Journal of Critical Care 42 (2017) 213–217

Contents lists available at ScienceDirect

Journal of Critical Care

journal homepage: www.jccjournal.org

Decision support system facilitates rapid decreases in pressure support and appropriate inspiratory muscle workloads in adults with respiratory failure

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ARTICLE INFO

Available online xxxx

Keywords:
Mechanical ventilation
Decision support
Weaning

ABSTRACT

Purpose: A commercially available decision support system (DSS) provides guidance for setting inspiratory pressure support (PS) to maintain work of breathing (WOB/min), breathing frequency (f), and tidal volume (V_T) in proper clinical ranges (*VentAssist™*). If these values are outside the proper clinical range patients may suffer fatigue, atrophy, hypoventilation, hyperventilation, volutrauma, or V_T deficiency. The purpose of our study was to evaluate the increase of the percentage of breaths in the targeted clinical ranges when the DSS guidance for setting the PS was followed.

Materials and methods: The study included 43 intubated adults with respiratory failure in an academic medical intensive care unit. Each of the patients had received ventilatory support for >24 h with no weaning trials attempted. Clinicians switched the ventilator to PS then proceeded to utilize the guidance recommended by the DSS for setting PS for 21 patients (intervention group); while the clinicians caring for the remaining 23 patients did not have access to the DSS (control group).

Results: The use of a DSS to set PS level increased the percentage of breaths in the targeted clinical range [28% to 48%, p value < 0.0001]. An unexpected result was that while following the DSS 18 of the 21 patients were rapidly weaned to minimal ventilator settings within 46 ± 38 min; however, when the DSS was not available weaning to minimal ventilator settings lasted 21 ± 12 h [p value < 0.0001].

Conclusions: The DSS is successful at assisting clinicians on how to set PS specific to a patient's individual demands (V_T and f) while accounting for their breathing effort (WOB/min). The DSS appears to promote rapid weaning of PS to minimal ventilator settings when appropriate.

1. Introduction

Patients may experience undesired outcomes if ventilator settings are inappropriately set. The undesired outcomes when ventilator pressure support (PS) levels are excessive may cause volutrauma, barotrauma, hyperventilation, and inspiratory muscle deconditioning. While if PS levels are insufficient the patient is predisposed to hypoventilation and diaphragmatic fatigue. Ventilator PS settings are altered as patient needs and demands change; however attempting to maintain clinically appropriate ranges of breathing frequency (f), tidal volume (V_T), and work of breathing (WOB/min) at times is challenging.

Decision support systems (DSS) for ventilators can assist clinicians in managing mechanical ventilation by determining appropriate pressure support levels. Decision support can be employed as a support system giving open-loop recommendations, [1-3] or automatically as a closed-loop system [4]. The primary target for decision support systems during weaning is to safely decrease the duration of mechanical ventilation by setting PS to avoid each of the aforementioned undesired outcomes. Recent studies investigating DSS have shown mixed results; some studies show a decrease [4,5] while others show no change in the duration of mechanical ventilation [6,7], indicating use of these DSS may not be applicable for all patients. It is still of paramount interest to hospitals and clinicians to develop a DSS, open-loop or automatic, which can decrease the clinician attention required to administer mechanical ventilation.

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http://dx.doi.org/10.1016/j.jcrc.2017.07.047
0883-9441/

VentAssist™, an open-loop DSS, combines *non-invasive* estimate of the WOB/min with f and V_T to provide guidance for setting PS [8,9]. This system not only describes the breathing load tolerance (f, V_T), but also the effort by the inspiratory muscles in response to that load (WOB/min). The approach of VentAssist™ is to maintain each of these three parameters in a target range (assumed to be the proper clinical range), which is defined as; V_T is 5 to 8 mL/kg ideal body weight, f is 10 to 30 breaths per minute, and WOB/min is 5 to 10 J/min [8]. The purpose of this study was to evaluate patient responses when the PS setting is guided by the DSS in a medical intensive care unit. The evaluation compared the WOB/min, f, V_T, $PetCO_2$, and plateau pressure before initiation of the trial and during use of the system of the interventional group. A separate control group was collected to compare weaning times with and without the employ of the DSS. We hypothesized following VentAssist recommendations would increase the percentage of breaths in the target clinical ranges for WOB/min, f, and V_T.

