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Correspondence
R. Farré
Unitat de Biofísica i Bioenginyeria
Facultat Medicina
Universitat de Barcelona-IDIBAPS and CIBER de
Enfermedades Respiratorias
Casanova 143
08036 Barcelona
Spain

E-mail: rfarre@ub.edu

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PRINCIPLES OF CPAP AND AUTO-ADJUSTING CPAP DEVICES

R. Farré[1,2], J.M. Montserrat[2,3]

[1] Biophysics and Bioengineering Unit, Faculty of Medicine,
[3] Pneumology Dept, Hospital Clinic, Faculty of Medicine, Universitat de Barcelona (IDIBAPS), Barcelona, and
[2] CIBER Enfermedades Respiratorias, Bunyola, Spain.

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SUMMARY

Obstructive apnoea–hypopnoea syndrome (OSAHS) is very prevalent. It causes a considerable reduction in patients' quality of life and induces important short- and long-term consequences, such as traffic accidents and cardiovascular diseases. The application of continuous positive airway pressure (CPAP) by means of a nasal mask is currently the most widespread and effective treatment for OSAHS. The present review article will address the following questions. What is the physiological rationale of CPAP? What are the principles of CPAP equipment? How can we optimise its use? What are auto-adjusting CPAP devices and how do they operate? To what extent are they useful in the treatment of OSAHS?

INTRODUCTION

OSAHS is the most prevalent of all sleep breathing disorders. This syndrome is currently a public health problem because, according to several studies, up to 5% and 2% of the adult male and female population, respectively, are suffering from OSAHS [1, 2]. Given that this sleep disorder is directly associated being overweight [3, 4], it is expected that the prevalence of OSAHS will increase in parallel with the growing epidemics of obesity in Western and developing countries [5].

OSAHS is characterised by recurrent obstructions during sleep caused by an abnormal increase in the collapsibility of the upper airway, which is triggered by several factors, including anatomical alterations and obesity [6, 7]. Figure 1a illustrates the case of a normal subject during sleep in supine position. During inspiration there is a negative (lower than atmospheric) pressure in the lumen of the upper airway and, consequently, its soft wall would tend to collapse. However, in a normal upper airway, the surrounding muscles are able to exert sufficient force to maintain the airway open, regardless of negative intraluminal pressure during inspiration, allowing normal ventilation during sleep (figure 1a). In contrast, in an OSAHS patient, the upper airway muscles are unable to withstand the collapsing force due to negative intraluminal pressure, so the upper airway tends to collapse. Depending on the degree of abnormal increase in upper airway collapsibility, the OSAHS patient can experience partial upper airway obstruction (figure 1b) or total collapse (figure 1c). In the former case, a hypopnoea appears because the reduction in airway lumen results in an increased resistance high enough to reduce ventilation, even though the inspiratory effort is increased. When the upper airway is completely collapsed (figure 1c), the patient is no longer able to inspire and experiences an obstructive apnoea. In the most severe cases of OSAHS the collapsibility of the upper airway during sleep increases considerably and collapse is induced even in cases where the intraluminal pressure is zero (atmospheric level) or slightly positive. In these severe patients, therefore, the upper airway is collapsed not only ▶

during inspiration but also during expiration.

Figure 2 shows some of the signals recorded during a polysomnographic study and illustrates the sleep events experienced by a patient with severe OSAHS. The breathing flow signal shows three apnoeas (identified by zero flow) lasting ~20 s each. These apnoeas were obstructive because the patient was exerting breathing efforts, as indicated by the thoraco-abdominal movement signals. Each obstructive event finished with a short arousal, as evidenced by the electroencephalogram (EEG) signals. Since the patient was temporarily awake during the arousal (although not conscious of the short awakening), the upper airway muscles were activated (indicated by the genioglossus electromyogram (EMG) in figure 2) and the airway was open; the patient was, therefore, able to ventilate. However, as the patient fell asleep again immediately after the arousal, airway obstruction resumed: after a few breathing cycles with snoring, a new apnoea ensued (figure 2). The arterial oxygen saturation measured by pulse oximetry (SpO_2) shows that, as a consequence of the recurrent apnoeas, this patient experienced intermittent hypoxaemia with a repetition period of ~40 s (figure 2).

