

Inter-machine variability in the stability of continuous positive airway pressure

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ABSTRACT: Two studies were performed to investigate the differences in pressure stability performance of the continuous positive airway pressure (CPAP) machines used by our patients.

The variations of mask pressures during each respiratory cycle were measured during overnight studies of two groups of patients with obstructive sleep apnoea, who were using either a Sleep-Easy III CPAP machine or a Si-Plan CPAP unit. The patients were well-matched for age, weight and neck circumference. The group using the Si-Plan unit had more constant mask pressures and were using lower CPAP pressures (mean 10.6 cmH₂O) than those using the Sleep-Easy III machine (mean 13.8 cmH₂O) ($p < 0.02$).

The pressure stability performance of five CPAP machines used by our patients was also compared using standardized simulated patient breaths produced by a negative pressure cuirass pump. There were large differences between the machines in ability to maintain a constant pressure. Using a tidal volume of 0.5 l and peak flow rates of between 20-40 l·min⁻¹ the pressure variation ranged from 0-67% of the minimum inspiratory pressure.

The maintenance of a constant pressure during inspiration and expiration lowers the mean pressure required to eliminate obstructive sleep apnoeas and reduces the likelihood of pressure related side-effects.

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Obstructive sleep apnoea is a common and more frequently recognized condition with a prevalence of up to 1% in men of working age. Since its introduction in 1981 [1], the effectiveness of nasal continuous positive airway pressure (CPAP) has become well-established and a large number of CPAP machines are now in use. Our own unit first offered CPAP treatment in 1986 and now has over 90 patients with machines at home.

When initiating CPAP it is usual to determine the minimum pressure that is effective in order to reduce the incidence of pressure related side-effects. This pressure is determined during an overnight study by gradually increasing the mask pressure until episodes of airway obstruction are abolished. We have observed wide variations in the measured mask pressure, both within respiratory cycles and with different CPAP machines.

We have performed two studies in order to investigate the magnitude of these pressure variations. In the first study, we measured the variation in mask pressure during each respiratory cycle in patients treated with two different CPAP machines. In the second study, we tested the stability of pressure delivered by five different CPAP machines which are in use by our patients by using a series of standard reproducible simulated patient breaths.

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Methods

Patient study

Twenty male patients (mean age 56 yrs) were studied. Ten used the Sleep-Easy III CPAP machine with the Sanders circuit (Respironics Inc., Monroeville, USA) and ten were using the Si-Plan unit (Si-Plan Electronics Research Ltd, Stratford upon Avon, UK), using a mask with a 4 mm blow-hole. Each group of 10 were consecutive admissions of patients using the two machines. The patients were well-matched for age, weight and neck circumference (tables 1 and 2). The patients using the Sleep-Easy III machine had been treated with CPAP for a longer time, reflecting the relatively recent introduction of the Si-Plan unit. Oxygen saturation (Ohmeda Biox 3700 pulse oximeter) and mask pressure were continually measured throughout an overnight study using a calibrated 0-50 cmH₂O pressure transducer (Si-Plan Electronics Research Ltd). The pressure was recorded on a thermal array recorder (Astra-Med Dash 2 recorder) at a chart speed of 10 mm·min⁻¹ to allow measurement of changes of pressure during individual breaths. The mean maximum and minimum mask pressures were calculated from measurement over 50 consecutive

breaths at three separate periods during the study. The periods were selected to be at times when the patients were observed to be asleep and oxygen saturation and mask pressure recordings stable. The changes in mask pressure were calculated as a percentage of both the minimum and maximum mask pressures.

Machine study

Five CPAP machines were studied. They were the Respironics Sleep-Easy III, Sefam Pression, Puritan-Bennett 515a, Healthdyne 9000 and the Si-Plan CPAP unit.

An inspiratory effort was simulated using a negative pressure cuirass pump (Newmarket Pump, Si-plan Electronics Research Ltd), to produce peak flow rates of 20–60 $l \cdot \text{min}^{-1}$ and cycle volumes of 0.5, 0.75 and 1 l . The pressure waveform was a half sine wave.

