Original articles

Effect of Ventilation Equipment on Imposed Work of Breathing

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ABSTRACT

Objective: *To determine the imposed work of different ventilation systems at 3 levels of pressure support.*

Design: *Laboratory study.*

Setting: *Teaching hospital respiratory laboratory.*

Participants: *Healthy, human volunteers.*

Interventions: *Measurement of imposed work of breathing (WOB_i) in six ventilators with alteration of ventilatory settings, humidification device, and triggering mechanisms.*

Results: *At 0 cmH_2O CPAP and 0 cmH_2O PSV, clinically significant (> 0. 1 joules per litre or J/L) WOB_i occurred in all systems. At 5 cmH_2O pressure support ventilation (PSV) median WOB_i ranged from 0.01 to 0.11 J/L. Removal of the pleated membrane heat and moisture exchanger (HME) significantly reduced WOB_i (0.38 vs. 0. 11 J/L, p < 0. 0001). Drawover humidification marginally increased WOB_i (0. 16 vs. 0. 11 J/L, p = 0. 0001). Flow triggering reduced WOB_i with the Servo (p < 0.0001) and Bennett ventilators (p = 0.001) but not with the Bear 1000 ventilator.*

Conclusions: *Up to 7 cmH_2O of PSV may be required to reduce WOB_i related to the ventilator, circuit and humdification devices. This pressure support does not address the additional resistive effect of the endotracheal or tracheotomy tube. Higher levels of PSV may therefore be required to offset WOB_i.* (**Critical Care and Resuscitation 2001; 3: 148-152**)

Key words: Monitoring, physiologic, artificial ventilation, work of breathing

Weaning patients from mechanical ventilation may be both problematic and difficult due, in part, to the influence of imposed work of breathing (WOB). Imposed work (WOB_i) is performed by a patient to trigger the ventilator and overcome the additional flow resistive effects of the circuit and the endotracheal or tracheotomy tube. That such imposed work may contribute to weaning failure has been suggested by recent studies.[1-4] Indeed, some investigators have coined the phrase "nosocomial respiratory failure" to describe this phenomenon.[5] The majority of ventilated patients in critical care units can be weaned without difficulty. WOB_i however, may hinder weaning in a number of patients who have marginal respiratory reserve. The importance of endotracheal tube size and partial intraluminal obstruction in contributing to imposed work is widely recognized. This study was undertaken to determine WOB_i independent of the effect of endotracheal or tracheotomy tube. We hypothesized that:

1) clinically significant WOB_i may occur at low levels of pressure support ventilation,

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2) pressure support ventilation in excess of 5 cm H_2O may be necessary to overcome such WOB_i, and

3) the presence of either a pleated membrane heat and moisture exchanger or drawover humdification system in ventilator circuits would significantly increase WOB_i.

MATERIALS AND METHODS

Six ventilators were employed, the Bear 2 and 1000 ventilators (Bear Medical Systems, Riverside, CA), Servo 300 ventilator (Elena AB, Solna, Sweden), Bird 8400SD ventilator (Bird, Palm Springs, CA), Puritan Bennett 7200A and Adult Star ventilators (Nellcor Puritan Bennett, Pleasanton, CA).

The authors of the study volunteered to breathe through the ventilator circuits via a sterilised mouth-piece while wearing a nose clip. Imposed work was measured using the method described by Banner,[2] utilising the Bicore CP- 100 Pulmonary Monitor (Allied Healthcare, Riverside CA). Flow was measured by the Varflex flow transducer (Allied Healthcare, Riverside CA). Distal airway pressure was tranduced and directly inputted to the CP-100 monitor, which then calculated WOB_i (the area within the distal airway pressure/ volume loop).

