VOX Index– A New Parameter Using Ultrasound to Predict Time of Applying Noninvasive Ventilation

Ruoxuan Wen

Chinese PLA General Hospital

Xingshuo Hu

Chinese PLA General Hospital

Zhimei Duan

Chinese PLA General Hospital

Han Fu

Chinese PLA General Hospital

Hongjun Gu

Chinese PLA General Hospital

Lixin Xie

Chinese PLA General Hospital

Fei Xie (✉ xiefei0522@163.com)

Chinese PLA General Hospital

Research

Keywords: Velocity oxygenation, Noninvasive ventilation, Ultrasound, oxygen pressure, intensive care unit

Posted Date: November 12th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-102977/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Background: Physicians have been utilizing respiratory status and arterial blood gases measurements of the patient for determining the need of noninvasive ventilation (NIV). There is actually no clear and accurate index to assess the appropriate time of using NIV. We hypothesized that diaphragmatic ultrasound in combination with arterial blood gases test can accurately predict when the patients require sequential NIV.

Objective: To investigate the feasibility of using the new VOX (velocity oxygenation) index, combining the diaphragmatic ultrasound and oxygen pressure analyses, as a reliable assessment tool for sequential NIV in intensive care unit (ICU) patients.

Method: A prospective study including patients admitted to ICU of People's Liberation Army General Hospital First Medical Center Respiratory Department between August 1st 2018 and March 31st 2020. Patients received either continuous low-flow oxygen therapy or sequential NIV based on the physician judgement. The diaphragm movement distance, contraction time, and velocity were recorded and the E-T (excursion-time) index, VOX index, and arterial blood gases were compared.

Result: The velocity of the diaphragmatic contraction (V_D) was higher (3.29 vs. 1.89, $P < 0.001$) and P/F ratio was lower (161 vs. 264, $P < 0.001$) in patients receiving NIV. In predicting the need of utilizing NIV, VOX index showed the largest area under curve of ROC (AUC= 0.97) which was significantly greater than the AUC of V_D and P/F ratio.

Conclusion: VOX index serves as an accurate indicator of predicting the time of using NIV for ICU patients. It is recommended to switch from invasive ventilation to NIV when $VOX < 109.89$.

Introduction

Noninvasive ventilation (NIV) has been reported to reduce work of breathing and inspiratory muscle effort in patients with acute respiratory distress syndrome (ARDS), as well as the risk of intubation and mortality of intensive care unit (ICU) patients^{1,2}. However, under the current clinical guidelines used worldwide, the use of NIV is subjected to the combination assessment of respiratory status and the arterial blood gases test of the patient made by individual physician³. Thus, a standard index to universally distinguish the appropriate time of using NIV and to serve as an early predictor of patients in need of NIV is of clinical importance.

Clinically, a broad aspect of analysis including the disease severity and progression, patient's consciousness, arterial blood gases test, and respiratory muscle movement are employed to decide the application of NIV. Among which, patient's respiratory condition and the arterial blood gases are the most important indicators³. The respiratory condition essentially represents the patient's respiratory muscle movement and if the patient experiences respiratory muscle fatigue. The Diaphragm is the most important respiratory muscle and produces 70% of the total tidal volume generated during one

respiration. It has been showed that mild diaphragm dysfunction can lead to difficulty of weaning from ventilation in ICU patients as 60% of patients with dyspnea had presented diaphragm dysfunction within 24 hours after admitting into ICU⁴. Transdiaphragmatic pressure (Pdi) is the traditional measure of diaphragm strength which is difficult to serve as a regular monitoring tool due to patient intolerance caused by the invasive technique⁵. Diaphragmatic ultrasound, on the contrary, has gained popularity in ICU as a new tool of assessing diaphragm functions providing its radiation free and noninvasive features⁶⁻¹⁰. Several studies have demonstrated the application of diaphragmatic ultrasound in predicting the NIV or extubation outcomes in ICU patients by measuring the diaphragm movement distance, velocity of contraction, thickness, and thickening fraction¹¹⁻¹⁴. Palkar et al. have also utilized the excursion-time index (E-T index) to indirectly assess the work of breathing and diaphragm strength, further predicting the extubation outcomes of ICU patients¹⁵.

