

Exploration of Diaphragm Excursion Inflection Point in Predicting Weaning From Mechanical Ventilation in Critically Ill Patients: An Observational Study

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Abstract

Objective

Pressure-supported ventilation is widely used in critically ill patients, and the patient's effort in spontaneous breathing is an important predictor of the success rate of weaning, but this index is difficult to measure accurately under clinical conditions. It has been demonstrated that the absolute value of diaphragm excursion is influenced by multiple factors and cannot be used as a predictor of weaning from mechanical ventilation. This study aims to reveal the characteristics of diaphragm excursion changes (respiratory excursion) at different levels of pressure support, and explore whether it can predict the weaning from mechanical ventilation.

Design

Prospective cohort study.

Setting

Single-center.

Patients

Patients admitted to the ICU who were mechanically ventilated and had met the criteria to perform an autonomic breathing test were enrolled. Patients with tracheal obstruction or after thoracic/gastric/esophageal surgery were excluded.

Interventions

Different levels of pressure support (20,15,10,5 and 0 cm H₂O) were applied in pressure-assisted ventilation mode, and the effort of each patient's inspiratory muscles at different support levels was observed by B- and M-mode ultrasonography to assess right side diaphragm mobility.

Measurements and Main Results

Respiratory mechanics parameters under deep/calm breathing, dynamic changes in diaphragm movement, diaphragm excursion inflection points and whether the patients were successfully deconditioned were recorded. Forty-one patients were enrolled, and the results showed that 78.6% (22/28) of patients with a deep breathing inflection point of 10 cmH₂O (nadir of 5 cmH₂O) and 33.3% (4/12) of patients with a deep breathing inflection point of 15 cmH₂O (nadir of 10 cmH₂O) successfully weaned from mechanical ventilation, with the former having a significantly higher rate than the latter. The success rate was statistically significant (Chi-square=7.556 P=0.006); 77.8% (21/27) of patients with calm breathing inflection point of 10 cmH₂O (lowest point of 5 cmH₂O) and 38.5% (5/13) of patients with calm breathing inflection point of 15 cmH₂O (lowest point of 10 cmH₂O). 13), the former had a statistically significant higher off-boarding success rate than the latter (Chi-square=5.962 P=0.0146).

Conclusions

In the process of weaning from mechanical ventilation patients, when performing a spontaneous breathing test, the right diaphragm excursion inflection point during deep/calm breathing can be measured by ultrasound to assess the patient's spontaneous breathing effort component, and this study found that the weaning success rate was lower in the group with an inflection point of 15 cm H₂O than in the group with an inflection point of 10 cm H₂O, so the diaphragm excursion inflection point may be a reliable indicator to predict the deconditioning success.

Introduction

The diaphragm is the main muscle that drives breathing. Impaired diaphragm function leads to respiratory complications and usually prolongs the duration of mechanical ventilation. Conversely, mechanical ventilation itself may lead to diaphragm atrophy and dysfunction, which is common in mechanically ventilated critically ill patients[1]. The pressure support ventilation (PSV) mode, which is widely used during weaning from ventilation in critically ill patients, is a mode that reduces the mechanical load on the respiratory muscles while avoiding muscle atrophy. In this mode, the patient's inspiratory muscles perform a portion of the work while the rest is provided by the ventilator. Too low a level of assistance may lead to fatigue and discomfort in patients and cause diaphragm dysfunction due to diaphragm overload, while too high a level of assistance may lead to ineffective triggering in patients and diaphragm atrophy due to mechanical ventilation[2].

In predicting weaning, the relative degree of patient's voluntary effort in assisted breathing mode is theoretically an important predictor, but it is difficult to measure objectively under clinical conditions. The rapid shallow breathing index (RSB)[3], which is widely used in spontaneous breathing trials, responds to some extent to the need for voluntary respiratory effort, but this index is influenced by a number of factors and does not directly and accurately reflect the degree of diaphragmatic contribution to the patient's voluntary effort, and it is its high sensitivity and low specificity that make it only an important screening index for predicting deconditioning, rather than a good diagnostic indicator for predicting deconditioning. The diaphragm, as the main muscular organ of inspiration, can also not be directly measured clinically. In experimental studies, several methods have been used to assess the contractile activity of the diaphragm. Among them, the results obtained by measuring the pleural (or esophageal and abdominal cavity pressures are considered to be relatively objective criteria for evaluating the contractile function of the diaphragm[4]. However, such a method still cannot be applied in routine clinical practice; therefore, there is a clinical need for simpler and objective methods to assess the degree of diaphragmatic contribution to force during voluntary effort in critically ill patients.

