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Effect of low-level PEEP on inspiratory work of breathing in intubated patients, both with healthy lungs and with COPD

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Abstract *Objective:* Evaluation of low-level PEEP (5 cm H_2O) and the two different CPAP trigger modes in the Bennett 7200a ventilator (demand-valve and flow-by trigger modes) on inspiratory work of breathing (W_i) during the weaning phase.
Design: Prospective controlled study.
Setting: The intensive care unit of a university hospital.
Patients: Six intubated patients with normal lung function (NL), ventilated because of non-pulmonary trauma or post-operative stay in the ICU, and six patients recovering from acute respiratory failure due to exacerbation of chronic obstructive pulmonary disease (COPD), breathing either FB-CPAP or DV-CPAP with the Bennett 7200a ventilator.
Interventions: The patients studied were breathing with zero end-expiratory pressure (ZEEP), as well as CPAP of 5 cm H_2O (PEEP), with the following respiratory modes: the demand-valve trigger mode, pressure support of 5 cm H_2O, and the flow-by trigger mode (base flow of 20 l/min and flow trigger of 2 l/min). Furthermore, W_i during T-piece breathing was evaluated.
Measurements and results: W_i was determined using a modified Campbell's diagram. Total inspiratory work (W_i), work against flow-resistive resistance (W_{ires}), work against elastic resistance (W_{iel}), work imposed by the ventilator system (W_{imp}), dynamic intrinsic positive end-expiratory pressure ($PEEP_{idyn}$), airway pressure decrease during beginning inspiration (P_{aw}) and spirometric parameters were measured. In the NL group, only minor, clinically irrelevant changes in the measured variables were detected. In the COPD group, in contrast, PEEP reduced W_i and its components W_{ires} and W_{iel} significantly compared to the corresponding ZEEP settings. This was due mainly to a significant decrease in $PEEP_{idyn}$ when external PEEP was applied. Flow-by imposed less W_i on the COPD patients during PEEP than did demand-valve CPAP. Differences in W_{imp} between the flow-by and demand-valve trigger models were significant for both groups. However, in relation to W_i these differences were small.
Conclusion: We conclude that the application of low-level external PEEP benefits COPD patients because it reduces inspiratory work,

mainly by lowering the inspiratory threshold represented by $PEEP_{idyn}$. Differences between the trigger modes of the ventilator used in this study were small and can be compensated for by the application of a small amount of pressure support.

Key words Work of breathing · Positive pressure respiration methods · Lung diseases · Obstructive therapy · Ventilator weaning · Mechanical ventilation

Introduction

Continuous positive airway pressure (CPAP) is widely used during the weaning phase of mechanically ventilated patients because of its positive effects on respiratory mechanics and gas exchange. The modern, microprocessor-controlled mechanical ventilator Bennett 7200a (Puritan-Bennett, Carlsbad, Calif., USA) offers two different flow-delivery systems for the trigger mechanism of a CPAP mode: a demand valve system (DV-CPAP) and a flow-by system (FB-CPAP). During DV-CPAP, the patient has to generate a negative pressure to open the demand valve, whereas the FB system provides a pre-set base flow. During DV-CPAP, no gas is delivered until the demand valve is opened. This delay in the delivery of gas during DV-CPAP might be shortened by using the pre-set base flow provided by FB-CPAP. In the FB mode, when the patient starts to inhale, the flow in the expiration limb decreases, causing the ventilator to provide a high flow volume of fresh gas. Thus, during FB-CPAP, the decrease in airway pressure at the beginning of inspiration (inspiratory airway pressure drop) should theoretically be less than during DV due to this particular trigger mechanism. Various authors have shown in lung models [1, 2], volunteers [3] and patients [4] that DV-CPAP imposes significantly more work of breathing than the FB mode. However, the performance of DV systems has improved over the past decade and the differences between the amounts of work of breathing imposed by the trigger mechanisms of the DV and FB systems has decreased considerably [1]. Therefore, it seems more important to consider the differences in the lung mechanics of individual patients than those between the trigger mechanisms.

The objective of the present study was to evaluate the effect of low-level external PEEP (5 cm H_2O) on the patient's inspiratory work of breathing (W_i) during the weaning phase. As FB-CPAP is reported to impose less W_i than DV-CPAP [2, 3], we examined patients during both modes. Furthermore, we determined if and to what extent a small pressure support (PS) of 5 cm H_2O added to the DV-CPAP mode compensates for the presumed additional W_i. Two groups of patients were studied: one group with normal lung function (NL) who were being ventilated for non-pulmonary reasons, and another group recovering from acute exacerbation of COPD.

Patients and methods

Twelve long-term intubated patients were studied. In the first group (NL) of six patients with normal lungs, three were recovering from severe head injury, one from multiple trauma and two from major surgery. The second group (COPD) consisted of six patients recovering from acute respiratory failure due to an exacerbation of COPD. COPD was defined by medical history, chronic drug treatment with bronchodilators before admission, and chest X-ray findings. The patients were in a stable condition and in the weaning phase. The patients' characteristics are given in Table 1. Informed consent was obtained from each patient or the next of kin. The study protocol was approved by the ethics committee of our medical faculty.

