IMPOSED WORK OF BREATHING DURING HIGH-FREQUENCY OSCILLATORY VENTILATION: A BENCH STUDY

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Abstract: Spontaneous breathing imposes work of breathing (WOB) on mechanically ventilated patients. In a bench test we assessed the imposed WOB using 3100 A/B SensorMedics high-frequency oscillatory ventilator. A piston driven test lung was used to simulate a spontaneously breathing patient during high-frequency oscillatory ventilation (HFOV). Spontaneous breath rate and volume, tube size and ventilator settings were simulated as representative for the newborn to adult range. Imposed WOB was calculated using the Campbell diagram. High peak inspiratory flow resulted in a significant increase in imposed WOB. Comparison of imposed WOB in low and high fresh gas flow rate measurements lead to values of 1.63 ± 0.32 J·l^{-1} and 0.96 ± 0.24 J·l^{-1} ($p = 0.01$) in small children, 1.81 ± 0.30 J·l^{-1} and 1.10 ± 0.27 J·l^{-1} ($p < 0.001$) in large children and 1.95 ± 0.31 J·l^{-1} and 1.12 ± 0.34 J·l^{-1} ($p < 0.01$) in adults. Mean airway pressure in the breathing circuit decreased dramatically during spontaneous breathing. Conclusions: Spontaneous breathing during HFOV resulted in considerable imposed WOB in the large pediatric and adult simulations. High fresh gas flow rate reduced imposed WOB. Physicians should be aware of this when allowing spontaneous breathing during HFOV.

Introduction

Maintenance of spontaneous breathing in mechanically ventilated patients augments ventilation perfusion matching and cardiopulmonary function, reduces sedative requirement and shortens intensive care stay [1-6]. High-frequency oscillatory ventilation (HFOV) is a useful ventilatory mode for neonatal application [7,8] and it is gaining interest in both pediatric and adult intensive care [9-12]. Neonatal and small pediatric patients can easily breathe spontaneously during HFOV. Muscular paralysis is avoided and only mild sedation needs to be applied to tolerate ventilation and reduce stress. However, in larger children and adults spontaneous breathing during HFOV is usually not well tolerated because of patient discomfort. Sedation level often has to be high and even muscular paralysis may be necessary [13]. We speculate that this discomfort is caused by a high imposed work of breathing (WOB). Imposed WOB is the work added to the physiologic WOB when patients breathe through a breathing apparatus. This includes work to overcome resistance added by the endotracheal tube, the breathing circuit, the heat-moisture exchanger and work required to trigger the ventilator demand flow system.

Physiologic WOB of 0.3-0.6 J·l^{-1} is considered normal in a healthy adult. Depending on ventilator settings, imposed WOB can contribute as much as 80% to the total work of breathing [14]. Imposed WOB is greatest during continuous positive airway pressure (CPAP), where the patient performs all the effort required to ventilate [15]. HFOV may in this respect be regarded as super-CPAP.

In a physical sense, work is performed when a transmural pressure (Ptm) changes the volume (V) of a distensible structure: $W = \int Ptm \cdot dV$, most often expressed as Joules per liter (J·l^{-1}). Applied to a breathing apparatus, imposed WOB is calculated by integrating pressure measured at the tracheal end of the endotracheal tube (Pett) times the volume change: imposed WOB = $\int Pett \cdot dV$. As inspiration is active and expiration usually passive, only inspiratory imposed WOB is generally considered. In a SensorMedics HFOV ventilator (3100A or 3100B, SensorMedics, Yorba Linda, CA, USA), imposed WOB is directly related to the difference in set mean airway pressure (MAP) level and Pett; the greater the difference, the greater imposed WOB and thus patient effort. MAP is regulated by a continuous fresh gas flow rate and an expiratory balloon valve. During inspiration of a patient, air is inhaled from the ventilator and Pett level drops. The magnitude of this drop is influenced by fresh gas flow rate, endotracheal tube size and inspiratory flow rate [16].

In order to find a solution to better tolerate spontaneous breathing during HFOV in large pediatric and adult patients we performed a bench test. In this bench test inspiratory imposed WOB and pressure fluctuations in mean airway pressure were assessed for newborn to adult simulations. We evaluated which factors contributed to imposed WOB in the SensorMedics HFOV ventilator: fresh gas flow rate, endotracheal tube size and inspiratory flow rate.

