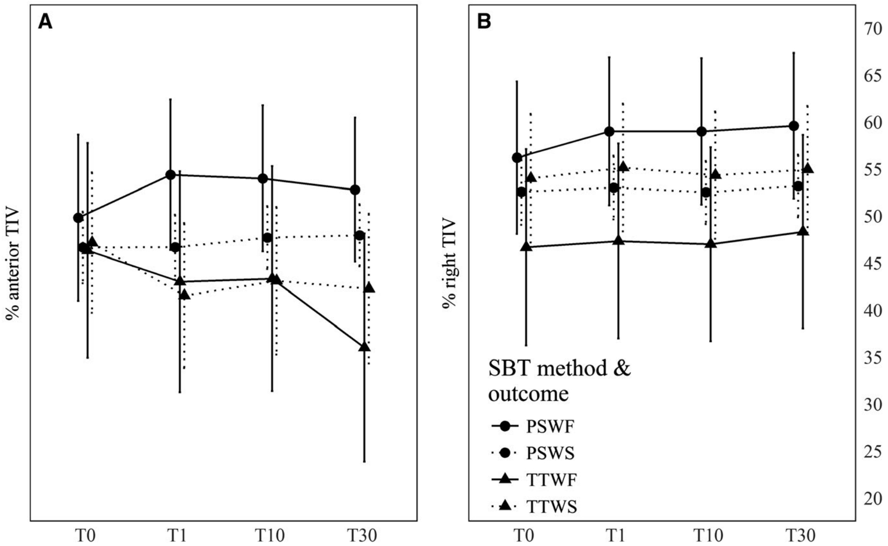

FIGURE 5 Time course of regional tidal impedance variation (%TIV) in anterior (panel A) and right regions (panel B). Only anterior and right regions are presented since percentages in posterior and left regions correspond to 100% minus their opposite percentages

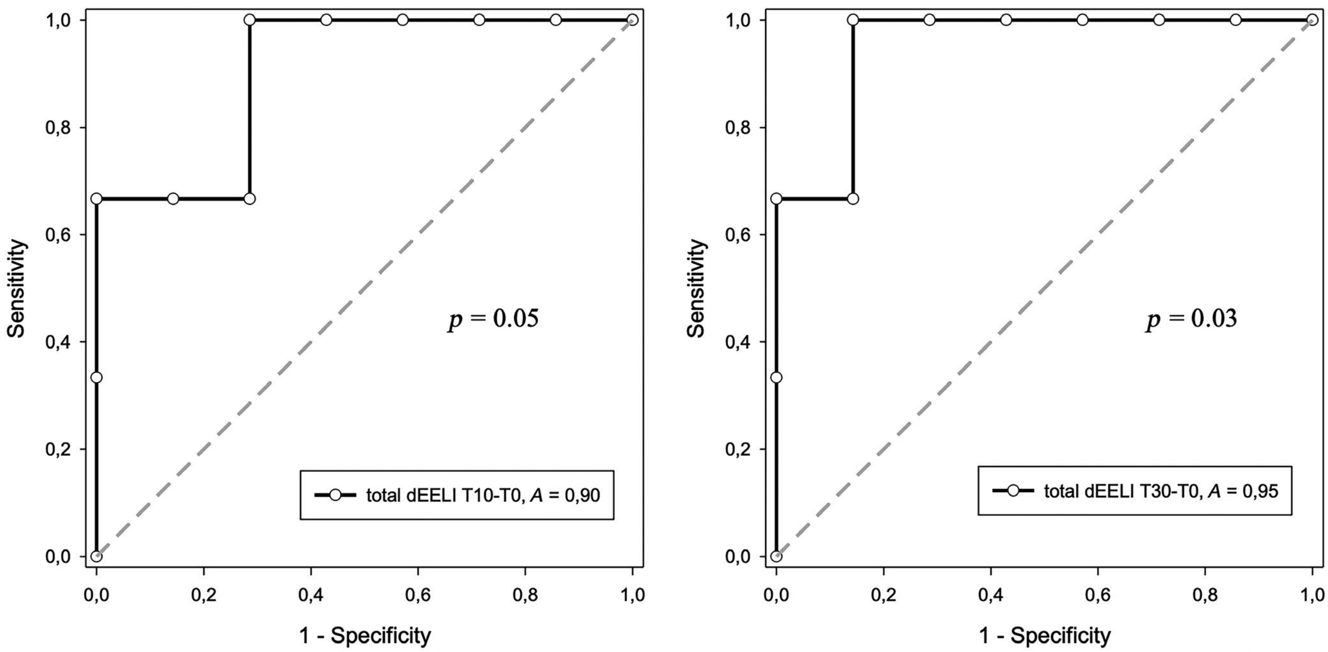

FIGURE 6 Receiver-operating characteristic (ROC) curves of the accuracy of decreases in total dEELI to predict weaning failure in subjects submitted to a T-tube spontaneous breathing trial (SBT). *Left curve*: decreases after 10 minutes of SBT (AUC = 0.905 (95% IC 0.695-1.114, *P* = 0.05); *Right curve*: decreases after 30 minutes of SBT (AUC = 0.952 (95% IC 0.817-1.087, *P* = 0.03)