All experiments were performed with the Bennett 7200a ventilator. Patients were studied in a semirecumbent position of approximately 45°. All patients were able to breathe spontaneously in the CPAP mode for several hours either with DV without pressure support or with FB. Six different ventilatory settings were applied in random order: FB with an external PEEP of 5 cm H_2O (FB_{PEEP}) and with zero end-expiratory pressure (FB_{ZEEP}); DV-CPAP with and without an external PEEP of 5 cm H_2O (DV_{PEEP}, DV_{ZEEP}); pressure support of 5 cm H_2O with and without an external PEEP of 5 cm H_2O (PS_{PEEP}, PS_{ZEEP}). The Bennett 7200a allowed only a demand valve trigger mode during pressure support. Additionally, all patients were studied while breathing through a T-piece.

The oxygen concentration was set to provide arterial oxygen saturation of at least 90%, monitored by continuous pulse oximetry. The resulting FiO_2 was between 0.3 and 0.45. It was not necessary to change FiO_2 during the study. In the DV mode, the trigger sensitivity of the demand valve was set to -1 cm H_2O. During FB, the base flow was set to 20 l/min and trigger sensitivity was determined by a flow trigger of 2 l/min.

Respiratory flow was measured with a heated pneumotachograph (Fleisch No. 2, Fleisch, Lausanne, Switzerland) at the proximal end of the endotracheal tube and connected to a differential pressure transducer. The pneumotachograph was calibrated with the patient's collected expired gas mixture using a motor-driven pump which delivered 1 l of gas with a sinusoidal flow. Airway pressure (P_{aw}) was measured at the same position with another differential pressure transducer (both Fenvyes and Gut, Basel, Switzerland). Oesophageal pressure (P_{es}) was measured using a nasogastric balloon catheter (Mallinckrodt, Argyle, N.Y., USA) connected to a further differential pressure transducer of the same type as described above. The balloon was positioned 2–3 cm above the dome of the diaphragm. The correct balloon position was verified by an occlusion test [5]. When the slope of the P_{es}/P_{aw} curve was different from 1 (range 0.7–1.2 in our patients), P_{es} was corrected, following the suggestion of Brunner et al. [6]. A second occlusion test was

Table 1 Patient characteristics (*NL* group with normal lung function; *COPD* group with chronic obstructive pulmonary disease, FEV_1 forced expired volume in 1 s, *FVC* forced vital capacity, *NA* not available)

No.	Group	Age (years)	Weight/height (kg)/(cm)	Sex	Underlying disease	Chronic drug treatment before admission	FEV_1 (l); FVC (l)	Days on mechanical ventilation before study
1	NL	25	73/180	M	Severe head injury			12
2	NL	69	89/175	F	Rib cage fracture			9
3	NL	80	63/172	F	Orthopaedic surgery			2
4	NL	17	50/163	F	Severe head injury			14
5	NL	48	75/185	M	Severe head injury			20
6	NL	84	77/182	M	Abdominal surgery			3
7	COPD	62	86/171	F	Respiratory tract infection	Beta adrenergics and theophylline	1.54; 2.60	8
8	COPD	63	90/172	M	Respiratory tract infection	Beta adrenergics and topical corticoid	NA	12
9	COPD	80	75/178	M	Laryngeal cancer, post-surgery		1.10; 2.58	7
10	COPD	76	65/169	M	Respiratory tract infection	Beta adrenergics and topical corticoid	0.9; 2.8	9
11	COPD	77	82/174	M	Respiratory tract infection	Beta adrenergics, topical corticoid and theophylline	0.55; 1.36	31
12	COPD	44	98/179	M	Respiratory tract infection	Beta adrenergics and theophylline	NA	15

performed at the end of the measurement period to exclude changes in balloon position which might possibly have influenced the slope of the P_{es}/P_{aw} curve. Data were sampled on-line by an analog-digital converter (DT 2801-A, Data Translation, Marlboro, Mass., USA) at a rate of 20 Hz and processed by an IBM 80386-compatible personal computer. The data acquisition and processing software were programmed with a commercially available software program (ASYST 4.0, Asyst Software Technologies, Rochester, N.Y., USA). The respired volume was obtained by numerical integration of the flow signal and expressed for BTPS conditions. Tidal volume (V_T), minute volume (V_E), respiratory rate (RR) and mean inspiratory and expiratory flow (V_t/T_i and V_t/T_e, respectively) were calculated. Dynamic intrinsic PEEP ($PEEP_{idyn}$) was obtained from oesophageal pressure tracings as the deflection in P_{es} before the initiation of inspiratory flow [7, 8]. $PEEP_{idyn}$ was measured relative to airway pressure rather than ambient pressure. This value was also defined to be the elastic recoil pressure of the chest wall [9] (Fig. 1). Patient's inspiratory work of breathing, W_i, (expressed as mJ/l) was calculated from P_{es}/volume plots according to Campbell's diagram [10]. Since it is still difficult to obtain reliable pressure-volume curves of the chest wall in spontaneously breathing patients during the weaning phase, we assumed chest wall compliance (Ccw) to be within normal values for both the NL and the COPD patients [11] and calculated Ccw, following Agostini and Mead [12], as 4% of vital capacity per cm H_2O. Values for vital capacity were taken from the literature [13] and extrapolated for age. For calculation of W_i, the Ccw line was passed through the end-expiratory elastic recoil pressure point of the chest wall at functional residual capacity (R; see Fig. 1) [14]. For DV and FB settings, total inspiratory work was separated into work to overcome elastic forces (W_{iel}) and work to overcome the flow-resistive properties of airways, lung tissue and the ventilator system (W_{ires}), according to Campbell's diagram (Fig. 1a). This differentiation seems somewhat arbitrary during PS, when P_{es} alone is no longer an estimate of transpulmonary pressure. Thus, with the aim of learning more about the influence of PS on the lungs themselves, we also calculated work imposed on the lungs (lung work, W_L) by transpulmonary pressure (P_{tp}), i.e. the difference between P_{es} and P_{aw}. W_L was calculated by planimetry from the difference in P_{tp} between inspiration and expiration at the instant of zero flow and V_T according to Katz [16]. W_{ires} includes work imposed by the ventilator system (W_{imp}). This particular component was also measured directly by calculating it from P_{aw}/V tracings when P_{aw} was less than PEEP [2, 15] (Fig. 1b). One should keep in mind that W_{imp} is a component of W_i that corresponds to the work done on the ventilator, and is not a quantity to be added to W_i.