Recently, bedside critical care ultrasound has been used as a simple and noninvasive test to quantify the contractile activity of the diaphragm. It measures diaphragm mobility to screen patients with diaphragm dysfunction[5]. However, it has been demonstrated that diaphragmatic excursion in patients in assisted ventilation mode is not only influenced by the patient's diaphragmatic autonomic effort but also influenced by the level of mechanical ventilation support, so diaphragmatic mobility, leaving aside the level of ventilation support, does not truly reflect the patient's diaphragmatic autonomic function. Although the diaphragm thickening rate can reflect the self-contraction properties of the diaphragm[6], it does not take into account the interaction between the patient's ventilatory demand and diaphragm contraction, so it cannot be used to predict deconditioning either.

The aim of this study was to discover a new method of measurement that could combine ventilation demand and diaphragmatic contraction properties, and to measure the degree of diaphragmatic autonomic effort during the patient's deconditioning test to predict whether deconditioning would be successful.

Materials And Methods

1.1 Ethical

This study was approved by the Ethics Committee of Xi'an Jiaotong University , under the approval number XJTU1AF2021LSK-191, June 11, 2021 . All research was performed in accordance with relevant guidelines/regulations, and where applicable informed consent was obtained from all participants and/or their legal guardians.

Patients

Patients admitted to the ICU of the First Affiliated Hospital of Xi'an Jiaotong University from October 2017 to October 2020 were enrolled in this retrospectively studied in an observational study. Each patient received mechanical ventilation (Evita XL, Drägerwerk AG, Dräger, Germany) with an artificial airway established according to clinical need. Analgesia was provided using fentanyl with a starting dose of 0.7/ kg * h of according to analgesic sedation guidelines, with an analgesic goal of a verbal numeric score <4 (NRS) or a pain behavior score of 3 to 4 (BPS) in awake patients; when combined with propofol sedation, the starting dose of propofol was 1.5 mg / kg * h and titrated to a Richmond agitation sedation score (RASS) score of 0 ~ -1.

Guidelines for weaning: well coughing ability, reduced tracheal secretions, stable clinical status, heart rate (HR) < 140 / min, patient's eligible for weaning trial is left to physician, systolic blood pressure between 90-140 mmHg, arterial partial pressure of oxygen / fractional inhalation oxygen rate (PaO₂ / FIO₂) ≥ 150 mmHg, respiratory rate < 35 / min, maximum inspiratory pressure < -20 cmH₂O, respiratory rate / tidal volume ratio < 105 breaths / (min* 1)[7].

Exclusion criteria were any of the following: hemodynamic instability requiring vasopressors, need for positive end-expiratory pressure (PEEP) > 10 cmH₂O or FIO₂ > 60% to obtain PaO₂ > 80 mmHg, pressure support (PS) level > 20 cmH₂O, body temperature > 38°C or < 35°C, deeply sedated state (defined by RASS score < -1), history of endogenous PEEP or chronic obstructive pulmonary disease (COPD). Patients following thoracic, gastric or esophageal surgery were also excluded.

The diaphragmatic excursion at different pressure support (PS) was measured by a dedicated person for each enrolled patient, and the dynamics were continuously observed. Patients were divided into a group with a diaphragmatic displacement inflection point of 15 cmH₂O and a group with a diaphragmatic displacement inflection point of 10 cmH₂O, and the success or failure of deconditioning was recorded.

