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Inspiratory Pressure Support Compensates for the Additional Work of Breathing Caused by the Endotracheal Tube

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Breathing through an endotracheal tube and a demand valve may increase the work performed by the respiratory muscles. Inspiratory pressure support (PS) is known to reduce this work and might therefore compensate for this increased requirement. To test this hypothesis, we measured the work of breathing (WOB) in 11 patients whose tracheas were intubated. Five had no intrinsic lung disease, but six had chronic obstructive lung disease. We compared WOB measurements taken under several sets of conditions: during assisted breathing at four levels of PS, during unassisted breathing and connection to a T-piece, and after extubation of the trachea. During unassisted breathing *via* the ventilator circuit (PS set at 0 cmH20), the WOB per minute was greater than that after extubation, with a mean increase (± standard deviation) of 68 ± 38% (10.3 ± 5.1 *vs.* 6.5 ± 3.7 $J \cdot min^{-1}$, $P < 0.01$). While breathing through the T-piece, the WOB was 27 ± 18% greater than after tracheal extubation (8.2 ± 5.1 *vs.* 6.5 ± 3.7 $J \cdot min^{-1}$, $P < 0.05$). The principal reason why inspiratory work decreased after extubation was that the ventilatory requirement decreased. For each patient, we determined retrospectively, after extubation, the level of PS that had reduced WOB to its postextubation value and obtained levels ranging from 3.4 to 14.4 cmH_2O. The PS level at which additional WOB was compensated for, was greater in patients with chronic lung disease than in those free of lung disease (12.0 ± 1.9 *vs.* 5.7 ± 1.5 cm H_2O, $P < 0.05$). These results suggest that PS can be used to compensate for the additional WOB caused by the endotracheal tube and demand valve but that pressure requirements differs substantially among patients, depending on the presence or absence of respiratory disease.

(Key words: Chronic obstructive pulmonary disease: work of breathing. Ventilation, mechanical: pressure support.

INABILITY TO BE SEPARATED from mechanical ventilation has been reported to occur in 20 to 50% of patients whose lungs are ventilated because of acute respiratory failure.[1–3] During the period of disconnection from the ventilator, excessive work of breathing may lead to diaphragmatic fatigue, and hence the patient's inability to tolerate the discontinuation of mechanical ventilation.[3–5] Several modes of ventilatory support allowing spontaneous breathing, such as intermittent mandatory ventilation or continuous positive airway pressure,[6] have been recommended for use with such patients. With unassisted breathing and the former mode, or spontaneous breathing and the latter using a ventilator circuit, the demand valve and tubings constitute an additional load for the respiratory muscles.[7–14] Similarly, during periods of breathing through an endotracheal tube and T-piece the endotracheal tube may also create additional resistance to breathing,[15–20] although this has never been quantified in patients.

Inspiratory pressure support (PS) is a form of partial ventilatory support in which each spontaneous breath is assisted to an extent that depends on the level of constant pressure applied during inspiration.[4,21–22] Both the work of breathing and the oxygen cost of breathing diminish when PS is applied.[4,21–22] The level of PS required to compensate for the added inspiratory work of breathing caused by endotracheal tube resistance and a ventilator demand valve system was recently evaluated in a mechanical model.[23] In this study, we assumed that for each individual, an adequate level of PS compensated for the additional work of breathing caused by the ventilator circuit and endotracheal tube. Knowledge of the usual range of PS required to compensate for this additional work would be of interest for the management of patients in whom separation from mechanical ventilation is in progress, because it might help predict the patient's ability to tolerate extubation without having to disconnect the endotracheal tube from the ventilator.

The aims of this study were:

1. to quantify the additional work of breathing due to the ventilator tubing and valves and that due to the endotracheal tube, by comparing the values obtained before and after tracheal extubation, and
2. to determine, after extubation, the range of PS that had been necessary to compensate for this additional work, in a group of patients without previous lung disease and a group with chronic lung disease.

Materials and Methods

PATIENTS

Eleven patients requiring mechanical ventilation were studied. In patients 1–6 (group A), acute respiratory failure was accompanied by chronic lung disease. Patients 7–11 (group B) were free of preexisting lung disease but required mechanical ventilation for a variety of reasons.

