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ORIGINAL RESEARCH

Performance and applications of bedside visual inspection of airway pressure–time curve profiles for estimating stress index in patients with acute respiratory distress syndrome

Phunsup Wongsurakiat[1] · **Nadwipa Yuangtrakul**[1]

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Abstract

To determine the performance of bedside visual inspection of airway pressure-time (Paw–t) curve profiles (VI) for estimating stress index (SI) in patients with acute respiratory distress syndrome (ARDS). A prospective study in 30 subjects with ARDS receiving mechanical ventilation at two peak inspiratory flow (PIF) settings: 60 or 40 L/min. For each study session, two physicians inspected real-time Paw–t waveforms from mechanical ventilator's monitoring screens at bedside for 30 s and interpreted which of the three patterns (tidal recruitment, noninjurious ventilation or tidal overdistension) the Paw–t curve profile was compatible with. Subsequently, the study was repeated again at the second PIF setting. SI was derived from a standardized dedicated software program and categorized into three groups: SI < 0.9, or tidal recruitment; SI = 0.9–1.05, or noninjurious ventilation; and SI > 1.05, or tidal overdistension. The lower PIF setting increased the sensitivity of VI to correctly estimate SI (75% vs. 50%; $p = 0.005$). At PIF 40 L/min, the likelihood ratio of a positive test was 3.6, 5.4 or 7 if the Paw–t curve profile was interpreted as noninjurious ventilation, tidal recruitment or tidal overdistension, respectively. The likelihood ratio of a negative test ranged from 0.55 for tidal recruitment to 0.32 and 0.19 for noninjurious ventilation and tidal overdistension, respectively. Experience in mechanical ventilation did not influence the accuracy. Bedside VI is moderately accurate for estimating SI and may be used to monitor injurious ventilation in patients with ARDS, in addition to plateau airway pressure.

Keywords Mechanical ventilation · Waveform · Ventilator-associated lung injury · Overdistension · Recruitment · Accuracy

Abbreviations

Pplat	End-inspiratory plateau airway pressure
SI	Stress index
Paw–t	Airway pressure–time
VI	Visual inspection of airway pressure–time curve profiles
PIF	Peak inspiratory flow
V_T	Tidal volume
BF	Baseline flow
LF	Lower flow
LE	Less experience
ME	More experience
LR	Likelihood ratio
PLR	Likelihood ratio of a positive test
NLR	Likelihood ratio of a negative test

1 Introduction

Lung protective ventilation directed toward prevention of alveolar overdistension and the use of positive end-expiratory pressure (PEEP) to maintain alveolar recruitment is currently the central goal in mechanical ventilation in patients with acute respiratory distress syndrome (ARDS) [1–3]. Current recommendations are to regularly monitor and keep end-inspiratory plateau airway pressure (Pplat) at ≤ 30 cm H_2O [4]. Recently, the drawbacks of using Pplat to monitor respiratory mechanics in patients with ARDS have been emphasized. Pplat could be used to monitor alveolar overdistension but it could not detect stress due to tidal recruitment. There might not be a safe Pplat in patients with

✉ Phunsup Wongsurakiat
phunsup.won@mahidol.ac.th

Nadwipa Yuangtrakul
nadwiyuang@yahoo.com

1 Division of Respiratory Disease, Department of Medicine, Siriraj Hospital, Mahidol University, Bangkoknoi, Bangkok 10700, Thailand

ARDS as some reports demonstrated that alveolar overdistension was still occurred despite values of Pplat of 30 cm H_2O or less [5–10]. Impairment of chest wall mechanics compromises the ability of Pplat to reflect overdistension. In the year 2000, Ranieri and colleagues introduced the stress index (SI) as a bedside monitoring tool for assessment of respiratory mechanics in ARDS. SI is calculated from the shape of the airway pressure–time (Paw–t) curve, and the SI value identifies the average changes in respiratory system compliance over an inspiratory time period. There have been several validation studies of the benefits of using SI strategy to reduce the occurrence of ventilator-associated lung injury in experimental animal models, as observed from inflammatory and histological evidence and lung computed tomography (CT) scan findings [11–16]. In clinical studies, the application of SI strategy to adjust mechanical ventilator settings has been shown to improve static lung elastance and gas exchange and to reduce inflammatory cytokines when compared with ARDS*net* ventilation [17–19]. Recently, Terragni et al. demonstrated that the diagnostic accuracy of SI to detect alveolar overdistension using CT scan criteria as a reference standard was better than Pplat > 30 cm H_2O [20]. Though altered mechanical properties of the chest wall, such as pleural effusion, may partly influence the SI [21], the effect of chest wall mechanics on SI was much less than on Pplat [20]. From the aforementioned data, SI represents a promising bedside parameter to determine alveolar overdistension and a potential alternative PEEP titration method. However, to obtain the SI value, an external respiratory physiology apparatus is required to be placed in the mechanical ventilator circuits to transfer lung mechanics data from the ventilators for analysis by a dedicated software program. Currently, there is only one commercially available ventilator in which the SI analysis program is implemented for routine use. Therefore, using SI in clinical practice is more complicated than measuring Pplat. ARDS is a dynamic disorder, with pulmonary mechanics changing over time [22]. The optimal monitoring tool should be readily available at bedside and in real time, with fast response, repeatability and easy use, in order to allow a quick change of ventilatory setting. A recent observational study in 50 countries found that Pplat was measured in only 40.1% of patients with ARDS [23]. Similarly, measuring SI to monitor injurious ventilation would not be widely employed unless it is simple and readily available for routine use.

