EVALUATION OF THE AMBU CPAP SYSTEM

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Continuous positive airways pressure (CPAP) is an established technique for improving arterial oxygenation when there is a mismatch of pulmonary ventilation and perfusion. This benefit is achieved largely by an increase in functional residual capacity (FRC) [1–3]. However, there is recent evidence to suggest that patients with ventilatory failure may benefit from the decrease in inspiratory work associated with the use of CPAP [1,4–6], and that CPAP may be a more physiological form of management than mechanical ventilation [1,7]. In patients with respiratory failure, atelectasis may reduce FRC, thereby decreasing compliance. Restoration of FRC towards normal increases compliance and decreases airways resistance and inspiratory work [6]. In order to keep the work of ventilation to a minimum, little or no variation in airway pressure should occur during breathing [1,5]. This is best achieved with a high gas flow in the patient circuit [8], or by using a lower flow with a weighted bellows or a large volume–high compliance reservoir bag [9–11]. These maintain the pressure in the system by buffering the changes in flow during inspiration and expiration.

DESCRIPTION OF APPARATUS

Ambu International Ltd of Denmark has introduced a system combining the advantages of a high flow in the patient circuit with a low consumption of fresh oxygen (fig. 1). The gas flow is achieved by a Venturi driven by oxygen at a pressure of 3–4 bar, entraining air into a large (5-litre) compliant reservoir bag. This mixture may be enriched further by additional oxygen through an inlet on the bag mount. The gas mixture passes through a 1-m length of disposable corrugated tubing (and humidifier if desired) to a patient Y-piece. The expiratory limb of the Y-piece is connected to an adjustable spring loaded valve which provides the pressure difference between the circuit and the atmosphere. The valve consists of a circular plate pressed against a plastic seating by two springs. The mechanism is encased in a plastic housing. The pressure of gas in the system lifts the plate against the springs and allows gas to escape through the orifice. As the flow across the valve increases, the orifice increases also so that a relatively constant pressure is maintained in the circuit. In the steady state the pressure created by the compliance of the bag is sufficient to drive gas

SUMMARY

We have assessed a Venturi driven device for delivering continuous positive airway pressure (CPAP) using a reservoir bag and expiratory valve under conditions of continuous flow and simulated spontaneous breathing. The system performed well and was economical, consuming only 3.5 litre min⁻¹ of fresh gas. One Venturi was partially blocked and performed inadequately, but the function of a second one was close to the manufacturer’s specification (inspired oxygen 33%, flow 20 litre min⁻¹ against end-expiratory pressures of 0–1.8 kPa). Compliance curves for two reservoir bags (new and old) were defined; these showed that compliance increased as the pressure in the circuit increased. The characteristics of the expiratory valve approached those of a threshold resistor. Small fluctuations in airway pressure occurred at all settings of CPAP and decreased with the increasing compliance of the circuit at higher values of CPAP. The method provided to monitor the airway pressure was inaccurate and overestimated the true pressure by 20% at pressures greater than 1 kPa.
AMBU CPAP SYSTEM

FIG. 1. Diagram showing the general arrangement of the Ambu CPAP system.

FIG. 2. The Ambu CPAP buffer reservoir bag showing the transparent strap provided to measure the pressure.

The CPAP is gauged by measuring the distension of the bag using a transparent strap with a graduated scale of numbers which hangs in front of a single horizontal line drawn on the bag (fig. 2).

The manufacturers state that the system supplies fresh gas at a flow of 20 litre min\(^{-1}\) to the patient circuit. It is capable of delivering CPAP between 0 and 1.8 kPa, with an \(F_{1o_2}\) of 0.33 (when the Venturi is driven by oxygen but with no auxiliary oxygen). The airway pressure should vary less than 0.2 kPa during quiet breathing. The Venturi consumes oxygen at 3.5 litre min\(^{-1}\).

The instructions for use indicate that the system, with the exception of the Venturi and reservoir bag, can be cleaned by any conventional heat, chemical or gas sterilizing method. The reservoir bag should not be autoclaved, and the Venturi does not require cleaning.

MATERIALS AND METHODS

The Venturi, reservoir bag and expiratory valve were studied separately.

