

The Application of Electrical Impedance Tomography During the Ventilator Weaning Process

Guan Wang
Lei Zhang
Bin Li
Bingyin Niu
Jian Jiang
Duo Li
Zhu Yue
Yibing Weng

Department of Critical Care, Beijing Luhe Hospital, Capital Medical University, Beijing, People's Republic of China

Background: This study proposes the investigation of electrical impedance tomography (EIT) as a useful predictor for ventilator weaning.

Methods: The study design was a nested case-control study and patients who were admitted to the intensive care unit and underwent their first tracheal intubation were enrolled. Those who successfully completed ventilator weaning and extubation after the first spontaneous breathing trial (SBT) were included in the weaning success group, while those who did not pass the SBT or received secondary intubation within 48 hours were included in the weaning failure group. In both groups, EIT was adopted to record the monitoring data in three phases: before the SBT (pre-SBT), during the SBT (SBT), and after the SBT (post-SBT).

Results: A total of 53 patients were enrolled, including 41 cases in the weaning success group and 12 cases in the weaning failure group. The logistic regression analysis showed that the pre-SBT global impedance (GI) and the SBT region of interest 2 (ROI2) were significantly higher in the weaning success group than in the weaning failure group ($p = 0.0001$ and $p = 0.002$). The pre-SBT GI predicted weaning success with a sensitivity of 0.524, a specificity of 0.818, a p -value of 0.0496, and a 95% confidence interval (CI) of 0.001–0.978. The sensitivity, specificity, p -value, and 95% CI for the SBT ROI2 were 1, 0.595, 0.0164, and 1.010–1.108, respectively.

Conclusion: For patients without contraindications to EIT, the application of EIT is recommended to be added to the existing evaluation system for ventilator weaning, as it could help improve the weaning success rate. Further cohort studies are needed to investigate the actual efficacy of EIT after it has been added to the evaluation system.

Keywords: electrical impedance tomography, mechanical ventilation, ventilator weaning, prediction

Background

Since the introduction of invasive mechanical ventilation in clinical practice, the question of when to conduct ventilator weaning and the rate of weaning success have been important issues in the field of intensive care. Clinical practitioners have worked tirelessly to establish a clinical evaluation system to help select the timing and predict the success of ventilator weaning. This system mainly includes the screening of patients pre-weaning together with the use of evaluation indicators at the time of ventilator weaning. Using this evaluation system, approximately 75–80% of patients complete the one-time ventilator weaning and extubation process, while the remaining 20–25% fail to be weaned.^{1,2} The exact causes of failed ventilator weaning are still debatable, but recent studies have shown that 60% of such cases could be avoided.^{3–6} This suggests that the current evaluation system

Correspondence: Yibing Weng
Department of Critical Care, Beijing Luhe Hospital, Capital Medical University, Beijing, People's Republic of China
Tel +86 10 69543901-2128
Email yibingweng@ccmu.edu.cn

needs to be improved by introducing new indicators, especially those that reflect patients' pulmonary ventilation dynamics before and after ventilator weaning.

Electrical impedance tomography (EIT) is a technique developed in recent years, which is based on the emission of impedance waves from 16 electrodes tied to defined sites in the thorax (generally between the fourth and sixth ribs for a positive body type [The body is well-proportioned, and the upper abdominal Angle is equal to 90°]). It calculates the attenuation of impedance waves between different tissues in the thorax and adopts the corresponding algorithm to reduce it to a tomographic image of the pulmonary tissue. The impedance wave emitted by the EIT electrodes is inconsistently attenuated in different tissue forms, resulting in a high impedance value in well-ventilated areas, a decreased value in less-ventilated areas, and a baseline impedance value (the minimum) in unventilated areas. It is similar to conventional computed tomography, but the difference is that EIT is continuous and dynamic, reflecting changes in the pulmonary tissue during inspiration and expiration in real time through the monitoring screen. It can also be used to precisely evaluate the ventilation status of a specific area of the tissue through the device's localized monitoring function, thus helping clinical staff determine whether a patient is in a pathological state or exhibiting a degree of recovery from a disease.^{7–13} In preliminary observations of ventilator weaning under EIT monitoring, we have found that a proportion of patients who meet the criteria for ventilator weaning according to the traditional evaluation system show poor inspiratory and expiratory imaging of the lungs when EIT is applied, ie, significantly smaller impedance values and decreased blood oxygen and respiratory muscle fatigue during the continuation of the spontaneous breathing trial (SBT). However, in other patients who do not fully meet the predictors for ventilator weaning, the EIT imaging suggests good ventilation of the lungs and continues to be stable after extubation. Therefore, the present study evaluates whether EIT could help predict ventilator weaning in patients undergoing invasive mechanical ventilation.

