Heat and Moisture Dynamics of the Human Airway

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ABSTRACT

The physiological heat and moisture balance of the human airway during normal conditions has been widely misunderstood in the past. The heated water-bath humidifier remains the most popular type of humidification apparatus used during mechanical ventilation, but this type of active humidifier adds an amount of water vapor to the inspirate that considerably exceeds the moisture content observed during spontaneous breathing through the intact upper airway. It is not necessarily justifiable to blithely assume that the substantial degree of overhydration of inspired gases that occurs by employing active humidification of this type will be innocuous for all patients. Unfortunately, alternative types of humidification devices, such as the heat/moisture exchanging filter, have been unfavorably compared to the heated water-bath by many clinicians who mistakenly considered the latter category of device to represent the "gold standard". The precise characterization of heat/water balance that has emerged since the development of the heated water-bath humidifier has provided clinicians with a benchmark for humidifier performance that is referable to the most effective humidification device the world has ever known, the intact human airway. Fortuitously, passive humidification is appreciably less expensive than active humidification, which represents an additional inducement to cost-conscious clinical managers who might be contemplating the use of the HMEF. If and when a contraindication for passive humidification exists, caregivers might be well advised to adjust the temperature of the active humidifier within a cooler range than they have been accustomed to employ in the past.

Heat and Humidity Status of the Human Respiratory Tract

It has long been recognized that the gases residing in the human alveolus exist at so-called "body temperature and pressure, saturated" (BTPS) conditions. The term "saturated" indicates that a gas is carrying the maximum amount of water vapor possible at the prevailing temperature and, at body temperature, or 37°Centigrade, this translates to 44 milligrams of water vapor per liter of gas. Positive-pressure mechanical ventilation was popularized in the 1950's, and the device that was developed for the humidification of inspired gases for that application was the heated water-bath humidifier. Predictably enough, then, the manufacturers of these early-vintage humidifiers configured them to deliver BTPS gases to the intubated airway during the inspiratory cycle. The precise determination of the heat and water content of inspired gases during spontaneous ventilation would have to wait until the

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rapid-response mass spectrometer was invented many years later. When that instrument was ultimately developed and applied to human respiration, biomedical engineers were able to position a catheter at the carina and withdraw gases through it in retrograde fashion throughout the entire breathing cycle[1)~4)]. This process enabled researchers to determine that : 1) exhaled gases do indeed exhibit a temperature of 37°C at the carina ; and 2) inspired gases at the carina exhibit a temperature that approximates 32°C. Saturated gas at 32°C contains 32 mg/l of water vapor, a far cry from the 44mg/l that had initially been assumed. We now realize, in retrospect, that strenuous efforts to present BTPS inspired gases to the airway of the mechanically ventilated patient is an exercise in overkill. Such gases considerably exceed the water vapor content of spontaneously inspired gases at the carina, the site at which the tip of an indwelling endotracheal or tracheostomy tube customarily resides.

"Water Vapor Content" Data versus "Water Loss" Data

We have already expressed the water vapor content of inspired gas in terms of its absolute humidity, in milligrams of water per liter of gas. As will be noted shortly, however, the specifications for heat/moisture exchangers (HMEs) and heat/moisture exchanging filters (HMEFs) commonly express their performance in terms of "water loss". The use of the latter convention might be initially confusing, but the two concepts can be easily reconciled.

Consider the Figure on the following page, excerpted from a Scientific & Technical Report[5)], recently published by Pall Medical Corporation, portraying the performance of the Ultipor® 100 HMEF. This Figure depicts the performance of the Ultipor® in the form of water loss, in mg/l, at various tidal volumes. These data are generated by ventilating a test apparatus, the configuration of which is rigidly specified by the International Standard Organization. The apparatus incorporates a water bath, maintained at 37°C, that simulates the heat/moisture conditions of the human alveoli. Dry gases are cyclically introduced into the apparatus in aliquots having the volumes listed, mimicking the tidal ventilation of a human subject. As these dry gases rapidly come into equilibrium within the apparatus, the "inspired" gases are brought to BTPS conditions. Then, as they are expelled from the apparatus, they carry moisture along with them in the form of water vapor. If this process were to proceed indefinitely, of course, the water initially present in bulk within the water bath would be removed in its entirety. The rate at which water is thus eliminated is measured by observing the reduction in weight of the apparatus in milligrams per liter of gas introduced. In the actual tests conducted with this HMEF, the test run proceeded over a 48-hour period. For purposes of explanation, we will consider a 100-minute increment within this 48-hour test run. A weight loss of approximately 10.9 grams was observed to occur when the Ultipor 100 was mounted in the inspiratory/expiratory circuit leading to/from the apparatus over a time interval of 100 minutes when a tidal volume of 1,000 milliliters was cyclically delivered to the test rig at a respiratory frequency of ten cycles per minute. Therefore, 10.9 grams of water were carried away from the apparatus when a total of 1,000 liters (1.0 liter per breath times 10 breaths per minute times 100 minutes) were used to ventilate the test rig. This converts to a water loss figure of 10.9 milligrams of water per liter, as noted by the height of the histogram over the "10 l/min" label in the **Figure 1**. The water vapor content of the gas expelled from the water bath is, of course, known to be

