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Additional Inspiratory Work in Intubated Patients Breathing with Continuous Positive Airway Pressure Systems

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Spontaneous breathing with continuous positive airway pressure (CPAP) increases arterial oxygenation in patients with adult respiratory distress syndrome (ARDS).¹ Two types of CPAP systems are currently used, continuous flow and demand valve systems. Clinically, the latter has the advantage of being more economical with fresh gas but is often poorly tolerated by patients. Studies in normal volunteers who were sitting have shown the total work of breathing to be increased more with demand valve systems than with a high-flow CPAP circuit without valves.^{2,3} However, no data were available in supine patients whose tracheas were intubated.

Under these conditions, both the changes in pleural pressure and the values of pleural pressure relative to

atmospheric pressure are required to distinguish the part of work done by the patient and that done by the CPAP device.³ The use of esophageal pressure for this determination is questionable in supine subjects.^{3,4} However, the increase in external inspiratory work added by a CPAP system can be evaluated. This superimposed inspiratory work (SIW) can be determined from simultaneous recordings of the flow and pressure difference across the CPAP device.⁵ We measured SIW in supine intensive care patients spontaneously breathing with CPAP and compared three demand valve systems with a continuous flow circuit.

MATERIALS AND METHODS

Patients. Four studies were carried out in each of 12 supine patients (11 male patients and one female patient) undergoing ventilatory treatment with CPAP according to a protocol approved by our institution's ethical committee on human research. Informed consent concerning the nature and purpose of the study was obtained from each patient. CPAP ventilation was being used in the weaning process in four patients recovering from ARDS secondary to severe trauma and in eight patients recovering from major surgical procedures. All 12 patients had arterial blood gases within normal limits at the time of the study, with an inspired oxygen concentration less than

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or equal to 0.4, had normal cardiovascular function, and were afebrile. All patients had their tracheas intubated. Except for the substitution of the CPAP system, all therapy was at the discretion of the managing physician.

Protocol. We studied four CPAP systems at the same level of positive end-expiratory pressure (PEEP). One was a continuous high-flow "homemade" device ($50 \text{ l} \cdot \text{min}^{-1}$) with fresh gas coming from a 40-l bag, a PEEP valve to provide end-expiratory pressure, and a one-way valve on the inspiratory tube to prevent rebreathing (fig. 1). The large gas flow used in this system caused the one-way valve on the inspiratory tube to open before the end of expiration. Three others were demand valve systems incorporated in ventilators. In these, an inspiratory effort initiated gas flow either by a fall of airway pressure in the inspiratory tube (Siemens Servo B[®]) or the expiratory tube (Siemens Servo C[®]) of the ventilator or by generation of gas flow in the inspiratory circuit (Engström Erica[®]).

The four CPAP systems were studied in a random order on the same day, after constant respiratory rate and tidal volumes were achieved. Each CPAP trial was achieved in 10 min; the recovery period between trials lasted at least 30 min.

MEASUREMENTS AND CALCULATIONS

Airway pressure (Statham P50[®]) and flow (pneumotachygraph—Gould) were measured simultaneously at the patient's mouthpiece level. Signals were recorded (Gould ES 1000[®]) and stored (Teac R 61[®]—magnetic recorder).

Signals were fed into a computer system (Kontron PSI 80[®]). They were digitized at a rate of 25 Hz, filtered, and

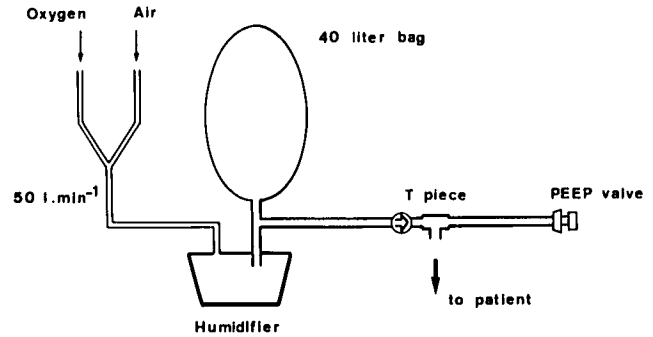


FIG. 1. "Homemade" type of continuous high-flow CPAP system ("PEEP" valve is Ambu type). A one-way valve is located on the inspiratory tube to prevent rebreathing. Because of the large gas flow used in this device, this valve is opened before the end of expiration.