We designated WOB_i of 0.1 joules per litre (J/L) to be clinically significant. This represents one third of the lower limit of normal WOB (0.3 - 0.6 J/L). A standard circuit was employed (figure 1).
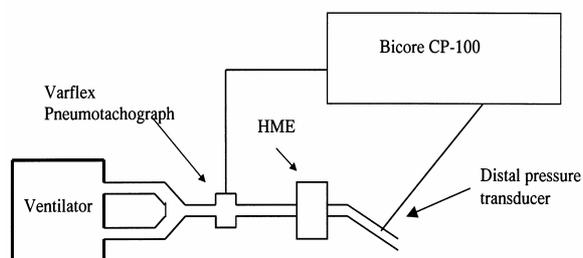
Figure 1. Diagrammatic representation of the circuit employed for the study

The compliance of the circuit tubing was 2.5 mL/cmH_2O (Bear Medical Systems, Riverside CA). The pneumotachograph was inserted into the circuit at the Y-piece. This was connected to the flow transducer input of the Bicore CP-100 monitor. Next, the humidification system was incorporated into the circuit. Pressure was measured at the end of the circuit via a neonatal extension tube (Bicore Monitoring Systems, Irvine, CA) connected to the catheter input of the CP- 100 monitor. The circuit tubing was straight; no elbows were incorporated. The humidification devices studied were (1) Fischer Paykel MR90 (Fischer and Paykel, Auckland

NZ) which is a drawover system, and (2) the PALL BB22-15 (Pall Biomedical Products, East Hills NY) which is a pleated membrane heat and moisture exchanger.

All ventilators with the exception of the Bear 2 ventilator were placed in pressure support ventilation (PSV) mode. The Bear 2 ventilator was set to continuous positive airway pressure (CPAP) mode. Five ventilator settings (with sensitivity set at -1 cmH_2O) were randomly assigned: 0 cmH_2O CPAP 0 cmH_2O PSV, 5 cmH_2O CPAP and 0 cmH_2O CPAP with 5, 7, or 10 cmH_2O PSV. In addition, the effect of flow triggering was studied where available (Bear 1000, Servo 300, Puritan Bennett 7200A ventilators) with 5 cmH_2O CPAP. Flow triggering was set to 6 L/min base flow and 2 L/min flow sensitivity on the Bear 1000 and Bennett 7200A ventilators and to the mid reference range on the Servo 300 ventilator. The effect of chang-ing humidification systems was examined. The ventilat-or setting for this comparison was 5 cmH_2O CPAP. Subjects were blinded from the ventilator settings. A five control minute period to allow familiarisation was followed by a five-minute measurement period. This provided a minimum of fifty breaths for each ventilat-ory setting. The data was downloaded digitally to a notebook computer for subsequent analysis.

All statistical analyses were performed using the Statview software package (Abacus Concepts Inc., Berkley CA.). Friedman's test was used for multiple group comparison. The Wilcoxon signed rank test with adjustment of statistical significance according to the number of comparisons was used for post-hoc comparisons between two groups. Values of imposed work are displayed as the median with interquartile range.

Our local institutional ethics committee determined that informed consent was not required for this study.

RESULTS

Figure 2 displays the WOB_i at 0 cmH_2O CPAP and 0 cmH_2O PSV and at 5 cmH_2O PSV in Figure 3. With 0 cmH_2O PSV all ventilators had clinically significant WOB_i (> 0.1 J/L). At 5 cmH_2O PSV clinically signif-icant WOB_i remained in one system. At 7 cmH_2O PSV, imposed work was reduced to negligible levels with all systems. A significant difference in tidal volume and inspiratory flow rate occurred between ventilators with the same ventilator settings (p < 0.01). Table 1 shows the effect of changing from a pleated membrane hygroscopic heat and moisture exchanger (HME) to a drawover humidification system. The pleated membrane HME caused a significant increase in WOB_i 0.17 - 0.27 J/L (p < 0.01). Drawover humidification led to a small (0.05 J/L) non-significant increase in WOB_I.

