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Total inspiratory work with modern demand valve devices compared to continuous flow CPAP

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Abstract. The inspiratory work exerted by an electromechanical lung model in drawing a 500 ml breath, was assessed by planimetry of pressure/volume loops for six commercial demand valve CPAP devices (Servo B and C from Siemens, EV-A and UV-2 from Dräger, the Puritan Bennett 7200 and the Engström ERICA) and compared to the loading of a conventional high flow CPAP system. The effect of trigger sensitivity and inspiratory pressure support on inspiratory work was also investigated in some cases. The lung model allowed for calibrated changes in compliance and airway resistance. In the non-assisted CPAP mode, all machines required slightly larger amounts of inspiratory work than the continuous flow CPAP system. Most machines were comparable in performance but the ERICA and the Servo B required up to 22% more work than the continuous flow CPAP system and represented the maximal increase of total work due to any given machine. The greater part of total inspiratory work was due to lung compliance and airway resistance, factors external to the machines. Halving compliance doubled the work and exchanging a 7 for a 9 mm i.d. endotracheal tube in the circuit increased work by about 3% regardless of machine. Decreasing trigger sensitivity from 0 to 2 cm H_2O for the Servo B increased work by up to 24%. Using 5 cm H_2O of inspiratory pressure support decreased work for all machines up to 36% maximally. In conclusion, under the chosen experimental conditions the inspiratory work of breathing was only minimally increased with the following demand valve systems in comparison to a continuous flow CPAP system: Servo C, EV-A, UV-2, and Bennett 7200. The remaining required additional work could be eliminated by using inspiratory pressure support. However, triggering effort remains the unavoidable additional load of demand valve CPAP systems.

Key words: Continuous flow CPAP – Demand valve CPAP – Electromechanical lung model – Work of breathing

The use of continuous positive airway pressure (CPAP) for the weaning of patients from mechanical ventilation has been well established [1–3]. Recently considerable attention has been focused on the necessity of minimizing the work of breathing imposed on a patient by the various CPAP delivery systems [4–12]. In addition, demand valve devices have been compared unfavorably with continuous flow CPAP in that the former have been considered to require greater breathing effort than the latter [4, 5]. Most studies in humans as well as with mechanical lung models relied on airway pressure recording as opposed to pleural pressure hence assessing the changes in additional resistive but not in total work due to the system. As will be shown, additional resistive work exaggerates the differences between machines and does not provide an optimal basis for comparing them.

Furthermore, studies involving human subjects precluded breath to breath reproducibility, thus we decided to employ a servocontrolled electromechanical lung model to compare the performance of six demand valve devices with a continuous flow "standard" CPAP system. Due to its reproducible breathing characteristics the lung model obviated statistical analysis and allowed calibrated changes in lung compliance and airway resistance. Variations in trigger sensitivity and inspiratory pressure support, available as options on some of the demand valve machines, were also studied in some instances. The results showed that under these experimental conditions some of the demand valve devices tested, performed almost as well as the standard continuous flow CPAP system.

