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Humidification in anaesthesia and critical care

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Key points

- The term humidity describes the amount of water vapour in a gas.
- Energy is required to heat and humidify dry gases. Humidifying and warming inspired dry gas accounts for ~15% of the body's total basal heat expenditure.
- Failure to provide humidified inspired gases can lead to complications and patient harm.
- Systems designed to humidify inspired gases can be described as active or passive and choice of device will depend on clinical scenario.
- Devices used for non-invasive ventilation (NIV) may not incorporate humidification, but the use of humidification during NIV has been shown to improve patient comfort.

Adequate humidification is an important consideration in the delivery of anaesthetic gases and supplementary oxygen therapy to those patients requiring additional respiratory support, including mechanical ventilation. Failure to provide humidified respiratory support can lead to unwanted complications and therefore the anaesthetist needs to be equipped with a fundamental understanding of the principles of humidification and the equipment used to provide it.

Physical principles of humidification

A liquid, such as water, consists of molecules. Such molecules have variable kinetic energy and the temperature of the liquid is determined by the mean kinetic energy of its molecules. At an interface between a liquid and a gas, molecules with sufficient kinetic energy will be able to overcome the forces of attraction within the liquid and escape into the gas as a vapour. The molecules escaping from the liquid surface are those with the greatest kinetic energy. As they leave, the mean energy of the molecules within the liquid (and therefore its temperature) will decrease as evaporation occurs. The molecules in the vapour formed above the liquid will exert a partial pressure within the gas. In a sealed container at constant temperature, equilibrium will develop where equal numbers of molecules escape and re-enter the liquid phase. At steady state, the gas is saturated with vapour and the partial pressure the vapour molecules exert on the container is known as the saturated vapour pressure. Saturated vapour pressure is dependent on temperature (Fig. 1). With the addition of heat energy to a liquid, the temperature of the liquid increases as does the mean kinetic energy of the molecules. Greater numbers of molecules are capable of escaping the liquid phase thereby exerting a greater saturated vapour pressure. The massic enthalpy of evaporation (latent heat of vaporization) is the heat required to convert 1 g of substance from the liquid phase to the gaseous phase at a given temperature. For molecules of a liquid to evaporate, they must be moving in the right direction near the surface and have sufficient kinetic energy. At a molecular level, there is no clear boundary between liquid and vapour states, and this is described as the Knudsen layer, whereby the phase is undetermined. Once the critical temperature has been reached, the substance will only exist as a gas (Table 1).

Humidification describes the addition of water vapour to a gas and absolute humidity is the mass of water vapour per unit volume of gas. It has units of g m^{-3}.

Relative humidity is the ratio of the actual mass of water vapour in a volume of gas to the mass of water vapour required to saturate that volume of gas at a given temperature. It is expressed as a percentage. Relative humidity can also be calculated as the water vapour pressure over the saturated water vapour pressure.

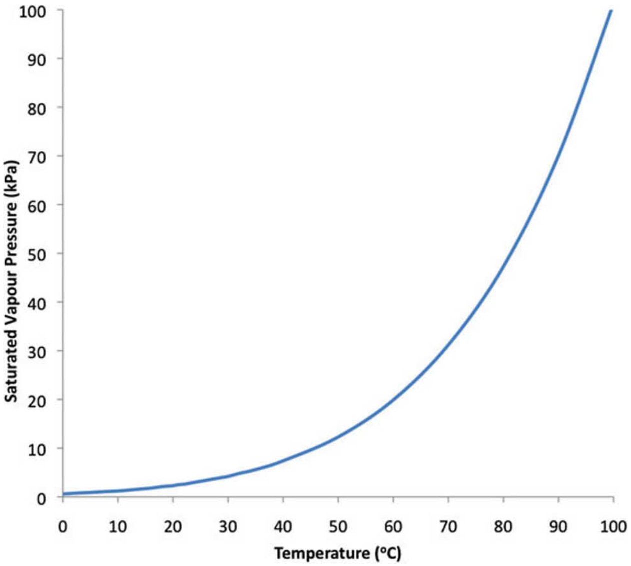

Fig 1 The non-linear relationship between the saturated vapour pressure of water and temperature.