WOB$_i$ at 0cmH$_2$O PSV

Work J/L
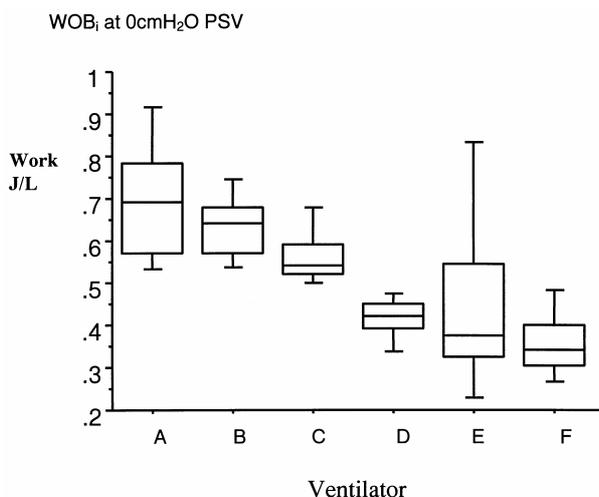
Figure 2. Imposed work of breathing (WOB$_i$) at 0 cmH2O pressure support ventilation (PSV). The median, 10th, 25th, 75th and 90th percentiles are displayed. A = Bear 2, B = Servo 300, C = Bird 8400SD, D = Puritan Bennett 7200A, E = Star, F = Bear 1000.

WOB$_i$ with 5 cmH$_2$O PSV

Work J/L
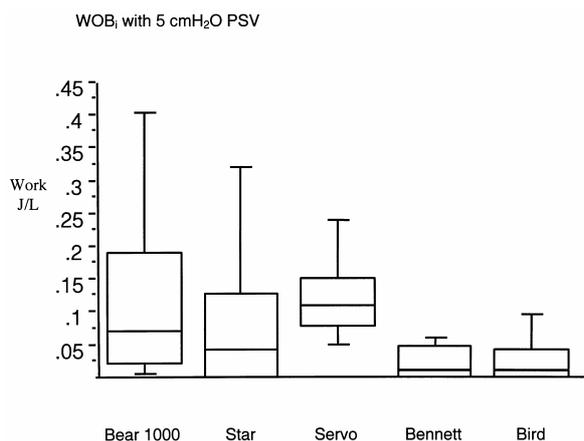
Figure 3. Imposed work of breathing (WOB$_i$) at 5 cmH$_2$O PSV. The median, 10th, 25th, 75th and 90th percentiles are displayed.

Table 1. Effect of pleated membrane heat and moisture exchanger and drawover humidification systems on imposed work of breathing (WOB$_i$)

Ventilator	Humidification	WOB$_I$(J/L)	Significance
A	Pleated membrane	0.69	ns.
A	None	0.52	p = 0.02
D	Pleated membrane	0.38	ns.
D	Drawover	0.16	ns.
D	None	0.11	p < 0.01

A = Bear 1000, D = Puritan Bennett 7200A

Table 2 displays the effect of flow triggering. Flow triggering produced a small non-significant difference with the Bear 1000 ventilator. In contrast, flow triggering resulted in a reduction in WOB$_i$ with both the Puritan Bennett 7200A ventilator (p < 0.001) and the Servo 300 ventilator (p = 0.041).

Table 2. Effect of flow triggering with the Bear 1000, Servo 300 and Puritan Bennett 7200A ventilators

Ventilator	Trigger	WOB$_I$(J/L)	Significance
A	Flow	0.44	
A	Pressure	0.41	ns.
C	Flow	0.32	
C	Pressure	0.39	p = 0.001
D	Flow	0.06	
D	Pressure	0.36	p < 0.01

A = Bear 1000, C = Servo 300, D = Puritan Bennett 7200A

DISCUSSION

Imposed work of breathing has been recognized as a potential cause of weaning failure. The imposed work of breathing is composed of (1) the resistive element (impedance) of the endotracheal or tracheotomy tube, (2) the presence of a triggering pressure sensor outside of the trachea, (3) the burden imposed by humidification systems, (4) the burden imposed by the triggering mechanisms of the ventilator itself.[1,6-14] These may not be clinically significant in stable patients with good cardiopulmonary function, but potentially induce failure to wean in patients with marginal reserve. These patients may then be kept ventilated unnecessarily. It is therefore important for clinicians to appreciate the degree to which ventilators can influence such work of breathing and the amount of pressure support that may be necessary to overcome it. Accordingly, this study determined the work imposed by different ventilation systems, the amount of pressure support required to offset such imposed work, and the influence of humidification systems and triggering modalities.

We demonstrated that at levels of pressure support commonly accepted as sufficient to offset imposed work of breathing (e.g. 5 cmH$_2$O) significant imposed work can still exist if pleated membrane HME's are incorporated in the circuit. Imposed work, as a result of the resistance of the endotracheal or tracheostomy tube, is additive to the work we determined. In clinical practice even higher levels of pressure support may be required.