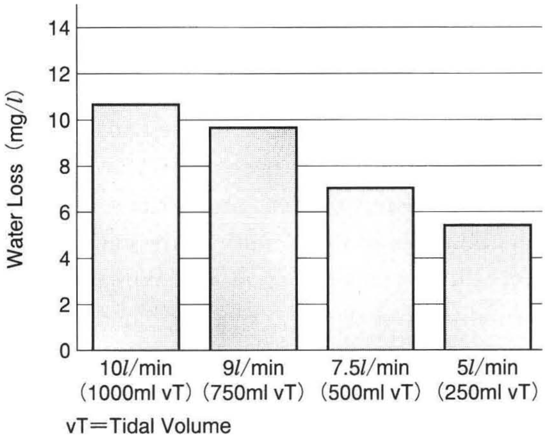

Fig. 1* Water Loss vs. Tidal Volume (ISO 9360-Draft 1998)
*Average Water Loss over a 48-hour test period.

44 mg/l, corresponding to BTPS conditions. Much, but not all, of this water vapor will be sequestered within the Ultipor as it traverses that HMEF during the simulated expiration, and this water will be returned to the simulated inspirate during the subsequent cycle. The water vapor content of that inspirate (33.1 mg/l) is easily calculated as the arithmetic difference between 44 mg/l and the water loss figure (10.9 mg/l) shown. Hence, we can easily convert between "water loss" data and "water vapor content" data by simple subtraction. Average water loss values at the tidal volumes listed were found to be : 10.9 mg/l at a tidal volume of 1,000 ml ; 9.8 mg/l at a tidal volume of 750 ml ; 7.0 mg/l at a tidal volume of 500 ml ; and 5.4 mg/l at a tidal volume of 250 ml. With reference to **Figure** 1, the water vapor content of inspired gas at tidal volumes of 1,000 ml, 750 ml, 500 ml, and 250 ml is 33.1, 34.2, 37.0, and 38.6 mg/l, respectively. These water vapor content figures are slightly to appreciably higher than the physiologic levels of moisture in the inspirate observed in the intact airway of normal man.

What Level of Filtration is "Safe" for Patients/Caregivers ?

In some hospitals, patients with active tuberculosis (TB) are frequently encountered. Consequently, it is not unusual in an institution of this type for mechanically ventilated patients to harbor active TB. But even if its incidence is low among the patient population of a given institution, TB remains a worrisome pathogen. This applies because patients afflicted with active TB are usually not identified at the time they are admitted or intubated. Thus, one often learns that a patient is suffering from active TB many days after s/he has been intubated. Obviously, it behooves us to proactively exercise vigilance in this area, in a fashion reminiscent of the universal precautions that have become routine with respect to human immunodeficiency virus (HIV). In order to avoid the risk of exposing themselves to blood harboring HIV, caregivers don appropriate garb in order to protect themselves whenever exposure to blood is likely to occur. One could persuasively argue that the concept of universal precautions should likewise be uniformly invoked with respect to TB, especially in view of the resistant strains of that organism that are being reported with alarming frequency. Universal precautions as applied to the mechanical ventilation of TB patients would render the placement of competent filters in the ventilator's expiratory limb imperative.

The Centers for Disease Control and Prevention (CDC) has promulgated guidelines[6] mandating that caregivers don masks that conform to high-efficiency particulate aerosol (HEPA) specifications when administering care to non-intubated patients who are known to harbor TB. Certainly, HEPA-grade filtration should prevail whenever these same patients are required to be intubated and, because one can almost never be sure that a given patient is free from TB, HEPA-grade filtration should be considered routine. Amazingly, most breathing circuit filters and HMEFs designed to be interfaced to mechanical ventilator circuits fall far short of the HEPA standard[7], exhibiting efficiencies that range between 1/47th and 1/20th of that level ! On the other hand, the performance of the resin-bonded ceramic fiber type of filter has been shown to exceed HEPA-grade filtration by more than thirty-fold[4]. Hence, caregivers can provide a greatly enhanced level of protection to patients, and themselves, by interposing this type of filter medium within the ventilator circuit.

