Heated Humidification Devices

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1.1 Introduction

During normal breathing, the upper airways condition inspired gases in order to prevent dryness and damage to the mucosae. During mechanical ventilation (MV) , the inspired gases are dry, and there are numerous studies that have demonstrated the negative effect of dry gases on the respiratory tract. The lack of adequate conditioning may thicken airway secretions, which increases the airway resistance, reduces the gas exchange effectiveness and increases the risk of respiratory infections [1]. For these reasons, gas delivered during MV must be warmed and humidified to avoid serious complications related to dry gases [2]. Humidification is recommended for every patient receiving invasive MV, and it is considered the standard of care according to the American Association for Respiratory Care [1]. There is no clear consensus on humidification during non-invasive ventilation, but humidification is highly suggested to improve comfort [1]. Several types of humidifiers have been produced for clinical use, each with advantages and disadvantages. Humidification devices can be divided into active heated humidifiers (HHs), which are devices heated by warm water; passive humidifiers (PHs) such as heat and moisture exchangers (HMEs), which capture the heat of exhaled air and release it at the next inspiration; and hot water humidifiers.

1.2 Active Heated Humidifiers

Active heated humidifiers (HHs) allow air passage inside a heated water reservoir and are usually placed in a ventilator circuit in the inspiratory limb. Air and water vapour travel along the inspiratory limb and reach the patient's airway. This system

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needs the addition of water traps due to the accumulation of water vapour condensate, which is formed when the temperature of the inspiratory limb decreases. These humidifiers have sensors at the outlet of the humidifier and at the Y-piece, near the patient. This sensor provides continuous feedback to a central regulator to guarantee a determined temperature at the distal level. When the temperature is too high or too low, the alarm system is triggered. In an ideal system, the alarm should be triggered by humidity levels, but it is actually triggered only based on temperature. The temperature setting is usually 37 °C. HHs have different techniques for humidification and different designs. They are divided into bubble, passover, counter-flow and inline vapouriser.

In bubble humidifiers, a gas is pushed through a tube in the bottom of water container. The gas forms bubbles because it escapes from the distal end and gains humidity as it rises from the water surface. These devices could have a diffuser that breaks gas into smaller bubbles. The vapour content is influenced by the size of bubbles, the gas–water interface, the amount of water in the container and the flow rate. In this case, slower flows guarantee more time for gas humidification. Bubble humidifiers may be unheated or heated. Heated bubble humidifiers are designed to work with high flow rates (100 L/min) and provide high humidity. They are usually used in oxygen delivery systems. These humidifiers give a high resistance to flow generating an increase in work of breathing. A problem with these humidifiers is that they may generate microaerosols, but it is not clinically significant regarding the risk of healthcare-associated pneumonia [3]. Bubble humidifiers are less used now than they had been in the past.

Passover humidifiers are the most used in both non-invasive and invasive MV because of their lower flow resistance and absence of microaerosols. In these devices, gas passes over a heated water reservoir carrying vapour to the patient. There are other types of passover humidifiers: hydrophobic and wick humidifiers. In hydrophobic passover humidifiers, dry gas passes through a hydrophobic membrane that allows the passage of water vapour but not liquid water. Aerosols and bubbles are not generated. In wick humidifiers, the gas enters a water reservoir and passes through a wick that has a distal end immersed in water. The wick pores provide the gas–water interface that allows for greater humidification with respect to simple passover humidification. The water in the reservoir is supplied manually or through a feed system that guarantees a constant water level. The gas enters and travels through the wick, but it is not submerged underneath the water surface, so bubbles are not generated. In this device, a temperature is guaranteed by a temperature probe placed near the Y-piece of the ventilator. This could generate a condensate in the tube, increasing resistance. Incremented resistance increases peak pressure in volume-controlled modes and decreases volume delivered in pressure-controlled modes. Nevertheless, to reduce the risk of condensation, the AARC clinical guidelines recommend the use of gas delivered at 37 °C and 100% humidity [1].

In an inline vapouriser, water vapour is injected into the gas of the inspiratory circuit, using a small plastic capsule. Gas is supplemented by a disc heater in the capsule. A peristaltic pump delivers water to the capsule. The amount of water is set by a clinician based on minute ventilation and can be adjusted constantly.

In a counter-flow humidifier, the water is heated outside the vapouriser and pumped to the top of the humidifier and through small-diameter pores to reach a large surface area, from where the gas flows in the counter direction. Air is moisturised and warmed during the passage through the chamber. In a study on an artificial lung, Schumann et al. [4] demonstrated that the counter-flow device requires less to breathe with respect to heated passover humidifiers and HMEs. These humidifiers are promising but more studies are needed to evaluate their benefits.

