Extubation Failure Prediction by Echography of the Diaphragm After Cardiothoracic Surgery: The EXPEDIA Study

Thibaut Genty, Florent Laverdure, Olivier Peyrouset, Saïda Rezaiguia-Delclaux, Jacques Thès, and François Stéphan

BACKGROUND: Successful extubation is difficult to predict. Ultrasound measurement of the diaphragm thickening fraction (DTF) might help predict weaning failure after cardiothoracic surgery. METHODS: We assessed the predictive performance of diaphragm ultrasound in a derivation cohort of 50 prospectively included cardiothoracic surgery subjects ready for a weaning trial and in a validation cohort of 39 subjects ventilated for ≥ 48 h. DTF was assessed by ultrasound during pressure support ventilation (PSV) then during a T-piece spontaneous breathing trial (SBT). DTF was the percentage change in diaphragm thickness between expiration and inspiration and DTF_{max}, the higher DTF value of the 2 hemidiaphragms. DTF_{max} during SBT (static study) and the difference in DTF_{max} between PSV and SBT (dynamic study) were analyzed. RESULTS: In the derivation cohort, DTF_{max} during SBT was 25.6 ± 17.3% in subjects with successful extubation and 65.2 ± 17.3% in those with weaning failure (difference 39.7 [95% CI 27.4–51.9], *P* < .01). During SBT, DTF_{max} ≥ 50% was associated with weaning failure (area under the receiver operating characteristic curve [AUC] 0.94 ± 0.05). In the dynamic study, a ≥ 40% DTF_{max} increase was associated with weaning failure (AUC 0.91 ± 0.06). In the validation cohort, DTF_{max} during SBT was 20.3 ± 17.1% in subjects with successful extubation and 82.0 ± 51.6% in those with weaning failure (difference 61.8 [95% CI 41.6–82.0], *P* < .01). During SBT, DTF_{max} ≥ 50% predicted weaning failure (AUC 0.99 ± 0.02). In the dynamic study, a ≥ 40% increase in DTF_{max} predicted weaning failure (AUC 0.81 ± 0.09). CONCLUSIONS: Measuring DTF_{max} during SBT and the DTF_{max} change when switching from PSV to SBT may help predict weaning failure after cardiothoracic surgery. The study was registered on ANZCTR. Clinical trial registration number: U1111-1180-1999. *Key words: weaning; mechanical ventilation; diaphragm ultrasound; cardiothoracic surgery.* [Respir Care 2022;67(3):308–315. © 2022 Daedalus Enterprises]

Introduction

Of the total duration of invasive mechanical ventilation, 40% is spent on weaning.[1] Weaning and extubation is a critical period about which knowledge has improved over the last 2 decades.[2,3] Weaning readiness can be assessed by either a trial of pressure support ventilation (PSV) or a spontaneous breathing trial (SBT) on a T-piece.[4] Weaning failure is often due to a combination of respiratory failure, heart failure, ineffective cough, neurologic disorders, and/or upper-airway obstruction. Factors that add to the difficulty of weaning after surgery include pain, atelectasis, and diaphragm dysfunction. Diaphragm dysfunction can result from reflex inhibition of diaphragm contractions

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due to muscle injury, presence of a chest tube, and/or phrenic nerve injury.[5] In studies of heart surgery, 7% of subjects needed re-intubation and 5% tracheostomy for prolonged ventilation.[6,7]

Ultrasound assessment of diaphragm thickening during contractions has been described as a noninvasive and reproducible method available at the bedside[8-10] and capable of providing information on muscle strength,[11] diaphragm dysfunction or diaphragm palsy,[12] work of breathing (WOB) in ventilated patients,[13,14] and progression of ventilator-induced diaphragm atrophy.[15,16] Moreover, the diaphragm thickening fraction (DTF) measured at the apposition zone during the respiratory cycle estimates the WOB.[17,18]

In patients with nonsurgical conditions, DTF measurement may help to predict weaning failure.[19-21] Little information is available about DTF after heart surgery, however. In a recent study, a decrease in diaphragm thickening was often found after heart surgery but was not associated with the respiratory outcome.[22] The potential usefulness of DTF measurement for predicting weaning failure after heart surgery has not been evaluated.

Here, our primary objective was to determine whether DTF values measured during the SBT predicted weaning failure after cardiothoracic surgery. The secondary objectives were to assess DTF changes during the transition from PSV to SBT and to determine whether these changes predicted weaning failure.

QUICK LOOK

Current knowledge

In nonsurgical patients, the diaphragm thickening fraction (DTF) measured by ultrasound may help to predict ventilator liberation. Little information is available about DTF after heart surgery. The potential usefulness of DTF measurement for predicting weaning failure after heart surgery has not been evaluated.

What this paper contributes to our knowledge

In subjects after cardiothoracic surgery, we found that 2 ultrasound indices based on DTF performed well in predicting ventilator liberation, namely DTF $\geq$ 50% for at least one hemidiaphragm during a T-piece spontaneous breathing trial (SBT) and a $\geq$ 40% increase in DTF during the switch from pressure support ventilation to the SBT.

