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Investigation of the spontaneous modes of breathing of different ventilators

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Abstract. We investigated six ventilator systems which were designed to allow spontaneous breathing. The time delay between initiation of inspiratory effort and the beginning of inspiratory gas flow was measured, as was the amount of negative (to ambient) pressure generated in the airway needed to produce the gas flow. We found that the flow-by program of the Puritan-Bennett 7200 caused minimal time delay and virtually no negative pressure was required to instigate gas flow. This should be contrasted with the other ventilator systems, which caused significant delay and inspiratory effort and hence increased work of breathing.

Key words: Spontaneous breathing – Ventilators – Work of breathing – Inspiratory pressure support – Flow-by systems – IMV circuits

In 1982 Gibney, Wilson, Pontoppidan, and subsequently other workers [1, 4, 6, 7, 10, 14] pointed out that ventilator systems based on a demand valve create an inspiratory resistance to spontaneous breathing which is unacceptable in clinical practice. All authors have suggested alternative sources of fresh gas supply based around an IMV one-way valve and reservoir bag, as illustrated in Figure 1. Various authors have estimated the work of breathing using either the demand valve systems or modifications of the circuit described above. The work of breathing was found to be excessive through the demand valves when compared to that measured using the continuous flow systems [6, 10]. Prior to this, in 1979, Gherini [5] showed that the inspiratory work of breathing on CPAP increased if the airway pressure decreased during inspiration.

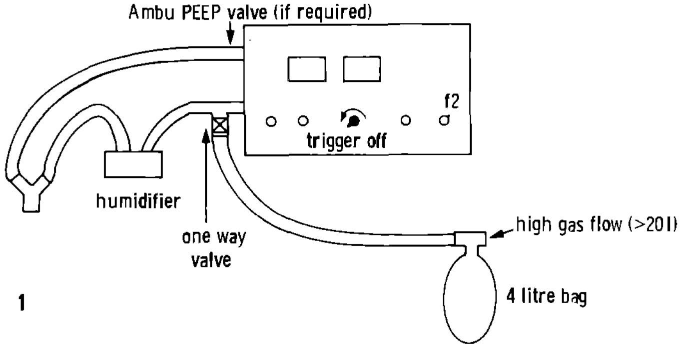
Since the early 1980's, the continuous flow system illustrated above (Fig. 1) has been in use in the Royal Free Hospital Intensive Therapy Unit and has proved clinically acceptable during the weaning of over 600 patients. Among reasons for its success are that there is minimal time delay between the instigation of inspiratory effort and the start of gas flow, and that the theoretical peak inspiratory flow is instantly available and far in excess of that which most patients requiring IMV could achieve. When used in conjunction with CPAP, the bag is stretched tightly and it is this tightness which has been thought to deliver a degree of inspiratory pressure support, leading to a reduction in the inspiratory work of breathing.

Manufacturers of ventilators have recognised the disadvantages of the demand valve systems and the last few years have seen the widespread introduction of systems with inspiratory assistance (pressure support) for the spontaneous phase of IMV. Whilst this will undoubtedly reduce the inspiratory work of breathing and thus the oxygen consumption [2, 8], the sensitivity of the ventilator to the inspiratory effort is still critical if no time delay before the onset of gas flow is to occur. The most recent attempt to further reduce the inspiratory work of breathing during the spontaneous phase has been the introduction of "flowby" on the Puritan-Bennett 7200.

The observed clinical advantages of the continuous flow systems led us to this investigation of recently introduced breathing systems using, variously, inspiratory pressure support (Siemens Servoventilator 900C, Engstrom Erica, Puritan-Bennett 7200, Drager EV-A) and continuous flow systems (Modified Siemens Servoventilator 900B, Puritan-Bennett 7200 flow-by).