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For other patient characteristics, see table 1. The mean duration of tracheal intubation (± standard deviation) was 9.9 days (± 9.6 days). All patients were studied on the day of tracheal extubation. All had given their informed consent to participate in the study, which had been approved by the Ethics Committee for Research of our university (Université Paris XII).

MEASUREMENTS

Air flow was recorded from a Fleisch number-1 pneumotachograph connected to a differential pressure transducer (Validyne MP45, ± 2 cmH_2O). The flow signal was integrated to yield tidal volume (V_T).

While the trachea was still intubated, the pneumotachograph was inserted between the endotracheal tube and the Y-piece of the ventilator. After extubation, the pneumotachograph was connected to a rubber mouthpiece, and the subject was fitted with a nose clip and asked to breathe *via* this mouthpiece. Airway pressure was measured at the mouth, using a differential pressure transducer (Sensym SDX001, ± 70 cmH_2O).

Esophageal pressure (P_{es}) was recorded using a balloon catheter connected to a differential pressure transducer (Validyne MP, 45 ± 50 cmH_2O). The validity of the P_{es} measurements was checked by the occlusion technique.[24]

All signals were sampled and digitized at 32 Hz, and the data were entered into an Apple IIe microcomputer. V_T, respiratory rate, and minute ventilation were obtained from the flow signal. The work of breathing per breath was computed from P_{es}/V_T loops and was expressed either as power of breathing (joules per minute) or as work per liter of ventilation (joules per liter). The inspiratory work of breathing per breath was computed according to the following principles.

Work per breath was calculated from the diagram of Campbell, by computing the area under the inspiratory P_{es}/V_T curve and that under the static P_{es}/V_T curve of the chest wall.[25] The P_{es} values at zero-flow points were considered as the beginning and end of inspiration. The theoretical value for chest wall compliance, which is 4% of the predicted value of the vital capacity per centimeter of water, was used to trace the static P_{es}/V_T curve for the chest wall.[26] Some degree of error in estimating chest wall compliance probably occurs in certain patients when estimation is based on this theoretical value. This error, however, is the same when different periods are compared and does not invalidate comparisons. The P_{es}/V_T curve was superimposed on the complete diagram, assuming that the end-expiratory elastic recoil pressure of the chest wall was equivalent to the P_{es} level at the beginning of inspiratory effort. The onset of effort was taken as the beginning of the negative deflection of the P_{es} curve. Any difference between this initial P_{es} level and the zero-flow point indicated the presence of end-expiratory positive alveolar pressure (fig. 1), and the value indicating this difference was referred to as intrinsic positive end-expiratory pressure (intrinsic PEEP).[27–30] The presence of intrinsic PEEP implies that the inspiratory muscles must generate sufficient force to counteract the opposing positive recoil pressure before inspiratory flow begins, and it therefore acts as an inspiratory threshold load. Because the static chest wall line is displaced from the zero-flow point, the presence of intrinsic PEEP increases the area enclosed in the Campbell diagram, and increases the work of breathing.

The power of breathing (joules per minute) was obtained by multiplying the mean work per breath by the respiratory rate. Power divided by minute ventilation yielded the work per liter of ventilation (joules per liter). Five to 30 breaths were necessary to compute average values, depending on breath-to-breath variability.

LUNG MECHANICS

Lung and airway resistance and dynamic lung compliance were calculated during the two periods of unassisted spontaneous breathing before and after tracheal extu-

TABLE 1. Patient Characteristics

Patient	Age (yr)	Sex	Duration of ventilation (days)	Pa_{O_2} (mmHg)	FI_{O_2}	Diagnosis
1	81	F	5	104	0.50	COPD, congestive heart failure
2	50	M	13	96	0.40	Bilateral pneumonia degenerative encephalopathy
3	80	M	3	140	0.40	COPD, vascular surgery
4	56	M	3	129	0.35	COPD, vascular surgery
5	76	F	24	111	0.50	COPD, congestive heart failure
6	78	F	28	97	0.50	Chronic asthma, bacterial pneumonia
7	80	M	3	125	0.40	Abdominal surgery
8	61	M	1	99	0.30	Drug overdose
9	64	F	14	165	0.50	Cardiac surgery (endocarditis)
10	16	M	1	99	0.35	Drug overdose
11	48	M	3	88	0.30	Bacterial meningitis

Shown are values of arterial oxygen tension (Pa_{O_2}) and fractional inspired oxygen concentration (FI_{O_2}) during mechanical ventilation before extubation.

