Humidification for Patients with Artificial Airways

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Introduction

The amount of water vapor in a gas can be measured and expressed in a number of ways. In medicine the most common terms are absolute humidity and relative humidity. Absolute humidity is the amount of water vapor present in a gas mixture. Absolute humidity is directly proportional to gas temperature—increasing with increasing gas temperature and decreasing with decreasing gas temperature (Table 1). Absolute humidity is typically expressed in mg/L, gm/cm^3, or as a partial pressure. At the alveolar level, gas is 37° C, 100% relative humidity, and contains 43.9 mg H_2O/L.

A gas mixture is said to be saturated or at the maximum capacity of water vapor if it contains the maximum possible amount of water vapor it is capable of holding at that temperature. The amount of humidity in a gas that is less than saturated can be determined by comparing the absolute humidity (the water vapor present) to the maximum capacity (the maximum possible water vapor) of the gas at a given temperature. This value is known as the relative humidity. Relative humidity is expressed as a percentage and calculated with the following equation:

Relative humidity (%) = (absolute humidity)/(maximum capacity) × 100.

The relative humidity of a gas saturated with water vapor at any temperature is 100%. The temperature at which a gas is 100% saturated is known as the dew point. These measurements are useful in determining the causes of some common clinical phenomena. For example, if gas leaves a heated humidifier outlet at a temperature of 34° C and 100% relative humidity and is heated by a heated wire circuit to 37° C at the airway, the relative humidity is decreased. In this instance, if the gas temperature were 37° C and the absolute humidity measured was 37 mg H_2O/L, then we can determine the relative humidity by comparing

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Table 1. The Relationship of Gas Temperature, Absolute Humidity, and Water Vapor Pressure

Gas Temperatue (C°)	Absolute Humidity (mg H_2O/L)	Water Vapor Pressure (P_{H_2O})
0	4.85	4.6
5	6.8	6.5
10	9.4	9.2
15	12.8	12.8
20	17.3	17.5
25	23.0	23.7
30	30.4	31.7
32	33.8	35.5
34	37.6	39.8
36	41.7	44.4
37	43.9	46.9
38	46.2	49.5
40	51.1	55.1
42	56.5	61.3
44	62.5	68.1

this value to the maximum capacity for water vapor at 37° C given in Table 1: relative humidity (%) = 37/43.9 × 100 = 84.3%.

This explains the occasional finding of dried secretions in the endotracheal tubes of patients using heated humidification and heated wire circuits. The greater the difference between temperature at the chamber and temperature at the airway, the lower the relative humidity. This temperature offset is important to keep the circuit free of condensate or "rain out." Unfortunately, in certain environments (eg, near windows, heating units, and air conditioning vents) environmental changes can affect heated wire circuit efficacy. However, clinicians should be careful to assure that the patient receives adequate relative humidity as a priority over keeping the circuit free from rain out. When a heated humidifier without a heated wire circuit is used, it is often necessary for the gas in the humidification chamber to reach 50° C in order for the temperature delivered to the airway to approach 37° C. This concept is illustrated in Figure 1. In this example, the maximum water vapor content of gas at 50° C is 83 mg H_2O/L, and the maximum water vapor content of gas at 37° C is 43.9 mg H_2O/L. The difference in water vapor content between the 2 gases (83 – 43.9 = 39.1 mg H_2O/L) represents the amount of rain out that will accumulate in the circuit. For a minute ventilation of 10 L/min, this would result in slightly greater than 0.5 L of rain out over a 24-hour period.[1]

If the relative humidity and temperature are known, the water vapor content can be calculated with the equation: water vapor content = relative humidity (%) × maximum capacity/100. For example, if a heat and moisture exchanger provides 32° C and 95% relative humidity, then: water vapor content = (95 × 33.8)/100 = 32.1 mg H_2O/L.

Normal Mechanisms of Heat and Moisture Exchange in the Respiratory Tract

During normal breathing, the upper respiratory tract warms, humidifies, and filters inspired gases, primarily in the nasopharynx, where gases are exposed to a large area of highly vascular, moist mucus membrane. The oropharynx and conducting airways also contribute to this process, but are less efficient because they lack the exquisite architecture of the nose. During exhalation, the upper airways reclaim a majority of the heat and moisture added during inspiration. Over the course of a normal day, the respiratory tract loses approximately 1470 J of heat and 250 mL of water.[2] This net loss of heat and moisture is predominantly due to water vapor escaping in expired gases. Little heat is actually lost through the warming of inspired gas, as the specific heat of air is very low.

The efficiency of the normal upper airway is quite remarkable. Even at extremes of inspired temperature and humidity, gas that reaches the alveolar level is 100% saturated at body temperature.[3] Although opinions differ slightly, it is generally agreed that after passing through the nasopharynx, inspired gases are at 29–32° C and nearly 100% relative humidity, and at the carina gases are at 32–34° C and nearly 100% relative humidity.[4–6]

The point at which gases reach alveolar conditions (37° C and 100% relative humidity) is known as the isothermic saturation boundary (ISB). Under normal conditions the ISB resides in the fourth to fifth generation of subsegmental bronchi. The position of the ISB is fairly constant, even at the extremes of environmental conditions. Lung disease and fluid status can also affect the ISB. Above the ISB, the respiratory tract performs the function of a countercurrent heat and moisture exchanger. Below the ISB, temperature and water content remain relatively constant.