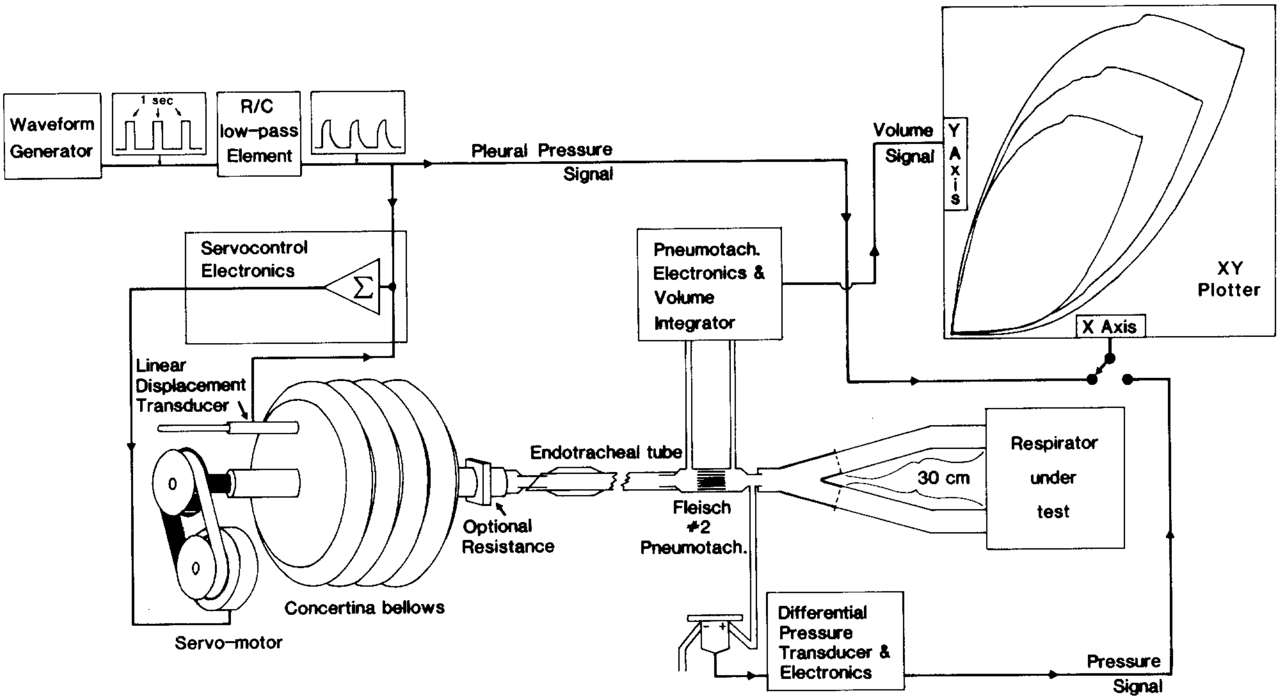

Fig. 1. Semischematic representation of the experimental set-up. Concertinal bellows with all servo loop components is shown on the left. Besides feedback from the displacement transducer the servo-control electronics also get a forcing waveform labeled "pleural pressure signal" from a waveform generator. The square pulses of the generator are shaped by the RC low pass filter to yield exponentially rising and falling flanks. Either this signal or that from an airway pressure transducer are applied to the X axis of the X/Y plotter whereby the Y axis is driven by the volume signal from a pneumotachograph-integrator system. Between the pneumotachograph and the bellows there was always interposed an endotracheal tube and a calibrated airway resistance as shown. The respirator or device under test (D. U. T.) was attached to the pneumotach either through two 30 cm lengths of corrugated respirator tubing as shown or through a patient circuit with in-line humidifier (not shown). A representative set of pressure-volume loops are shown for a given machine at three different tidal volumes

Materials and methods

The lung simulator (Dräger AG) consisted of a round concertina bellows with reinforced almost non-elastic walls and 2 l maximum capacity (Fig. 1). A servomotor drove the bellows. A linear displacement transducer connected to the bellows provided a volume proportional servo feedback signal. The gain of the servo loop set the compliance of the bellows-motor system anywhere between 5 and 100 ml/cm H_2O. The loop forcing voltage determined the negative or positive pressure developed by the bellows, with a sensitivity of -10 cm H_2O for $+1$ volt deviation from zero.

The measured air flow resistance of the bellows and its inlet was 10 cm H_2O/l/s whereby calibrated fixed resistors of 5 and 20 cm H_2O/l/s could be connected in series with the bellows. Although large, these resistances were sometimes used intentionally to exagerate the differences between machines which otherwise would have been unmeasurable. The bellows tidal volume was measured independently by a Fleisch No. 2 pneumotachograph driving a Godard-Statham type 17212 differential transducer-integrator system. The integrator was calibrated with a 500 ml plexiglass syringe taking care not to exceed 60 ml/s flow when pumping through the pneumotachograph. The volume signal from the integrator was displayed on the Y (vertical) axes of a storage oscilloscope (Tektronix 564 B) and an X/Y recorder (Hewlett-Packard 7004 B with 17178 A attenuators in each channel).

The X (horizontal) axes of both instruments displayed the bellows driving waveform which came from a signal generator and was proportional to "pleural" pressure. The signal generator provided square pulses 1 s in duration repeated 4/min and modified by a 1/2 s RC element to yield exponentially rising and falling flanks (Fig. 1). The shape therefore resembled that generated by a patient, rising abruptly, approaching peak exponentially, falling suddenly from peak and descending to zero exponentially. The amplitude of the driving waveform determined the volume pumped by the bellows through a given resistance. Comparison of this waveform with the signal from an equivalently calibrated pressure transducer connected to measure pressure inside the bellows, yielded overlapping results. The driving waveform however, was preferable to the signal from the pressure transducer because of high frequency turbulence oscillations in the latter which degraded repeatability. With this set-up loops of volume vs. pleural pressure could be plotted as shown for three different tidal volumes in Fig. 1 yielding an estimate of total inspiratory work.