The short-term symptoms described by OSAHS patients are related to alterations in normal ventilation (choking, gasping or dry mouth) and disruption of sleep architecture caused by recurrent arousals (excessive sleepiness, lack of attention and irritability). Patients with OSAHS have an increased risk of traffic accidents, probably as a result of somnolence [8]. Moreover, the nocturnal events chronically experienced by OSAHS patients contribute to the development of long-term comorbidities, such as cardiovascular and cerebrovascular diseases and inflammatory, metabolic, cognitive and mood alterations [9-14]. ▶

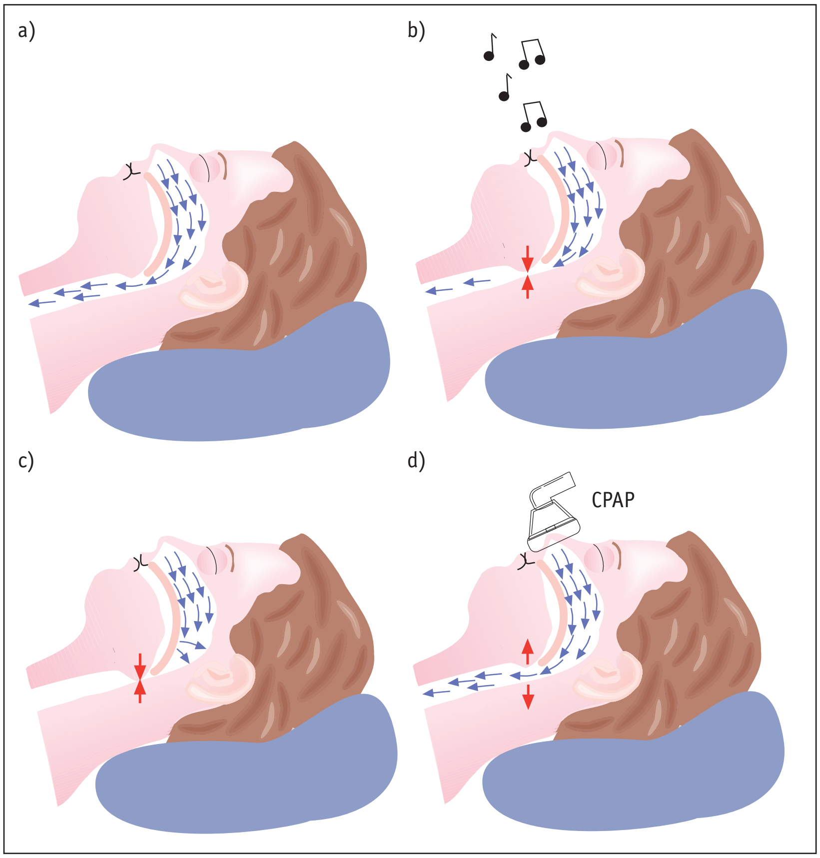

Figure 1. Diagram showing the upper airway patency during inspiration: a) in a normal subject; b) in a patient experiencing an obstructive hypopnoea with snoring (represented by the sound produced); c) in a patient experiencing an obstructive apnoea; and d) in a patient subjected to nasal CPAP. The red arrows in b) and c) indicate net collapsing force on the upper airway wall. The red arrows in d) indicate that application of nasal CPAP results in a net force opening the upper airway.

Figure 2. Physiological signals recorded during a nocturnal polysomnography in a patient with OSAHS. EEG1 and EEG2 correspond to the C4/A1 and C3/A2 EEG channels. EMG refers to EMG of the genioglossus. Snoring was monitored by a sound recording. Flow refers to the breathing flow. Red rectangles in EEG1 indicate arousals. Vertical white lines indicate 10-s periods. Tho: Thoracic breathing effort; Abd: Abdominal breathing effort; SpO_2: arterial oxygen saturation measured by pulse oximetry (ranging from 93–76% in this example).

CPAP

Several approaches can be used to treat OSAHS. The first option is to recommend that the patient loses weight, avoids sleeping in a supine position and avoids the consumption of alcohol and sedative drugs. However, in most patients, these behavioural measures are not effective for normalising sleep, and more active treatments are required. It has been shown that in some patients the nocturnal use of mandibular advancement devices aimed at protruding the mandible could be effective for increasing the dimensions of the upper airway and maintaining its patency during sleep [15]. Other patients could benefit from surgical treatment to reduce anatomical upper airway obstruction in the nose, oropharynx and hypopharynx [16]. However, for the vast majority of OSAHS patients the most effective treatment is the nocturnal application of nasal CPAP [17].

