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TECHNICAL NOTE

Do turbines with servo-controlled speed improve continuous positive airway pressure generation?

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Do turbines with servo-controlled speed improve continuous positive airway pressure generation? F. Lofaso, L. Heyer, A. Leroy, H. Lorino, A. Harf, D. Isabey. ©ERS Journals 1994.

ABSTRACT: Nasal continuous positive airway pressure (CPAP) devices with a servo-mechanism to control pressure have recently been developed. We evaluated six such devices and three conventional systems in terms of effectiveness in maintaining constant pressure.

Machines were tested with pressure levels of 5, 10 and 15 cmH$_2$O. Dynamic behaviour was evaluated: 1) by calculating the imposed work of breathing during simulated breath generated by a sinusoidal pump; and 2) by following the fall in pressure after a transient flow of 1 $l \cdot s^{-1}$. Quasi-static behaviour was evaluated by simulating a predetermined air leak.

Under dynamic conditions, work of breathing was lowest with one conventional nasal CPAP device and three servo-controlled nasal CPAP devices; whereas, the highest levels of work of breathing were recorded with two servo-controlled nasal CPAP devices. The pressure-time response to a transient flow yielded similar results, with a significant inverse correlation between pressure values observed after 300 ms and imposed work of breathing during simulated breathing (r=-0.91). Under quasi-static conditions, microprocessor servo-controlled devices exhibited the best performance.

These results suggest that microprocessor servo-controlled nasal CPAP devices are not always the best systems for maintaining constant airway pressure in dynamic situations. However, they are more effective in ensuring maintenance of the desired pressure in the event of an air leak at the mask.

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Nasal continuous positive airway pressure (nCPAP) was introduced in 1981 by SULLIVAN *et al.* [1], and has considerably improved the treatment and prognosis of patients suffering from obstructive sleep apnoea. Although nCPAP is well-tolerated in most patients, an additional effort as compared with spontaneous breathing is required to overcome the impedance of the nCPAP device. This effort may be detected as variations in the airway pressure signal (Paw), which fluctuates during the respiratory cycle instead of remaining constant. To compensate for this unnecessary workload, some manufacturers have developed new nCPAP devices in which the speed of the turbine is servo-controlled to minimize Paw variations. These systems are also claimed to compensate for air leaks at the mask, thereby guaranteeing that the pressure remains at the desired level.

We evaluated nine commercially available nCPAP devices, of which six featured a servo-mechanism (table 1). To analyse efficiency and reliability under difficult test conditions, a bench evaluation of mechanical performance assessed on pressure control and imposed work of breathing was performed.

Methods

Experimental set-up (fig. 1)

Each nCPAP device was connected to a standard circuit comprising a hose with a 4 mm expiratory blow-hole located a few centimeters from its tip. Pressure

Table 1. – CPAP devices tested

Constant-speed motor devices
COMPANION 318, Puritan Bennett, Lenexa, Kansas, USA
REMSTAR, Respironics, Murrysville, Pennsylvania, USA
SULLIVAN, ResCare Ltd, Sydney, Australia
Devices with servo-controlled system
TRANQUILITY PLUS, Healthdyne technologies, Marietta, Georgia, USA
REM + CONTROL, Sefam, Nancy, France
MORPHEE+, Pierre Médical, Verrière Le Buisson, France
CP90, CFPO, Paris, France
GOOD NIGHT, DP Médical, Meylan, France
IPNOS, Saime, Savigny Le Temple, France

CPAP: continuous positive airway pressure.

