Humidification During Invasive Mechanical Ventilation

10

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10.1 Introduction

Humidification of gases delivered to patients on invasive mechanical ventilation has been recommended since the early days of mechanical ventilation in intensive care units [1]. The deleterious impact of dry gases on airway mucosa was described very early [2]. Abundant human and animal literature is available demonstrating a relationship between airway mucosal dysfunction, inflammation, and atelectasis and (i) the level of gas humidity delivered during invasive mechanical ventilation and (ii) the duration of exposure to this gas [3]. There is still an ongoing debate around the optimal level of inspiratory gas humidity. There are several recommendations published on this optimal level of humidification required during invasive mechanical ventilation. Most of these publications are not recent. In general, it is recommended that the humidification systems should provide at least 30 mgH_2O/L for the inspiratory gases [4–8]. Many studies were published that allow us to better determine what a safe level of humidification is. If we consider as a minimum clinical requirement to avoid obstruction of endotracheal tube, slightly lower levels of humidity may be sufficient [9]. However, tube occlusion is a late marker, and impacts on tracheal tube diameter, on mucociliary transport system, and on bronchial inflammation probably occur before tube occlusions. Few authors recommend to use levels of humidity of gas corresponding to the water content in the alveoli or 44 mgH_2O/L which corresponds to 100% of relative humidity at 37 °C [10]. These latter requirements are not usually attained with humidification systems used so far [9, 11]. Until now, no study really did compare stable systems delivering 40 mgH_2O/L

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with stable systems delivering 30 mgH_2O/L. In some clinical situations, such as patients ventilated with ARDS or severe asthma, other criteria than the level of humidification should be considered, in particular, to take into account the mechanical characteristics of the different humidification systems (especially the dead space) [12]. Finally, the issue of the humidification systems' cost cannot be set aside at the time of the choice.

Recently, the SARS-CoV-2 pandemic has shown that both aspects of humidification devices (dead space and humidification properties) may have a relevant impact on the management of ARDS patients [13].

10.2 Hygrometric Performances of the Main Humidification Systems

10.2.1 What Is the Optimal Level of Humidification During Invasive Mechanical Ventilation?

This difficult question has been debated for a long time, and if the answer is more accurate, it has not changed much since 50 years. Chamney in 1969 defined the targets that were required by the humidification systems used in patients intubated or tracheostomized [14]. Among these conditions, the author recommended that the gases reaching the trachea should be between 30 and 36 °C in the range of 30 to 40 mgH_2O/L. In an editorial in 1987, "A rational basis for humidity therapy," Chatburn proposed to provide saturated gas at 32–34 °C (33.9–37.7 mgH_2O/L), which is the humidity level of the gas at the trachea in healthy subjects [15]. He also concluded in the same editorial that there was no rationale for proposing to issue gas saturated at 37 °C.

Several different organizations have provided recommendations for humidifying gases during invasive mechanical ventilation. The British Standards Institution has recommended providing an absolute humidity of 33 mgH_2O/L in 1970 [4]. In 1979, ANSI (American National Standards Institute) has recommended a minimum level of moisture delivered of 30 °C at 100% of relative humidity (i.e., 30.4 mgH_2O/L of absolute humidity) with the heated humidifier [5]. In addition, the AARC (American Association for Respiratory Care) recommended a minimum humidity delivered of 30 mgH_2O/L with HMEs and between 33 and 44 mgH_2O/L with active humidification [8]. ISO 8185 also recommended 30 mg/L for humidification systems in 1988 [6]. Finally, the ISO 8185 standards recommended 33 mgH_2O/L, but this standard "does not apply to heat and moisture exchangers" (1.1) [16].

10.2.2 Effects of Under-Humidification of Delivered Gases

There is an abundant literature that describes the impact of under-humidification on airway mucosal and mucociliary transport dysfunction and bronchial inflammation [3]. Epithelial dysfunction modifies the properties of the mucus, leading to intraluminal depositions of viscous mucus, reduction of endotracheal diameter [17, 18],

increased tube resistance [19], or endotracheal tube occlusions [9] in a few hours. This may require an emergent change of the endotracheal tube, cardiac arrest, or even death [20]. More frequently, sub-occlusions result in increased resistance of the endotracheal tube [19] and increased respiratory drive and work of breathing, potentially aggravating the lung injuries or delaying weaning.

However, it may not be easy for the clinicians to recognize early signals of under-humidification. On the other hand, endotracheal tube occlusion is a late marker but easy to recognize as it is frequently associated with emergent need to change ETT and is half of the cases associated with cardiac arrest [20, 21]. This potentially fatal complication was very rare and usually below 1% [20, 21].

During the recent pandemic, very high rates of occlusions have been described with COVID-19, up to 72% [22–27]. Some authors had questionable recommendations such as the systematic change of endotracheal tube every week in these patients [25] or the systematic use of ETT cleaning devices [24], procedures at high risk of viral contamination for healthcare workers. The main reason that explained these high rates of ETO was probably the under-humidification of the gases delivered to the patients [28].

Recently, Al Dorzi et al. provided additional evidence that optimization of humidification during mechanical ventilation had a major impact on the rate of endotracheal tube occlusions and other clinical endpoints [29]. After modification of the humidification strategies, the authors report that the rate of endotracheal tube occlusions was strikingly reduced (8.1 vs. 1.0 tube occlusion per 1000 ventilator day). Interestingly, ETO were not suspected in 94.4% of the cases. When compared with 51 matched controls, ETT occlusion cases had significantly longer duration of mechanical ventilation (13.5 vs. 4.0 days; $P = 0.002$) and ICU stay (26.5 vs. 11.0 days; $P = 0.006$) and more tracheostomy (55.6% vs. 9.8%; $P < 0.001$) [29].

10.2.3 Risk Scale for Endotracheal Tube Occlusion

The hygrometric performance of the humidification devices is the first parameter to consider when assessing such systems. There are several hygrometric techniques that make difficult the comparison of the humidification devices. We had the opportunity to measure with the same technique (psychrometric method) the hygrometric performances of a wide variety of humidification systems currently available on the market, the majority of heated humidifiers of previous generations as well as the most recent ones, many heat and moisture exchangers (HME), and the majority of active HME available on the market [9]. Comparing our results with those of the literature (Table 10.1) [17, 30–46], we have designed a risk scale for endotracheal tube occlusion according to the humidification systems used and their conditions of use (Fig. 10.1). Above 28 mgH_2O/L of humidity delivered (measured with the psychrometric method), the risk of endotracheal tube occlusion seems to be low [9, 47], when other risk factors of tube obstruction (such as bloody secretions) are not present. We discuss in this chapter the main characteristics of the currently available humidification devices.