Measurements of each ventilatory setting were taken for at least 5 min after a steady pattern of respiration had been achieved. All variables were calculated as the average of 5 min per ventilator setting after exclusion of artefacts such as swallowing or coughing.

Two-way analysis of variance (ANOVA) was used for statistical analysis, followed by post hoc testing of least significant difference between means for multiple comparisons. Probability values less than 0.05 were considered as significant.

Results

Work of breathing

W_i was always higher ($P < 0.05$) in the COPD group than in the group with normal lungs (126% to 173% for the corresponding settings; see Fig. 2). It was a general observation that W_i was lower during breathing with PEEP than with the corresponding ZEEP settings

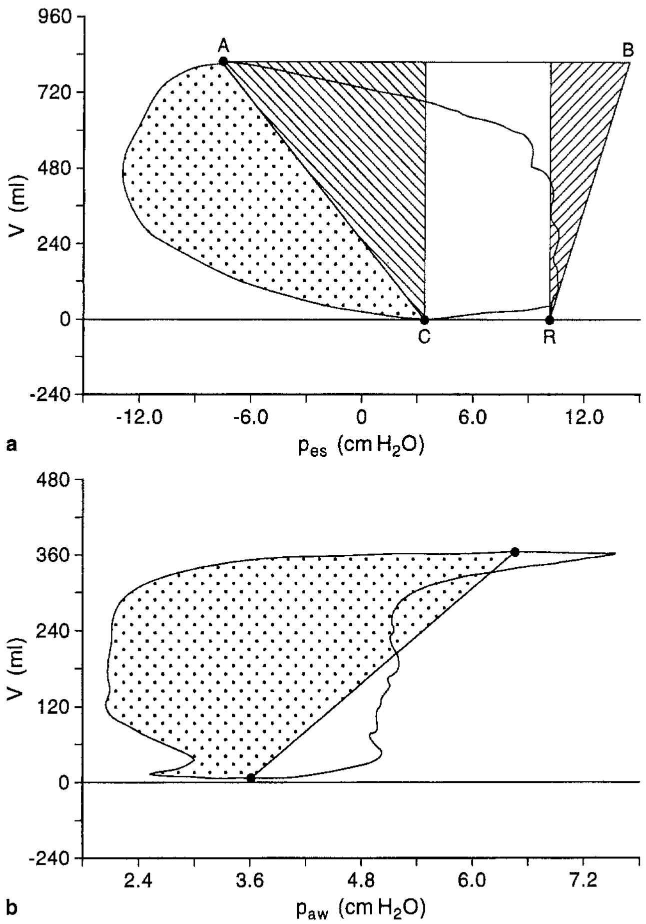

Fig. 1 a Modified Campbell's diagram. *Dotted area* work done against flow-resistive loads of lungs and ventilator system, *hatched area* work done against elastic forces of lungs, *obliquely hatched area* work against elastic forces of chest wall, *white area* work due to intrinsic PEEP and trigger sensitivity; *area ABRC* includes all components of work against elastic forces. The line of chest wall compliance is passed through the point of end-expiratory recoil pressure (*R*). R was defined as the deflection in the P_{es} tracing before initiation of inspiratory flow. (Original registration from patient 8: FB_{ZEEP}; $PEEP_{idyn}$ 6.3 cm H_2O; predicted chest wall compliance 203 ml/cm H_2O; W_i = 2271 mJ/l). **b** P_{aw}/volume plot. *Dotted area* work imposed (W_{imp}) by the ventilator system. The patient has to generate a P_{aw} below the applied external PEEP throughout the whole inspiratory cycle to maintain airflow. (Original registration from patient 9: DV_{PEEP}; W_{imp} = 257 mJ/l)

(Fig. 2). However, in the NL group, these differences were small and clinically irrelevant.

In the COPD group, we always observed a significant decrease in total W_i, as well as in both of its components, W_{ires} and W_{iel}, during breathing with PEEP compared to the corresponding ZEEP settings and T-piece breathing (Fig. 2a–c). W_i was comparable between DV_{PEEP} and PS_{ZEEP}. W_i during DV_{PEEP} was lower than W_i during FB_{ZEEP} and DV_{ZEEP}. On the other hand, PS_{ZEEP} did not reduce W_i compared to FB_{ZEEP} and DV_{ZEEP}. W_i during T-piece breathing was comparable to that during FB_{ZEEP} and DV_{ZEEP}, but W_{ires} was even lower.