Analysis of the Venturi entrainment system

The device was assessed to see how the amount of CPAP would affect the total gas flow delivered to the patient circuit. The Venturi was connected to the hospital oxygen pipeline system at 4 bar. The patient Y-piece was replaced by a connection with a side arm attached to a spirit-filled manometer calibrated in mbar (0.1 kPa). Because of the difficulty in collecting gas issuing from the CPAP valve, the valve was replaced by a length of silastic tubing with an adjustable gate-clip. This was connected to a dry gas meter (Singer DTM-115) to measure the total flow through the system at ambient pressure. The time for 100 litres of gas to pass at constant flow through the system at pressures of 0–1.8 kPa was recorded and the flows expressed in litre min\(^{-1}\). At each value of CPAP three flow measurements were made; in addition, the mean concentration of oxygen was calculated from three gas samples which were withdrawn from the system into a 100-ml oiled ground-glass syringe and analysed using a paramagnetic oxygen analyser (Servomex OA 101 MkII).

Analysis of the compliance characteristics of the reservoir bag and system

To investigate the compliance characteristics of the whole system, the pressure in the system was measured with the manometer as 100-ml increments of air were added from the ground-glass syringe through a three-way tap. The Y-piece in the patient circuit, the additional oxygen inlet to the bag and the CPAP valve at the end of the expiratory limb were sealed with rubber bungs (fig. 3). There is a one-way valve at the outlet from the bag mount directed into the patient circuit which prevents free communication between all parts of the system; this outlet was also sealed with a bung and the circuit connected to the bag mount via the Venturi inlet port and a double side arm for the attachment of the syringe and manometer. The whole system was tested for
leaks using soap solution before the pressure measurements were made. To see if the compliance of the bag changed with age and use, a new bag and a bag which had been pressurized during use for several hours were tested. The reading taken from the transparent strap on the side of the bag was compared with the manometer pressure.

Analysis of the Ambu CPAP valve

The pressure across the valve was measured at different flows to see whether the valve functioned as a flow or as a threshold resistor. The manometer and CPAP valve were placed in series with a calibrated flow meter delivering air up to 100 litre min⁻¹. The valve was adjusted to give a pressure of 0.5 kPa at 20 litre min⁻¹ flow and at that setting a series of pressure measurements was made as the flow was increased from 10 to 70 litre min⁻¹ in 10-litre min⁻¹ steps. Another set of readings was taken as the flow was reduced in stepwise fashion from 70 to 10 litre min⁻¹. The process was repeated for pressure settings of 1.0, 1.5 and 2.0 kPa.

In addition, measurements were made to demonstrate the effect of gravity on the characteristics of the valve. First, the valve was set to give a pressure of 1.0 kPa at a flow of 20 litre min⁻¹ whilst held with its axis horizontal. The pressures were measured as the flow was changed stepwise between 10 and 70 litre min⁻¹ as above, but with the distal end of the valve pointing upwards, horizontally or downwards.

Pressure variation during the ventilatory cycle

In order to examine the pressure fluctuations which occur whilst breathing at different values of CPAP, the system was connected to a lung model which simulates spontaneous ventilation. Flow, tidal volume and pressure in the bag and at the Y-piece were measured during the ventilatory cycle. A mechanically operated lung simulator was constructed to ensure a similar pattern of inspiratory and expiratory flow at all values of CPAP. It consisted of a pair of spring loaded bellows mounted in parallel on a rigid frame, and therefore linked mechanically. One bellows was driven by a ventilator (Penlon Nuffield Series 200), whilst the other bellows acted as the lung model for spontaneous ventilation. A resistance of 2.0 kPa litre⁻¹ s⁻¹ was placed in series with the lung bellows (fig. 4). A flow approximating to a square wave was generated during inspiration, with a decreasing flow in expiration. The Y-piece of the CPAP circuit was attached to the lung model through a Fleisch No. 1 pneumotachograph and the pressure across it was measured with a differential pressure transducer (Validyne) to derive flow. Electrical integration of the flow signal (Morgan Respiration Integrator Mk11) gave tidal volume. The pressure in the circuit was
measured with a pressure transducer (Gould) connected between the Y-piece and the pneumotachograph, whilst the pressure in the bag was measured simultaneously through the auxiliary fresh gas port. The four signals were displayed on a chart recorder (Electromed MX19).