Nasal CPAP does not eliminate the primary causes that increase upper airway collapsibility in OSAHS. In fact, CPAP is a palliative treatment for mechanically preventing upper airway obstruction. Nocturnal CPAP, applied by means of a nasal mask (figure 1d), imposes a positive intraluminal pressure on the upper airway that plays a role similar to that of normal upper airway muscles. As illustrated in figure 1d, CPAP opens the upper airway and prevents its partial or total obstruction. The effectiveness of CPAP in preventing upper airway collapse in OSAHS is illustrated by the computed tomography (CT) scan of a patient's pharyngeal area during sleep (figure 3). The upper images (figure 3a and b) show two sections of the upper airway obtained when the patient was sleeping under normal conditions (no CPAP). The right scan section (figure 3b) shows that the lumen of the upper airway was extremely reduced, indicating a virtually closed airway. When the patient was subjected to CPAP, the upper airway lumen increased considerably at this point of obstruction. The other upper airway sections also increased their lumen when CPAP was applied, indicating that nasal pressure prevented obstruction along the whole collapsible airway (figure 3c and d).

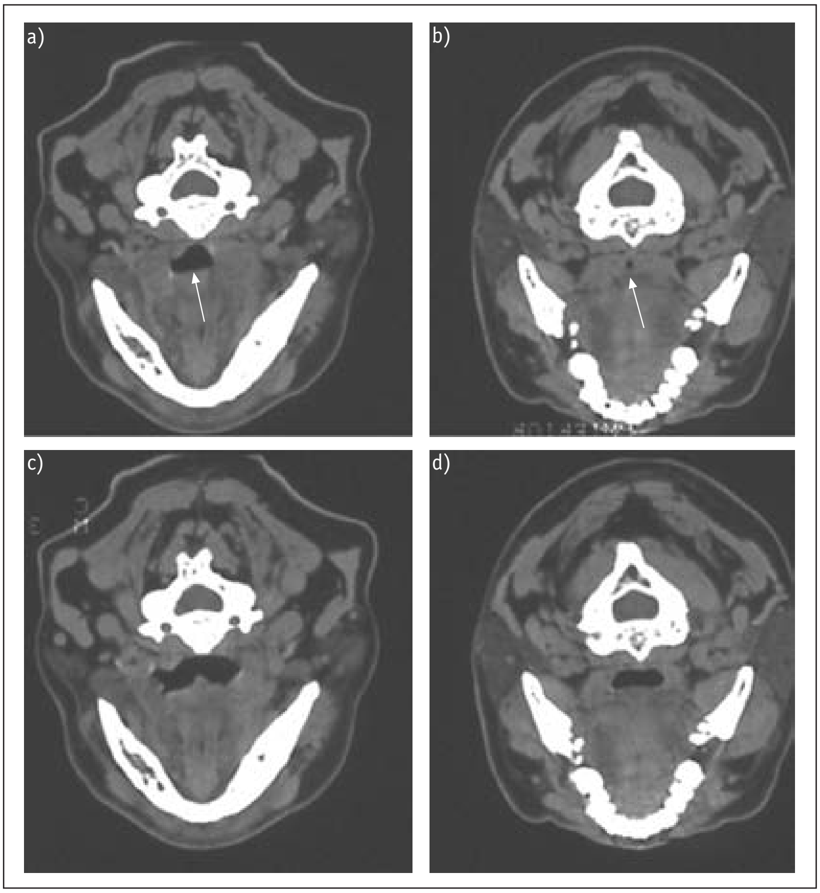

Figure 3. Axial CT scans of the upper airway obtained during sleep from a patient with OSAHS. a) and b) Two head sections of the untreated patient. c) and d) The same two sections during application of CPAP. The yellow arrows indicate the upper airway lumen.