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Materials and methods

Bench test set-up: A custom made artificial lung was used to simulate a spontaneously breathing subject with variable age (Figure 1). This test lung consisted of a 10 cm diameter tube with a computer controlled piston. It was connected to a HFOV ventilator (3100A or 3100B, SensorMedics, Yorba Linda, CA, USA), with an endotracheal tube (Mallinckrodt Medical, Athlone, Ireland). Different patient circuits were used for each HFOV ventilator (3100A or 3100B, SensorMedics, Yorba Linda, CA, USA). The same heat-moisture exchanger was used for both ventilators (MR225 humidification chamber, Fisher and Paykel, Auckland, New Zealand). A sinusoid flow simulated inspiration of spontaneous breathing. An exponential decelerating flow expiration (Figure 2).

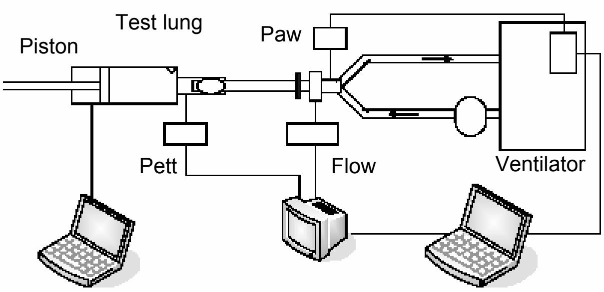

Figure 1: Schematic drawing of the experimental set-up. The ventilator circuit of a Sensor Medics 3100 A/B oscillator is connected to a piston driven test lung by an endotracheal tube. Measurements: Pett and Paw are the pressure in the test lung and ventilator circuit respectively. Flow is measured at the proximal end of the endotracheal tube.

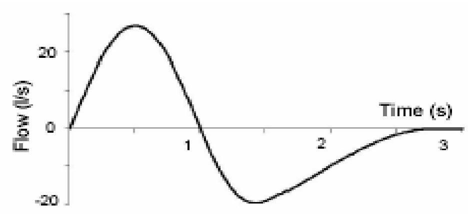

Figure 2: Simulated spontaneous breath.

Inspiratory and expiratory airway flow in the endotracheal tube was measured with a hot-wire anemometer (Florian, Acutronic Medical Systems AG, Switzerland). Tidal volume (Vt) of spontaneous breathing was calculated by flow integration. Pressure at the tracheal end of the endotracheal tube (Pett) was measured using the Florian respiration monitor. The pressure at the Y-piece in the ventilator circuit was measured using the unfiltered electronic signal of the internal pressure sensor of the HFOV ventilator. Flow and airway pressures were sampled at 100 Hz and stored on a laptop computer for off-line analysis.

HFOV was set to specific patient size as prescribed by the operator’s manual for management of acute respiratory distress syndrome (ARDS) [17,18]. We tested five patient weight ranges, from newborn to adult (Table 1). Ventilator fresh gas flow rate was set at two different levels: low and high level. For all different patient sizes, three tidal volumes (Vt) of spontaneous breathing were simulated. The table provides the peak inspiratory flow rate these tidal volumes result in. Three different sizes of endotracheal tubes were used for each patient size (Table 1). In total 90 different settings were tested.

Imposed work of breathing: For each experimental condition, 12 to 20 breaths were recorded. Inspiratory imposed WOB was calculated for each simulated spontaneous breath, based on the modified Campbell diagram (Figure 3) [19,20]:

$$\text{Imposed WOB} = \Sigma_{INSP} (CDP - MAPett)\, dV \qquad (1)$$

Where CDP is continuous distending pressure or set MAP level on the SensorMedics oscillator. MAPett is the mean airway pressure in the test lung. This was calculated by low pass filtering of the Pett signal to eliminate pressure changes on account of oscillations. Imposed WOB was averaged over all breaths and expressed as $J \cdot l^{-1}$.

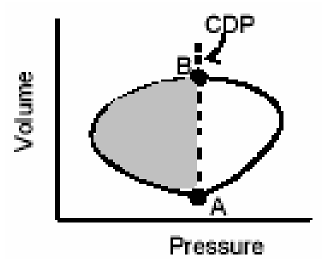

Figure 3: Modified Campbell diagram, where A is the start of inspiration, B the end of inspiration. The grey area is the area representing the imposed inspiratory WOB.