Following intubation, the ISB is shifted down the respiratory tract, as the normal upper airway heat and moisture exchanging structures are bypassed (Fig. 2). This places the burden of heat and moisture exchange on the lower respiratory tract, a task for which it is poorly suited. The delivery of cold, anhydrous medical gases also burdens the lower respiratory tract and pushes the ISB farther down the bronchial tree. The combined effects of intubation and mechanical ventilation result in severe losses of heat and moisture from the respiratory mucosa, and, in extreme cases, damage to the respiratory epithelium. This includes functional and structural changes that have clinical implications.[6–9]

The provision of heat and humidity during mechanical ventilation is the worldwide standard of care for patients

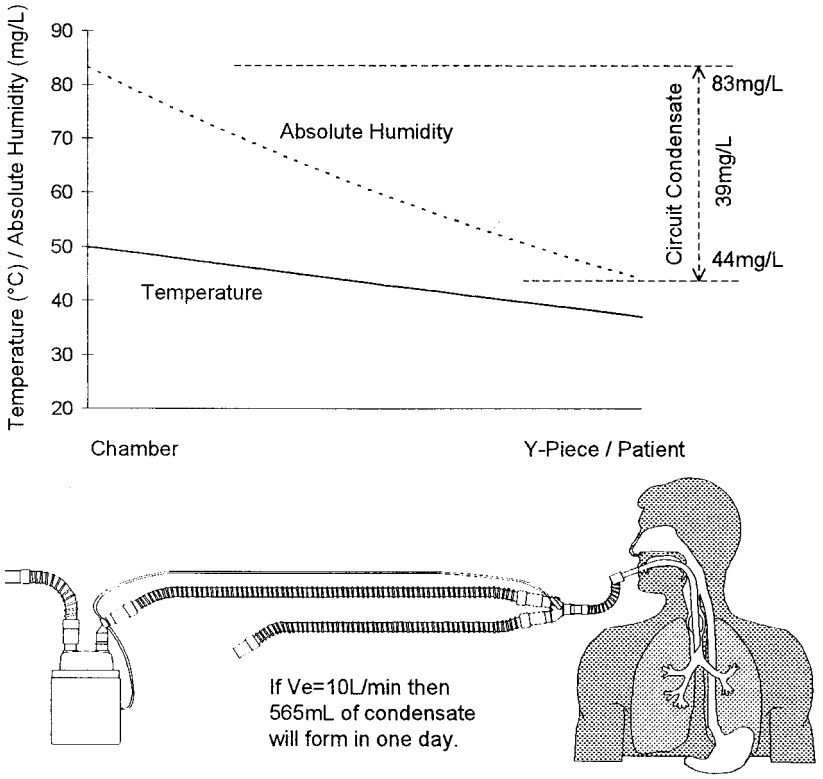

Fig. 1. Gas cooling and condensate formation when a heated humidity generator and unheated delivery system are combined. (From Reference 1, with permission.)

with artificial airways,[10,11] but there is considerable disagreement about the amount of humidity to provide and how best to provide it. The methods for providing humidity include active, microprocessor-controlled, heat and humidifying systems (heated humidifiers) and simple, passive, heat and moisture exchangers (artificial noses). Table 2 compares the advantages and disadvantages of the humidification devices discussed herein.

High-Flow Humidifiers

High-flow humidifiers are capable of providing a wide range of temperatures and humidities.[12] High-flow humidifiers generically consist of a heating element, water reservoir, temperature control unit (including temperature probe and alarms), and a gas/liquid interface that increases the surface area for evaporation. Most high-flow humidifiers fit into one of the following categories: pass-over humidifiers, wick humidifiers, or bubble humidifiers. Because these devices are heated, they also prevent loss of body heat from the patient, which is particularly important in neonatal applications. When heated humidifiers are used, the temperature at the patient's airway should be monitored continuously with a thermometer or thermistor. It may also be desirable to monitor the relative humidity at the proximal airway, although this is not commonly done.

With high-flow humidifiers, the water level in the reservoir can be maintained manually, by adding water from a bag through a fill-set attached to the humidifier, or by a float-feed system to keep the water level constant. Manual methods tend to increase the risk of reservoir contamination and pose the additional risk of spilling and overfilling, so fill-set and float-feed systems are preferable. The float-feed systems also avoid fluctuations in the temperature of gas delivered, which occurs when cold water is added to the humidifier.

Most humidifiers are servo-controlled; that is, the operator sets the desired gas temperature at the thermistor, and the system maintains control of the gas temperature regardless of changes in gas flow or reservoir level. These systems are equipped with audiovisual alarms to warn of high temperature conditions. It is important to recognize that the thermistors in these systems have a relatively slow response and only reflect the average temperature of the inspired gas. Actual temperatures may fluctuate above and below the average temperature with cyclic gas flow, as may occur in a mechanical ventilator circuit.

In recent years it has become popular to heat the tubing that carries gas from the humidifier to the patient. These circuits contain electric wires that heat the gas as it traverses the heated ventilator wire circuit. Heated wire circuits provide a more precise gas temperature delivered to the pa-

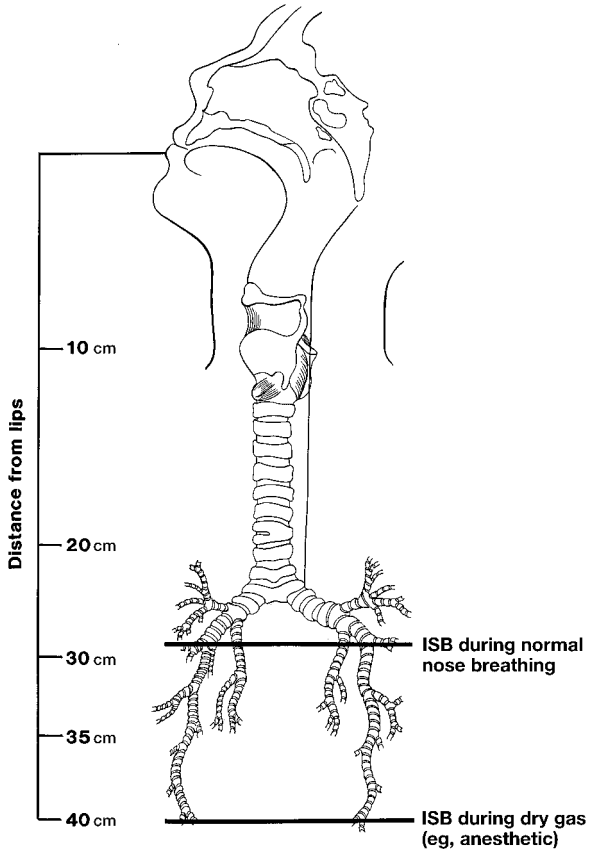

Fig. 2. Position of the isothermic saturation boundary (ISB) during normal nose breathing and during inhalation of dry gases (during intubation).