Methods

Study Design

The present study was a nested case–control study conducted at the Beijing Luhe Hospital, Capital Medical University, Beijing, China. Patients admitted to the Department of Intensive Care Medicine and who

underwent tracheal intubation for invasive mechanical ventilation between December 1, 2017, and September 30, 2018, were enrolled. Those who successfully completed ventilator weaning and extubation after the first SBT were included in the weaning success group, while those who failed to pass the SBT or received secondary intubation within 48 hours following extubation were included in the weaning failure group. The present study was approved by the hospital's ethics committee, with the approval number 2018LH-KS-015 and the clinical trial registration number ChiCTR1800015680.

The Inclusion and Exclusion Criteria

The inclusion criteria were as follows: patients who were intubated for the first time and who were expected to be intubated for at least 72 hours. The exclusion criteria were as follows: patients with a body mass index (BMI) >35 kg/m², patients with cardiac pacemakers or implanted electronic devices, patients undergoing spinal surgery, patients with confirmed neurogenic ventilator dependency or anticipated tracheotomy, patients with moderate to severe acute respiratory distress syndrome, and patients who were pregnant.

SBT Methods

The pre-weaning SBT screening followed the protocol set out in the “Guidelines for Mechanical Ventilation Withdrawal in Critically Ill Patients,”¹⁴ jointly issued by the American Thoracic Society and American College of Chest Physicians. Here, t-tube and ventilator weaning with a tube were adopted in the SBT, with complete aspiration and disconnection of the ventilator from the T-tube before weaning. The oxygen flow rate was 6 L/min, and the duration of weaning was three minutes. If there was no noticeable change in a patient's vital signs and oxygenation, ventilator weaning was continued for 30 minutes. The tracheal tube was extubated when the arterial blood gas (ABG) oxygenation index decreased by no more than 30% compared with pre-weaning values. Following extubation, oxygen inhalation with an oxygen flow rate of 6–8 L/min was administered.

The SBT was repeated in the weaning failure group after elective evaluation until extubation. Those who underwent the SBT ≥ 3 times were excluded from the study. The body position of the patients was maintained at a 30-degree head elevation during the SBT.

Data Collection

EIT was adopted to record all impedance data before the SBT (pre-SBT), during the SBT (SBT), and after the SBT (post-SBT) in both groups. Details on the patients' demographic characteristics; primary diagnosis; main diagnosis on admission to the intensive care unit; ABG at 30 minutes pre-SBT; ABG at 30 minutes after extubation; levels of hemoglobin, platelets, and leukocytes; and blood biochemistry were collected in both groups.

EIT Data Analysis

EIT imaging was divided into four regions of interest (ROI) in the horizontal mode: ROI1, ROI2, ROI3, and ROI4. The sum of the ROI impedance values was taken as the global impedance (GI). MATLAB 7.2 software (The MathWorks Inc., Natick, MA, USA) was used to design a processing program to analyze the four ROIs and the impedance values reflected by the GI (Figure 1).

Statistical Processing

SAS 9.4 software (SAS Institute Inc., Cary, NC, USA) was employed for the statistical analysis. Countable variables, such as gender, were expressed as categorical data. Measured data, such as age, height, weight, BMI, and impedance values, were expressed as the mean \pm standard deviation ($\bar{x} \pm s$). The Kruskal–Wallis test was used for

non-normally distributed data. Logistic regression was used to screen for factors associated with ventilator weaning success, such as the impedance values, demographic characteristics, and blood biochemical indicators. A p -value <0.05 was considered statistically significant for all tests.