COPD = chronic obstructive pulmonary disease.

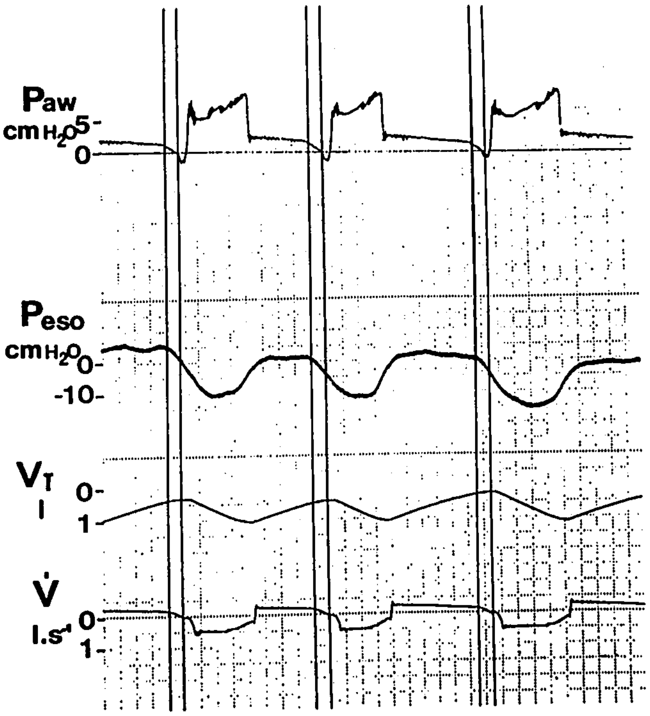

FIG. 1. Computation of intrinsic positive end-expiratory pressure (PEEP$_i$), in a spontaneously breathing patient, from the esophageal pressure tracing. *Top to bottom*: airway pressure (P$_{aw}$), esophageal pressure (P$_{es}$), tidal volume (V$_T$), and flow (V̇). The two vertical lines drawn on the breathing cycles pass through the beginning of inspiratory muscle activity (left line) and the beginning of inspiratory flow (right line), respectively. The negative P$_{es}$ deflection occurring before the beginning of inspiratory flow represents PEEP$_i$.

bation of the patients. Signals of transpulmonary pressure (P$_{es}$ minus airway pressure) were used for this computation. Because airway pressure was measured at the external tip of the endotracheal tube, the resistance of the artificial airway was included in the computation of lung and airway resistance before extubation. Plots of pressure against volume were obtained in the same way as values for work of breathing. The zero-flow points, *i.e.*, the beginning and end of inspiration, determined the line of the static pressure–volume curve of the lung and delineated the resistive work located between this line and the dynamic inspiratory pressure–volume trace. When the mean resistive pressure per breath was divided by the mean inspiratory flow rate, it gave an estimate of the inspiratory resistance to flow of the lung and airways. Dynamic lung compliance was calculated as the ratio of mean V$_T$ to the changes in transpulmonary pressure during inspiration.

PROTOCOL

Patients were first studied while the trachea was still intubated. They were connected to a Siemens Servo 900 C ventilator on the PS mode with an fractional inspired oxygen level of 0.35–0.40 (a level sufficient to obtain greater than 90% arterial oxyhemoglobin saturation). PS was set at 12 cmH$_2$O. Patients were allowed to breathe *via* this mode for 30 min, and respiratory mechanics were recorded during the last 5 min of this period. PS was then reduced by 4 cmH$_2$O every 20 min, and additional recordings were made at the end of each period of 20 min (at PS of 12, 8, 4, and 0 cmH$_2$0). A PS of 0 cmH$_2$0 represented a period of spontaneous breathing *via* the ventilator circuit.