In each patient with the pressure support ventilation, diaphragmatic excursion changes with the stepwise decrease of pressure support level. At the beginning, as the level of pressure support decreases, the diaphragmatic excursion of the patient during deep and calm breathing decreases simultaneously, while when it reaches the lowest point, the diaphragmatic excursion increases along with the further decrease of pressure support level, and the lowest point was defined as "diaphragmatic excursion inflection point"

Ultrasound Measurements

Ultrasound examinations were performed by the same trained operator (respiratory therapist) with LogiQ7 (GE Healthcare, Little Chalfont, UK) equipped with a high-resolution 10-MHz linear probe and a 7.5-MHz convex phased-array probe. The recorded images were analyzed by a trained investigator, and the investigator was blind to the ventilation situation.

The convex probe was placed along the midclavicular line below the right rib margin as previously described [8], in order to place the ultrasound beam perpendicular to the posterior third of the corresponding hemimembrane. The patient was scanned along the long axis of the rib space, with the liver serving as the acoustic window.

M-mode was then used to show septal excursion s and three subsequent measurements were averaged. Diaphragm amplitude values of 1.8 ± 0.3 cm were reported for healthy individuals during quiet breathing[8].

Assessment of reproducibility of ultrasonographic indices

Twenty recordings (from separate patients) were randomly selected to assess reproducibility: the same group of recordings was analyzed twice by the same ultrasound measurer and twice by a different ultrasound recorder[8].

Study Protocol

Patients were placed in the semi-recumbent position throughout the study, sedation and analgesia targets were kept constant, and patient PEEP and FIO₂ were set according to mechanical ventilation guidelines and maintained throughout the study measurements. In each patient, five levels of PS (20,15,10,5 and 0 cmH₂O) were applied in sequence from highest to lowest for ventilation. Each level was applied for at least 30 minutes, and after 20 minutes the patient reached a steady state. Representative of diaphragm mobility measured by B ultrasound during deep breathe (A) and calm breathe (B) at pressure support of 0 cmH₂O were shown in Figure 1. Tidal volume (V_t), respiratory rate (RR), respiratory resistance (R), pulmonary compliance (C), shallow rapid breathing index (RSBI), and peak airway (P_{peak}) were recorded in each patient. The right diaphragm excursion was also measured.

The protocol was allowed to stop, and during the descent of PS, when the patient showed one of the above signs of respiratory distress such as RR> 35 beats/min, oxygen saturation (SpO₂) < 90%, HR> 140 beats/min or variation > 30 at baseline, ABP> 180

mmHg, sweating or anxiety, the test protocol was stopped and continued after at least 30 minutes of rest. Conversely, if the PS was 20 cmH₂O or 15 cmH₂O when the patient experienced hyper-assisted ventilation (e.g., cough, V_t > 15 mL / kg, and/or choking time > 15 s), the PS level was reduced to the value before the start of the study.

Result

During the study period, 102 patients met the inclusion criteria; 47 were excluded from the study (COPD 18, chest surgery 15, gastric surgery 9, esophageal surgery 5). Among the remaining 55 patients, 14 were excluded due to technical/organizational problems (ultrasound machine unavailable, lack of study staff, unconscious patients). Forty patients were subsequently registered; all completed measurements in an appropriate ultrasound window. Individual patient data for different diaphragm excursion inflection point in the different steps of the study during deep breathe were shown in Figure 2. The dark lines indicate successful weaning, while the red lines indicate failed weaning.

Demographics and clinical data of patients were shown in Table 1. PEEP and FIO₂ were set by the treating physician according to the study protocol and were kept constant throughout the study period. The mean values of PEEP and FIO₂ were 5.4±1.6 cmH₂O and 0.38±0.12 cmH₂O, respectively. All patients responded to the study protocol well and no respiratory distress or hyperventilation was observed.

Influence of different levels of pressure support on the ventilation and hemodynamics

The respiratory mechanics parameters during the five steps of the study were shown in Table 2. As expected, tidal volume (V_t) decreased with decreasing support level, while respiratory rate (F) pulmonary compliance (C), RSBI increased and airway resistance (R), peak pressure (P_{peak}) decreased. Neither whole lung hemodynamic nor gas exchange parameters changed as the level of ventilatory assistance decreased.

The weaning results of patients treated with different support level

As shown in Table 3, when patients breathed deeply, the success rate of weaning was found to be significantly higher at an inflection point of 10 cmH₂O than at an inflection point of 15 cmH₂O (P=0.006). When patients were breathing calmly, the weaning success rate was found to be significantly higher at an inflection point of 10 cmH₂O than at an inflection point of 15 cmH₂O (P=0.0146).