2. Methods

With Institutional Review Board approval, and after obtaining informed consent, 21 adults from a medical intensive care unit were included in the study between January 2014 to December 2014 as the intervention group. At a later date, March to April 2015, with Institutional Review Board approval, 23 adults from the same medical intensive care unit were included in the study as the control group. All patients were intubated (endotracheal tube size ranged from 6.5 to 8.5 mm internal diameter) and diagnosed with respiratory failure from various etiologies (Table 1).

Patient screening located hemodynamically stable patients requiring moderate to long term mechanical ventilation support prior for inclusion in the study. Hemodynamic stability inclusion criteria included: mean arterial pressure > 70 mm Hg, heart rate < 110/min with no severe dysrhythmias, and sedation reflecting a Richmond Agitation Sedation Scale (RASS) score of "0" to "1" [10]. Excluded from the study were patients with hemodynamic instability defined as mean arterial blood pressure < 70 mm Hg, traumatic neurological injury, severe obstructive sleep apnea, myopathy, pregnancy, children (<18 years old), and elderly (>89 years old). To locate patients requiring moderate to long term ventilation, patients were enrolled only if mechanical ventilation had already been >24 h and had no previous weaning trial attempted. Furthermore a subjective assessment from the attending physician at the patient's bedside indicated that there were no anticipation of a weaning trials to be performed on the patients in the next 24 h.

All patients enrolled in the study were receiving mechanical ventilation with the assist control ventilator mode (Model 840 ventilator, Puritan Bennett). A combined pressure/flow/exhaled carbon dioxide sensor, positioned between the endotracheal tube and Y-piece of the ventilator breathing circuit, directed data to a respiratory monitor containing the DSS software (NM 3, Philips) that provided WOB/min, f, V_T, inspiratory and expiratory flow rates, minute ventilation (MV), peak inflation pressure for PS, PEEP, and partial pressure end-tidal carbon dioxide ($PetCO_2$) parameters, and guidance for setting PS (Fig. 1). Airway resistance, plateau pressure, and respiratory system compliance were estimated using an expiratory time constant method [11]. Weaning time, in both groups, was defined as the elapsed time when patient screening and enrollment were finalized until the time when the ventilator settings were classified as minimal, which at our institution was PS = 5 cm H_2O and PEEP = 5 cm H_2O.

After the screen and enrollment of the control patients, the DSS was not presented to the clinician for use, but rather their standard clinical care was administered. A study investigator returned to the patient's bedside as needed to record mechanical ventilation times.

For the patients in the intervention group the DSS was introduced to the clinician as an FDA cleared tool which titrates PS levels as needed for the patient to maintain safe and appropriate levels of V_T, f, and WOB/min. In order to implement the DSS in the intervention group, the ventilator was switched to PS such that the initial support level matched the V_T, f, and breathing comfort from the previous ventilator mode setting. Positive end expiratory pressure (PEEP) and FIO_2 were maintained and treated by the attending physician and respiratory therapist per standard of care protocol, such that, pulse oximeter hemoglobin oxygen saturation (SpO_2) was maintained ≥92%.

Attending physicians (N = 8) who directed patient care in the intervention group viewed data from the monitor and followed DSS guidance for setting PS. The DSS was employed for up to 8 h or until the patient was at minimal ventilator settings (PS = 5 cm H_2O and PEEP = 5 cm H_2O) for at least 30 min. Per the hospital's extubation protocol, if a patient showed stability (no apparent stress for 30 min) at minimal ventilator settings they were recommended for extubation. Guidance for settings PS from the DSS is not a specific value but rather an indication to either increase or decrease PS. Guidance to "Increase PS" was inferred to mean increase PS by 2 cm H_2O. Similarly, guidance to "Decrease PS" was inferred to mean decrease PS by 2 cm H_2O. For patient safety, the attending physician was the final authority for ensuring the PS setting was appropriate. If he/she determined PS guidance to be inappropriate, then the guidance was rejected—a situation that never occurred during the study. The maximal PS applied was limited to 25 cm H_2O to limit the potential for barotrauma.