Table 10.1 Summary of published studies comparing HME and heated humidifiers (upper table) or evaluating only HMEs (lower table) for which the frequency of catheter occlusion is reported [17, 30–46]. The humidification systems are reported. For HMEs, performance measured by the psychrometric method is reported [9]

	Heated humidifiers			Heat and moisture exchangers			
First author [reference]	Device	Included patients/ occlusions	Percentage of endotracheal tube occlusions	Device	Included patients/ occlusions	Percentage of endotracheal tube occlusions	Absolute humidity (psychrometry) in mgH_2O/L
Cohen [30]	Cascade	81/1	1.2	BB2215	170/15	8.8	21.8
Martin [31]	HHBW (32 °C)	42/0	0.0	BB2215	31/6	19.4	21.8
Misset [32]	MR 450 (32–34 °C)	26/2	7.7	BB2215	30/4	13.3	21.8
Roustan [33]	Aquapor (31–32 °C)	61/0	0.0	BB2215	55/9	16.4	21.8
Branson [41]	ConchaTherm III (32–34 °C)	32/0	0.0	Aqua+	88/0	0.0	ND
Dreyfuss [36]	MR 450	70/0	0.0	Hygrobac	61/1	1.6	31.7
Villafane [17]	MR 310 (32 °C)	7/1	14.3	BB2215	8/3	37.5	21.8
				Hygrobac	8/0	0.0	31.7
Boots [35]	MR 730 (37/35)	41/0	0.0	Humid-vent light	75/0	0.0	30.8
Hurni [37]	F&P (32 °C)	56/1	1.8	Hygroster	59/0	0.0	30.7
Kirton [39]	Marquest	140/1	0.7	BB100	140/0	0.0	26.8
Kollef [46]	MR 730 (35–36)	147/0	0.0	Duration	163/0	0.0	NA
Thomachot [40]	Cascade 2 (32 °C)	20/0	0.0	Humid-vent light	9/0	0.0	30.8
Jaber [42]	MR 730 (37/40)	34/2	5.9	Hygrobac	26/1	3.8	31.7
Lacherade [38]	MR 730 (37/40)	185/5	2.7	Hygrobac	185/1	0.5	31.7
Boots [34]	MR 730 (37/40 or 37/35*)	191/0	0.0	Humid-vent light	190/0	0.0	30.8
	Total HH	**1133/13**	**1.1%**	**Total HME 1**	**1298/40**	**3.1%**	

				Total HME 1 (excluding BB2215)	**814/3**	**0.4%**	
Thomachot [45]				Humid-vent light	66/1	1.5	30.8
				BB100	70/1	1.4	26.8
Thomachot [44]				Humid-vent	77/1	1.3	30.8
				Clear-Therm	63/0	0.0	26.2
Boisson [68]				MaxiPleat	12/0	0.0	20.1
Davis [78]				Aqua+ (24 h)	100/0	0.0	NA
				Duration (120 h)	60/0	0.0	NA
				Aqua+ (120 h)	60/0	0.0	NA
Markowicz [103]				Hygrobac	21/0	0.0	31.7
				Humid-vent	20/0	0.0	30.8
				Clear-Therm	20/0	0.0	26.2
Ricard [77]				Hygrobac	33/0	0.0	31.7
Thomachot [43]				Thermovent Hepa+ (1j)	84/0	0.0	27.8
				Thermovent Hepa+ (7 days)	71/0	0.0	27.8
Boyer [111]				EdithFlex	22/0	0.0	NA
				Hygrolife	21/0	0.0	NA
				Total HME 2	**800/0**	**0.4%**	
				Total HME 1 + 2	**2098/43**	**2.0%**	
	Total HH	**1133/13**	**1.1%**	**Total HME 1 + 2 (excluding BB2215)**	**1614/6**	**0.4%**	

NA not available

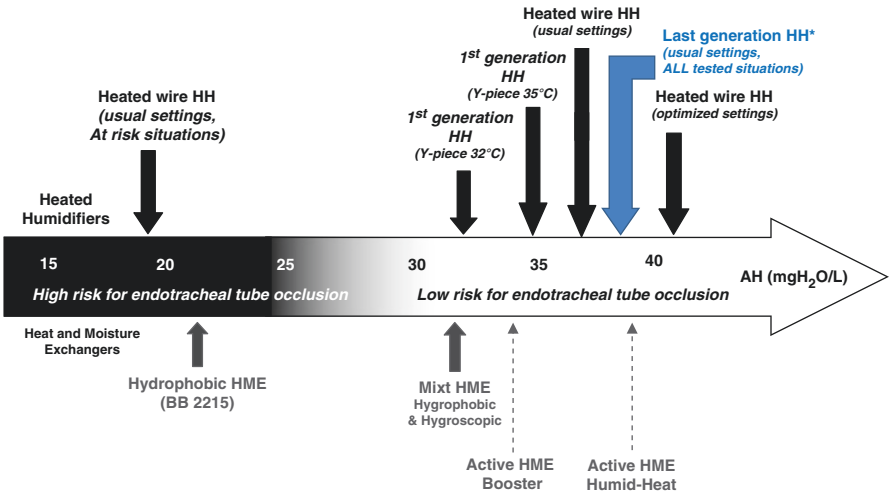

Fig. 10.1 Psychrometric risk scale. Position of different humidification systems in connection with their humidification performance based on the same technique of measurement (psychrometric method) (personal data combined with the literature data) [9, 11, 23, 28, 51, 52, 69, 71, 118]. Between 25 and 30 mgH_2O/L of absolute humidity is a gray zone where the risk of occlusion exists but is less known. Under 25 mgH_2O/L, that risk is probably important [17, 30–33], and above 30 mgH_2O/L, the risk is low [36, 38, 77, 102]. Furthermore, there is a potential risk of over-humidification with systems with the highest performances in terms of hygrometry [114]. However, this risk is currently difficult to estimate. The "at-risk situations" is high ambient or ventilator temperature which are associated with low humidification performances with these devices. The last-generation HH stands for recent HH with advanced closed-loop regulations (that incorporate ambient temperature, inlet temperature, heater plate temperature, humidity sensor, etc.). *Heated humidifiers FP950 (Fisher & Paykel) and VHB20 (Vincent Medical) were tested on bench with ambient temperature from 20 to 30 °C and minute ventilation at 10 and 15 L/min and provide highly humidified gases (between 31 and 39 mgH_2O/L) under all tested conditions. *HH* heated humidifiers, *HME* heat and moisture exchangers