To make results comparable to a previous study [8] however, volume vs. airway pressure was also plotted. These loops estimated the additional resistive work due to a given CPAP system. For these, airway pressure was measured as in Fig. 1 between the pneumotachograph and the device under test by a Hewlett-Packard type 270 airway pressure transducer and a 78205B carrier amplifier calibrated for 1 V/10 cm H_2O.

The basis for comparison with the commercial demand valve devices was a "standard" high flow CPAP system composed of a 25 l latex rubber bag (compliance 1 l/cm H_2O at 10 cm H_2O filling pressure) fed by compressed air at 40 l/min, connected in parallel through T pieces and corrugated tubing (2.3 cm i.d.) to the lung model and a 10 cm H_2O PEEP (Positive End Expiratory Pressure) load. This latter consisted of equal bore stand pipe submerged under 10 cm of water in a beaker. Total tubing length did not exceed 2 m. Six demand valve machines were tested in two separate series due to the availability of the machines at different times and are tabulated as follows:

Series I: Puritan-Bennett 7200, Dräger EV-A, Engström ERICA;
Series II: Siemens Servo B, Siemens Servo C, Dräger UV-2.

All machines were tested with two different sets of connecting tubing: the first with commercially available standard patient circuit and in-line humidifier and the second with two 30 cm lengths of corrugated tubing and Y piece as in Fig. 1. Trigger sensitivity variations were systematically investigated for the Servo B. In addition, 5 cm H_2O of inspiratory pressure support were tested for the EV-A, the Bennett 7200, the Servo C, and the ERICA. Inspiratory pressure support is a feature that upon triggering delivers enough additional flow during inspiration to raise and maintain airway pressure a specified amount (here 5 cm H_2O) above PEEP level (here always 10 cm H_2O).

Pressure/volume loops were recorded for each machine and condition with volume on the Y axis and either the driving waveform as "pleural" pressure analog or airway pressure from the transducer on the X axis. After connecting the given CPAP device to the simulator, the amplitude of the driving waveform was adjusted to yield 500 ml of inspiratory volume at the point of occurrence of peak pressure. The stability and reproducibility of the loop were monitored on the storage scope, and a single loop was written on the X/Y recorder. The spatial resolution of the X/Y records was 2.5 cm H_2O of pressure per linear cm on the X axis and 50 ml of volume per linear cm on the Y axis. The area enclosed by the inspiratory or ascending leg of each loop and the Y axis was obtained by planimetry using a Haff No. 317 planimeter with a minimum resolution of 0.1 cm^2, and the inspiratory work of breathing for each single breath thus derived, was expressed in Newton-meters or joules.

Results

Figures 2 and 3 summarize the results for the total inspiratory work of breathing. The figures display the curves of the standard high flow CPAP system (labelled 1); curves of each individual machine operated without the pressure support option activated, and the trigger set at maximal sensitivity (0.5 cm H_2O) (labelled 2); curves for 5 cm H_2O pressure support for the machines with this provision (labelled 3); and finally curves for the Servo B with trigger set at −2 cm H_2O (labelled 4). All curves were obtained using a 9 mm i.d. endotracheal tube in the circuit and with 30 and 60 ml/cm H_2O lung compliance in the top and bottom of the figures respectively.

The Figures confirm that without pressure support all demand valve machines require more total inspiratory work than the standard CPAP system. The pressure-volume areas within the curves of each device under test are larger than those of the corresponding standard CPAP curves. However, with the more recently developed machines, e.g. Bennett 7200, EV-A, Servo C and UV-2, the overall increase in total work compared with the standard CPAP is small remaining below 9%. The slightly older machines such as the ERICA and the Servo B required up to 22% more inspiratory work than the standard CPAP. It was also noted that lung compliance and resistance, factors external to the machines, had a profound influence on inspiratory work in all the systems studied including the standard CPAP system. Reducing the compliance by half doubled the work and changing from a 9 to a 7 mm i.d. endotracheal tube (not shown) increased the work by about 3% on the average. Switching from the commercially available patient circuit with humidifier to the two 30 cm lengths of corrugated tubing (Fig. 1) however, had no discernible effect on the inspiratory work in any of the machines. Activation of 5 cm H_2O of inspiratory pressure support in the machines equip-