In the COPD group, W_L was significantly reduced whenever external PEEP was applied. No differences in W_L were observed among PS, FB and DV. In the NL group, PS_{PEEP} caused a significantly higher W_L than DV_{PEEP} (Fig. 2d). This might be explained by the small increase in V_t (not significant) during PS (Table 2).

Differences in W_i and W_{ires} between the two trigger modes FB and DV were observed only in the COPD group. During FB_{PEEP}, total W_i was lower than during DV_{PEEP} but similar to PS_{PEEP} (Fig. 2a). W_{ires} was lower during FB than during DV for PEEP and ZEEP settings (Fig. 2c). In W_{iel}, we observed no differences between FB and DV.

W_{imp} was significantly less during FB mode in comparison with DV mode for both CPAP levels (Fig. 3). However, the changes observed were small in relation to the total inspiratory workload (W_i). During PS, W_{imp} was similar to FB or even less. There was no difference in W_{imp} between the two groups of patients for all settings. This indicates that changes in W_{imp} must be related to the ventilatory setting or the trigger mode rather than to differences in lung mechanics.

Spirometric variables

Changes in RR and V_t were small in all our patients. Whereas no differences of clinical relevance could be observed in the NL group, the COPD patients generally had a slightly lower respiratory rate during breathing with PEEP. Again, V_t was only slightly increased by an external PEEP during PS (PS_{PEEP} vs PS_{ZEEP}). However, the observed changes in RR and V_t were small, exceeding 10% in only three patients (see Table 2 for details). V_t/T_i and V_t/T_e remained nearly constant for all settings.

During ZEEP, the mean end-expiratory airway pressure was significantly higher during FB than during DV for both groups (1.3 ± 0.7 vs 0.3 ± 0.5 respectively; $P < 0.001$). This means that there is an inherent external PEEP during FB. Also during PEEP of 5 cm H_2O, we observed higher mean end-expiratory airway pressure with FB than with DV (6.0 ± 0.5 vs 4.8 ± 0.4, respectively; $P < 0.001$). The decrease in P_{aw} at the beginning of inspiration was always greater for DV than for FB (2.2 ± 1.0 vs 1.8 ± 0.7 for PEEP, 2.7 ± 1.4 vs 2.0 ± 0.9 for ZEEP), but the difference was significant only for the ZEEP settings ($P < 0.01$).