Airway pressure: Swings of the pressure in the ventilator circuit (Paw) due to oscillations were removed by low pass filtering. As a result, all changes in airway pressure were attributable to the settings chosen to mimic spontaneous ventilation. Pressure fluctuations due to spontaneous breathing (ΔMAP) are expressed as deviation from CDP in cm H_2O. ΔMAPinsp is the maximum deviation from mean airway pressure during inspiration. ΔMAPexp is the maximum deviation during expiration. ΔMAPinsp and ΔMAPexp were calculated separately as inspiratory and expiratory flow pattern of spontaneous breathing differed.

Statistical analysis: Data are expressed as mean ± standard deviation. Comparison of means for normally distributed data was performed with independent t-test. A value of $p < 0.05$ was considered statistically significant. Linear regression was performed to explore relations between imposed WOB, endotracheal tube size, fresh gas flow rate, and peak inspiratory flow.

Table 1: Spontaneous breathing simulation and ventilator settings. PIF = peak inspiratory flow; I/E ratio = inspiratory/expiratory ratio; CDP = continuous distending pressure; ΔP = proximal pressure amplitude; RR = respiratory rate; V_T = tidal volume; HFOV ventilator = SensorMedics 3100 A or B HFOV ventilator.

	Newborn	Infant	Small child	Large child	Adult
Assumed weight (kg)	3.5	10	25	40	70
Spontaneous breathing simulation					
RR (min^{-1})	35	30	25	20	12
V_T ($ml \cdot kg^{-1}$) / PIF ($l \cdot min^{-1}$)	5 / 2.6	5 / 6.3	5 / 13	5 / 17	5 / 18
	7 / 3.6	7 / 8.9	7 / 19	7 / 24	7 / 25
	10 / 5.1	10 / 12	10 / 27	10 / 34	10 / 36
I/E ratio			1 : 2		
Ventilator settings					
HFOV ventilator	3100 A	3100 A	3100 B	3100 B	3100 B
Tube size	3.0 – 4.0	4.0 – 5.0	5.5 – 6.5	6.5 – 7.5	7.5 – 8.5
Bias flow ($l \cdot min^{-1}$)	15 / 20	20 / 40	20 / 60	20 / 60	20 / 60
CDP (cm H_2O)	18	25	25	25	25
ΔP (cm H_2O)	35	50	50	50	50
Oscillation Frequency (Hz)	10	8	8	6	6

Statistical analyses were performed using SPSS 11.5 for Windows (SPSS Inc., Chicago, Ill, USA).

Results

Imposed work of breathing: Imposed WOB was 0.22 ± 0.07 $J \cdot l^{-1}$ for all measurements in the newborn simulations, and 0.87 ± 0.25 $J \cdot l^{-1}$ in the infant simulations (Figure 4) p = 0.64 for newborns and p = 0.94 for infants (SensorMedics 3100A oscillator). An independent contributor to imposed WOB was peak inspiratory flow; higher peak inspiratory flow increased imposed WOB ($p < 0.001$). There was a trend that tube size influenced imposed WOB. Fresh gas flow rate and tube size however did not independently contribute to imposed WOB (p = 0.92 and p = 0.92).

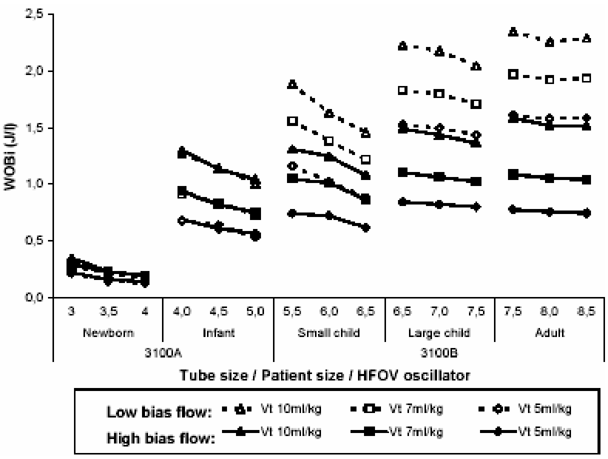

Figure 4: Imposed WOB for all simulations. Results for all measurements done with the 3100A and 3100B SensorMedics oscillator.