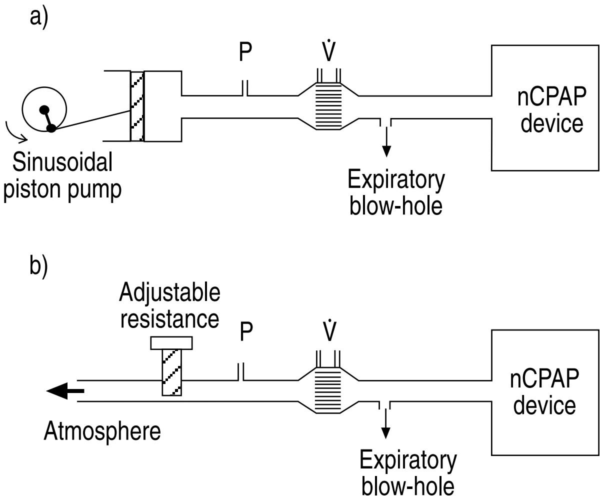

Fig. 1. – Experimental set-up: a) in dynamic condition; and b) in quasi-static condition. In dynamic condition the circuit of the nCPAP device was connected to a sinusoidal piston pump (tidal volume 0.5 *l*; peak inspiratory flow 0.5 *l*·s^{-1}; and breathing frequency 20 breaths·min^{-1}). In quasi-static condition, a variable leak at the mask was simulated by using an adjustable resistance. Pressure (P) and flow (V̇) were measured at the extremity of the nCPAP circuit. NCPAP: nasal continuous positive airway pressure.

and flow were measured at the end of the hose using a differential transducer (Validyne DP 45, ±50 cmH$_2$O, Northridge, CA, USA) and a pneumotachograph (Fleisch No. 2, Lausanne, Switzerland) connected to a differential transducer (Validyne DP 45, ±3 cmH$_2$O, Northridge, CA, USA). Tidal volume (VT) was obtained by integration of the flow signal. Signals were digitized at 128 Hz and sampled by an analogic/numeric system (MP100, Biopac Systems, Goleta, USA).

Dynamic study

To simulate spontaneous breathing, the experimental set-up was connected to a sinusoidal piston pump (fig. 1a). Tidal volume was set at 0.5 *l*. Peak inspiratory flow rate was 0.5 *l*·s^{-1} for a breathing rate of 20 breaths·min^{-1}. Pressure-volume loops (P-V) were used to quantify work of breathing [2]. The surface area of the airway P-V loop represented the work done by the patient to overcome ventilator resistance.

To estimate the transient dynamic response of the microprocessor servo-controlled nCPAP devices, we set the nCPAP devices at a pressure of 10 cmH$_2$O and followed the pressure signal for 1.5 s after production of a sudden leak of 1 *l*·s^{-1} at the extremity of the hose.

Quasi-static study

We sought to determine whether each nCPAP was able to maintain the preset pressure in the presence of a leak at the level of the mask or through the subject's open mouth. To simulate a leak, the hose of the nCPAP system was connected to an adjustable resistance opened to the atmosphere (fig. 1b). This resistance was made of a valve, the opening of which was predetermined to provide a constant flow at 0.5, 1 or 1.5 *l*·s^{-1}. Measurements were performed once stability of pressure in the system was obtained. Pressure was plotted against flow leak for each device.

All measurements were made at continuous positive airway pressures (CPAPs) of 5, 10 and 15 cmH$_2$O, except for the study of the transient dynamic response to a sudden leak, in which measurements were performed only at a CPAP level of 10 cmH$_2$O. Measurements were made in triplicate on the same day and the data were averaged.

Results

Dynamic study

Figure 2 shows the pressure-volume curves obtained with each type of nCPAP device when CPAP was set at 10 cmH$_2$O. During the inspiratory and expiratory phases of the respiratory cycle, airway pressure was lower than and higher than the preset CPAP level, respectively. Figure 2 shows that the goal of maintaining a constant pressure throughout the respiratory cycle was clearly not reached with some of the devices.

Work imposed by the nine nCPAP devices is shown in figure 3, for each pressure level tested. There were considerable differences in the behaviour of the machines. Four devices imposed a small amount of work of breathing, whereas five were responsible for a much higher load. Surprisingly, one of the four devices associated with a low work level had a constant-speed motor, whereas the two devices which imposed the highest workloads were microprocessor servo-controlled machines.