While the current clinical research publications focus mainly on the NIV or extubation outcomes of patients in ICU or emergency care, studies on determining the time of using NIV therapy are limited. In addition, the aforementioned studies employed solely the diaphragm function and condition for outcome prediction, the arterial blood gases test was not included when performing the assessment¹⁶. We therefore seek a new indicator with a broad coverage of patient's respiratory condition which combines arterial blood gases and diaphragm function, to better predict the opportune use of NIV therapy.

The patient oxygenation status and inspiratory muscle condition should be considered when predicting the need of NIV. The ratio of partial pressure of arterial oxygen to fraction of inspired oxygen (PaO_2/FiO_2 , P/F ratio) is a good indicator of assessing the oxygenation status clinically. The higher the P/F ratio, the better the patient oxygenation status and the less likely of a patient to receive NIV therapy. Although the twitch transdiaphragmatic pressure (twPdi) is regarded as the diagnostic gold standard of measuring inspiratory muscle strength, the required invasive operation poses difficulties in routine monitoring⁵. The velocity of diaphragm contraction (V_D), however, is easy to obtain and has been demonstrated to be negatively correlated with Pdi¹⁷. The inspiratory muscle strength can thus be assessed using V_D . Furthermore, Wang et al. have shown that V_D was significantly lower in patients with successful weaning and that V_D can be used as a extubation outcome predictor¹⁸. In this study, we introduced the ratio of P/F ratio and V_D , representing oxygenation status and diaphragm function respectively. The derived velocity-oxygenation index (VOX index) was used as a new parameter in predicting the use of NIV therapy, where the lower the VOX index, the higher the necessity of applying NIV.

This study investigated the feasibility of using diaphragmatic ultrasound, in combination with arterial blood gases test, as a reliable tool for NIV therapy selection. We also examined whether the new VOX index can be used as the predictor of NIV application in ICU patients.

Method

Patients

Patients with respiratory and severe disease admitted in 18-bed ICU of People's Liberation Army General Hospital First Medical Center were included in this 20-months prospective observational study. The study was approved by Institutional Review Board (S2018-212-01) and consent forms were obtained from all the patients included in the study. The eligible patients were free from artificial airways when admitted to ICU and were above age 18. Pregnant subjects, patients requiring immediate intubation, and those who did not agree on receiving NIV were not included. Patients with neuromuscular diseases, chest wall deformities, diaphragmatic paralysis, shock, or hemodynamic instability were also excluded. All the treatment decisions were made by ICU physicians who were blinded from the study objective.

Oxygenation therapy

Patients were admitted to ICU and continuous low-flow oxygen therapy or sequential NIV were given according to the physicians' judgements. One of the following criteria should be met when giving NIV to patients: 1) respiratory rate > 25 breaths/min; 2) blood pH $\leq$ 7.35; 3) PaCO₂ > 45 mmHg; 4) PaO₂/F_IO₂ $\leq$ 200 mmHg; 5) accessory muscle of respiration were involved in patient respiration^{3,19}. The treatment selection, parameter setting, and intubation during the study were determined by the physicians without any interferences from the study researchers.

Data collection

The demographic features including gender, age, weight, body mass index (BMI) were recorded when admitted in the ICU. The assessments of disease severity, sepsis-related organ failure assessment (SOFA), and acute physiology and chronic health evaluation II (APACHE II) were calculated 24 hours before admitting to ICU. The arterial blood gases test and diaphragmatic ultrasound were later obtained when physicians determined the primary oxygenation therapy for the patients.

Ultrasonography assessment

Patients were examined in semi-recumbent position (30°–45°) with a Mindray M5 portable ultrasound system. A convex 3.5 MHz–5 MHz transducer was placed horizontally at the right costal margin along the midclavicular line. Liver was set as the ultrasound window with the ultrasound beam being directed cephalad and perpendicular to the posterior third of the diaphragm (Fig. 1). The M-mode line was ensured to align vertically to the right diaphragmatic line during the respiration. Three consecutive quiet breathing cycles were recorded and the diaphragm excursion (DE) and inspiratory time (Ti) were measured. DE was determined as the vertical distance between the lowest and the highest points of the diaphragm displacement, and V_D was defined as the DE during one breathing cycle. E-T and VOX indexes were then calculated accordingly. The overall duration of the ultrasound examination was less than 5 minutes.