tient and prevent condensation of water in the tubing. The temperature of the wire can be controlled by the humidifier temperature control—or separately. If the temperature of the heating wires is controlled separately from the humidifier, this can affect the relative humidity delivered to the patient. If the temperature of the tubing is greater than the temperature of the gas leaving the humidifier, then the relative humidity of the gas decreases, which can result in drying of secretions and endotracheal tube obstruction.[13] On the other hand, if the temperature of the tubing is lower than the temperature of the gas leaving the humidifier, condensation will occur in the tubing.

The use of servo-controlled heated-wire circuits can become complex when the gas is delivered to a neonate in an incubator or under a radiant heater.[14] The problem is that the delivered gas is exposed to 2 temperatures: room temperature and the temperature in the incubator (or under the radiant heater). In these applications, the thermistor should be placed directly outside the incubator (or out from under the radiant heater) rather than at the proximal airway of the patient.

In systems that do not use heated wire circuits, water that collects in the tubing is a potential source of nosocomial infection. Water in the tubing can also result in accidental airway lavage during turning. Water that condenses in the tubing can be collected in a water trap. This water should be considered contaminated and should never be allowed to drain back into the humidifier.

Pass-over Humidifiers

In a pass-over humidifier, gas from the ventilator is introduced into the humidifier chamber, passes over the surface of the water reservoir, and exits to the ventilator circuit. This is the simplest form of heated humidifier.

Wick Humidifiers

The wick humidifier is a variation of the pass-over humidifier. In the wick humidifier, gas enters a cylinder that is lined with a wick of blotter paper. The wick is surrounded by a heating element and the base of the wick is immersed in water. As the gas passes the moist, heated wick, the relative humidity of the gas increases.

Bubble Humidifiers

In a bubble humidifier, gas from the ventilator is directed through a tube submerged in a water reservoir. The gas bubbles through the water, through a diffuser or grid, and enters the ventilator circuit. One type of bubble humidifier is the cascade-type humidifier, in which gas from the ventilator passes through a submerged grid, creating a froth of small bubbles. Humidifier temperature is maintained by a thermostat, and a thermometer or thermistor at the patient's airway monitors the temperature of the gas delivered. Unless the tubing between the humidifier and the patient is heated, the gas temperature decreases as it moves downstream of the humidifier, resulting in condensation. Although the cascade-type humidifier efficiently delivers water vapor, it may also deliver microaerosols that can transmit bacteria if the reservoir becomes contaminated.[15] However, the temperature in the water reservoir inhibits the growth of pathogens.[16]

Artificial Noses

Artificial nose is a generic term used to describe a group of similar humidification devices. The term artificial nose comes from the similarity in function to the human nose. By definition, an artificial nose is a passively acting humidifier that collects the patient's expired heat and moisture and returns it during the following inspiration. These devices are also collectively referred to as passive humidifiers, a term that is more specific to function.[12]

There are several types of artificial noses. Heat and moisture exchangers (HMEs) use only physical principles

Table 2. Advantages and Disadvantages of Humidification Devices

Device	Advantages	Disadvantages
Heated humidifier	Universal application (neonates to adults)	Cost
	Wide range of temperature and humidity	Water usage
	Alarms	Condensation
	Safety	Risk of circuit contamination
	Temperature monitoring	Over heating
	Reliability	Small risk of burns/electric shock
	Elimination of condensate with heated wire circuit	Colonization of chamber (heated wire circuit)
Artificial nose	Cost	Not applicable in all patients
	Passive operation	Increased dead space
	Simple use	Increased resistance
	Elimination of condensate	Potential for occlusion
	Portable	
Active heat and moisture exchanger	Elimination of condensate	Potential for occlusion
	Reduced water usage	Additional weight on endotracheal tube
	Minimum output always provided	Increased dead space
	Eliminates water loss from the respiratory tract	Increased resistance
	Temperature monitoring	Small risk of burns/electric shock
HME-Booster	Simple	Small improvement in moisture output may not be worth additional cost
	Inexpensive	
	Improves heat and moisture exchanger performance by 2–4 mg H_2O/L	No temperature monitoring
		Small increase in dead space
	Reduced water usage	Increased resistance
	Minimum output always provided	Potential for occlusion
		Small risk of burns/electric shock

of heat and moisture exchange. The addition of a filter to an HME results in a heat and moisture exchanging filter (HMEF). Hygroscopically treated devices are called hygroscopic heat and moisture exchangers (HHME), or, if the device if fitted with a filter, it is called a hygroscopic heat and moisture exchanger filter (HHMEF).