SI is calculated from the shape of the Paw–t curve. Some authorities have recommended using bedside Paw–t waveforms to estimate SI for guiding mechanical ventilation settings in patients with ARDS [24, 25]. However, no study has systematically evaluated this aspect of practice. Therefore, the authors undertook a prospective study to determine: (1) the performance of bedside visual inspection of Paw–t curve profiles (VI) for estimating SI; (2) the impact of different mechanical ventilator peak inspiratory flow (PIF) settings on the performance; (3) the impact of physician expertise on the performance; and (4) the impact of different patterns of Paw–t curve profiles interpreted by VI on the performance.

2 Materials and methods

2.1 Study population

A prospective study was conducted from December 2015 to September 2016 at a university hospital in Thailand. All patients admitted to the critical respiratory care unit, who were intubated and had received mechanical ventilation for at least 24 h, were potentially eligible for this study. Patients were enrolled into the study if they met all the following criteria: age > 18 years; one or more clinical insults known to be associated with ARDS; diagnosis of ARDS according to the Berlin ARDS definition [26]; being ventilated with either pressure control continuous mandatory ventilation (PC-CMV) or volume control continuous mandatory ventilation (VC-CMV); continuous infusion of sedatives and/or neuromuscular blockade; and $P_{aO2} \geq 60$ mm Hg or $S_{pO2} \geq 90\%$. Exclusion criteria were the following: pregnancy; head injury or possible increased intracranial pressure; more than 7 days elapsed since ARDS criteria were met; presence of any form of barotrauma (pneumothorax, pneumomediastinum, pneumoperitoneum, pneumopericardium or subcutaneous emphysema); preexisting chronic obstructive pulmonary disease; or unstable hemodynamics.

All of the enrolled subjects were ventilated with Hamilton-G5 mechanical ventilators (Hamilton Medical, Bonaduz, Switzerland). Ventilator settings were left to the discretion of the treating physicians. During the study period, if the enrolled subjects were ventilated with VC-CMV mode, the ventilation mode, the tidal volume (V_T), PEEP and the remaining breathing pattern parameters, and the F_{IO2} were kept the same. If the initial flow pattern was not constant, it was changed to a constant flow waveform. If the enrolled subjects were ventilated with PC-CMV mode, the ventilation mode was changed to VC-CMV mode with constant flow waveform. The V_T, PEEP and the remaining breathing pattern parameters, and the F_{IO2} were kept the same. The inspiratory trigger was always set at 2 L/min bias flow. For purposes of the study, each study session consisted of two levels of PIF settings, the baseline flow (BF) and the lower flow (LF) settings. The BF was set at 60 L/min. Subjects were ventilated at BF for 2 min, and inspiratory time, expiratory time and Pplat were recorded. Then PIF was decreased to 40 L/min for 2 min; inspiratory time, expiratory time and Pplat were recorded again. If Pplat was unchanged from the Pplat at BF, the LF would be set at 40 L/min for that subject during the study session. However, if the decrease in PIF resulted in longer inspiratory time, such that the Pplat was changed from the Pplat at BF, the LF setting was gradually increased to 45, 50, 55 or 60 L/min, respectively. The lowest PIF setting from BF (60 L/min) to 40 L/min, at which Pplat was not changed from the Pplat at BF, would be the LF setting for that subject during the study session. Finally, the LF settings were all set at 40 L/min.

2.2 Study protocol

Physicians who participated in the study were characterized according to their level of experience in taking care of mechanically ventilated patients. Group 1 included 20 first-year internal medicine residents who rotated working in the respiratory care unit during the study period—considered the less experience (LE) group. Group 2 included 10 pulmonary fellows who had been taking care of mechanically ventilated patients for at least 6 months—considered the more experience (ME) group. For each study session, two physicians, one from the LE group and one from the ME group, who were not directly taking care of the studied subject were randomly selected to inspect the subject's Paw–t curve profile. Prior to the study session, a short introduction on the shape of the Paw–t curve or SI was presented to the participating physicians. Examples of the three patterns of Paw–t curve profiles (Fig. 1) were demonstrated: downward concavity, or SI < 0.9 (tidal recruitment); linear, or SI = 0.9–1.05 (noninjurious ventilation); and upward concavity, or SI > 1.05 (tidal overdistension). The physiological background and how to interpret the shape of the Paw–t curve were explained to the physicians. Then the study session started at bedside, as follows. All subjects were sedated and absent of spontaneous effort. The two participating physicians independently inspected the real-time Paw–t curve from the mechanical ventilator's monitoring screen for 30 s and interpreted which of the three patterns (tidal recruitment,

