STUDIES ON CONTINUOUS POSITIVE AIRWAY PRESSURE BREATHING SYSTEMS

D. COX AND D. J. NIBLETT

SUMMARY

A study was undertaken to compare CPAP/IMV systems shown to be in common use in the U.K. The most frequently used system (Servo 900B) has characteristics which are likely to increase the work of breathing. Recommendations are made regarding the theoretically most acceptable systems.

Continuous positive airway pressure (CPAP) is an established and widely used technique in both adult and neonatal intensive therapy. Among the beneficial physiological effects is an increase in the efficiency of gas exchange, which may signify a decrease in the work of breathing (Cogswell et al., 1975).

A significant decrease (25%) in the work of breathing has been demonstrated in babies when CPAP was administered (Cogswell et al., 1975) and it has been suggested that there may be a similar decrease in adults (Venus, Jacobs and Lim, 1979). However, there is only indirect evidence to support this assumption (Venus, Jacobs and Lim, 1979; Simonneau et al., 1982). It has been established that, to minimize the work of breathing by a patient receiving CPAP, the airway pressure should be maintained at a constant value throughout the respiratory cycle. If the airway pressure decreases below the set CPAP value during inspiration, added inspiratory work is imposed, and if it increases above the set value in expiration, additional expiratory work is required (Gherini, Peters and Virgilio, 1979). Thus, it is important that any CPAP system maintains a constant value of pressure.

In addition, it is important that the time delay occurring between the instigation of the patient's inspiratory effort and the onset of inspiratory gas flow should be minimal, since the longer that inspiratory effort is sustained, the greater will be the inspiratory work. These two requirements apply also to the spontaneous phase of IMV.

A survey was undertaken of 55 major ITUs, to determine the types of adult CPAP system in most widespread use in the United Kingdom. Of the 71% of units which used CPAP, only 10% used it on more than 25% of their adult patients with respiratory problems. Of the ITUs using adult CPAP, 82% used a "home-made" circuit similar to that shown in figure 1, and 78% used a ventilator equipped with a CPAP system (that is, most units used both). The ventilators used are listed in table I.

Of the replies, 34% specifically mentioned reservations regarding the performance of the Servo 900B CPAP/IMV system, particularly noting the increased inspiratory effort that seemed necessary, and that "the patients had to work harder" to breathe on CPAP, or during the spontaneous phase of IMV. These findings, and our own clinical impressions, led us to examine in detail various methods of CPAP delivery.

MATERIALS AND METHODS

Since the ideal CPAP system must maintain a constant airway pressure throughout the respiratory cycle, this investigation considered: the resistance to constant gas flow of individual CPAP devices at set nominal values of CPAP; and the changes in pressure, changes in flow rate and inspiratory time lags.

<table>
<thead>
<tr>
<th>Ventilator type</th>
<th>% ITU using this ventilator for CPAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Servo 900B</td>
<td>83</td>
</tr>
<tr>
<td>Servo 900C</td>
<td>27</td>
</tr>
<tr>
<td>Bennett MA2</td>
<td>22</td>
</tr>
<tr>
<td>Bourne Bear I</td>
<td>16</td>
</tr>
<tr>
<td>Engstrom Erica</td>
<td>16</td>
</tr>
<tr>
<td>Other unspecified</td>
<td>3</td>
</tr>
</tbody>
</table>

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during the respiratory cycle, using various CPAP systems.

**Resistance to constant gas flow**

A U-tube water manometer was used to measure the mean resistances to known gas flows provided by Cape, Servo and Ambu PEEP valves, and a water bottle with submerged 22-mm tubing. Two different Servo valves were assessed: an older type which has a brushed aluminium resistor plate with a spring behind it of slightly heavier duty than that in the (second) newer type, which can be identified by its black anodized aluminium plate.

Oxygen flows were supplied through a pre-calibrated, pressure-compensated flowmeter (GEC Elliot 2100). Measurements of resistance (represented by water displacement in the U-tube manometer) were taken at flows of 10, 20, 30, 40, 50, and 60 litre min⁻¹, and at nominal PEEP values of 0, 5, 10 and 15 cmH₂O.

The peak expiratory flow rate in quiet respiration is of the order of 25 litre min⁻¹ (Nunn, 1977). It was considered that a flow rate of 60 litre min⁻¹ would represent the upper limit of expiratory flow normally encountered in ITU practice.