The HME is the simplest of these devices and was the first passive humidifier introduced. An HME usually consists of a layered aluminum insert with or without an additional fibrous element. Aluminum exchanges temperature quickly, and during expiration condensation forms between the aluminum layers. The retained heat and moisture are returned during inspiration. The addition of a fibrous element aids in the retention of moisture and helps reduce pooling of condensate in the dependent portions of the device. HMEs are the least efficient passive humidifiers and are not often used. These devices tend to be cheaper than other passive humidifiers and may be used in the operating room for short-term humidification. These devices have a nominal moisture output, providing 10–14 mg H_2O/L at tidal volumes (V_T) of 500–1000 mL.[17,18]

HMEFs are fitted with a spun and pleated filter media insert, over and through which the inhaled/exhaled gas passes. Laboratory evaluations of these devices indicate a moisture output of 18–28 mg H_2O/L at V_T of 500–1000 mL.[19–28]

The HHME is the most popular style of artificial nose. These devices vary widely in shape, size, and type of media insert. Most HHMEs use a paper or polypropylene insert treated with a hygroscopic chemical, usually calcium or lithium chloride, to enhance moisture conservation. Comparative studies have shown that HHMEs can provide a moisture output of 22–34 mg H_2O/L at V_T of 500–1000 mL. The addition of a filter media to an HHME creates an HHMEF.[12] The filter media is typically placed between the ventilator connection and the HHMEF's media insert. This places the hygroscopically-treated material between the patient's expired gas and the filter. Typical filtration material is made from spun polypropylene, which is electrostatically-charged, attracting airborne materials and trapping them in the media. This filter is poorly suited as a heat and moisture exchanging media, but when combined with the hygroscopic element, appears to increase moisture output by 1–2 mg H_2O/L.[19–28] Note that the presence of the filter also increases the resistance of the device.

Moisture Output

The amount of heat and humidity provided by an artificial nose is typically referred to as moisture output. Moisture output is measured under laboratory conditions and reported in mg H_2O/L. There are currently no standards

for the minimum moisture output of an artificial nose. The standard for heated humidifiers suggests a minimum of 33 mg H_2O/L.[29] Application of this standard to HME and HHME is not very helpful. The American Association for Respiratory Care recommends that the required moisture output be determined relative to the application and duration of use.[10] For example, a patient with normal respiratory function requiring intubation for a 2-hour operative procedure probably only requires 15–20 mg H_2O/L. Mechanically ventilated patients with normal secretions appear to require a minimum of 26 mg H_2O/L to prevent drying of secretions and to maintain mucociliary function. Patients with increased secretion production probably require additional heat and moisture that an artificial nose cannot supply. Heated humidification should be used in patients with thick or copious sputum.

The moisture output reported in an HME's package insert is based on a certain V_T, inspiratory time, respiratory rate, and temperature,[30] and clinicians should bear in mind that the actual moisture output varies in relation to those factors. As V_T increases, moisture output decreases. The amount of the decrease depends on the efficiency of the device and the dead space. Larger devices tend to be less affected by an increase in V_T because of rebreathing. That is, if an HME with an internal volume of 100 mL is used, 100 mL of each inspiration will contain expired gases. An increase in respiratory rate or decrease in inspiratory time will also decrease moisture output. Likewise, an increase in expiratory flow due to a decrease in lung compliance also decreases moisture output. In each of these instances, the decrease in transit time (gas moves through the media more quickly) reduces the ability of the device to remove moisture from exhaled gas and add moisture to inspired gas.[31] Remember, when using an artificial nose there is always a net heat and moisture loss from the respiratory tract.

The International Standards Organization testing of and standards for artificial noses[30] use a model to simulate patient expiration of warm, humidified gas. The model assumes a constant output regardless of the minute ventilation, inspired gas temperature, or efficiency of the device tested. The devices are tested at V_T of 500 mL and 1000 mL, and at respiratory frequencies of 10 and 20 breaths per min. The moisture output listed on the package insert reflects the results of this controlled, laboratory testing, and the actual clinical performance varies with patient temperature, minute ventilation, V_T, inspiratory-expiratory ratio, and patient lung health. Most investigators agree that the accuracy is ± 2 mg H_2O/L.

Resistance

Resistance to gas flow in an artificial nose increases as media density increases and as dead space decreases. This increase in resistance can adversely affect the patient's work of breathing.[32–35] However, compared to the added resistance of the endotracheal tube, this increase is small. Most devices currently manufactured have a resistance < 3.5 cm H_2O. During use, as the media absorbs water, resistance increases slightly. After prolonged use, the increase in resistance to expiratory flow may cause air-trapping and auto-positive end-expiratory pressure (auto-PEEP).

The greatest concern about increased HHME resistance is that the media can become occluded with secretions, blood, or water from a secondary source. Several researchers have reported an increase in resistance because of water and blood accumulating in the media.[36–42] In one instance, saline (intended to aid in loosening secretions prior to suctioning) accumulated in the HHME media.[41] Aerosolized drugs can also increase resistance if the drug or its carrier collects in the media or filter. The artificial nose should be removed from the airway prior to delivery of aerosolized medications. During mechanical ventilation, the need for frequent aerosol treatments may necessitate switching to heated humidification.

Manufacturing defects that have resulted in total or partial occlusion of artificial noses have been reported in 3 separate instances.[43–45] In each case, a remnant from the plastic housing remained in the path of gas flow. Clinicians should visually inspect each device prior to use.

Dead Space

Placing an artificial nose on the end of the patient's airway increases dead space. In order to maintain normal alveolar ventilation, respiratory rate, V_T, or both must increase, or arterial carbon dioxide will increase. This effect is most pronounced in spontaneously breathing patients, and is a function of the relationship between V_T and dead space. Consider this example: a 70 kg patient with a spontaneous V_T of 400 mL and a respiratory rate of 15 breaths per min has a minute ventilation of 6.0 L/min. If the patient's anatomic dead space is 150 mL, then alveolar ventilation will be: 15 breaths/min $\times$ (400 mL – 150 mL) = 3.75 L/min.

If an HME with a dead space of 100 mL is added to the airway and minute ventilation is unchanged (6.0 L/min), alveolar ventilation decreases to: 15 $\times$ 400 mL – (150 mL + 100 mL) = 2.25 L/min.

In order to restore alveolar ventilation to 3.75 L/min, minute ventilation must increase via an increase in respiratory rate, V_T, or both: 15 $\times$ 500 mL – (150 mL + 100 mL) = 3.75 L/min and minute ventilation = 7.5 L/min.