The value of nasal pressure that normalises breathing during sleep does not depend on the severity of a particular patient's OSAHS, as measured by the number of nocturnal respiratory events (apnoeas and hypopnoeas per h) but, instead, depends on the degree of collapsibility of the patient's upper airway. Accordingly, each patient should be subjected to an individual CPAP titration procedure during sleep, in order to determine the optimal nasal pressure for treatment. Figure 4 shows the data corresponding to a 1-night CPAP titration in a patient with OSAHS. At the beginning of the night, when awake, the patient was subjected to a minimal CPAP of 4 cmH_2O (0.4 kPa). When the patient started to sleep, respiratory events (mainly obstructive apnoeas) and marked oxygen desaturations appeared. The sleep technician then gradually intensified the application of nasal pressure. As CPAP increased, the number of apnoeas decreased and the number of hypopneas increased, indicating that the upper airway obstruction was being progressively reduced and breathing was being normalised (figure 4). Similarly, the magnitude of oxygen desaturations was also progressively decreasing. When CPAP was equal to 9 cmH_2O (0.9 kPa), there were no longer any obstructions or desaturations.

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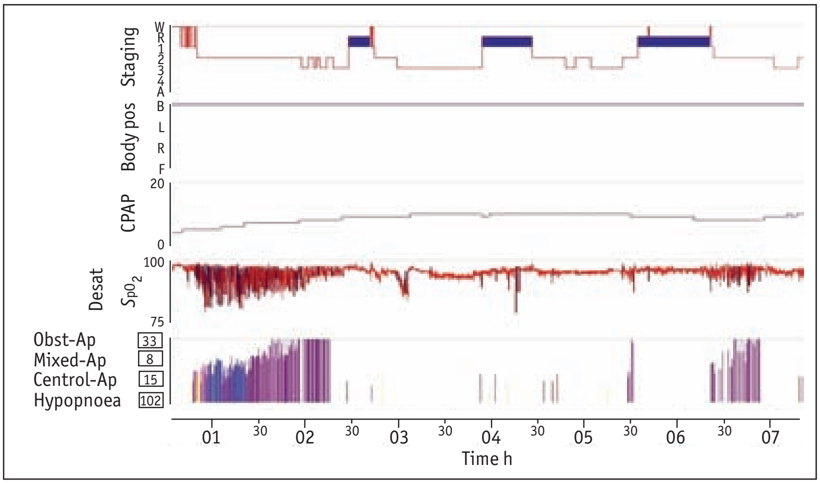

Figure 4. Data from a 1-night CPAP titration in a patient with OSAHS. Staging: sleep status (W: wake; R: REM; 1-4: non-REM sleep stages 1-4). Body pos: body posture. CPAP: nasal pressure applied. Desat: arterial oxygen desaturation, as indicated by SpO_2. The plot at the bottom indicates the number of different respiratory events detected: obstructive apnoeas, mixed apnoeas, central apnoeas and hypopnoeas. The numbers in the boxes shows the total number of events with a fall in SpO_2 >4%. The time scale indicates time from titration start.

The normalisation of sleep was reflected by the fact that the patient achieved rapid eye movement (REM) sleep. Subsequently, the technician maintained CPAP at 9-10 cmH_2O (0.9-1.0 kPa) for 3-4 h, observing no clear improvement between 9 and 10 cmH_2O. The quality of sleep was good, as the patient experienced two more REM sleep periods. To test whether CPAP could be reduced while maintaining normal sleep, the technician reduced nasal pressure to 8 cmH_2O (0.8 kPa), with the result that hypopnoeas and oxygen desaturations appeared again, indicating that 9-10 cmH_2O (0.9-1.0 kPa) was the optimal nasal pressure for treating this OSAHS patient.

PRACTICAL ISSUES REGARDING CPAP EQUIPMENT

Although in a patient treated with CPAP the primary causes of OSAHS remain present, from the functional viewpoint, his/her sleep resembles that of a healthy subject. However, CPAP is effective only as long as the patient is subjected to the treatment. In this regard, it has been shown that there is a linear dose-response relationship between the number of hours of CPAP use per night and the attainment of normal levels of objective and subjective daytime sleepiness [18]. Accordingly, any effort made to improve the patient's acceptance of CPAP treatment will enhance the effectiveness of the therapy [19]. To this end, it is important to select high-quality CPAP equipment, use it in accordance with the manufacturer's specifications and train patients on CPAP therapy.

