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BRIEF REPORT

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Flow-triggering reduces inspiratory effort during weaning from mechanical ventilation

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Abstract *Objective*: To investigate whether a new flow-triggered (FT) system can reduce the patient's inspiratory effort compared to a traditional pressure-triggered (PT) system during weaning from mechanical ventilation.
Design: Prospective study.
Setting: Intensive care unit of a General Hospital.
Patients and participants: 10 mechanically ventilated patients, without chronic airway disease, ready to wean.
Measurements: Minute ventilation, breathing pattern, lung mechanics, inspiratory work of breathing ($\dot{W}I$) and pressure time product (PTP) of Ppl were obtained in two conditions: 1) unsupported spontaneous breathing through the ventilator circuit (SB); 2) spontaneous breathing with continuous positive airway pressure set at 5 cmH_2O (CPAP). Two triggering systems, namely PT and FT, were used in each condition.
Results: Though there was no change in breathing pattern, minute ventilation, and lung mechanics, the magnitude of the inspiratory effort decreased significantly with FT compared to PT in both instances. The added resistance (total flow resistance minus pulmonary resistance) decreased by 37% on average when FT replaced PT. PTP decreased, on average, 27% and 15% during SB and CPAP, respectively, with FT compared to PT ($p<0.05$). A similar significant decrease was observed in $\dot{W}I$.
Conclusion: The new FT system, i.e. flow-by system, reduces the unintentional ventilatory workload upon the patients' inspiratory muscles compared to traditional PT system during weaning from mechanical ventilation.

Key words Acute respiratory failure · Mechanical ventilation · Respiratory muscles · Respiratory mechanics · Continuous positive airway pressure (CPAP) · Flow trigger (FT)

Introduction

Recent works suggested that a flow-triggered (FT) system can decrease the patient's inspiratory muscle effort during assisted mechanical ventilation and weaning in normals [1] and COPD patients [2], compared to the traditional pressure-triggered (PT) system. In the FT system, called also flow-by (FB) system, fresh gas flows continuously within the ventilator inspiratory and expiratory circuit at a constant rate (between 5 and 20 l/min). The continuous gas flow provides the base flow (BF). When the subject's inspiratory flow reaches a preset threshold value, called the flow-sensitivity, the ventilator turns on and adds gas to the circuit. The flow sensitivity can be varied between a minimum value of 1 l/min and a maximum value of no greater than half of the set base flow. The ventilator stops adding gas to the circuit when the subject begins to exhale. Once the gas flow within the circuit decreases to 5 l/min, the preset BF return within 0.5 s. Flow-trigger can help to reduce the unintentional load upon the respiratory muscles which may unduly prolong the weaning period and increase the risk of complication related to prolonged intubation.

The purpose of this study was to investigate whether FT could reduce the amount of patient's inspiratory effort, compared to traditional PT system, during weaning from mechanical ventilation in a group of patients without COPD, which has not been systematically investigated yet. We also provide in this work detailed measurements of lungs mechanics in those patients, in that condition.

Materials and methods

Ten mechanically ventilated patients admitted to the Intensive Care Unit (ICU) of the Padova General Hospital because of acute respiratory failure were examined in this study. The investigative protocol was approved by the Institutional Ethic Authorities. Informed consent was obtained from the patients of from their next of kin. For the inclusion in the study the patients had to be judged ready to wean by their primary physicians, according to his/her clinical judgement. Characteristics of patients and arterial blood gases before the starting of the procedure are shown in Table 1. All patients were intubated with a Portex cuffed endotracheal tube (ETT), internal diameter ranging from 7.5–8.5 mm and were mechanically ventilated with the Puritan-Bennet 7200a ventilator (Puritan Bennet Corp., Carlsbad, CA) with constant inspiratory flow ($\dot{V}$I). The patients had been mechanically ventilated for a period from 6–14 days prior to the present investigation in the SIMV mode with common ventilatory settings. As prescribed by the primary physicians, the setting before the beginning of our experimental procedure was the following: VT 10–12 ml/Kg, f 5–8, I/E 1:2; without any positive end-expiratory pressure (PEEP).