Figure 4 shows the dynamic pressure response within the first 1.5 s following a sudden leak with the six servo-controlled nCPAP devices when pressure was set

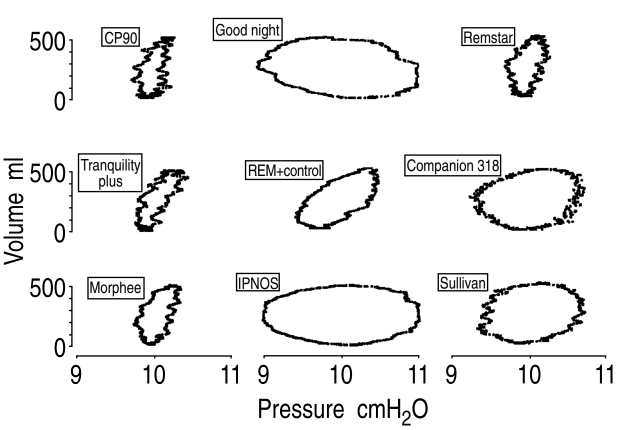

Fig. 2. – Pressure-volume curves for each of the nCPAP devices set at a pressure of 10 cmH$_2$O. Simulated breath is produced by means of a sinusoidal pump, using a tidal volume of 0.5 *l*, a peak flow rate of 0.5 *l*·s^{-1} and a respiratory rate of 20 breaths·min^{-1}. During a respiratory cycle, the signal travels along a pressure-volume loop in the clockwise direction. Results with the three constant-speed motor machines are presented in the right-hand column of the figure. nCPAP: nasal continuous positive airway pressure.

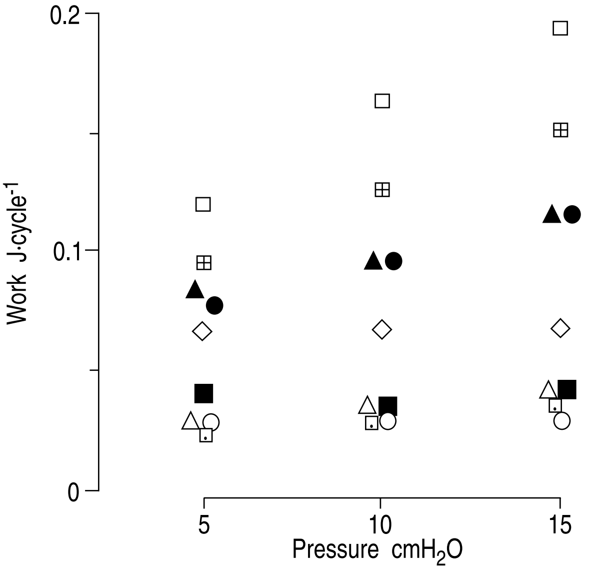

Fig. 3. – Comparison of the imposed work of breathing computed for each of the nasal continuous positive airway pressure (nCPAP) devices set at a CPAP of 5, 10 and 15 cmH_2O. Simulated patient breath was produced by a sinusoidal pump using a tidal volume of 0.5 *l*, a peak flow rate of 0.5 *l*·s^{-1} and a respiratory rate of 20 breaths·min^{-1}. Dark symbols are used for the three constant-speed motor machines. ⊡ : CP90; ❍ : TRANQUILITY PLUS; Δ : MORPHEE; ◆ : REM+CONTROL; ☐ : IPNOS; ⊞ : GOOD NIGHT; ● : COMPANION 318; ▲ : SULLIVAN; ■ : REM-

at 10 cmH_2O. We found that the two devices with the smallest pressure compensations during the first 1.5 s following the initial flow change-induced decrease in pressure, (IPNOS and GOOD NIGHT), were those which imposed the greatest amount of work of breathing. With most of the other devices, pressure correction occurred mainly within the first 0.5 s; however, with REM+ CONTROL pressure increased during most of the 1.5 s. We found a highly significant inverse correlation between imposed work of breathing and pressure values observed 300 ms after the leak was initiated (r=-0.91; p<0.001) (fig. 5).