Table 1 Basic definitions of principles relating to humidification

A gas is a state of matter formed when a liquid is heated above its critical temperature. In the gaseous state, the molecules are in constant motion without a structure. The mean distance separating individual molecules is great and the Van der Waals force between individual molecules is negligible
A vapour is matter in its gaseous state below its critical temperature. Unlike a gas, the molecules are however capable of re-entering the liquid phase and at any one temperature, an equilibrium occurs where the number of molecules leaving the liquid equals the number entering it
Critical temperature is the temperature above which a vapour can no longer be liquefied by any amount of pressure. Above this temperature, the substance is a gas
Vapour pressure is the pressure created by the molecules that have left the liquid phase in favour of the gaseous phase, expressed as kPa
Saturated vapour pressure is the vapour pressure when the liquid and vapour phase are in equilibrium, expressed as kPa
Latent heat (massic enthalpy) of vaporization is the heat required to convert 1 g of a substance from the liquid to the gaseous phase, expressed as J g^{-1}
Boiling point is the temperature at which saturated vapour pressure equals ambient pressure

As temperature increases in a closed system, the relative humidity decreases. For example, fully saturated air at 20°C contains 17 g m^{-3} water content and at 37°C, it contains 44 g m^{-3}. If 1 m^3 of air at 20°C contains 17 g water and subsequently that air is heated to 37°C, it will contain the same mass of water vapour, but the relative humidity will be 39% (17/44×100).

At normal atmospheric pressure of ~100 kPa, and at room temperature, the moisture content at 50% relative humidity is ~10 g m^{-3}. If the temperature decreases, the relative humidity increases. Eventually, the air becomes fully saturated with water vapour (at ~11°C). This temperature is known as the dew point. A further decrease in temperature below this leads to some of the moisture condensing, as the maximum water vapour capacity is exceeded.

The physiology of humidification within the airways

During nose breathing, inspired air becomes heated and fully saturated as it passes distally to the alveoli, which at body temperature have an absolute humidity of 44 g m^{-3}. The anatomical point at which the inspired gases become fully saturated in the airways is termed the isothermic saturation boundary (ISB). Temperature and humidity are constant distal to the ISB, while the airways proximal to the ISB function as heat and moisture exchangers (HMEs). Under resting conditions, the ISB is thought to be just below the carina.[1] The ISB moves distally when cold and dry gases are inhaled, as a greater proportion of the airways have to participate in heat and moisture exchange to achieve full saturation.

The nose functions as an excellent humidifier. While inhaled air is cold and dry, the highly vascularized nasal mucosa facilitates heat and moisture exchange and this is further enhanced by the presence of nasal turbinates. These increase available surface area and alter the characteristics of the airflow, thus maximizing the transfer of heat and water. As the nasal mucosa gives up water to the dry inspired air, there is some heat loss through massic enthalpy of evaporation. Consequently, warm expired air is cooled, with subsequent condensation of the water vapour. Compared with the amount of water added during inspiration, only a proportion will condense during expiration and within a 24 h period, there is approximately a 250 ml loss of water from the respiratory tract.

Within the airways, humidification is achieved by evaporation of water from the airway surface liquid contained within the mucus, present on all respiratory surfaces. Respiratory mucus consists of two interacting layers: a luminal gel layer containing mucin and a deeper aqueous sol layer, which is produced by serous cells. Mucus not only provides a mechanism for humidification, but also entraps inhaled debris. Embedded within the mucus layer are cilia, which beat 1000 times per minute in a co-ordinated fashion, allowing the transport of mucus and debris back up to the pharynx.

When humidity of an inspired gas is too low, greater amounts of water evaporate from the mucus. There is initially movement of water from the aqueous layer to the gel layer, but this compensation is limited with eventual increased viscosity of the mucus. Hyper-viscous secretions may obstruct bronchi or tracheal tubes, leading to increased airway resistance, atelectasis, increased propensity to infection, reduced functional residual capacity, reduced compliance, and greater ventilation/perfusion mismatch. Mucus flow is significantly reduced at a relative humidity of <50%, and there is subsequent loss of cilia number and function. The impaired mucociliary elevator further adds to atelectasis through sputum retention and this compounds intrapulmonary shunting.[2] Damage is time-dependent, but may start with as little as 1 h of exposure to dry gas.[3] With prolonged exposure to cool, dry gases, the cilia themselves disappear and the tracheal epithelium undergoes keratinization, ulceration, and necrosis. Pulmonary complications for patients undergoing anaesthesia with dry gases exceed those compared with patients breathing humidified gases.[4]

Conversely, if the humidity of inspired gas is too high, the viscosity of the mucus reduces. Mucus volume increases, which can overwhelm the mucociliary elevator leading to potential for super-added infection and risk of atelectasis through condensation of water droplets throughout the airways. Significant heat gain may also result, with thermal injury to airway mucosa.

