REVIEW

Humidification of inspired gases during mechanical ventilation

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ABSTRACT

Humidification of inspired gas is mandatory for all mechanically ventilated patients to prevent secretion retention, tracheal tube blockage and adverse changes occurring to the respiratory tract epithelium. However, the debate over "ideal" humidification continues. Several devices are available that include active and passive heat and moisture exchangers and hot water humidifiers Each have their advantages and disadvantages in mechanically ventilated patients. This review explores each device in turn and defines their role in clinical practice. *(Minerva Anestesiol 2012;78:496-502)*

Key words: Respiration, artificial - Humidity - Tracheostomy.

Mechanical ventilation uses dry, piped gas instead of room air to ventilate the lungs which bypass the body's normal warming and humidifying mechanisms. Dry gas has detrimental effects on the respiratory tract in intubated patients, damaging epithelium and causing secretions to become more viscous. To prevent this occurring, several types of humidifiers have been produced for clinical use and each has its own advantages and disadvantages.

Defining humidity

Humidity refers to the amount of water vapor in a gaseous environment. It can be expressed in two ways. Absolute humidity (AH) is the mass of water in a given volume of gas, usually expressed in mg H_2O/L or Kg H_2O/m^3.

Relative humidity (RH) is the amount of water vapor present in a volume of gas as a percentage of the amount of water vapor that is required to fully saturate the same volume of gas at the same temperature and pressure.

The temperature must be specified, as the maximum amount of water vapor that a volume of gas can hold increases as temperature increases. Conversely, as gas that is fully saturated with water is cooled, the gas can no longer accommodate all the water vapor present and water condenses out onto the surroundings. A common example of this occurs within the expiratory limb of breathing circuits.

Humidity and heat within the respiratory tract

Indoor atmospheric air at 20 °C has a AH of around 10 mg H_2O/L water and a RH of 55-60%. As this air passes through the nose and upper airways it is warmed and moistened. In the alveoli, the air is at 37 °C and is fully saturated with 44 mg H_2O/L water (RH=100%). This provides optimal conditions for gas exchange at the alveolar-capillary interface and is referred to as "body temperature and pressure saturated with water vapor" (BTPS). The airway provides both heat and moisture to inspired air to meet these conditions.

Heat losses may result as heat energy is ex-

pended to convert liquid moisture within the airway epithelium to vapor (latent heat of vaporisation) and by direct transfer of heat from mucosa to incoming air.

Effects of inadequate humidification

Inadequate humidification causes increased mucus viscosity and inspissation, depressed ciliary function, tracheal inflammation and mucosal ulceration. Later changes include epithelial cell necrosis and squamous metaplasia. These changes may result in an increased incidence of respiratory tract infection and airway obstruction or atelectasis due to retained secretions. Additionally, as the body tries to humidify dry gas, there is an increased loss of body water and heat. Although this may be of insignificant consequence in adults, it may have important clinical implications in children, particularly neonates who have a higher minute ventilation to body surface area ratio. Bissonnette *et al.*[1] showed a reduction in core body temperature of 0.75 °C in anesthetised children after 90 minutes in those not receiveing any form of humidification compared with those who did. Hypothermia has many adverse effects. Amongst these, ventilation with cold dry gases may cause deterioration in FEV_1 of up to 21% in asthmatic patients and a less favorable improvement in FEV_1 in non-asthmatic patients that would normally occur in warm humid conditions.[2] This may result in greater work of breathing and impair weaning from mechanical ventilation.

Effects of over humidification

Currently, there are no criteria for over-humidification. In some reports, it has been suggested that over humidification occurs when tracheal gas is fully saturated above around 32 °C, a point where water vapor content is higher during inspiration than expiration and exchanges of heat and water are reversed during a respiratory cycle.[3] Others suggest over-humidification occurs when delivered inspired gas is above BTPS.[4] Overhumidification reduces mucus viscosity, increases the pericillary layer, dilutes surfactant and causes neutrophilic infiltration of lungs and bronchioles. The resulting effect of these changes causes secretion retention, atelectasis, worsening lung compliance, increased pulmonary shunt fraction with an increased alveolar-arterial oxygen gradient.[4] These changes may result in pulmonary and generalized edema, weight gain, hyponatremia and increased local susceptibility to bacterial invasion leading to bronchopneumonia. Delivering inspired over-humidified gas may cause water to condense on the walls of the breathing circuit resulting in increased airflow resistance with further potential for infection from retained droplets. Problems with under and over humidification are summarised in Table I.