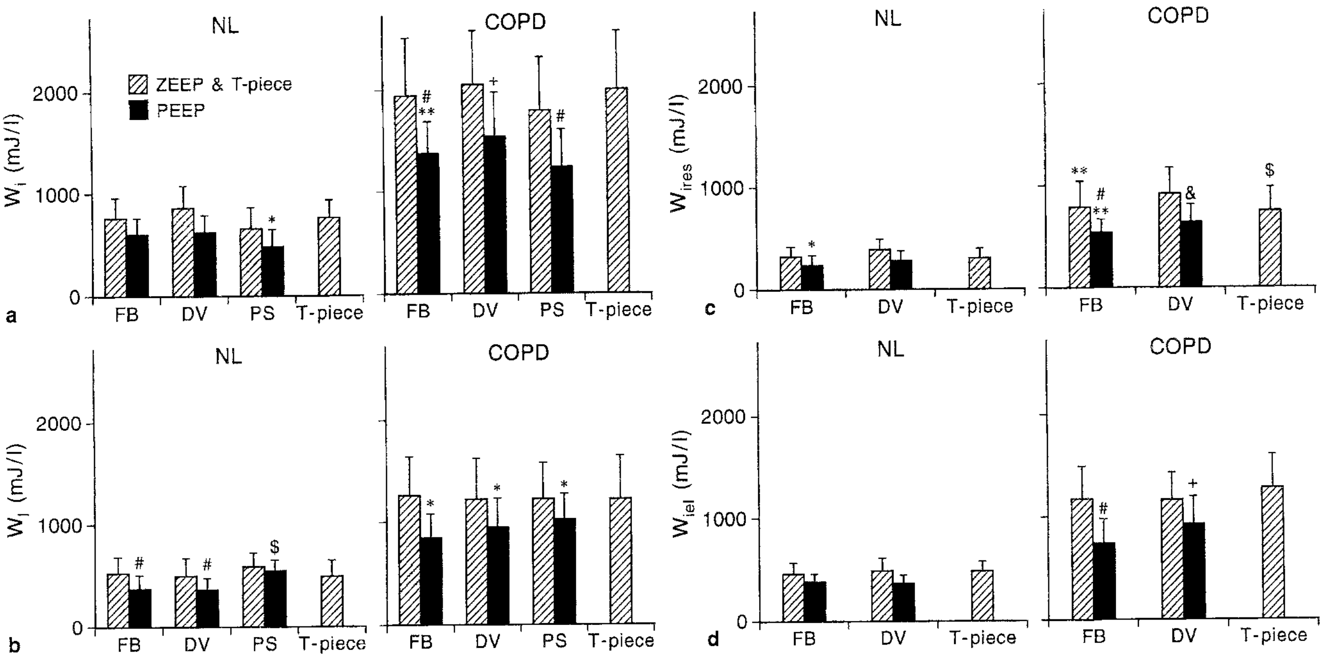

Fig. 2 a-d Work of breathing during the different ventilatory settings. Values are given as mean and standard error. *NL* Patient group with normal lung function, *COPD* patient group with chronic obstructive pulmonary disease, *ZEEP* zero end-expiratory pressure, *PEEP* end-expiratory pressure of 5 cm H_2O, *FB* flow-by, *DV* demand valve, *PS* pressure support of 5 cm H_2O. **a** Total inspiratory work (W_i): * $P < 0.05$ (PS_{PEEP} vs FB_{ZEEP}, DV_{ZEEP} and T-piece), ** $P < 0.05$ (FB_{PEEP} vs DV_{PEEP}), # $P < 0.005$ (PS_{PEEP} and FB_{PEEP} vs all ZEEP settings), + $P < 0.05$ (DV_{PEEP} vs FB_{ZEEP}, DV_{ZEEP} and T-piece). **b** Work done on the lungs (W_L): $ $P < 0.05$ (DV_{PEEP} vs PS_{PEEP}), # $P < 0.05$ (FB_{PEEP} and DV_{PEEP} vs PS_{ZEEP}), * $P < 0.01$ (all settings with PEEP vs corresponding ZEEP settings). **c** Inspiratory work against flow-resistive resistance (W_{ires}): * $P < 0.05$ (FB_{PEEP} vs DV_{ZEEP} and T-piece), ** $P < 0.05$ (FB_{PEEP} vs DV_{PEEP}, FB_{ZEEP} vs DV_{ZEEP}), # $P < 0.005$ (FB_{PEEP} vs all ZEEP settings, T-piece), & $P < 0.001$ (DV_{PEEP} vs DV_{ZEEP}), $ $P < 0.001$ (T-piece vs DV_{ZEEP}). **d** Inspiratory work against elastic resistance (W_{iel}): # $P < 0.001$ (FB_{PEEP} vs all ZEEP settings), + $P < 0.01$ (DV_{PEEP} vs FB_{ZEEP}, DV_{ZEEP} and T-piece)

$PEEP_{idyn}$ was generally low even in the COPD patients (mean during T-piece breathing 2.9 cm H_2O, range 0.6–6.3). It was greater than 5 cm H_2O in only two patients (patients 8 and 11, see Table 1). In these two patients, $PEEP_{idyn}$ decreased from 5.8 to 3.5 cm H_2O and from 6.3 to 4.2 cm H_2O, respectively, during breathing with PEEP of 5 cm H_2O. $PEEP_{idyn}$ in the COPD group was significantly lower during all settings with external PEEP than with ZEEP. In contrast, no significant changes were observed in the NL group.

Discussion

The results of our study seem to indicate that an external PEEP of 5 cm H_2O is a more important factor in reducing the patients' inspiratory workload than the differences in the particular trigger modes of the ventilator used in this study. Although the different trigger modes also contribute to reducing components of W_i, as was shown by analysing W_{imp}, this did not result in reduced W_i to the same extent as did the external PEEP. The small difference between the different trigger modes in total W_i disappeared completely when no external PEEP was applied. A small pressure support may reduce W_i when used in combination with PEEP, whereas a PS of 5 cm H_2O without PEEP seems to be less effective than PEEP alone. This is indicated by the finding that in the COPD group, W_i during PS_{ZEEP} was different neither from DV_{PEEP} nor from DV_{ZEEP} and FB_{ZEEP}, whereas W_i was reduced during DV_{PEEP} in comparison with both DV_{ZEEP} and FB_{ZEEP}. All effects were pronounced in the COPD patients, whereas the patients with normal lungs showed few significant differences and none that were clinically relevant. A difference in W_i between FB and DV was observed only in the COPD group. Only for W_{imp} could differences be detected in the NL group.

PEEP may be beneficial for patients with acute lung injury not only because of alveolar recruitment, but also because it reduces their inspiratory work of breathing. Katz and coworkers [16] studied patients

Table 2a, b Spirometric data. **a** Patients with normal lungs; **b** patients with chronic obstructive pulmonary disease. Values are given as mean and standard deviation (*SD*) *RR* Respiratory rate, *Vt* tidal volume, $PEEP_{idyn}$ dynamic intrinsic PEEP, *PEEPe* external PEEP of 5 cm H_2O. Significant differences ($P < 0.05$, ANOVA and post-hoc test): *a* FB_{PEEP} vs FB_{ZEEP}, *b* FB_{PEEP} vs DV_{ZEEP}, *c* FB_{PEEP} vs PS_{ZEEP}, *d* FB_{PEEP} vs T-piece, *e* DV_{PEEP} vs T-piece, *f* DV_{ZEEP} vs T-piece, *g* PS_{PEEP} vs PS_{ZEEP}, *h* PS_{PEEP} vs FB_{ZEEP}, PS_{PEEP} vs DV_{ZEEP}, *j;i* PS_{PEEP} vs T-piece, *k* PS_{ZEEP} vs DV_{ZEEP}, *l* PS_{ZEEP} vs T-piece, *NS* not significant