Discussion

The main results of this study can be summarized as follows: during the *spontaneous breathing trials of patients* weaning from mechanical ventilation, measurement of the inflection point of right diaphragm excursion by ultrasound during deep/calm breathing can reveal the patient's effort of breathing. This study showed that the group with an inflection point of 15 cm H₂O had a lower rate of successful deconditioning than the group with an inflection point of 10cm H₂O, so the inflection point of diaphragm excursion may be a reliable predictor of successful deconditioning.

PSV is a commonly used mode of ventilation, both as stand-alone ventilation support in acute respiratory failure and in the deconditioning phase of mechanical ventilation[9]. However, the rationale for its use and clinical guidelines remain rather unclear. The aim of this modality is to relieve respiratory muscles and maintain spontaneous contraction, thus avoiding atrophy. Low levels of support may lead to fatigue and discomfort, while over-assistance may result in patient-ventilator dys synchrony [10] and diaphragmatic dysfunction due to mechanical ventilation[2].

Various non-invasive metrics have been proposed to assess deconditioning such as respiratory rate (f), tidal volume (V_t), respiratory tidal volume ratio (f / V_t) and shallow fast breathing index (RSBI) for clinical assessment. Respiratory driven assessments such as oral closure pressure (P_{0.1}) or pressure generated by the inspiratory muscles (PMI). Other studies have proposed the off-ramp index WI = RSBI × EI × VDI (the first index is the elasticity index (EI = peak pressure / NIF) and the second is the ventilatory demand index (VDI = minute ventilation / 10)), IWI = C_{st,rs} × arterialoxygen saturation / f/ V_t ratio) [11], and Wi

= $V_T \times$ end-expiratory CO_2 . However, they either lack sufficient sensitivity/specificity or require cooperative patients to be ventilated. Many recent studies have proposed the ability to assess diaphragmatic contractile activity using ultrasound metrics, and some have shown that diaphragmatic thickening is a reliable indicator of respiratory effort, while diaphragmatic excursion should not be used to quantitatively assess diaphragmatic contractile activity[6]. We aimed to assess the ability of diaphragmatic contractile activity using ultrasound metrics by titrating pressure support parameters (PS).

As in other similar physiological studies[12], we explored the behavior of ultrasound metrics under a range of respiratory muscle loading conditions by varying the level of PS. The upper level of PS was set at 20 cmH₂O, as this value indicates that the respiratory muscles completely take over the main respiratory work of the patient. We also evaluated the relationship between ultrasound indices of diaphragmatic contractile activity and ventilation indices. As expected, V_t decreased as the level of support decreased, while F, C, RSB increased and R, Ppeak decreased. There was no change in whole-pulmonary hemodynamic parameters as the level of ventilatory assistance decreased.

As an indicator of diaphragmatic contractile activity, diaphragmatic excursions have been extensively studied[13]. However, all these studies were performed in spontaneously breathing patients, and the role of the offset in the functional assessment of diaphragmatic contractile activity during assisted mechanical ventilation is not as clear. In fact, diaphragmatic excursion during assisted breathing represents the sum of two forces acting in the same direction: the force of the diaphragm contracting by itself and the pressure provided by the passive displacement of the diaphragm caused by the ventilator. As the level of PS increases, the diaphragm is unloaded and the ventilator performs more and more of the respiratory work. Although different levels of respiratory muscle effort are shown, a similar degree of diaphragmatic excursion results. In this case, there is no way to distinguish which part of the displacement is passive and which part is active. Therefore, during PSV, the excursion may not represent a reliable indicator for monitoring diaphragmatic contractile activity and assessing inspiratory effort. Thus, during PS, we proposed a new concept, the diaphragmatic offset inflection point, also known as the diaphragmatic comfort point. The point was identified by titrating the PS. Initially, the PS is high and the diaphragm is passively offset, as the PS decreases, the diaphragm offset decreases, the alveoli contract until the minimum volume at the end of inspiration, thus stimulating an enhanced central drive, an enhanced diaphragmatic retraction reflex, the diaphragm begins to actively contract, the alveoli expand, and the patient reaches the optimal comfort point, also known as the inflection point. Subsequently, the PS continues to decrease, the patient's diaphragm active contraction continues to increase, and the diaphragmatic excursion leaps past the nadir and continues to increase. It is easy to see that the greater the PS value at this inflection point, the greater the patient's dependence on the ventilator and the lower the success rate of deconditioning. In this experiment, the optimal comfort point was specified by diaphragmatic ultrasound, thus defining a new indicator of deconditioning.