Materials and methods

The changes in airway pressure, gas flow rates and inspiratory time lag were measured in the following systems:



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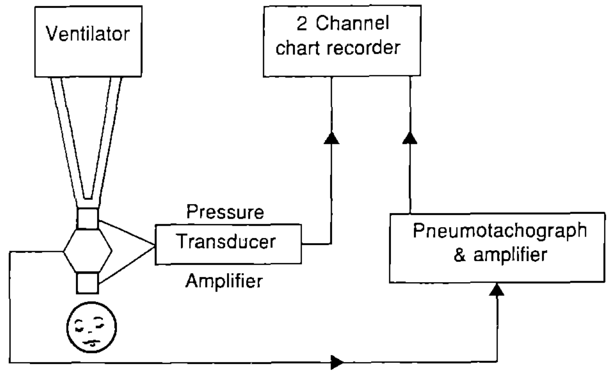

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Fig. 1. Royal free hospital continuous flow modification to servo 900B ventilator

Fig. 2. Schematic diagram of experimental apparatus

1a. Servo 900B
 b. Servo 900B with IMV modification
2 Servo 900C with different inspiratory pressure support levels
3a. Puritan-Bennett 7200, spontaneous breathing mode with different levels of inspiratory pressure support
 b. Puritan-Bennett 7200 flow-by mode.
4 Engstrom Erica 2 with different inspiratory pressure support values
5 Drager EV-A with different inspiratory pressure support levels.

Measurements were made with a system previously described [4] using a Hewlett-Packard pneumotachograph with a Fleish head (47303 A digital Vertek series) in parallel with a Gould P23XL pressure transducer in the inspiratory limb. The amplified signals from these were recorded on a Hewlett-Packard two-channel recorder (type 7702B). The experimental apparatus is illustrated in Figure 2.

The inspiratory time lag between the instigation of inspiratory effort and the onset of inspiratory gas flow was calculated from the chart showing simultaneous traces of the pressure and flow rate in the system, the chart speed being increased from 5 mm/s to 25 mm/s.

Five healthy adult volunteers (3 male, 2 female) breathed through a sealed mouthpiece connected to the various systems. A steady state was assumed to have been reached after 5 min. After this, recordings were taken for a minimum of 20 breaths.

All ventilators were calibrated to the manufacturer's specification before use. The measuring system was also calibrated before and after each set of

Table 1. Sensitivity and delay values

Ventilator	Pressure support (cm H_2O)	Mean (SD) sensitivity (cm H_2O)	Mean (SD) time delay (ms)
Servo 900B		-6.3 ± 0.4	407 ± 53
Servo 900B (modified)		-2.7 ± 0.5	74 ± 30
Puritan-Bennett 7200	0	-1.1 ± 0.2	23 ± 22
	5	-0.3 ± 0.0	73 ± 45
	10	-0.1 ± 0.1	72 ± 52
Puritan-Bennett 7200	15 l/min	-0.3 ± 0.1	13 ± 10
(Flow-by mode)	10 l/min	-0.3 ± 0.1	15 ± 11
Drager EV-A	0	-1.4 ± 0.3	104 ± 38
	5 (min)	-1.1 ± 0.3	128 ± 46
	5 (max)	-1.3 ± 0.4	105 ± 14
	10 (min)	-1.5 ± 0.7	156 ± 52
	10 (max)	-1.1 ± 0.4	118 ± 18
Servo 900C	0	-1.3 ± 0.3	163 ± 24
	5	-0.9 ± 0.1	185 ± 58
	10	-1.0 ± 0.1	167 ± 46
Engstrom Erica 2	0	-1.8 ± 0.4	134 ± 42
	5	-1.2 ± 0.3	134 ± 39
	10	-1.0 ± 0.5	110 ± 34