The CPAP systems used for OSAHS treatment are usually based on a blower and an exhalation port (intended leak orifice), as shown in figure 5. The blower takes room air and generates a constant airflow through a flexible tubing (~1.5 m length, ~2 cm internal diameter). When the patient is not breathing and the nasal mask is adequately fitted on the patient's face to avoid leaks between the mask and the skin, all the airflow generated by the blower reaches the atmosphere again through the exhalation port. Accordingly, the pressure (CPAP) at the nasal mask is the product of the airflow and the resistance of the exhalation port. For a given exhalation port, the value of CPAP can be increased or decreased by modulating the magnitude of the flow generated by the blower. In addition to being the nasal pressure source, the airflow generated by the blower plays also the important role of avoiding rebreathing. To this end, a minimum airflow through the exhalation port is required to adequately renew the air inhaled by the patient. In commercially available CPAP devices, the pressure ensuring sufficient air renewal, and, therefore, the minimum selectable CPAP value, is generally ~4 cmH_2O (0.4 kPa). In most devices, the exhalation port is an orifice characterised by nonlinear resistance. This type of resistor has the advantage of a range of blower airflow (and therefore machine noise) covering the full range of therapeutic CPAP values (4-16 cmH_2O; 0.4-1.6 kPa) that is lower than that of an exhalation port with linear resistance. The exhalation port can be either an orifice in the mask wall (as in figure 5) or a special device connecting the tubing outlet and the nasal mask. In the latter case, the air volume in the nasal mask is an additional small dead space for breathing.

As indicated in figure 5, for a given airflow generated by the blower the value of nasal pressure is constant, as long as the patient is not breathing. When the patient inspires, however, an air fraction from the blower flow enters the lungs and hence the airflow through the exhalation port is reduced. Therefore, nasal pressure, which depends on this flow magnitude, is decreased and the equipment represents a load to the patient's breathing. This conventional design of CPAP equipment (figure 5) poses two main technical problems with regard to optimising the system for patient comfort. First, given that the effective resistance of the exhalation port is considerable, the patient's breathing flow mainly circulates through the tubing and ▶

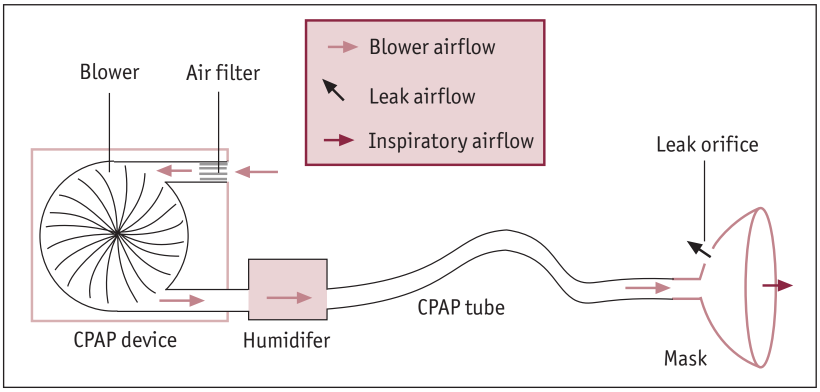

Figure 5. Diagram of a conventional CPAP system.

blower [20]. Consequently, the blower should be designed to generate high pressure while presenting a low load (resistance) to breathing. Secondly, in order to keep the nasal pressure (*i.e.* CPAP) constant, the blower should be able to automatically modify the generated airflow with the aim of keeping the airflow constant through the exhalation port, regardless of the patient's breathing. One common method for this type of regulation is the measurement of the flow and pressure generated at the CPAP device and the calculation of the pressure at the nasal mask from the known airflow resistance of the tubing and exhalation port. This procedure requires the tubing and the exhalation port connected to the CPAP machine to be matched, otherwise the calculation of nasal pressure would be incorrect. In order to circumvent this potential problem, some CPAP devices measure mask pressure directly by means of a thin catheter placed along the CPAP tubing. As it is important to maintain a fairly constant nasal pressure, the main CPAP device quality index is given by the magnitude of the "swings" in nasal pressure during breathing: the smaller the swings, the better the CPAP equipment.