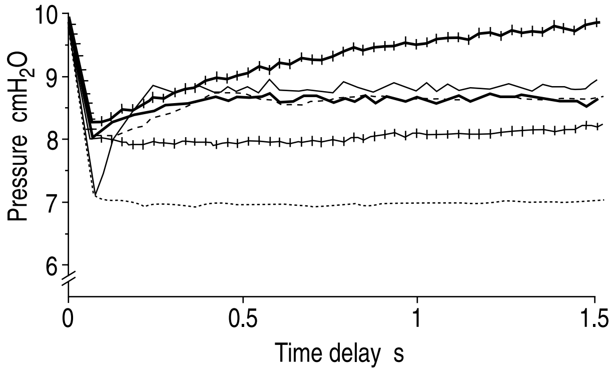

Fig. 4. – Time-profile of the pressure response for each of the microprocessor servo-controlled nasal continuous positive airway pressure (nCPAP) machines. The graph depicts the pressure signal during the first 1.5 s following the sudden occurrence of a 1 *l*·s^{-1} inspiratory flow. Two nCPAP machines (IPNOS and GOOD NIGHT) failed to achieve effective pressure compensation during the period studied. ++++ : REM+CONTROL; ······ : MORPHEE; — : CP90; ++++ : GOOD NIGHT; - - - : IPNOS; —— : TRANQUILITY PLUS.

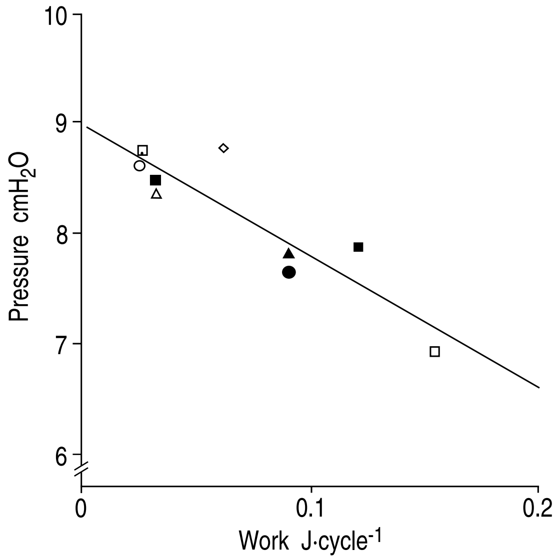

Fig. 5. – Regression analysis of the imposed work of breathing observed during a simulated breath on the pressure response to a sudden 1 *l*·s^{-1} flow. Pressure was measured 300 ms after onset of the flow. For both experimental conditions, nasal continuous positive airway pressure (nCPAP) machines were set to a pressure of 10 cmH_2O. A highly significant correlation was found: r=-0.91; p<0.001. ⊡ : CP90; ❍ : TRANQUILITY PLUS; Δ : MORPHEE; ◆ : REM+ CONTROL; ☐ : IPNOS; ● : COMPANION 318; ▲ : SULLIVAN; ■ : REMSTAR.

Quasi-static study

Relationships between measured pressures (for a fixed preset level of CPAP) and flow of the leak are presented in figure 6 for each of the three CPAP levels tested. We found that pressure generated by the nCPAP devices fell when the leak was increased. However, the magnitude of the fall in pressure varied across devices, ranging 0.4–4 cmH_2O for pressure and flow values set at 15 cmH_2O and 1.5 *l*·s^{-1}, respectively. The ability to maintain a constant pressure during a leak was clearly better for the servo-controlled nCPAP devices. However, with pressure and flow values set at 15 cmH_2O and 1.5 *l*·s^{-1}, respectively, one of these machine (CP90) showed performances similar with those of the non-servo-controlled machines.

Discussion

Although an ideal nCPAP device should generate a constant level of airway pressure, commercially available devices with constant-speed motors are known to be responsible for airway pressure variations within the respiratory cycle, causing an additional work of breathing. With these nCPAP devices, inspiratory pressure is lower than expiratory pressure. Such a pattern is not optimal for the treatment of sleep apnoea syndrome (SAS), as demonstrated by SANDERS *et al.* [3], who showed that, on the contrary, inspiratory positive pressure should be higher than expiratory positive pressure. Consequently, the best strategy when using such devices is to set the