Results

General Characteristics

Fifty-three patients were included in the study: 41 in the weaning success group and 12 in the weaning failure group. There were no statistical differences in the demographic characteristics, duration of mechanical ventilation, or days of admission between the two groups (Table 1, Figure 2).

Screening of the Positive Factors by Logistic Regression Analysis During the First Ventilator Weaning Process in the Weaning Success Group and the Weaning Failure Group

EIT Positive Factors

The pre-SBT GI was significantly higher in the weaning success group than in the weaning failure group ($327,179.69 \pm 225,318.54$ versus $286,800 \pm 147,891$, respectively; $\chi^2 = 14.7321$; $p = 0.0001$). Similarly, the

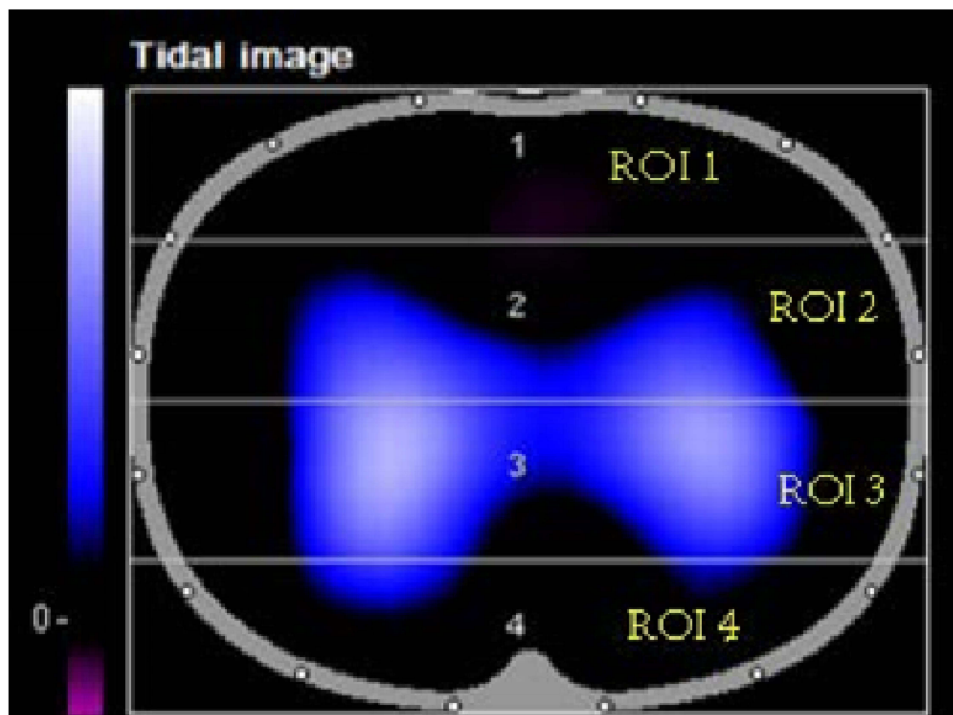


Figure 1 Schematic diagram of EIT dynamic image horizontal distribution (ROI = region of interest).

Table 1 Patients Characteristic (Total Cases n=53)

	$\bar{x} \pm s$	Experimental Group n=41	Control Group n=12	p value
Patient characteristics				
Age (Years)	62±12	61±16	59±19	0.885
Weight (Kg)	67.1±13.6	66.8±13.3	68.3±15.4	0.753
Height(m)	1.66±0.10	1.66±0.09	1.68±0.10	0.640
BMI	23.5±4.5	23.4±4.8	24.0±2.8	0.693
Duration of MV (day)	7±4	6±4	5±4	0.237
Gender (M: F)	33:20	28:13	7:5	0.412
Diagnosis n (%)				
Cardiosurgery		8(19)	4(33.3)	/
Chest surgery		2(4.8)	/	/
Gastrointestinal surgery		17(40.5)	4(33.3)	/
Cardiovascular diseases		5(11.9)	2(16.7)	/
Urinary surgery		2(4.8)	/	/
Trauma		3(7.1)	/	/
Pneumonia		5(11.9)	2(16.7)	/