a

Ventilator mode	Flow-by		Demand valve		Pressure support		T-piece	$P < 0.05$
PEEP (cm H_2O)	0	5	0	5	0	5		
RR (min^{-1})								
Mean	29	26	28	26	28	27	30	a-d; h
SD	5	5	7	6	7	5	7	
Vt (ml)								
Mean	442	431	455	421	461	469	439	NS
SD	92	75	54	50	51	69	34	
$PEEP_{idyn}$ (cm H_2O)								
Mean	1.0	0.7	1.3	0.8	1.4	0.8	1.3	NS
SD	0.7	0.6	1.0	0.7	0.9	0.7	1.3	

b

Ventilator mode	Flow-by		Demand valve		Pressure support		T-piece	$P < 0.05$
PEEP (cm H_2O)	0	5	0	5	0	5		
RR (min^{-1})								
Mean	26	25	25	25	25	23	27	a ; d-j; l
SD	8	7	7	7	8	7	6	
Vt (ml)								
Mean	458	499	450	491	504	538	444	d; f-h; i; k; l
SD	194	199	199	208	229	241	189	
$PEEP_{idyn}$ (cm H_2O)								
Mean	2.9	1.6	2.9	2.1	3.0	1.9	2.9	All PEEPe
SD	2.7	1.3	2.4	2.0	2.4	1.8	2.5	vs ZEEP

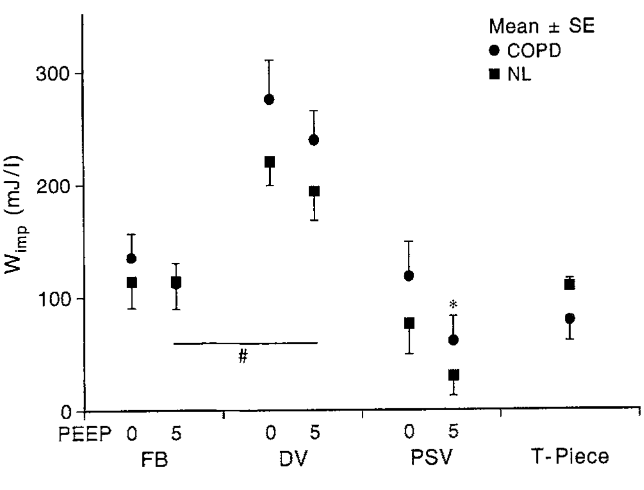

Fig. 3 Additional work on ventilator system (W_{imp}): values given as mean ± standard error. *NL* Patient group with normal lung function, *COPD* patient group with chronic obstructive pulmonary disease. # $P < 0.001$ (FB vs DV for PEEP and ZEEP), * $P < 0.005$ (PS_{PEEP} vs FB_{PEEP})

recovering from acute respiratory failure due to trauma, laparotomy, severe head injury or pulmonary oedema. They found a decrease mainly in the flow-resistive component of inspiratory work when low levels of PEEP were applied and related this to an increase in effective compliance, which represents both the resistive and the elastic forces expended to inflate the lung. Although no significant changes in W_{iel} were seen, the authors argued that an increase in compliance, which would have caused a decrease in W_{iel}, was offset by an increase of V_t [16].

In COPD patients, it was demonstrated by Petrof and coworkers that increasing PEEP mainly reduces the elastic component of W_i [7]. This was related to a decrease in intrinsic positive end-expiratory pressure ($PEEP_i$). The patients in their study had a mean $PEEP_{idyn}$ of 4.2 ± 0.6 cm H_2O. $PEEP_{idyn}$ represents the lowest level of positive alveolar pressure (P_{alv}) at end-expiration [8, 17]. Higher intrinsic PEEP in other parts of the lung may still lead to a regional redistribution at the onset of a patient's inspiratory effort. A low level of external PEEP counterbalances the end-expiratory positive recoil pressure due to hyperinflated areas of the lungs by reducing the downstream pressure gradient [18]. Thus, it reduces the inspiratory threshold load caused by $PEEP_i$. The effective sensitivity to trigger the ventilator is determined by the sum of intrinsic PEEP and the pre-set trigger level at the ventilator. Thus, the application of a low level of external PEEP (below the level of the intrinsic PEEP to avoid further increases in P_{alv}) [19], leads to a decrease in elastic work, i.e. that component of W_{iel} that is necessary to trigger the ventilator (see Fig. 1).

In our patients – mainly in the COPD group – we observed a significant but similar decrease in both partitions of W_i during all ventilatory settings with PEEP. The smaller change in W_{el} relative to W_{ires} than in Petrof et al.'s patients [7] may be related to an occult pressure support during DV as well as FB, indicated by a positive elastic work done by the ventilator which could be observed by analysing the P_{aw}/volume plots (Fig. 1b). This effect has also been found by other authors [2, 4]. Our COPD patients had a lower $PEEP_{idyn}$ level than was reported by Petrof and coworkers. However, $PEEP_{idyn}$ during ZEEP settings was significantly higher than during settings with PEEP. Therefore, the part of W_i done due to intrinsic PEEP and trigger sensitivity (part of W_{iel}) was less during settings with PEEP. Since $PEEP_{idyn}$ represents only the minimal intrinsic PEEP and flow limitation in other parts of the lungs can still be present at the onset of inspiratory flow, it is likely that in our patients, the observed differences in W_i were related in part to the same mechanisms as reported by Petrof and colleagues and discussed above.