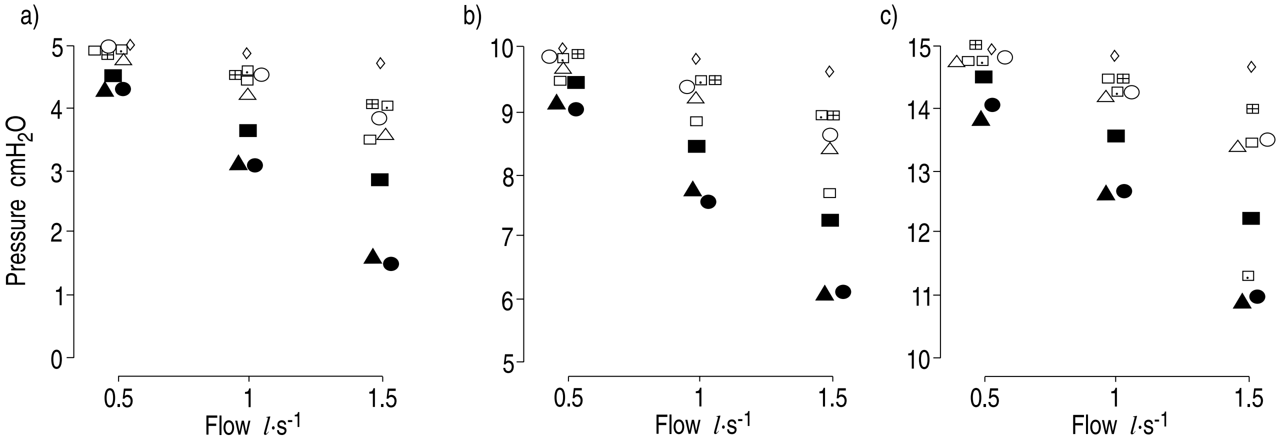

Fig. 6. – Quasi-static study: the fall in pressure was recorded for each nasal continuous positive airway pressure (nCPAP) device during a simulated constant leak at the mask with a flow rate of 0.5–1.5 $l \cdot s^{-1}$. CPAP was set to: a) 5 cmH$_2$O; b) 10 cmH$_2$O; c) 15 cmH$_2$O, for each of the tested devices. Dark symbols are used for the three machines with a constant-speed motor. ⊡ : CP90; ○ : TRANQUILITY PLUS; Δ : MORPHEE; ◇ : REM+CONTROL; □ : IPNOS; ⊞: GOOD NIGHT; ● : COMPANION 318; ▲ : SULLIVAN; ■ : REMSTAR.

mean pressure at a level higher than the constant pressure required to avoid apnoea. In addition, these nCPAP devices are obviously not able to compensate for gas leaks at the mask.

In intensive care units, the value of CPAP for weaning patients from mechanical ventilation is well-established, and considerable attention has been directed to the need for minimizing the work of breathing imposed to the patient [3–7]. To improve CPAP devices used in intensive care units, systems ensuring that the pressure generated is regulated and maintained at a constant level throughout the respiratory cycle have been developed [4, 7]. Similarly, some nCPAP devices proposed for the treatment of obstructive sleep apnoea feature a variable-speed motor controlled by a microprocessor system. Our study was designed to determine whether these new devices improve pressure stability. Our findings demonstrate that, even with these machines, airway pressure does not remain stable throughout the respiratory cycle and falls if a gas leak occurs at the mask. Results have also shown that pressure stability varies substantially across devices.

Previous assessments of CPAP machines were either quasi-static studies examining the pressure response to constant high inspiratory flows [6], or dynamic studies evaluating pressure variations [8], or work of breathing [9], during spontaneous ventilation or a simulated breath. Quasi-static and dynamic studies can be considered equivalent in the case of a non-servo-controlled nCPAP, since the response is then dependent on the internal impedance of the machine, which should be high in comparison to the external load [10]. However, with the new nCPAP devices, in which turbine speed is servo-controlled to minimize airway pressure variations, overall performance is dependent both on the internal impedance of the system and on the dynamic response to transient changes in flow.