Methods

Study Design and Subjects

The derivation cohort was recruited prospectively in a single 23-bed cardiothoracic ICU. The protocol was approved by the appropriate ethics committee (Comité de protection des personnes d'Ile de France [#2013-A01552]) and was registered on ANZCTR (U1111-1180-1999). Informed consent was obtained from all subjects or next of kin. Patients who were receiving mechanical ventilation, admitted to the ICU after cardiothoracic surgery between May 2016–November 2016, and ready to undergo a first SBT were eligible. Weaning readiness was defined as effective cough; absence of excessive tracheobronchial secretions; stable cardiovascular and metabolic status; and adequate oxygenation, pulmonary function, and mentation.[23] We excluded patients with a history of stroke or diaphragmatic surgery as well as tracheostomized patients. Subjects were included only for the first SBT. Patients in whom diaphragmatic palsy was diagnosed during the ultrasonography were also excluded. The derivation cohort served to define the diaphragmatic ultrasound index that best predicted weaning failure. The same operator made all measurements (TG). No minimum duration of previous ventilation was required.

The validation cohort consisted of subjects who received invasive mechanical ventilation for at least 48 h after cardiothoracic surgery during the 12-month period from October 2016–September 2017 and who met the above-listed weaning-readiness criteria. All ultrasound measurements were performed by the same operator (FL).

Study Protocol

All subjects in both cohorts initially received PSV adjusted to provide a tidal volume of 8 mL/kg of ideal body weight and to eliminate signs of acute respiratory failure. PEEP was 5–10 cm H_2O.

Two diaphragm ultrasound assessments were performed in each subject, the first during PSV and the second within the next hour, during the SBT, after at least 5 min of stable continuous breathing. We were thus able to evaluate changes in diaphragm thickness between 2 different work load conditions. The SBT lasted 30–60 min, during which subjects received an oxygen (O_2) flow of 6–12 L/min to maintain peripheral S_{pO_2} $\geq$ 92%. Forced inspiration was not used for the measurements.

Successful extubation was defined as extubation without re-intubation within the following 48 h.[23] Weaning failure was defined as SBT failure or extubation followed by re-intubation within 48 h. SBT failure was defined as any of breathing frequency > 35 breaths/min, S_{pO_2} < 90% with 12 L/min O_2, signs of respiratory distress (use of accessory muscles, intercostal recession, nasal flaring), heart rate > 140 beats/min, systolic arterial pressure increase > 20%, arrhythmia, or altered consciousness.[23] After SBT failure, subjects received PSV at a level that kept them comfortable. Requiring bi-level positive airway pressure (BPAP) or high-flow nasal cannula (HFNC) oxygen after extubation was not classified as extubation failure. The use of these oxygenation methods in cardiothoracic surgery subjects has been reported previously.[24]

We collected the following data: age, sex, body mass index, history of COPD, diabetes, heart failure (left-ventricular ejection fraction $< 40\%$), Simplified Acute Physiology Score II, surgical procedure, duration of ventilation, duration of PSV, ICU length of stay, tracheostomy, and death.

Diaphragm Ultrasound

The diaphragm ultrasound examinations were performed by 2 experienced operators (TG and FL) who were blinded to extubation decisions. They used a 3.5-MHz Vivid 6 ultrasound probe (GE Healthcare, Chicago, Illinois) to measure diaphragm excursion along the midaxillary line on the left and right sides, with the goal of identifying subjects with diaphragm palsy.[12] The diaphragm was identified as an echogenic curved structure located between the abdominal organs (liver or spleen) and the lungs. Diaphragm palsy was defined as the absence of movement or as paradoxical motion during the breathing cycles.[10]

Diaphragm thickness was measured using a 7–10-MHz linear Vivid 6 ultrasound probe (GE Healthcare). Measurements were performed as previously described[8,11,25,26] using the leading-edge method to minimize thickness overestimation due to inclusion of the peritoneal membrane. The breathing frequency curve was connected to the ultrasound device to locate end expiration and end inspiration on the ultrasound images. Diaphragm end-expiratory thickness (eET) was measured just before thickening started and end-inspiratory thickness (eIT) at the inspiratory peak. The DTF was computed as follows: DTF=(eIT-eET)/eET. For this study, we computed DTF as the mean of measurements during 3 consecutive breaths. DTF was measured separately for each hemidiaphragm in each subject; the higher of the 2 values was defined as DTF_{max}. ΔDTF_{max} was defined as the change in DTF_{max} when switching from PSV to the SBT: ΔDTF (%) = (DTF_{max} SBT-DTF_{max} PSV)/DTF_{max} PSV.

Statistical Analysis

To have 80% power for evidencing a 30% increase in DTF during the SBT compared to PSV (as observed in a test sample), with the alpha risk set at 5%, 48 subjects were needed in the derivation cohort.

The normality of data distribution was assessed by the Kolmogorov-Smirnov test. Quantitative variables were described as mean ($\pm$ SD) and compared using Student *t* test if normally distributed and were described as median (interquartile range [IQR]) otherwise. We described qualitative variables as number (%). The best DTF_{max} cutoff value was determined during the SBT (static cutoff) and after the switch from PSV to the SBT (dynamic cutoff) using receiver operating characteristic (ROC) curves. ROC curves were compared according to Hanley et al.[27] The significance threshold was set at $P < .05$.

As previously reported,[9] we assessed measurement reproducibility between the 2 observers (TG and FL) in 17 subjects during spontaneous breathing or PSV by computing the intraclass correlation coefficient.