However, a positive end-expiratory pressure represents $PEEP_{idyn}$ only when expiratory muscle activity is absent. Expiratory muscle activity could be excluded by measurement of gastric pressure, which was not performed in our study. Since we could not completely exclude expiratory muscle activity, a second calculation of W_i was performed assuming the extreme case that all measured $PEEP_{idyn}$ in our patients would have been positive gastric pressure due to active expiration. For this, the influence of $PEEP_{idyn}$ was excluded by setting the elastic recoil pressure of the lung and the chest wall at identical levels (see Fig. 1: R was set at the same level as C, resulting in exclusion of the work done due to $PEEP_{idyn}$ (this corresponds to the white area in the modified Campbell's diagram). Even with these extreme assumptions, identical significant differences for W_i were found between corresponding ventilatory settings with and without external PEEP (data not shown). This indicates that the application of a low level of external PEEP of 5 cm H_2O was nevertheless of benefit for COPD patients regarding W_i.

It was consistently observed in the COPD group that W_{ires} was lowered by application of a PEEP of 5 cm H_2O during both CPAP modes (i.e. DV and FB). In the NL group, we observed the same tendencies for W_{ires}. Thus, significant differences in the flow resistive components of work of breathing W_{ires} were mainly due to the external PEEP and not to the different trigger modes. This may indicate a decrease in pulmonary resistance by PEEP. The reason for this might be that external PEEP dilates and stabilises flow-limited airways, as suggested by Smith and Marini [20], leading to a decrease in patients' work of breathing. Additionally, a decrease in the oesophageal pressure-time product during application of a PEEP of 5 cm H_2O was described by Sassoon and coworkers [21] and explained by a decrease in pulmonary resistance due to external PEEP.

We observed differences in total W_i between FB and DV only in the COPD group. The COPD patients had a significantly higher total workload during DV_{PEEP} compared to FB_{PEEP}. Without PEEP, this difference was only visible in W_{ires}. Recently, Sassoon et al. [4] compared the effects of DV-CPAP and FB-CPAP on a Bennett 7200a and a conventional continuous-flow (CF) system on W_i in nine intubated patients with COPD. They demonstrated that DV imposes a significantly higher workload than the FB and CF systems. In their study, FB was set at a base flow of 10 l/min. Two years earlier, the same group had demonstrated a significant difference in healthy volunteers between DV and FB with 5 l/min of base flow at a CPAP level of 5 cm H_2O [3], whereas FB with 20 l/min of base flow was not significantly different from DV at this CPAP level. Likewise, Vallverdú and coworkers [22] showed that the higher the base flow, the higher W_i might be. Moran et al. confirmed this effect in a lung model [2]. Also, Sassoon et al. [3] found a higher end-expiratory airway pressure during FB (base flow 20 l/min) than during FB (base flow 5 l/min), and thus a greater drop in P_{aw} at the onset of inspiration for FB (base flow 20 l/min). This airway pressure drop was pronounced during ZEEP and may be an explanation for the tendency toward higher W_i during high base flows [3]. The fact that we saw less pronounced differences in W_i between FB and DV settings in our patients than did others might have been due to the selected base flow of 20 l/min in our study. End-expiratory airway pressure was significantly higher in our patients during FB compared to DV, independent of the applied PEEP, whereas the inspiratory airway pressure drop between FB and DV differed only during ZEEP. It is possible that the higher effective PEEP during FB_{PEEP} contributed to a reduction in total W_i in the COPD patients by narrowing the pressure gradient from the alveolus to the airway opening as described above. On the other hand, it did not reduce the drop in P_{aw} during the respective PEEP settings and, hence, total W_i in patients with normal lungs. Therefore, only in COPD patients could a difference between FB and DV in total W_i be detected when an external PEEP was applied. This difference might thus be regarded as an effect of PEEP rather than of the trigger mechanism. During ZEEP, this effect in W_i was masked by the higher workload due to the higher $PEEP_{idyn}$. Nevertheless, since the level of base flow seems to influence W_i significantly, further studies are recommended to evaluate the optimal level of base flow.

Differences in W_{ires} between FB and DV were seen during PEEP as well as during ZEEP and might be attributed to the ventilator tubes and valve system, since W_{ires} includes W_{imp}. Analysing W_{imp}, we found significant differences between DV and FB for both PEEP levels and in both groups of patients. These differences might have been due to the high resistance of the DV circuit compared to FB, as described by Sassoon et al. [3], and to the quality of synchronisation between the patient and the ventilator. However, in relation to the total inspiratory work, these differences were minor.

Pressure support is known to reduce W_i [23, 9, 24]. It increases V_t, decreases RR and leads to a better synchronisation of patient and machine. The small PS of 5 cm H_2O used in our study tended, indeed, to improve those variables in certain cases compared to DV. W_L did not differ between the PS and DV or FB in our COPD patients but was significantly reduced by the application of PEEP compared to the corresponding ZEEP settings. This indicates that external PEEP directly alters pulmonary mechanics, whereas a low level of pressure support helps to overcome external resistance, such as from the endotracheal tube, but apparently has less direct effect on the lungs.