Statistical analysis

Data analyses were performed with SPSS 21.0 software. Data was shown as mean $\pm$ SD if passing normality test, otherwise, median of the data was used. Independent sample t test or Mann-Whitney U test

were used for continuous variables as appropriate. Categorical variables were shown as frequencies and percentages and chi-squared test was performed to determine the intergroup differences. Receiver operating characteristic curve (ROC) based on sensitivity and specificity was performed and z test was used to compare the area under curve between each index. A 95% confidence interval was used and $P < 0.05$ was considered statistically significant.

Results

Patient characteristics

A total of 48 subjects were included during the study period from August 2018 to March 2020. Twenty-three patients were given NIV after admitted into ICU and were categorized as NIV group. The 25 patients received continuous low-flow oxygenation were included in the control group. Baseline characteristics were shown in Table 1. There were no intergroup differences on gender, age, BMI, and APACHE II score. While no significant difference of ICU stay was observed between the two groups, NIV group had a significantly lower SOFA score ($P = 0.04$) on admission to ICU and a higher ICU mortality ($P = 0.036$).

Table 1
Patient Demographics

	Control group (N = 25)	NIV group (N = 23)	<i>P</i>
Male, No (%)	76%	52.17%	0.085
Age, years	80 (30)	74 (18)	0.302
APACHE II	11.2 ± 6.25	13.78 ± 6.65	0.172
SOFA	2 (5.5)	5 (5)	0.04*
BMI, kg/m ²	23.38 ± 5.41	22.54 ± 4.02	0.547
ICU stay, days	13 (8.5 to 25)	17 (8 to 44)	0.522
ICU mortality, No	4	10	0.036*
APACHE II: Acute Physiology and Chronic Health Evaluation II; SOFA: Sepsis-related Organ Failure Assessment; BMI: Body mass index; * $P < 0.05$			

Monitoring indexes analyses

The arterial gases test showed no respiratory acidosis among the patients (Table 2) and no statistical difference was observed for PaCO₂ between the two groups (37.1 vs. 42, $P = 0.089$). However, NIV group exhibited lower P/F ratio compared with control group (264 vs. 161, $P < 0.01$), suggesting a less therapeutic efficacy of NIV.

Table 2
Arterial blood gas and diaphragm ultrasound data

	Control group (N = 25)	NIV group (N = 23)	<i>P</i>
PH (median, IQR)	7.41 (7.40 to 7.45)	7.41 (7.35 to 7.45)	0.223
P/F,mmHg (median, IQR)	264 (229.5 to 296)	161 (119 to 222)	≤0.001*
P _a CO ₂ ,mmHg (median, IQR)	37.10 (35.6 to 42)	42.00 (36.8 to 56)	0.089
DE,cm (median, IQR)	1.76 (1.60 to 2.10)	2.12 (1.66 to 2.93)	0.110
Ti,s (median, IQR)	0.99 (0.89 to 1.09)	0.66 (0.63 to 0.71)	≤0.001*
V _D ,cm/s (median, IQR)	1.89 (1.53 to 2.17)	3.29 (2.31 to 4.31)	≤0.001*
E-T index (mean ± SD)	1.61 ± 0.96	1.56 ± 1.07	0.087
VOX index (mean ± SD)	151.48 ± 54.36	57.08 ± 47.51	≤0.001*
DE: diaphragm excursion; Ti: inspiratory time; V _D : diaphragm contraction velocity; E-T index: the excursion-time index; P/F: PaO ₂ /FiO ₂ ; VOX index: diaphragm contraction velocity-oxygenation index; * <i>P</i> ≤ 0.05			

The diaphragmatic ultrasonography demonstrated significant intergroup differences in inspiratory time (Ti), diaphragm contraction velocity (V_D), and VOX index. NIV group presented shorter Ti (0.66 vs. 0.99, *P* < 0.001) and higher V_D (3.29 vs. 1.89, *P* < 0.001) compared with the control group. NIV group also showed considerably lower VOX index (57.08 vs. 151.48, *P* < 0.001). However, we did not observe significant differences in DE and E-T index.