Sensitivity was the ability of DTF_{max} during SBT or of ΔDTF_{max} during the PSV-to-SBT switch to correctly identify subjects who would experience weaning failure. Specificity was the ability of DTF_{max} during SBT or of ΔDTF_{max} during the PSV-to-SBT switch to correctly identify subjects who would be successfully extubated. Statistical analyses were performed with Statview 5.0 statistical packages (SAS Institute, Cary, North Carolina).

Results

Study Population and Outcomes

Figure 1 is the subject flow chart. Of 70 patients screened for the derivation cohort, 20 were excluded for the following reasons: history of stroke, $n = 10$; tracheotomy, $n = 6$; and diaphragmatic palsy diagnosed by ultrasonography, $n = 4$. The remaining 50 subjects were included. Among them, 10 (20%) failed weaning and 40 (80%) were successfully extubated. Of the 10 subjects with weaning failure, 7 failed during the SBT, and 3 were re-intubated due to respiratory insufficiency. In this cohort, none of the successfully extubated subjects required re-intubation beyond 48 h.

In the validation cohort, of 66 screened patients, 27 were excluded for the following reasons: tracheotomy, $n = 15$; history of stroke, $n = 8$; and diaphragmatic palsy diagnosed by ultrasonography, $n = 4$. Of the remaining 39 subjects, 11 (28%) failed weaning and 28 (72%) were successfully extubated. Of the 11 subjects with weaning failure, 7 failed during the SBT, and 4 were re-intubated within 48 h for respiratory insufficiency. Of the 28 successfully extubated subjects, 4 required re-intubation beyond 48 h (pneumonia, $n = 2$; surgical complication, $n = 1$; and heart failure, $n = 1$). Table 1 reports the main subject characteristics and Table 2 the ventilation parameters.

DTF_{max} Values during the SBT

The interobserver intraclass correlation coefficient for DTF measurements was 0.86 (95% CI 0.65–0.95), indicating good reliability. Table 3 shows that the DTF_{max} during the SBT differed significantly between the groups with failed versus successful weaning in both the derivation and the validation cohorts. The AUC for DTF_{max} during the SBT was 0.94 (0.05) in the derivation cohort and 0.99

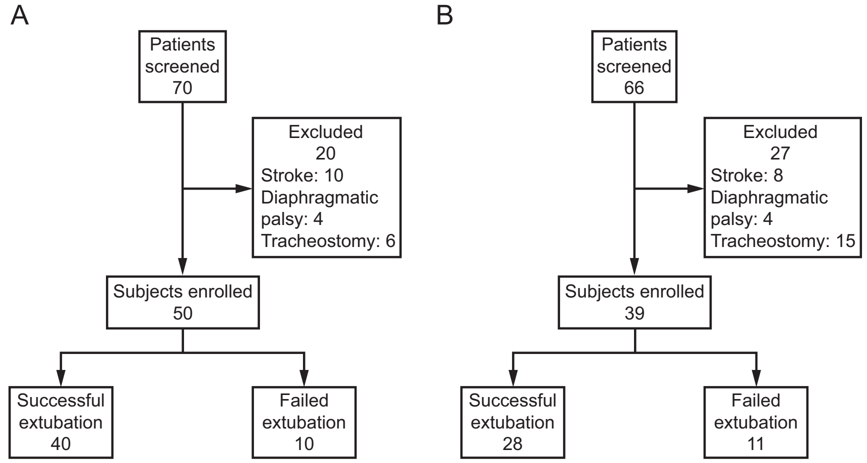

Fig. 1. Flow charts of the derivation (A) and validation (B) cohorts.

Table 1. Main Baseline Characteristics of the Subjects in the Derivation and Validation Cohorts

	Derivation Cohort ($n = 50$)	Validation Cohort ($n = 39$)
General		
Men, *n* (%)	30 (60)	25 (64)
Age, y	62 (13)	58 (15)
Body mass index, kg/m^2	26.3 (5.3)	25.1 (4.2)
SAPS II score	31 (13)	37 (13)
Duration of extracorporeal circulation, min	145 (80)	193 (50)
Duration of aortic clamping, min	91 (52)	104 (31)
Duration of mechanical ventilation, d	3.4 (6.2)	7.2 (4.7)
Duration of PSV, d	1.0 (1.5)	2.9 (2.3)
ICU length of stay, d	8.9 (10.6)	17.0 (15.8)
Reason for ICU admission, *n* (%)		
Coronary artery bypass surgery	11 (22)	2 (5)
Valve replacement	16 (32)	6 (15)
Pulmonary endarterectomy	11 (22)	14 (36)
Lung transplantation	3 (6)	8 (21)
Vascular surgery	4 (8)	3 (8)
Other	5 (10)	6 (15)
Medical history, *n* (%)		
COPD	8 (16.0)	10 (25.6)
Diabetes	5 (10.0)	2 (5.1)
Left ventricular dysfunction	14 (28.0)	10 (25.6)

Data are shown as mean (± SD) unless otherwise indicated.
SAPS II = Simplified Acute Physiology Score II
PSV = pressure support ventilation

(0.02) in the validation cohort (see related supplemental material at http://rc.rcjournal.com).