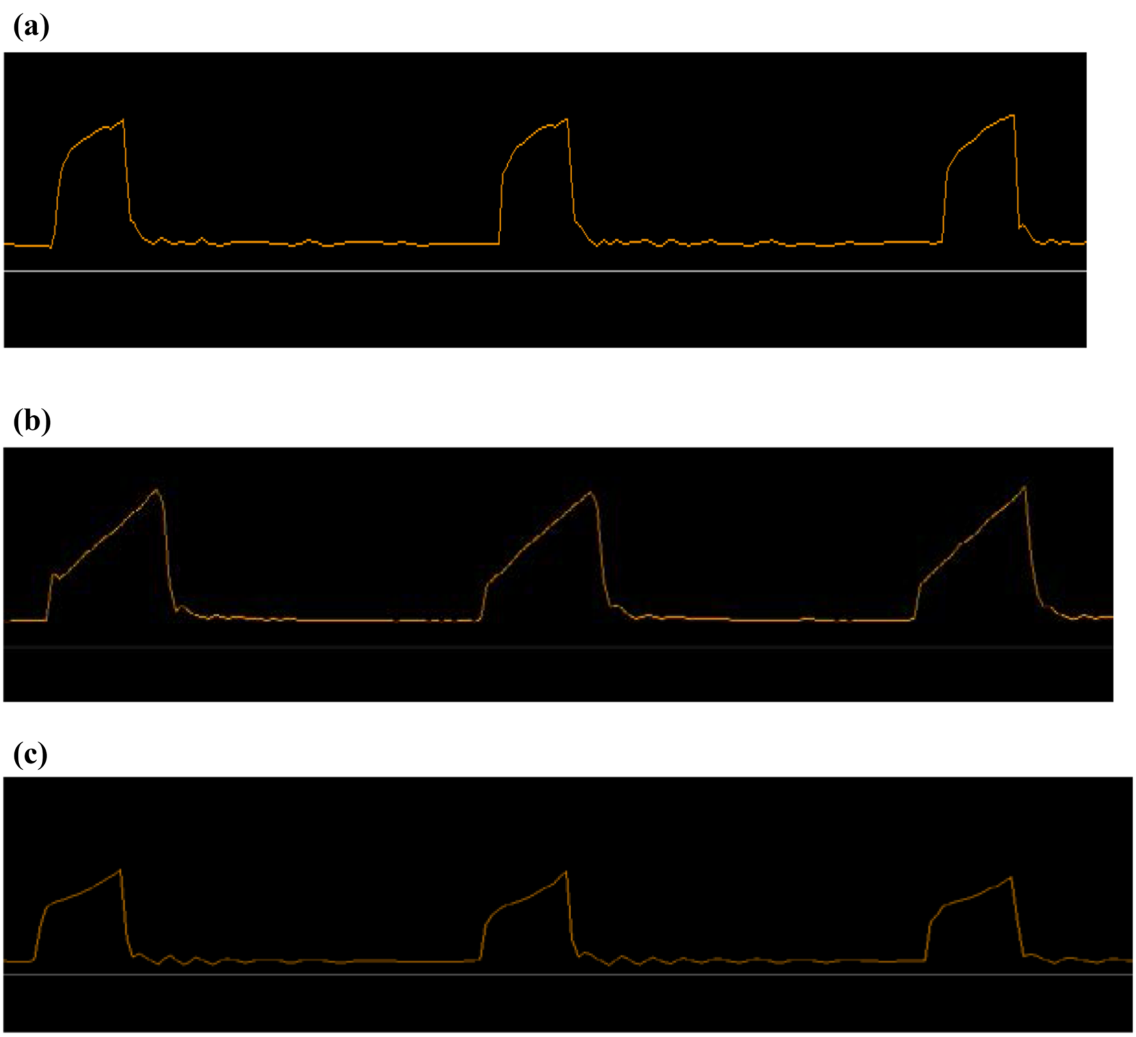

Fig. 1 An example of the three patterns of airway pressure–time (Paw-t) curve profiles. **a** Paw–t curve presents a downward concavity (tidal recruitment). **b** Paw–t curve is linear (noninjurious ventilation). **c** Paw–t curve presents an upward concavity (tidal overdistension)

noninjurious ventilation, or tidal overdistension) the Paw–t curve was compatible with. Then the procedure was repeated at the second flow setting (BF or LF). The flow settings were applied in random order, and the participating physicians were unaware of the changes. The flow chart of study protocol is shown in Fig. 2. Finally, for each study session there were two 30-s Paw–t curve profiles at two PIF settings and two interpretations of each Paw–t curve profile by each of two participating physicians (one LE and one ME).

The study protocol was approved by the Siriraj Hospital Ethics Committee on Human Research (No. SIRB 414/2558-EC2). Informed consent was obtained from each subject or the subject's next of kin.