Table 1. — Details of patients using the Si-Plan CPAP unit

Pt. no.	Age yrs	Time on CPAP months	Wt kg	Ht cm	Neck circ. cm	Occ. hose pressure cmH_2O
1	67	5	112.8	170	47	15
2	69	5	117.5	176.5	45	11.5
3	45	4	95.7	178	43	8
4	49	3	83.7	167.5	42.5	9
5	40	6	123.5	178	45	13
6	71	3	86.5	175.5	43.5	9
7	72	2	93.3	178	43	11
8	44	2	74.7	173	40	6
9	50	1	106.5	185.5	43.5	8
10	56	4	147.6	190.5	52.5	15
Mean	56	3.5	104.2	177.25	44.5	10.6
sd	12.4	1.58	21.9	6.8	3.4	3.1

CPAP: continuous positive airway pressure; circ.: circumference; Pt.: patient; Occ.: occluded.

Table 2. — Details of patients using Sleep-Easy III machine

Pt. no.	Age yrs	Time on CPAP months	Wt kg	Ht cm	Neck circ. cm	Occ. hose pressure cmH_2O
1	39	12	127	174	48	16
2	66	6	85.3	179	42.5	14.5
3	33	14	144	178	47	16
4	60	48	92.5	173	44.5	17
5	62	20	155.2	171.5	59	13
6	67	7	83	175.5	42	16
7	67	16	86.3	170.5	42	11
8	71	3	86.5	175.5	43.5	12
9	48	24	97.5	180.5	43	8.8
10	50	2	90.6	164	43	14
Mean	56	15.2	104.8	174.2	45.5	13.8
sd	13.1	13.6	26.9	4.8	5.2	2.6

CPAP: continuous positive airway pressure; circ.: circumference; Pt.: patient; Occ.: occluded.

Flow and volume were measured using a pneumotachograph (P.K. Morgan Ltd). Pressure was measured using a calibrated 0–20 cmH_2O pressure transducer (Si-Plan Electronics Research Ltd). All signals were recorded on a computer-based data logger and hard copies made on a plotter (fig. 1).

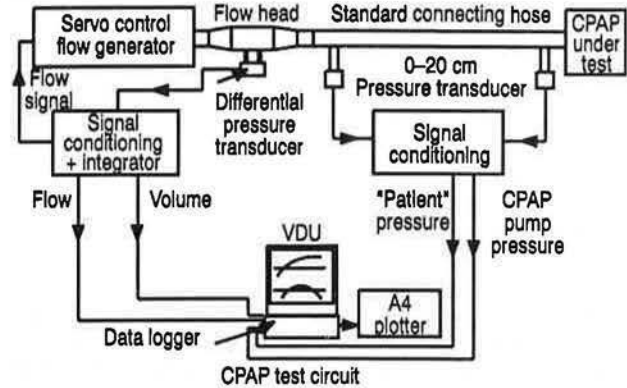


Fig. 1. — Circuit diagram of the machine study. CPAP: continuous positive airway pressure machine; VDU: visual display unit.

The CPAP machines were each set at 5, 10 and 15 cmH_2O with the set pressure being that recorded at the patient end of the hose with that end occluded. The change of pressure at the patient end of the hose was measured during the simulated inspiratory efforts.

A similar comparison was made with the machines set at 10 cmH_2O and with the cuirass pump pressure delivered as a full sine wave simulating inspiration and expiration producing a peak flow rate of 45 $l \cdot \text{min}^{-1}$.

The differences between occluded pressures used by the patients and the overnight mask pressure variations were analysed using the two sample t-test, taking $p < 0.05$ to indicate a significant difference.

Results

Patient study

The patients treated using the Si-Plan unit tended to use lower CPAP pressures (mean 10.6 cmH_2O , sd 3.08) compared with those using the Sleep-Easy machine (mean 13.8 cmH_2O , sd 2.62 cmH_2O) ($p < 0.02$). During sleep the mask pressures varied between 0.5–1.5 cmH_2O (mean 0.96 cmH_2O) in the Si-Plan group and between 2–3.9 cmH_2O (mean 2.68 cmH_2O) in the Sleep-Easy group ($p < 0.001$). As percentages of the minimum (inspiratory) pressure this was equivalent to a fall of pressure of between 16.1–34.2% in the group using the Sleep-Easy III machine and between 3.9–13.9% in the group using the Si-Plan unit. Similarly as a percentage of the maximum (expiratory) level the pressure falls represented between 13.9–25.5% in the Sleep-Easy group and between 3.8–13% in the Si-Plan group. The individual pressure variations in the two groups are shown in figure 2 and the percentage falls of pressure in relation to the maximum and minimum mask pressures are shown in figure 3a and b.

