Part II: Respiratory Failure

Chapter 24: Humidification

T E Oh

The upper airway normally warms, moistens and filters inspired gas. When these functions are impaired by disease factors, or when the naso-oropharynx is bypassed by endotracheal intubation, artificial humidification of inspired gases must be provided.

Physical Principles

Humidity is the amount of water vapour in a gaseous environment. The two measures of humidity are:

1. *Absolute Humidity (AH)*

This is the total mass of water in a given volume of gas at a given temperature (g/m^3).

2. *Relative Humidity (RH)*

This is the ratio, expressed as a percentage, of the mass of water in a given volume of gas to the mass of water required to saturate the same volume of gas, at a given temperature.

The mass of water contained in a unit volume of gas when fully saturated exerts a saturated vapour pressure (SVP). SVP is proportional to temperature and this relationship is exponential (Table 1). Hence the addition of further water vapour to the gas can only occur with a rise in temperature.

Physiology

The respiratory tract from the nose to terminal bronchioles is lined with columnar mucus-secreting epithelium. Inspired gas is warmed and humidified in the naso-oropharynx and reaches the upper trachea with a RH of about 90% and a temperature of 32-36 °C. Humidification and warming continue down the airways so that alveolar gas is fully saturated at 37 °C (i.e. AH or water content of 43 g/m^3). Normal breathing through the nose adds about 75% of the total water content before the inspired gas reaches the larynx, whereas with mouth-breathing, inspired gas is only about 25% saturated above the pharynx.

Heat is required to warm the inspired gas to 37 °C and to provide for the latent heat of vaporization of water. A normal man under resting conditions loses approximately 250 mL of water and 1.5 kJ (350 kcal) per day from the respiratory tract. A proportion of heat and water (10-25%) is returned to the mucosa of the upper respiratory tract on expiration, i.e. there is a condenser effect which conserves heat and water.

Watery mucus coating the tracheobronchial mucosa is moved towards the glottis, along with solid particles, by cilia (at a rate of 10 mm/min at 37 °C and 100% RH). Ciliary activity ceases at temperatures above 41 °C, and slows down when RH falls below 75% at 37 °C (AH of 32 g/m^3). Temperature appears to be unimportant if RH is between 75% and 100%.

The humidifying functions of the airway above the trachea can be impaired by many factors including cold, dry inspired gases, upper respiratory tract infection (URTI), dehydration and hyperventilation.

Clinical Applications of Humidification

1. Tracheal Intubation

The need for humidification of intubated and recently tracheostomized patients in the ICU is unquestioned. The naso-oropharynx is bypassed and the inspired gas RH falls to 50% or less. This presentation of cold, dry gases to the trachea and bronchi has adverse effects such as:

(a) Increased mucus viscosity with crusting, inspissation, tracheal inflammation, and even frank mucosal ulceration.

(b) Depressed ciliary function.

(c) Microatelectasis from obstruction of small airways.

(d) Airways obstruction due to tenacious or inspissated sputum.

The inspired gases should be delivered to the endotracheal tube or tracheostomy close to saturation at body temperature (i.e. a minimum RH of 75% when warmed to 37 °C).

It has been shown that humidification of anaesthetic gases reduces postoperative pulmonary complications and prevents undue falls in body temperature during surgery.

Humidification in an ambulant patient with a permanent tracheostomy presents many practical problems. Fortunately in such a patient, continuous humidification is unnecessary as metaplasia of the tracheal epithelium occurs, so that eventually the trachea is able to humidify the inspired gas. Nevertheless, humidification may be indicated during an acute respiratory infection.

2. Rewarming

The respiratory tract is an important avenue by which body temperature can intentionally be adjusted by heat exchange. The heat content of saturated gases may be used as a central warming device in the treatment of hypothermia.

3. Drug Delivery

Drugs may be delivered to the respiratory mucosa via micro-droplets of water (aerosols) in the inspired gas. Aerosol therapy is commonly used to administer bronchodilators. The distribution and deposition of aerosol determine the effectiveness of endobronchial drug application. Aerosol drug delivery should be aimed at the lower respiratory tract. Most of the drug deposited in the upper respiratory tract will be removed with secretions, with only a small proportion absorbed.

4. Acute Upper Respiratory Tract Infection (URTI)

The aim of humidification therapy in URTI is to thin and prevent desiccation of secretions. It is unclear whether the deposition of water micro-droplets on inflamed mucosal membranes is beneficial. Aerosol therapy is provided for adults and older children via masks using high flows and saturation at body temperature. Small children with URTI are generally managed in mist tents.

5. Lower Respiratory Tract Disease

Aerosol therapy has been used in lower respiratory tract diseases such as cystic fibrosis, emphysema and chronic bronchitis, in conjunction with other supportive measures (i.e. physiotherapy, mucolytic agents, bronchodilators, and intermittent positive pressure breathing by mask). The use of humidification to prevent secretion desiccation during an acute illness in these patients is useful, but the true benefits of long-term aerosol therapy, although theoretically sound, are largely unproven.

