Continuous positive airway pressure and humidification

Educational aims

To demonstrate the side-effects of CPAP on the upper airways.
To discuss the principles of humidification of breathing.
To explain the operating mode and distinctions of different heated humidifiers.

Summary

Upper airway complications are very common during noninvasive positive-pressure ventilation, particularly continuous positive airway pressure (CPAP). Acceptance of CPAP is compromised if such complaints occur; thus proactive management is very important for the achievement of good compliance. The use of conventional heated humidifiers is standard therapy when complications with upper airways arise during CPAP therapy. The performance of different types of heated humidifiers has not been fully considered in terms of their therapeutic effect. In particular, changes in ambient conditions should be taken into account. Advanced controlled heated humidifiers with heated breathing tubes monitor the amount of air flow, e.g. when mouth or mask leaks occur, as well as changes in ambient temperature. These more advanced techniques have been proven to reduce side-effects.

Introduction

In recent years, various techniques of artificial ventilation have been subject to widespread debate and discussion in terms of their efficacy and performance. This review will focus on the importance of humidification, with the main emphasis on noninvasive ventilation, particularly CPAP.
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In invasive ventilation, the upper airways are bypassed through an orotracheal tube or tracheal cannula; therefore, the natural humidification of air, which usually takes place in the upper airways, is no longer possible. Consequently, humidification of inspired air is mandatory in all cases of invasive mechanical ventilation, either with a heat and moisture exchange filter or through a heated humidifier [1, 2].

In noninvasive ventilation, a passage of air is provided through the upper airway and natural humidification occurs. Subsequent research refers primarily to noninvasive ventilation in the form of CPAP therapy, which has the largest number of users and has been the subject of the most clinical studies.

Obstructive sleep apnoea

Approximately 2% of females and 4% of males of working age currently suffer from obstructive sleep apnoea (OSA) syndrome [3]. Due to repetitive collapse of the upper airway during sleep, patients develop recurrent oxygen desaturations and arousals [4], resulting in nonrestful sleep [5], reduction in the quality of life [6, 7], increased rate of road traffic accidents [8], greater risk of developing arterial hypertension [9–11] and a higher risk of mortality from cardiovascular diseases.

The "gold standard" therapy for OSA is CPAP. CPAP prevents the collapse of the upper airway by means of a pneumatic splint. This therapy improves quality of life by reducing the effects of OSA, such as daytime sleepiness and road traffic accidents [12, 13]. CPAP for ≥4 h per night normalises the risk of mortality [14, 15]. However, it is not known how long the minimum usage per night must be to improve daytime symptoms [16, 17] and to have a favourable effect in the long term. It is possible that an average usage of >1 h CPAP therapy per night may reduce mortality [18]. For general considerations, total acceptance during the whole night would be desirable to prevent the collapse of the upper airway during the entire sleep time and to minimise the impacts on health as much as possible.

While therapeutic efficacy of CPAP treatment is excellent in sleep laboratories, the effectiveness in daily routine is significantly lower [19–22]. In total, 30-50% of all patients are not using CPAP treatment consistently in the long term for various reasons. There are no known serious sideeffects of CPAP therapy [23, 24]; however, some patients find tight-fitting masks and the higher airway pressure unpleasant. Furthermore, a considerable group of patients complain about mucus membrane problems, such as increased dryness of the upper airways [25, 26].

Technical developments in pressure applications, for example auto-adjusting CPAP [27–29], bi-level positive airway pressure [30] and pressure relief CPAP (C-flex) [31], are aimed at reducing the administered positive airway pressure in order to decrease side-effects and subsequently increase acceptance. However, as yet no modification of pressure device can demonstrate superiority compared with fixed pressure systems [32, 33]. Some advantages have been demonstrated in small patient subgroups, such as REM or sleep position-dependent OSA.

The other main technical approach for improving CPAP acceptance, based on the subjective experience of dryness, is the development of humidifying systems. Humidification with CPAP therapy makes treatment more comfortable and helps the patient consistently use CPAP. The following section discusses the fundamental concepts of humidification and how they are applied to CPAP therapy.

Physical background

Air can only hold a certain amount of water vapour or moisture. This certain amount of water vapour is known as maximum capacity and is influenced by the ambient temperature. The basic principle is the higher the temperature the greater the air capacity to hold water vapour and vice versa. Absolute humidity refers to the amount of water vapour or moisture that exists in the air and is measured in mg per L (figure 1). Figure 1 shows the relationship between temperature and humidity.

![Figure 1](image-url)  

**Figure 1**  
Relationship between temperature and maximum capacity.
Humidity can also be expressed in relative terms. Relative humidity is the ratio of true water content to maximum possible water content at a certain temperature, expressed as a percentage. Dew point refers to the temperature at which condensation begins to form. This occurs when the ambient temperature drops, causing the amount of moisture in the air to exceed the capacity of moisture that air can hold at that temperature, resulting in condensation.