Medical gases from either a piped supply or cylinders are cool with minimal water content. Oxygen, for example, is stored in bulk within a vacuum insulated evaporator and the contents are kept at −150°C. When a patient is intubated, the upper airways are bypassed and the cool gases are delivered directly to the trachea. Water and energy are then required to humidify and warm the gas.

An example of the energy required to heat and humidify respiratory gases can be seen below:

The energy required to heat and humidify dry gas:

An 80 kg man is ventilated with tidal volume 0.5 litre at a frequency of 12 bpm, so the minute ventilation is 6 litre min^{-1}

The moisture content of the lungs is 0.044 g litre^{-1}, so the total amount of water required to humidify the gas is 6×0.044=0.26 g min^{-1}

The massic enthalpy of evaporation of water is 2.4 kJ g^{-1} at 37°C. Therefore, the heat required is 2.4×1000×0.26=633 J min^{-1} (~10.5 W). This is 13% of the total basal heat loss for an average man (80 W)

The specific heat capacity of air is 1 J g^{-1} K^{-1} and the density of air is 1.2 g litre^{-1}. To raise the temperature of the 6 litre min^{-1} ventilation gas from 22 to 37°C (295–310 K) requires 6×1.2×1×(310−295)=108 J min^{-1} (1.8 W)

This illustrates why the conditioning of inspired gases is necessary to minimize energy expenditure and prevent the deleterious changes in respiratory mucosa and pulmonary function.

Equipment used to humidify inspired gases

Humidification systems are classified according to their requirement for an energy, water supply, or both and the performance and safety standards for medical respiratory gas humidifiers is covered by the International Organisation of Standardization (ISO) document ISO 8185:2007. The properties of an ideal system are summarized below. There is little conclusive evidence to suggest the superiority of one humidification device over others.

Ideal properties of a humidification device are:

- Ability to warm and humidify gases to physiological conditions
- No additional resistance to gas flow
- No additional dead space
- No additional risk of infection
- Easy and safe to use
- Cost-effective

Passive humidifiers

Passive humidifiers do not require an external power or water supply. The most common example of passive humidifiers encountered in clinical practice is the HME.

Heat and moisture exchanger

HMEs are placed in the circuit between the patient and the Y connector of the inspiratory and expiratory limbs. They consist of a housing and a membrane that can be constructed from a range of materials (paper, cellulose, polyurethane foam, ceramic, or metal fibres). This membrane can be either hygroscopic or hydrophobic in nature. Hygroscopic substances have the ability to attract and hold water molecules from the atmosphere and this may increase the amount of water condensed on expiration.

During the expiratory phase of breathing, warm exhaled gas cools as it passes through the membrane, resulting in condensation and release of latent heat energy (massic enthalpy of vapourization) to the membrane. During inspiration, cool and dry gases pass through the membrane and the absorbed heat evaporates the condensate, which cools the membrane. A hygroscopic layer further releases water molecules when the vapour pressure is low. HME occur maximally when the temperature difference across the membrane is greatest. Under normal operating conditions, this is an efficient process allowing a relative humidity of up to 70% to be achieved, but it can take up to 20 min to reach maximum efficiency.

HMEs are simple and cheap to use and can incorporate a microbiological filter. They are, however, relatively bulky and must be placed close to the patient to minimize the addition of dead space. They function poorly at high minute volumes (>10 litre min^{-1}), at low patient temperatures (<32°C), with excessive patient leaks (>30% inspired tidal volume) and are at risk of being blocked by secretions.

HMEs can be used in the critical care setting, but may account for considerable dead space when smaller tidal volumes are utilized, for example, during lung-protective ventilation. Some studies have suggested that HME devices incorporating a bacteria filter may reduce the incidence of ventilator-associated pneumonia.[5]

Active humidifiers

Active humidifiers require an external power, water supply, or both. They consist of a humidifier and delivery system, which add water vapour to a flow of gas independent of the patient. Examples include: bubble humidifiers, nebulizers, and heated humidifiers.