Ideal Humidification

The basic requirements of a humidifier should include the following features.

1. The inspired gas is delivered into the trachea at 32-36 °C and with a water content of 33-43 g/m^3.

2. The set temperature remains constant and does not fluctuate.

3. Humidification and temperature is unaffected by large ranges of fresh gas flow - especially high flows.

4. The device is simple to use and to service.

5. Humidification can be provided for air, oxygen or any mixture of inspired gas (including anaesthetic agents).

6. The humidifier can be used with spontaneous or controlled ventilation.

7. There are safety mechanisms (with alarm) against overheating, overhydration, and electrocution.

8. The resistance, compliance, and dead space characteristics do not adversely affect spontaneous breathing modes.

9. The sterility of the inspired gas is not compromised.

Methods and Devices

1. Saline Drip

Direct instillation of water or saline by continuous drip has no place in the ICU (with the exception of short-term use in high frequency jet ventilation). This method is inefficient and may cause loss of alveolar surfactant similar to that from excessive bronchial lavage. The risks of drowning are substantial.

2. Condensers

A condenser performs the function of the nasopharynx by retaining heat and moisture from expired gas through condensation, and returning them to the inspired gas which passes over the condensate. Heat and moisture exchanger (HME) and "Swedish nose" are alternative names.

A range of new, light disposable units are now available which use various arrangements of hygroscopic materials and chemicals. The Engstrom "Edith" uses a lithium chloride coated polypropylene sponge (with chlorhexidine as a bacteriostatic agent); Pall "Ultipor" uses a pleated resin-bonded hydrophobic fibre sheet; Portex "Humidvent" uses a calcium chloride impregnated microporous corrugated paper; and Siemens SH 150 and SH 151 devices use cellulose sponge with a nylon felt insert. Terumo "Brethaid" although disposable, is of the older multiple gauze type. The Pall "Ultipor" is also an effective in-circuit bacterial filter in the intensive care setting.

These new material HMEs are capable of providing up to 30 mg/L AH at 27-30 °C. While they are useful in anaesthesia and for short-term spontaneous or controlled ventilation in the ICU, they are still not satisfactory alternatives to heated humidifiers for long-term ventilation. Airway humidification may not always be adequate, resulting in endotracheal tube occlusions. Humidification is decreased if air leak around the endotracheal tube is significant, especially when used for neonates.

3. Cold Water Bubble Humidifier

An unheated bubble unit screwed directly onto an oxygen flowmeter delivers partially humidified oxygen with water content less than 9 gm/m^3 (i.e. about 50% RH at ambient temperatures). It is inefficient and presents risks of microbiological contamination. Routine use of cold water humidifiers in ICUs to deliver oxygen by simple face masks should not be necessary.

4. Water Bath Humidifiers

With these devices, inspired gas is driven over or through a heated water reservoir. In order to achieve an adequate inspired humidity, the reservoir may be heated to 45-60 °C so that the gas leaving the humidifier contains more than 43 g/m^3 of water, although not fully saturated. As the gas passes along the delivery tube, cooling occurs and the RH approaches 100%. If the reservoir heater is thermostatically controlled to produce an inspired gas temperature close to 37 °C at the patient end of the delivery tube, then the delivered gas will be fully saturated at this temperature. It is commonly believed that water bath humidifiers do not produce aerosol, but there is now conflicting opinion. Micro-droplets mostly under 5 microm in diameter has been reported with these humidifiers.

Although efficient, hot water humidifiers present the following problems in usage.

(a) Thermostats may not allow fine control of water temperature. Failure may occur. Temperatures above 41 °C are likely to damage the trachea. Continuous supervision by the bedside ICU nurse is necessary.

(b) Condensation occurs from the cooling of inspired gas in the delivery tube. This problem is reduced by lagging of the delivery tubes, and overcome by heated delivery tubes. Nonetheless, a water trap should be installed in the circuit, and the humidifier should always be placed below the endotracheal tube to avoid flooding of the airway by condensed water.

(c) Efficiency is not constant. Gas temperature and humidity is dependent on gas flow rate, surface area of the vaporizing surface, and water temperature. A large vaporizing surface increases RH but the internal compliance of the humidifier is also increased.

(d) Infection is a hazard.

Despite the disadvantages, hot water humidifiers are the most commonly used method of providing humidification in the ICU. Two examples are:

(a) *Fisher-Paykel Humidifier*

This humidifier increases vaporizing surface area without significantly addint to internal compliance to the breathing system. The inspired gas passes over an aluminium spiral scroll lined with absorbent paper within a disposable humidifying module. The reservoir temperature control is variable for flows in the range 3-25 L/min. The delivery tube is heated by an insulated heating wire, adjusted manually to achieve a patient delivery temperature close to 37 °C, and RH about 90%. An additional servo controller unit can be fitted to the Series 328. It senses and indicates delivery temperature and controls the temperature of the heating wire. Audible alarms indicate sensor disconnection and variation of greater than 2 °C of set delivery temperature. The Dual Servo unit combines the heater base and servo controller into one unit.