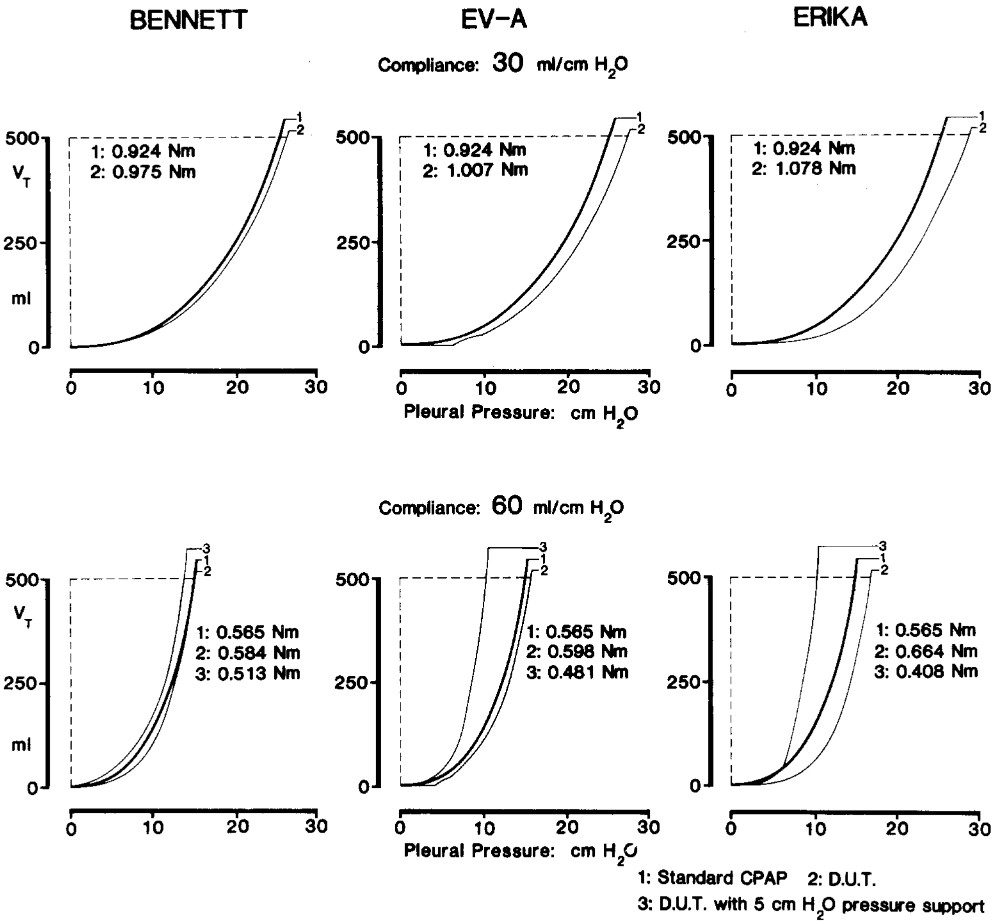

Fig. 2. Pressure-volume areas for three different ventilators or devices under test (D. U. T.) as labeled, compared to a continuous high flow CPAP system. The latter is represented by a thick line in each case labeled with the numeral 1. The numeral 2 refers to the curve of each D. U. T. operated in passive CPAP mode while the numeral 3 refers to the curves of the same machines but with 5 cm H_2O of inspiratory pressure support. The upper half refers to a lung compliance of 30, while the bottom to 60 ml/cm H_2O. In all cases a 9 mm I. D. endotracheal tube was used. Only the inspiratory leg of the curves is shown since the expiratory leg would unnecessarily confuse the pictures. Note the large decrease in work from top to bottom half due only to doubling of compliance irrespective of machine. Note the relatively small differences in work between the high flow CPAP system and each D. U. T. and the large reduction in work upon use of inspiratory pressure support

ped with this option, produced the curves labelled with the numeral 3 in the Figures. The support pressure is subtracted from the pleural pressure effort thereby substantially reducing the inspiratory work. The extent of this reduction is presented in Table 1 for the machines involved.

Figures 2 and 3 also show that for the higher compliance (60 ml/cm H_2O) all machines exhibited an isovolemic pressure excursion at the beginning of the breath because of the triggering effort which is not associated with a volume shift until the machine is activated. The phenomenon is most pronounced for the Servo B and the ERICA. The curves labelled 4 in Figure 3 for the Servo B were obtained with the trigger set at -2 cm H_2O as opposed to all the other curves in Figures 2 and 3. The decrease in trigger sensitivity raised the total work of inspiration by 15% at 30 and by 24% at 60 ml/cm H_2O compliance in this particular instance.