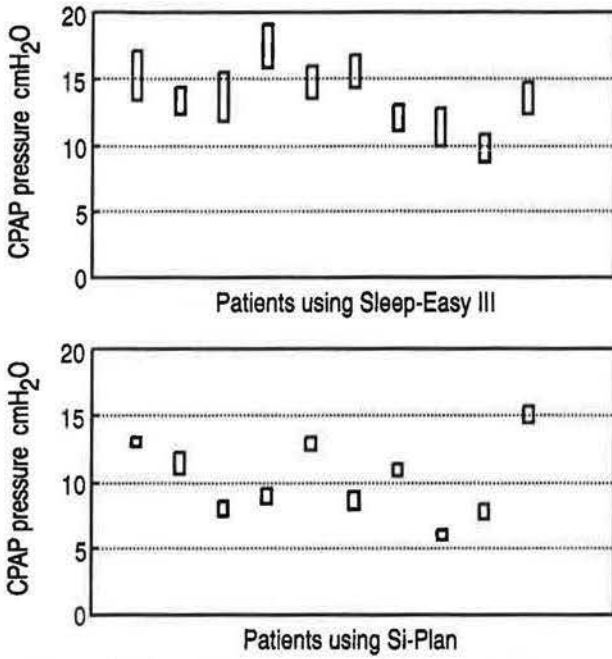


Fig. 2. - Individual mask pressure variations in the two groups of patients. CPAP: continuous positive airway pressure.

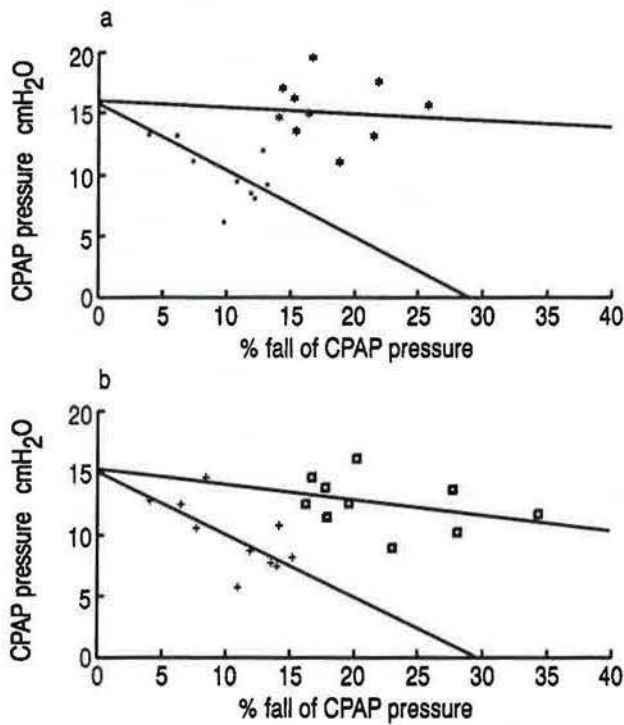


Fig. 3. - a) Falls of mask pressure as a percentage of the maximum mask pressure. —●— : Si-Plan; —◆— : Sleep-Easy. b) Falls of mask pressure as a percentage of the minimum mask pressure. —+— : Si-Plan; —■— : Sleep-Easy. CPAP: continuous positive airway pressure.

Machine study

There was little intra-machine variability on repeated testing at individual settings of flow, volume and set pressure. There were, however, considerable differences between the performance of the five machines.

When the CPAP machines were subjected to a simulated inspiration of 0.5 l at peak flow rates of 20–40 l·min⁻¹ the falls of pressure varied between 0–67% of the lowest ("inspiratory") pressure. The larger falls were recorded with the combination of lower set pressures and higher "inspiratory" flow rates (fig. 4). At higher flow rates of 50 and 60 l·min⁻¹ and a tidal volume of 0.75 l the same trend was observed, with falls of delivered pressure of between 2.7–95% of the inspiratory level. The Si-Plan unit performed best at all combinations of tidal volume and inspiratory flow.