10.2.4 Heated Humidifiers' Humidification Performances

Heated humidifiers are usually considered as the most efficient systems in terms of humidification performances. This conviction must be qualified. It has been shown that the performances of heated humidifiers with heated wires vary widely, from 20 to 40 mgH_2O/L, and are influenced by external conditions, particularly ambient and ventilator outlet temperatures [11]. When these temperatures are high, inlet chamber temperature is high leading to the reduction of the heater plate temperature. Indeed, with these humidifiers, the regulation of the heater plate temperature aims at maintaining a constant humidification chamber temperature (usually set at 37 °C). The temperature of the water in the humidification chamber is related to the heater plate temperature. Water with a low temperature will not produce moisture. Consequently, there is a strong inverse relationship between the inlet chamber temperature and the humidification performances (Fig. 10.2) [11]. Thus, the very low

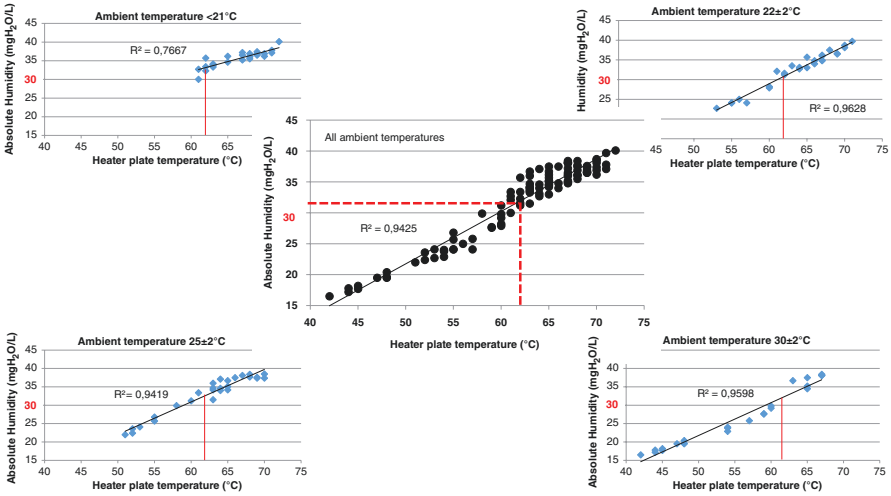

Fig. 10.2 Correlation between heated wire humidifier performance and heater plate temperature. A very close correlation was found between humidifier performance (absolute humidity [mgH_2O/L] of inspiratory gas) and heater plate temperature (°C). This correlation was hardly modified by ambient temperature. The monitoring of this parameter should be promoted in the case of sticky secretions or situations at risk (from reference 23). Above heater plate temperature of 62°C, the absolute humidity delivered is most frequently above 30 mgH O/L. In a recent study we showed that this relation is influenced by minute ventilation (reference 60)

humidity levels (around 20 mgH_2O/L and even lower), described as being likely to cause endotracheal tube obstruction, are delivered by these systems in the most adverse conditions (high ambient temperature, turbine ventilators delivering high temperatures, and high minute ventilation) [48]. These humidity levels are comparable to or even lower than those measured with the HME BB2215, with which the incidence of endotracheal tube occlusions ranged from 10 to 20% [17, 30–33]. Furthermore, even in favorable situations (normal ambient and ventilator temperatures), measured performances are below what is advertised by manufacturers (44 mgH_2O/L) [11, 49]. This again argues for an independent evaluation of humidification systems [9, 50].

In another study, we evaluated the influence of ambient temperature and ventilator output temperature for many heated humidifiers, particularly those of previous generations without heated wire (requiring water traps in the ventilator circuits) [51]. This study showed that for settings equivalent to heated humidifiers with heated wire (35 and 37 °C at the Y-piece), the heated humidifiers without heated wire (i) have more stable hygrometric performances with little influence from external conditions and (ii) deliver gases with inspiratory absolute humidity levels above 30 mgH_2O/L. In contrast, (iii) for more traditional settings (32 °C), the performances of these systems were near the limit of 30 mgH_2O/L and sometimes below.

We also evaluated heated humidifiers with different technologies (counter-flow heated humidifier) and devices incorporating an algorithm to reduce the risk of under-humidification [52]. We found significant improvements with the algorithm

that compensates for low humidity with the MR 850 (Fisher & Paykel) and good performances with the humidifier HC 200 (Hamilton Medical) to obtain inspiratory water content between 35 and 40 mgH_2O/L, with moderate influence of ambient and ventilator temperatures, flows, and tidal volumes used [52]. Similar data have been published for counter-flow heated humidifiers [53]. In addition to compensation algorithm, specific settings that increase the temperature of the humidification chamber (and reduce the gap with the Y-piece temperature) can be used to prevent from under-humidification on most several models of heated wire humidifier.

Recently, several new heated humidifiers with advanced algorithm have been launched. The new FP950 (Fisher & Paykel) has been evaluated on bench, and it was shown that whatever the conditions of ambient temperature (from 20 to 30 °C), the mean absolute humidity delivered was around 35 mgH_2O/L [54]. We also evaluated the new humidifier VHB20 (Vincent Medical) on bench and found that humidity delivered was above 35 mgH_2O/L, even when ambient temperature was above 25 °C [55].

Even if the humidification performance improves with most recent heated humidifiers (with new algorithms and specific settings), the problem of condensation in the circuit remains in spite of heated wires in certain circumstances. This question has been raised since a long time with the heated humidifiers [56], and the objective of heated wires was to limit this risk. Yet, the frequency of condensation in the inspiratory circuit is high [57], especially with the turbine ventilators and in case of low or variable ambient temperatures [58]. New "porous" expiratory circuits limit the problem in the expiratory circuit, while in the inspiratory circuit, this issue is still there. The interest of the "porous" circuits is to reduce the water content in the expiratory limb, which could limit the risk of condensation of gases that carries potential interference with measures of expiratory flow with some pneumotachograph [59].