2.3 Data collection

The following baseline data were collected: age, gender, cause of ARDS, duration of mechanical ventilation, and lung mechanics data including: V_T, PEEP, Pplat, respiratory rate and F_{IO2}. During the study session, lung mechanics data—including airway pressure, air flow and V_T—was transferred from the mechanical ventilator to a personal computer using specific acquisition software (Datalogger version 5; Hamilton Medical).

2.4 Measurement of stress index

The SI was calculated using the dedicated software (ICU-LAB; KleisTEK, Bari, Italy), which is a standard computer software that has been used in many previous studies [11, 17, 19]. From the flow and airway pressure (Paw) signals collected, individual flow and Paw signals were averaged, and the resulting mean flow and Paw signals were displayed. The constant flow portion was identified. The beginning (time 0) and end of that segment (time 1) and the corresponding portions of the mean airway opening pressure curve were marked with cursors. The power equation: airway opening pressure = a* inspiratory time^b + c was then fitted to this segment of the mean airway pressure signal curve. The software calculated the coefficient R of the power equation fitting and displayed it. The fitting algorithm provided the coefficients a, b, and c that best described the Paw–t curve in such time interval. The coefficient a represented the slope of the Paw–t curve, and the coefficient c represented pressure at inspiratory time = 0. Coefficient b (stress index) is a dimensionless number that describes the shape of the curve.

2.5 Statistical analysis

The SI derived from the standardized dedicated software program was considered the gold standard in the analysis. According to previous studies, SI values were categorized into three groups: (1) SI < 0.9, or tidal recruitment; (2) SI = 0.9–1.05, or noninjurious ventilation; and (3) SI > 1.05, or tidal overdistension [17–20]. Likewise, the patterns of Paw–t curve profiles observed by VI were interpreted as follows: (1) tidal recruitment; (2) noninjurious ventilation; and (3) tidal overdistension. Subjects'

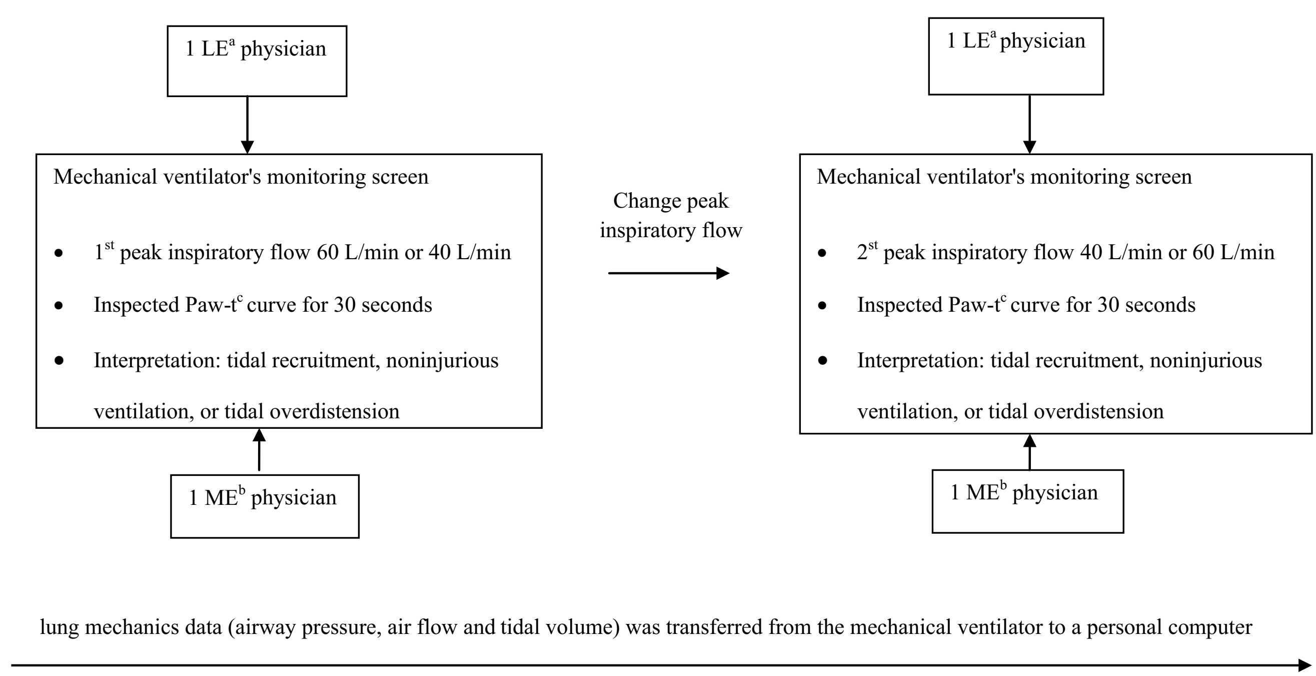

Fig. 2 Flow chart of study protocol. [a]*LE* less experience (internal medicine residents); [b]*ME* more experience (pulmonary fellows); [c]*Paw–t* airway pressure–time

