Long-term Effects of Different Humidification Systems on Endotracheal Tube Patency

Evaluation by the Acoustic Reflection Method

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Background: **Accumulation of mucous secretions in an endotracheal tube (ETT) increases its resistance, and the amount of deposit may be affected by the quality of humidification and heating of the inspired gas.**

Methods: **The authors assessed the impact of two humidification systems, a heated humidifier (HH) and a hygroscopic–hydrophobic heat and moisture exchanger (HME), on the ETT patency in patients selected to require mechanical ventilation for more than 48 h. This comparison was performed over two consecutive periods and used the acoustic reflection method, which characterizes the amount and site of ETT obstruction and allows estimating ETT inner volume and resistance. Measurements were performed three times a week over the period of mechanical ventilation. Comparisons were performed at mid duration and at the end of the mechanical ventilation period.**

Results: **The HH was used in 34 patients, and the HME was used in 26 patients. The two groups had similar severity and duration of mechanical ventilation. At mid duration of mechanical ventilation (5.5 ± 3.3 *vs.* 4.8 ± 3.3 days; *P* = 0.4), no difference was observed in ETT volume and resistance between the two groups. At the end of the study period (10.5 ± 5.8 *vs.* 9.6 ± 6.3 days of mechanical ventilation; *P* = 0.4), ETT volume was reduced to a greater extent with HME than with HH (−3.3 ± 2.9 *vs.* −5.1 ± 2.5%; *P* = 0.008), and ETT resistance increased significantly more with the HME than with the HH (8.4 ± 12.2 *vs.* 19.4 ± 17.7%; *P* = 0.001).**

Conclusion: **Prolonged use of humidification systems results in progressive reduction of ETT patency, and to a greater extent with HMEs than with HHs.**

IN mechanically ventilated patients with an endotracheal tube (ETT) in place, the nose and upper airway functions are bypassed.[1,2] An inadequate conditioning of respiratory gases can induce structural and functional damages of the tracheobronchial system[3–5] and can lead to reduction in ETT patency and partial obstruction.[6–9] Partial obstruction may facilitate a sudden occlusion of the tube[6–9] and may increase the load imposed on the respiratory muscles.[10] The level of humidity and temperature required by intubated and mechanically ventilated patients has been a matter of debate. It has been suggested[5] that for optimal humidification, inspired gas should be conditioned to body temperature and saturated with water vapor (*i.e.*, 37°C, 100% relative humidity or 44 mg H_2O/l). Two systems are commonly used to humidify and warm inspired gases: heated humidifiers (HHs) and heat and moisture exchangers (HMEs), also called "artificial noses."

Several studies have compared the ability of the two devices to adequately humidify and warm inspired gases,[6,7,11–13] but they used only indirect parameters, such as ventilator peak pressure with a poor diagnostic accuracy, or only studied short-term effects, which may be insufficient to reveal differences. In addition, the latest generation of hygroscopic HMEs offers better performance in terms of adequate gas conditioning than the initially proposed hydrophobic HME.[14,15]

In a previous study, our group has shown that permanent secretion deposits on the inner wall of the ETT were directly influenced by the quality of gas conditioning.[9] ETT patency was therefore used as a relatively specific index indirectly reflecting the quality of heating and humidification of inspired gas in mechanically ventilated patients[9] and its influence on the quality of secretions. In this previous study,[9] the overall reduction in mean diameter was significantly greater with a hydrophobic HME than with a hygroscopic HME or an HH, with no difference between these two. The duration of the study, however, was less than a week in this trial.[9] Because it has been suggested that time may be an important factor before observing any consequence of inadequate humidification on secretions, we wondered whether a longer period (> 7 days) of intubation might allow identification of a difference between a hydrophobic–hygroscopic HME and an HH.