Calibration of the pressure and volume signals was carried out with the manometer and a 1-litre syringe, and the flow signal was calibrated with air from a flowmeter. The lung simulator was adjusted to give tidal volumes of 500 ml at a rate of 12 b.p.m. with an inspiratory:expiratory time ratio of 1:2. Inspiratory flow was approximately 15 litre min$^{-1}$ with a peak expiratory flow of approximately 40 litre min$^{-1}$ increasing to 50 litre min$^{-1}$ at greater values of CPAP as the bellows compliance decreased. At each 0.2-kPa increment between 0 and 1.8 kPa, the CPAP valve was adjusted to give the required airway pressure at a constant flow with the lung simulator “switched off”. During simulated spontaneous breathing, recordings were made of the fluctuation of pressure in the bag and at the Y-piece, with the flow and volume changes.

RESULTS

Characteristics of the Venturi and bag

The first Venturi studied (A) delivered a lower than expected flow, because of a partial blockage in the jet. A second Venturi (B) was tested subsequently. When CPAP was increased from 0 to 1.8 kPa using Venturi A, there was a mean reduction of gas flow through the patient circuit of 7.20 litre min$^{-1}$ (from 18.69 litre min$^{-1}$ to 11.49 litre min$^{-1}$) and the inspired oxygen concentration increased from 31.0% to 34.7%. For Venturi B, the flow was 20.33 litre min$^{-1}$ at 0 kPa, decreasing to 18.69 litre min$^{-1}$ at 1.8 kPa. The inspired oxygen concentration increased from 35.1% to 36.2%.

As the pressure increased, the strap reading overestimated the actual pressure (table I).

As the volume of the two bags increased, compliance increased progressively and there was virtually no difference in compliance between the new and used bags (fig. 5).

![Diagram](https://example.com/diagram.png)

**Fig. 4.** Flow diagram showing how the system was connected to the simulated lung and monitoring (see text).

![Graph](https://example.com/graph.png)

**Fig. 5.** Compliance of the system. □——□ = New bag; ■——■ = worn bag.
TABLE I. The characteristics of the Ambu Venturi with increasing pressure in the airway. Two Venturis were assessed after Venturi A was found to have a partially blocked orifice causing the air entrainment to be lower than expected. The strap on the side of the reservoir bag was set initially to zero when the manometer reading was zero. Each value shown is the mean of three readings.

<table>
<thead>
<tr>
<th>Manometer reading (kPa)</th>
<th>0</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>1.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strap reading</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Venturi A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow in circuit (litre min⁻¹)</td>
<td>18.69</td>
<td>17.34</td>
<td>13.76</td>
<td>12.26</td>
<td>11.49</td>
</tr>
<tr>
<td>Oxygen delivered (%)</td>
<td>31.00</td>
<td>31.75</td>
<td>32.50</td>
<td>32.85</td>
<td>34.70</td>
</tr>
<tr>
<td>Venturi B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow in circuit (litre min⁻¹)</td>
<td>20.33</td>
<td>19.86</td>
<td>19.42</td>
<td>18.86</td>
<td>18.69</td>
</tr>
<tr>
<td>Oxygen in circuit (%)</td>
<td>35.10</td>
<td>35.25</td>
<td>35.50</td>
<td>35.93</td>
<td>36.20</td>
</tr>
</tbody>
</table>

TABLE II. The pressure decrease (kPa) measured across the Ambu CPAP valve. The valve was adjusted to each setting with a flow of 20 litre min⁻¹, and the flow was then varied between 10 and 70 litre min⁻¹ while the actual pressure change was measured with the manometer. Measurements were made as flow was increased to 70 litre min⁻¹ (up), and again as flow was decreased to 10 litre min⁻¹ (down).