An adequate selection of CPAP equipment (*i.e.* compatible CPAP machine, tubing and exhalation mask) does not ensure correct treatment application, as two types of unintended leaks could reduce the performance of the CPAP setting. An air leak between the nasal mask and the skin as the result of an unsuitable mask fitting could affect the therapy: the flow generated by the blower would increase (and, hence, the noise) and the nasal pressure could be lower than expected. Such a leak could also cause patient discomfort, particularly if the leak airflow is directed toward the eyes. The need to reduce mask leaks as much as possible highlights the importance of adequately choosing the nasal mask type that best fits the patient. Good mask fitting should be achieved without any excessive compression, as this would damage the patient's skin and, therefore, compromise tolerance of CPAP. Another type of leak that could negatively affect CPAP treatment occurs when the patient's mouth is partially open. In this case, there is a constant airflow through the upper airway, from the nostrils at positive pressure to the mouth at zero (atmospheric) pressure, with the result that the effective pressure at the upper airway lumen is lower than expected. The use of a chinstrap could help to prevent mouth leaks in some patients. An important additional problem related to mouth opening during CPAP is the presence of a continuous flow of dry and cold room air, which could result in nasal and throat mucosa dryness and irritation, thereby causing discomfort, and even rhinitic symptoms, to the patient. A possible way of reducing the risk of this nasal drying is to use a heated humidifier (figure 5) [21]. The potential advantage of a humidifier is counterbalanced by some potential drawbacks: the need to clean the water chamber to avoid contamination; more expensive equipment; and increased breathing route resistance. Although humidifiers are useful for some patients, there is no clear evidence to recommend their systematic use for CPAP therapy in OSAHS patients.

Prescribing updated and high-quality CPAP equipment is obviously important for patient

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Figure 6. Training session on the use of CPAP.

compliance. However, it should be mentioned that patient adherence to CPAP is considerably improved by implementing some routine protocols to the start and follow-up of the treatment [19, 22]. On the one hand, initial educational and training sessions before CPAP titration allow the patient to better understand the treatment and improve adaptation to the equipment (figure 6). On the other hand, periodic follow-up sessions are useful for answering any questions posed by the patient about the treatment, and also for the early detection and solution of problems, such as discomfort with the mask, air leaks or rhinitic side-effects, that could reduce adherence to the treatment [19, 22].

AUTO-ADJUSTING CPAP DEVICES

Upper airway collapsibility in OSAHS patients depends on several factors; therefore, it may vary in the short and long term. Different body postures during sleep (supine posture promotes airway collapse, compared with lateral decubitus) could cause changes within a single night. This well-known fact is taken into account during routine CPAP titration, when at least supine sleep posture is studied. Moreover, changes in upper airway collapsibility within consecutive nights could be the result of alcohol ingestion or drug treatment, particularly with drug affecting muscle tone. Furthermore, within a longer time period (over a period of weeks or months), upper airway collapsibility could change as the patient's body weight varies. Given that the CPAP required to avoid obstructive events is directly determined by upper airway collapsibility, the optimal CPAP would be not the same over time. Consequently, a conventional CPAP device would apply a fixed nasal pressure that could be higher or lower than required, depending on the patient's current situation. Auto-adjusting CPAP devices are designed to solve this problem. These "intelligent" devices are intended to detect a patient's respiratory events and modify the applied CPAP to normalise patient's breathing.

In addition to conventional CPAP equipment elements (figure 5), auto-adjusting CPAP devices incorporate a complex algorithm (figure 7). The sensors in the device estimate the patient's breathing by assessing snoring, flow pattern and, in some devices, airway obstruction. The first step in the algorithm of an auto-adjusting CPAP device is to correctly detect and classify the different breathing events (normal breathing, apnoea, hypopnoea, snoring and flow limitation) from the available signals. The device must be able to distinguish true obstructive events from typical artefacts, such as those caused by awakening of the patient, cough, sighs or mouth breathing. The second step in the auto-adjusting CPAP device algorithm is to modify the nasal pressure applied in response to the breathing events that are detected. Figure 8 is an example of the functioning of an auto-adjusting CPAP device. The device was subjected to a bench test by connecting it to a simulated OSAHS patient who, depending on the applied pressure, exhibited apnoeas, hypopnoeas, flow limitation events or normal breathing. Initially, the simulated