The significance of WOB$_i$ remains controversial. While a number of authors have implicated it as a cause of failure to wean,[3,4,15,16] other groups have argued that the work of breathing is increased after extubation, possibly secondary to upper airway oedema, and WOB$_i$ merely offsets this increase in work following extubat-

ion.[17,18] Difficult to wean patients, however, frequently have tracheotomies in situ; any increase in WOB due to upper airway abnormality will not contribute to WOB_i in this group of patients. For this reason we believe WOB_i in patients with tracheotomies cannot be ignored. WOB_i may still be a contributory factor in weaning difficulty in this group. This study did not measure imposed work due to the endotracheal or tracheotomy tube. Several other authors have determined this previously.[8-10,19]

When gas flow is laminar, work increases inversely proportionally to the fourth power of their internal radii and directly proportionally to their length. Under these test conditions, the six ventilators displayed different levels of imposed work. It is not possible however to suggest one ventilator is superior to another because of the methodology employed. In this study neither the tidal volume nor flow rate were standardised; the test conditions were similar but not identical. Significant differences in both tidal volume and flow rate occurred at different ventilator settings and between ventilators.

Imposed work is related to the tidal volume and inspiratory flow rate. Comparison of the WOB_i occurring with the different ventilators at similar settings was therefore not made.

Volume and flow rates did not differ significantly during evaluation of flow triggering and humidification devices; comparison of WOB_i related to triggering mechanisms and humidification systems can therefore be made. With flow triggering, a significant reduction in WOB_i occurred in both the Bennett 7200A and Servo 300 ventilators. In contrast, the Bear 1000 ventilator demonstrated no difference in imposed work when flow triggering was employed. We hypothesise this difference may in part be attributed to the site of the triggering mechanism. With the 7200 series and Servo 300 ventilators, the pressure and flow measurement sites are on the expiratory side of the ventilator whereas the Bear 1000 measures pressure at the Y piece. In addition, with the 7200 series ventilators, there are differences in the limit variable and cycling mechanisms when flow triggering is employed. In contrast, in adult mode, the Servo 300 ventilator flow triggering mechanism is uncalibrated: a continuous flow of 2L/min is set and the limit variable and cycling mechanism are the same in both pressure and flow trigging modes. This may explain why the reduction in imposed work seen with the Bennett 7200A ventilator with flow triggering is greater than the Servo 300 ventilator. Flow triggering has been previously shown to reduce work of breathing with Bennett 7200 series ventilators. Other studies however, have failed to demonstrate any difference.[26] Similarly, with the Servo 300 ventilator, previous studies have demonstrated conflicting results.[27-29]

The impact of pleated membrane hygroscopic HME's versus a drawover humidification system was also determined. We demonstrated that a pleated membrane hygroscopic HME adds a clinically significant WOB_i. A new HME was used for each test, reducing the possibility that any additional WOB_i was due to an individual filter or filter fatigue. Our findings are in agreement with the study of Johnson *et al*,[3] who also determined that commercially available HME's add to the flow resistive work. In our institutions HME's are frequently used where short-term ventilation is likely. The use of a drawover humidification system is difficult with some ventilators and HME's are often substituted. When pleated membrane HME's are used, it is emphasised that, at 5 cmH_2O CPAP and 5cmH_2O PSV clinically significant WOB_i may still occur.

In conclusion, this study demonstrates that the commonly used ventilators may have relatively high levels of imposed work even with levels of pressure support previously thought to offset such work. These high levels of imposed work occur as a result of the ventilator and circuit. Importantly, the work performed to overcome the endotracheal or tracheotomy tube is additive to this and was not measured by this study and further pressure support will be required to overcome it.

Clinically significant imposed work is particularly likely when a pleated membrane HME is incorporated in the circuit. WOB_i may also be reduced by the use of flow triggering where the ventilators triggering mechanism lies in the expiratory limb of the circuit. High levels of WOB_i are a potential cause of weaning failure; its incidence and severity in critically ill patients require further investigation. Appreciation of their magnitude may assist clinicians in their approach to weaning.

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