A good example that can be used to illustrate how condensation develops is on a glass mirror while taking a shower. During a shower, the steam from the hot water increases humidity inside the bathroom to 100%, despite the fact that there is no change in temperature. When the fully saturated air hits the cold surface of the mirror, condensation begins and water droplets appear on the mirror’s surface. Modern homes sometimes have a heated element behind the mirror that maintains the surface temperature of the mirror above dew point which prevents condensation from occurring. Another example would be the formation of dew drops on grass, which can be seen early in the morning. As the temperature changes overnight, the moisture laden air hits the cool surface of the grass and results in dew drops.

Changes in temperature significantly affect absolute humidity. This is demonstrated by the following practical example. If the room temperature is 15°C and relative humidity is <50%, then absolute humidity under these conditions is 6 mg per L. Heat and moisture is added to inhaled air on its way through the airways from the nose to the alveoli, and relative humidity rises to 100% and 44 mg per L. Thus the air has to absorb >30 mg of water per L to be conditioned to a moisture level of 30 mg per L at 30°C and 90% relative humidity. Most of the conditioning of the inhaled air occurs at the level of the nasopharynx. As the air passes through the trachea, the inhaled air is further humidified to ~42 mg per L at 36°C and 100% relative humidity. Therefore, by the time the air reaches the alveoli the air is fully saturated to 44 mg per L at 37°C, reaching the core body temperature [34].

Humidity and CPAP

Experimental data show that there is a drop in absolute humidity at the anterior turbinates area of the nose from 17.4±3.8 to 15.3±2.3 mg per L under a CPAP pressure of 8 cmH2O [35]. When simulating a leak in the mask, the increased airflow causes an additional drop in humidity to 13.8±2.3 mg per L. This can be alleviated by a heated humidifier. To compensate for the high airflow, it is imperative that the air delivered via CPAP is humidified in order to avoid patient discomfort.

A particular burden on nasal mucosal membranes is the occurrence of a mouth leak, which results in a high unidirectional airflow in the nose and out through the mouth [36]. When experimentally simulating a mouth leak, nasal mucosal membranes dry out quickly; this subsequently increases the blood circulation around the mucous membranes, causing the resistance to air flow to increase severely [37]. Mouth leaks are predominantly seen when the patient uses a nasal mask [38]. To accommodate mouth breathers, full face masks can also be used. However, it is not always possible to convert nasal mask users to full face masks and they could continue to experience feelings of claustrophobia and reduced acceptance of CPAP [39]. The only reliable solution is to use humidification alongside CPAP therapy.

Physics of humidification

Humidification is based on a process called free evaporation, which is the principle of water molecules colliding and having sufficient energy to
escape the liquid as water vapour. The process of free evaporation can be achieved by increasing air-water surface area and airflow mass and by raising the temperature of the water. A conventional heated humidifier consists of a regulated heater plate that heats a water bath. The air stream travels over the warmed water where it absorbs heat and moisture.

The amount of humidity delivered by a CPAP system is very dependent on the ambient temperature and the amount of air flow. Modern humidification systems are designed to monitor both ambient conditions and air flow within the system to ensure the right amount of humidity is delivered. An algorithm that enables a subjective default adjustment considers ambient measurements and adjusts the temperature of the heater plate accordingly. Changing ambient conditions need to be factored into the design of the humidifier to prevent water condensation in the breathing tube; this is especially prevalent in colder environments.

A method that is used to overcome the limitations of humidification is to combine the humidifier with a heated tube. The temperature inside the tube is controlled by a copper wire, which coils around the walls of the tube. By maintaining a constant temperature along the length of the tube, the humidified gas is isolated from the influences of changing ambient conditions and condensation in the tube is prevented. This means that no moisture or humidity is lost as the gas travels along the length of the tube.

**Clinical benefit of humidifiers**

Cold pass-over systems are inferior to heated humidifying systems and have not achieved clinical relevance [40]. Various studies have analysed the effects of heated humidification on acceptance and side-effects of CPAP therapy [41]. The results are variable and inconclusive. While a general increase in CPAP acceptance in one randomised prospective study was shown [42], other studies failed to prove such an effect [43, 44]. There is no clear explanation for this variety of results, but it should be noted that the optimum level of humidification needed to reliably reduce the side-effects of CPAP therapy affecting the mucosa and the upper airways is not yet known. The performances of most conventional heated humidifiers, which can be combined with a CPAP device, vary significantly [45]. In summary, it can be said that it is possible to reduce the extent of upper airway discomfort with heated humidification; however, present studies show no general increase in the use of CPAP therapy.

Everyday experience shows that side-effects affecting the mucous membranes are to be expected in approximately one third of all patients treated with CPAP. Specific risk groups for the occurrence of such disorders are those who have undergone an uvulopalatopharyngoplasty, have a nasal medical history or who take medication, all of which have an impact on nasal blood
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circulation [46]. Several studies have shown that when upper airway disorders occur during CPAP therapy, the extent of these complaints could be reduced by the application of a heated humidifier [47], which leads to an increase in everyday use of CPAP. For practical purposes a step concept proved successful: when problems occur after an initial conservative CPAP trial, it is the standard practice to apply heated humidifiers [48].