characteristics were summarized, with proportions, mean ± SD or median and interquartile range according to the type of variable and distribution of the data. The influence of the V_T, PIF setting, physician's level of experience, and category of SI on the sensitivity (i.e., the ability to correctly estimate SI) of VI was ascertained using a Chi square test. True or false identification of the category of SI for the PIF setting (BF or LF) that provided higher sensitivity allowed determination of the sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV), with their respective 95% CI values. The predictive power of each pattern of Paw–t curve profile interpreted by VI was also assessed by likelihood ratios (LRs) [27]. The LR of a positive test (PLR) was computed as [sensitivity/(1 − specificity)], and the LR of a negative test (NLR) was computed as [(1 − sensitivity)/specificity]. All analyses of differences were two-tailed, and $p < .05$ was considered to indicate statistical significance.

Sample size calculation was based on the assumption that 70% of the VI correctly estimated SI calculated by dedicated software. It was necessary to study at least 25 stress index measurements.

3 Results

A total of 30 subjects with ARDS were studied. Their clinical characteristics and lung mechanics data are shown in Table 1. Most exhibited mild to moderate ARDS. Most (60%) of the subjects had SI in the range of 0.9–1.05 (noninjurious ventilation). Twenty-one subjects (70%) had Pplat ≤ 30 cmH_2O, and two subjects in this group (9.5%) had an SI compatible with tidal overdistension (SI > 1.05). Seven subjects (23.3%) had Pplat between 30 and 35 cm H_2O, and two subjects in this group (28.6%) had an SI compatible with noninjurious ventilation. Representative Paw–t

Table 1 Baseline demographic and clinical characteristics of the subjects

Characteristics	Subjects' data (n = 30)
Age (year)	58.5 ± 16
Male subjects [n (%)]	9 (30)
Risk factors for acute respiratory distress syndrome	
Community-acquired pneumonia [n (%)]	8 (26.7)
Hospital-acquired/ventilator-associated pneumonia [n (%)]	15 (50)
Pneumonia in immunocompromised host [n (%)]	4 (13.3)
Extrapulmonary sepsis [n (%)]	1 (3.3)
Alveolar hemorrhage [n (%)]	1 (3.3)
Pancreatitis [n (%)]	1 (3.3)
Duration of acute respiratory distress syndrome (days)	2.3 ± 1.1
Tidal volume (mL)	354.3 ± 5.4
Tidal volume/predicted body weight (mL/kg)	7.4 ± 1.2
P_{aO2}/F_{IO2}	
$200 < P_{aO2}/F_{IO2} \leq 300$	14 (46.7)
$100 < P_{aO2}/F_{IO2} \leq 200$	14 (46.7)
$P_{aO2}/F_{IO2} \leq 100$	2 (6.7)
F_{IO2}	0.55 ± 0.14
Positive end-expiratory pressure, cm H_2O [n (%)]	
< 8	9 (30)
8–15	19 (63.3)
> 15	2 (6.7)
Plateau airway pressure, cm H_2O [n (%)]	
< 25	5 (16.7)
25–30	16 (53.3)
> 30–35	7 (23.3)
> 35	2 (6.7)
Stress index [n (%)]	
< 0.9 (tidal recruitment)	3 (10)
0.9–1.05 (noninjurious ventilation)	18 (60)
> 1.05 (tidal overdistension)	9 (30)

Data are presented as mean ± SD or No. (%) unless otherwise indicated curves obtained from three subjects, showing each pattern of Paw–t curve profile, are illustrated in Fig. 3.

The influence of different mechanical ventilation settings, category of SI, and experience of participating physicians on the sensitivity of VI to correctly estimate SI are shown in Table 2. Only lower PIF (40 L/min) was associated with higher sensitivity.

At a PIF of 40 L/min, the performance of each pattern of Paw–t curve profiles interpreted by VI is shown in Table 3. None of the Paw–t curve profile interpretations displayed overlap in the 95% CI of PLR and NLR except for NLR in case it was interpreted as tidal recruitment. There was no significant difference in the performance of VI between the LE and the ME participating physicians.

4 Discussion

This study is the first to determine the performance of VI for estimating the SI. A lower PIF setting increased the sensitivity to correctly estimate SI. This is likely explained by the lower rate of change of airway pressure and longer inspiratory time that occurred when the PIF was lower. SI is estimated from the change of airway pressure over an inspiratory time period, and therefore, when the inspiratory time is longer, the ability to recognize the shape of the Paw–t curve is better. Tidal overdistension, which is presented as an upward concavity of the Paw–t curve, occurs in the later part of the curve and would be missed if the inspiratory time was too short. For the purpose of determining the influence of PIF on the performance, we arbitrarily selected a PIF of 60 L/min as the baseline flow setting. This PIF setting is commonly used in general mechanically ventilated patients [28]. Also, 60 L/min is the PIF setting frequently used to assess lung mechanics, such as airway resistance. We arbitrarily selected a PIF of 40 L/min as the lower flow rate, as it was not sufficiently different from the baseline flow to cause a change in SI. This was confirmed by the similar Pplat at both PIF settings.