At the end of this period, the endotracheal tube was disconnected from the ventilator, and the patient was allowed to breathe for 30 min *via* the endotracheal tube connected to a T-piece at an identical fractional inspired oxygen level. New recordings were made, and the endotracheal tube was withdrawn after careful endotracheal suctioning. Tracheal extubation was conducted with the assistance of a respiratory therapist, and expectoration was facilitated. When the breathing pattern of the patient seemed stable, a 30-min period of spontaneous breathing was initiated. Supplemental oxygen was administered *via* a nasal cannula to avoid significant changes in arterial oxyhemoglobin saturation. At the end of this last 30-min period, respiratory mechanics were again measured with the subject wearing a nose clip and breathing through a mouthpiece. Data were recorded during several periods of 15 s, during which supplemental oxygen was temporarily stopped. No changes in breathing pattern or P$_{es}$ swings were observed during these periods. Patients were kept in a semirecumbent position throughout the study.

Determination of the Level of Pressure Support that Compensates for the Additional Work of Breathing Created by the Endotracheal Tube and Demand Valve

For each patient, the level of PS that compensated for the additional work caused by the endotracheal tube and demand valve was defined as that which had allowed the patient to breathe at the same level of power before and after tracheal extubation, and was computed after extubation. Linear regression was performed in all patients plotting the four values of work per minute, against the PS levels in cmH$_2$O. The PS level corresponding to a power of breathing equal to the power measured after extubation was obtained by interpolation.

This level was computed from the values for power of breathing and not for work per liter of ventilation, because we previously found that power of breathing was more closely correlated with the oxygen cost of breathing than with work per liter of ventilation.[4]

STATISTICAL ANALYSIS

Data are means ± standard deviation. Work of breathing and breathing pattern values were analyzed by two-way analysis of variance and two-by-two comparison using

Tukey's test. Lung mechanics before and after extubation were compared by a paired two-tailed *t* test. The Wilcoxon test for small samples was used to compare the two groups of patients. A probability level of 0.05 was considered significant.

Results

PATTERN OF BREATHING

As illustrated in figure 2, V_T and minute ventilation were significantly greater during all the periods preceding extubation than after extubation. During these periods when PS was set at 12 cmH_2O, the respiratory rate was less than that after extubation.

WORK OF BREATHING AND LUNG MECHANICS

Our principal findings for the work of breathing, illustrated in Figure 3, are as follows.

1. The power of breathing, *i.e.*, work of breathing per minute, increased when the PS level was reduced and was higher when PS was set at 0 cmH_2O than after extubation, amounting to 168 ± 38% of the power measured after extubation (10.3 ± 5.1 *vs.* 6.5 ± 3.7 $J \cdot min^{-1}$, $P < 0.05$).
2. During the period of disconnection, the power of breathing was slightly but significantly greater than after extubation, amounting to 127 ± 18% of the power measured after extubation (8.2 ± 5.1 *vs.* 6.5 ± 3.7 $J \cdot min^{-1}$, $P < 0.05$).
3. When PS was set at 0 cmH_2O, but not during the period of disconnection, the work per liter of ventilation was higher than after extubation (1.07 ± 0.48 *vs.* 0.81 ± 0.39 $J \cdot l^{-1}$, $P < 0.05$).

Lung and airway resistance, including that for artificial airways, diminished slightly but not significantly after extubation (8.8 ± 4.5 during disconnection *vs.* 8.1 ± 3.8 $cmH_2O \cdot l^{-1} \cdot s$ after extubation, $P = 0.14$). Dynamic lung compliance did not change significantly after extubation (64 ± 40 *vs.* 59 ± 36 ml/cmH_2O, $P = 0.39$).

The PS level that compensated for the additional work of breathing was computed for each individual and ranged from 3.4 to 14.4 cmH_2O (table 2). This mean level of PS was significantly greater in the six patients with chronic lung disease that in those free of intrinsic lung disease (12.0 ± 1.9 cmH_2O for group A *vs.* 5.7 ± 2.2 cmH_2O for group B, $P < 0.001$).