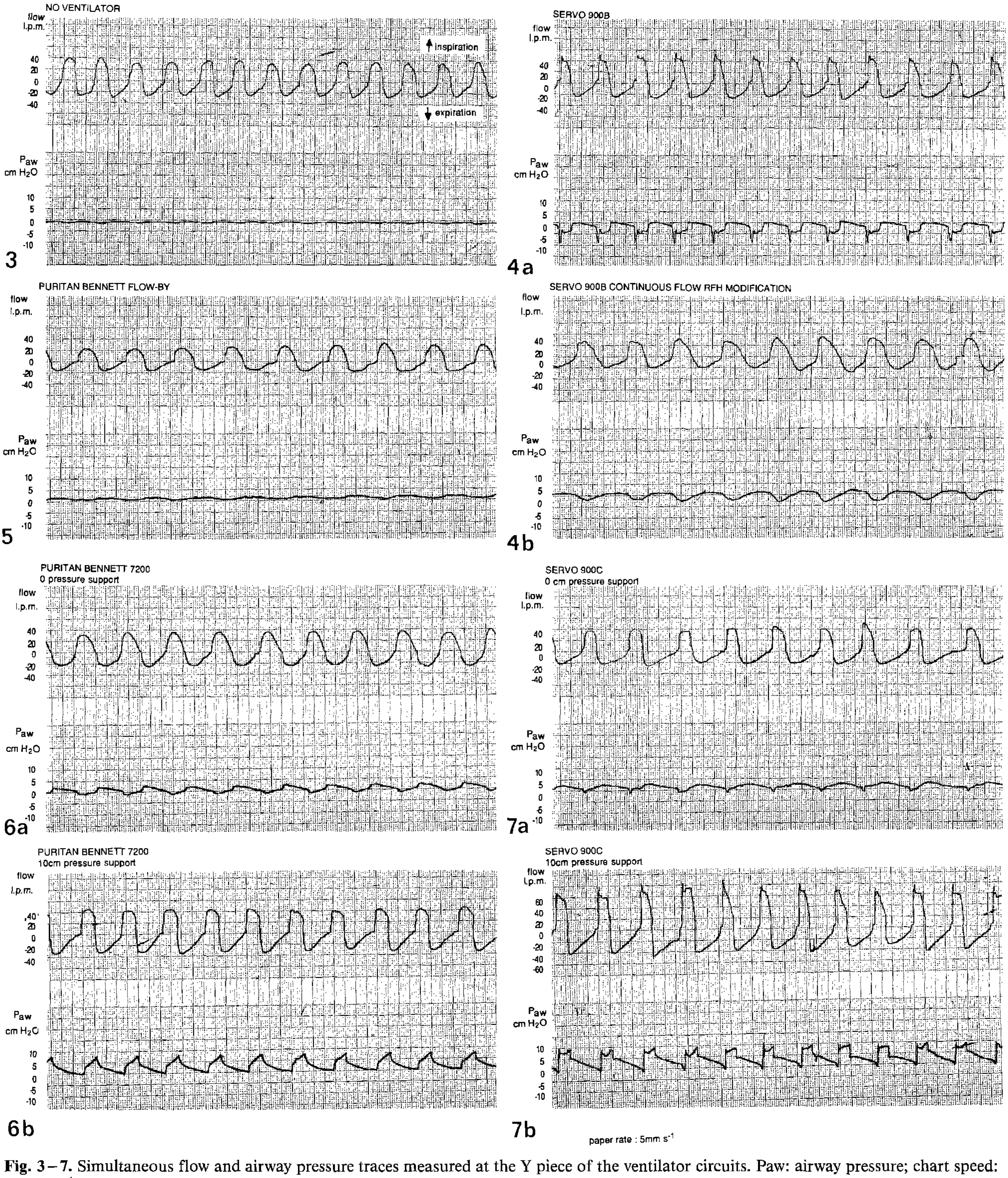

Fig. 3–7. Simultaneous flow and airway pressure traces measured at the Y piece of the ventilator circuits. Paw: airway pressure; chart speed: 5 mm s^{-1}

readings. All ventilators were tested at their maximum sensitivity setting, and in the case of the EV-A at the maximum and minimum flow rate for Assisted Spontaneous Breathing (ASB max/min). All humidification systems were by-passed so that any extra inspiratory resistance caused by these was not recorded. Any bacterial filters which were intrinsic to the ventilator, either on the inspiratory or expiratory limb were left in place.

All significance testing was done using the Student's "*t*"-test.