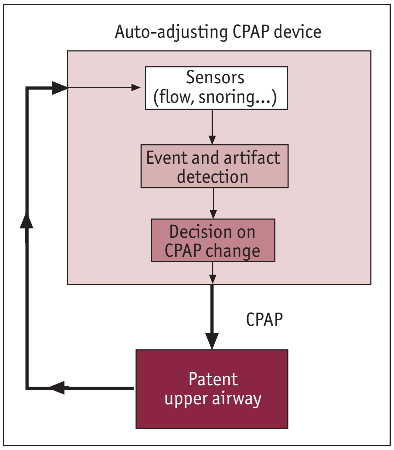

Figure 7. Diagram showing the rationale of automatic CPAP devices.

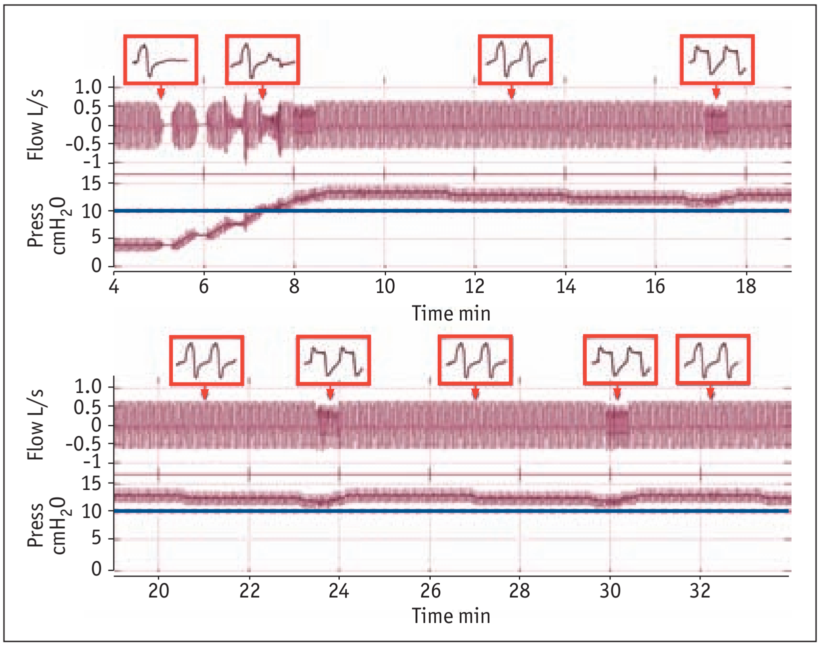

Figure 8. Nasal pressure applied by a commercially available auto-adjusting CPAP device when subjected, on the bench, to a simulated patient with OSAHS. As indicated by the time scale, the bottom plot is the continuation of the plot on top. Details of the flow pattern are shown at different relevant times (positive flow corresponds to inspiration). The green lines indicate 10 cmH_2O (1 kPa) of nasal pressure (Press).

patient was breathing normally and the applied CPAP was 4 cmH_2O (0.4 kPa). Subsequently, as the simulated patient fell asleep, apnoeas ensued. The device detected the apnoeas and increased the CPAP. As the CPAP became progressively higher, the simulated patient then exhibited hypopneas and flow limitation; finally, the breathing pattern was normalised when CPAP reached 12 cmH_2O (1.2 kPa). From then on, the auto-setting device slightly decreased or increased CPAP to detect the appearance and disappearance of abnormal breathing. This process maintained the optimal CPAP (minimum value avoiding breathing events) for the simulated patient.

Given that auto-adjusting CPAP is a relatively new technology, some issues affecting its potential clinical use are still open to debate. In contrast to the detection and classification of events [23], there are no generally accepted criteria for defining the optimum method of modifying nasal pressure in response to breathing events. For instance, after how many apnoeas/hypopnoeas/snoring events should pressure be increased? What should the step for increasing pressure be? What should the rate for modifying pressure be? If no events are detected, how long should the device wait before reducing pressure? Given the number of open points, each manufacturer of an auto-adjusting CPAP device uses a proprietary algorithm that is usually undisclosed. Consequently, devices provide different results when subjected to the same breathing pattern [24, 25]. As an example, figure 9 shows the response of three currently available auto-adjusting CPAP devices when subjected to a normal breathing pattern, followed by a persistent period of flow limitation during a well-controlled bench test. Two devices responded by increasing nasal pressure, but the pressure increase rate was clearly different. The third device did not modify pressure when subjected to an abnormal breathing pattern (figure 9). This lack of response could be caused by the device's inability to detect the event when it occurred, or it could mean that the device algorithm did not consider this well-detected and classified event as a reason for modifying pressure. Such differences between devices, which have also been documented in patient studies, make it difficult to assess the cost-effectiveness of auto-adjusting CPAP and to compare different clinical studies, as the results are always dependent on the device used in each test [25]. ▶