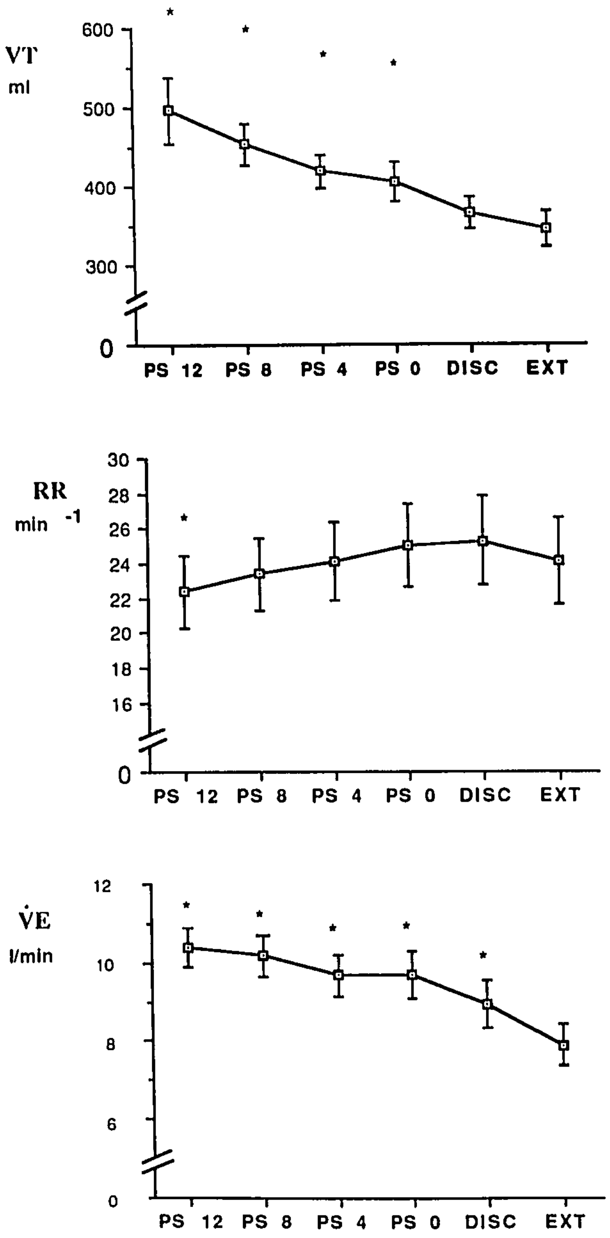

FIG. 2. Comparison of tidal volume (V_T), respiratory rate (RR), and minute ventilation ($\dot{V}_E$) for the six periods of ventilation. PS 12, PS 8, PS 4, and PS 0 are the levels of pressure support (12, 8, 4, and 0 cmH_2O). DISC = the period of disconnection from the ventilator before tracheal extubation; EXT = the period studied 30 min after extubation. Values are means ± SEM. *Significant differences relative to EXT ($P < 0.05$).

Discussion

In this study we found that the presence of an endotracheal tube, with or without a demand valve, increased the work of breathing during spontaneous breathing by patients undergoing tracheal intubation. The level of PS required to compensate for this additional work ranged from 3.4 to 14.4 cmH_2O and was greater in patients with chronic lung disease.

Breathing *via* a demand valve increases the work of breathing, as demonstrated by several studies in which continuous-flow continuous positive airway pressure circuits were compared to demand-valve systems.[7-12] Although new types of demand valve have shortened valve opening time, and although in the present study the triggering level was set at its minimal value (0 cmH_2O), we found that the work of breathing was 27% greater when