Unfortunately, HMEFs cannot be interfaced to every category of patient, because certain contraindications apply to their use. The protocol appearing on the following page[7] identifies situations wherein the use of an HMEF might be contraindicated. In such scenarios, one will be obliged to employ a heated water-bath humidifier in lieu of an HMEF. However, it remains very important to ensure that an adequate level of filtration prevails under these circumstances, in order to continue to protect patients and caregivers who find themselves in the vicinity of mechanical ventilators. In these instances, a competent filter should be placed in the ventilator's expiratory limb before the patient is interfaced to the machine. Respiratory therapists, who might otherwise assume that the multiple-use filters incorporated within the circuitry of certain brands/models of ventilators (such as the Omni® filter manufactured by Mallinckrodt) are competent, should be aware that these devices fall short of the HEPA standard.

Thermo-and Hydrodynamics of the Respiratory Tract

Many clinicians seem to harbor the subjective impression that the employment of a heat/moisture exchanger, in lieu of a heated water-bath humidifier, imposes a water deficit upon the respiratory tract as compared to normal. Actually, precisely the opposite is true.

As was noted earlier, the Ultipor delivers inspired gases to the vicinity of the carina that have a water vapor content approximating the normal level of 32 mg/l. When we inhale gases under most conditions, the ambient air has a water vapor content that is substantially lower than 32 mg/l. Consider the situation that prevails when we are spontaneously breathing air that is saturated with water vapor at a temperature of 72°F ahrenheit through the intact upper airway ; the water vapor content of such air is about 20 mg/l. In its passage from the environment to the carina, this gas will be supplied with about 12 mg/l of additional water, bringing it to the level cited earlier. Hence, that portion of the respiratory tract (the naso-and/or oropharynx, hypopharynx, larynx, and trachea) lying proximal to the carina will undergo a water loss sufficient to compensate for the moisture deficit that prevails between ambient air and normal inspirate at the carinal level. An intubated patient fitted with an HMEF, such as the Ultipor, that bypasses the upper airway will not be required to supply additional moisture from the upper respiratory tract, however, because the device succeeds in doing this. Therefore, the water loss that would otherwise occur in the proximal airway will be abolished. Consequently, net water loss will be less than would have been the case had the patient been breathing through the intact airway. Caregivers might be prompted to compare an HME or HMEF unfavorably with a heated water-bath humidifier, which conveys visibly more water to the respiratory tract than do those devices. But, as noted earlier, clinicians should not be misled that the water-bath humidifier is creat-