Data recorded from each patient in the intervention group collected prior to the change to PS, before the DSS was employed (Pre VentAssist ™ Group), and thereafter when the DSS was employed (VentAssist™ Group). Distributed data were analyzed using a bidirectional student *t*-test (MATLAB, ttest2) and an F-test (MATLAB, vartest2) while

Table 1
Demographics and diagnosis for study patients. COPD—chronic obstructive pulmonary disease.

		Control group	DSS group	95% CI	P value
Age (years)		62 ± 17	59 ± 21	[−9 to 15]	0.60
BMI (kg/m^2)		24 ± 22	27 ± 4	[−6 to 12]	0.54
Gender (F)		8 (34.8%)	15 (71.4%)	–	–
Diagnosis	Respiratory failure	8 (35%)	7 (33%)	–	–
	Sepsis	4 (17%)	6 (29%)	–	–
	Congestive heart failure	3 (13%)	4 (19%)	–	–
	COPD exacerbation	5 (22%)	1 (5%)	–	–
	Pneumonia	3 (13%)	1 (5%)	–	–
	Cystic fibrosis	0	1 (5%)	–	–
	Pulmonary interstitial fibrosis	0	1 (5%)	–	–

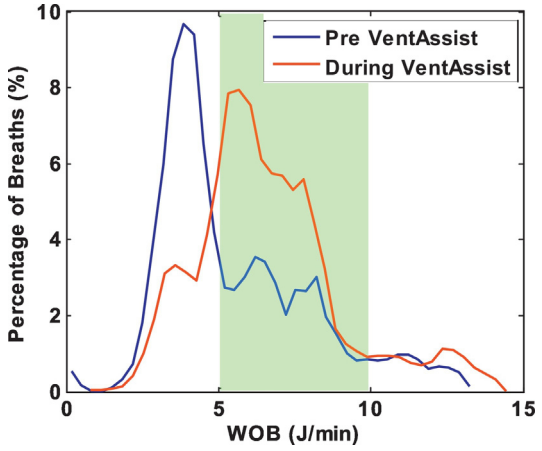

Fig. 1. The distribution of WOB/min values from all breaths for the pre-VentAssist™ group (blue) and the VentAssist™ group (red). The green shaded region indicated the target WOB/min range. The WOB/min increased on average from 5.1 to 6.4 ($p < 0.01$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

proportional data were analyzed with a Chi-quared test. Alpha was set at 0.05 for statistical significance.

3. Results

The percentage of breaths in every target range (WOB/min, f, V_T, SpO_2, and plateau pressure) increased after the DSS was employed [28% to 48%, p value < 0.0001]. The primary parameter influencing the increase of this percentage was the WOB/min; the distribution of the WOB/min values shifted towards the target range, Fig. 1. The change in the percentage of breaths in the target ranges for f, V_T, SpO_2, and Pplt were minimal [<5%], as listed in Table 2. Pulse oximeter hemoglobin O_2 saturation and partial pressure end-tidal CO_2 were in proper ranges, and all patients were hemodynamically stable during the study period.

In the intervention group initial PS ranged from 9 to 24 cm H_2O and decreased significantly in the first 2 h (Fig. 2). With employ of the DSS, ventilator pressure settings were decreased to minimal settings much quicker than in the control group [46 ± 38 min with the DSS, 21 ± 12 h without the DSS; p < 0.0001] As expected, the rapid decrease in PS increased WOB/min while decreasing the airway resistance, tidal volume, and minute ventilation (Table 3), yet still within the clinical ranges. The PS recommendations from the DSS were accepted by the clinicians every time. While most of the patients in the intervention group were weaned, three (15%) of the patients were not weaned during the 8 h trial period. One patient experienced excess visible agitation accompanied with an increase in breathing frequency, to accommodate the comfort of the patient the clinician administered sedation and applied assist control ventilation. The other two patients, which did not wean to minimum ventilator settings, had diagnoses of pulmonary interstitial fibrosis and cystic fibrosis.