Analyses of variables related to predicting the need of NIV

The accuracy of predicting the need of NIV based on P/F ratio, V_D, and VOX index variables was assessed by AUCROC (Fig. 2). VOX index exhibited higher AUC with better accuracy (AUC = 0.97, 95% CI 0.876–

0.998) in NIV application prediction compared with V_D (AUC = 0.88, 95% CI 0.754–0.956) and P/F ratio (AUC = 0.867, 95% CI 0.738–0.948). According to the ROC curve, the best cutoff point for the V_D was estimated to be 2.22 cm/s with a sensitivity and specificity of 87% and 80% respectively when $V_D \geq 2.22$ cm/s was used to predict the need of NIV. While the best cutoff point for P/F ratio was estimated as 204.5 and the sensitivity and specificity were 96% and 73.9% when $P/F < 204.5$, VOX index was estimated with a best cutoff point of 109.89 with 88% sensitivity and 95.7% specificity when $VOX < 109.89$.

To compare the accuracy of the 3 indexes in predicting the need of NIV, z-test was performed on AUCROC of the indexes. VOX index showed significant differences from P/F ($P = 0.048$) and V_D ($P = 0.0372$) while no statistical difference was observed between P/F and V_D , suggesting that VOX index is more accurate in NIV application prediction.

Discussion

The present study shows 4 major findings. 1) Diaphragmatic ultrasonography is a reliable tool to assess whether the ICU patients require NIV therapy. 2) The patient's oxygenation status and diaphragm function are related to the need of NIV. 3) We also observed a significantly higher velocity of diaphragm contraction in patients receiving NIV than those who received continuous low-flow oxygenation therapy, although no statistical difference was observed in E-T index between groups. 4) Assessing the patients' need of NIV using the combination of parameters from arterial blood gas and diaphragmatic ultrasound provided better accuracy and specificity compared with using parameters from a single test.

Several studies have shown better association between inspiratory muscle strength and diaphragm function assessed by diaphragmatic ultrasound^{6,17}. Physicians could perform real time assessment of patient's inspiratory muscle strength through monitoring the diaphragm thickness and movement distance, achieving early diagnosis of diaphragmatic atrophy and prediction of extubation outcomes in mechanically ventilated patients^{14,15,20–22}. The real time assessment can also be used to determine if NIV is needed for patients with dyspnea in the emergency department, further predicting the NIV outcome^{12,16}. Despite the limited amount of studies regarding the velocity of diaphragm contraction, the great association between V_D and inspiratory muscle strength has been demonstrated and used for extubation outcome prediction, which proved the reliability of V_D ^{6,18}. In this study, we not only assessed the regular diaphragmatic ultrasound parameters, but also introduced a new index to better predict the need of NIV in ICU patients. Palkar et al. showed that E-T index represents the work performed by the diaphragm during spontaneous breathing trial and can well predict the outcome of extubation¹². The higher the E-T index is, the more work is done to overcome the inspiratory load and thus the better the diaphragm functions and the subsequent success rate of extubation. Moreover, patient oxygenation status and inspiratory muscle strength are determinants of the need of NIV clinically, we therefore presented the novel VOX index to predict the opportune time of NIV therapy for ICU patients.

Surprisingly, we did not observe intergroup differences in DE and E-T index, which might be related to patients' respiratory statuses. The data obtained indicating resting state diaphragm movement as the diaphragmatic ultrasound was measured when patients performed quiet breathing. We noticed that most of the patients receiving NIV were under hypoxia condition when taking the diaphragmatic ultrasound where subjects presented respiratory distress, contraction of accessory muscle of respiration, and significantly lower Ti compared with patients receiving continuous low-flow oxygen (0.99 vs. 0.66, $P < 0.001$). Most NIV patients thus hardly maintain quiet breathing and displayed forced inspiration. Although study had shown significant difference in DE between quiet breathing and deep breathing among healthy adults²³, other study indicated that subjects with dyspnea exhibited significantly shorter DE when performing forced inspiration compared with healthy adults and ICU patients due to inherent diaphragm fatigue¹⁶. This can explain why we did not observe statistical difference in DE between the two groups. In addition, as E-T index represents the product of DE and Ti at resting state, it can also contribute to the lack of intergroup statistical difference in E-T index in our study.