For the larger patient size simulations (Sensor Medics 3100B oscillator) imposed WOB was significantly higher in the low fresh gas flow rate in comparison with the high fresh gas flow rate condition: In the small child simulation imposed WOB was 1.63 ± 0.32 $J \cdot l^{-1}$ (low fresh gas flow rate) versus 0.96 ± 0.24 $J \cdot l^{-1}$ (high fresh gas flow rate) (p = 0.01), in the large child 1.81 ± 0.30 $J \cdot l^{-1}$ versus 1.10 ± 0.27 $J \cdot l^{-1}$ ($p < 0.001$) and 1.95 ± 0.31 $J \cdot l^{-1}$ versus 1.12 ± 0.34 $J \cdot l^{-1}$ in the adult simulation ($p < 0.001$). Independent contributors to imposed WOB were: fresh gas flow rate ($p < 0.001$) and peak inspiratory flow ($p < 0.001$). High fresh gas flow rate decreased imposed WOB. High peak inspiratory flow increased Imposed WOB. Tube size did not independently contribute to imposed WOB (p = 0.07).

Airway pressure: Mean airway pressure in the ventilator circuit decreased dramatically during spontaneous breathing, most markedly at low fresh gas flow rate (Figure 5). In this example mean airway pressure in the ventilator circuit even becomes negative. This effect was observed when fresh gas flow rate was low and with a Vt of 7 or 10 $ml \cdot kg^{-1}$ for the large child and adult patient simulations. In these simulations peak inspiratory flow exceeded fresh gas flow rate. Are the simulated conditions chosen physiologic? This is a key question and there should be a clear justification of the patient weight/tidal volume/peak inspiratory flow rates chosen. This triggered the automatic ventilator shut-off, a safety feature of the SensorMedics oscillator.

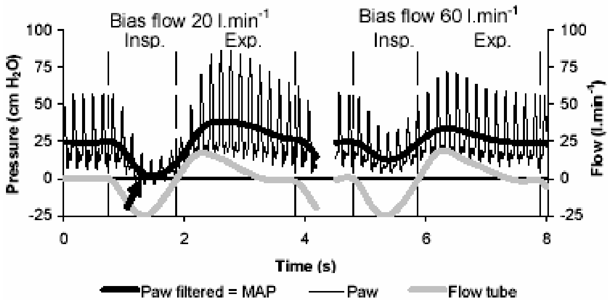

Figure 5: Example of fluctuations in pressure in the ventilator circuit for both low and high bias flow. Paw is the unfiltered airway pressure, Paw filtered is the mean airway pressure calculated by low pass filtering of the

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Paw signal. Example of the changes in Paw and Paw filtered during the simulation for a large child, 40 kg, Vt 280 ml, for both low and high bias flow. Note that pressure changes decrease with higher bias flow and thus imposed WOB decreases. In this example in the low bias flow testing the pressure in the ventilator circuit becomes negative as the inspiratory flow exceeds bias flow (arrow). Insp = inspiration; Exp = expiration.

ΔMAPinsp and ΔMAPexp for all measurements in the newborn simulations were not significantly different comparing low and high fresh gas flow rate (Table 2). In the infant simulations ΔMAPinsp was significantly lower in the high fresh gas flow rate simulations in comparison with low fresh gas flow rate testing ($p = 0.002$). There was no difference in ΔMAPexp (SensorMedics 3100A). For the larger patient size simulations (Sensor Medics 3100B oscillator) ΔMAPinsp and ΔMAPexp were significantly lower in the high fresh gas flow rate in comparison with the low fresh gas flow rate condition (Table 2).

Discussion

An effective way to reduce imposed WOB in HFOV is desirable. A possible solution is the use of a demand flow system instead of continuous fresh gas flow rate. This demand flow system is a technical challenge.

Work of breathing: Compared to the WOB of a healthy adult (0.5 $J \cdot l^{-1}$) the imposed WOB is high if spontaneous breathing is simulated during HFOV [16]. As physiologic WOB is not considered in this bench test, total WOB is even higher in a patient breathing spontaneous during HFOV. An elevated WOB results in dyspnea and discomfort [21,22]. The optimal workload for critically ill patients is unclear. Research focuses mainly on WOB in the weaning phase [23,24]. A WOB in the physiologic range (approximately 0.5 $J \cdot l^{-1}$) seems to correspond with an optimal workload. Fully unloading induces loss of respiratory muscles. Excessive respiratory muscle loading may cause muscle fatigue and weaning failure [25]. The workload of 0.5 $J \cdot l^{-1}$ seems not only optimal during weaning but also in the acute phase of respiratory failure [26,27].