Bubble humidifiers

Bubble humidifiers offer a simple way of humidifying inspired gases. They work by passing (i.e. bubbling) the fresh gas flow through a water reservoir. The bubbles absorb water vapour as they pass to the surface of the reservoir. On their own, they are relatively inefficient as they do not heat the inspiratory gas and further heat is lost from the water by massic enthalpy of vaporization. With higher gas flows, the water content and temperature of the gas becomes much lower and efficiency is reduced further. Bubble humidifiers are most effective at flows of <5 litre min^{-1} and can achieve an absolute humidity of 10–20 mg litre^{-1}. Despite their inefficiency, they are frequently used as a method of humidifying supplemental oxygen on general wards. They can be incorporated into heated humidifiers to improve efficiency as detailed below.

Nebulizers

Nebulizers can be used to deliver hydration and medications to the airways. They do not vaporize liquids but produce a mist of droplets suspended in a gas. Ideally, the droplets should be of diameter 2–5 μm. The production of an aerosol can occur in several ways. Jet nebulizers drive a high-pressure gas supply through a Venturi which produces a pressure differential, leading to liquid been drawn from a reservoir and broken up into a spray. Directing this spray at an anvil can further break up these droplets. Spinning disc nebulizers draw water onto a rotating disc and this centrifugal generator produces microdroplets. Finally, ultrasonic nebulizers use a transducer vibrating at high frequencies to produce a saturated mist of water droplets.

The design of the nebulizer can be tailored to produce droplets of a particular size. The size of the droplet influences the location that will be reached within the respiratory system. Droplets of

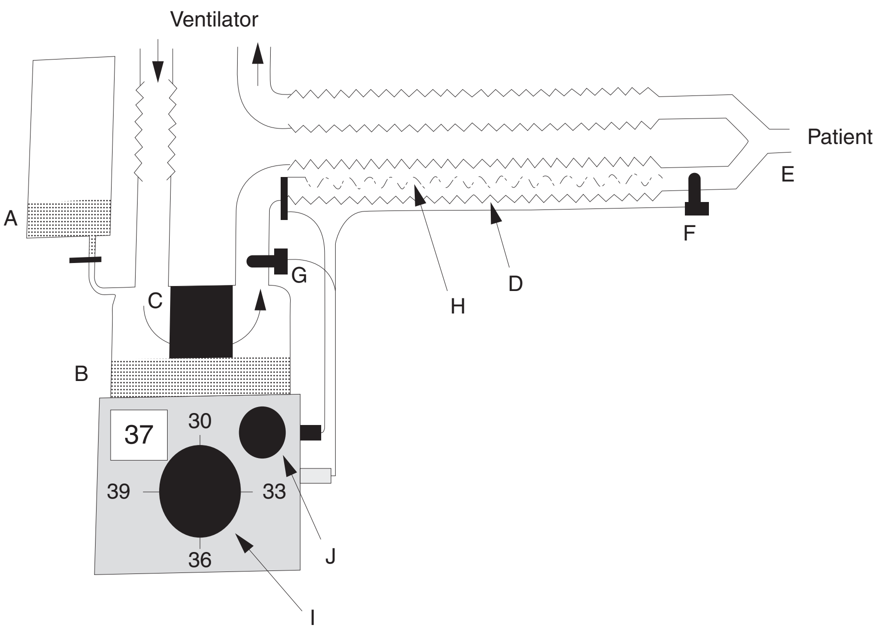

Fig 2 Basic components of a heated humidifier. A, water reservoir; B, humidification chamber; C, wick; D, delivery tube; E, patient connection; F/G, temperature sensors; H, heated wire; I, temperature control; J, relative humidity control. Reproduced with kind permission from Oxford University Press, A.R. Wilkes, *CEACCP* 2001; **1**: 42 (CCC license no 3263540013696).

2–5μm will be deposited within the bronchial tree. Smaller droplets of 0.5–1 μm will be deposited within the alveoli. Very small droplets of <0.5 μm may be carried out with the expired gases, while very heavy particles of >5 μm can be deposited within the main airways resulting in increased airway resistance.