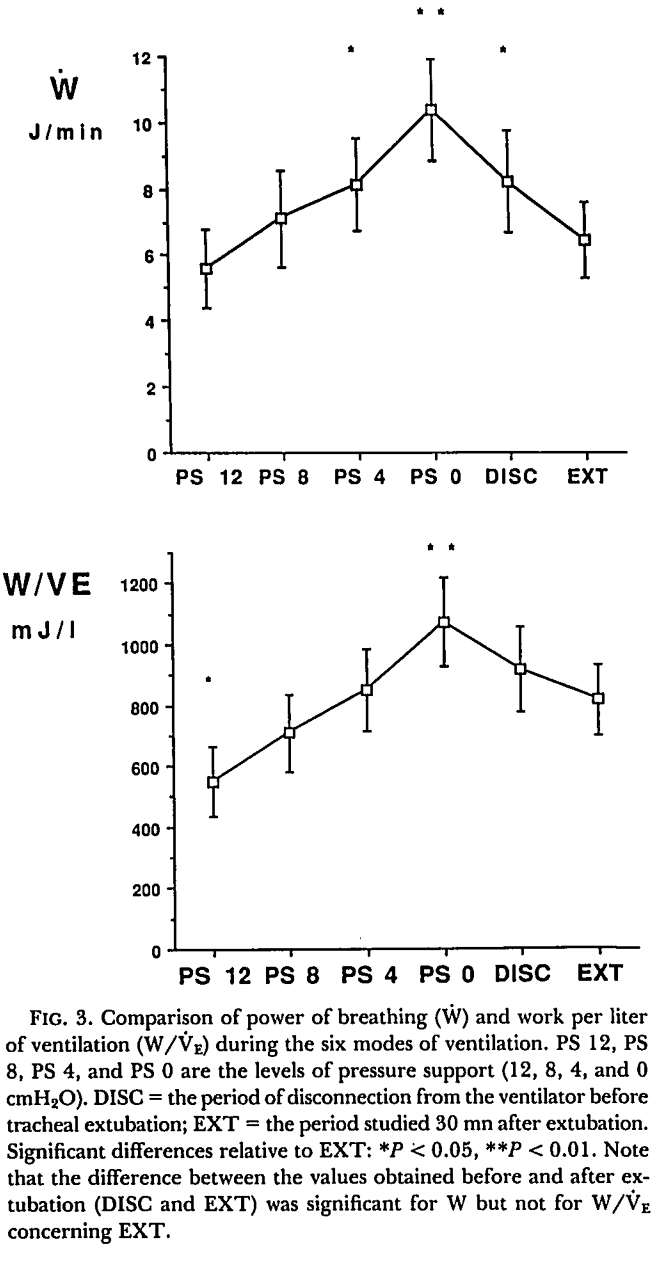

FIG. 3. Comparison of power of breathing (Ẇ) and work per liter of ventilation (W/$\dot{V}_E$) during the six modes of ventilation. PS 12, PS 8, PS 4, and PS 0 are the levels of pressure support (12, 8, 4, and 0 cmH$_2$O). DISC = the period of disconnection from the ventilator before tracheal extubation; EXT = the period studied 30 mn after extubation. Significant differences relative to EXT: $*P < 0.05$, $**P < 0.01$. Note that the difference between the values obtained before and after extubation (DISC and EXT) was significant for W but not for W/$\dot{V}_E$ concerning EXT.

PS was set at 0 cmH$_2$0 than during disconnection. Compared to extubation, we found that the total additional work of breathing caused by the demand valve and endotracheal tube was 68 ± 38% greater than that at baseline. When the work of breathing was expressed per liter of ventilation, the additional work was smaller. This indicated that a large proportion of the changes in power of breathing resulted from a decrease in minute ventilation after tracheal extubation.

Our data provide evidence that, as suggested by others,[16–20] the presence of an endotracheal tube alone increased the work of breathing (here, by 27%), although the total resistance of the respiratory system did not decrease significantly after removal of the endotracheal tube. Values for resistance, however, must be interpreted cautiously. Both in the endotracheal tubes and upper airways, the relationship between pressure drop and air flow is nonlinear. Ideally, resistances should be compared at the same flow rate and for the same flow profile. Under the conditions of this study, it is difficult to determine whether or not endotracheal tube resistance exceeded the upper airway resistance, again as suggested by others.[16–20]

In five of the six patients with chronic lung disease, we found before extubation a small degree of intrinsic PEEP that decreased after extubation (from 2.3 ± 1.9 to 0.6 ± 1.3 cmH$_2$O). Since intrinsic PEEP acts as an inspiratory threshold load and increases the work of breathing, the decrease in intrinsic PEEP in these patients after extubation contributed to the decrease in work observed at that time. Minute ventilation is one of the main determinants of the level of intrinsic PEEP, and the significant decrease in minute ventilation observed after extubation probably explains these findings. The decreases in intrinsic PEEP are, however, of minor importance, since changes in the work of breathing were similar when this parameter was not taken into account when computing the P_{es}–V_T loops. Although changes in minute ventilation seem to be a key feature explaining our results, it is difficult to separate the respective effects of airway resistance, endotracheal tube resistance, intrinsic PEEP, inspiratory flow and minute ventilation, because most of these parameters are interconnected. In addition, changes in bronchomotor tone may occur after intubation of the trachea.[31] The design of this study did not allow assessment of the individual effects of each parameter. Our findings are consistent with the fact that in some patients, ventilatory requirements decreased concomitantly with dynamic hyperinflation, since both process led to a reduction in the power of breathing.