There was no respiratory acidosis observed in both groups based on the arterial blood gas test as the medians of PaCO₂ in control and NIV group were 37.10 mmHg and 42.00 mmHg respectively. The test performed upon admission to ICU showed medians of pH 7.41 in both groups and a lower Ti in the 23 NIV patients. We supposed that NIV patients mitigated dyspnea condition through increasing respiratory frequency and oxygen consumption, compensating the existing hypoxia and decreased diaphragm muscle strength.

In consistent with our presumption, P/F and V_D were well associated with predicting the need of NIV where patients receiving NIV present greater V_D and poor oxygenation status compared with those receiving continuous low-flow oxygen. V_D closely represents the patients diaphragm movement condition. During quiet breathing, the more obvious manifestation of dyspnea presented with bigger movement of forced inspiration, the greater the diaphragm contraction and the subsequent V_D. Previous study demonstrated that the increased inspiratory resistive loading induces significant changes in respiratory patterns in healthy adults. Ti and Ti/TOT (inspiratory time to total cycle time) decreases first in volunteers without changes in DE²⁴. V_D therefore better manifests early dyspnea symptoms in patients compared with DE as Ti, which is more sensitive to inspiratory resistive loading, is involved in the calculation of V_D. P/F generally decreases in patients with hypoxia and is an indicator of the need of NIV. However, both P/F and V_D assess patients' condition through a single aspect which the former represents patient oxygenation status and the later measures the inspiratory muscle strength and diaphragm movement. In this study, we presented novel VOX index which integrated patient oxygenation status and inspiratory muscle condition. We have demonstrated that VOX index combines the parameters of oxygenation status and diaphragm strength, serving as a better determinant for predicting patients requiring NIV.

There were several shortfalls of our study. The major limitation of this study was that the diaphragmatic ultrasonography was performed under quiet breathing, whereas other studies performed the ultrasonography during deep breathing^{16,25}. This is done for the following reasons. First, deep breathing

imposes additional work consumption to ICU patients who might need NIV, and it affects measurement accuracy if patients had shown dyspnea symptoms as subjects had difficulty completing the task. Additionally, obscuration of the diaphragm by the descending lung can interfere the accuracy of the measurement²³. Moreover, several researches have established great correlation between V_D and twPdi under quiet breathing in both healthy adults and patients with respiratory muscle weakness. Resting state diaphragmatic ultrasound thus provides reliable measures to the inspiratory muscle strength^{17,26,27}.

As a single center study, the other limitation was the small sample number included and further investigations and verifications conducted under similar clinical environment should be performed. The third shortfall was that only the right diaphragm was evaluated in patients as measuring the left diaphragm during emergency condition can be difficult. Forth, the fact that decisions of patients needing NIV were made solely by the physicians despite the VOX index proposed could impose certain impacts on the study results. Lastly, we compared only the clinical parameters upon admission to ICU without dynamic monitoring during patients' stay in ICU. The therapy and time in ICU could also influence the outcome and thus require further investigation in our future study.

Conclusion

Our study demonstrated that diaphragmatic ultrasonography is a reliable clinical tool in assessing whether to select NIV as the treatment. VOX index is a great indicator in predicting the opportune time of using the NIV in ICU patients. NIV is recommended when $VOX < 109.89$.

Declarations

Ethics approval and consent to participate and Consent for publication Our study was approved by Institutional Review Board (S2018-212-01) and consent forms were obtained from all the patients included in the study and the individual data of patients agree to be published.

Availability of data and materials The datasets during and/or analyzed during the current study available from the corresponding author on reasonable request.

Conflict of interest: the authors declare no competing interests.

Authors' contribution: Ruoxuan Wen and Xingshuo Hu participated in the conception and design of the paper; Ruoxuan Wen took the lead in patient recruitment, data collection, data analysis and research interpretation; Ruoxuan Wen completed the first draft of the manuscript, Zhimei Duan and Han Fu reviewed the important academic content of the manuscript. All authors contributed to the experimental design and data acquisition, contributed to the analysis and interpretation of the data, and read as well as recognized the final manuscript.

Funding This study was supported by National Natural Science Foundation of China 61976223 and National Basic Research Program of China 2019YFC0121703. The funders had no role in study design,

data collection and analysis, preparation of the manuscript, or the submission process.