Clinicians must be aware of these technical issues to interpret specific clinical situations (i.e., thick secretions or endotracheal tube occlusion or sub-occlusion in spite of heated humidifier use). When used in normal conditions, heated humidifiers are performing systems. Normal conditions mean (i) stable and moderate ambient temperature (south-facing rooms with sun on the humidifier may be a problematic situation!) and (ii) moderate output ventilator temperature with a specific precaution in case of turbine ventilator use.

Based on new data that demonstrate an excellent correlation between heater plate temperature and humidity delivered (with MR 850) [60], this parameter should be used to monitor the performances of the humidifiers when under-humidification is suspected (high ambient temperature, thick secretions, endotracheal tube occlusions or sub-occlusions).

During the COVID-19 pandemic, endotracheal tube occlusions have been described even with heated humidifiers [13, 24, 26]. In one US center, it was recommended to switch off the humidifier to avoid aerosolization [26]. We measured humidity delivered of 7.8 mgH_2O/L with such condition (corresponding to cold humidification) which is not acceptable even for few hours [28]. There are several studies that reported ETO even when heated humidifiers were used. In the largest

cohort of patients, 11 endotracheal tube occlusions occurred out of 187 patients managed for COVID-19 [24]. Seven cases were related to poor-performing HME [28], while four were related to HH [24]. In a study comparing two humidification strategies to manage this population, three endotracheal tube occlusions occurred within few weeks, while HH were used, due to high ambient air in the rooms with recently installed negative pressure devices [23]. A strategy to avoid under-humidification stopped the epidemic of tube occlusions: heated humidifier performances were regularly evaluated with heater plate temperature monitoring, the air conditioning system was changed to control the ambient temperature, and compensation algorithm of the HH was activated [61].

10.2.5 Heat and Moisture Exchangers' Humidification Performances

10.2.5.1 Comparison with the Literature on the Risk of Tracheal Occlusion (Fig. 10.3)

Heat and moisture exchangers (HMEs) are the most commonly used humidification devices in Europe [62] and are being increasingly used in North America [63].

As for heated humidifiers, many technological improvements have led to the emergence of new models of performing HME on the market. The very first

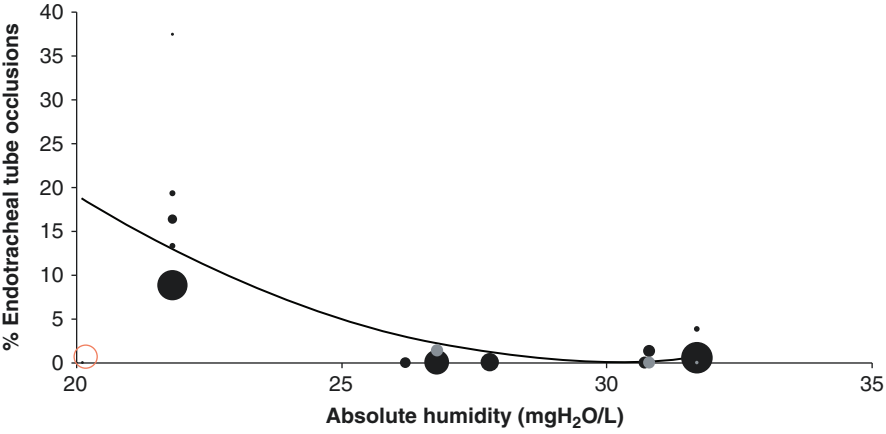

Fig. 10.3 Frequency of endotracheal tube occlusions reported in the literature with heat and moisture exchangers [17, 30–46, 77] in relation with the absolute humidity delivered by the HMEs measured using the bench test apparatus (see Table 10.1) (from reference 9). One study (red circle) is an outlier [68] with no endotracheal occlusions despite very poor humidification. However, this study only included 12 patients, which is not enough to reach a conclusion about the safety of the device tested. A hydrophobic HME (Pall BB2215), which delivered a measured absolute humidity of 21.8 ± 1.5 mgH_2O/L, has been associated with high rates of endotracheal tube occlusions in five previously published studies [17, 30–33] (Table 10.1). A number of studies are represented by gray dots to make them stand out. The sizes of the dots are proportional to the number of patients in the studies

metallic HMEs were not disposable and generated significant resistance [64–66]. The first disposable HME was available in 1976 and was used during anesthesia [67]. The first HMEs proposed for ICU patients (hygroscopic HME) had insufficient humidification performances, responsible for their poor reputation [17, 30–33]. This poor reputation is not justified anymore. Improved materials have reduced the size of HMEs and improved their performances. We conducted a large-scale evaluation of the humidification performances of 48 devices (HME, HMEF, antibacterial filters) [9]. The main result was the heterogeneous performances of these systems. Antibacterial filters should not be used to humidify gases. However, some of the filters have fairly similar appearance compared with HME or HMEF, but water contents are very different, with the possibility of confusion. The most efficient HMEs provide humidity of inspired gases slightly above 30 mgH_2O/L, but some systems proposed for airway humidification provide water contents below 25 and sometimes below 20 mgH_2O/L. Moreover, comparing with data from manufacturers, we have observed some significant differences, which again call for independent evaluations.

We used data from this study and from the literature to try to assess the humidification level associated with a risk of endotracheal tube occlusions. The BB2215 device with performance of about 22 mgH_2O/L resulted in a significant increased risk of occlusions [17, 30–33]. HMEs providing absolute humidity above 25 mgH_2O/L seem to be at lower risk. But there is little data with humidification systems with intermediate performance (between 25 and 30 mgH_2O/L); the few studies available show that the risk of catheter occlusion is also low in that zone [39, 43, 45]. However, it is likely that this risk is directly linked to the hygrometric performances. Although no formal data exist on the risk of occlusion around 25 mgH_2O/L, caution is warranted and it is recommeded to approach or exceed 30 mgH_2O/L to minimize these risks.