Figure 2 depicts the DTF_{max} values during the SBT in the groups with failed and successful weaning in both cohorts. The 2 ROC curves are comparable ($P = .13$). A DTF_{max} cutoff of $\geq$ 50% during the SBT predicted weaning failure with 90.0% (95% CI 0.54–0.99) sensitivity and 92.5% (95% CI 0.78–0.98) specificity in the derivation cohort. Corresponding values in the validation cohort were 90.9% (95% CI 0.57–0.99) and 100% (95% CI 0.85–1.00).

DTF_{max} Values during PSV

Table 3 shows that DTF_{max} values in subjects receiving PSV differed significantly between subjects with failed versus successful weaning in both cohorts.

Change in DTF_{max} Values: (ΔDTF_{max})

In successfully extubated subjects, DTF_{max} values were similar during PSV and during the SBT (Fig. 3). In contrast, in subjects who failed weaning, DTF_{max} increased significantly after switching from PSV to the SBT (Fig. 3). The median ΔDTF_{max} was small in successfully extubated subjects in both cohorts (−1.5% [IQR −24.3 to 22.2] in the derivation cohort and 7.1% [IQR −27.0 to 37.4] in the validation cohort) and large in subjects with weaning failure (130.0% [IQR 48.0–148.0] in the derivation cohort and 80% [IQR 57.0–142.0] in the validation cohort).

The AUC for ΔDTF_{max} was 0.91 (0.06) in the derivation cohort and 0.81 (0.09) in the validation cohort (see related supplemental material at http://rc.rcjournal.com). $\Delta DTF_{max} \geq 40\%$ predicted weaning failure with 90.0% (95% CI 0.54–0.99) sensitivity and 90.0% (95% CI 0.75–0.97) specificity in the derivation cohort. Corresponding values in the validation cohort were 90.9% (95% CI 0.57–0.99) and 100% (95% CI 0.85–1.00), respectively.

Discussion

In our study, both $DTF_{max} \geq 50\%$ during the first SBT (static assessment) and $\Delta DTF_{max} \geq 40\%$ after switching

Table 2. Respiratory Parameters and Blood Gas Values in Subjects Receiving Pressure Support Ventilation and During the Spontaneous Breathing Trial

	Derivation Cohort ($n = 50$)	Validation Cohort ($n = 39$)
Ventilator parameters		
F_{IO_2}	0.44 (0.06)	0.41 (0.08)
PS, cm H_2O	13.9 (3.2)	12.7 (2.8)
PEEP, cm H_2O	4.9 (0.9)	5.2 (0.7)
Tidal volume, mL/kg IBW	8.4 (1.7)	7.5 (2.4)
Clinical parameters on PSV		
Frequency, breaths/min	19 (6)	21 (5)
S_{pO_2}	99.0 (1.6)	98.0 (2.0)
Systolic arterial pressure, mm Hg	119 (20)	119 (15)
Diastolic arterial pressure, mm Hg	63 (11)	67 (10)
Heart rate, beats/min	87 (16)	95 (17)
Clinical parameters during the SBT		
Frequency, breaths/min	28 (6)	25 (7)
S_{pO_2}, %	97.5 (2.5)	97.0 (2.1)
Systolic arterial pressure, mm Hg	120 (19)	123 (18)
Diastolic arterial pressure, mm Hg	64 (10)	68 (13)
Heart rate, beats/min	90 (16)	96 (20)
Oxygen support, L/min	6.6 (1.9)	6.7 (1.3)
Blood gas values at the end of the SBT		
P_{aO_2}, mm Hg	120.7 (35.2)	93.7 (20.2)
P_{aCO_2}, mm Hg	39.7 (4.5)	39.7 (4.5)
pH	7.39 (0.05)	7.45 (0.04)
P_{aO_2}/F_{IO_2}	260 (84)	201 (53)
Bicarbonate, mmol/L	23.8 (2.5)	27.7 (2.7)

IBW = ideal body weight
PS = pressure support
PSV = pressure support ventilation
SBT = spontaneous breathing trial on a T-piece

from PSV to the first SBT (dynamic assessment) total performed well for predicting weaning failure in subjects admitted to the ICU after cardiothoracic surgery. In the 89 total subjects, the re-intubation rate (7.8%) and SBT failure rate (16%) are consistent with previous reports.[6,28]

Diaphragm ultrasonography with DTF measurement is a noninvasive tool that accurately assesses WOB.[9,13,14] DTF correlates significantly with diaphragm electrical activity and transdiaphragmatic pressure.[14,18] In healthy individuals, the mean DTF value during quiet inspiration is about 20%,[29] and the highest DTF values can reach 200% during maximal inspiration.[30] Thus, marked diaphragmatic thickening during forced breathing reflects the diaphragmatic reserve.[31]

DTF is a good marker for estimating changes in WOB.[13,17,18] In patients receiving various levels of pressure support (PS) (PSV, BPAP, or HFNC oxygen), DTF decreases in proportion to the increase in PS,[13,17,18] with higher PS levels being associated with weaker diaphragm contractions. Thus, DTF might serve as a subclinical marker for detecting an increase in WOB.[13]