In the large pediatric and adult simulation, the imposed WOB exceeded the normal physiologic WOB by as much as 200%. There are very few studies reporting normal WOB values for pediatric patients. WOB in healthy children and adolescents (6-18 yr) range between 0.1 - 0.6 $J \cdot l^{-1}$[28]. In healthy preterm and term infants WOB is 0.02 - 0.2 $J \cdot l^{-1}$ [29]. For these patients optimal WOB during mechanical ventilation is even more unclear.

Ventilator settings in different modes of assisted mechanical ventilation influence WOB. With correct settings imposed WOB is reduced to a minimum. Excessive physiological WOB, as in ARDS, is also relieved. We show that the level of imposed WOB is high during spontaneous breathing in HFOV. In simulations for larger subjects high fresh gas flow rate reduces imposed WOB but not to an acceptable level. This will be the same for patient WOB. The HFOV ventilator imposes a high level of WOB and does not unload the patients' WOB. For the simulations for newborns and infants imposed WOB was not influenced by fresh gas flow rate. This may be explained by the small difference in level of low and high fresh gas flow rate. Simulations for newborns show a low level of imposed WOB. This is in agreement with the fact that these patients tolerate spontaneous breathing during HFOV. Our results show that in order to reduce imposed WOB the fresh gas flow rate has to exceed peak inspiratory flow by far.

Airway pressure: Large fluctuations in mean airway pressure in the breathing circuit are responsible for a high imposed WOB. They may also lead to unwanted alarms of the ventilator during HFOV or even shutdown. Upper and lower alarm limits are routinely set 3 cm H_2O above and under the desired mean airway pressure [17,18]. This is a safety precaution against unnoticed mean airway pressure changes due to changes in respiratory system compliance, which may lead to alveolar derecruitment or overdistension. Airway pressure fluctuations exceeded the alarm limit of 3 cm H_2O in all simulations on the SensorMedics 3100B ventilator.

Limitations of the study: Imposed WOB is strongly related to the choice of tidal volume, respiratory rate,

Table 2: Maximum deviation of mean airway pressure from set continuous distending pressure during inspiration and expiration. ΔMAP_{INSP}, maximum deviation of mean airway pressure (MAP) from continuous distending pressure (CDP) during inspiration; ΔMAP_{EXP}, maximum deviation of MAP from CDP during expiration.
[a]Low bias flow: 3100A 15 $l \cdot min^{-1}$, 3100B 20 $l \cdot min^{-1}$; [b]High bias flow: 3100A 20 $l \cdot min^{-1}$, 3100B 60 $l \cdot min^{-1}$

	ΔMAP_{INSP} (cm H_2O)			ΔMAP_{EXP} (cm H_2O)		
Bias flow ($l \cdot min^{-1}$)	Low[a]	High[b]	*p* Value	Low[a]	High[b]	*p* Value
SensorMedics 3100A						
Newborn	2.17 ± 0.24	1.75 ± 1.04	NS	0.83 ± 0.27	0.71 ± 0.44	NS
Infant	6.85 ± 1.34	4.56 ± 1.24	0.002	3.73 ± 1.77	3.59 ± 1.70	NS
SensorMedics 3100B						
Small child	17.0 ± 3.11	8.91 ± 2.11	< 0.001	8.90 ± 2.49	5.21 ± 1.70	0.002
Large child	23.0 ± 2.60	12.8 ± 2.62	< 0.001	13.2 ± 2.01	8.76 ± 1.66	< 0.001
Adult	25.5 ± 2.51	13.7 ± 3.50	< 0.001	15.9 ± 2.97	8.34 ± 2.18	< 0.001

breathing pattern, and tube size. In this in vitro study we aimed to choose realistic test conditions. However, in vivo conditions may differ from our bench test. These findings need validation in clinical practice.

Conclusions

The main result of this study is that imposed work of breathing can be markedly increased during HFOV in large subjects, especially at low fresh gas flow rate rates. This can be a good explanation for the discomfort seen in a larger pediatric or adult patient breathing spontaneously during HFOV. Fresh gas flow rate and peak inspiratory flow are strongly related to imposed WOB. Mean airway pressure is not maintained in the breathing circuit when inspiratory flow exceeds fresh gas flow rate and can even lead to ventilator shutdown.

Acknowledgement

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