Several authors have observed the adverse effects of added dead space on respiratory mechanics.[46–49] In each report the addition of an HME or HHME with a dead space of 100 mL resulted in an increase in the work of

breathing, an increase in the required minute ventilation, and an increase in auto-PEEP. When patients were able to increase respiratory rate and/or V_T, arterial CO_2 remained constant. When patients were unable to increase minute ventilation (weak respiratory muscles), arterial CO_2 concentrations increased. Pressure support ventilation can be used to overcome the additional work of breathing, but can also lead to higher airway pressures and increased auto-PEEP. When choosing an artificial nose, select the device that provides adequate humidification while increasing dead space as little as possible.

Additives

To increase moisture output, HHMEs utilize either calcium chloride or lithium chloride as hygroscopic additives. Some manufacturers also add chlorohexadine as a bacteriostatic treatment. Lithium, delivered by mouth or injection, is used in the treatment of certain psychological disorders, including depression and mania. It has been suggested, though not yet demonstrated, that lithium from HHME media might be released into the trachea and absorbed into the bloodstream at a therapeutic concentration.[50,51] The only report of a patient seen to have elevated serum lithium levels while using an HHME was of a patient who had also taken lithium orally prior to admission to the hospital. The small amount of lithium in these devices appears to make this concern unwarranted.

Cost

Cost is an important feature of any medical equipment. At present the average cost of an HHME is $3.25, though the range of costs is wide ($1.95 to $5.75), with HHMEFs and HMEFs being the most expensive devices.

Choosing an Artificial Nose

In the intensive care unit (ICU) setting, the most important factors regarding an artificial nose are moisture output, dead space, resistance, and cost. I believe an acceptable artificial nose should have a minimum moisture output of 28 mg H_2O/L, a dead space of $<$ 50 mL, a resistance of $<$ 2.5 cm H_2O/L/s, and a price $<$ $2.50. For short-term use in the operating room, where patients are paralyzed, dead space is a less important issue. Also, because most patients in the operating room require only several hours of ventilatory support, the minimum moisture output requirement can be reduced in some cases. Similarly, the dead space recommendation may vary with respect to the patient's V_T.

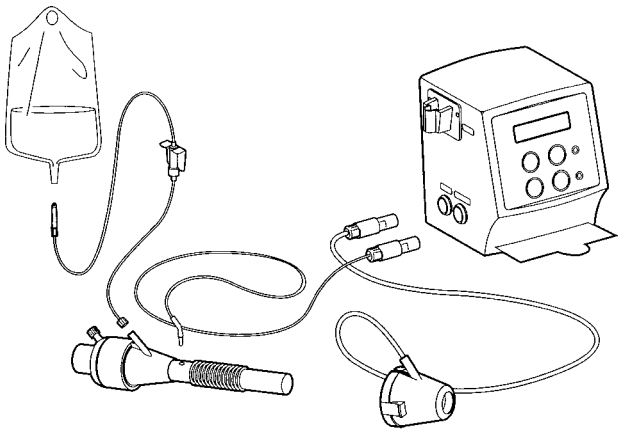

Fig. 3. Schematic diagram of an active heat and moisture exchanger, the Humid-Heat (Gibeck AB, Sweden).

Active Hygroscopic Heat and Moisture Exchangers

Artificial noses cannot be used in all situations, since some patients require the addition of heat and moisture to the respiratory tract. In an effort to expand the use of HHME, Gibeck-Dryden (Gibeck AB, Sweden) has introduced the active HHME (Fig. 3), which incorporates an HHME into a heated housing. The housing contains a paper element that acts as a wick to provide the surface area for gas/moisture transfer. A water source continuously drips water onto the paper element, and the heat from the housing causes the water to evaporate, thereby increasing the humidity of the gas. This system works much like a wick humidifier, except that the source of heat and moisture is added at the airway. This eliminates condensate in the inspiratory limb and thus obviates the water trap. In addition, if the water source runs out, this device continues to operate as an HHME. Thus, there is never the possibility of delivering dry gas to the airway, as can occur with a traditional heated humidifier.

In a recent evaluation, we found that the active HHME provided temperatures of 36–38° C and 90–95% relative humidity. Compared to a heated humidifier and to a heated humidifier with a heated wire circuit, the active HHME provided equivalent efficiency with lower water usage. The disadvantages of this product are the potential for skin burns and the increase in dead space compared to a heated humidifier or HHME alone. The external temperature of the housing is near 37° C. Under normal conditions this temperature is safe. However, patients with peripheral edema or low cardiac output may have reduced blood flow to the skin, in which case heat transfer is reduced and even modest temperatures can cause local burns. The experience with this device is presently scant and further studies are needed to determine if this device provides any additional benefit compared to conventional heated humidifiers.[52]