1.3 Passive Humidifiers

The working principle for PHs is based on their capacity to retain heat and humidity during expiration and to deliver at least 70% of the inhaled gas during subsequent inspiration. It is a passive system because all heat and moisture are derived entirely from the patient and no energy is added to the system. This 'passive' function can be achieved by different mechanisms, and the classification of these devices is based on their mechanism.

There has been growing acceptance of PHs in recent years because of their low cost, simple operation and elimination of condensate from the breathing circuit [1]. Concern over adverse ventilator effects of PHs has mainly been aimed at the increased resistance imposed by the foam or paper insert. The working principle of PHs implies that a higher volume of condenser material will yield better device performance. For this reason, the 'ideal' dead space for a humidifier is approximately 50 mL [5].

Their performance ultimately depends on a number of factors such as ambient temperature, inspiratory and expiratory flow rates, surface area and water vapour content of the medium. These humidifiers are inexpensive, easy to use and silent and do not require water or an external energy source, temperature monitor or alarms. Moreover, there is no danger of over-hydration, hyperthermia or burns. As disadvantages, they can deliver only limited humidity, contribute insignificantly to temperature preservation and are less effective than AHs, especially when intubation lasts for several days. When the dead space increases, it may be necessary to augment the tidal volume, which would increase the work of breathing [6].

The simplest passive humidifiers are the heat and moisture exchangers. Heat and moisture exchangers (HMEs) are also called artificial noses because they act as nasal cavity in gas humidification. HMEs operate passively by storing heat and moisture from the patient's exhaled gas and releasing it to the inhaled gas. They are simple condensers constructed with elements made of disposable foam, synthetic fibre or paper, with a significant surface area that can generate an effective temperature gradient through the device delivering heat on each inspiration. A condenser element retains moisture from every exhaled breath and returns it back to the next inspired breath. These humidifiers are placed between the patient and Y-piece of ventilator, increasing resistance in the airflow during expiratory and inspiratory phase, which makes the humidifier part of the instrumental dead space [1].

Initially, simple HMEs were made from condenser made of metallic elements with a high thermal conductivity, and they recaptured 50% of a patient's exhaled moisture, providing a humidification of 10–14 mgH_2O/L at tidal volume [7]. They created high resistance during ventilation and are no longer used. Newer types of HMEs are hydrophobic, hygroscopic, filtered or pure hygroscopic HME.

Hydrophobic HMEs use a water-repellent element with a large surface area and low thermal conductivity that maintains higher temperature gradients than in the case of simple HMEs. Hydrophobic membranes have small pores and are pleated to increase the surface area. At usual ventilatory pressure, they allow the passage of water vapour but not liquid vapour. They have efficient bacterial and viral filters. High ambient temperature may impair their performance. Combined hygroscopic and hydrophobic HMEs are made with synthetic fibre. A hygroscopic chemical product (calcium chloride or lithium chloride) is added inside the hydrophobic HME, which absorbs expired water vapour and delivers it to the inspired gas, optimising the delivery of humidity. The synthetic fibre also helps to decrease the accumulation of condensation in a device-dependent position. Pure hygroscopic HMEs have only the hygroscopic compartment. During expiration, vapour is condensed in the element as well as in the hygroscopic salts, and during inspiration, vapour is obtained from the salt. They provide humidity between 22 and 34 mgH_2O/L. Despite the theoretical advantages of hygroscopic HMEs compared with hydrophobic devices, researchers found no differences in the quantity of tracheal aspirates, mucus viscosity, atelectasis, tracheal tube occlusion, bacterial colonisation and ventilator-associated pneumonia (VAP) [8].

In purely hydrophobic HMEs, the condenser is made of a water-repellent element as a hydrophobic membrane with low thermal conductivity that maintains higher temperature gradients than in the case of simple HMEs. They allow passage of water vapour but not liquid water. Adding a filter to a hydrophobic or hygroscopic HME produces a heat and moisture exchange filter (HMEF).