Flow ($\dot{V}$) was measured by means of a heated pneumotachograph (Fleisch no. 1) inserted between the proximal tip of the endotracheal tube and the "Y"of the ventilator tubings by means of a flexible T connector, and connected to a Hewlett-Packard 47304A flow transducer. Volume (V) was determined by numerical integration of the flow signal. Tracheal pressure (Ptr) was recorded by means of a polyethylene catheter, 90 cm long and 1.7 mm in internal diameter, whose distal tip with a few spiral side holes was positioned in the trachea 2 cm below the distal side of the ETT, while the proximal tip was connected to a differential pressure transducer (Honeywell 143 PC 03 D). Changes in pleural pressure (P_{pl}) were estimated from changes in esophageal pressure (P_{es}) which was recorded using a double-lumen nasogastric tube with a thin-walled vinyl balloon (10 cm long and 3.8 cm in circumference) incorporated in the lower midportion of the tube (Mallinckrodt Inc., Argyle, NY) and connected to a differential pressure transducer (Honeywell 143PC03D) through a polyethylene catheter 90 cm long and 1.7 mm in internal diameter. The balloon was filled with about 0.7 ml of air and properly positioned using the "occlusion test" as recommended [3] and previously described [4]. All physiological variables were fed into a personal computer via a 12-bit analog-to-digital converter (Data Translation DT2801/A) at a sampling rate of 50 Hz.

A standard set of ventilator tubings supplied with the machine for adult patients was used. The humidifier was omitted from the inspiratory line during the period of the experimental procedure, in order to reduce the effects of the compliance of the system connecting the patients to the ventilator. Special care was devoted to avoid gas leaks in the equipment, particularly around the tracheal cuff which was checked frequently. Also the esophageal balloon was checked frequently throughout the procedure. Particular attention was paid to keeping the tracheal catheter free from secretions, and positioned.

Procedure and data analysis

The medical treatment was left unaltered during the study for all the patients. Blood gases were measured with an IL 1302 blood gas analyser (Table 1). Patients were examined in the semirecumbent position, and a physician not involved in the procedure was always present. ECG was monitored throughout the study. The airway was suctioned before the start of the measurements as well as when needed throughout the procedure. First any ventilatory support was withdrawn and the patients were spontaneously breathing (SB) through the ventilator tubings and circuit with the pressure sensitivity set at $-2\ cmH_2O$. After about 30 min the PT was replaced by the FT with the base flow set at 12 l/min and a flow sensitivity of 3 l/min. The levels of sensitivity selected for PT and FT were those commonly used in the ICU where the study was done for weaning of non COPD patients. Previous report demonstrated that the base flow values do not affect inspiratory work [5]. The flow sensitivity was the minimum sensitivity compatible with non autocycling of

Table 1 Patients' characteristics

Patient	Sex	Age (years)	Diagnosis	FIO_2	pH	$PaCO_2$ (mmHg)	PaO_2 (mmHg)
1	M	23	Head trauma	0.5	7.35	38.4	237
2	M	54	Sepsis	0.5	7.32	38.7	118
3	F	70	Coma	0.4	7.37	36.4	91
4	F	78	Polytrauma	0.4	7.45	31.9	164
5	F	51	Miastenia	0.5	7.33	38.3	189
6	F	65	Polytrauma	0.5	7.40	33.7	70
7	M	60	Polytrauma	0.5	7.43	36.5	168
8	F	70	Post-surgery	0.5	7.46	39.6	122
9	M	62	Post-surgery	0.5	7.32	46.2	178
10	F	80	Post-surgery	0.4	7.40	32.0	160
Mean		61		0.47	7.38	37.17	149
SD		16		0.05	0.05	4.2	49

the ventilator. A similar procedure, namely PT followed by FT was used after 5 cmH_2O of continuous positive airway pressure (CPAP) was set on the ventilator. Each condition was maintained for 30 min. The last 3 min of the 30 min period, data were collected through the A/D converter and used for data analysis. Subsequent data analysis was performed using the software package ANADAT (RHT-Infodat, Montreal, Quebec).