SBT ROI2 was significantly higher in the weaning success group than in the weaning failure group ($316,615 \pm 521,982$ versus $237,090 \pm 197,280$, respectively; $\chi^2 = 9.5871$; $p = 0.002 < 0.01$) (Table 2, Figure 3).

Other Factors

In the weaning success group, the pre-SBT pH, bicarbonate, and hemoglobin values, and the post-SBT arterial pH and CO₂ partial pressure (PCO₂) were all better than those in the weaning failure group ($p < 0.0001$). However, the results of

arterial blood lactate and serum alanine aminotransferase (ALT) analysis suggest that the weaning success group is not better than the weaning failure group ($p < 0.0001$) (Table 3).

Specificity and Sensitivity of Pre-SBT GI and SBT ROI2 in Predicting Weaning Success

In EIT, the most important indicators for predicting ventilator weaning success are the pre-SBT GI and the SBT

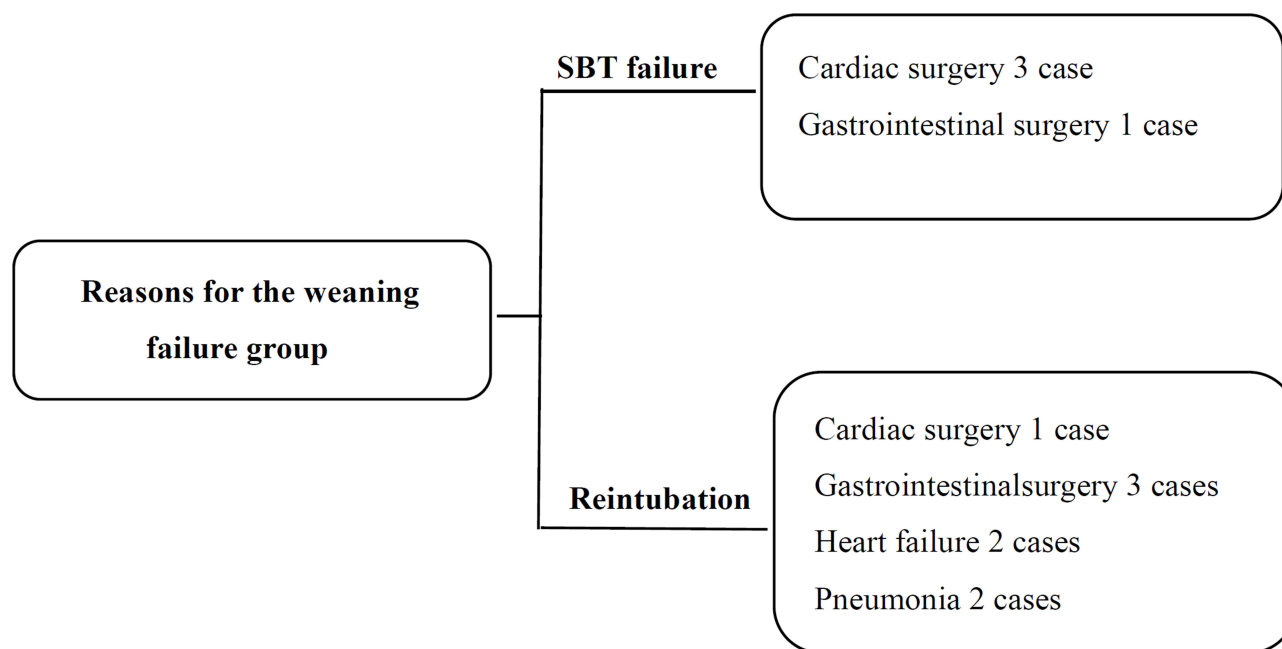


Figure 2 Reasons for weaning failure in the weaning failure group.