The applied filter can operate based on mechanical or electrostatic filtration, so the filters can be incorporated into pleated or electrostatic filters. Pleated filters have low electrostatic charges but denser fibres, so they represent a barrier for viruses and bacteria. The nature of the membrane causes turbulent airflow, increasing the deposition of viral and bacterial particles on the internal side of the filter. Moreover, they increase airflow resistance. Electrostatic filters have less dense fibres but high electrostatic charges, and they depend on an electric field. Bacteria and viruses have an electric charge, so they get trapped inside the electric field of the filters. They are characterised by large pores and work based on electric fields, contributing very little to the humidification process and increasing resistance [9]. For this reason, they are used to protect patients from bacteria and viruses [2].

HMEs vary considerably in terms of performance and durability [10, 11]. Some devices perform suboptimally leading to increased airway resistance and tracheal tube occlusion from retained secretions. Lellouche et al. [11] independently tested the performance of 48 p-HMEs and showed only 37.5% performed well (AH $\geq$ 30

mgH_2O/L) with 25% performing poorly, providing AH of 4 mgH_2O/L. This finding has been replicated elsewhere [12]. While some manufacturers use the gravimetric method to test performance (as employed by the international standard ISO 9360 11), which involves weighing the humidifier before and after the period of operation under strictly controlled conditions, others use the psychrometric method. Although there is little discrepancy between both methods in vitro [10, 11], only a psychrometric test can be used in patients, and future devices should be benchmarked against this technique in vivo. Current evidence suggests that HMEs that can deliver gases with an AH of >30 mgH_2O/L have a low risk of tracheal tube occlusions, while those providing AH of 30 mgH_2O/L have a longer lifespan, extending to 48 h [13] or even as long as 1 week in certain patients without any increase in the risk of tracheal tube occlusion or bacterial colonisation [14]. However, further testing of devices that consistently achieve AH > 30 mgH_2O/L in vivo and determining the durability of each device are needed.

An important characteristic of HME filters is that there is no problem with tube condensation, preventing the development of ventilator-associated pneumonia, but in well-maintained circuits, this factor is controversial. The presence of secretions and blood in the device increases the airway resistance and work of breathing. Aerosol medication cannot be administered, and HMEs should be removed from the device.

1.4 Active Heat and Moisture Exchangers

Active heat and moisture exchangers (aHMEs) include a regular HME but place a small heater between the HME and the patient that vapourises added water, converting them from passive to active and increasing the humidification capacity. There are various existing models. The Humid-Heat® device (Gilbeck AB, Sweden) is a hygroscopic HME that allows water to drip onto a heated paper element that acts as a wick. They have pre-set values for humidity and temperature, but the minute volume of the ventilator must be set. The HME Booster® (Medisize, Belgium) features a heater covered with a Gore-Tex® membrane. Water is added to the surface of the heater and vapourised, allowing passage through the membrane, a phenomenon that regulates the amount of water vapourised. The heating unit is incorporated between the patient and the HME. The Performer device has a metal plate placed between two hydrophobic and hygroscopic membranes; it is heated by an external source that has three temperature levels: 40, 50 and 60 °C. Water is provided at one end of the humidifier, reaching the two membranes and the metal plate that heats it. The water vapour produced increases the vapour content in the inspired gas. The Hygrovent Gold is an active hydrophobic HME. There is a heating element and a water line that provides water in the HME. These devices have the advantage such as they run dry and the HME functions normally. There is an increased flow resistance with this active device.

1.5 Hot Water Humidifiers

Hot water humidifiers (HWH) are considered the gold standard in humidification. They deliver gas at 37 °C with an AH of 44 mgH_2O/L, but in clinical use, they may only deliver AH between 35 and 40 mgH_2O/L [15]. They comprise a heating element that heats the water within a chamber. Dry gas is then passed through this chamber over the hot liquid surface or bubbled through the water to become humidified. The temperature within the chamber is thermostatically controlled, which allows fully saturated gas to be produced at a variety of temperatures. They are more efficient in providing humidification compared with passive HMEs, but the risks are greater, and they are more expensive. The main risks are overheating, causing inhalational burns, and the possibility of water condensing within the inspiratory limb of the ventilator tubing as gas cools, leading to bacterial colonisation. This may be reduced by incorporating heated wires within the walls of the tubing. The risk of colonisation may also be reduced by increasing the temperature of the water bath up to 45–60 °C (continuous pasteurisation) [16], adding antibacterial agents to the water or breathing circuit tubing [17] or maintaining a closed sterile system. Increasing temperature poses an increased risk of inhalational thermal injury. Antibacterial agents are rarely used due to the risk of ingestion, and maintaining a closed sterile system is difficult to achieve. Unless visibly soiled, breathing circuits need not be replaced routinely [18], and unnecessary manipulations and breaks in circuit tubing should be avoided.

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