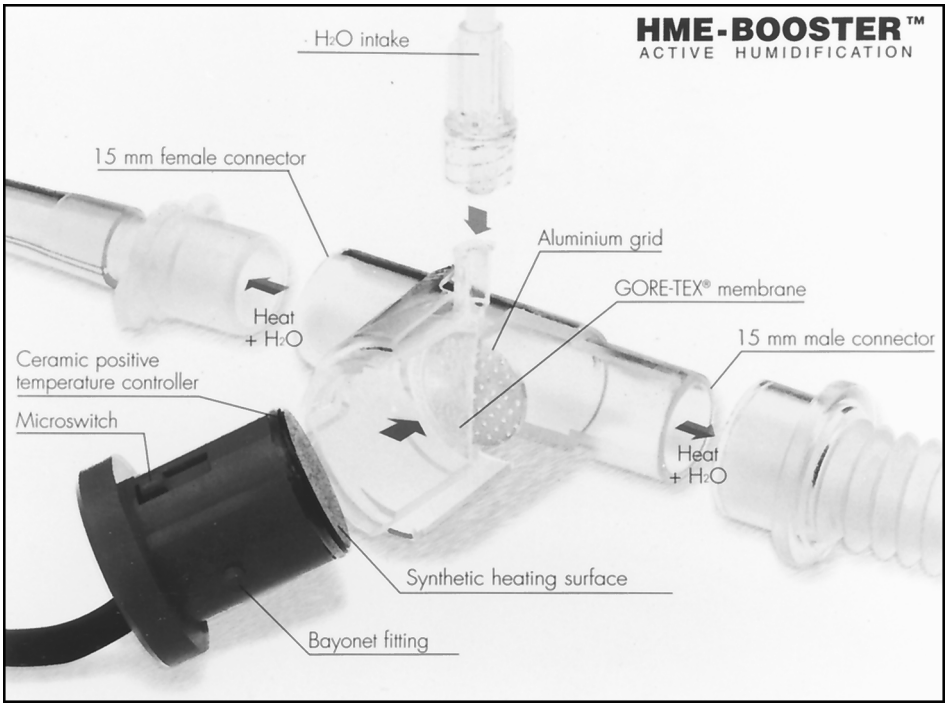

Fig. 4. The HME (heat and moisture exchanger) Booster. (Courtesy of TomTec, Belgium).

HME-Booster

The HME-Booster (TomTec, Belgium) is similar in concept to an active HME, but simpler and less efficient. The booster is a small heating element placed between the passive humidifier and the patient. The heating element is covered with a Gore-Tex membrane. Water flows onto the surface of the heating element and is vaporized, then passes through the membrane and is delivered to the patient during inspiration (Fig. 4). During expiration, the additional moisture is trapped in the passive humidifier, serving to load the media with moisture. Some of the moisture escapes through the HME. The water flow is controlled by a pin-hole-sized orifice adjacent to the heating element. This prevents pooling of excess water. Reports of the booster's use are scant.[53] Our laboratory experience suggests that the device can add an additional 3–4 mg H_2O/L to inspired gases, depending on the V_T, inspiratory-expiratory ratio, and type of passive humidifier used. Whether this small increase in moisture output is worth the additional equipment and expense remains to be seen.[53]

Use of Humidification Devices During Mechanical Ventilation

Clinicians should bear in mind that even the most efficient artificial noses return only 70–80% of the patient's expired humidity, so use of an artificial nose always involves a net loss of heat and moisture. Artificial noses are not as efficient as heated humidification devices and should be used after evaluation of the patient's humidification needs. Figure 5 shows an algorithm for safe and judicious use of artificial noses in the ICU.[54] This protocol uses contraindications to artificial nose use to advise practitioners when to use heated humidification. Contraindications to artificial nose use include the presence of thick, copious sputum, grossly bloody secretions, and hypothermia ($<$ 32° C).

Artificial noses are attractive alternatives to heated humidifiers because of their low cost, passive operation and ease of use, but not all patients can use an artificial nose. Patients with preexisting pulmonary disease characterized by thick, copious, or bloody secretions should receive heated humidification, because secretions and blood can occlude the media or filter and result in excessive resistance, air trapping, hypoventilation, and possibly barotrauma. Because artificial noses only return a portion of the heat and moisture exhaled, patients with hypothermia should receive heated humidification. If patient body temperature is 32° C (absolute humidity of 32 mg H_2O/L), even a very efficient HHME (80% moisture returned), can only deliver an absolute humidity of 25.6 mg H_2O/L. A patient with a bronchopleural fistula or incompetent tracheal tube cuff should also not use passive humidifiers. Because the device relies on collecting expired heat and moisture, any problem that allows expired gas to escape to

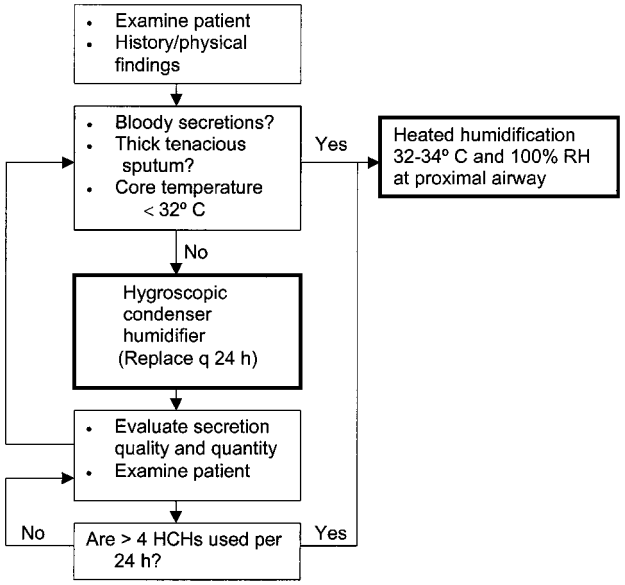

Fig. 5. Algorithm to determine the safe use of a passive humidifier. RH = relative humidity. HCH = hygroscopic condenser humidifier. (Adapted from Reference 54.)

the atmosphere without passing through the media will reduce humidity.

Passive humidifiers should never be used in conjunction with heated humidifiers. Particulate water in the media increases resistance and prevents adequate delivery of humidity from either device. If water occludes the filter, the patient cannot be adequately ventilated and may be unable to completely exhale during positive pressure ventilation. Delivery of aerosolized bronchodilators using a small volume nebulizer requires that the HME be taken out of line, and this frequent breaking of the circuit increases the risk of circuit contamination. Thus, patients requiring frequent medication delivery via a small volume nebulizer should not use an HME. A metered dose inhaler (MDI) can be used with an HME if the MDI adapter is placed between the HME and the endotracheal tube. If spacer devices are used in the inspiratory limb, the HME should be taken out of line. A patient requiring frequent use of an MDI or other aerosol therapy might be better served by a heated humidification system.