Table 2 Screening of Positive Factors During Weaning in the Weaning Success and Weaning Failure Group

Effect	$\bar{x}\pm s$	df	Wald	Pr>ChiSq
GI of pre-SBT				
Success	327179±225318	1	14.7321	0.0001
Failure	286800±147891			
ROI2 of SBT				
Success	316615±521982	1	9.5871	0.0020
Failure	237090±197280			

Abbreviations: success, weaning success group; failure, weaning failure group; GI of pre-SBT, global impedance on pre-SBT; ROI2 of SBT, ROI2 impedance on SBT.

ROI2. In the present study, the pre-SBT GI predicted the weaning success with a sensitivity of 0.524, a specificity of 0.818, a p-value of 0.0496, and a 95% confidence interval (CI) of 0.001–0.978. The sensitivity, specificity, p-value, and 95% CI for the SBT ROI2 were 1, 0.595, 0.0164, and 1.010–1.108, respectively (Table 4, Figure 4).

Screening of the Positive Factors by Logistic Regression Analysis During the Two Ventilator Weaning Processes in the Weaning Failure Group

EIT Positive Factors

For the pre-SBT GI and ROI3, SBT ROI4, and post-SBT ROI1, all impedance values during the second weaning were significantly higher than those during the first ventilator weaning, with statistical values of $t = 1.328$, $p = 0.026$, $t = 1.334$, $p = 0.015$, $t = 2.212$, $p = 0.046$, $t = 2.504$, and $p = 0.003$, respectively ($p < 0.05$) (Table 5).

Other Positive Factors

The pre-SBT PCO_2 , base excess, and creatinine levels and the post-SBT pH results all suggested that the second

ventilator weaning was better than the first ($p < 0.05$) (Table 5).

Discussion

Since the ventilator was first adopted by Bjorn Ibsen in 1953 to treat patients with respiratory failure, the question of how to safely conduct ventilator weaning has been an important issue in critical care medicine. Weaning is a gradual process in which patients go from machine support to unassisted breathing and consists of three key steps. First, when the patient's clinical condition permits it, ventilation support is gradually reduced. Second, an SBT is conducted to assess the patient's ability to breathe spontaneously; this phase can comprise either disconnection of the ventilator or the provision of low-level pressure support. Third, the patient is completely disconnected from the ventilator.¹⁵ Issues arising in any of these steps will result in weaning failure. Currently, the clinically applied evaluation system for ventilator weaning¹⁶ mainly consists of disease scoring, patient physiological indicators, and ABG value analysis. Therefore, the system has obvious shortcomings since it relies heavily on the subjective judgment of the physician and less on direct indicators of pulmonary ventilation status.

EIT is a valuable tool that allows clinicians to observe the dynamics of pulmonary ventilation in patients in real time at the bedside, and its application in guided studies of ventilator weaning has been reported in recent years. In one such study,¹⁷ researchers used EIT to record the SBT process in 30 patients and classified the images and data obtained into patterns of gas distribution in the ventral and dorsal lung regions during inspiration. Of the 13 patients with classical pattern ventilation (that is, with a relatively uniform gas pattern in the lungs), only one patient failed to be weaned. In comparison, of the 17 patients with non-