In the literature, there are several conflicting studies with the previous results. In the study of Boisson et al. [68], no occlusion occurred while a low-performing hydrophobic HME was used (absolute humidity just above 20 mgH_2O/L). But this study had included only 12 patients. While the main issue is safety, we cannot conclude positively considering the small number of patients. Moreover, Kapadia et al. [20, 21] reported the incidence of endotracheal tube occlusions over a series of nearly 8000 patients during a period of 5 years. While the HMEs used were BB2215 (22 mgH_2O/L) and Cleartherm (26 mgH_2O/L), the frequency of occlusions was "only" 0.16%. In analyzing the results, it appears that the average duration of mechanical ventilation was less than 2 days, which probably explains the low rate of occlusion in this study. The duration of ventilation must obviously be taken into consideration when analyzing the risk of endotracheal tube occlusion. Thus, these discordant publications should not be reassuring. During the COVID-19 pandemic, several studies reported endotracheal tube occlusions in patients on invasive mechanical ventilation (Table 10.2). The high rate of tube occlusion may be explained by several factors including prolonged durations of intubation in this population, reduction of suctioning frequency, and utilization of low-performing HME [28]. In a recent study, the ISO 9360 standard used to ensure ECH

Table 10.2 Studies reporting endotracheal tube occlusions in COVID-19 patients. Rate of endotracheal tube occlusions, type of humidification device, and absolute humidity according to the manufacturer and measured on bench with the psychrometric method

Authors (reference)	No. of patients with COVID-19	Rate of ETO	Humidification device used	AH (mgH_2O/L) according to the manufacturer (ISO)	AH (mgH_2O/L) measured with psychrometric method
Lavoie-Bérard et al. [23]	6 HME 14 HH	HME: 0 (0%) HH: 3 (21%)	HME[a] HH (MR 850)	Hygrobac S: 33.6	Hygrobac S: 28.9 ± 1.1 MR 850 (normal AT): 35.2 ± 1.8 MR 850 (high AT): 23.4 ± 2.4
Wiles et al. [24]	187	12 (6.4%)	HME (7 ETO)[b] HH (4 ETO)	Medline: 31.0 SunMed: 33.4	Medline: 25.1 ± 0.6 SunMed: 25.4 ± 0.4
Rubano et al. [25]	110	28 (25%)	?	NA	NA
Perez Acosta et al. [22]	22	16 (72%)	?	NA	NA
Panchamian et al. [115]	48	14 (29%)	HME[c] (anesthesia machines)	Aero-pro (not reported) AirLife Edith 1000: 30.0	Aero-pro: NA AirLife Edith 1000: NA
Zaidi and Narasimhan [26]	?	"Frequent ETO"	HH turned off	NA	MR 850 off: 7.8 ± 0.2
Bottirolli et al. [27]	17	3 (18%), 1 death	HME (anesthesia machines)	NA	NA
Sugimoto et al. [116]	Case report	1	HME[d]	Inter-Therm: 32.3	Inter-Therm: 26.9 ± 0.6
Van Boven et al. [117]	Case reports	2	HME[e]	Hydro-guard: 23.0	NA

[a] DAR™ Adult – pediatric electrostatic filter HME (small) (previously Hygrobac S)
[b] Sunmed FH603008 and the Medline DYNJAAHME1B
[c] Aero-Pro™ HEPA Light Machine and AirLife® Edith 1000
[d] Inter-Therm, Intersurgical
[e] Hydro-Guard, Intersurgical
ETO Endotracheal Tube Occlusion, *HME* Heat and Moisture Exchanger, *HH* Heated Humidifier, *AH* Absolute Humidity, *AT* Ambient Temperature

manufacturers' market devices that provide minimal humidity to intubated patients has been called into question. Indeed, this method and standard failed to detect poor-performing HMEs that were responsible for ETO [28]. All HMEs responsible for ETO during the pandemic passed the ISO 9360 test (mean ± SD delivered absolute humidity with ISO = 32.2 ± 1.2 mgH_2O/L), while they all performed very poorly on the hygrometric test bench (mean ± SD delivered absolute humidity with

psychrometric method to evaluate humidity = 25.8 ± 1.0 mgH_2O/L).The main message is the heterogeneity of the performances of the HME on the market and that the data provided by the manufacturers may not be helpful in choosing the right device based on the current ISO standards [9].

10.2.5.2 Impact of External Conditions on HME's Hygrometric Performances

HMEs are more stable and less influenced by environmental conditions but may be influenced by patient's core temperature. We studied the impact of ambient temperature on HME and showed that high ambient temperature did not affect HME performances [69]. Croci et al. showed with hydrophobic HMEs that low ambient temperature (20 °C vs. 26 °C) slightly reduces their efficiency (21 vs. 23 mgH_2O/L) [70].

HME's performances may be significantly influenced by the patient's core temperature. Indeed, with these devices, the quantity of water delivered to the patient during inspiration is highly dependent on the amount of water present in the exhaled gas (Fig. 10.4). In patients with induced hypothermia to 32 °C [71], the expiratory water content is about 27 mgH_2O/L, while it is about 35 mgH_2O/L in patients with a normal core temperature [71, 72]. Therefore, even best-performing HMEs can