Effects of excess heat

Overheating the respiratory tract causes mucosal sloughing, impairment of mucociliary clearance and deposition of fibrin casts in small airways. This results in mechanical obstruction leading to carbon dioxide retention and impaired oxygenation with ventilation-perfusion mismatch. The temperature at which these changes occur is also dependent on humidity and duration of exposure, but it has been recommended that respiratory gases that arrive at the tracheal end of the endotracheal tube should average less

Table I.—*Summary of the adverse effects of under and over humidification.*

Ia Effects of dry gas inhalation	Ib Effects of excess pulmonary water delivery
– Mucosal ulceration	– Excessive pulmonary secretions
– Destruction of cilia	– Edema (pulmonary and generalized)
– Hyperaemia and inflammation	– Weight gain
– Desquamation of cells	– Hyponatremia
– Disorganisation of basement membrane and epithelial layer	– Decreased pulmonary compliance
– Cytoplasmic and nuclear degeneration	– Reduced vital capacity
– Microatelectasis from obstruction of small airways and reduced surfactant leading to reduced lung compliance	– Lowered alveolar-arterial oxygen gradient

than 42 °C to prevent the adverse effects associated with thermal injury.[5]

Methods of humidification

Passive heat and moisture exchangers

Passive heat and moisture exchangers (p-HME) sit between the tracheal tube and ventilator tubing and work by trapping heat and moisture as a patient expires and returning them to the patient in the next inspiration. Because all heat and moisture is derived entirely from the patient and no energy is added to the system this is a passive system. Under optimal conditions they can provide up to 30-32 mgH_2O/L AH at 27-30 °C [6] but their ultimate performance is dependent on a number of factors such as ambient temperature, inspiratory and expiratory flow rates, surface area and water vapour content of the medium.

They are composed of material of high thermal capacity and conductivity that is arranged in a spun and pleated fashion to allow gas to cool and condense on expiration and warm and evaporate on inspiration. Some have a hygroscopic element, usually calcium or lithium chloride, which improves water retention following expiration and hence improveseefficiency.[7]

Despite the theoretical advantages of hygroscopic p-HMEs compared with hydrophobic devices no differences were shown in the quantity of tracheal aspirates, mucus viscosity, atalectasis, tracheal tube occlusion, bacterial colonization and ventilator associated pneumonia (VAP).[8]

Studies looking at different types of p-HMEs, have been shown to vary considerably in terms of performance and durability.[6, 7, 9] Some devices perform sub-optimally leading to increased airway resistance and tracheal tube occlusion from retained secretions. Lellouche *et al.*[6] independently tested the performance of 48 p-HMEs and showed only 37.5% performed well (AH ≥30 mgH_20/L) with 25% performing poorly, providing AH <25 mgH_20/L, a level associated with tracheal tube occlusion. Furthermore, there was a significant discrepancy between the measured AH and the manufacturers data, where in 36% of devices the difference of AH was >4 mg H_20/L. This finding has been replicated elsewhere.[10] While some manufacturers use the gravimetric method to test performance (as used 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 discrepency between both methods *in vitro*,[6, 7] only a psychrometric test can be used in patients and future devices should be benchmarked against this technique *in vivo*.

Current evidence suggests that p-HMEs that can deliver gases with an AH >30 mg H_20/L have a low risk of tracheal tube occlusions while those providing AH of <25 mg H_20/L are associated with a significant increase in tracheal tube occlusion and should be avoided.[6] Providing AH between 25 and 30 mg H_20/L is considered a "grey zone" and those using a device providing this range of AH, should consider to the risk of tracheal tube occlusion. In terms of durability, manufacturers recommend that p-HMEs are changed every 24 hours, but providing an AH >30 mgH_20/L is achieved and maintained, the life-span of these devices could be extended to 48 hours [12] or even as long as one week in certain patients without any increase in the risk of tracheal tube occlusion or bacterial colonisation.[9] However, further testing of devices that consistently achieve AH levels >30 mg H_20/L *in vivo* and determining the durability of each device are needed.

Active heat and moisture exchangers

Active heat and moisture exchangers (a-HMEs) include a regular HME, but place a small heater between the HME and the patient that vaporises added water.

The Humid-Heat® device (Gilbeck AB, Sweden) allows water to drip onto a heated paper element that acts as a wick. The HME Booster® (Medisize, Belgium) features a heater covered with a Gore-Tex® membrane. Water is added to the surface of the heater and vaporised, allowing passage through the membrane, that regulates the amount of water vaporised. Both devices

have the advantage that should they run dry, the HME functions normally.

In vitro studies comparing a-HMEs with passive devices have consistently shown increased inspired AH with airway temperature ranging from 31.9 to 37 °C and AH from 34.3 to 44 mg H_2O/L.[13-15] Similar results have been produced *in-vivo*, where the same device (the Performer) provided significantly higher levels of humidification (AH range 30-36 mg H_20/L) when used as an active device compared with its use as a passive device.[14] In the same study, whilst the efficacy of p-HMEs worsened at minute ventilation both above or below 10 L/min, a-HMEs retained their function suggesting these devices may be more suitable for extremes of minute ventilation. Others have shown that the aHME retains its efficiency between 3 and 25 L/min.[15]

In hypothermic conditions, Pelosi *et al*. demonstrated that a-HMEs perform better, providing AH of 27.1 mg H_2O/L compared with 24.6 mg H_20/L from the best performing passive device when expired airway temperature was 28 °C.[13] Overall, data for a-HMEs looked promising at first but has not translated into widespread clinical use.