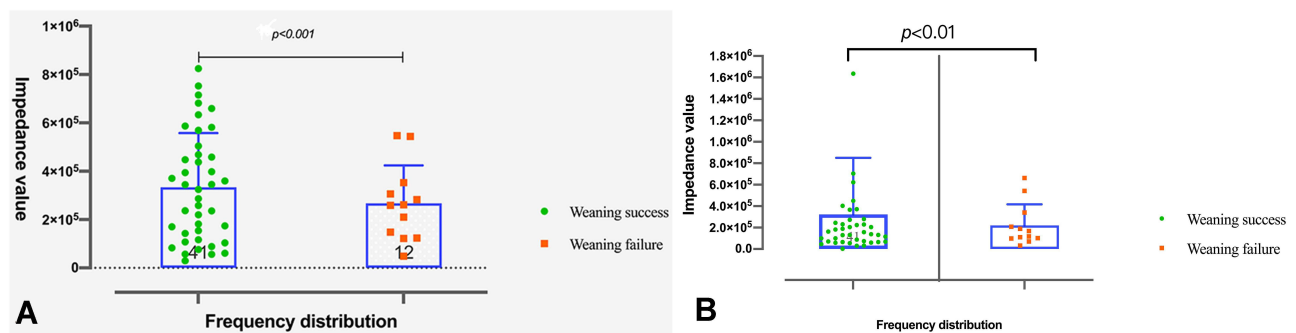


Figure 3 (A) Comparison of pre-SBT EIT global impedance (GI) values between the weaning success and weaning failure groups. (B) Comparison of SBT EIT ROI2 impedance values between the weaning success and weaning failure groups.

Table 3 Screening of Other Positive Factors During Weaning in the Weaning Success and Weaning Failure Group

Effect	$\bar{x}\pm s$	df	Wald	Pr>ChiSq
pH on pre-SBT				
Success	7.44±0.54	1	18.7657	<0.0001
Failure	7.44±0.06			
Lac on pre-SBT				
Success	1.74±2.64	1	19.5007	<0.0001
Failure	1.55±1.11			
HCO₃⁻ on pre-SBT				
Success	23.28±4.75	1	30.3414	<0.0001
Failure	22.39±3.48			
Hb on pre-SBT				
Success	95.81±20.68	1	25.1999	<0.0001
Failure	92.90±22.37			
ALT on pre-SBT				
Success	46±76	1	26.9516	<0.0001
Failure	22±9			
pH on post-SBT				
Success	7.40±0.03	1	23.7715	<0.0001
Failure	7.39±0.04			
PCO₂ on post-SBT				
Success	38.08±4.83	1	22.7772	<0.0001
Failure	35.60±4.64			

Abbreviations: pH on pre-SBT, pH of artery blood gas (ABG) on pre-SBT; lac on pre-SBT, lactic acid on pre-SBT; HCO₃⁻ on pre-SBT, HCO₃⁻ of ABG on pre-SBT; Hb on pre-SBT, hemoglobin on pre-SBT; ALT on post-SBT, alanine aminotransferase on pre-SBT; pH on post-SBT, pH of ABG on post-SBT; PCO₂ on post-SBT, CO₂ pressure of ABG on post-SBT.

Table 4 Specificity and sensitivity of two positive factors related to EIT

Effect	AUC	95% CI	P value	CP	Se	Sp
GI of pre-SBT	0.686	0.001–0.978	0.0496	0.830	0.524	0.818
ROI2 of SBT	0.768	1.010–1.108	0.0164	0.595	1	0.595

Abbreviations: AUC, area under the curve; CP, cutpoint; Se, sensitivity; Sp, specificity; GI of pre-SBT, global impedance on pre-SBT; ROI2 of SBT, ROI2 impedance on SBT.

classical pattern ventilation, eight were unsuccessfully weaned. These results indicate that intrapulmonary gas distribution during inspiration is correlated with the outcome of ventilator weaning. In another study,¹⁸ researchers used EIT to monitor regional pulmonary ventilation in patients with delayed ventilator weaning. EIT recordings were made before and after weaning, and SBT success was adopted as the study's endpoint. The results showed that patients with a global inhomogeneity index of >40 were more likely to fail in the SBT. These studies indicate that EIT might have the potential to be added to the clinical evaluation system for ventilator weaning as a new indicator.