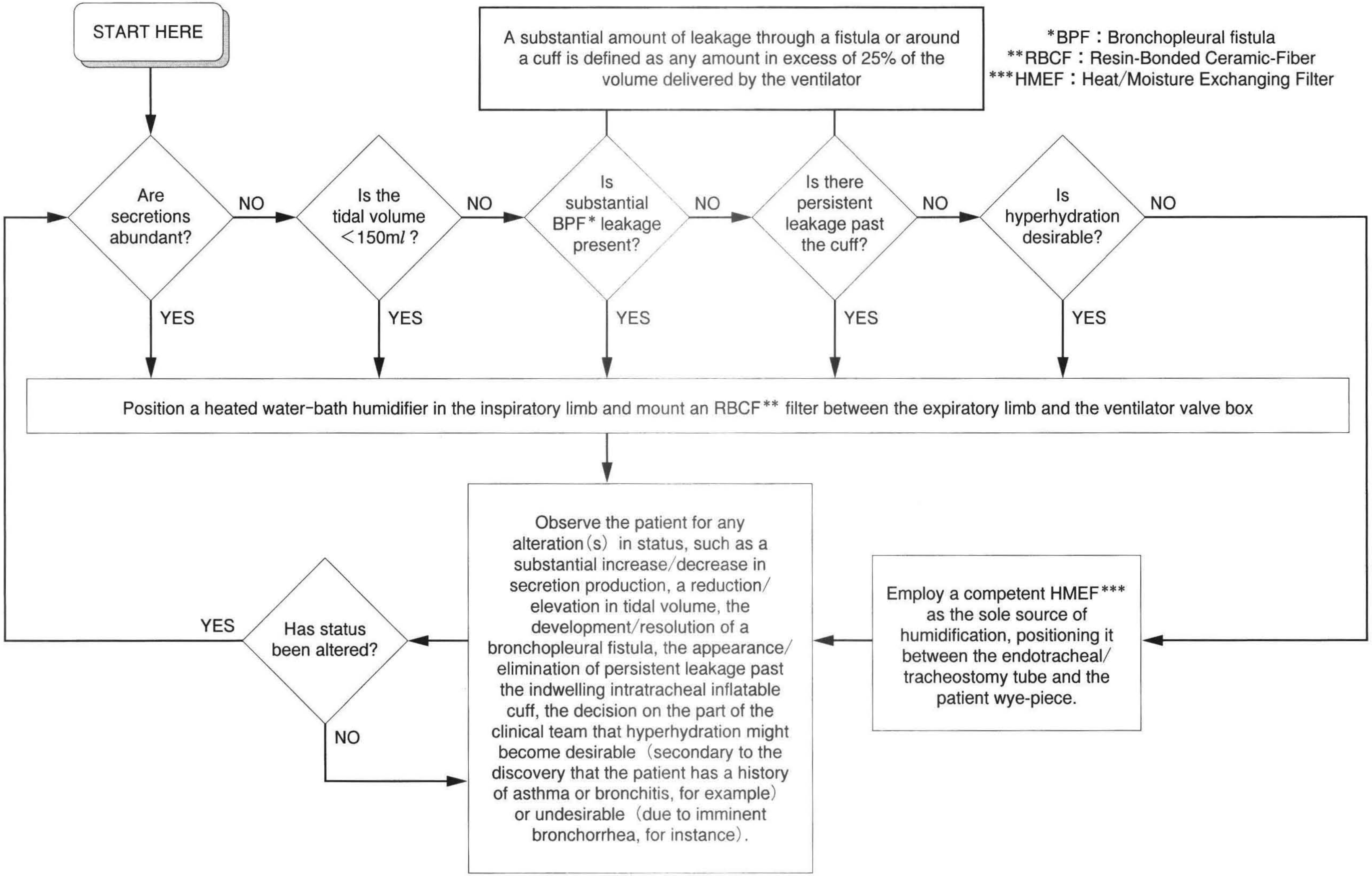

Fig. 2 A Protocol for Selecting the Appropriate Humidification/Filtration System for a Mechanically Ventilated Patient

ing a situation that even remotely resembles the normal physiologic thermo-and hydrodynamic state. As previously discussed, water-bath humidifiers overhydrate inspired gases by an appreciable degree, and we should resist the tendency to regard them as anything resembling "normal" or "physiologic" in terms of water or heat balance. In other words, the heated water-bath humidifier is illsuited to be considered a standard for comparison with any other device, because its performance diverges so markedly from the normal physiologic state.

The heat loss that occurs at the mucosal surface of the airway relates not only to that membrane's conduction of heat to the relatively cool inspired gases, but much more so to the evaporation taking place there. The heat of vaporization of water is considerable : 540 calories per gram. Over one hour's time, a normal subject will inhale about 360 liters of air. If this air were to exhibit the absolute humidity level used in the preceding example, 20 mg/l, the respiratory tract will be obliged to supply an additional 24 mg/l to the inspirate in its journey from the atmosphere to the alveolus. Half of that amount will be supplied proximal to the carina, and the remainder will be added between the carina and the alveoli, bringing alveolar gas to a level of 44 mg/l at 98.6° (37°C). Hence, the total water loss from the tracheobronchial tree over this time interval will be (24 mg/l × 360 l =) 8,640 milligrams or 8.64 grams. The thermal energy supplied by the body in the process of evaporating this amount of water will be (540 cal/g × 8.64 g =) 4,666 calories, or 4.67 kilocalories. It is for this reason that an appreciable amount of the body's evaporative cooling can occur within the respiratory tract even when inhaling hot air, provided that that air is relatively dry. Fortunately for desert dwellers, the high ambient temperatures associated with that environment almost always coexist with very low humidity levels.

Under certain climatic conditions, the heat/moisture exchange function of the upper airway can be rendered inoperable. Consider, for example, the conditions that might prevail in a location such as New Orleans, Louisiana on a hot August day. Suppose that the afternoon temperature were to climb to 100°F, with a relative humidity of 66% ; the absolute humidity of such air is approximately 32 mg/l. Inhaling this air would not necessitate the addition of any water whatsoever enroute to the carina, because the water vapor content of this inspirate is already equivalent to that normally prevailing at that level. Hence, the moisture exchange role of the upper airway is rendered superfluous here.

Indeed, we can sometimes encounter conditions in tropical climes wherein the heat and moisture content of ambient air actually exceeds BTPS conditions. Imagine slogging through a tropical rain forest where the prevailing temperature is 100°F and the relative humidity is 100%. Under these conditions (that are, mercifully, seldom encountered!), heat and moisture will actually be extracted from the gases traversing the respiratory tract during inspiration. Neither heat nor moisture will be donated to inspired air under such conditions, either in the upper or the lower airway. Stated another way, condensation, and not evaporation, might occur within the airway during inspiration while slogging through the equatorial jungle. The evaporative cooling that ordinarily attends inspiration will be sorely lacking here, which will only add to the sensation of sweltering heat perceived by those exposed to these rigorous conditions.

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