(b) *Grant Humidifier*

This humidifier uses a simple heated reservoir tank with no attempt made to saturate the inspired gas initially. The water in the tank is maintained at a constant elevated temperature such that the gases leave the tank with a temperature of 41 °C and an RH of about 80%. The inspired gas undergoes a controlled temperature drop along the delivery tube (achieved by a spiral heating element embedded in the tube) so that it is delivered to the patient fully saturated and at body temperature. A platinum resistance sensor at the delivery point regulates the delivery tube heater, thus achieving a low thermal inertia system with a rapid response. There is built-in compensation for changes in gas flow rate and ambient temperature, as well as fail-safe alarms for both tank and delivery tube heaters.

5. Aerosol Generators (Nebulizers or Atomisers)

These devices deliver micro-droplets of water suspended in a gaseous medium. The quantity of water delivered is not limited as vapour by gas temperature, and super-saturation of the gas is possible (with ultrasonic nebulizers). Aerosols are more stable if the micro-droplets are smaller in diameter, the humidity of the carrier gas is greater, and the surface tension is increased (i.e. by the addition of propylene glycol). Aerosols are used to achieve humidification as well as deposition of water and medications in peripheral airways.

It is generally accepted that particles smaller than 1 microm reach the alveoli, those of 5 microm are deposited in bronchi, and larger micro-droplets of 7-10 microm are deposited in the nose or oropharynx. The types of aerosol generators are:

(a) *Gas-driven nebulizer.* The droplets produced have a size range of 5-20 microm.

(i) A high pressure gas issues as a jet through a fine nozzle which is close to the tip of another tube immersed into the water reservoir. A Bernoulli suction effect draws up the water which is broken up into a fine spray. Smaller microdroplets are produced by directing the jet spray onto an anvil or baffler (i.e. Bird and Puritan nebulizers).

(ii) Another method of producing gas-driven nebulization uses a high pressure jet placed within a fine film of water held in place by surface tension. The film of water is continuously renewed and an anvil of baffle is again incorporated (i.e. Win Liz nebulizer). Mist density is increased when the water reservoir is heated, otherwise gas-driven nebulizers are generally disappointing in clinical use.

(b) *Mechanical (Spinning disc)*

Water is drawn up from the reservoir by an Achimedean screw and impinges onto a spinning disc which flings water micro-droplets into the delivery system by centrifugal force. A spectrum of micro-droplets sizes with low mist density is produced.

(c) *Ultrasonic nebulizer*

These devices utilizes piezo-electric crystal transducers vibrating at radiofrequencies. There are two types:

(i) where drops of water are added onto the surface of the trasnducer;

(ii) where a layer of water lies on top of the transducer.

There is no need for provision of either heating or a high pressure gas source. Smaller, more uniform microdroplets (less than 5 microm) are produced capable of giving a very high mist density of 100-200 g/m^3. The disadvantages of ultrasonic nebulizers are the risk of infection, overhydration and increased airway resistance.

Hazards of Humidifiers

Safe use of humidifiers demands an understanding of the principles of humidification, adherence to the manufacturers' directions for use, close monitoring of the patient and equipment, and a knowledge of potential hazards.

1. Infection

All types of humidifiers are subject to bacterial contamination. Water reservoirs have frequently grown *Pseudomonas* which multiply rapidly at 45 °C. Generation of aerosols from water bath humidifiers (previously thought not to occur), may deposit organisms from the water reservoir to the lungs. In some humidifiers, infection can be controlled by an operating temperature of 60 °C (continuous pasteurization) or by adding 0.02% chlorhexidine gluconate. With all humidifiers, the water reservoir and tubing should be changed every 24-48 hours.

Aerosol generators are potential sources of infection. Bacteria can be carried in water microdroplets to the alveoli, particularly with ultrasonic nebulizers. Nebulizers can also be difficult to clean and sterilize. All units should be replaced and sterilized daily. Sterile water only should be used for refilling the reservoir.

From studies with the Servo devices, the newer, condenser HMEs do not appear to increase the risk of infection from airborne organisms, despite the devices becoming heavily bacteria laden.

2. Overhydration

Fluid overload from alveolar absorption is most relevant with the use of ultrasonic nebulizers in paediatric practice. "Drowning" with condensed water is avoided with heated delivery tubes and by positioning the humidifier below the tracheostomy or endotracheal tube.

3. Overheating

A constantly elevated inspired gas temperature can contribute to hyperpyrexia. Correct functioning of the thermostat and alarms, and monitoring of the inspired gases at the patient end should avert scalding of the patient's trachea. A delivered gas temperature of 35 °C is satisfactory and provides an adequate margin for safety.

4. Electrical Hazards (See Chapter 75, Electrical Injuries).