Level of experience did not influence the performance of VI for estimating SI. This study was based only on ventilator waveform interpretation and did not consider

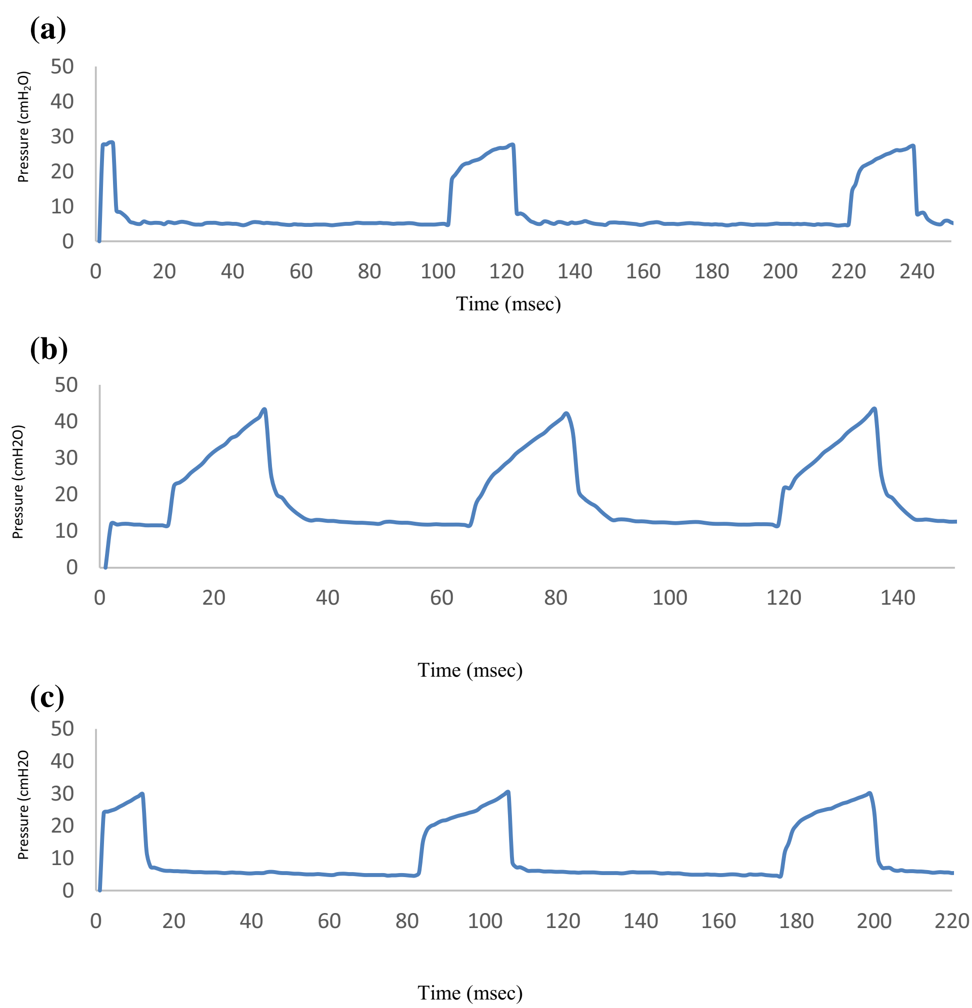

Fig. 3 Representative airway pressure–time curve profiles obtained in three subjects; SI = Stress index derived from the standardized dedicated software program. **a** Subject no. 28, SI = 0.77. **b** Subject no. 27, SI = 0.98. **c** Subject no. 17, SI = 1.31

Table 2 Influence of different mechanical ventilation settings, category of stress index, and experience of participating physicians on sensitivity of visual inspection of airway pressure–time curve profiles to correctly estimate stress index

	Stress index		Mean difference (95%CI) or proportion difference (95%CI),%	P value
	Correct estimation (N = 75)	Incorrect estimation (N = 45)		
Tidal volume (mL)	359.3 ± 57.7	346 ± 45.4	− 13.3 (− 33.3 to − 6.6)	0.19
Tidal volume/predicted body weight (mL/kg)	7.2 ± 1.1	7.6 ± 1.2	0.3 (− 0.1 to 0.8)	0.12
Peak inspiratory flow				
60 L/min (n = 60)	30 (40%)	30 (66.7%)	0.27 (− 0.09 to − 0.4)	0.005*
40 L/min (n = 60)	45 (60%)	15 (33.3%)	− 0.27 (− 0.4 to − 0.09)	
Category of stress index				
< 0.9 (tidal recruitment) (n = 12)	8 (10.7%)	4 (8.9%)	− 0.02 (− 0.13 to 0.09)	0.37
0.9–1.05 (noninjurious ventilation) (n = 72)	41(54.7%)	31(68.9%)	0.14 (− 0.03 to 0.3)	
> 1.05 (tidal overdistension) (n = 36)	26 (34.7%)	10 (22.2%)	− 0.12 (− 0.3 to 0.04)	
Experience				
Less experience (n = 60)	37 (49.3%)	23 (51.1%)	0.02 (− 0.2 to 0.2)	0.8
More experience (n = 60)	38 (50.7%)	22 (48.9%)	− 0.02 (− 0.2 to 0.2)	