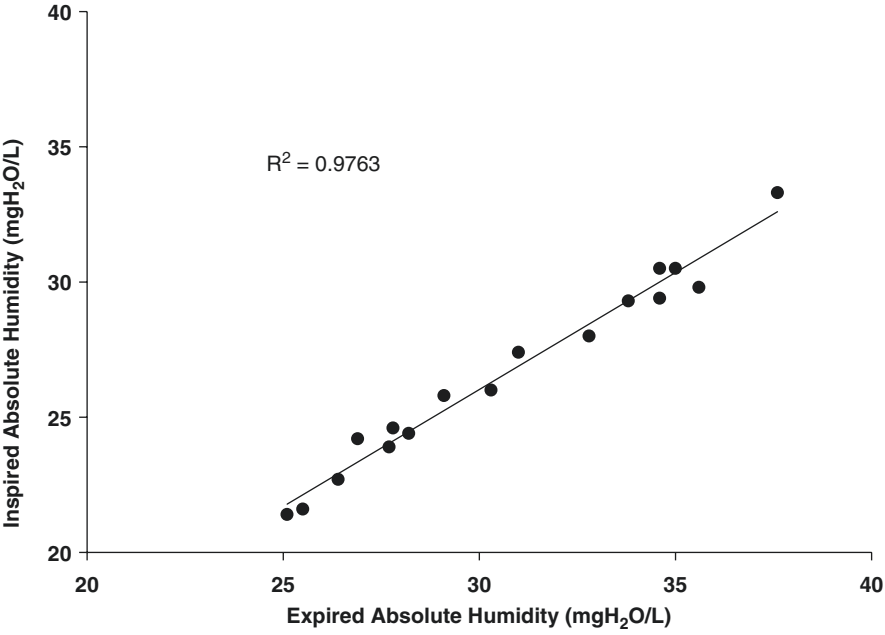

Fig. 10.4 Correlation between inspired and expired absolute humidity of the gas (expressed in mgH_2O/L) with heat and moisture exchangers. A strong correlation exists between inspired and expired gas hygrometry with heat and moisture exchangers. With the high-performing heat and moisture exchangers used in this study, the rate of inspired humidity corresponded to 87% of expired humidity [71]

only deliver inspiratory gases with water content around 25 mgH_2O/L during hypothermia. In this situation, even heated humidifiers provided non-optimal levels, and the moisture target is uncertain during hypothermia.

HME's performances can be reduced in case of high minute ventilation [73, 74]. This has been described with hydrophobic HMEs, but most recent hydrophobic and hygroscopic HMEs do not seem to be influenced by the level of minute ventilation [69].

10.2.5.3 Other Parameters to Evaluate Airway Humidification Impact

Furthermore, we must wonder about the value of this clinical parameter, that is, the occlusion of endotracheal tube, used in most studies. This parameter is easy to detect, but it represents only the easily visible part of the problem. Studies using other parameters are difficult to interpret because they compare humidification systems with close performances and few provide humidification measurements to better understand what is effectively compared. Studies from Hurni et al. [37] and Nakagawa et al. [75] used original techniques (cytology of bronchial cells in one case and rheological properties of secretions in another) and compared HME with first-generation heated humidifiers. But the performances of these systems are very similar (probably within 5 mgH_2O/L), which does not allow demonstrating significant difference. Moreover, the study of Jaber et al. [42] using the acoustic method to evaluate the resistance of endotracheal tube with HME and HH (with heated wire) did not provide humidity data. Again, this makes it difficult to interpret these results, especially as humidifiers used in this study had no compensation system and that their humidification performances are highly variable [11]. To note, during the same time, a study showed a non-significant increased risk of endotracheal tube occlusion with heated wire heated humidifiers compared to HME (2.7% vs. 0.5%, $P = 0.12$) [38]. In these studies comparing the HME to HH and more generally in the literature, there is an implicit starting premise that HH outperform HME. We have shown that it cannot be used as a given, especially with humidifiers with heated wire [76].

Another issue with HMEs is their obstruction or occlusion with plugged secretions. In the study by Ricard et al. with HME elevated above the endotracheal tube to limit the passage of secretions in the device, this risk was 10% despite a period of prolonged use of HMEs up to 7 days [77]. Replacement of HMEs secondary to obstruction was 15% in the study of Kollef et al. [46]; again HME could be used up to 7 days. In the study by Davis et al. where there were no specific precautions, the frequency of partial occlusion was 3% when the HMEs were changed every 24 h and 9% when the HMEs were changed every 5 days [78]. In the same study, resistances of 12 partially occluded HMEs were measured [78]. The devices' resistances increased from a mean of 1.1 before use to 2.8 cmH_2O/L/s. The highest resistance involved two cases of partial occlusion by hemorrhagic secretions where the resistance went from 0.85 before use to 5.8 cmH_2O/L/s. This increase in resistance of the HME or of the endotracheal tube associated with inadequate humidification or thick secretions may delay weaning patients and remains a real problem.

10.2.5.4 Active HME

The place of active HME is probably very limited. This type of device was first described in 1992 by Kapadia et al. [79] The Booster™ is positioned between the HME and the patient. A metal part is covered with a membrane that allows to heat external water. The membrane made of Gore-Tex™ allows the production of water vapor. This system can be used with any HME in order to improve their performance [80]. Another system, the Humid-Heat™, is based on a similar principle, with a heated humidifier piece surrounding a specific HME, also with a supply of extra water [81]. A third "active" HME has been described, the "performer," running on the same principle [82]. The latter was evaluated with the psychrometric method in the study conducted by Chiumello et al., which allows a comparison with our results. The system delivered inspiratory gases with a water content from 3 to 5 mgH_2O/L above HME with good performance [69, 82]. The active HME tested had higher humidification performances in comparison with effective HMEs: a gain of approximately 3 mgH_2O/L with Booster™ and about 5 mgH_2O/L with the Humid-Heat™ under standard conditions of use. However, the clinical benefit to increase humidity from 30 to 35 mgH_2O/L is not clear in the literature. In comparison with best-performing HMEs, the potential benefits of a few extra mgH_2O/L versus added complexity and cost without removing dead space make the use of active ECH questionable.

10.3 Mechanical Proprieties of Humidification Systems (Resistances and Dead Space)

In addition to the humidification properties, mechanical aspects of HME and HH (especially resistance and dead space) must be taken into consideration in specific clinical situations. There is significant heterogeneity of the dead space and resistance among humidification devices [9, 47, 83–85]. The dead space more than the resistance between HME and HH should be considered. Indeed, humidification systems' resistances are fairly similar [86]. The HH circuit's resistance is not negligible, especially if the heated wire is in the circuit. Resistance is probably less if the heated wire is integrated into the wall. Several studies showed that during assisted ventilation, HME increased the work of breathing and the minute ventilation and decreased alveolar ventilation in comparison with HH [87–92]. During controlled ventilation, HMEs decrease the alveolar ventilation in comparison with HH [92–98]. In patients with ARDS, it is possible to obtain the same alveolar ventilation with lower tidal volumes when using heated humidifiers due to the reduction of the instrumental dead space. In Moran study, when replacing the HME by a heated humidifier, with the same alveolar ventilation target, it was possible to reduce the tidal volume from 521 ± 106 to 440 ± 118 ml ($p < 0.001$) without significant changes in $PaCO_2$, and plateau airway pressure decreased from 25 ± 6 to 21 ± 6 cmH_2O ($p < 0.001$) [94]. Similar data were shown in Pitoni study in ARDS patients with brain injury [98].