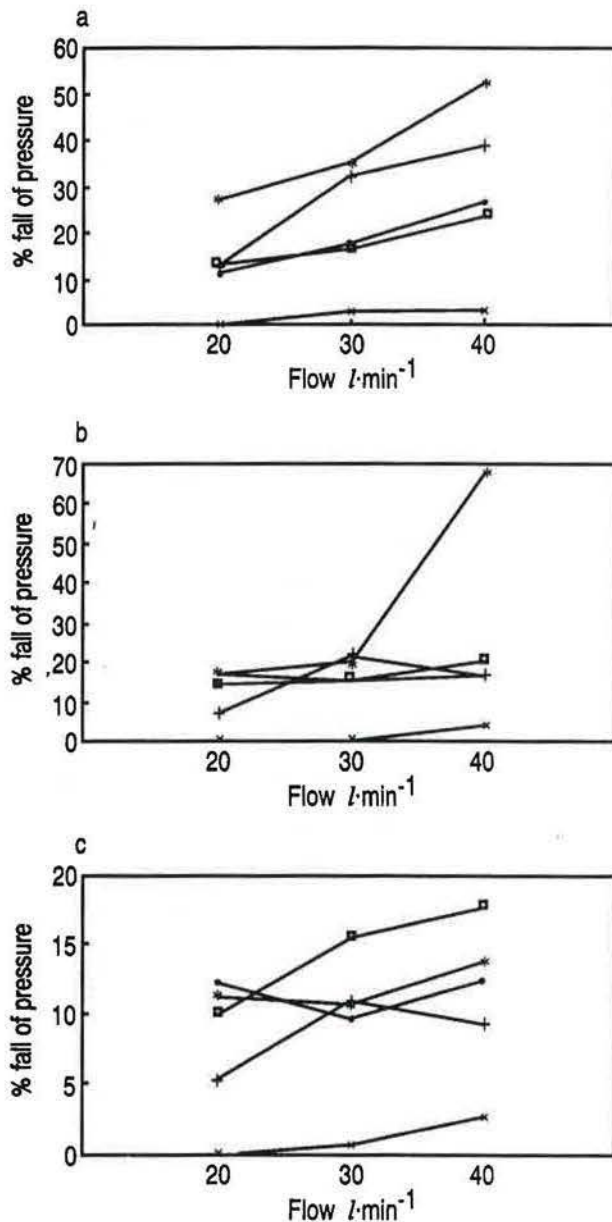


Fig. 4. - Machine study: falls of pressure expressed as a percentage of the minimum pressure when subjected to simulated inspiration of 0.5 l at flow rates of 20, 30 and 40 l·min⁻¹. CPAP pressure set at: a) 5 cmH₂O; b) 10 cmH₂O; c) 15 cmH₂O. —x— : Si-Plan; —+— : Sleep-Easy III; —◆— : Puritan Bennett 515a; —□— : Healthdyne; —●— : Sefam.