Author information: Ruoxuan Wen (co-first author), Xingshuo Hu (co-first author), Zhimei Duan (co-first author), Han Fu¹, Hongjun Gu¹, Lixin Xie (co-correspondent), Fei Xie (co-correspondent).

Address: Chinese PLA General Hospital, No.28 Fuxing Road, Haidian District, Beijing, China.

Acknowledgement: the authors would like to express their appreciation to the Department of Respiratory and Critical Care Medicine of the Chinese PLA General Hospital for its support for the experimental research.

References

1. L'Her E, Deye N, Lellouche F, et al. Physiologic effects of noninvasive ventilation during acute lung injury. *Am J Respir Crit Care Med*. 2005;172(9):1112–8. doi:10.1164/rccm.200402-226OC.
2. Stefan MS, Nathanson BH, Higgins TL, et al. Comparative effectiveness of noninvasive and invasive ventilation in critically ill patients with acute exacerbation of chronic obstructive pulmonary disease. *Crit Care Med*. 2015;43(7):1386–94. doi:10.1097/CCM.0000000000000945.
3. Rochwerg B, Brochard L, Elliott MW, et al. Official ERS/ATS clinical practice guidelines: Noninvasive ventilation for acute respiratory failure. *Eur Respir J*. 2017;50(4):1602426. doi:10.1183/13993003.02426-2016.
4. Demoule A, Jung B, Prodanovic H, et al. Diaphragm dysfunction on admission to the intensive care unit: Prevalence, risk factors, and prognostic impact - A prospective study. *Am J Respir Crit Care Med*. 2013;188(2):213–9. doi:10.1164/rccm.201209-1668OC.
5. American Thoracic Society/European Respiratory Society ATS/ERS Statement on Respiratory Muscle Testing T. HIS J OINT S TATEMENT OF THE A MERICAN T HORACIC, S OCIETY (ATS), AND THE E UROPEAN R ESPIRATORY S OCIETY (ERS) WAS ADOPTED BY THE ATS B OARD OF D IRECTORS, M ARCH 2001 AND BY THE ERS E XECUTIVE C OMMITTEE, J UNE 2001. doi:10.1164/rccm.166.4.518.
6. Fayssol A, Nguyen LS, Ognia A, et al. Diaphragm sniff ultrasound: Normal values, relationship with sniff nasal pressure and accuracy for predicting respiratory involvement in patients with neuromuscular disorders. *PLoS One*. 2019;14(4). doi:10.1371/journal.pone.0214288.
7. Haji K, Royse A, Green C, Botha J, Canty D, Royse C. Interpreting diaphragmatic movement with bedside imaging, review article. *J Crit Care*. 2016;34:56–65. doi:10.1016/j.jcrc.2016.03.006.
8. Naik LYS, Sondekoppam RV, Jenkin Tsui J, Tsui BCH. An ultrasound-guided ABCDE approach with a sniff test to evaluate diaphragmatic function without acoustic windows. *Can J Anesth*. 2016;63(10):1199–200. doi:10.1007/s12630-016-0685-z.
9. Matamis D, Soilemezi E, Tsagourias M, et al. Sonographic evaluation of the diaphragm in critically ill patients. Technique and clinical applications. *Intensive Care Med*. 2013;39(5):801–10. doi:10.1007/s00134-013-2823-1.