The aim of this study was to assess the impact of two humidification systems (a hygroscopic–hydrophobic HME *vs.* an HH set at 40°C at the Y piece) on *in vivo* ETT patency during long-term (> 7 days) mechanical ventilation (MV). This evaluation was performed with the noninvasive acoustic reflection method, also called *acoustic reflectometry*, which can be used to estimate the site and the extent of an ETT obstruction *in situ*.[16–19]

Materials and Methods

Patients

All patients who stayed in the hospital over a 10-month period in the Medical Intensive Care Unit of Henri Mon-

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dor Hospital (Créteil, France) and who required continuous MV for more than 48 h were included. Patients likely to die within the next 48 h, with hemorrhagic disorders, and those in whom the trachea was intubated for more than 24 h before arrival were not included.

The experimental protocol was approved by the ethics committee of the French Society of Intensive Care Medicine. The requirement for informed consent was waived because this observational study was performed as part of our routine clinical practice.

Study Design

Two consecutive periods of 5 months, with two distinct types of humidification, were compared. During the first period of the study, which lasted from August 26, 1998, to January 27, 1999, all the patients were ventilated with an HH (MR730 Respiratory Humidifier; Fisher & Paykel Healthcare, Auckland, New Zealand) with a dual heated-wire circuit. The setting permitted gas to be delivered at a temperature of 40°C at the Y piece and at 37°C in the humidification chamber. During the second period, which lasted from March 8 to August 2, 1999, all the patients were ventilated with a hygroscopic–hydrophobic HME (DAR SpA, Mirandola, Italy). HMEs were replaced every 48 h as recommended.[20]

During the two periods, the inner volume of the ETT and the resistance to inspiratory flow were measured three times a week (Monday, Wednesday, and Friday). The measurements were performed until the first extubation or the death of the patient. Tracheal suctioning was performed before each series of measurements.

Measurements of Inner Volume and Resistance

The ETT area profile, A{x}, was inferred by the two-microphone acoustic reflection method as previously described.[16–19,21,22] Briefly, the device used consisted of two microphones (piezoresistive pressure transducers 8510-B; Endevco France, Le Pré Saint-Gervais, France) and a horn driver mounted on a wave tube (overall length, 22 cm; ID, 0.35 cm) connected to the ETT connector. The other end of the wave tube was open to the atmosphere, allowing the subject to breathe spontaneously. A pressure wave is generated by the horn driver. The resulting pressure in the wave tube is recorded *via* the microphones in a microcomputer to infer A{x} with a spatial increment, ΔL, of approximately 0.4 cm. This setup is derived from a two-microphone device furnished by Benson Hood Laboratories (Pembroke, MA) with a homemade wave tube (ID, 8 mm). The area was inferred using a deconvolution algorithm in the frequency domain. Such a setup was shown to be able to measure the area of a 50-cm-long ETT.[19] The measurement procedure consists of connecting the wave tube, recording the pressure, and unconnecting the wave tube and takes less than 45 s. The ETT inner volume, Vol, is estimated by integrating the inner area along the longitudinal axis:

$$\mathrm{Vol} = \sum_{n=1}^{n=L/\Delta L} A\{x = n\Delta L\} \cdot \Delta L,$$

where L is the ETT length. The resistance of the ETT is estimated by using the Blasius formula along the ETT, as previously published.[21]

$$R_{ETT} = \sum_{n=1}^{n=L/\Delta L} 0.24 \cdot \mu^{0.25} \cdot \rho^{0.75} \cdot \Delta L \cdot \left(\frac{4 \cdot A\{x = n\Delta L\}}{\pi}\right)^{-2.375} \cdot \dot{V}^{0.75}$$

where L is the ETT length, μ is the viscosity, ρ is the density, and $\dot{V}$ is the inspiratory flow.