4. Discussion

When the clinicians utilized recommendations from the DSS the frequency of the f, V_T, and WOB/min values in their target clinical ranges increased. The largest increase was in the increase of the WOB/min value within its target clinical range. When setting the PS to appropriately maintain WOB/min the PS for the majority of the patients decreased; suggesting that, unknown to the clinician, in general the patients were over assisted. Although this study was not intended to evaluate patient weaning, this intervention group of patients, which were not expected to be weaned for the next 24 h, were weaned to minimum ventilator settings more rapidly than expected. None of the patients enrolled in the study were being weaned; i.e., without enrollment in the study the clinician expected the patient needed high levels of support. However, when the DSS was applied, rapid weaning was found to be feasible in 85% of the intervention group. This seems to indicate that the patients likely did not need ventilatory support and could be extubated when all other clinical criteria were met. The authors did not anticipate patients to be weaned to minimal ventilator settings within the 8 h study time period; however, after initial review of the rapid weaning of patients in the intervention group the authors added the control group to the study for comparison.

The DSS recommends PS based on a multifaceted process including WOB/min, V_T, and f. During employ of the DSS 39% of the breaths were observed to have WOB/min values above or below the clinical range. The breaths with low WOB/min were attributed to the DSS being limited at the minimal ventilator settings (pressure support of 5 cm H_2O), as a result 30% of the breaths after employ of the DSS had a WOB/min < 5 J/min. When the clinician observed these patients

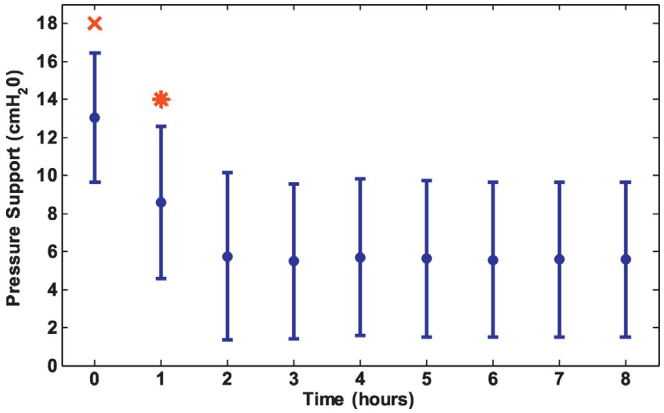

Fig. 2. Average PS for all patients during employ of the DSS. The PS decreased from hour 0 to hours 1–8 (indicated by the red x, p < 0.05). The PS decreased from hour 1 to hours 2–8 (indicated by the red *, p < 0.05). The average weaning time, for the 18 of the 21 patients that were weaned to a PS of 5 cm H_2O, was 46 ± 38 min. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
The range for each parameter are the values which the DSS targets. The pre VentAssist™ percentages for are the proportion of the total breaths below, within, or above that target range before the DSS was employed. The VentAsisst™ percentages are the proportion of total breaths below, within, or above the target range while the DSS was used. Red shading indicates regions above or below the green shaded target range.