In order to demonstrate the additional work of inspiration due to the resistance of the tested device, air-

Table 1. Inspiratory work of breathing performed by the lung simulator with and without 5 cm H_2O inspiratory pressure support for four demand valve machines. The column on the right shows the percent decrease in inspiratory work under pressure support

	Pressure support 0 cm H_2O (Nm)	Pressure support 5 cmH_2O (Nm)	Decrease in insp. work (%)
Bennett 7200	0.613	0.542	11.6
EV-A	0.617	0.407	34.0
Servo-C	0.498	0.321	35.6
Erica	0.665	0.580	12.8

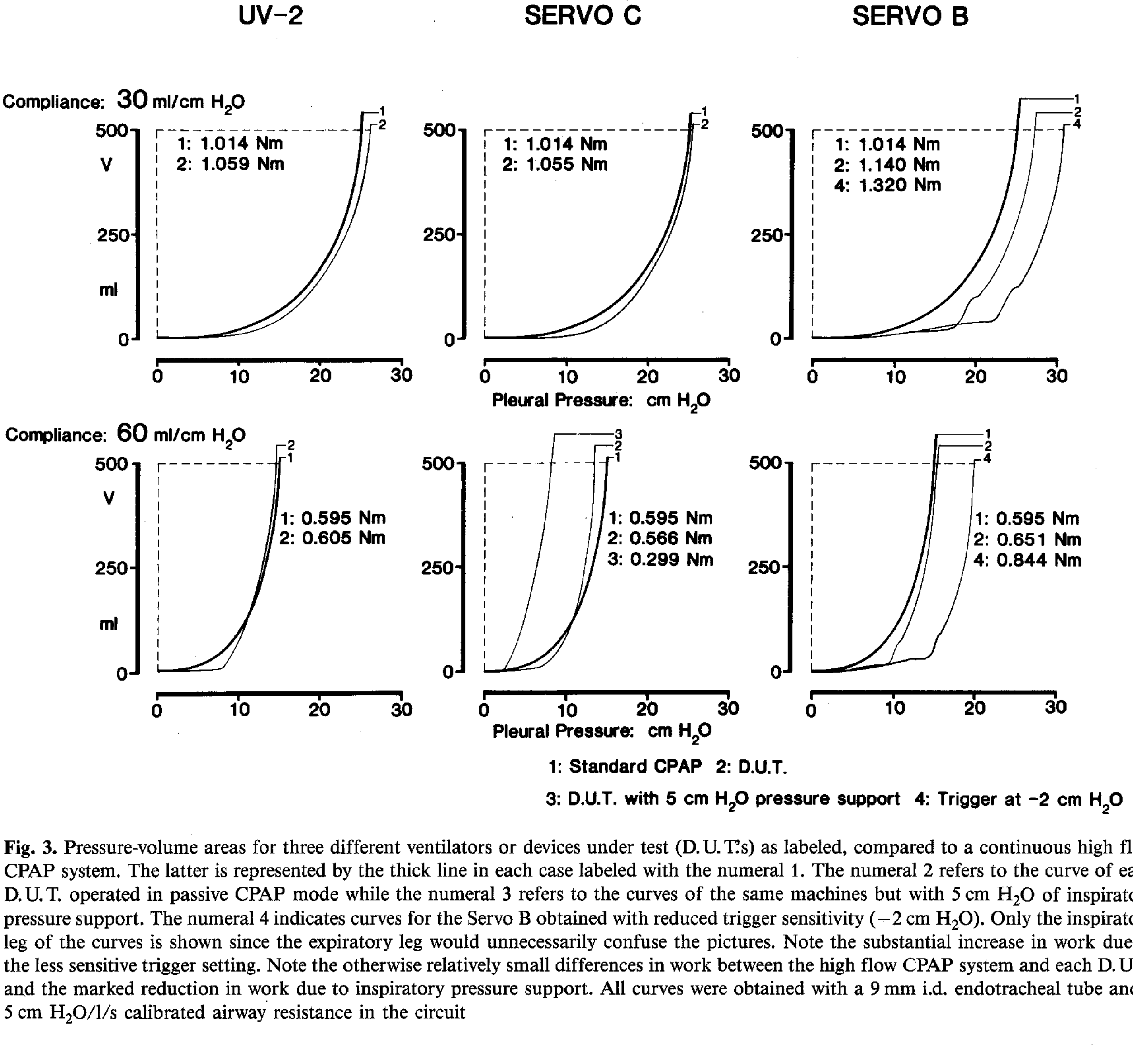

Fig. 3. Pressure-volume areas for three different ventilators or devices under test (D. U. T.'s) as labeled, compared to a continuous high flow CPAP system. The latter is represented by the thick line in each case labeled with the numeral 1. The numeral 2 refers to the curve of each D. U. T. operated in passive CPAP mode while the numeral 3 refers to the curves of the same machines but with 5 cm H_2O of inspiratory pressure support. The numeral 4 indicates curves for the Servo B obtained with reduced trigger sensitivity (−2 cm H_2O). Only the inspiratory leg of the curves is shown since the expiratory leg would unnecessarily confuse the pictures. Note the substantial increase in work due to the less sensitive trigger setting. Note the otherwise relatively small differences in work between the high flow CPAP system and each D. U. T. and the marked reduction in work due to inspiratory pressure support. All curves were obtained with a 9 mm i.d. endotracheal tube and a 5 cm H_2O/l/s calibrated airway resistance in the circuit