displayed on a screen. Visual examination allowed elimination of breaths containing artifacts.

Figure 2 shows a typical example of some selected respiratory cycles acceptable for analysis. We marked the start of the inspiratory effort at the onset of the drop of airway pressure after end expiration, *i.e.*, when airway pressure was equal to PEEP. The delay time (DT) signified the time between the start of inspiratory effort and the onset of inspiratory gas flow. Inspiratory time (T_1) was measured on the flow curve. SIW subsequently was calculated throughout inspiration by numeric integration of the product $(P_{PEEP} - P[t]) \times \dot{V}(t)$ in which $P(t)$ was airway pressure and $\dot{V}(t)$ was airway flow at the instant t . Inspiratory flow was considered positive. SIW was expressed as millijoules (mJ) per liter of tidal volume (TV). From

FIG. 2. Example of typical airway pressure and flow curves recorded in one patient. Inspiratory flow is positive. A. Continuous flow system. B. Servo B[®]. C. Servo C[®]. D. Erica[®]. The dotted vertical line marks the end of expiration. Note that with the continuous flow system, the time between the end of expiration and the start of inspiration flow is very short, compared with the three demand valve systems.

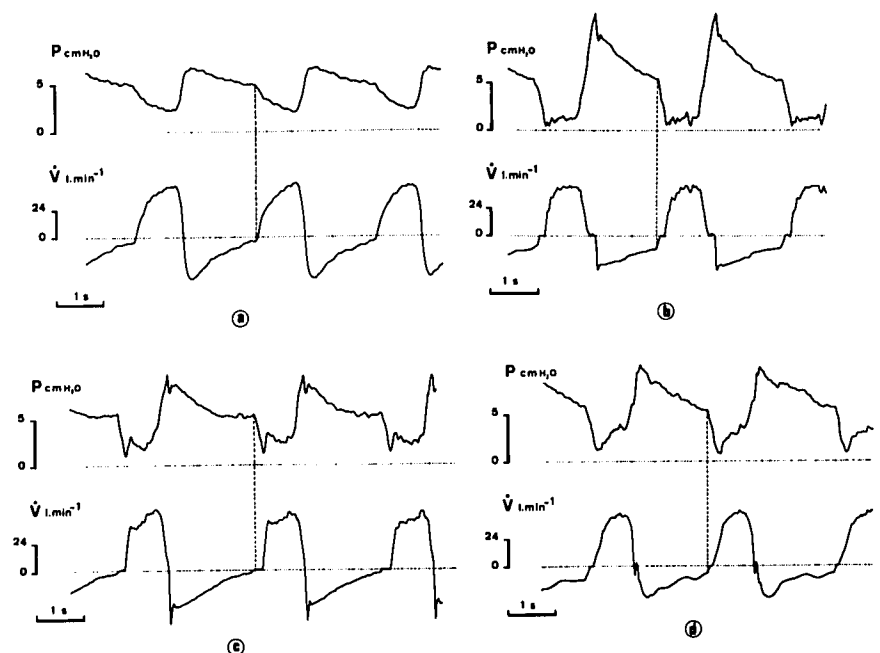


TABLE 1. Mean Results for the Four CPAP Systems*

	Siemens Servo B®	Siemens Servo C®	Engström Erica®	Continuous Flow
Respiratory rate (min ⁻¹)	24.9 ± 1.5	25 ± 1.5	25.1 ± 1.6	25.7 ± 1.8
PEEP (cmH ₂ O)	6.5 ± 0.3	6.4 ± 0.3	6.7 ± 0.3	6.3 ± 0.3
TV (ml)	407 ± 21	412 ± 24	411 ± 29	397 ± 18
T _I (ms)	1,109 ± 49	1,044 ± 43	1,076 ± 65	1,063 ± 43
DPmax (cmH ₂ O)	5.6 ± 0.5†	5.1 ± 0.5†	4.9 ± 0.4†	2.5 ± 0.3
DPmean (cmH ₂ O)	4.2 ± 0.4†‡	3.2 ± 0.3†	3.4 ± 0.4†	1.8 ± 0.1
\dot{V} max (l · min ⁻¹)	32.7 ± 2.4	37.3 ± 2.7	36.4 ± 2	32.9 ± 1.7
DT (ms)	245 ± 15†§	217 ± 20†	181 ± 20†	33 ± 6
SIW (mJ · l ⁻¹)	405 ± 39†‡	277 ± 42†	289 ± 32†	190 ± 24

* Values are means ± SE.
† Significant compared with the continuous flow system value (P < 0.01).

‡ Significant compared with both Erica® and Servo C® values (P < 0.01).
§ Significant compared with the Erica® value (P < 0.05).