In a previous study, DEMIROZU *et al.* [6] compared the ability of non-servo-controlled nCPAP devices to maintain airway pressure at various simulated constant inspiratory flows. Under these quasi-static conditions, the devices tested behaved similarly to those in our study, with pressure drops of 0.5–3 cmH$_2$O when CPAP and inspiratory flow were set at 15 cmH$_2$O and 1 $l \cdot s^{-1}$, respectively. For the three non-servo-controlled machines in our study, work of breathing was directly related to the pressure drops observed under the quasi-static conditions: in fact, the REMSTAR was responsible for both a smaller pressure drop (fig. 6) and less work of breathing (fig. 3) than the COMPANION and SULLIVAN nCPAP devices. By contrast, with each of the servo-controlled nCPAP devices, we found negligible pressure drops with increasing flows (except with the CP90 at the highest pressure and flow settings, which probably corresponded to the maximal speed attainable by the turbine motor). For these devices, there was obviously no relationship between this excellent quasi-static behaviour and the large variations in work of breathing observed during the dynamic study.

In a recent study, JACKSON *et al.* [8] examined pressure variations during actual and simulated ventilation with five nCPAP devices, and found substantial intermachine variability. In our study, we extended this evaluation to other commonly used machines, and measured the work of breathing induced by pressure variations during the respiratory cycle. Furthermore, by examining the response to transient changes in flow, we tried to assess factors involved in the dynamic behaviour of the devices tested.

When CPAP was set at 15 cmH$_2$O, the differences of imposed work of breathing between machines attained 0.15 $J \cdot cycle^{-1}$ (fig. 3), and, thus, corresponded to a non-negligible imposed inspiratory workload (above 1 $J \cdot min^{-1}$) compared to the inspiratory work during quiet breathing (4 $J \cdot min^{-1}$) [2]. This extra workload may bring work near the level at which fatigue occurs (above 8 $J \cdot min^{-1}$) [11].

Surprisingly, under dynamic conditions, the two machines responsible for the highest work of breathing levels were nCPAP devices with variable-speed motors. Figure 4 shows that these two machines failed to develop an effective pressure response during the first 1.5 s after a sudden change in flow. This suggests that the magnitude of work of breathing superimposed by the nCPAP is dependent on the speed of response of the servo-controlled system. Similarly, imposed work of breathing was closely correlated to the pressure response measured after 300 ms (fig. 5). Thus, those servo-controlled systems, which are slow to correct pressure, proved ineffective for minimizing work of breathing.

The pressure response of a servo-controlled system occurring between 500 ms and 1.5 s may cause an unwanted increase in the imposed work of breathing. This is suggested by our results with REM+CONTROL, which was the best device for maintaining and correcting pressure 300 ms and 1 s after a sudden 1 $l \cdot s^{-1}$ leak (fig. 4), but was not associated with the lowest imposed work of breathing (fig. 3). Pressure changes with the REM+ CONTROL after a sudden flow of 1 $l \cdot s^{-1}$ occurred gradually over 1.5 s, whereas the other servo-controlled CPAP devices which imposed less work of breathing responded within 500 ms. Pressure responses occurring after 500 ms may be ascribable to a persistent decrease or increase in the speed of the turbine at the beginning of inspiration or expiration, respectively. This hypothesis is in keeping with the appearance of the REM+ CONTROL device pressure-volume loop (fig. 2), where the minimal and the maximal pressure levels occurred at the beginning of inspiration and expiration, respectively, rather than near the middle of inspiration and expiration, *i.e.* at maximal inspiratory or expiratory flow. These results suggest a deleterious overshoot effect of the servo-controlled system of this machine.

In conclusion, the fact that a nCPAP device incorporates a servo-mechanism does not guarantee minimization of imposed work of breathing as compared to conventional constant-speed motor nCPAP devices. In fact, in this study, one of the constant-speed motor nCPAP devices was among the most satisfactory in terms of work of breathing because its low internal impedance was responsible for minimal changes in pressure in face of variable inspiratory flow rates. Similar satisfactory performances were seen with three of the six servo-controlled machines evaluated in our study, whereas the excessively slow response of the other three machines in this group precluded significant improvements in superimposed work of breathing. However, servo-controlled machines can be considered more effective in ensuring that pressure remains at the desired level in the event of leaks at the mask, because this situation involves relatively quasi-static phenomena. The ideal device would exhibit both low internal impedance and promptness of servo-controlled responses.

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