Ultrasonic nebulizers are highly efficient, and there is a significant risk of excessive water delivery to the alveoli, resulting in impaired gas exchange and atelectasis. Nebulized droplets can also function as an ideal carrier for microbes, and it is essential that water used is sterile.

Heated humidifiers

Heated humidifiers contain two essential components: a humidification chamber and a delivery system (Fig. 2).

The humidification chamber contains a reservoir of water and a heating element. Evaporation occurs as the water is heated. The fresh gas flow is passed through the humidification chamber so that it can be saturated with water vapour. This can either occur by allowing the fresh gas flow to pass over the water, bubble through the water or come into contact with wicks dipped in the water, thereby dramatically increasing the surface area available for evaporation.

If the temperature set in the humidifier is greater than in the delivery system, the gas will cool as it passes along it and condensation will form, but the gas will have 100% relative humidity when it reaches the patient. If the temperature set in the delivery system is greater than in the humidifier, the gas will be warmed as it passes, condensation will be reduced, but the gas reaching the patient will have a relative humidity <100%. Frequently, the gas does cool within the delivery system and to minimize this, a heating element is often contained within the respiratory limb to ensure the temperature is maintained throughout the length of the delivery tubing. These heated wires must be designed in such a way that they cannot overheat and burn the patient, damage the circuit, or be a fire risk in the oxygen-rich environment. Temperature sensors are placed both at the humidifier and at the patient end of the circuit. A servo control feedback mechanism regulates the output generated by the two heating elements, thus safeguarding excessive condensation and thermal injury to the patient. A water trap can be placed below the level of the patient to collect any excessive condensation; however, such a reservoir needs to be emptied regularly to prevent colonization with bacteria. Ventilator malfunction may also occur in the presence of excessive water within the delivery system. Some modern breathing circuits have an expiratory limb created from material that is permeable to water vapour.

Comparison of active and passive systems

The most commonly used humidification devices in clinical practice are HMEs and heated humidifiers. HMEs tend to be used in anaesthetic practice where their ease of use, low cost, and ability to provide an antimicrobial filter makes them ideal. Heated humidifiers tend to be reserved for use on the intensive care unit, although these may be inferior to HMEs when comparing the incidence of ventilator-associated pneumonia.[6]

A reduction in tracheal tube patency, due to deposition of secretions, is demonstrably lower with heated humidifiers than with HMEs in patients ventilated for extended periods of time.[7] HMEs can increase airway resistance by increasing dead space and this is an important consideration when weaning patients, using lower tidal volumes and within the paediatric population. HMEs have been found to be less efficacious when used for patients in whom moderate hypothermia has been induced.[8]

Humidification and non-invasive ventilation

Humidification is also an important consideration for non-invasive ventilation (NIV). Technically, during NIV, the usual physiological mechanisms for humidification are not bypassed, but the inspiration of dry cold medical gases compared with normal ambient room air during NIV may still suggest a benefit for humidification.

In many modes of NIV provision, humidification is not always an integral component of the system. For example, the continuous positive airway pressure hood relies on the high internal gas volume as a mixing chamber. The final humidity depends on the humidity of the patient's expired gases and the flow of medical gas entering the hood.

Despite the theoretical advantages, there are currently no data suggesting improved outcomes with the addition of humidification to NIV. High minute ventilation, unidirectional airflow, and the presence of air leaks will all contribute to significant drying of the airway. Healthy volunteers undergoing a trial of NIV reported severe discomfort relating to mouth dryness in the absence of humidification.[9] Airway resistance and secretion load may also build up during NIV with no humidification, and this may have an implication on both the requirement for, and difficulty of, any future intubation.[10]

Summary

The rationale behind humidification is clear and we have a good understanding of the problems relating to under- and over-humidification. However as yet, the optimum level of heat and humidity that needs to be provided has not been defined. Targets of humidification are variable and range from minimum humidification (to prevent tracheal tube occlusion) through to physiological equivalence or beyond to achieve optimal mucociliary clearance with supra-physiological gas temperatures. Conditioning the inspired medical gas is essential, but measuring the delivered humidity is infrequently undertaken. Ultimately, when providing humidification, many variables need to be considered and the choice of device therefore needs to take into account the status of the patient, the duration for which the humidification device will be necessary, mode of ventilation, and underlying respiratory pathophysiology.

Declaration of interest

None declared.

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