Respiratory rate (f), tidal volume (V_T), minute ventilation ($\dot{V}_E$), inspiratory (T_I) and total respiratory cycle duration (T_{TOT}) were calculated from the flow signal. Dynamic intrinsic PEEP ($PEEP_{i,dyn}$) was measured from the decrease in P_{es} preceding the inspiratory flow. P_{es} was subtracted from P_{tr} in order to compute transpulmonary pressure (P_L). Dynamic lung elastance ($E_{dyn,L}$) and total pulmonary resistance (R_L) were computed from changes in volume, flow, and transpulmonary pressure according to the Mead and Whittemberger technique [6]. Briefly, $E_{dyn,L}$ was computed as the ratio of ΔP_{es} over tidal volume between the beginning and the end of inspiration. Total pulmonary resistance was computed as the ratio of change in ΔP_L over change in $\dot{V}$ between two isovolume points at mid tidal volume. Total flow resistance (R_{TOT}), including the endotracheal tube plus ventilator tubings and devices, and without the chest wall resistance, was computed from the ratio of isovolume ΔP_{es} over changes in flow. We assumed that the upstream pressure, i.e. from where gas starts to flow, was equal to atmospheric pressure. The difference between R_{TOT} and R_L provides the value of total added flow resistance, i.e. endotracheal tube and ventilator circuits, while R_L do not include upper airway resistance. To estimate the amount of patients' inspiratory effort, we measured: a) $\Delta P_{es,peak}$ as the change in P_{es} from the onset to the peak of negative deflection; b) the area under the P_{es} swing between the onset of the inspiratory effort and the end of inspiration. Measurement of such area was referred to the chest wall (CW) static recoil pressure vs time relationship to obtain the pressure time product for one breath. The CW static recoil pressure-time curve was not measured directly in these patients, but was computed from the value of static CW elastance obtained in a previous work, in mechanically ventilated patients, without COPD [4]. The pressure time product for minute (PTP) was obtained multiplying the pressure time product per breath by respiratory frequency. Artefacts due to esophageal spasm were easily identified and excluded from the analysis. The averaging procedure was the result of a breath by breath analysis, not of an automatic overlapping of breath records. At least 10 breaths were analysed for each condition. The inspiratory work of breathing per breath was calculated as the area subtended by the inspired volume-esophageal pressure curve and the relaxation pressure-volume curve of the chest wall. The inspiratory work of breathing over one minute ($\dot{W}I$) was computed by multiplying the work per breath by respiratory frequency. The CW relaxation line was computed as previously described.

Statistical analysis

Statistical analysis was performed using the analysis of variance (ANOVA). Then differences between groups of data were examined using the Wilcoxon rank test for paired observation after ANOVA was significant. A $p<0.05$ was accepted as significant.

Results

A representative experimental record is shown in Fig. 1. The reduction in P_{tr} swings when FT replaced PT (arrow), illustrated by the example in Fig. 1, was observed systematically in all patients during both unsupported SB and CPAP. A small $PEEP_{i,dyn}$ slightly greater than 1 cmH_2O on average, was present in almost all patients though no patient had chronic airway disease. The mean values of ventilatory patterns, lung mechanics, PTP and $\dot{W}I$ are shown in Table 2. There was no significant change in minute ventilation, ventilatory pattern, and lung mechanics throughout the procedure. In contrast R_{TOT}, $\Delta P_{es,peak}$, PTP and $\dot{W}I$ were significantly ($p<0.05$) lower with FT than with PT during unsupported SB as well as after application of CPAP. When FT replaced PT, R_{TOT} decreased, on average by 25 and 29% during SB and CPAP 5 cmH_2O, respectively. If R_L is subtracted by R_{TOT} to compute the added resistance only, the average reduction due to the use of FT instead of PT was 37%, in both unsupported and CPAP breathing. $\Delta P_{es,peak}$ decreased