<table>
<thead>
<tr>
<th>Gas flow (litre min⁻¹)</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Up</td>
<td>Down</td>
<td>Up</td>
<td>Down</td>
</tr>
<tr>
<td>10</td>
<td>0.48</td>
<td>0.48</td>
<td>0.99</td>
<td>0.98</td>
</tr>
<tr>
<td>20</td>
<td>0.50</td>
<td>0.50</td>
<td>1.0</td>
<td>0.99</td>
</tr>
<tr>
<td>30</td>
<td>0.54</td>
<td>0.54</td>
<td>1.03</td>
<td>1.01</td>
</tr>
<tr>
<td>40</td>
<td>0.58</td>
<td>0.55</td>
<td>1.07</td>
<td>1.04</td>
</tr>
<tr>
<td>50</td>
<td>0.61</td>
<td>0.57</td>
<td>1.07</td>
<td>1.05</td>
</tr>
<tr>
<td>60</td>
<td>0.61</td>
<td>0.60</td>
<td>1.08</td>
<td>1.05</td>
</tr>
<tr>
<td>70</td>
<td>0.64</td>
<td>0.60</td>
<td>1.06</td>
<td></td>
</tr>
</tbody>
</table>

Characteristics of the Ambu CPAP valve

There was a slight increase in pressure as flow across the valve increased. This was least when the valve was set at 1 kPa (table II). There was also a hysteresis between pressures measured whilst flow was increased and decreased, the pressure being slightly lower during the decreasing phase. The pressure was consistently 0.16 and 0.18 kPa greater at all flows when the valve was held outlet-upwards, compared with outlet-downwards (table III).

Pressure variation during the ventilatory cycle

At a constant flow, the pressure in the bag (PB) was 0.1 kPa greater than at the Y-piece (PY) at all values of CPAP (table IV). When 500-ml tidal volumes were inspired by the simulated lung, PY and PB fluctuated, decreasing to less than their set values during inspiration and increasing above them during expiration. As CPAP increased between 0.2 kPa and 1.6 kPa, the fluctuation of PY declined from 0.4 kPa to 0.16 kPa. The fluctuation in PB decreased from 0.16 kPa to 0.07 kPa between 0.2 kPa and 1.6 kPa CPAP. At 1.6 kPa CPAP, the increase in PB during expiration disappeared, and the fluctuation resulted only from the decrease in pressure during inspiration (fig. 6).

DISCUSSION

Venturi

Although large compliant bags and adjustable valves have been used to deliver CPAP, they required a supply of 20–30 litre min⁻¹ of fresh gas to buffer the effects of the ventilatory cycle. In contrast, this Venturi driven system uses only 3.5 litre min⁻¹ of oxygen, but still supplies 20 litre min⁻¹ of gas to the patient circuit. One of its major features is that it is more economical than many other devices. Increasing the CPAP decreased the pressure change across the Venturis and this
TABLE III. Variation in pressure decrease measured across the Ambu CPAP valve with the valve in the horizontal, distal end upwards and distal end downwards positions. The valve was set to 1.0 kPa with a flow 20 litre min\(^{-1}\) whilst in the horizontal position. Measurements of actual pressure change were made using the manometer at flows between 10 and 70 litre min\(^{-1}\).

<table>
<thead>
<tr>
<th>Gas flow (litre min(^{-1}))</th>
<th>Pressure decrease across CPAP valve (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upwards</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>20</td>
<td>1.11</td>
</tr>
<tr>
<td>30</td>
<td>1.13</td>
</tr>
<tr>
<td>40</td>
<td>1.14</td>
</tr>
<tr>
<td>50</td>
<td>1.16</td>
</tr>
<tr>
<td>60</td>
<td>1.15</td>
</tr>
<tr>
<td>70</td>
<td>1.16</td>
</tr>
</tbody>
</table>

TABLE IV. Fluctuation of pressure in the bag (PB) and at the patient Y-piece (PY) recorded throughout the ventilatory cycle as CPAP was increased from 0.2 kPa to 1.6 kPa. PY includes the initial transient “opening” pressure of the valve.

<table>
<thead>
<tr>
<th>CPAP (kPa)</th>
<th>0.2</th>
<th>0.6</th>
<th>1.2</th>
<th>1.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>PY (kPa)</td>
<td>0.40</td>
<td>0.23</td>
<td>0.30</td>
<td>0.16</td>
</tr>
<tr>
<td>PB (kPa)</td>
<td>0.16</td>
<td>0.10</td>
<td>0.08</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Fig. 6. Traces obtained during simulated spontaneous breathing at 0.2, 0.6, 1.2 and 1.6 kPa CPAP. The pressure was set at the Y-piece. The zero was offset on the PY and PB traces to record pressures at 1.2 kPa and again at 1.6 kPa. Inspiratory flow is negative on the trace.