The use of a heated humidifier in order to reduce dead space has a real impact mainly in patients in whom a ventilator strategy including "permissive

hypercapnia" is required (especially in cases of ARDS or severe asthma). This is especially true during ARDS, as the high respiratory rate increases the dead space effect [12, 99, 100]. During a spontaneous breathing trial, performed with minimal pressure support levels, the interpretation of the breathing pattern should take into account the humidification system used [87, 101]. To compensate for the HME's dead space, the minimum level of pressure support should be increased by about 5 to 8 cmH_2O in comparison with a spontaneous breathing trial conducted in pressure support with a heated humidifier [87, 89, 91].

10.4 Comparison of Humidification Devices' Cost

Several studies have compared the costs of different humidification systems [32, 35–37, 41, 46, 77, 102–104]. The comprehensive studies are difficult to perform and should take into account the following:

1. The costs of devices and circuits.
2. The human costs: time to set up heated humidifiers, time to change HMEs, and time to empty the water traps (when heated wires are not used).
3. The miscellaneous costs: cleaning, storage, and maintenance of humidifiers, water used in humidifiers, water traps, etc.

Not surprisingly, most evaluations have shown that the costs associated with heated humidifiers are much larger compared with the HME. Branson et al. compared HME with heated humidifiers with and without heated wire [104]. In this study, the use of heated humidification without heated circuit caused a heavy workload in relation to water trap emptying (on average nine times per 24 h), a procedure whose duration was estimated to 5 min. Therefore, 45 min per day was spent to empty water traps with this system. The cost of using heated humidifiers (with or without heated wire) was much larger than the HMEs in this study (Table 10.3). Moreover, during this study, HMEs were changed every 24 h. With less frequent changes (every 2 to 3 days and up to 7 days), the daily costs of these devices are even lower [43, 77, 78, 102, 103].

The duration of ventilator circuit use was 24 h in the study of Craven who challenged this practice [56]. Other studies followed and showed that the spacing change and even the lack of change for the same patient resulted in a reduction of costs and especially the rate of ventilator-acquired pneumonia [105–109], which went against the generally accepted idea. The question of duration of use of HMEs follows the same path, but there is still a fear of prolonged use of these devices based on the

Table 10.3 Daily cost for different humidification devices (in US dollars (from reference 104))

Humidification device	Day 1	Day 2	Day 3	Day 4	Day 5
HME	5.2	4.6	4.5	4.4	4.7
HH with heated wire	30.2	16.1	12.6	9.9	9.0
HH without heated wire	27.8	21.7	19.6	18.6	18.0

HH heated humidifiers, *HME* heat and moisture exchangers

risks of poorer humidification performance and of increased resistance of the HMEs. Most manufacturers recommend changing these devices every 24 h. Yet many studies have argued for lifetimes greater than 24 h [40, 43, 46, 68, 77, 78, 102, 103, 110, 111] and up to 7 days [43, 46, 77]. With prolonged use, humidification performances do not change a lot with the most efficient HMEs, with the exception of the results in Ricard et al. study that showed in 3 COPD patients over 10 included, a reduction over time of HME's effectiveness with absolute humidity below 27 mgH_2O/L (with a minimum of 24.9 mgH_2O/L in a patient on day 5) after several days of use [77]. However, among 23 other patients without COPD included and the majority of COPD patients, the values of absolute humidity measured daily remained stable during the 7 days of use. Similarly, no endotracheal tube occlusion has occurred with this practice. In this same study, the resistances of the devices were not significantly changed after use [77].

In addition to the maximum duration of a single HME, the issue of the maximum duration of use of this humidification system in patients with prolonged ventilation has been raised. Branson et al. have proposed an algorithm which limited the use of HME to a maximum of 5 days [41, 112], replacing them with a heated humidifier after this period. There is no clear data now to limit the duration of HME use. Numerous studies have demonstrated that prolonged use of HME did not result in any particular risk for patients [36, 38, 113]. Especially in the study conducted by Lacherade et al., who compared HME and HH on the rate of ventilator-acquired pneumonia, the duration of use was 2 weeks on average in the HME group ($n = 185$) without specific problems being noted [38]. The rate of ventilator-acquired pneumonia (28.8% vs. 25.4%, $P = 0.48$), the duration of mechanical ventilation (14.9 ± 15.1 vs. 13.5 ± 16.3, $P = 0.36$), and the mortality (34.2% vs. 32.8%, NS) were similar. A trend for more endotracheal tube occlusion was noted in the heated humidifier group in comparison with HME group (6 vs. 1, $P = 0.12$).

10.5 Conclusion (Table 10.4 and Fig. 10.5)

Humidification of the gases delivered to the patients while upper airways are bypassed is mandatory *at all times* in intubated patients to avoid severe complications related to under-humidification, from mucus thickening to deadly endotracheal tube occlusions.

Table 10.4 Advantage and drawbacks for different humidification devices

Humidification device	Humidification performances	Circuit condensation (I/E)	Dead space	Resistance	Cost
Passive HME	– to ++	0/0	+ to +++	+	–
Active HME	++	0/0	++	+	+
Heated humidifier	– to +++	0 to ++/0 to +	0	0[a] to +	+
This system still does not exist	+++	0/0	0	0	–