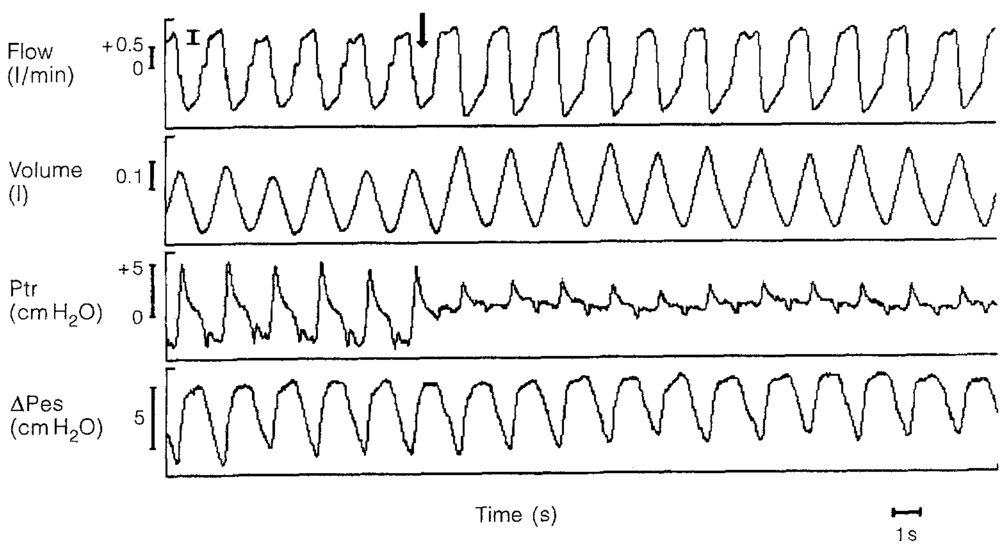

Fig. 1 From top: tracings of flow, volume, tracheal pressure (*Ptr*) and esophageal pressure (*ΔPes*) from a representative patient during spontaneous breathing through the ventilator circuit on pressure-triggered system (*on the left* of the *arrow* on the flow tracing) and flow-triggered system (*on the right* of the *arrow*). The *I* indicated the inspiratory limb of the flow tracing

Table 2 Ventilatory pattern, lung mechanics, pressure time product and inspiratory work of breathing

		V̇E (l/min)	F (b/min)	VT (l)	TI (s)	PEEPi,dyn (cmH_2O)	Edyn,L (cmH_2O/l)	RL (cmH_2O/l/s)	R_{TOT} (cmH_2O/l/s)	ΔPes,peak (cmH_2O)	PTP (cmH_2O.s/min)	ẆI (Joule/min)
SB	PT	8.64	24.3	0.36	1.01	2.2	16.7	3.1	14.6	13.9	332	11.64
		(2.06)	(5.5)	(0.05)	(0.32)	(2.5)	(5.4)	(2.0)	(4.3)	(5.2)	(132)	(6.38)
	FT	8.70	24.2	0.036	0.99	1.2	14.2	3.7	10.9*	10.6*	242*	8.85*
		(2.13)	(4.2)	(0.06)	(0.16)	(1.7)	(3.3)	(1.7)	(5.1)	(5.9)	(118)	(5.74)
CPAP	PT	8.27	23.2	0.36	1.00	1.2	15.6	3.4	14.8	12.3	276	10.23
		(1.85)	(3.7)	(0.06)	(0.16)	(1.3)	(5.2)	(2.0)	(5.0)	(6.5)	(126)	(6.36)
	FT	8.34	24.0	0.35	0.99	1.2	13.9	3.3	10.5*	10.4*	235*	8.81*
		(1.97)	(4.2)	(0.06)	(0.16)	(1.5)	(3.7)	(2.4)	(5.1)	(5.8)	(115)	(6.09)