**Pressure changes: flow rate changes**

The changes in airway pressure, gas flow rates and any inspiratory time lag were measured in the following CPAP systems: (i) the Servo 900B, using various PEEP/CPAP valves (via. Servo type 1 and 2, Cape and Ambu valves, and a water bottle); (ii) a Servo 900B modified such that the patient airway was connected directly to the inspiratory pressure transducer (Peters and Bennett, 1981); (iii) Servo 900C; (iv) Bennet MA2; (v) Engstrom Erica (these last three incorporate an integral CPAP system); and (vi) a "home-made" high flow circuit with a large inspiratory reservoir bag and either a water bottle or Ambu valve on the expiratory limb (fig. 1).

Measurements were made using a Hewlett-Packard pneumotachograph with Fleisch head (4703A digital Vertek series) in parallel with a Hewlett-Packard pressure transducer (series 1280) in the inspiratory limb. The amplified signals from these were recorded on a Hewlett-Packard two-channel chart recorder (type 7702). The inspiratory time lag between the instigation of inspiratory effort and the onset of inspiratory gas flow was calculated from the chart.

A healthy human male volunteer (DJN) breathed through a sealed mouthpiece connected to the various CPAP systems. A steady state was assumed to have been reached after 5 min and, following this recordings were taken for a minimum of 20 breaths.

The Servo ventilator systems were calibrated to the manufacturer's specification before use.

**RESULTS**

**Resistance to constant gas flow**

The resistances to gas flows at set nominal values of PEEP/CPAP on various valves are shown in figures 2–5. It can be seen that only the Ambu and water bottle systems were consistently uniform in performance when set to provide end-expiratory pressures. Moreover, it should be noted that, when no CPAP or PEEP was set on the valves, considerable resistance to flow was still encountered.

**Pressure changes and flow rate changes**

Maximum deviations from the "ideal" or baseline CPAP value during inspiration and expiration were measured. The mean values (n > 20 breaths in each case) are plotted in figure 6. The system which caused the greatest deviation was the Servo 900B combined with various PEEP/CPAP valves, including a water bottle used as an expiratory valve. The least deviation occurred when the conventional "home-made" reservoir bag/bottle circuit described
FIG. 2. Resistance to gas flow through various valves set at zero CPAP or PEEP.

FIG. 3. Resistance to gas flow with valves set at 5 cm H₂O CPAP.

FIG. 4. Resistance to gas flow with valves set at 10 cm H₂O CPAP.

FIG. 5. Resistance to gas flow with valves set at 15 cm H₂O CPAP.
earlier was used. The circuit fitted with the Ambu PEEP valve gave very similar results.

The Servo 900B showed considerable inspiratory delay which was significantly increased ($P < 0.001$) when any of the valves were added (fig. 7). However, when a water bottle was used in place of a PEEP/CPAP valve, this increase was not significant ($P > 0.1$). All significance testing was by Students' $t$ test. The "home-made" system with either a water bottle or Ambu PEEP/CPAP valve showed no inspiratory time delay (fig. 8).

The modification suggested by Peters and Bennett (1981) caused a significant reduction in the time delay compared with the unmodified Servo 900B,
but this was accompanied by a greatly increased inspiratory effort, possibly as a result of the narrow bore and increased length of the inspiratory pressure transducer tubing.

The Servo 900C system showed significantly less time delay than the 900B system \( (P < 0.001) \) with maximum inspiratory time delay 0.15 s. Both the Engstrom Erica and Bennet MA2 systems showed some inspiratory time delays, but again these were significantly shorter than the delay on the 900B \( (P < 0.01) \).

DISCUSSION

The results support our initial clinical impression and those of many who responded to our survey.

The Servo 900B system has considerable disadvantages when used in its spontaneous modes: that is, CPAP and the various IMV settings. These are, first, that there is an initial inspiratory time delay of up to 0.7 s during normal quiet respiration, which must increase the work expended during inspiration and, second, the large total deviation from the set CPAP value during both inspiration and expiration \( (\Delta P) \) which has been established as a further cause of an increase in the work of breathing (Gherini, Peters and Virgilio, 1979).

From the results it can be seen that the \( \Delta P \) is greatest in the Servo 900B systems and least with the "home-made" water bottle system.