3.2.6 | dEELI behavior after extubation success

Since dEELI was the sole impedance parameter that consistently changed during T-tube SBT, we compared its evolutive behavior between the PSES and TTES groups both during the SBT period but also 6 and 12 hours after extubation (Figure 7). While dEELI remained stable in PSES subjects during SBT, it decreased progressively in TTES. Six hours after extubation, dEELI increased significantly in the PSES group and remained significantly greater than in the TTES group. At 12 hours, the values of dEELI were already similar between groups. Unfortunately, impedance parameters of subjects that failed extubation were not available.

4 | DISCUSSION

In this single-center, prospective, observational, exploratory study, we were able to describe the physiological behavior of many impedance parameters during SBT and hypothesized that dEELI, a variable related to lung aeration and recruitment that is not usually available at the bedside, may be a relevant additional parameter to evaluate the chance of weaning success. This result seems particularly true for subjects submitted to a T-tube SBT in whom abrupt lung depressurization has occurred, in contrast to those submitted to a PSV-SBT. All evaluated EIT parameters provided unremarkable results in cases of PSV-SBT in our study. Our findings were similar to the preliminary

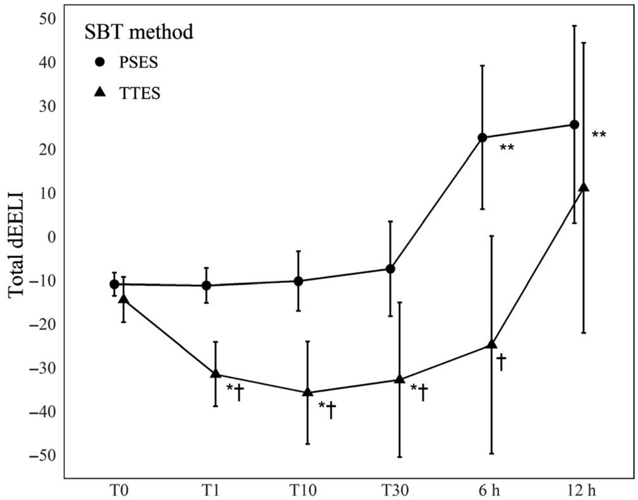

FIGURE 7 Time course of variations in total dEELI in subjects successfully extubated, separated by spontaneous breathing trial (SBT) method. T0 corresponds to time immediately before the beginning of SBT. **P* ≤ 0.01 in comparison to T0 (within TTES group); †*P* < 0.05 in comparison to the same time in the PSES group; ***P* ≤ 0.01 in comparison to T0 (within PSES group). Abbreviations: PSES, pressure-support weaning and extubation success; TTES, T-tube weaning and extubation success

observations of Longhini et al[20], who also observed early and significant decreases in dELLI in patients with failing SBT in comparison to those with successful SBT, while TIV parameters were similar regardless of weaning outcome.

A recent study[17] has suggested that the application of EIT during T-tube SBT can support clinical decisions in tracheotomized subjects undergoing prolonged weaning, and a decrease in dEELI during T-tube SBT was also observed.

Since a T-tube SBT involves complete depressurization of the lungs, some degree of decrease in the residual functional capacity (corresponding to the total dEELI) was physiologically expected, and these data per se only serve to assure that data obtained by the EIT device were reliable in our study. However, a major finding of the present analysis was that the magnitude of this decrease might be related to the weaning outcome, possibly because it reflects the condition experienced by the subject following extubation. In subjects with T-tube SBT success, only minor (albeit significant) decreases in dEELI occurred, while in cases of failure, an apparently more abrupt decrease in dEELI occurred soon after depressurization (even a single minute after), followed by an additional progressive decrease over SBT. Such additional decreases in dEELI between 10 minutes and the end of SBT likely explained the improved accuracy of the ΔdEELI if the values at the end of SBT were used (Figure 6). It is noteworthy that analyses involving dEELI were not available to the professionals during SBT throughout the entire study period, and thus there was no bias related to the simultaneous evaluation of clinical parameters and dEELI monitoring to define weaning failure. Indeed, the weaning outcome was defined herein solely on a clinical basis with no influence of EIT variable monitoring.