Our findings suggest that the pre-SBT GI might be an important indicator of a patient's overall pulmonary ventilation, and it appears that larger values imply higher weaning success rates. This is consistent with data previously collected from healthy adults. Moreover, the high impedance values in ROI2 reflect good ventilation of the pulmonary tissue near the hilum and are also reflected in the significant difference between the weaning success and weaning failure groups in the study, with higher ROI2 levels reflecting higher weaning success rates. Additionally, the receiver operating curve reflects the high sensitivity of ROI2 in predicting the success of ventilator weaning, indicating its potential as a clinical

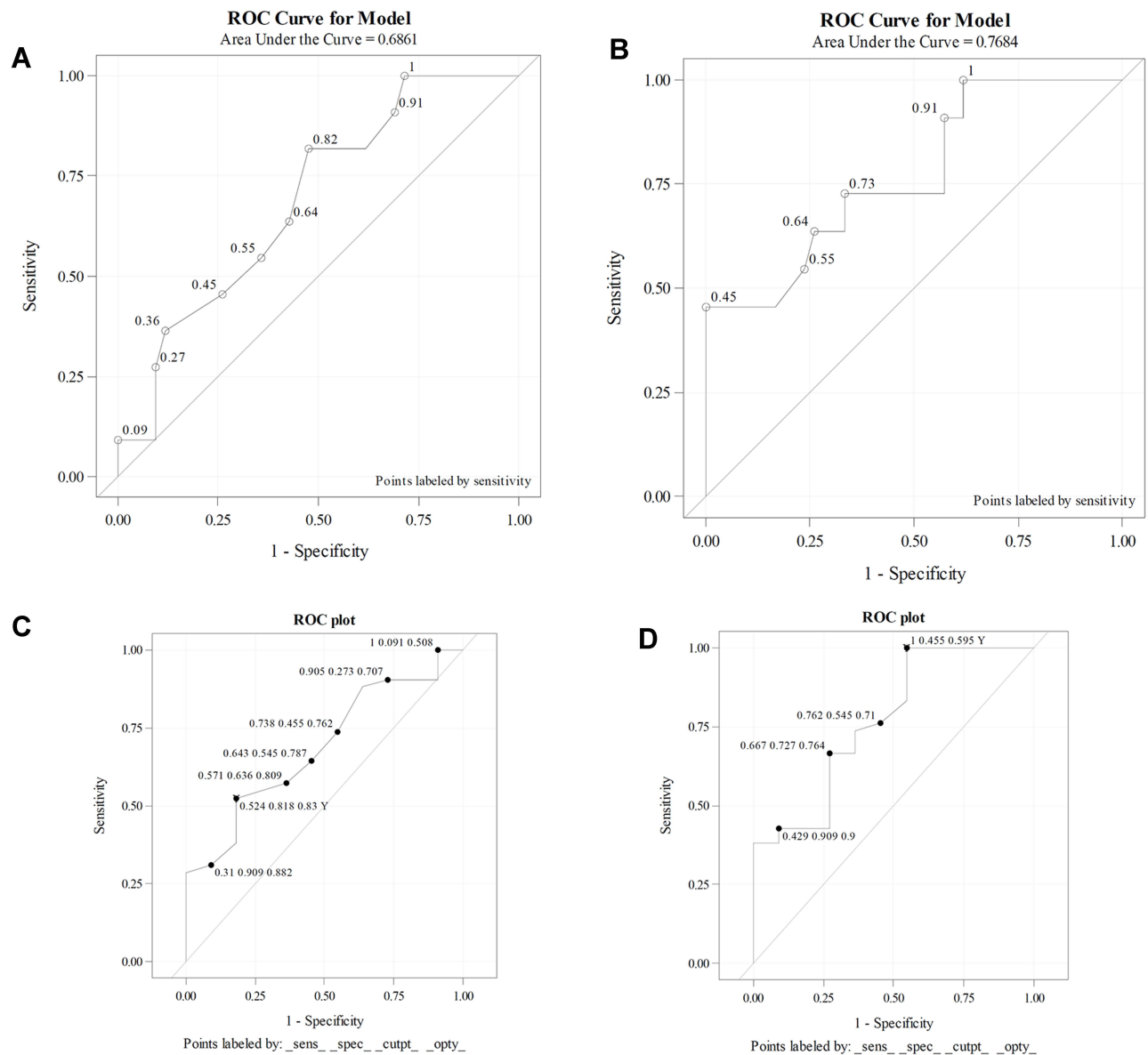


Figure 4 ROC curve for predicting the success of weaning. **(A)** It shows the AUC of pre-SBT GI is 0.686. **(B)** The AUC of ROI2 of SBT is 0.768. Pre-SBT GI has a higher specificity, and SBT ROI2 is more sensitive. **(C)** Cut-point value, sensitivity and specificity are 0.83, 0.524, and 0.818, respectively, in pre-SBT GI. **(D)** Cut-point value, sensitivity and specificity are 1, 0.455, and 0.595, respectively, in SBT ROI2.