[a] If heated wire are within the circuit wall
HME heat and moisture exchangers

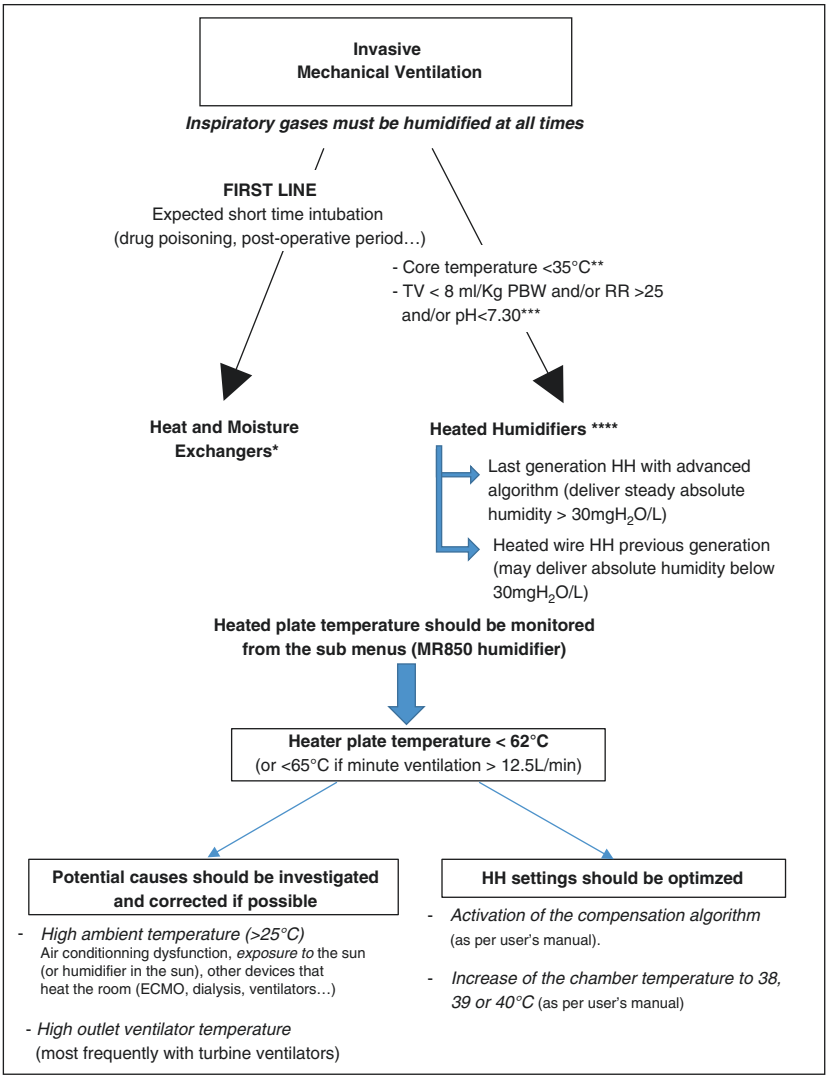

Fig. 10.5 Recommendations for humidification management during invasive mechanical ventilation. *Using a HME delivering at least 28 mgH_2O/L based on independent evaluation [9]. **The other contraindications of HME are the presence of bronchopleural fistula, hemoptysis/bloody secretions, or intoxication with substances with respiratory elimination. ***In the event of threatening hypercapnic or mixed acidosis with pH < 7.30 and when there is a risk of auto-PEEP limiting the increase in respiratory rate. When the minute ventilation before intubation was high (measured or estimated). ****Situations at risk of malfunction with heated humidifiers with heating wire should be avoided (using them in high ambient temperatures, humidifiers being directly exposed to the sun, utilization of turbine ventilators with high outlet temperature). Monitoring where possible of the HH heater plate's temperature (if heater plate temperature > 62 °C for the MR 850, the absolute humidity is probably adequate). Heater Plate Monitoring Video: (126) Monitoring of MR 850 humidification performances with heater plate temperature - YouTube. **Optimization of HH settings video:** (126) How to increase outlet chamber temperature on MR850 to improve humidity delivery - YouTube. *HH* Heated Humidifier, *TV* Tidal Volume, *RR* Respiratory Rate, *PBW* Predicted Body Weight

The choice of a humidification system during mechanical ventilation should take into account the humidification performance, of course, but also the mechanical properties and finally the cost of the device. For the majority of the patients, a good-performing HME can be used when mechanical ventilation is initiated. Clinicians should be aware of the wide heterogeneity in humidification performance among available devices and the inability to detect underperforming HMEs with current ISO standards. For specific situations, when instrumental dead space reduction is considered, especially when lung-protective ventilation is implemented with low tidal volumes and high respiratory rates [12], utilization of heated humidifiers is a better choice. Clinicians have to be aware of the impact of external conditions and especially ambient or outlet ventilator temperature (heated humidifiers) or patient core temperature (heat and moisture exchangers) on the humidification device performances.

Heated humidifiers with heated wire have very reduced performance if the inlet temperature of the humidification chamber is high, which can happen when the ambient temperature is high (absence of air conditioning or humidifier "in the sun") or when the outlet temperature of ventilator is high (using turbine ventilators). This issue is partially improved with compensation algorithm and with specific technologies (counter-flow humidifiers), but these systems are not available in all countries. The monitoring of the heater plate temperature with MR 850 may help clinicians to ensure adequate humidity is delivered to patients [60]. With last generation of heated humidifiers, humidity delivered seems steady around 35–40 mgH_2O/L or slightly above, and the question of the over-humidification is raised, and clinicians must be aware of this potential risk, which did not exist with previous systems [114].

The performances of *humidifiers without heated wire* are influenced by the settings as expected but are much less influenced by external conditions. Recommended settings with those humidifiers (Y-piece temperature around 30 to 32 °C) deliver gas around 30 mgH_2O/L or slightly above.

Heat and moisture exchangers have very heterogeneous humidification performances, and only a few reach 30 mgH_2O/L. Systems with similar external appearance can have very different humidification performances, which may be responsible for potentially serious confusion. The HME performance is mainly influenced by the expiratory humidity which is mainly related to patient's core temperature. In hypothermic patient whose water content of the expiratory gas is lower than the normothermic patients, HMEs have poor performance. However, there is a lack of clinical data for short-term periods of hypothermia (as for therapeutic hypothermia after cardiac arrest that is usually used for 24 h). The additional instrumental dead space with HME causes a reduction in alveolar ventilation. This may have an impact particularly in patients with protective ventilatory strategy (low tidal volume and high respiratory rate). In these cases, heated humidifiers should be used instead of HMEs. Also, HME can increase the work of breathing during assisted ventilation, which may be an issue for severe COPD patients, and the minimal level of pressure support used for spontaneous breathing trials should be 10 to 12 rather than 5 to 7 cmH_2O if a HME is used.

There is not much argument for using an active HME when effective HMEs exist, and the added complexity of these devices may not be worth it.

Independent data on humidification systems' performance should be known by the users [9, 50]. In addition, the other characteristics that differentiate HMEs and heated humidifiers (mainly resistance, dead space, and costs) must be known by the clinician to choose the optimal humidification system for the patients on mechanical ventilation.

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