Since there were no weaned subjects that failed extubation in the T-tube group, we could not evaluate whether there was a relevant increment in the accuracy of extubation success prediction with the addition of dEELI monitoring. Moreover, no subjects that failed T-tube SBT were extubated to test whether major decreases in dEELI were related to extubation failure. We only hypothesized that there might be an increment in the specificity to predict extubation success when clinical parameters were favorable (including no increases in RR or RSBI) *and* decreases in dEELI were less prominent (no major derecruitment) during T-tube SBT. The post-extubation success in our study was characterized by a significant increase in dEELI, with similar values after 12 hours regardless of the SBT method.

It is not clear in the literature whether one method of SBT is superior to another.[21] In this study, the subjects were very similar between groups, except for the increased MecV period before SBT in the T-tube group. This observation suggested that, although PSV-SBT is usually preferred in our ICU (Table 1), T-tube is reserved for subjects with an increased MecV duration and potentially considered to have a higher risk of extubation failure. Notably, the difference in MecV duration before SBT between groups and the small samples precluded any conclusion regarding an eventual superiority of 1 SBT method over the other in our study in terms of weaning outcome. The absence of significant differences in Vt/kg and MinV as well as in TIV and %TIV between the weaning success and failure groups using both SBT methods provides important insight into the weaning failure process: dEELI, a surrogate for end-expiratory lung volume,[22] seems to be more relevant than total and regional lung ventilation in the weaning outcome. It is important to emphasize that decreases in lung impedance may be related not only to a reduced thoracic air content but also to an increased liquid content, so that SBT failure could be due to other reasons such as pulmonary edema.

Ventilation parameters are more clinically accessible than lung volume or impedance. Of note, regional evaluations of EIT parameters do not seem to add much information to the evaluation obtained with total lung analysis, including RR/TIV, which provided similar results regardless of the use of total or any regional TIV and with apparently no advantage over classic RSBI.

One possible reason for the absence of differences in both clinical and EIT parameters in PSV-SBT was that most subjects had MecV parameters before the beginning of the SBT that were already very similar to the parameters used during SBT (Table 1). Thus, SBT in PSV did not impose any significant additional stress to the respiratory system in most subjects (as in T-tube SBT), which seems to be an important element to distinguish weaning success or failure. It is possible that, hypothetically, abrupt decreases in dEELI due to an abrupt decrease in PEEP in PSV-SBT would also predict weaning failure in this group.

An alternative interpretation of our findings is that major decreases in dEELI observed in some patients subjected to T-tube SBT are indeed the cause and not a predictor of weaning failure, since the work of breathing and lung derecruitment may be even greater during this SBT than after extubation.

Progressive increases in dEELI during the subsequent hours after successful extubation were observed in both SBT groups

(Figure 7). Although these increases could represent true lung volume recovery, we could not rule out the contributions of a possible drift in measurements and changes in the electrical properties in the thorax during this long period of time. Considering that such variables would interfere similarly in both groups, we speculate that successful extubation in the present study was related to progressive restoration of lung volume which required a longer time for T-tube SBT subjects due to their lower dEELI values at the end of SBT.

In the present study, extubation failure occurred only in the PSV-SBT group. As previously mentioned, the design of our study precluded any conclusion regarding a more in-depth analysis and evaluation concerning the superiority of one SBT method over the other. We evaluated the causes of extubation failure of the 4 patients and in 3 of them the cause was not primarily lung failure (stridor in 1 patient and depressed level of consciousness in 2 patients). Hence, we were unable to reach any conclusion regarding the utility of EIT parameters during PSV-SBT to predict extubation failure related to lung impairment.

Our study has other several limitations. First, it was a small, single-center study, which increases the chance of type beta errors and imposes some difficulty in the external validation of our findings. The major finding was retrieved from the T-tube group, which represented the minority of subjects. No definitive conclusion could be made regarding the PSV-SBT groups. Albeit these limitations, the statistically significant difference in the behavior of dEELI between T-tube groups, even in a small sample, suggests that this finding could be physiologically and clinically relevant.

5 | CONCLUSIONS

Early and progressive decreases in dEELI occur in T-tube SBT, and they are more prominent in cases of SBT failure. In addition to the contribution of this parameter to our understanding of weaning failure pathophysiology, its monitoring may improve accuracy in determining extubation readiness and outcome. Although no single EIT parameter was able to predict weaning/extubation outcome of the PSV-SBT subjects in our study, the study limitations precluded any definitive conclusion concerning this SBT method. Larger studies are needed to better define the role of EIT and dEELI in the MecV weaning process, as well as to evaluate the cost-effectiveness of the EIT device.

CONFLICT OF INTEREST

There are no conflicts of interest of any of the authors to declare. Timpel S/A only provided the EIT device during the study period.

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