the start of inspiration, the integration was followed up as long as the difference P_{PEEP} - P(t) remained positive. In addition, we calculated the following variables: TV, by integration of positive instantaneous flow, and mean inspiratory pressure drop (DPmean), by integration of the difference P_{PEEP} - P(t) during the inspiration time.

Maximum inspiratory flow (\dot{V} max) and pressure drop (DPmax) were identified by the computer. For each patient, and for each CPAP system, 25 respiratory cycles

were chosen and analyzed from the 10-min trial period. The results are presented as the means ± SE, and further statistical analysis used two-way analysis of variance and Duncan's multiple range test for comparison of means whenever analysis of variance showed significance.

RESULTS

No sign of patient intolerance, e.g., tachycardia, skin color changes, increased perspiration, was observed during the measurements with any of the four systems.

The levels of respiratory rate and PEEP were not different between the four CPAP systems. TV, T_I, and therefore, mean inspiratory flow (TV/T_I) were quite similar for all systems (table 1). The continuous flow system was characterized by very low levels of SIW, DT, DPmax, and DPmean, by comparison with the three demand valve systems (figs. 2 and 3 and table 1). SIW was essentially the same with the Siemens Servo C® and the Engström Erica® but was greater with the Siemens Servo B®. DT was shorter with the Engström Erica®, and \dot{V} max was slightly, but not significantly, lower for the Siemens Servo B®. Although DPmax values were the same for the three systems, DPmean was significantly higher for the Siemens Servo B® than for the Siemens Servo C® and the Engström Erica®.

DISCUSSION

CPAP systems are widely used to wean patients recovering from ARDS. In such patients, sometimes clinical improvement in tolerance to CPAP is observed when one system is substituted for another. We wondered, therefore, if this improvement in tolerance did not correspond to a difference in inspiratory work among the different CPAP devices.

When a patient is breathing through a CPAP apparatus, his inspiratory work of breathing can be divided into three components⁶: 1) elastic work, i.e., the work necessary to