Data are expressed as mean values and standard deviation; *V̇E* minute ventilation; *F* respiratory frequency; *VT* tidal volume; *TI* inspiratory time; *PEEPi,dyn* dynamic intrinsic positive end-expiratory pressure; *Edyn,L* dynamic lung elastance; *RL* lung resistance; R_{TOT} total resistance; *ΔPes,peak* peak esophageal tidal swing; *PTP* pressure time product over one minute; *WI* inspiratory work of breathing over one minute; *PT* pressure-trigger; *FT* flow-trigger

* $= p < 0.05$ FT compared to PT

significantly ($p < 0.05$), by 24% during unsupported SB, and by 15% during CPAP 5 cmH_2O, on average when FT replaced PT. PTP and ẆI decreased significantly ($p < 0.05$), by 27 and 24% during unsupported SB, and by 15 and 14% during CPAP 5 cmH_2O, on average respectively. Application of 5 cmH_2O CPAP did not cause significant change in PTP and ẆI, neither with PT nor with FT. On the overall mean PTP and ẆI decreased almost 30% from SB PT to CPAP 5 cmH_2O FT. Individual and mean values of PTP and ẆI are illustrated in Fig. 2.

Discussion

The results of this study show that during weaning from mechanical ventilation of patients without COPD, the patients' inspiratory effort was significantly lower when FT replaced the traditional PT, as shown by the significant decrease of PTP and ẆI in the absence of significant modifications in the ventilatory pattern and lung mechanics. This was the case during unsupported spontaneous breathing as well as after application of 5 cmH_2O of CPAP. Also Sassoon and colleagues [2] found that ventilatory patterns and lung mechanics were not affected by the triggering system. $PEEP_{i,dyn}$, $E_{dyn,L}$, and R_L did not change when FT replaced PT. In contrast the added resistance due to endotracheal tubes and ventilator circuits (R_{TOT}-R_L) decreased by 37% with FT compared to PT. Since the endotracheal tube was the same, clearly this reduction was entirely due to a decrease in the resistance of ventilator circuits. This changes in the pressure-flow characteristics of the inhalation circuit of the ventilator with FT system, compared to traditional PT, were already pointed out by Sassoon and colleagues [2, 5, 7]. They have shown that the pressure-flow characteristics of the inhalation and exhalation circuits with PT and FT are different. The pressure drop is greater at any given flow with PT than with FT [5]. Sassoon et al. suggested that the difference should essentially reflect a reduction in the pressure required to open the pneumatic valves rather than in the true physical resistance of the circuit [2]. In addition, the patient's earliest demand for flow can be satisfied by