Hot water humidifiers

Hot water humidifiers (HWH) have traditionally been considered to be the gold standard in providing humidification as they deliver gas at 37 °C with an AH of 44 mg H_2O/L, but in clinical use may only deliverAH levels between 35 and 40 mg H_2O/L.[16] They have a heating element, which 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. It is more efficient in providing humidification when compared to p-HMEs, but the risks and costs are greater. Risks include overheating, causing inhalational burns and the possibility of water condensing within the inspiratory limb of ventilator tubing as gas cools, which may lead 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),[17] adding antibacterial agents to the water or breathing circuit tubing [18] 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 [19] and unnecessary manipulations and breaks in circuit tubing should be avoided.

Choice of humidifier

Although providing some sort of humidification is essential in mechanically ventilated patients, it is still unknown what device is most beneficial. Table II summarises each device.

The ideal humidifier should provide optimal temperature and humidification with low risk of adverse events, be simple to use and inexpensive. One reason for lack of such a device is that the optimal level of humidity and temperature is still unknown. Standards for humidifiers for medical use state that p-HMEs should provide at least 30 mgH_2O/L at 30 °C when tested at tidal volumes greater that 250 mL (ISO 9360[11]) and that HWHs should be able to provide at least 33 mgH_2O/L with maximum respiratory gas temperature not exceeding 42 °C (ISO 8185[5]). However, these standards are based on *in-vitro* testing and set a minimum performance for humidifiers, but do not define a level of humidification that provides maximum clinical benefit.

While p-HMEs provide AH of up to 32 mg H_2O/L at 27-30 °C, HWHs and the newer a-HMEs can provide AH close to 44 mg H_2O/L at 37 °C. Providing such conditions with HWH and a-HMEs may not be necessary and can result in over-humidification and heat related airway injury.[20] Both p-HMEs and a-HMEs can become occluded with blood, secretions or condensate resulting in an increased resistance to airflow and work of breathing. In hypothermic patients p-HMEs and possibly a-HMEs

Table II.—*Comparison of different types of humidifiers.*

	Advantages	Disadvantages
Cold water humidifier	Simple	Inadequate humidity
	Cheap	Infection risk
Nebuliser device	Suitable for high frequency jet ventilation	Risk of over humidification, hypothermia and infection
Passive HME device	Simple	Increased dead space
	Cheap	Increased circuit resistance
	Provides adequate humidity for many patients	Risk of obstruction
		Inadequate in some cases
Active HME device	Relatively simple	Increased dead space
	Relatively cheap	Increased circuit resistance
	Boosted humidity output compared to HME.	Risk of obstruction
	Still performs as pHME if allowed to run dry	
Hot water humidifier	Delivers maximal humidification at 37 °C	Complex to setup and run
		Expensive to acquire and maintain
		Risk of infection
		Risk of aspiration of water
		Risk of burns/electric sock
		Over-humidification possible
		Large number of connection to become disconnected

have limited performance and should be used with caution, while HWHs can potentially lead to over-humidification.[20] The American Association of Respiratory Care guidelines suggest p-HMEs should be avoided for patients with body temperature less than 32 °C.[21] Both active and passive HMEs should also be used cautiously with patients undergoing low tidal volume ventilation (such as in acute respiratory distress syndrome) as HMEs increase dead space by up to 90 mL, which may increase the risk of hypercapnia.[22] Similarly, HMEs should not be used for patients with an expired tidal volume less than 70% the delivered tidal volume (*e.g.* those with large bronchopleurocutaneous fistulas or incompetent or absent tracheal tube cuffs) [21] nor should they be used in difficult to wean patients with chronic respiratory failure, such as chronic obstructive pulmonary disease.[23] P-HMEs may also be contraindicated in patients with high minute volumes exceeding 10 L/min as they have reduced efficacy.[23, 24]

In some situations the choice of humidification method may be influenced by cost effectiveness. Boots *et al.* in 2006 evaluated daily cost of p-HME compared with HWHs, taking into account purchasing and maintenance costs.[25] The daily cost of p-HMEs were comparable to HWHs (AUS $ 8.62 *vs.* AUS $ 8.98, respectively). These costings were based on changing HMEs daily in accordance to manufacture recommendations. Studies showing safe use of p-HMEs beyond the 24 hour period [12] should be repeated and if p-HMEs can be used safely for more prolonged periods, such as up to 48 hours, it would represent a major cost advantage for p-HMEs over HWHs.