		Percentage of breaths in Target Ranges		
VentAssist Parameter		Below Target	On Target	Above Target
WOB/min (J/min)	Range	< 5 J/min	5-10 J/min	>10 J/min
	Pre VentAssist™ Group	57% [a]	33% [b]	9%
	VentAssist™ Group	30% [a]	61% [b]	9%
V_T (mL/kg)	Range	<5 mL/kg	5-8 mL/kg	>8 mL/kg
	Pre VentAssist™ Group	40% [c]	58% [d]	2% [e]
	VentAssist™ Group	44% [c]	53% [d]	3% [e]
Respiratory Rate (breaths/min)	Range	<12 bpm	12-30 bpm	>30 bpm
	Pre VentAssist™ Group	14%	81% [f]	5% [g]
	VentAssist™ Group	14%	78% [f]	8% [g]
SpO_2	Range	< 88%	> 88%	n/a
	Pre VentAssist™ Group	1% [h]	99% [i]	-
	VentAssist™ Group	3% [h]	97% [i]	-
Pplt (cmH_20)	Range	n/a	<30	>30
	Pre VentAssist™ Group	-	100%	0
	VentAssist™ Group	-	100%	0

[a–i]Indicates Chi-squared statistical difference between Pre VentAssist™ Group and VentAssist™ Group, p value < 0.0001.

Table 3
The collected and calculated parameters (mean ± standard deviation) for each patient before (Pre VentAssist™) and after (VentAssist™) implementation of the DSS. The p-value as calculated from the *t*-test are listed for each parameter. The f-test indicated the variances were distinct between groups for all parameters except the PEEP setting. WOB/min—work of breathing per minute, PSV—pressure support ventilation, PEEP—positive end expiratory pressure, V_T—tidal volume, Pplt—plateau pressure, SpO2—oxygen saturation.

Parameter	Pre VentAssist™ Group	VentAssist™ Group	*t*-Test p value
PSV (cm H_2O)	13.2 ± 3.2	5.4 ± 3.2	<0.01
PEEP (cm H_2O)	7.4 ± 2.1	7.6 ± 2.1	0.76
Airway resistance (cm H_2O/L/s)	10.4 ± 4.5	6.4 ± 3.7	<0.01
Compliance (L/cm H_2O)	0.08 ± 0.07	0.14 ± 0.09	0.02
V_T (mL/kg)	6.2 ± 2.7	5.3 ± 2.0	0.24
Minute ventilation (L/min)	9.1 ± 4.4	8.7 ± 3.7	0.76
Respiratory rate (br/min)	19.8 ± 7.8	21.6 ± 7.6	0.46
Pplt (cm H_2O)	14.7 ± 3.5	11.2 ± 2.2	<0.01
SpO_2	96.4 ± 2.6	95.4 ± 3.3	0.29
WOB/min (J/min)	5.1 ± 3.2	6.4 ± 2.5	<0.01
Number of breaths	11,169	67,495	

with PS at 5 cm H_2O for longer than 30 min a recommendation for extubation was made. The DSS did not recommend a rapid decrease of PS on the patients with the diagnosis of pulmonary interstitial fibrosis and cystic fibrosis. We speculate the underlying pathophysiology of both patients had elevated WOB/min which could not be alleviated by increasing PS while maintaining appropriate V_T. For both patients, the V_T was approaching 9 mL/kg ideal body weight with excessively high inspiratory muscle workloads, the DSS attempted to unload inspiratory muscles up to the point until the average V_T's for both patients were borderline too high predisposing to hyperinflation/over distention of alveolar units and lung trauma. To ensure patient lung protection the DSS guided to maintain, rather than increase PS for both patients and not unload their inspiratory muscles. The clinicians agreed with the DSS recommendation for setting PS on both of these patients. The DSS is not a weaning tool rather it features a heuristic approach to setting mechanical ventilation, i.e., setting PS to maintain WOB/min, f, and V_T in clinically acceptable ranges.

Setting PS to appropriately unload inspiratory muscles is important because insufficient levels of PS predispose to increased inspiratory muscle loading and fatigue, while too much PS for too long predisposes to weakened muscles [12,13], both conditions may prolong weaning of PS and liberation from mechanical ventilation. Welvaart et al. found that when inspiratory muscles of patients were totally unloaded by applying controlled mechanical ventilation (analogous to unwittingly applying excessive PS) for as little as 2 h during thoracotomy surgery, there was marked diaphragm muscle fiber weakness, characterized as ventilator induced diaphragm dysfunction [14]. In two studies [8,15] evaluating breathing patterns and related clinical observations of breathing load-tolerance, it was determined that a clinical acceptable/tolerable range for work of breathing in adults with respiratory failure is 5 to 10 J/min, slightly higher than the normal range [16]. These observations are in accordance with Kirton et al. who found that intubated adults with respiratory failure and receiving ventilatory support tolerated a work of breathing in the range of approximately 5 to 10 J/min [17].