After heart surgery, mechanical ventilation is briefer and diaphragm muscle wasting less likely to develop than in patients with ARDS,[32] in whom the main mechanisms of diaphragmatic damage are ventilator-induced diaphragmatic dysfunction and sepsis-related diaphragmatic muscle damage.[33] After heart surgery, diaphragmatic dysfunction is the rule, even in patients who are successfully extubated.[22] The multiple underlying mechanisms include phrenic nerve control inhibition by a reflex mechanism independent of pain, phrenic nerve stretching or injury during surgery, ventilator-induced diaphragmatic dysfunction, and neuromyopathy.[34-37] A role for atelectasis and chest drains is suspected but has not been proven.[38]

A recent study showed that a low DTF_{max} before heart surgery helped to identify subjects at increased risk for

Table 3. Maximum Diaphragmatic Thickening Fraction in the 2 Cohorts According to Weaning Outcome

	Successful Weaning	Failed Weaning	Difference Between Successful and Failed Weaning	*P*
Derivation cohort, $n = 50$				
DTF_{max} PSV	24.5% (11.3)	32.6% (11.4)	8.1 [0.05–16.10]	.049
DTF_{max} SBT	25.6% (17.3)*	65.2% (17.3)†	39.7 [27.4–51.90]	< .001
Validation cohort, $n = 39$				
DTF_{max} PSV	20.0% (11.7)	38.9% (14.9)	18.9 [9.7–28.0]	< .001
DTF_{max} SBT	20.3% (9.5)‡	82.0% (51.6)§	61.8 [41.6–82.0]	< .001

Variables are described as mean (± SD), and between-group differences are reported with their 95% CI in square brackets.
DTF = diaphragmatic thickening fraction
DTF_{max} = the best DTF value of one of the two hemidiaphragms
PSV = pressure support ventilation
SBT = spontaneous breathing trial on a T-piece
* Difference between DTF_{max} with PSV and SBT in derivation cohort subjects with successful weaning: (1.1% [95% CI −2.6 to 4.8], $P = .56$).
† Difference between DTF_{max} with PSV and SBT in derivation cohort subjects with weaning failure: (32.7% [95% CI 19.2–46.1], $P < .001$).
‡ Difference between DTF_{max} with PSV and SBT in validation cohort subjects with successful weaning: (0.6% [95% CI −3.9 to 5.1], $P = .79$).
§ Difference between DTF_{max} with PSV versus SBT in validation cohort subjects with weaning failure: (43.2% [95% CI −9.8 to 76.5], $P = .02$).

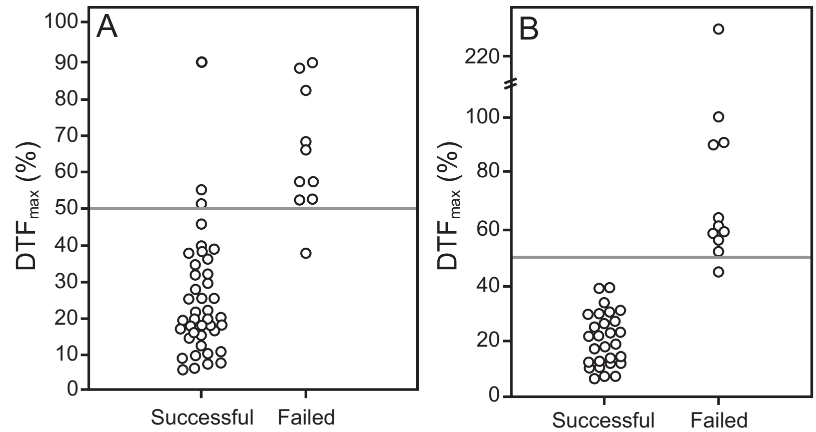

Fig. 2. Values of DTF_{max} (%) according to weaning outcome in the derivation (A) and validation (B) cohorts. DTF_{max}: the best diaphragmatic thickening fraction value of one of the 2 hemidiaphragms. The gray lines represent the DTF_{max} value of 50%, beyond which subjects were at risk for weaning failure. In the derivation cohort, the outlying circle represents a subject with successful extubation despite a major increase in DTF_{max} to 90% after switching from pressure support ventilation to the spontaneous breathing trial; during extubation, the physician in charge observed that the endotracheal tube was obstructed by a solid mucous plug. DTF_{max} measured after extubation decreased to 25%.