The early part of the study demonstrated that the resistances to gas flow of the water-bottle and the Ambu valve were comparable in remaining almost constant with increasing flow rates. With all other valves resistance increased as gas flow increased, and this would cause an increase in \( \Delta P \).

\( \Delta P \) in a normal erect subject during quiet respiration at ambient airway pressure is zero. In practice it was decided that 5 cm H\(_2\)O should represent the maximum acceptable \( \Delta P \) in a CPAP system. The only ones which met this requirement were the home-made circuits using either a water-bottle or Ambu valve, and the Servo 900C. The Engstrom Erica and Bennet MA2 failed marginally to meet this criterion; in the case of the Erica the inspiratory assist mode may help to overcome the inspiratory resistance, and this is the subject of further investigation. In the majority of cases the \( \Delta P \) value for the Servo 900B was clearly well in excess of 5 cm H\(_2\)O, and at lower values of CPAP almost three times this value, thus increasing the work of breathing. This is clearly undesirable, especially during attempted weaning from IPPV. Even when no CPAP or PEEP is applied on the Servo 900B system, as in IMV, the \( \Delta P \) value of 10 cm H\(_2\)O and the inspiratory time delay of 0.33 s will both add considerably to the respiratory work demanded of the patient. We consider this to be an important factor in the poor acceptance of IMV by both patients and their attending clinicians in the U.K. compared with the United States, noting that 83% of our U.K. sample were using the Servo 900B in its spontaneous mode. These findings led us to develop a new method of IMV administration when using the Servo 900B (fig. 9). The IMV selector switch is used in the normal way, but the patient trigger control is turned to -20 cm H\(_2\)O. This ensures that the expiratory

![Graph showing mean inspiratory time delay using various CPAP delivery systems (n > 20 breaths).](image-url)
Ambu PEEP valve (if required) ±

![Diagram of IMV circuit attached to Servo 900B][1]

**Fig. 9.** IMV circuit attached to Servo 900B to overcome inspiratory time delay and therefore inspiratory work during the spontaneous phase. (Water bottle can be added at point indicated instead of Ambu PEEP valve.)

The valve is open throughout the spontaneous respiratory cycle, and only closes during mandatory inspiration. The high flow (approximately 20 litre min⁻¹) via the reservoir bag keeps the one-way valve added to the inspiratory limb open at all times except during mandatory inspiration from the ventilator.

Obviously, some of the commonly used methods of CPAP/IMV delivery are less than satisfactory. The discrepancy between the theoretical advantages of CPAP and IMV and the observed clinical benefits may well be attributable to these technical shortcomings.

The 900B system fulfils none of the requirements we lay down for either acceptable adult CPAP or the spontaneous phase of IMV (an inspiratory time delay < 0.15 s and ΔP < 5 cm H₂O). However, the "spontaneous" phase of IMV and CPAP modes of the Servo 900C system fulfil these requirements.

We believe that the most acceptable adult CPAP delivery system is the traditional "home-made" type using a high flow rate (30 litre min⁻¹), a large inspiratory reservoir bag, and either a water bottle or Ambu PEEP/CPAP valve to provide the positive pressures required (fig. 1).

If IMV is used, the inspiratory part of this circuit may be attached via a T-piece and one-way valve to the inspiratory limb of the ventilator (fig. 9).

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**References**


Nous avons entrepris de comparer les différents systèmes de CPAP/IMV en usage courant au Royaume-Uni. Le système le plus utilisé (Servo 900B) a des caractéristiques susceptibles d'accroître le travail respiratoire. Nous exposons ici quelques recommandations quant aux systèmes théoriquement les plus appropriés.

In einer Studie wurden die in Großbritannien meistbenutzten CPAP/IMV-Systeme miteinander verglichen. Das am häufigsten benutzte System (Servo 900B) hat Charakteristika, die mplierweise die Atemarbeit erhöhen. Es werden Empfehlungen bezüglich der theoretisch am meisten akzeptablen Systeme unterbreitet.

Se empredió un estudio para comparar los sistemas CPAP/IMV que son práctica corriente en el Reino Unido. El sistema más frecuente utilizado (Servo 900B) presenta características que seguramente incrementarán el esfuerzo respiratorio. Se efectúan recomendaciones relativas a los sistemas más aceptables desde el punto de vista teórico.