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Brief Communication

# Pressure stability with CPAP devices: A bench evaluation

Bruno Louis [a], Karl Leroux [b], Maud Boucherie [c], Daniel Isabey [a], Véronique Grillier-Lanoir [b], Brigitte Fauroux [d,e], Frédéric Lofaso [a,f,*]

[a] INSERM, Unit 841, and Université Paris 12, Faculté de Médecine, Créteil F94010, France
[b] ADEP Assistance, Puteaux, Paris, France
[c] Respiratory Division, Covidien, Elancourt, France
[d] AP-HP, Hôpital Armand Trousseau, Pediatric Pulmonary Department, Paris, France
[e] Université Pierre et Marie Curie-Paris 6, INSERM UMR S-893, équipe 12, Paris, France
[f] AP-HP, Raymond Poincaré Teaching Hospital, Université Versailles-St Quentin en Yvelines, Physiology – Functional Testing, and Technological Innovations Centre, 92380 Garches, France

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ABSTRACT

*Background:* Continuous positive airway pressure (CPAP) maintains a constant pressure to reduce the patient's work of breathing (WOB). The aim of this study was to measure the additional WOB imposed by four current CPAP devices during simulation of a difficult but commonly encountered clinical situation.
*Method:* Flow contour, respiratory system compliance and total lung-airway resistance of a patient under CPAP were simulated. The devices were tested at a CPAP of 15 cm $H_2O$ with a heated humidifier and a nasal pillow, which increased circuitry resistance and with and without a simulated unintentional leak.
*Results:* With no leak, positive end-expiratory pressure (PEEP) at the interface varied across devices from 14.0 to 15.3 cm $H_2O$. With a leak of 1 L/s, PEEP varied from 11.5 to 17.1 cm $H_2O$. Imposed inspiratory WOB ranged from less than 0.1 J/min to 0.45 J/min with no leak, and the range broadened with leaking. Findings were similar for the imposed expiratory WOB.
*Conclusion:* The performances of CPAP devices are variable. The device that calibrated for the pressure loss in the circuitry under dynamic conditions and made appropriate pressure adjustments outperformed the other devices.



## 1. Introduction

Continuous positive airway pressure (CPAP) devices for treating obstructive sleep apnoea syndrome (OSA) at home generally use turbine motors. Since the 1980s, the turbines are servo-controlled to reduce the impedance of the respiratory system [1], which is known to induce respiratory discomfort [2]. Servo-controlled CPAP devices have been improved over the years. In parallel, the conditions of CPAP use have changed. The circuitry resistance has been increased by the standard practice of using a heated humidifier, as recommended by the American Academy of Sleep Medicine [3], and by the growing use of nasal pillows as a first-line interface [4,5]. High CPAP levels may be required in patients with severe obstruction, and manufacturers claim that their CPAP devices compensate for major unintentional leaks.

The aims of this study were to assess the ability of four current CPAP devices to maintain a constant airway pressure during a simulated respiratory cycle with the above-described circuitry and to maintain the set pressure when leaks occur.

## 2. Material and method

### 2.1. CPAP devices tested

We tested the Sandman Auto™ (Covidien, Elancourt, France; Boulder, CO), the Spirit 8 V1® and Spirit 8 V2® (ResMed, Saint Priest, France; North Ryde, Australia), and the Remstar Mseries Auto Aflex® (Respironics, Nantes, France; Murrysville, PA). The interface was the Mirage Swift™ II (ResMed) nasal pillow because only ResMed recommended using their own masks. All the tested CPAPs had an integrated heated humidifier. The resistances of these humidifiers were similar and were nearly twice as high as the resistance of the circuit (length 1.80 m). For example, the resistances of the circuit, the Sandman humidifier, the Spirit 8 humidifier and the Remstar humidifier were respectively 0.33, 0.73, 0.68 and 0.62 cm $H_2O$/L/s at 1 L/s. When the intentional leak was

* Corresponding author. Address: Service de Physiologie-Explorations Fonctionnelles, Hôpital Raymond Poincaré, 92380 Garches, France. Tel.: +33 147 107 941; fax: +33 147 107 943.
*E-mail address:* f.lofaso@rpc.ap-hop-paris.fr (F. Lofaso).

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occluded, the nasal pillow pressure drop was 0.4 cm $H_2O$ for a 0.5 L/s flow rate and 1.8 cm $H_2O$ for a 1 L/s flow rate.

### 2.2. Experimental set-up

The experimental set-up has been described elsewhere [6,7]. Briefly, the auto-CPAP device was connected via a standard circuit to a two-chamber Michigan test lung. To simulate breathing cycles, the second chamber of the Michigan test lung (driving chamber) was connected to a flow-rate generator that could produce various waveforms previously stored in a microcomputer. This breath waveform simulator was developed in our laboratory. It relies on pressurized air, flow-rate measurement, and a servo-valve. The simulator continuously adjusts the servo-valve via a microcomputer to produce the desired flow rate. To mimic the mechanical characteristics of an overweight patient, the compliance of the testing chamber was adjusted to 60 mL/cm $H_2O$. A parabolic resistance (Rp5, Pneuflo®, Michigan Instruments, Grand Rapids, MI) of 2.7 cm $H_2$/L/s at 1 L/s was added at the entrance of the testing chamber. A small metal component allowed the driving chamber to displace air into the testing chamber, but not the opposite. Flow rate and pressure were measured between the extremity of the nasal pillow and the parabolic resistance. Flow rate was inferred using a pneumotachograph (Fleisch #2, Lausanne, Switzerland) connected to a differential pressure transducer (Validyne MP 45, Northridge, CA; ±3 cm $H_2O$), and pressure was inferred using a pressure transducer (Validyne MP 45; ±35 cm $H_2O$). Pressure and flow-rate signal outputs were digitized at 200 Hz (MP100, Biopac Systems, Goleta, CA) and recorded in a microcomputer for further analysis.