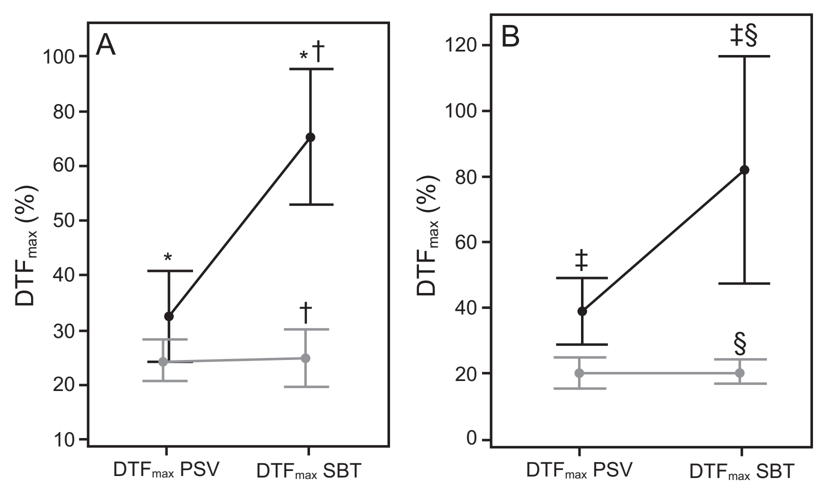

Fig. 3. ΔDTF_{max} (%) after switching from pressure support ventilation (PSV) to the spontaneous breathing trial (SBT) in the derivation (A) and the validation (B) cohort. Gray represents subjects with successful weaning and black those with weaning failure. DTF_{max}: the best DTF value of one of the 2 hemidiaphragms; SBT: spontaneous breathing trial on a T-piece. * Difference between DTF_{max} during PSV and SBT in the group with weaning failure in the derivation cohort: (32.7 [95% CI 19.2–41.6], $P < .001$). † Difference between DTF_{max} values during the SBT in the groups with successful and failed weaning in the derivation cohort: (39.7 [95% CI 27.4–51.9], $P < .001$). ‡ Difference between DTF_{max} values during PSV and SBT in the group with failed weaning in the validation cohort: (43.2 [95% CI 9.8–76.5], $P = .02$). § Difference between DTF_{max} values during the SBT in the groups with successful and failed weaning in the validation cohort: (61.8 [95% CI 41.6–81.9], $P < .001$).

postoperative pulmonary complications.[39] Surgery is followed by a decrease in inspiratory muscle strength[40] and by diaphragmatic dysfunction with reductions in diaphragm excursion and thickening.[22,34] This dysfunction is transient.[34] DTF values may reflect the balance between the work of the diaphragm and the respiratory needs.[9,17,18,41] We performed the ultrasound during the period of maximum diaphragmatic dysfunction,[34] when a small WOB increase may disrupt this balance. Subjects with high DTF_{max} values during the SBT already had a high WOB and were consequently at greater risk for SBT failure or re-intubation due to diaphragmatic fatigue. Subjects with COPD were recently shown to have an increased diaphragmatic work load and a reduction in diaphragmatic force reserve compared to healthy volunteers.[31]

However, DTF measurement is still a matter of controversy. In several studies of nonsurgical subjects, a higher DTF value was associated with better weaning outcomes.[19-21,42-45] The diaphragm was evaluated during PSV,[45] during an SBT, or after an SBT.[19] Diaphragm dysfunction was defined as < 30% of thickening of a least one hemidiaphragm.[19,46] An increase in DTF at total lung capacity indicates that diaphragmatic function is preserved and that a diaphragmatic force reserve is available to tackle an increase in WOB.[31] In contrast, a DTF increase during breathing at rest probably indicates that no further reserve is available.[47] A recent multi-center study suggests that a low DTF may not be a good marker of diaphragmatic dysfunction.[46] We agree that a low DTF is not a major factor in determining weaning failure. On the contrary, our results suggest that a high DTF value may be the most useful indicator.

In all studies of diaphragmatic ultrasound during weaning, DTF was viewed as a static predictor of extubation.[46,48] This may explain the discrepancies with our study. We used DTF as not only a static but also a dynamic index that allowed us to observe diaphragmatic function under 2 different WOB conditions (PSV and SBT). A DTF increase after switching from PSV to the first SBT indicated an increase in respiratory load and a higher risk of weaning failure.

In a population at low risk for weaning failure, diaphragm ultrasound to guide weaning of the ventilator may be seen as excessive monitoring associated with unnecessary costs. Diaphragm ultrasound may be most beneficial in the event of SBT failure to provide information on the diaphragmatic work load.

There are several limitations to our work. First, this is a single-center study whose results require confirmation at other centers. Second, the PS level was not standardized. However, in the dynamic study, this level was not a major factor since diaphragmatic contraction was assessed under the same work load conditions during the SBT in all subjects. Third, there is a risk of measurement bias, as the diaphragm is not very thick. Nonetheless, the intraclass correlation coefficient indicated good interobserver reliability in our study. Fourth, we did not add a DTF measurement during maximal inspiration, which would have allowed us to evaluate the diaphragmatic force reserve. It is difficult for patients to perform a maximal inspiration in the early postoperative period. Finally, we defined weaning failure as clinical SBT failure or as re-intubation within 48 h after the initial extubation. A more recent definition of weaning failure includes re-intubation up to 7 d after the initial extubation.[49] However, it seems unlikely that diaphragm fatigue can result in re-intubation after more than 48 h of spontaneous breathing.

Conclusions

Our results suggest that the DTF_{max} value measured by ultrasound during the SBT and the DTF_{max} change after switching from PSV to SBT may help to predict weaning failure after cardiothoracic surgery.