In our patients, PS effectively compensated for the additional work induced by the endotracheal tube and ventilator circuit. Although the values we found were not very far from those previously obtained with mechanical models or in nonintubated normal subjects,[23] significantly higher levels of PS were required for the patients with chronic lung disease than for those free of such disease. There are several possible explanations for these findings, including differences in breathing patterns, baseline levels of work per breath, and the reductions in intrinsic PEEP. The presence of an artificial airway has in itself been reported to decrease end-expiratory lung volume in postoperative cardiac surgery patients during T-piece trials.[32,33] This decrease should reduce compliance and thus increase the work of breathing. Although we did not measure lung volume, we did not find any systematic increase in dynamic lung compliance after extubation. In addition, the decrease that some of our patients exhibited in intrinsic PEEP suggested a reduction in dynamic hyperinflation, although this does not constitute a direct measurement of lung volume. It may be that in the pop-

TABLE 2. Individual Values for Lung Mechanics and for the Pressure Support Level Compensating the Additional Work of Breathing

Patient	R_L ($cmH_2O \cdot L^{-1} \cdot s$)	Tube Diameter (mm)	C_L (ml/cmH_2O)	Pressure Support Level (cmH_2O)	Intubation	Group
1	10.4	8.0	29	12.4	N	A
2	10.0	8.0	60	12.3	N	A
3	9.7	8.0	49	14.4	O	A
4	10.6	8.0	37	11.6	O	A
5	14.1	8.5	21	12.4	N	A
6	6.6	8.0	32	8.6	N	A
7	8.0	9.0	51	5.4	O	B
8	2.7	8.5	123	7.1	N	B
9	10.6	7.5	48	5.6	N	B
10	1.8	8.0	132	6.9	N	B
11	4.6	8.0	68	3.4	N	B

Tube diameter: internal diameter of endotracheal tube. Pressure support: level of pressure support compensating for the additional work of breathing caused by the endotracheal tube and demand valve. This level was obtained after extubation by interpolation, from the relationship between pressure support and the power of breathing. Intubation: O = oral; N = nasal. Group A = patients with chronic lung disease; Group B = patients free of intrinsic lung disease. Tube sizes: internal diameter 7.5 mm, length 28 cm; internal diameter 8 mm, length 30 cm; internal diameter 8.5 mm, length 32 cm; internal diameter 9 mm, length 34 cm.

ulation studied here, which included patients with chronic lung disease, some patients behaved differently from those studied in previous series. Here, inspiratory PS was delivered with a Siemens Servo 900 C ventilator. It is possible that the results observed vary a little with other ventilators, because triggering sensitivity and pressure-wave shape can vary from one ventilator to another and thereby possibly alter the work of breathing. With the Servo 900 C, expiration starts when inspiratory flow decreases to a value amounting to 25% of the peak flow. With certain other ventilators, inspiration is prolonged to near zero flow. This generally lengthens the inspiratory time and may also lengthen it relative to the total duration of the breathing cycle.[26] With such ventilators, the combination of higher V_T and a higher ratio for inspiratory time to breathing cycle duration may result in higher end-expiratory lung volume and greater elastic work.

The time at which patients tracheas should be permanently extubated is sometimes difficult to define, and many indices have been proposed as a guide to extubation.[34] In our patients with chronic lung disease, a PS level of 8 cmH_2O resulted in slightly more work than after extubation. Thus, our results also suggest that in addition to providing comfort and efficacy, this mode of assistance can supply the physician with information regarding the respiratory status of the patient. For instance, a patient with chronic obstructive pulmonary disease exhibiting a satisfactory clinical and gas exchange status during PS ventilation set at 8 cmH_2O could be considered a good candidate for tracheal extubation, provided there is no major hypoxemia or difficulty in coughing.

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