### 2.3. Protocol

We simulated a rounded inspiratory flow contour with a frequency of 15 cycles per $\min^{-1}$ for 2 min. The inspiratory flow contour mimicked a patient with OSA successfully treated with CPAP, as demonstrated by Condos et al. [8] (Fig. 5, first cycle). Tidal volume was 420 mL, maximal inspiratory flow 520 mL/s, and inspiratory time 1.15 s. Expiratory time was adjusted to obtain an adequate respiratory frequency. Measurements were made at a CPAP of 15 cm $H_2O$. A leak valve was added to simulate leaking through the mouth during CPAP. Three leak levels were tested (0, 0.5, and 1 L/s). For each condition, at least 20 stable cycles were analyzed.

### 2.4. Analysis

A pressure–volume loop was used to quantify the imposed WOB, as previously described [1]. The loop was split by a line passing through the values corresponding to zero-flow points. Imposed inspiratory WOB corresponded to the area between this line and the inspiratory pressure curve below, and imposed expiratory WOB corresponded to the area between this line and the expiratory pressure curve above. We measured mean inspiratory and expiratory pressures, positive end-expiratory pressure (PEEP), pressure variation during inspiration ($\Delta P$), and time delay from inspiration onset to the minimal airway-pressure value ($\Delta T$) (Fig. 1).

## 3. Results

Fig. 2 shows the pressure–volume curves obtained with the four devices with and without leaks. Considerable differences were observed across devices. PEEP, mean inspiratory and expiratory pressures, and the effects of leaks differed between all the devices (Fig. 2, Table 1). With and without leaks, mean inspiratory pressure

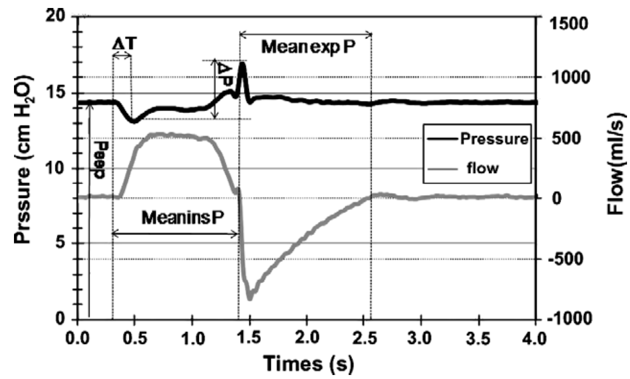


**Fig. 1.** Graphic measurement of positive end-expiratory pressure (PEEP), mean inspiratory pressure (Mean ins $P$), mean expiratory pressure (Mean exp $P$), pressure variation from PEEP to the minimal value during inspiration ($\Delta P$), and time from inspiration onset to the minimal airway-pressure value ($\Delta T$).

exceeded mean expiratory pressure with the Sandman device, whereas the opposite occurred with the three other devices (Fig. 2, Table 1).

With no leak, PEEP ranged from 15.3 cm $H_2O$ with the Sandman device to 14.0 cm $H_2O$ with the Remstar device (Table 1). Between the best and worst device, imposed WOB during inspiration and expiration increased 5-fold and 10-fold, respectively (Table 1).

Leaks increased the differences across devices (Fig. 2, Table 1). PEEP decreased with three devices but increased with the Sandman device (Fig. 2, Table 1). With a leak of 1 L/s, PEEP ranged from 17.1 cm $H_2O$ with the Sandman device to 11.5 cm $H_2O$ with the Remstar device (Table 1). Imposed WOB, $\Delta P$, and $\Delta T$ increased with the size of the leak (Fig. 2, Table 1).

## 4. Discussion

The devices tested in this study failed to maintain the desired PEEP and to keep the airway pressure constant throughout the respiratory cycle. The pressure instability generated additional WOB. Pressure variation and imposed WOB differed across devices, and these differences increased when leaks occurred. With three devices, the increase of WOB during leaks was associated with decreased PEEP; in contrast, PEEP increased substantially with the Sandman Auto™ device.

Previous studies demonstrated differences among servo-controlled CPAP devices for maintaining a constant pressure with CPAP devices when simulating breathing [1,9,10]. Our study confirmed these previous studies [1,9,10] and extended this observation to the last generation of CPAP devices. It also showed that pressure fluctuation increased and mean pressure and PEEP decreased in some devices when leaks occurred.

The breathing pattern chosen for this study [8] did not correspond to a high ventilatory demand. Our circuits included heated humidifiers and a nasal pillow which are increasingly used [11]. We acknowledge, however, that although the high pressure level used in the study might occur in clinical practice, it is rarely prescribed. In fact, the characteristics of our set-up (pressure level, heated humidifier, nasal pillow, and leaks) were chosen to test the performances of the CPAP devices in a difficult but possible condition. As such, a high level of CPAP is generally more difficult to maintain than a lower one [9], and increased resistance of the circuitry may favor pressure variations. We evaluated the effects of leaks, which are common when using high pressure levels and which can affect CPAP device performance by increasing the delivered flow [1,9]. The imposed WOB was smallest with the Sandman Auto™ device. Like the other devices, the Sandman Auto™ device