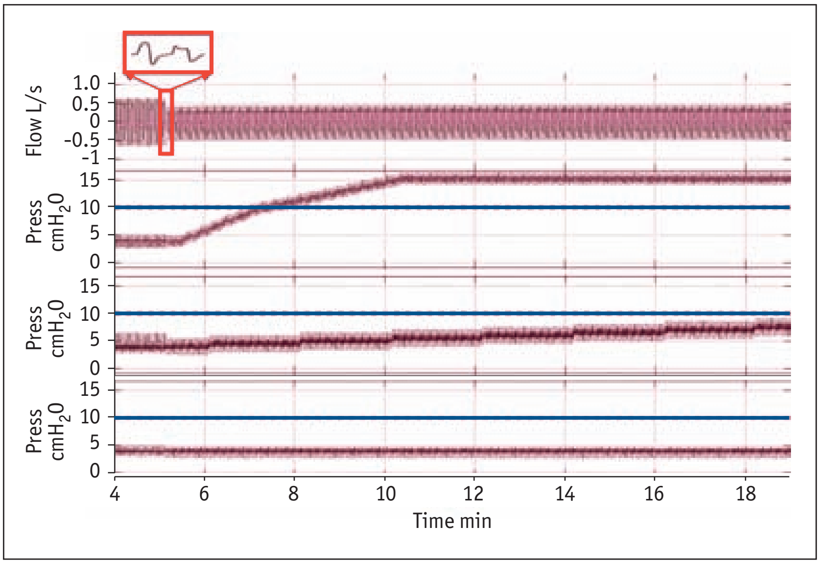

Figure 9. Nasal pressure applied by three commercially available auto-adjusting CPAP devices when subjected, on the bench, to an initial pattern of normal breathing (up to minute 5) followed by a pattern of persistent flow limitation. The flow signal is shown on the top; a detail of the flow patterns in minute 5 shows the transition from the normal to the flow-limited breathing pattern (positive flow corresponds to inspiration). The green lines indicate 10 cmH$_2$O (1.0 kPa) of nasal pressure (Press).

To date, several clinical studies have been carried out to test the therapeutic application of auto-adjusting CPAP for treating OSAHS. Although these devices have been shown to apply a mean nasal pressure lower than conventional fixed CPAP devices, their effectiveness in reducing the number of sleep breathing events is similar with both nasal pressure modalities [26-28]. Accordingly, the currently available data do not make it possible to recommend systematic application of auto-adjusting CPAP to the general spectrum of OSAHS patients, particularly taking into account its great cost when compared with conventional CPAP. This CPAP modality could be better suited for selected subpopulations of OSAHS patients, for instance those exhibiting a clear number of respiratory events when changing body posture or those treated with a high level of CPAP. However, the cost-effectiveness of auto-adjusting CPAP for OSAHS treatment needs to be better substantiated in future studies [17].

Interestingly, auto-adjusting CPAP devices can be also used for an application different from the original intention (continuous tailoring of a patient's treatment). In fact, these devices are able to carry out simplified CPAP titration either in the sleep laboratory or in a patient's home. Instead of manually modifying nasal pμressure to determine the optimal CPAP, auto-adjusting devices can automatically determine the optimal pressure, thereby reducing the workload in sleep laboratories (figure 8). CPAP titration at home has the advantage that the patient is sleeping in his/her actual environment and that the titration process can be extended to several nights at an affordable cost (when compared with titration in the sleep laboratory). Simplified titration with auto-adjusting CPAP devices has proven useful when applied to selected subpopulations of patients [29, 30]. However, the generalised use of this titration modality should be cautious [17, 31], as a number of patients require full polysomnographic CPAP titration in the sleep laboratory. ■

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