Several meta-analyses have shown no difference in VAP rates or airway occlusion between HMEs and HWHs.[26, 27] There were also no differences seen with respect to atelectasis, $PaCO_2$, work of breathing, secretion clearance and length of ICU stay.[27] The only differences observed were a lower body temperature and lower cost in the p-HME group.

There is not one method of humidification that is universal for every patient in every situation, so the choice of device should be tailored to the individual patient. A number of algorithms have been developed to aid choice of humidifier in each situation. One suggested example was developed by Branson *et al.* at the University of Cincinnati [28] (Figure 1).

In this study, the quality of pulmonary secretions aspirated by suction catheter was used as a measure of adequacy of humidification, based on the scale described by Suzukawa *et al.*[29] (Table III). The algorithm was evaluated in 120 patients and was shown to be cost effective and safe in one surgical ICU.

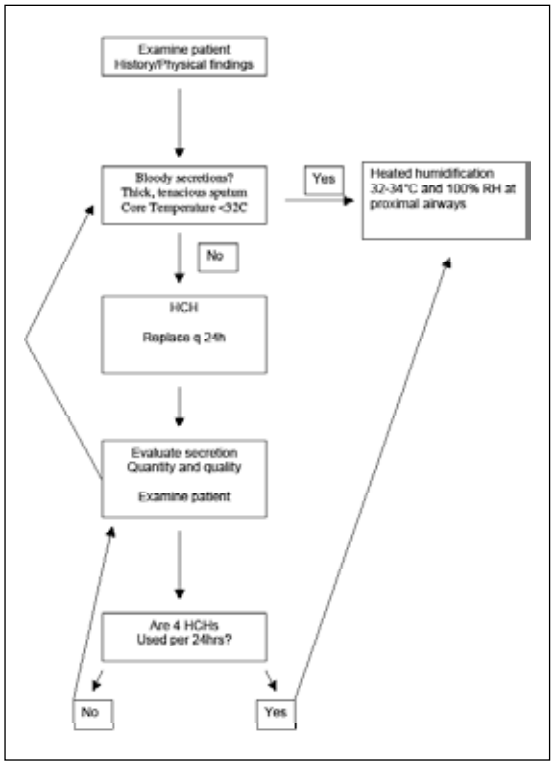

Figure 1.—Algorithm to aid choice of humidification (developed by Branson *et al.*[28]). HCH: hygroscopic condenser humidifier (equivalent to p-HME).

Humidification during non-invasive ventilation

Gas delivered when using non-invasive ventilation (NIV) passes through the upper airways and is exposed to the body's normal humidifying system. Despite this there is increasing evidence that additional humidification is needed. Firstly, patient comfort is key to NIV success and not providing additional humdification significantly reduces patient comfort levels (mostly nose and mouth dryness) which may contribute to NIV failure.[30] Secondly, If NIV fails as a result of insufficient humidification, subsequent tracheal intubation may be more difficult owing to mucosal drying and secretion retention.[31] Lellouche *et al.*[30] studied the impact of HMEs and HWHs in normal volunteers exposed to NIV in the presence and absence of mask leak for one hour. No humidification provided an AH of around 5 mg H_2O/L, while use of either an HME or HWH provided AH of inspired gases to between 25-30 mg H_2O/L. In the presence of mask leaks the AH of delivered dry gas decreased to 15 mgH_2O/L with HMEs but was maintained at 30 mg H_2O/L with HWHs. Because of inevitable air leaks which occur around the mask, the gas flow associated with NIV is mostly unidirectional and therefore the amount of heat and moisture that can be exchanged with HMEs is reduced. However, using HMEs during NIV increases work of breathing because of the additional dead space added to the circuit.[32, 33] Although humidification should be provided, HWHs should be used in preference to HMEs. These factors may decrease patient adherence to therapy and ultimately cause NIV failure.[32, 33]

Conclusions

The devices most suited for humidification include the HWH, the p-HME and more recently the a-HME. The HWH and a-HME undoubtedly provide higher humidity levels for inspired gas but in some patients, p-HMEs may have advantages. There is no one method of humidification that suits all patients and clinicians need to tailor the method used to the patient's needs.

Table III.—*Grading of secretions aspirated with suction catheter.*

Type of secretion	Description
Thin	Suction catheter clean after use
Moderate	Secretions adhere to inside of catheter after suctioning but are easily cleared by aspirating water
Thick	Secretions adhere to inside of catheter after suctioning, but cannot be cleared by aspirating water

Reproduced from Suzukawa *et al.*[29]

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Conflicts of interests.—GRP Consults to Inspired Technologies Ltd, who design novel active heat and moisture exchanging humidifiers.
Received on March 31, 2011. - Accepted for publication on January 11, 2012.
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