way pressure instead of pleural pressure was plotted on the X axis in Figure 4. The graphs on top were obtained without pressure support, while for those on the bottom 5 cm H_2O of pressure support was used. All these loops represent only the flow resistive work due to each system and were obtained under 60 ml/cm H_2O compliance and a 9 mm i.d. endotracheal tube. Without pressure support all systems including the standard high flow CPAP allowed the inspiratory pressure to fall below the nominal 10 cm H_2O PEEP because of loading resistances. This pressure decrease was smallest for the standard CPAP circuit followed by the EV-A and the Bennett, attesting to the relatively low internal resistances of these systems. The largest pressure decrease was found with the ERICA. The Servo C loop in the top half shows the effect of a small amount of pressure support which is already present even when this option is not activated. The inspiratory limb of its loop therefore is mostly above 10 cm H_2O. As inspiratory pressure support was increased for the EV-A, the Bennett 7200, the Servo C, and the Engström ERICA in the bottom half of Figure 4 the inspiratory limb of the loop was shifted to the right of the expiratory limb (ideally to 15 cm H_2O), and the loop reversed direction (clockwise without, and counterclockwise with pressure support). The flow resistive work that the test lung had to do without pressure support was thereby compensated and the pressure support did work on the lung to the extent already presented in Table 1. As can be seen all the machines performed this task more or less satisfactorily in that they all managed to raise pressure well above the 10 cm H_2O PEEP during inspiration with the EV-A and the Servo C coming closest to maintaining the nominal