Data are presented as mean ± SD or No. (%) unless otherwise indicated

CI confidence interval

*Statistical significance difference

Table 3 Performance of each pattern of airway pressure–time curve profile interpreted by visual inspection for estimating stress index

Pattern[a]	Sensitivity (95% CI)	Specificity (95% CI)	PPV[b] (95% CI)	NPV[c] (95% CI)	PLR[d] (95% CI)	NLR[e] (95% CI)
Tidal recruitment						
LE[f]	66.7 (9.4–99.2)	88.9 (70.8–97.6)	40.0 (5.3–85.3)	96.0 (79.6–99.9)	6.0 (1.58–22.8)	0.38 (0.08–1.9)
ME[g]	33.3 (0.8–90.6)	92.6 (75.7–99.1)	33.3 (0.8–90.6)	92.6 (75.7–99.1)	4.5 (0.56–36.1)	0.72 (0.32–1.6)
All	50 (11.8–88.2)	90.7 (79.7–96.9)	37.5 (8.5–75.5)	94.2 (84.1–98.8)	5.4 (1.7–17.2)	0.55 (0.25–1.2)
Noninjurious ventilation						
LE[f]	77.8 (52.4–93.6)	83.3 (51.6–97.9)	87.5 (61.7–98.4)	71.4 (41.9–91.6)	4.7 (1.3–16.9)	0.27 (0.11–0.66)
ME[g]	72.2 (46.5–90.3)	75.0 (42.8–94.5)	81.3 (54.4–96.0)	64.3 (35.1–87.2)	2.9 (1.04–8.02)	0.37 (0.16–0.84)
All	75.0 (57.8–87.9)	79.2 (57.8–92.9)	84.4 (67.2–94.7)	67.9 (47.6–84.1)	3.6 (1.6–8.03)	0.32 (0.17–0.58)
Tidal overdistension						
LE[f]	88.9 (51.8–99.7)	95.2 (76.2–99.9)	88.9 (51.8–99.7)	95.2 (76.2–99.9)	18.7 (2.7–128.2)	0.12 (0.02–0.74)
ME[g]	77.8 (40.0–97.2)	81.0 (58.1–94.6)	63.6 (30.8–89.1)	89.5 (66.9–98.7)	4.08 (1.6–10.5)	0.27 (0.08–0.95)
All	83.3 (58.6–96.4)	88.1 (74.4–96.0)	75.0 (50.9–91.3)	92.5 (79.6–98.4)	7.0 (3.0–16.3)	0.19 (0.07–0.53)

CI confidence interval

[a] *Pattern* pattern of airway pressure–time curve profiles interpreted by visual inspection

[b] *PPV* positive predictive value

[c] *NPV* negative predictive value

[d] *PLR* likelihood ratio of a positive test

[e] *NLR* likelihood ratio of a negative test

[f] *LE* less experience group (internal medicine residents)

[g] *ME* more experience group (pulmonary fellows)

additional signs and parameters available at the bedside. A previous study reported that expertise significantly increased the sensitivity for detecting patient–ventilator asynchrony [29]. However, estimating SI from the Paw–t curve requires recognition of only three patterns of the Paw–t curve profiles. This is much less complicated than the detection of patient–ventilator asynchrony. Only a short introduction on how to interpret the shape of the Paw–t curve led to a similar ability to estimate the SI between LE and ME physicians. Of note, the PLR was highest for tidal overdistension patterns, follow by tidal recruitment patterns and noninjurious ventilation patterns, respectively, among both LE and ME physicians. Likewise, the NLR was lowest for tidal overdistension patterns, followed by noninjurious ventilation patterns and tidal recruitment patterns, respectively, for both LE and ME physicians. This supports the notion that the performance of VI depends upon pattern recognition rather than experience or knowledge.

The predictive power of each pattern of Paw–t curve profile for estimating SI was also assessed by LRs. PLR describes how the probability of disease shifts when the finding is present and NLR describes how the probability of disease shifts when it is absent. In a single number, LRs provide the best measure of diagnostic accuracy. LRs relate the probability of a test result to the presence or absence of a disorder, and thus are particularly applicable to clinical decision making. Tidal overdistension was the most accurate profile, as represented by the highest PLR (7) and lowest NLR (0.19). This means that if a tidal overdistension pattern was detected by the participating physician, the odds that there was in fact tidal overdistension (SI > 1.05) were seven times higher than in those situations in which there was no tidal overdistension (SI ≤ 1.05). The implications of this increase in likelihood are considered to be moderate, with an increase in post-test probability of tidal overdistension, as referenced by SI, of approximately 35–40% [30]. Conversely, the absence of a tidal overdistension pattern of the Paw–t curve profile decreased the post-test probability of tidal overdistension by around 30–45% [30]. The PLR and NLR of a noninjurious ventilation pattern had less predictive power than those of a tidal overdistension pattern. The PLR of a tidal recruitment pattern was 5.4, which was also considered to indicate a moderately increased post-test probability of tidal recruitment, as referenced by SI < 0.9. However, the NLR of a tidal recruitment pattern was 0.55, which was the least accurate pattern. More importantly, there were overlaps in the 95% CI of NLR. This pattern presents as a downward concavity at the early part of the Paw–t curve, which may make it the most difficult pattern to ascertain.