Limited research exists on the use of heated breathing tubes during CPAP therapy. A study by NILIUS et al. [49] measured the effect of a conventional humidifier added to CPAP compared with a controlled heated breathing tube on sleep quality during two separate nights in the sleep laboratory. The study found that a heated breathing tube improved patient sleep quality (increased total sleep time, REM and stage 3/4 sleep). It also showed reduced side-effects with heated breathing tubes. These findings are important as they provide a true measure of therapy. Compliance is a useful outcome measure; however, it only relates to use, not to sleep. Theoretically, a patient can be compliant on their device, but awake all night. This research indicates that higher levels of humidity actually improve the quality of sleep, proving it to be a strong outcome measure.

A recent study by MASSENGILL and LEWIS [50] investigated the effect humidification has on titrated CPAP therapy in a controlled laboratory environment. The group found that with heated breathing tubes the average titrated pressure was 1.1 cmH2O, lower than titrating patients without the heated breathing tube. The proposed mechanism of action for this reduction was a decrease in nasal airway resistance with heated breathing tubes. This is an interesting finding, which should be investigated its importance in the role of CPAP titration. While the studies are limited and small in number, they show some noteworthy outcomes that are prospects for future research.

**Condensation**

The cooling down of the humidified air in the tube system after it has passed through the humidifier results in a reduction in the absolute level of water which can be dissolved in the gaseous phase of the air. If the temperature of the gas falls below the dew point, some of the moisture will condense in the tube. Depending on the level of water in the tube, the effective breathing pressure may fall distal to the stenosis and may compromise the quality of ventilation. As the air from CPAP passes over the condensate inside the tube, fluctuations in delivered pressure can be seen due to the increased resistance in the circuit. A study by BACON et al. [54] showed that the pressure can fluctuate by as much 5.6 cmH2O with as little as 10 mL of condensate inside the tube. Not only does the pressure fluctuate dramatically but gurgling noises can also stem from the accumulation of condensation. These noises can be disruptive to the patient and their bed partners, resulting in poor quality of treatment [49]. If condensation persists every night, this could cause the patient to abandon the therapy for good.

**Technical aspects of a good humidification system**

In short, a good humidifier is one that is able to deliver adequate levels of humidification without causing condensation or rain out. A heated humidification system typically comprises a chamber containing water and a heater plate, with some systems also having a heated breathing tube. The chamber or reservoir should be designed to hold sufficient water to last one full night of use. Some chambers have a baffle on the interior, which is designed to split the stream of air generated by CPAP in order to increase the surface area contact between air and water. The baffle, combined with the air flow, helps mix the air and water which is created by the turbulence generated by the air stream. Again, it is this turbulence that aids in collecting the moisture and delivering it to the patient.

**Side-effects**

Two main disadvantages of heated humidifiers have to be considered.

**Infections**

While various older studies do not show any evidence of increased bacterial transfer from the water reservoir to the air breathed [51], a newer survey proved such an association [52]. However, it is not clear if this finding has clinical relevance. A possible bacterial colonisation in the mask, tube or humidifier has to be considered when infections appear. Protection with a hydrophobic breathing filter may prevent such transmission. In particular, patients who do not follow hygienic recommendations seem to show a slightly increased risk of infection [53].
Critical to the delivery of optimal humidity is a high-performance heater plate, normally made of stainless steel, which is responsible for transferring thermal energy to the water contained inside the reservoir. A good heater plate heats the water as quickly as possible so that high levels of humidity are delivered to the patient from the outset of therapy.

A heated breathing tube assists in the delivery of high levels of humidity without condensation changing ambient conditions. If the power supplied to the heater plate and heated breathing tube is insufficient, it is highly likely that rain out will occur. Therefore, low-powered humidifiers are more susceptible to rain out when overnight temperatures decrease.

CPAPs without a heated breathing tube may be limited to delivering gas at room temperature. This means they can only deliver gas at the maximum saturation of the room temperature. Trying to deliver gas above this temperature will cause rain out as the gas cools to room temperature in the nonheated tube. A recent bench study showed that conventional humidifiers were only able to achieve 18 mg per L (absolute humidity) at 22°C (room temperature) while heated humidification with a heated breathing tube is able to reach 28 mg per L without condensation [55].

Conclusion

If nasopharyngeal sideeffects occur sufficient humidification is of great importance in order to ensure that a patient receives effective CPAP therapy. Delivering effective CPAP therapy is the only noninvasive treatment option available, which needs to be sustained for the lifetime of the patient once diagnosed with OSA. Since most patients find CPAP an unnatural experience to start with, it is important that an effective humidification system reinforces CPAP therapy to make it a comfortable and natural experience.

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