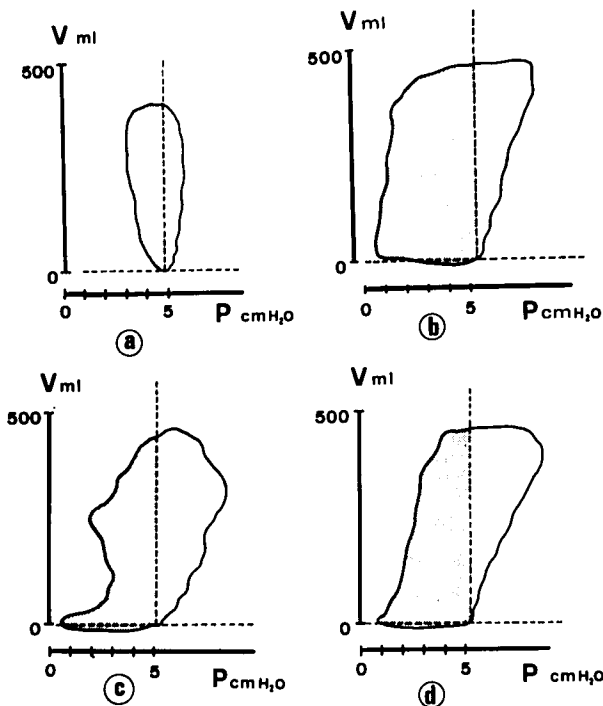


FIG. 3. Pressure-volume loops recorded in one patient. Volume (in ordinate) is calculated by integration of instantaneous flow. The shaded area represents SIW. Note the different shapes of the inspiratory limb of the pressure-volume loops. Frames A-D represent the conditions as in figure 2.

overcome elastic forces when a volume change occurs; 2) flow-resistive work, *i.e.*, work necessary to overcome internal resistance (tracheal tube and airways) and nonelastic deformation of the tissues; and 3) external superimposed flow-resistive work (SIW), *i.e.*, the work expended by the patient in overcoming the apparatus resistance. In this study, the elastic work apparently was the same for all systems because the tidal volume and the PEEP (and thus, the FRC) were unchanged from one system to another. This assumption can be made for the flow-resistive work, since \dot{V}_{max} , mean inspiratory flow, and T_I also remained the same for the four systems. Therefore, the differences we have found in SIW from one CPAP device to another do represent a change in inspiratory work imposed on the patient.

Compared with data obtained in supine, tracheally intubated, anesthetized patients who were spontaneously breathing without CPAP devices, the SIW determined from our data represents 60–90% of the total inspiratory work of breathing.⁷ Compared with the data of Gibney *et al.*,³ it represents 40–60% of the total inspiratory work in patients breathing through CPAP devices. However, any quantitative comparison with Gibney's data should consider that their measurements were made in normal, seated volunteers whose tracheas were not intubated.

Several authors have suggested that the inspiratory work of breathing during CPAP ventilation depends mainly on the difference between the set CPAP value and the inspiratory airway pressure.^{2,8,9} In fact, with the high-flow CPAP circuit, airway pressure remained fairly stable during inspiration and SIW was found to be low. Conversely, with the demand valve systems, the relatively large decreases in airway pressure required to open the demand valve account for a greater DP_{max} and SIW.

Among the three demand valve systems, the largest SIW values were measured with the Siemens Servo B[®]. This could be explained by the combination of slightly higher DP_{max} and lower \dot{V}_{max} , compared with the Siemens Servo C[®] and the Engström Erica[®]. In addition, as also recently observed by Cox and Niblett⁸ in one healthy volunteer, the Siemens Servo B[®] shows a longer DT. But the more striking finding with the Siemens Servo B was

the larger DP_{mean} when compared with the two other devices: instantaneous flow seemed to be insufficient to meet the patient's flow demands, thus causing a sustained pressure drop throughout the inspiratory phase (fig. 3).

In conclusion, we employed a method for the measurement of SIW, which can be applied in tracheally intubated, supine patients. Our results indicate that the SIW is significantly less in a valveless continuous flow system than in several commonly employed demand valve systems. In this study, we observed no differences in clinical tolerance among the various systems. However, in patients with a limited ability to perform ventilatory work, the additional SIW required by the demand valves could cause an intolerable increase in SIW and aggravate existing respiratory failure. Therefore, we conclude that when using CPAP to wean such patients, a continuous flow system should be used even though it is less economical in its usage of gas.

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