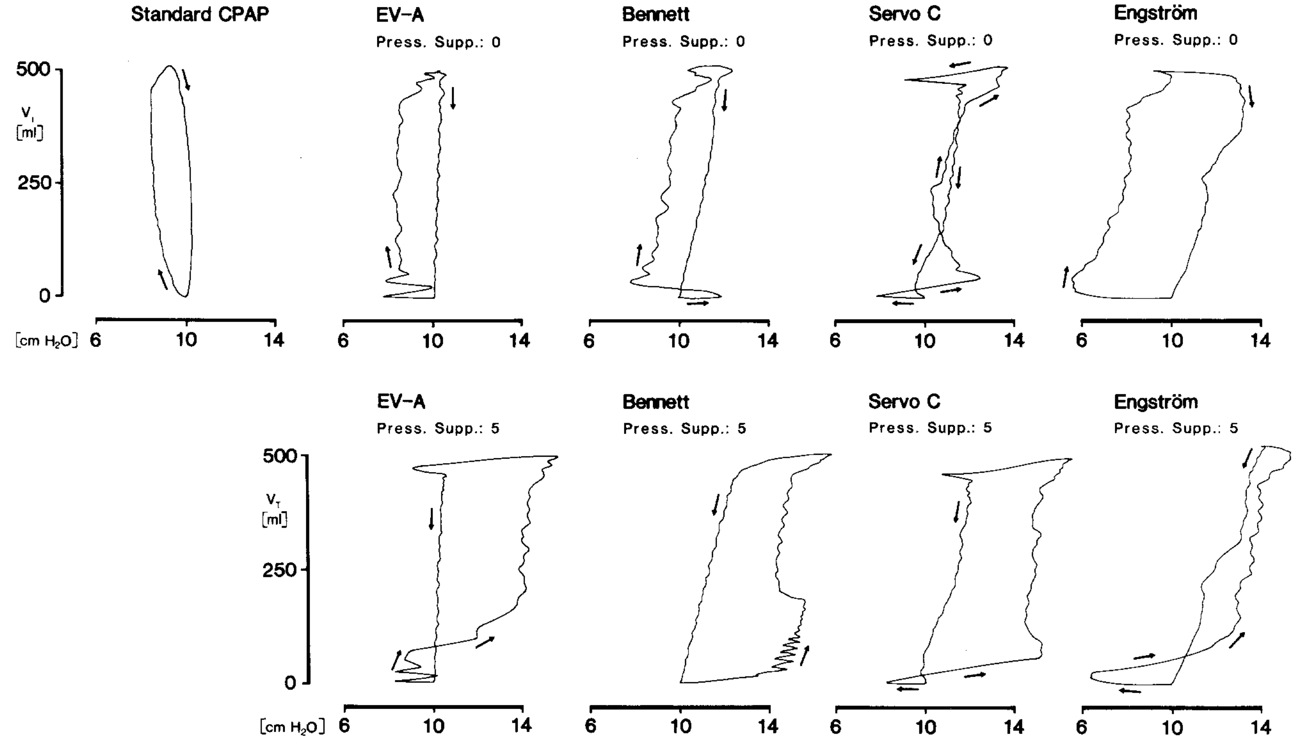

Fig. 4. Pressure-volume loops using airway instead of pleural pressure on the X axis. These loops represent the flow resistive additional work due to each machine. The top row refers to passive CPAP conditions whereas the loops in the bottom row were obtained with 5 cm H_2O of inspiratory pressure support. During passive CPAP in all loops including the high flow standard CPAP system, the airway pressure decreases below the nominal 10 cm H_2O during inspiration and increases somewhat above this during expiration. The width of the loop, i.e. its pressure excursion indicates the internal resistance of the machine in question. The wider the loop the greater the resistance, the larger the additional work. As inspiratory pressure support is applied, the loops reverse direction, i.e. upon triggering the airway pressure is maintained about 5 cm H_2O above CPAP (approx. 15 cm H_2O) and drops down to 10 cm H_2O during expiration. Only the triggering effort remains negative. The magnitude of the triggering effort shows the basic trigger sensitivity of each machine. Although in all cases the triggers were set at maximum sensitivity the triggering efforts are distinctly different from machine to machine. For instance the Bennett 7200 at this setting is self triggering and requires no discernible triggering effort

15 cm H_2O during inspiration. Under pressure support therefore, the remaining portion of work that the test lung had to do was the triggering effort seen in the negative pressure excursion in every curve except that of the Bennett in the bottom of Figure 4. The magnitude of this triggering effort allows for the comparison of the maximal sensitivities of the triggers of these machines. Despite being set as close as possible to 0 cm H_2O none of the machines except the Bennett seem to trigger at that level. At its most sensitive setting (-0.5 cm H_2O) the Bennett however became autocycling. The other machines triggered between -2 and up to -6 cm H_2O (ERICA).

Discussion

The main goal of this study was to measure the total inspiratory work required for spontaneous inspiration using commercial ventilators equipped with a demand flow device and to compare them with a continuous flow CPAP system. For clear cut comparisons very good repeatability of breathing effort was necessary. Only an electromechanical lung model (Dräger AG, Lübeck FRG) with its large variability of operating characteristics (compliance, resistance) and a high degree of reproducibility could fulfill these criteria.

The breathing characteristics were chosen to simulate a weaning patient. A 500 ml tidal volume corresponded to the lower limit of normal, and a 1 s inspiratory duration, assuming an I:E ratio of 1:1, would simulate a frequency of 30 breaths/min, often encountered clinically. Regardless of the ventilator the peak flows encountered in these experiments were well below the region of pneumotachograph non-linearity.

The compliances approach that of a normal thorax with a relatively healthy lung (60 ml/cm H_2O) and a stiff lung (30 ml/cm H_2O). Using the driving voltage as a "pleural" pressure analog assessed total work in contrast to previous studies [6, 8] where airway pressure and therefore added resistive work alone was measured. The assessment of added work is most sensitive to changes in inspiratory work required to overcome external resistances however it does not provide information on the magnitude of added work as a proportion of total inspiratory work required to take a breath. For instance a 100% increase in added work may represent a change of only 5% or less of total inspiratory work. Hence, alterations in added work which seem large may be a clinically insignificant proportion of the total inspiratory work. Therefore it is only by measuring total work of inspiration that this study could make three main points. (1) Conditions external to CPAP delivery systems i.e. compliance and external resistance, contribute more to total inspiratory work than the systems themselves. (2) Most demand valve devices provide an inherent means of compensating for added work due to their internal resistance, namely inspiratory pressure support. (3) The setting of the trigger sensitivity determines primarily the amount of work added by the demand valve system over that of a high flow CPAP system.