predictor. While the GI, ROI2, and ROI3 values are not significantly different, the impedance values of ROI1 and ROI4 (reflecting ventilation in the apical and basal pulmonary regions) play a key role. These two regions seem to reflect a patient's ventilation reserve capacity. When the values are compared both before and after the ventilator weaning process in the weaning failure group, it is found that higher levels of ROI1 and ROI4 ventilation imply a greater likelihood of successful weaning. Morphological analysis of EIT images also shows that those patients who were weaned successfully exhibited uniform gas distribution in the lungs and a ventilation

status that was mostly consistent with the anatomical features of chest x-ray imaging.

To understand whether EIT is influenced by other factors when used as a weaning indicator, we closely observed the ABG and blood biochemistry results in the weaning success and weaning failure groups, both before and after successful weaning. The pH and HCO_3^- in the pre-SBT ABG showed important values during ventilator weaning. When the pH and HCO_3^- levels in the pre-SBT ABG were more alkaline, the weaning outcome tended to be more favorable. We theorize that this scenario shows the ability of the pulmonary tissue to balance the internal

Table 5 Screening of the Influencing Factors of Twice Weaning in the Weaning Failure Group

Effect	Mean±SD	t	p
EIT			
ROI3 of pre-SBT			
1st	93264 ± 50699	1.328	0.026
2nd	158918 ± 124351		
GI of pre-SBT			
1st	286800 ± 147892	1.334	0.046
2nd	385800 ± 202001		
ROI4 of SBT			
1st	21085 ± 15559	2.212	0.015
2nd	24917 ± 23302		
ROI1 of post-SBT			
1st	43913 ± 48393	2.504	0.003
2nd	52209 ± 55810		
Additional factors			
PCO2 on pre-SBT			
1st	42.5 ± 23.1	-2.120	0.043
2nd	39.6 ± 3.7		
BE on pre-SBT			
1st	-2.3 ± 3.8	-2.703	0.024
2nd	-0.3 ± 2.3		
Cr on pre-SBT			
1st	105 ± 100	2.343	0.044
2nd	64 ± 26		
pH on post-SBT			
1st	7.39 ± 0.1	-2.447	0.037
2nd	7.40 ± 0.0		

environment during the recovery phase of the disease, ie, compensatory activity for the acid–base imbalance triggered by the accumulation of acidic metabolites in the body. These findings were also reflected in the pre-SBT ALT levels and the post-SBT pH and PCO₂.

Conclusions

As mentioned above, we believe that the existing evaluation system for ventilator weaning should be improved by the introduction of new indicators. In the present system, the indicators for ventilator weaning that reflect pulmonary ventilation are indirect (eg, ABG values and rapid shallow breathing indices). In this study, we demonstrate the better sensitivity and specificity of EIT as a tool for the direct observation of pulmonary ventilation status, especially using pre-SBT GI and SBT ROI2 as predictors. We assert that, by using these

methods, clinicians could be aided to make more accurate judgments. An additional cohort study that explores the use of EIT versus the existing evaluation system would help provide more robust supporting evidence for the use of EIT in ventilator weaning.

Ethics Approval and Consent to Participate

This study was conducted with approval from the Ethics Committee of Beijing Luhe Hospital, Capital Medical University, approval number 2018LH-KS-015. This study was conducted in accordance with the declaration of Helsinki. Written informed consent was obtained from all participants.

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Disclosure

The authors report no conflicts of interest in this work.

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