Another interesting finding of our study is that there is also a nadir in dynamic pulmonary compliance (C). This may be due to the fact that as the PS decreases after the start of the titration, when the dynamic lung compliance is dominated by the ventilator, as the PS decreases, the dynamic compliance also decreases, thus stimulating the patient's central nervous system to make the patient breathe harder, and when this balance reaches a nadir, the subsequent dynamic lung compliance starts to be dominated by the patient, so that as the PS decreases, the dynamic compliance starts to increase instead.

In our study population, no difference could be found between diaphragmatic excursions and PEEP levels. This may depend on the relatively low PEEP levels in the patients we studied.

On the other hand, an apparently counterintuitive finding is that the diaphragmatic excursion remained almost constant despite the associated increase in TV between PS0 and PS20. The most likely explanation is that as PS levels increase, a higher fraction of tidal volume is allocated to the non-dependent lung region, due to the presence of better compliance in this region, a finding that can be observed recently as in electrical impedance tomography analysis[14]. Another possible explanation is that at PS20, the patient's respiratory muscles may have been over-assisted and their diaphragm may have simply triggered the ventilator and then relaxed, so they were passively ventilated with passive septal replacement during most of the inspiratory phase and tidal volume was again distributed to the non-dependent region where compliance was higher[14].

A common drawback of ultrasonography is its operator dependence. Therefore, we assessed diaphragmatic excursion observer and interobserver reproduction, measuring three times to take the average. We found good reproducibility of the overall values

assessed, where the intra-group correlation coefficient was well above 0.75, which is generally considered to indicate good agreement. Nevertheless, our results did not differ from those reported in studies of spontaneously breathing patients or patients receiving noninvasive ventilation[15].

There are other limitations of this study. The small sample size of this study is comparable to the results included in similar physiological studies. Another limitation comes from the patient selection criteria: it is not clear if these results translate to patients with unconsciousness or COPD, as these are exclusion criteria. We only evaluated the right hemidiaphragm because the left side of the stomach and intestinal gas often obstructs imaging and its visualization is more difficult. This limitation is common in other studies on ultrasound assessment of diaphragmatic contractile activity[15]. A limitation of diaphragmatic ultrasound is that the ultrasound window is not well found and has been reported to occur in a small number of patients, with an incidence between 2% and 10%[5, 15].

Conclusion

In conclusion, we found that diaphragmatic excursion inflection is a good indicator of respiratory muscle effort in patients with spontaneous respiratory assistance. We suggest using when the diaphragmatic offset inflection point is at a PS of 10 cmH₂O (nadir of 5 cmH₂O) as an indicator of successful deconditioning and when the diaphragmatic offset inflection point is at a PS of 15 cmH₂O (nadir of 10 cmH₂O) as an indicator of failed deconditioning. Further studies are necessary to assess whether this applies to a wider range of patients with different diseases and whether the diaphragm thickening inflection point is more valid than the offset inflection point.

Declarations

Ethical Approval and Consent to participate

Ethical Approval is applicable. The ethical number is XJTU1AF2021LSK-191.

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Conflicts of interest

The authors declare no conflict of interest.

Consent for publication

Not applicable.

Availability of data and material

All datasets analyzed during the study are available from the corresponding author on reasonable request.

Contributions

ZJZ designed the study and is accountable for all aspects of the work. JYB and XQZ performed the statistical analyses, interpreted the results. YXW compiled the manuscript, interpreted the results and provided critical revisions for the manuscript.

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ZJZ designed the study and is accountable for all aspects of the work. JYB and XQZ performed the statistical analyses, interpreted the results. YXW compiled the manuscript, interpreted the results and provided critical revisions for the manuscript. YNG performed statistical analyses and provided critical revisions for the manuscript.