In the ICU, an artificial nose can be used for extended periods; our experience suggests that 5 days is safe and effective. This recommendation is based on numerous studies that have found that partial or complete obstruction of endotracheal tubes appears to occur around 5 days.[55–58] Patient sputum characteristics should be assessed with every suctioning attempt. If the secretions appear thick on 2 consecutive suctioning procedures, the patient should be switched to a heated humidifier. We recommend Suzukawa's method[59] for judging the quality of sputum, as follows:

Thin: The suction catheter is clear of secretions following suctioning.

Moderate: After suctioning, the suction catheter has secretions adhering to the sides, but the adhering secretions are easily removed by aspirating water through the catheter.

Thick: After suctioning, the suction catheter has secretions adhering to the sides, and the adhering secretions are not removed by aspirating water through the catheter.

Recent work has suggested that the presence of condensate in the elbow or flex tube between the HME and the patient implies adequate humidification.[60] This makes sense, because the presence of condensate suggests that the gases are saturated with water vapor. This observable condensate criteria should help clinicians decide on a case-by-case basis the advisability of switching the patient from an artificial nose to a heated humidifier. However, artificial noses have been used for up to 30 days.[61]

Other methods of determining humidifier efficiency involve fairly complex techniques, including radioactive isotopes and bronchoscopic evaluation. For the clinician, sputum consistency and the presence of condensate in the flex tube are the most readily available means.

We believe patients requiring mechanical ventilation for greater than 5 days are, by definition, critically ill. At day 5, if lung function has not improved, heated humidification should be considered to prevent secretion retention and to maximize mucociliary function. If the patient begins the weaning process at day 5, the added dead space and resistance of the artificial nose may hinder spontaneous breathing. This point may be debated, but we believe it represents the best compromise between cost efficiency, humidification efficiency, and patient safety. Using the clinical evaluation of humidification performance may allow the 5-day time period to be extended for certain patients.

Most manufacturers suggest artificial noses be changed every 24 hours, but recent research indicates that if the device remains free of secretions, the change interval can be increased to every 48 or 72 hours without adverse effect.[62–64] This requires that respiratory therapists inspect for secretions frequently and change the device as required. If the device is contaminated frequently by secretions and requires > 3 changes daily, the patient should be switched to heated humidification. The frequent soiling of the device suggests that the patient has a secretion problem and the frequent changes will negate any cost savings.

Early work suggested that the use of passive humidifiers might decrease the incidence of nosocomial pneumonia. However, no reliable evidence supports this conclusion. In fact, artificial noses in patients with bacteria in their sputum readily become colonized. If there is no sputum contamination of the media, however, replication of bacteria appears controlled.[65]

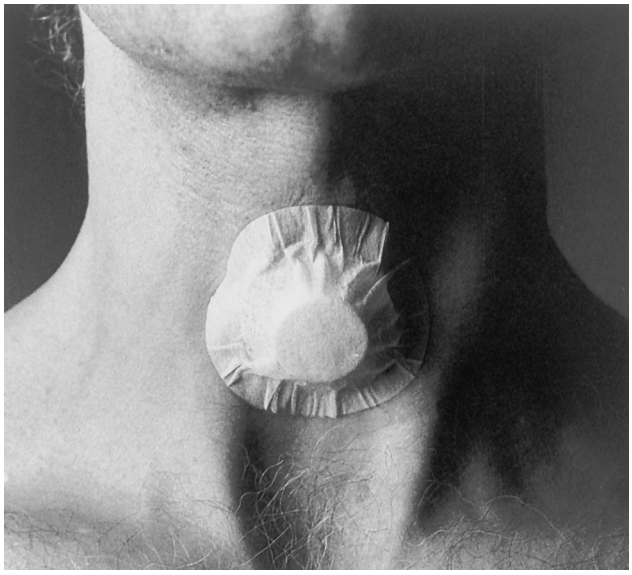

Fig. 6. A heat and moisture exchanger (HME) for the laryngectomy patient.

Patients requiring tracheostomy and prolonged mechanical ventilation in subacute care hospitals and long-term care facilities may use artificial noses for much longer periods. The maximum duration has yet to be determined. There are several reasons for this prolonged use. Patients requiring tracheostomy have their upper airway permanently bypassed and the morphologic structure of the lower airway may adapt to provide greater heat and moisture exchange capabilities. Additionally, many of these patients have chronic diseases and are not subject to the multitude of homeostasis problems seen in the hospital. The decision to use heated humidification in this setting should, however, be similar to that described previously.

Use of Heated Humidification

I believe that the ideal inspired gas conditions are 32–34° C and 100% relative humidity. Heated humidifiers without heated wire circuits use more water, produce more condensate, and are more expensive with time, compared to use with a heated wire circuit.[65] Heated wire circuits eliminate condensate, reduce water usage, and decrease cost, and ventilator operation is more efficient if condensation is prevented. The longer the heated wire circuit is used, the greater the cost savings. The initial investment of heated wire circuits is greater, but if used for patients requiring long-term support, heated wire circuit costs approach the costs of HME use over a period of about a week.[65] There are no proven advantages to the patient when using a heated wire circuit versus a nonheated wire circuit. The choice is generally one of clinician preference and cost.

Use by Ambulatory Patients

Patients who require long-term tracheostomy or tracheostoma for upper airway disease may also benefit from use of artificial noses. The device not only aids in maintaining humidity, but also serves as a filter to prevent the inhalation of large particles of dust and other airborne debris (Fig. 6). Several authors have shown that use of an HHME in patients with tracheostoma reduces sputum production and number of coughing episodes per day.[66–68] To clinicians these findings are not particularly striking, but can be important to the patient's quality of life. A patient who typically has 15–20 coughing episodes per day to expectorate sputum through the stoma can realize a reduction to 10–12 episodes with use of an artificial nose. This allows the patient improved sleep habits and greater confidence in traveling outside the home.