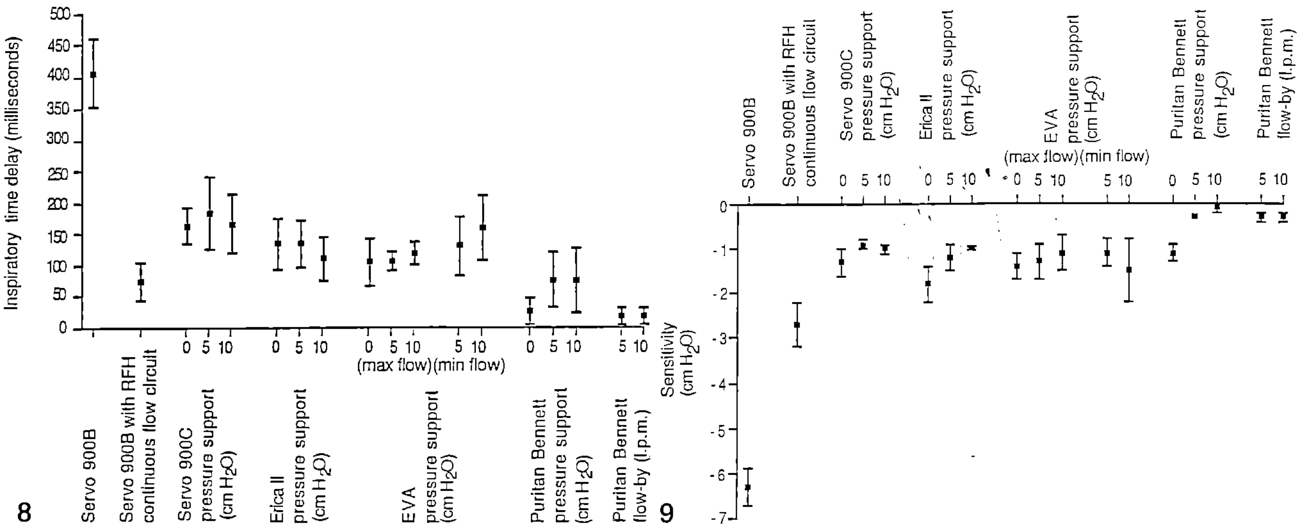

Fig. 8. Inspiratory time delay for various ventilator systems between start of inspiratory effort and gas flow

Fig. 9. Sensitivity (negative effort made by subject) required to instigate gas flow

Results

The sensitivity of the different ventilator systems tested varied from -6.3 cm H_2O less than -0.5 cm H_2O. The delay between the inspiratory effort and the onset of gas flow varied from less than 20 ms to as much as 400 ms. The results are summarised in Table 1. Figures 3–7 are examples of recordings obtained from some of the systems investigated. Figures 8–9 are graphs of the data from Table 1. These values are to be compared with the negligible effort needed when breathing through the measuring system without any ventilator attached (Fig. 3).

Discussion

There are many arguments in favour of maintaining the maximal spontaneous breathing activity. The advantages include reduction in sedation, ease of neurological assessment, increased lung lymphatic flow, less cardiovascular instability, less V/Q mismatch, a reduction in potential barotrauma, and a theoretical reduction of ventilatory muscle wasteage. The ventilator used should have the most sensitive demand valve possible to reduce inspiratory effort and hence work of breathing, however this introduces a practical problem in that the demand valve cannot be too sensitive. For instance, on IMV during the mandatory post-expiratory phase, if the compliance of the lungs approaches that of the ventilator circuit the hysteresis response of the system may lead to self-triggering of the ventilator.

Work of breathing

In animal experiments the diaphragm has been reported to extract 10–18 volume percent of oxygen during shock states. In the dog the blood flow to the diaphragm during laboratory induced respiratory failure is greater than $2\,ml\,g^{-1}\,min^{-1}$ in submaximal conditions – a 26-fold rise over resting conditions [11]. If the above results are translated to the human where the total respiratory muscle mass is 4–5 kg, then the equivalent blood flow is of the order of $8-10\,l\,min^{-1}$ to the respiratory muscles alone [12]. This blood flow requirement is in the presence of a normal oxygen saturation and haemoglobin, and if either of these falls, as in sepsis or other disease states, blood flow will have to be even higher if the respiratory muscles are not to become fatigued. It should be noted that during these experiments respiratory failure was induced by making the animal breathe against an increased inspiratory resistance.

The mechanical work performed in inflating the chest during inspiration whether during spontaneous ventilation or by a ventilator during mechanical ventilation is given by the equation:

$$W = \int_{t_1}^{t_2} P \cdot \dot{V}\, dt$$

where

P = airway pressure (inspiratory effort)
$\dot{V}$ = rate of volume change
$t_2 - t_1$ = duration of inspiration.

From the above equation, it is clear that in any spontaneously breathing patient, in order to achieve a given tidal volume with the least expenditure of energy, the critical variables are the inspiratory effort and the duration which this effort has to be sustained.

The process of weaning a critically ill patient from mechanical ventilator dependence can be a long drawn out phase [3]. Should there be any extraneous load imposed on the mechanical function of the inspiratory muscles, eg increased CO_2 production or increased inspiratory resistance, respiratory failure will ensue. It should be remembered that the endotracheal tube itself may impose increased inspiratory work [13].