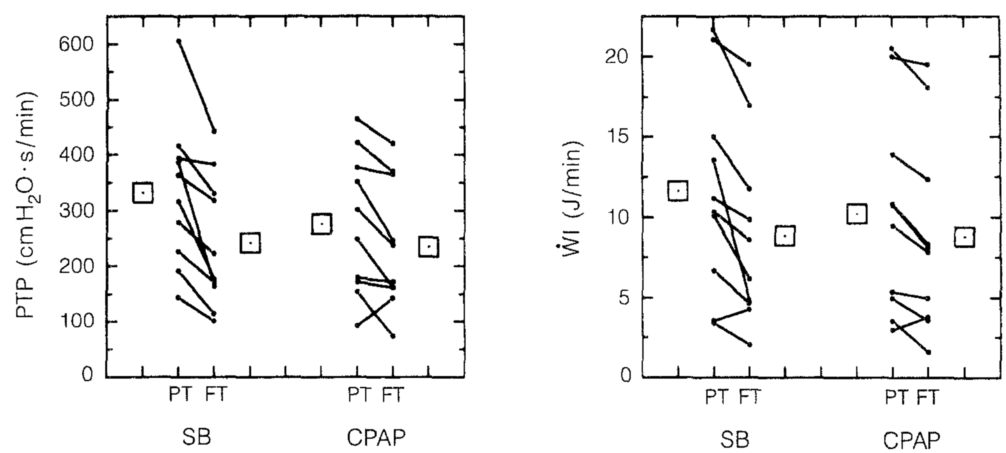

Fig. 2 Individual values (*dots* and *lines*) and mean results (*open squares*) for pressure-trigger (*PT*) and flow-trigger (*FT*) system, during unsupported spontaneous breathing through the ventilator circuit (*SB*), and with 5 cmH_2O of continuous positive airway pressure (CPAP), for pressure time product over one minute (PTP), *left panel*, and inspiratory work of breathing over one minute (*ẆI*), *right panel*, * $= p < 0.05$

the base flow with FT but not, clearly, with PT [7]. It should also be noted in Table 2 that, in the non COPD patients of this study, R_L are only a small portion (slightly >20%) of R_{TOT}, indicating that the additional flow resistance due to endotracheal tubes and ventilator circuits are a substantial component of total flow resistance against which the patient has to breath. Therefore the use of FT, by decreasing significantly the added flow resistance, can help to reduce the unintentional load upon the respiratory muscles in the process of resuming spontaneous ventilation. These results confirm and extend previous work by Sassoon and colleagues who have shown that FT reduced the work of breathing and the inspiratory muscle effort in normals [5] and in COPD patients [1, 2] compared to the traditional PT system. Also, Cox and coworkers [8] demonstrated that, the flow-triggering mode required less inspiratory effort and less inspiratory time delay than conventional PT.

In this study we computed both PTP and $\dot{W}I$ to assess changes in patients' inspiratory effort. Both $\dot{W}I$ and PTP decreased significantly when FT was introduced in the ventilator circuit replacing PT (Fig. 2). We computed both parameters because measurement of work of breathing is widely used while PTP seems to be better correlated to respiratory muscle's oxygen consumption [9]. The decrease in total flow resistance can account for the lower PTP and $\dot{W}I$ when FT replaced PT in the ventilator circuit to trigger lung inflation.

In the patients of this study application of 5 cmH_2O CPAP neither changed lung mechanics, nor determined a significant reduction of $\dot{W}I$ and PTP, though a slight decrease can be observed (Table 2, Fig. 2). These results are clearly different from the results obtained by Petroff and colleagues [10] in COPD patients in whom CPAP counterbalanced intrinsic PEEP. Our results are also different from those reported by Katz and Marks [11] who showed that CPAP reduced total pulmonary power during inspiration while improving oxygen and carbon dioxide exchange in patients with acute respiratory failure. This apparent discrepancy can be due in part to differences in patients populations, for example lung elastance did not change with CPAP in our patients whereas lung compliance increased in those patients [11], and in part to the fact that we did not look at different levels of CPAP to seek for optimal CPAP. Our results are also different from the results by Sassoon and coworkers [1] who found a significant decrease in PTP during FT with application of 5 cmH_2O of CPAP. However in that study [1] patients with COPD were not excluded, such that the reduction in PTP with CPAP 5 could be due to a reduction in $PEEP_i$ as suggested by Petroff [10]. In another study on COPD patients, but with very low values of $PEEP_i$ similar to the values found in our non COPD patients, Sassoon and colleagues [2] failed to find a significant effect of FT versus PT at 8 cmH_2O CPAP on work of breathing. This difference with our results might reflect differences between COPD [2] and non COPD patients with small amount of $PEEP_i$.

In summary, we conclude that FT compared to traditional PT can reduce the unintentional load upon the inspiratory muscles and hence it can be one factor, among others, to help a successful discontinuation from mechanical ventilation in patients with [1, 2] and without COPD (present study).

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