Reduced air entrainment and total gas flow in the circuit. Thus the oxygen:air ratio increased with increasing CPAP. Venturi B exceeded the manufacturer’s claim of 33% oxygen in the circuit at all values of CPAP. The flows obtained from Venturi A were much less than expected because of a partial blockage of the Venturi orifice, causing a low oxygen flow and reduced air entrainment. We presume that this was caused by dirt from the hospital pipeline, but it is possible that it was a manufacturing fault. In clinical use, reduced flows would remain unnoticed. Although the entrained air passes through a sintered brass filter, there is no filter before the Venturi jet to prevent silting. As the instructions state, the Venturi cannot be disassembled for cleaning. In addition, the Venturis were rather noisy.

Reservoir bag

The Ambu CPAP bag is constructed from latex and its compliance increases with increasing CPAP. Whilst the bags appear to withstand the pressures at which they would be used clinically without changing their compliance characteristics, extrapolation of the compliance curve (fig. 5) indicates that at approximately 2.3 kPa progressive distension and bursting of the bag would occur without any further increase in pressure. This makes it impossible to generate dangerously high pressures in the patient’s airway if the outlet from the circuit becomes obstructed.

CPAP valve

The Ambu CPAP valve acted as a reasonably good threshold resistor, because the resistance decreased as the flow across the valve increased. The Ambu valve performed better than some other designs [12, 13] as the pressure decrease across the valve increased only a little as the flow
increased. However, the pressure was greater when it was held with its distal end upwards than downwards. This is because gravity acts with the spring in the former position, but against the spring when it is held end downwards. To overcome this, there is a plastic loop on top of the bag-mount to hold the valve in the horizontal position. The pressure change across the valve at each level of flow was higher when increasing the flow in incremental steps than when decreasing it. This hysteresis is characteristic of stress deformation [14], but is seen more often with synthetic materials than with metals.

Airway pressure variation during the ventilatory cycle

In any system where there is airflow resistance in the breathing circuit, the airway pressure decreases during inspiration and increases during expiration. However, if there is a continuous flow in the circuit greater than the patient's inspiratory flow, the resistance sensed by the patient during inspiration is negligible [15] and the characteristics of the CPAP valve govern the pressure change. If the valve acts as a pure threshold resistor, airway pressure during inspiration should not decrease until inspiratory flow exceeds the continuous flow in the circuit. When this occurs, the pressure in the circuit is maintained by the elastic properties of the bag, and decreases as gas in withdrawn from the bag according to its compliance characteristics. Further, during expiration, airway pressure should not increase above the value of CPAP set by the valve if it has threshold characteristics.

PY and PB deviated from their settings even though inspiratory flow did not exceed the continuous flow from the Venturi. The valve is therefore not a true threshold resistor, and the bag is necessary to buffer the change in pressure by supplementing the inspiratory flow. Because of the shape of the compliance curve of the reservoir bag, this effect might be expected to decrease as CPAP increases [11] (fig. 5), and the study confirmed this (table IV, fig. 6). PY decreased least during inspiration when the CPAP valve was set at approximately 1 kPa (fig. 6), when the threshold properties of the valve are most efficient (table II).

During expiration, the characteristics of the bag are not relevant because, as soon as the pressure in the circuit exceeds that in the bag, the one-way valve closes and diverts all the gas from the Venturi into the bag, and all the expired gas out through the CPAP valve. Following a high transient, expiratory pressure increases to that expected during peak expiratory flow (table II). The initial high transient appears to be a result of inertia in the valve. Expiratory work is related to the area under the expiratory pressure curve. The additional work required to overcome this opening pressure is therefore the area enclosed by this transient peak, and is probably not significant clinically compared with the total work of expiration.

The pressure measured in the bag was consistently 0.1 kPa greater than that measured at the Y-piece, because of the resistance of the one-way valve at the connection of the circuit to the bag mount and that of the circuit (approximately 0.3 kPa litre⁻¹ s⁻¹). Although the system was assessed without a humidifier, this would affect the pressure fluctuations during quiet breathing by adding further resistance to the circuit.

In conclusion, this system is well designed and performs adequately. Its economical consumption of fresh gas makes it suitable particularly for long-term use in the intensive therapy unit.

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