With reference to the first point, compliance of the lung and to a lesser extent loading resistance, especially of the endotracheal tube (7 or 9 mm i.d.) contributed the greater part of the total work of breathing since the standard continuous flow CPAP system showed almost the same behavior with respect to these parameters as the rest of the machines. For larger tidal volumes and higher flows others [9] have shown that endotracheal tube diameter can add up to a 154% increase in work so that it is desirable to minimize these external loading factors e.g. by the use of large bore endotracheal tubes in the clinical setting.

The second point concerns the possibility inherent in the design of demand valve devices of overcoming most external loads. In a continuous flow CPAP system a large reservoir bag has been deemed desirable [10] since the larger capacitance buffers the patient's flow demand maintaining a more constant inspiratory positive pressure which in turn is an attempt to relieve the patient of some of his inspiratory effort. As an active breathing amplifier however, a demand valve device can, through pressure support, raise inspiratory pressure arbitrarily above PEEP level thereby theoretically relieving the patient completely of his inspiratory effort if necessary. Since the inspiratory supporting pressure is subtracted from the pleural pressure effort the result works like an effective increase in compliance (Figs. 2 and 3). The only remaining investment on the part of the patient under these conditions is the triggering effort which leads to the last point of discussion.

Despite setting the triggering sensitivities at minimum triggering pressure the older machines needed considerable negative pressure to respond. Since the rest of the subsequent pressure-volume excursion rides on the initial isovolemic pressure movement, the triggering effort accounts in most instances for the greater part of the added work of breathing by demand valve systems. A detailed analysis of the triggering effort for most of the machines included here has recently been published [13] and shows that triggering sensitivity could be generally improved. On the other hand a hypersensitive trigger as we chose on the Bennett 7200 renders the machine self triggering whereby the machine delivers pressure support without any initiative from the patient.

In summary, under the conditions tested here by mimicking the function of a continuous flow CPAP system the demand valve devices performed almost as well as a continuous flow CPAP system. The added work due to the demand valve devices could be traced to the internal and external loading resistances and to the triggering effort. Work due to resistive loads could be eliminated by proper use of inspiratory pressure support. Trigger sensitivity could be improved on most of the machines although too sensitive a trigger results in self triggering or mandatory breaths. The best combination of trigger sensitivity and pressure support needs more clinical testing to be determined.

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References

1. Gherini S, Peters MM, Virgilio RW (1979) Mechanical work on the lungs and work of a breathing with positive end-expiratory pressure and continuous positive airway pressure. Chest 76:251
2. Schlobohm RM, Falltrick RT, Quan SP, Katz JA (1981) Lung volumes, mechanics and oxygenation during spontaneous positive pressure ventilation: the advantage of CPAP over EPAP. Anesthesiology 55:416
3. Katz JA, Marks JD (1985) Inspiratory work with and without continuous positive airway pressure in patients with acute respiratory failure. Anesthesiology 63:598
4. Gibney RTN, Wilson RS, Pontoppidan H (1982) Comparison of the work of breathing on high gas flow and demand valve continuous positive airway pressure systems. Chest 82:692
5. Thies WR, Härter P, Falke KJ (1983) Increased work of breathing with demand flow CPAP systems (abstract). 2nd European Congress on Intensive Care, Geneva
6. Viale JP, Annat G, Bertrand O, Godart J, Motin J (1985) Additional inspiratory work in intubated patients breathing with continuous positive airway pressure systems. Anesthesiology 63:536
7. Hillman DR, Finucane KE (1985) Continuous positive airway pressure: breathing system to minimize respiratory work. Crit Care Med 13:38

8. Katz JA, Kraemer RW, Gjerde GE (1985) Inspiratory work and airway pressure with continuous positive airway pressure delivery systems. Chest 88:519
9. Bolder PM, Healy TEJ, Bolder AR, Beatty PCW, Kay B (1986) The extra work of breathing through adult endotracheal tubes. Anesth Analg 65:853
10. Bshouty ZH, Roeseler J, Reynaert MS, Rodenstein D (1986) The importance of the balloon reservoir volume of a CPAP system in reducing the work of breathing. Intensive Care Med 12:153
11. Mecklenburgh JS, Latto IP, Al-Obaidi AA, Swai EA, Mapleson WW (1986) Excessive work of breathing during intermittent mandatory ventilation. Br J Anesth 58:1048
12. Brandl M, Lang M, Obermayer A (1986) Vergleichende Untersuchungen von CPAP Systemen an einem Atmungssimulator. Anaesthesist 35:73
13. Hillman K, Friedlos J, Davey A (1986) A comparison of intermittent mandatory ventilation systems. Crit Care Med 14:499

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