In conclusion, the results of our study suggest that a small PEEP should be applied during the weaning trial even for patients with airflow limitation, e.g. COPD. A small external PEEP level may reduce W_i, and it may counterbalance some of the adverse effects of $PEEP_i$ by minimising the threshold load on inspiratory muscles. It may also stabilise small airways. Our results do not imply a general superiority of either FB_{PEEP}, DV_{PEEP} or PS mode, but each may improve the breathing workload of certain patients. The differences in W_i in our patients with normal lungs were small and without clinical relevance. Thus, it cannot be concluded from this study that PEEP has any beneficial effects on W_i in patients with normal lungs.

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References

1. Samodelov LF, Falke KJ (1988) Total inspiratory work with modern demand valve devices compared to continuous flow CPAP. Intensive Care Med 14: 632–639
2. Moran JL, Homan S, O'Fathartaigh M, Jackson M, Leppard P (1992) Inspiratory work imposed by continuous positive airway pressure (CPAP) machines: the effect of CPAP level and endotracheal tube size. Intensive Care Med 18: 148–154
3. Sassoon CSH, Giron AE, Ely EA, Light RW (1989) Inspiratory work of breathing on flow-by and demand-flow continuous positive airway pressure. Crit Care Med 17: 1108–1114
4. Sassoon CSH, Lodia R, Rheeman CH, Kuei JH, Light RW, Mahutte CK (1992) Inspiratory muscle work of breathing during flow-by, demand-flow, and continuous-flow systems in patients with chronic obstructive pulmonary disease. Am Rev Respir Dis 145: 1219–1222
5. Baydur A, Behrakis PK, Zin WA, Jaeger M, Milic-Emili J (1982) A simple method for assessing the validity of the oesophageal balloon technique. Am Rev Respir Dis 126: 788–791
6. Brunner JX, Wolff G (1988) Pulmonary function indices in critical care patients. Springer, Berlin Heidelberg New York, pp 118–121
7. Petrof BJ, Legar M, Goldberg P, Milic-Emili J, Gottfried SB (1990) Continuous positive airway pressure reduces work of breathing and dyspnea during weaning from mechanical ventilation in severe chronic obstructive pulmonary disease. Am Rev Respir Dis 141: 281–289
8. Marini JJ (1988) Monitoring during mechanical ventilation. Clin Chest Med 9: 73–100
9. Brochard L, Harf A, Lorino H, Lemaire F (1989) Inspiratory pressure support prevents diaphragmatic fatigue during weaning from mechanical ventilation. Am Rev Respir Dis 139: 513–521
10. Agostini E, Campbell EJM, Freedman S (1970) Energetics. In: Campbell EJM, Agostini E, Newsom Davis J (eds) The respiratory muscles. Lloyd-Luke, London, pp 115–124
11. Sharp JT, Van Lith P, Briney R, Johnson FN (1968) The thorax in chronic obstructive lung disease. Am J Med 44: 39–46
12. Agostini E, Mead J (1964) Statics of the respiratory system. In: Handbook of physiology, sect 3, vol 1. American Physiological Society; Washington, DC pp 387–409
13. Quanjer P (1983) Standardised lung function testing. Bull Eur Physiopathol Respir 19 [Suppl 5]: 1–95

14. Fleury B, Murciano D, Talamo C, Aubier M, Pariente R, Milic-Emili J (1985) Work of breathing in patients with chronic obstructive pulmonary disease in acute respiratory failure. Am Rev Respir Dis 131: 822–827
15. Katz JA, Kraemer RW, Gjerde GE (1985) Inspiratory work and airway pressure with continuous positive airway pressure delivery systems. Chest 88: 519–526
16. Katz JA, Marks JD (1985) Inspiratory work with and without continuous positive airway pressure in patients with acute respiratory failure. Anesthesiology 63: 598–607
17. Haluszka J, Chartrand DA, Grassino AE, Milic-Emili J (1990) Intrinsic PEEP and arterial PCO_2 in stable patients with chronic obstructive pulmonary disease. Am Rev Respir Dis 141: 1194–1197
18. Marini JJ (1989) Should PEEP be used in airflow obstruction? (editorial) Am Rev Respir Dis 140: 1–3
19. Tan IKS, Bhatt SB, Tam YH, Oh TE (1993) Effects of PEEP on dynamic hyperinflation in patients with airflow limitation. Br J Anaesth 70: 267–272
20. Smith TC, Marini JJ (1988) Impact of PEEP on lung mechanics and work of breathing in severe airflow obstruction. J Appl Physiol 65: 1488–1499
21. Sassoon CSH, Light RW, Lodia R, Sieck GC, Mahutte CK (1991) Pressure-time product during continuous positive airway pressure, pressure support ventilation, and t-piece breathing during weaning from mechanical ventilation. Am Rev Respir Dis 143: 496–475
22. Vallverdú I, Ortiz A, Bak E, Net A, Benito S, Mancebo J (1993) Effects of demand valve continuous positive airway pressure (CPAP) and flow-by CPAP during weaning from mechanical ventilation. Intensive Care Med 18 [Suppl 2]: S64
23. Brochard L, Pluskwa F, Lemaire F (1987) Improved efficacy of spontaneous breathing with inspiratory pressure support. Am Rev Respir Dis 136: 411–415
24. Tokioka H, Saito S, Kosaka F (1989) Effect of pressure support ventilation on breathing patterns and respiratory work. Intensive Care Med 15: 491–494