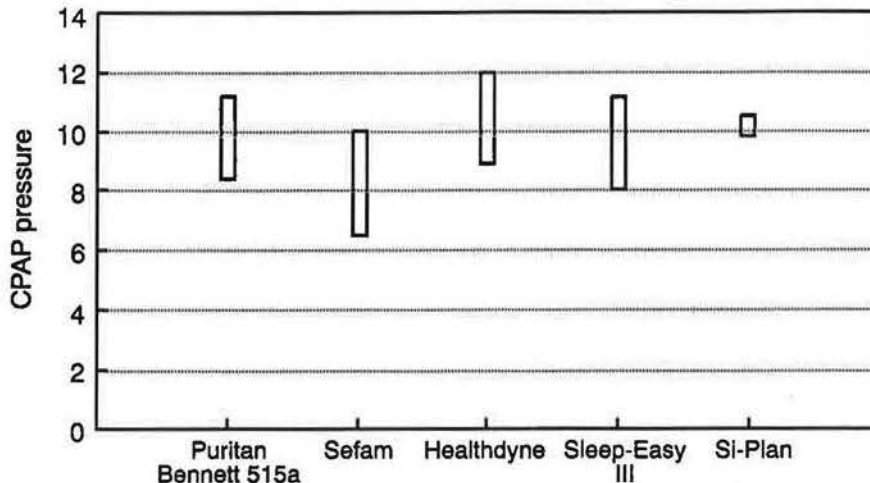


Fig. 5. - Machine study: CPAP variation in response to simulation of full respiratory cycle. Sine pressure wave form CPAP set at 10 cmH₂O. Flow 45 l·min⁻¹. TV 0.5 l. CPAP: continuous positive airway pressure; TV: tidal volume.

The full respiratory cycle simulation, with a tidal volume of 0.5 l and a peak flow rate of 45 l·min⁻¹ at a set pressure of 10 cmH₂O, resulted in pressure falls of between 0.2–3.5 cmH₂O during the inspiratory phase and an expiratory overshoot of between 0–2 cmH₂O with the different machines (fig. 5).

Discussion

The mechanism of action of CPAP has been the subject of a number of studies. Some have suggested that the maintenance of upper airway patency is mediated by lung inflation with a raised functional residual capacity (FRC) [2–4]. It is, however, more likely that CPAP works primarily as a pneumatic splint [5, 6], with the raised intraluminal pressure opposing the forces tending to collapse the airway.

The timing of airway closure during sleep apnoeas has been investigated, with some authors relating it to the negative intraluminal pressures generated on inspiration [7–9] and others to the narrowing of the airway that occurs on expiration [10, 11]. It is likely that both factors are important, with a narrowed airway at end expiration completely closing when negative pressure develops at the onset of inspiration. Obstructive sleep apnoea occurs most commonly in obese individuals, probably because of mass loading of the collapsible portion of their upper airways [12–14], which increases the likelihood of airway narrowing on expiration.

The importance of the timing of the application of the positive pressure during the respiratory cycle has recently been investigated. Although positive airway pressure is conventionally delivered during both inspiration and expiration, studies using a machine in which the inspiratory and expiratory airway pressure could be independently adjusted (Bi-PAP) showed that a lower level of expiratory positive airway pressure (EPAP) was required when delivered with an inspiratory positive airway pressure (IPAP) which is no different to the effective CPAP pressure [15].

The patient's inspiratory effort draws air from the CPAP circuit and tends to lower the pressure. The minimum pressure during inspiration is conventionally taken as the CPAP pressure. Most CPAP machines maintain this minimum inspiratory pressure at the expense of expiratory pressures that are higher than required. During expiration, the exhaled gas from the patient is added to the CPAP system and the pressure rises unless it is controlled by a rapidly responding servo-system. The ideal machine would maintain the critical (minimum) inspiratory pressure throughout inspiration with little rise in expiratory pressure.

The machine study has shown that there is a great variation in the ability of the different CPAP machines to maintain a constant pressure level. If the level of the minimum inspiratory pressure is the critical determinant of airway stability then the peak to trough difference is the pressure unnecessarily delivered during expiration. Our study has shown that a considerable pressure may be unnecessarily delivered during expiration by some machines but that this can be clearly reduced under comparable conditions of flow and volume by using a machine with good maintenance of inspiratory pressure.

The patient study has shown that the mask pressure varies by as much as 34% of the minimum mask pressure with conventional machines. This variability can be considerably reduced by using a machine such as the Si-Plan unit, which allowed, at most, a fall of only 12% of the minimum mask pressure.

The clinical importance of using a machine with a well-maintained inspiratory pressure is that it reduces the mean CPAP pressure required to achieve upper airway stability and abolish the obstructive apnoeas. This is reflected in the patient study by the lower CPAP pressures required in patients using the Si-Plan CPAP unit.

The use of machines which will deliver the minimum required inspiratory pressure in this way will reduce the adverse effects of high pressure such as middle ear symptoms, gastric distension and air leaks

which may cause conjunctival irritation [16]. A lower peak mask pressure may also allow looser adjustment of the CPAP mask and reduce the likelihood of pressure sores.

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