REFERENCES

1. Esteban A, Alía I, Ibañez J, Benito S, Tobin MJ. Modes of mechanical ventilation and weaning. A national survey of Spanish hospitals. The Spanish lung failure collaborative group. Chest 1994;106(4):1188-1193.
2. Coplin WM, Pierson DJ, Cooley KD, Newell DW, Rubenfeld GD. Implications of extubation delay in brain-injured patients meeting standard weaning criteria. Am J Respir Crit Care Med 2000;161 (5):1530-1536.
3. Esteban A, Alía I, Tobin MJ, Gil A, Gordo F, Vallverdú I, et al. Effect of spontaneous breathing trial duration on outcome of attempts to discontinue mechanical ventilation. Spanish lung failure collaborative group. Am J Respir Crit Care Med 1999;159(2):512-518.
4. Subirà C, Hernández G, Vázquez A, Rodríguez-García R, González-Castro A, García C, et al. Effect of pressure support vs T-piece ventilation strategies during spontaneous breathing trials on successful extubation among patients receiving mechanical ventilation: a randomized clinical trial. JAMA 2019;321(22):2175-2182.
5. Warner DO. Preventing postoperative pulmonary complications: the role of the anesthesiologist. Anesthesiology 2000;92(5):1467-1472.
6. Rady MY, Ryan T. Perioperative predictors of extubation failure and the effect on clinical outcome after cardiac surgery. Crit Care Med 1999;27(2):340-347.
7. Nozawa E, Azeka E, Feltrim Z, Auler Júnior JOC. Factors associated with failure of weaning from long-term mechanical ventilation after cardiac surgery. Int Heart J 2005;46(5):819-831.
8. Gottesman E, McCool FD. Ultrasound evaluation of the paralyzed diaphragm. Am J Respir Crit Care Med 1997;155(5):1570-1574.
9. Zambon M, Greco M, Bocchino S, Cabrini L, Beccaria PF, Zangrillo A. Assessment of diaphragmatic dysfunction in the critically ill patient with ultrasound: a systematic review. Intensive Care Med 2017;43 (1):29-38.
10. McCool FD, Tzelepis GE. Dysfunction of the diaphragm. N Engl J Med 2012;366(10):932-942.
11. Cohn D, Benditt JO, Eveloff S, McCool FD. Diaphragm thickening during inspiration. J Appl Physiol 1997;83(1):291-296.
12. Lerolle N, Guérot E, Dimassi S, Zegdi R, Faisy C, Fagon J-Y, et al. Ultrasonographic diagnostic criterion for severe diaphragmatic dysfunction after cardiac surgery. Chest 2009;135(2):401-407.
13. Umbrello M, Formenti P, Longhi D, Galimberti A, Piva I, Pezzi A, et al. Diaphragm ultrasound as indicator of respiratory effort in critically ill patients undergoing assisted mechanical ventilation: a pilot clinical study. Crit Care 2015;19:161.
14. Goligher EC, Laghi F, Detsky ME, Farias P, Murray A, Brace D, et al. Measuring diaphragm thickness with ultrasound in mechanically ventilated patients: feasibility, reproducibility and validity. Intensive Care Med 2015;41(4):642-649.
15. Zambon M, Beccaria P, Matsuno J, Gemma M, Frati E, Colombo S, et al. Mechanical ventilation and diaphragmatic atrophy in critically ill patients: an ultrasound study. Crit Care Med 2016;44(7):1347-1352.
16. Goligher EC, Fan E, Herridge MS, Murray A, Vorona S, Brace D, et al. Evolution of diaphragm thickness during mechanical ventilation. Impact of inspiratory effort. Am J Respir Crit Care Med 2015;192 (9):1080-1088.
17. Laverdure F, Genty T, Rezaiguia-Delclaux S, Herve P, Stephan F. Ultrasound assessment of respiratory work load with high-low nasal oxygen versus other noninvasive methods after chest surgery. J Cardiothorac Vasc Anesth 2019;33(11):3042-3047.
18. Vivier E, Mekontso Dessap A, Dimassi S, Vargas F, Lyazidi A, Thille AW, et al. Diaphragm ultrasonography to estimate the work of breathing during noninvasive ventilation. Intensive Care Med 2012;38 (5):796-803.