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Discussion

Durbin: I would like to expand on your comment about patients with "thickening" secretions as opposed to "thick" secretions. I assume you meant a change in the secretion pattern. You then recommend a heated wire or a more efficient heated humidification. Intuitively, I think that makes sense, but I don't know that I've ever seen any objective documentation of clinical effectiveness. Most people look at indirect measures of effectiveness of humidification. Most report clogging of endotracheal tubes and needing to frequently change the HME, but are there any data that indicate that with thickening secretions one technique, or a higher humidity level, is better than another?

Branson: I didn't show the algorithm, but we have an algorithm that we use. It's not that the therapists look at it, but if the patient comes in with known thick secretions or bloody secretions, or they're hypothermic, they use the heated humidifier from the first day on the ventilator. We check the secretions over a period of days (see our studies in *Chest*[1] and in RESPIRATORY CARE[2]), and if the secretions are thick (as defined by Suzukawa[3]) during 2 consecutive suctioning attempts, we change to heated humidification. That's based on our analysis of the data in the studies by Cohen,[4] Martin,[5] Misset,[6] and Roustan.[7] These all reported incidences of occlusion of the endotracheal tube, and the majority of problems occurred between the fifth and the seventh day. So, for any patient who stays on for longer than about 5 days, if they have any problems with secretions, we switch them to a heated humidifier. I don't know the answer, to be honest with you. A lot of people say, "Put an HME on everybody, and if you have a problem, then switch to a heated humidifier." I don't know if that's right or not.

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Hess: In patients whom you have changed from an HME to an active humidification system because of thickened secretions, have you followed up to see if their secretions change after they're on the active humidification?

Branson: We've watched some of them. Some get a change in the secretions, but most of them don't. They generally have thickened secretions because they have a process going on, such as pneumonia, and in those patients, increasing the humidity probably doesn't change secretion quality.

But I really have the feeling that if you had left them on an artificial nose, the secretions would have dried and they would start to get encrustation of secretions inside the endotracheal tube.

Hess: So, we really don't know.

Branson: We don't know. But, for me, it's just safety. It's still my opinion that if an artificial nose weren't cheaper, nobody would have ever used one. I'm sure all those of you who were trying to get people to use them were just sure they couldn't possibly work, and now I'm to the point where I'm concerned because people think they're going to use them on everybody because they're so much cheaper. But all those cost savings totally disappear if you have even one plugged endotracheal tube and have to resuscitate even one patient.

Ritz: We've been wrestling with this issue of HMEs on all patients—to start them off that way—and the really complex problem that I'm not sure we have the solution to yet is what to do about nebulized drugs or MDIs. If you want to instill medications between the HME and the patient, it seems like you'd add a lot of cumbersome apparatus between the HME and the patient. On the other hand, if you mount the aerosol delivery system away from the patient, you have to disconnect the tube and remove the HME to administer the medications. Any suggestions?

Branson: I agree. In the last study that we did, working in a surgical ICU, where we do most of our work, we found using an HME very easy probably two-thirds of the time. But in a medical ICU, we found we could use an HME only about a quarter of the time. One of the reasons for not using it there is the problem you brought up. If you're going to use an MDI, you usually have to use an MDI right at the end of the endotracheal tube, or if you're going to use an MDI farther down with a spacer or you're going to use an updraft nebulizer, you have to remove the HME every time you do a bronchodilator treatment. We hardly do any bronchodilator in the surgical ICU (20-year-old trauma patients don't tend to have bronchospasm) but in a medical ICU, almost everybody is on frequent bronchodilator therapy. That is an issue. In the medical ICU, we find we use HMEs much less frequently than the surgical ICU.

Hess: I think that outside the United States that's not necessarily true. It seems to me that the use of active humidifiers is very much an American, New Zealand, or Australian kind of phenomenon, and when you get into Europe and Central and South America, my sense is that there is a lot more use of passive humidifiers. I just visited an ICU in Mexico City, and they had everybody on an HME. They said they have not used an active humidifier in years, and they didn't even think they had one anymore. So, the sense that I have is that we could probably use a lot more passive humidification in the United States, but because of our health care delivery system, or whatever, we've not adopted that practice.

Branson: I agree. I've been to New Zealand and seen John Lawrence's group, who deliver 39°C gas to the airway at 100% relative humidity, and could never imagine doing anything else. And Didier Dreyfuss told me he doesn't own a heated humidifier either. But I've also talked to John Marini, and he'd never use a passive humidifier, because of the dead space. I think the right answer is somewhere in the middle, and that's the principle we adopted. Use it on everybody for whom it's appropriate; you'll save money, and it's simpler and less complex.

Durbin: Can I ask Jim Reibel to comment on airway humidification in patients following laryngectomy? Is this a big issue or a concern of your specialty (otorhinology)?

Reibel: In the United States, it's not. The Europeans, interestingly, have been very active in promulgating the use of a passive humidification device for laryngectomy patients, saying that it improves their pulmonary function. It's not been something we've adopted in the United States, I think mostly because of issues regarding surgeon preference and patient compliance. I've tried a lot of different things on laryngectomy patients, and simple is better.

Branson: I worked with a group in Indianapolis who make a speaking valve for laryngectomy patients, and one of their goals was to add a heat and moisture exchanging filter to the outside. We published a paper about it in *Laryngoscope*,[1] and one of the physicians who was doing the patient side (we just did the evaluation in the laboratory) found that the patients who used this device with adding heat and moisture had about a third less coughing episodes per day. I didn't think that could be a very big deal until they told me that the average patient coughs up into a 4×4 about 30 times a day. Well, if you only cough up into a 4×4 ten times a day, I would think that, from the patient's standpoint, that's a substantial improvement in quality of life.

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Reibel: The down side to that in the laryngectomy patient, though, is that, for these things to work, they have to be fixed to the skin with adhesive. If a patient coughs forcefully enough, he will dislodge the whole thing and have to go through the laborious process of reapplication. So, most of the folks who've used the valve you mentioned for their speech rehabilitation cough it off a few times and throw up their hands and give up using it.