From Table 1 and Figures 3–9, it can be seen that the ventilator system in which the least inspiratory effort is required is the Puritan-Bennett 7200 in its flow-by mode. This is significantly less than the other systems investigated ($p<0.01$). The Servo 900B has the least satisfactory performance, but is markedly improved by the addition of a continuous flow IMV circuit. The duration of the inspiratory effort before gas flow occurs, i.e. the time delay is less in the Puritan-Bennett (flow-by) than in the other systems. It should be emphasised that this time delay adds to the t_1-t_2 integral in the equation above and thus directly affects the work of breathing.

Inspiratory pressure support values

Although the inspiratory pressure support value was preset on the ventilator the actual value measured at the airway was not always consistent with this (Figs. 6b, 7b). The pressure support waveform generated was different with the various ventilator systems (Fig. 6, 7). It could be argued that a square wave type of pressure support system allows for very rapid inspiratory flows and therefore reduced inspiratory work.

During inspiratory pressure support the ventilator is triggered by the patient's inspiratory effort to maintain a preset constant positive pressure in the airway during inspiration. The amount of inspiratory effort the patient has to make to trigger the ventilator varies from ventilator to ventilator (see results). Kanak, Brochard and colleagues [2, 8] have shown that inspiratory pressure support reduces the inspiratory work of breathing: patients no longer have to maintain a negative pressure to keep the demand valve open as they would have to without the pressure support. They have also shown a highly significant correlation between an increase in inspiratory pressure support and a reduction in work of breathing (oxygen cost of breathing).

Continuous flow systems

The continuous flow circuit on the Servo 900B (modified as described) and the "flow-by" programme of the Puritan-Bennett 7200 allow the patient to breathe from the ventilator with theoretically no valve to open and therefore no inspiratory resistance due to the valve. This in turn will lead to a reduction in the work of breathing. Essentially this is an adult version of the characteristics recognised as necessary in neonatal and paediatric ventilators such as the Bourne, Babylog and Sechrist, where the need to open a demand valve would be hazardous in view of the effort required, and the small tidal volumes and flows involved.

The disadvantage of the modified circuit applied to the Servo 900B (or Servo 900C) is that it nullifies the monitoring and some of the alarm functions of the ventilator since there is a continuous flow of 10–15 l of fresh gas through the circuit and the expiratory pneumotachograph at all times. A further problems is that PEEP has to be applied to the system so that the bag is kept stretched in order ensure that the one-way valve stays open. Otherwise, the patient may need to make an effort to open the one-way valve (Fig. 4b).

On the flow-by program of the Puritan-Bennett 7200, there is a continuous flow of fresh gas which can be preset between 5 and 20 l min^{-1} and additionally there is no demand valve to be opened to initiate inspiratory flow. If the ventilator expiratory flow sensor detects a reduction of 0.02 l s^{-1} from the preset basal flow, extra inspiratory gas is added to the breathing circuit throught the inspiratory solenoid. Thus the base flow can been augmented to a maximum of 180 l min^{-1} during the inspiratory phase, with the ventilator flow valves being feed-back controlled by the airway pressure signal to the microprocessor. Any excess gas is allowed to vent from the exhalation valve during inspiration. At the beginning of an exhalation following a spontaneous breath base flow is reduced, decreasing resistance to the patient's exhaled flow. Base flow is later raised to the selected level in preparation for the next inspiratory effort. All the monitoring functions of the ventilator are maintained throughout. An added advantage is that the target end-expiratory pressure is the operator-selected PEEP or CPAP level rather than the "sensitivity" value below PEEP.

Conclusion

The choice of a ventilator system is critical in the management and weaning of some intensive therapy unit patients. The newer ventilators are a major advance on the Servo 900B for spontaneous breathing. The flow-by continuous flow system, in particular, is an important new refinement in the search for the ideal ventilator. With continuous flow the goal is to eliminate the patient's work attributable to the ventilator and its demand valve. With pressure support the aim is to eliminate the work due to the endotracheal tube, the circuit and the patient's own respiratory system. We would conclude that that these methods (flow-by and pressure support) need not exist in isolation, as is at present the case. The combination of the two principles, ultra-sensitive microprocessor controlled flow-triggering and inspiratory pressure support, may reduce the work of breathing even further.

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