10. Goligher EC, Laghi F, Detsky ME, et al. Measuring diaphragm thickness with ultrasound in mechanically ventilated patients: feasibility, reproducibility and validity. *Intensive Care Med.* 2015;41(4):642–9. doi:10.1007/s00134-015-3687-3.
11. Spadaro S, Grasso S, Mauri T, et al. Can diaphragmatic ultrasonography performed during the T-tube trial predict weaning failure? The role of diaphragmatic rapid shallow breathing index. *Crit Care.* 2016;20(1):305. doi:10.1186/s13054-016-1479-y.
12. Cammarota G, Sguazzotti I, Zanoni M, et al. Diaphragmatic Ultrasound Assessment in Subjects With Acute Hypercapnic Respiratory Failure Admitted to the Emergency Department. *Respir Care.* 2019;64(12):1469–77. doi:10.4187/respcare.06803.
13. Luo L, Li Y, Chen X, et al. Different effects of cardiac and diaphragm function assessed by ultrasound on extubation outcomes in difficult-to-wean patients: a cohort study. *BMC Pulm Med.* 2017;17(1):161. doi:10.1186/s12890-017-0501-8.
14. Huang D, Ma H, Zhong W, et al. Using M-mode ultrasonography to assess diaphragm dysfunction and predict the success of mechanical ventilation weaning in elderly patients. *J Thorac Dis.* 2017;9(9):3177–86. doi:10.21037/jtd.2017.08.16.
15. Palkar A, Narasimhan M, Greenberg H, et al. Diaphragm Excursion-Time Index: A New Parameter Using Ultrasonography to Predict Extubation Outcome. *Chest.* Published online 2018. doi:10.1016/j.chest.2018.01.007.
16. Bobbia X, Clément A, Claret PG, et al. Diaphragmatic excursion measurement in emergency patients with acute dyspnea: toward a new diagnostic tool? *Am J Emerg Med.* 2016;34(8):1653–7. doi:10.1016/j.ajem.2016.05.055.
17. Spiesshoefer J, Henke C, Herkenrath SD, et al. Noninvasive Prediction of Twitch Transdiaphragmatic Pressure: Insights from Spirometry, Diaphragm Ultrasound, and Phrenic Nerve Stimulation Studies. *Respiration.* 2019;98(4):301–11. doi:10.1159/000501171.
18. San-qiang W, Bin C. SY. The value of ultrasound detection of diaphragm contraction velocity in predicting mechanical ventilation withdrawal. *Chinese J Clin Med.* 2019;26(6):915–8.
19. Liu J, Duan J, Bai L, Zhou L. Noninvasive ventilation intolerance: Characteristics, predictors, and outcomes. *Respir Care.* 2016;61(3):277–84. doi:10.4187/respcare.04220.
20. Dubé BP, Dres M, Mayaux J, Demiri S, Similowski T, Demoule A. Ultrasound evaluation of diaphragm function in mechanically ventilated patients: Comparison to phrenic stimulation and prognostic implications. *Thorax.* 2017;72(9):811–8. doi:10.1136/thoraxjnl-2016-209459.
21. Farghaly S, Hasan AA. Diaphragm ultrasound as a new method to predict extubation outcome in mechanically ventilated patients. *Aust Crit Care.* 2017;30(1):37–43. doi:10.1016/j.aucc.2016.03.004.
22. Goligher EC, Dres M, Fan E, et al. Mechanical ventilation-induced diaphragm atrophy strongly impacts clinical outcomes. *Am J Respir Crit Care Med.* 2018;197(2):204–13. doi:10.1164/rccm.201703-0536OC.
23. Boussuges A, Gole Y, Blanc P. Diaphragmatic motion studied by M-mode ultrasonography. *Chest.* 2009;135(2):391–400. doi:10.1378/chest.08-1541.

24. Soilemezi E, Tsagourias M, Talias MA, et al. Sonographic assessment of changes in diaphragmatic kinetics induced by inspiratory resistive loading. *Respirology*. 2013;18(3):468–73. doi:10.1111/resp.12011.
25. Palkar A, Mayo P, Singh K, et al. Serial Diaphragm Ultrasonography to Predict Successful Discontinuation of Mechanical Ventilation. *Lung*. 2018;196(3):363–8. doi:10.1007/s00408-018-0106-x.
26. Spiesshoefer J, Henke C, Kabitz HJ, et al. The nature of respiratory muscle weakness in patients with late-onset Pompe disease. *Neuromuscul Disord*. 2019;29(8):618–27. doi:10.1016/j.nmd.2019.06.011.
27. Cardenas LZ, Santana PV, Caruso P, Ribeiro de Carvalho CR, Pereira de Albuquerque AL. Diaphragmatic Ultrasound Correlates with Inspiratory Muscle Strength and Pulmonary Function in Healthy Subjects. *Ultrasound Med Biol*. 2018;44(4):786–93. doi:10.1016/j.ultrasmedbio.2017.11.020.

Figures

图 1

Figure 1

Representative diaphragmatic ultrasound from patient enrolled in this study.

Figure 2

ROC (receiver operating characteristic) curves for model. P/F: PaO₂/FiO₂; VD: Diaphragm excursion velocity; VOX index: diaphragm contraction velocity-oxygenation index.