Given the feasibility, accuracy and predictive power of bedside VI demonstrated in our study, the following clinical implications may be inferred from our findings.

1. Tidal overdistension is currently monitored using Pplat. Current recommendations are regular monitoring, and maintaining Pplat at ≤ 30 cm H_2O. Some previous reports demonstrated that alveolar overdistension still occurred despite Pplat values of ≤ 30 cm H_2O, and merely achieving a Pplat of ≤ 30 cm H_2O may not be sufficient to optimize survival from ARDS [6–9]. Impairment of chest wall mechanics compromises the ability of Pplat to reflect overdistension [20]. Because of these issues, a Pplat level around the target of 30 cm H_2O, i.e. from 25 to 35 cm H_2O, may lead to uncertainty regarding tidal overdistension. A Pplat of 25–35 cm H_2O is the range commonly occurring in patients with ARDS. There have been several validation studies regarding these issues, on the benefits of applying SI strategy to adjust mechanical ventilator settings. Paw–t curve profiles may be a potential bedside surrogate for SI and provide additional piece of information. Given Pplat as indicating the pre-test probability of tidal overdistension, bedside VI may change the post-test probability of tidal overdistension, as shown in Table 4. For example, the pre-test probability of tidal overdistension, based on SI > 1.05, for Pplat = 32 cm H_2O in this study population was 71.4%. If bedside VI did not detect a pattern of tidal overdistension, the NLR was 0.19. This would bring the pre-test probability of tidal overdistension of 71.4% down to a post-test probability of 39.9% and refine clinical judgement in the management of mechanical ventilation accordingly.
2. Currently, there is no simple bedside monitoring tool to detect tidal recruitment. Because of the moderate PLR (5.4) to predict tidal recruitment, bedside VI may be a

Table 4 Plateau pressure pretest probability, likelihood ratio of the pattern of airway pressure–time curve profile interpreted by visual inspection, and posttest probability of tidal overdistension based on stress index at various plateau pressure levels

Plateau pressure	Tidal overdistension (stress index > 1.05)			
	Pretest probability* (%)	Pattern of tidal overdistension by visual inspection of airway pressure–time curve profile (likelihood ratio)	Approximate change in probability (%) [30]	Post-test probability (%)
≤ 30 cm H_2O	6.7	YES (7) No (0.19)	+ 37.5 − 31.5	44.2 0
> 30–35 cm H_2O	71.4	Yes (7) No (0.19)	+ 37.5 − 31.5	100 39.9
> 35 cm H_2O	100	Yes (7) No (0.19)	+ 37.5 − 31.5	100 68.5

*Pretest probability of tidal overdistension (stress index > 1.05) at various plateau pressure levels based on the data from this study population practical approach to monitor tidal recruitment. However, the absence of a tidal recruitment pattern by VI cannot exclude tidal recruitment because of the poor NLR.

Our study was a single-center study, so the results might be not generalizable. The participating physicians might not be implied to represent all other medical personnel, such as ICU staff physicians. For the purpose of the study, i.e. to determine the influence of PIF settings on the performance of VI, and because of the small number of subjects we could compare only two PIF settings instead of performing the study at the patients' baseline mechanical ventilation settings. Though altered mechanical properties of the chest wall may partly influence the SI [21], however, the effect of chest wall mechanics on SI was much less than on Pplat [20]. Paw–t curve profiles may not be a perfect tool for monitoring injurious ventilation in patients with ARDS. However, the Paw–t curve profiles may be a potential bedside surrogate for SI, which provide additional piece of information in addition to Pplat, for monitoring injurious ventilation as shown in Table 4. Each study session was a short period of only 30 s. It is unknown whether the performance of VI would be increased if the duration of bedside observation was longer or the ventilator waveforms were printed out and carefully examined later.

5 Conclusions

Bedside VI is moderately accurate for estimating SI. The detection of a tidal overdistension pattern moderately increases the probability of tidal overdistension, and the absence of a tidal overdistension pattern moderately decreases the probability of tidal overdistension, as referenced by SI. Likewise, the detection of a tidal recruitment pattern moderately increases the probability of tidal recruitment; however, the absence of a tidal recruitment pattern cannot be used to exclude tidal recruitment. Bedside VI may be used to monitor injurious ventilation in patients with ARDS, in addition to plateau airway pressure.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants or the participants' next of kin.

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