Because the DSS is automatic and continuously operational in estimating respiratory parameters and providing potentially useful guidance for setting PS, it may be useful in venues having limited manpower and where highly skilled, expert critical care physicians are not always available to direct ventilatory care, for example, small community/rural hospitals, remote medical care areas, and mass-casualty intensive care centers like military field and shipboard hospitals. Also, we speculate the DSS may be the basis for a closed-loop system to provide automatic control for PS to maintain appropriate inspiratory muscle workloads, f, and V_T.

The DSS utilized in this study, VentAssist™, is an *open-loop* system distinct from the *closed-loop* system *Smart Care™* (Drager Medical, Lubeck, Germany) [18]. *Smart Care™* does not measure inspiratory muscle workloads, it assesses only the tolerance for workloads as reflected by f and V_T. It employs f, V_T and $PetCO_2$ as feedback dependent (response) variables to formulate decisions to automatically up- and down-regulate the independent (treatment) variable PS to maintain f between 12 and 28 breaths/min, $V_T > 0.3$ L (or 0.25 L if the patient weighs <55 kg), and maintain $P_{ET}CO_2 < 55$ mm Hg (or <65 mm Hg if the patient has COPD). Because work of breathing is not measured or taken into consideration when automatically applying PS, *Smart Care ™* is incapable of informing the clinician if inspiratory muscle workloads are too low or high, so *Smart Care™* might apply PS inappropriately, i.e., excessive or insufficient PS predisposing to inspiratory muscle weakening and fatigue, respectively. This may explain, in part, why reductions in weaning duration initially demonstrated with *Smart Care™* were not confirmed when it was compared to weaning managed by experienced clinicians [18].

One critique for open/closed loop ventilation systems is the fear that erroneous recommendations will create an unsafe environment for the patient. While following the recommendations from the DSS, at all PS settings, all patients were appropriately oxygenated and ventilated. For all patients, mean arterial blood pressure and heart rate values were similar to those values at enrollment and within clinically acceptable ranges throughout the study period.

One limitation of the study is the patient population was selected from the medical intensive care unit where the primary ventilator mode is assist control. With different ventilator modes in the control group the results may not be as obvious. The results of the study are also limited because the study group patient selection was not prospectively randomized and blinded. We made every effort to match patient selection and diagnosis in control group to the interventional group, but the data from the interventional group was collected first followed by data from the control group which may introduce unknown discrepancies. However, patient enrollment in this study was random depending on the patients presented to the medical intensive care unit. Another limitation of the study is the interpretation of weaning; this study protocol measured weaning time as the time for the clinician to recognize the patient is ready to wean in addition to the decreasing PS levels to minimal ventilator settings. The intervention group may have expedited the time for the clinician to recognize when a patient is ready to wean, the collected results do not differentiate this distinction. This implementation study was designed as a pilot, thus the data collection was limited, but yet illustrates the feasibility and safety of further using the DSS.

5. Conclusion

In conclusion, the DSS guidance can aid clinicians in setting PS to target the clinical ranges for WOB/min, f, and V_T. At the study outset, none of the patients were considered as candidates for weaning; however, the clinicians we were surprised by how rapidly PS was safely decreased. The DSS may play a role in assisting the appropriate unloading of inspiratory muscles during weaning and decrease duration of mechanical ventilation.

Funding sources

The project was funded by Convergent Engineering under a subcontract with Philips Healthcare.

Acknowledgement

The authors acknowledge Dr. Michael J. Banner for his comments with the preparation of the manuscript.

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