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Tables

Table 1. Demographics and clinical data of patients

characteristic	value
Age,year	60(22;89)
sex	
Male	29(73%)
Female	11(27%)
Artificial airway	
Tracheal intubation	28(70%)
Tracheotomy	8(20%)
Nasal intubation	4(10%)
Mechanical ventilation time	8.2±6.97
Length of stay	35.5±31.58
ICU time	34.4±31.84
VAP	
Yes	10(25%)
No	30(75%)
APECH2	21±7.46

Table 2. Individual patient data in the different steps of the study

	PS/cmH ₂ O	20	15	10	5	0	P value
Deep Breathe	Diaphragm Excursion	30.56±6.92	28.40±7.84	28.36±10.66	27.1±8.58	29.93±8.99	0.1
	Respiratory Time	1.45±0.49	1.33±0.48	1.40±0.57	1.48±0.99	1.40±0.58	0.3452
Calm Breathe	Diaphragm Excursion	21.93±7.50	19.19±7.11	17.83±7.22	17.88±6.33	20.73±6.48	0.4768
	Respiratory Time	1.30±0.49	1.31±0.39	1.12±0.46	0.96±0.24	1.04±0.40	0.0832
Respiratory Mechanical Parameters	Vt	858±239.99	680.92±207.73	547.2±163.78	414±131.33	361.57±120.18	0.0001
	Respiratory Frequency	13.92±3.47	13.71±3.04	16.28±6.45	20.07±5.95	22.14±6.38	0.0006
	Resistance	16.47±5.16	14±4.15	11.52±3.87	7.32±2.45	-	0.0001
	Compliance	68.91±29.42	64.26±28.47	77.52±31.52	120.2±71.73	-	0.0159
	RSBI	14.07±7.79	19±11.60	35±26.28	56.2±37.88	68.92±46.72	0.0004
	P_{peak}	25.57±1.15	20.07±1.97	15.42±0.64	10.28±1.32	6.78±0.80	0.0001

Table 3 Correlation between inflection point and success rate of weaning

	Inflection point /cmH2O	Success	Fail	Chi-square	P
Deep breathe	10	22(78.6%)	6(21.4%)	7.556	0.006
	15	4(33.3%)	8(66.7%)		
Calm breathe	10	21(77.8%)	6(22.2%)	5.962	0.0146
	15	5(38.5%)	8(61.5%)		