19. DiNino E, Gartman EJ, Sethi JM, McCool FD. Diaphragm ultrasound as a predictor of successful extubation from mechanical ventilation. Thorax 2014;69(5):423-427.
20. 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.
21. Ferrari G, De Filippi G, Elia F, Panero F, Volpicelli G, Aprà F. Diaphragm ultrasound as a new index of discontinuation from mechanical ventilation. Crit Ultrasound J 2014;6(1):8.
22. Moury P-H, Cuisinier A, Durand M, Bosson J-L, Chavanon O, Payen J-F, et al. Diaphragm thickening in cardiac surgery: a perioperative prospective ultrasound study. Ann Intensive Care 2019;9(1):50.
23. Boles J-M, Bion J, Connors A, Herridge M, Marsh B, Melot C, et al. Weaning from mechanical ventilation. Eur Respir J 2007;29(5):1033-1056.
24. Stéphan F, Barrucand B, Petit P, Rézaiguia-Delclaux S, Médard A, Delannoy B, et al; BiPOP Study Group. High-flow nasal oxygen vs noninvasive positive airway pressure in hypoxemic patients after cardiothoracic Surgery: a randomized clinical trial. JAMA 2015;313 (23):2331-2339.
25. Summerhill EM, El-Sameed YA, Glidden TJ, McCool FD. Monitoring recovery from diaphragm paralysis with ultrasound. Chest 2008;133(3):737-743.
26. Matamis D, Soilemezi E, Tsagourias M, Akoumianaki E, Dimassi S, Boroli F, et al. Sonographic evaluation of the diaphragm in critically ill patients. Technique and clinical applications. Intensive Care Med 2013;39(5):801-810.
27. Hanley JA, McNeil BJ. The meaning and use of the area under a receiver operating characteristic (ROC) curve. Radiology 1982;143 (1):29-36.
28. Ladeira MT, Vital FMR, Andriolo RB, Andriolo BNG, Atallah AN, Peccin MS. Pressure support versus T-tube for weaning from mechanical ventilation in adults. Cochrane Database Syst Rev 2014(5): CD006056.
29. Harper CJ, Shahgholi L, Cieslak K, Hellyer NJ, Strommen JA, Boon AJ. Variability in diaphragm motion during normal breathing, assessed with B-mode ultrasound. J Orthop Sports Phys Ther 2013;43(12):927-931.
30. Kim M, Lee K, Cho J, Lee W. Diaphragm thickness and inspiratory muscle functions in chronic stroke patients. Med Sci Monit 2017;23:1247-1253.
31. Rittayamai N, Chuaychoo B, Tscheikuna J, Dres M, Goligher EC, Brochard L. Ultrasound evaluation of diaphragm force reserve in patients with chronic obstructive pulmonary disease. Ann Am Thorac Soc 2020;17(10):1222-1230.
32. Jaber S, Petrof BJ, Jung B, Chanques G, Berthet J-P, Rabuel C, et al. Rapidly progressive diaphragmatic weakness and injury during mechanical ventilation in humans. Am J Respir Crit Care Med 2011;183 (3):364-371.
33. Dres M, Goligher EC, Heunks LMA, Brochard LJ. Critical illness-associated diaphragm weakness. Intensive Care Med 2017;43 (10):1441-1452.
34. Tralhão A, Cavaleiro P, Arrigo M, Lopes J-P, Lebrun M, Rivas-Lasarte M, et al. Early changes in diaphragmatic function evaluated using ultrasound in cardiac surgery patients: a cohort study. J Clin Monit Comput 2020;34(3):559-566.
35. Simonneau G, Vivien A, Sartene R, Kunstlinger F, Samii K, Noviant Y, et al. Diaphragm dysfunction induced by upper abdominal surgery. Role of postoperative pain. Am Rev Respir Dis 1983;128(5):899-903.
36. Dureuil B, Cantineau JP, Desmonts JM. Effects of upper or lower abdominal surgery on diaphragmatic function. Br J Anaesth 1987;59 (10):1230-1235.
37. Ford GT, Whitelaw WA, Rosenal TW, Cruse PJ, Guenter CA. Diaphragm function after upper abdominal surgery in humans. Am Rev Respir Dis 1983;127(4):431-436.
38. Fayssoil A. Diaphragm dysfunction after cardiac surgery: a global approach. J Clin Monit Comput 2020;34(3):615.
39. Cavayas YA, Eljaiek R, Rodrigue É, Lamarche Y, Girard M, Wang HT, et al. Preoperative diaphragm function is associated with postoperative pulmonary complications after cardiac surgery. Crit Care Med 2019;47(12):e966-e974.
40. Estenne M, Yernault JC, De Smet JM, De Troyer A. Phrenic and diaphragm function after coronary artery bypass grafting. Thorax 1985;40(4):293-299.
41. Bellani G, Pesenti A. Assessing effort and work of breathing. Curr Opin Crit Care 2014;20(3):352-358.
42. Jung B, Moury PH, Mahul M, de Jong A, Galia F, Prades A, et al. Diaphragmatic dysfunction in patients with ICU-acquired weakness and its impact on extubation failure. Intensive Care Med 2016;42(5):853-861.
43. Samanta S, Singh RK, Baronia AK, Poddar B, Azim A, Gurjar M. Diaphragm thickening fraction to predict weaning-a prospective exploratory study. J Intensive Care 2017;5:62.
44. Yoo J-W, Lee SJ, Lee JD, Kim HC. Comparison of clinical utility between diaphragm excursion and thickening change using ultrasonography to predict extubation success. Korean J Intern Med 2018;33 (2):331-339.
45. Blumhof S, Wheeler D, Thomas K, McCool FD, Mora J. Change in diaphragmatic thickness during the respiratory cycle predicts extubation success at various levels of pressure support ventilation. Lung 2016;194(4):519-525.
46. Vivier E, Muller M, Putegnat J-B, Steyer J, Barrau S, Boissier F, et al. Inability of diaphragm ultrasound to predict extubation failure: a multi-center study. Chest 2019;155(6):1131-1139.
47. Orozco-Levi M, Gayete A, Rodríguez C, Ramírez-Sarmiento A, Méndez R, Tous F, et al. Noninvasive functional evaluation of the reserve in fatigue and the diaphragm structure using transthoracic echography in B and M modes. Arch Bronconeumol 2010;46(11):571-579.
48. Theerawit P, Eksombatchai D, Sutherasan Y, Suwatanapongched T, Kiatboonsri C, Kiatboonsri S. Diaphragmatic parameters by ultrasonography for predicting weaning outcomes. BMC Pulm Med 2018;18 (1):175.
49. Béduneau G, Pham T, Schortgen F, et al. Epidemiology of weaning outcome according to a new definition. The WIND study. Am J Respir Crit Care Med 2017;195(6):772-783.