Figures

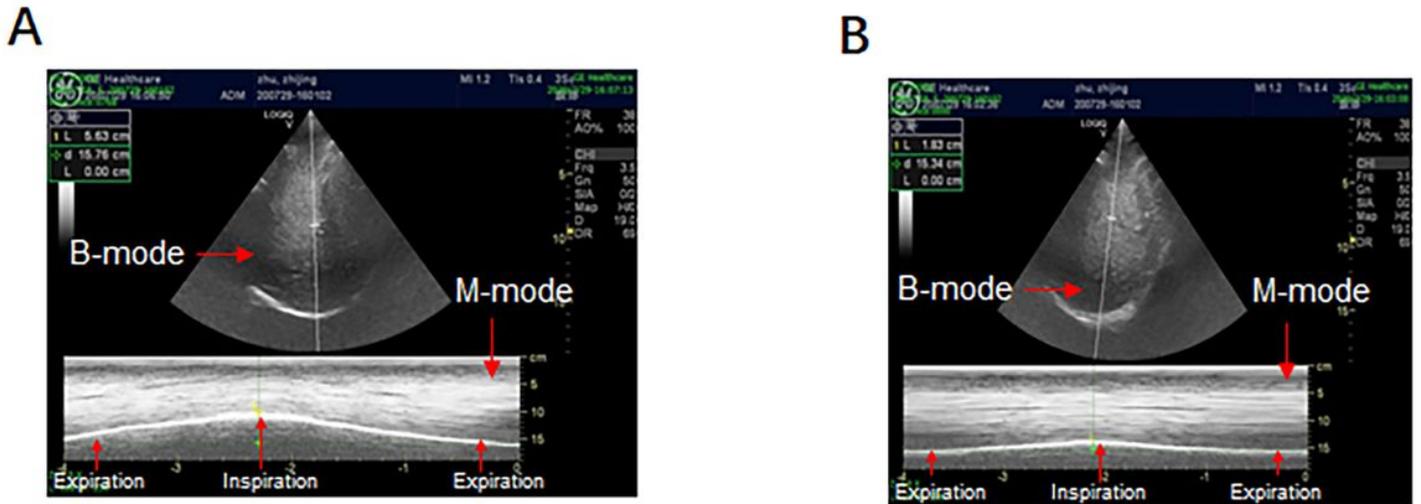
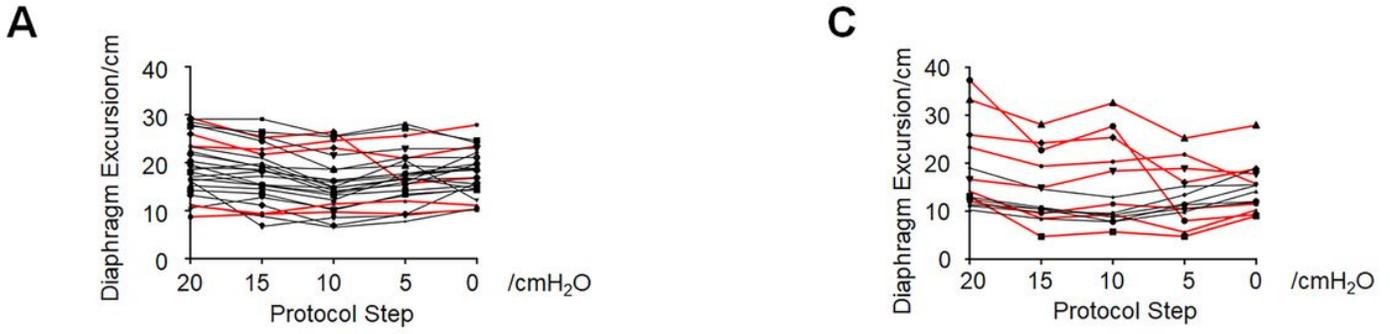


Figure 1

Representative of diaphragm mobility measured by B ultrasound during deep breathe (A) and calm breathe (B) at pressure support of 0 cmH2O.

Inflection point at 10 cmH₂O



Inflection point at 15 cmH₂O

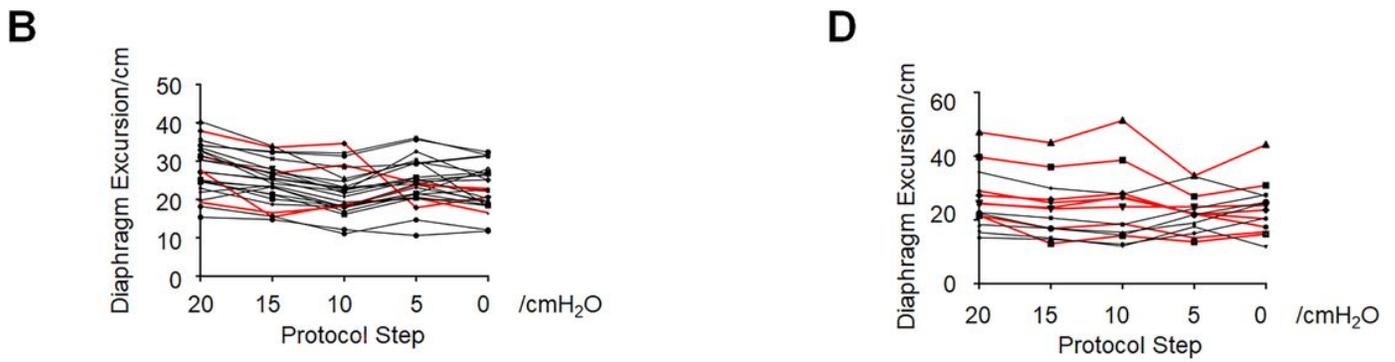


Figure 2

Individual patient data for different diaphragm excursion inflection point in the different steps of the study during deep breathe. The dark lines indicate successful weaning, while the red lines indicate failed weaning.