Statistical Analysis

Results were expressed as mean ± SD or as the number of patients affected. Because the duration of ventilation and the number of measurements varied among patients, we considered for each patient the mid duration of MV and the total duration of MV period studied (defined by the period from the first day of MV to the last), for comparison of the reduction in ETT volume and the increase in ETT resistance. ETT volume and resistance were expressed as a percentage of the *in vitro* value obtained with a clean tube. We used the value obtained with a clean tube because in several patients the first value did not coincide with the first day of MV. To ensure that the individual differences in duration of the study period did not affect the results, we also calculated the mean daily reduction in ETT volume as the ratio of the total reduction to the number of days of the study period. Comparisons between groups (HH *vs.* HME) were performed using the Mann–Whitney U test for continuous variables and the chi-square test with Yates correction when appropriate for categorical variables. A *P* value below 0.05 was considered the limit of significance.

Results

Study Population

Forty-eight patients were initially enrolled during the first period (HH), and 34 were enrolled during the second period (HME). Fourteen patients in the HH group and 8 in the HME group were ventilated for less than 48 h (7 HH group and 4 HME group patients died, and 7 and 4, respectively, were extubated). Therefore, 34 patients in the HH group and 26 patients in the HME group were considered for the evaluation.

The two groups did not differ in terms of demographics, the presence of chronic obstructive pulmonary dis-

Table 1. Characteristics of the Patients

	Group 1 (HH) (n = 34)	Group 2 (HME) (n = 26)	*P* Value
On admission			
Age, yr	62 ± 14	64 ± 15	0.55
Sex (M/F), n	25/9	16/10	0.48
SAPS II	57 ± 15	54 ± 20	0.57
Minute ventilation, l/min	12.1 ± 3.3	12.0 ± 2.9	0.82
F_{IO_2}, %	54 ± 14	47 ± 16	0.11
Indication for MV, n (%)			
Chronic airway obstruction	6 (18)	4 (15)	>0.99
Other pulmonary disorders	11 (32)	9 (35)	>0.99
Postoperative respiratory failure	9 (26)	7 (27)	>0.99
Drug overdose	3 (9)	2 (8)	>0.99
Stroke	3 (9)	2 (8)	>0.99
Miscellaneous	2 (6)	2 (8)	>0.99
Overall duration of MV, during the study days	13.0 ± 6.9	11.0 ± 7.7	0.29

F_{IO_2} = fraction of inspired oxygen; HH = heated humidifier; HME = heat and moisture exchanger; MV = mechanical ventilation; SAPS = Simplified Acute Physiology Score.

ease, markers of the severity of illness, mean fractional concentration of oxygen, and minute ventilation averaged throughout the study (table 1). Also, there was no significant difference between the HH and HME groups for half the duration (5.5 ± 3.3 *vs.* 4.8 ± 3.3 days; *P* = 0.40) or the total duration (10.5 ± 5.8 *vs.* 9.6 ± 6.3 days; *P* = 0.42) of the study period. All patients were orotracheally intubated with HI-LO tubes (Mallinckrodt Medical, Athlone, Saint-Louis, Ireland). ETT diameters ranged from 7.0 to 9.0 mm. Between the two groups, the average ETT diameter did not significantly differ (8.0 ± 0.3 *vs.* 7.9 ± 0.3; *P* = 0.55), nor did the value obtained with a clean tube *in vitro* for ETT volume (14.0 ± 1.8 *vs.* 13.9 ± 1.8 ml; *P* = 0.79) or ETT resistance (2.6 ± 0.6 *vs.* 2.8 ± 0.6 cm $H_2O \cdot l^{-1} \cdot s^{-1}$; *P* = 0.42).

Clinical Events

Three patients experienced substantial ETT obstruction (two using the Fisher & Paykel humidifier and one using a DAR HME). Two patients, one in each group, needed emergency reintubation, and in one patient (No. 25) in the HH group, extubation and reintubation was decided because the acoustic method had shown a 10.3% ETT volume reduction and a 30.5% increase in Blasius resistance. Serial measurements obtained from this patient with the acoustic method during the course of MV are presented in figure 1. The incidence of obstruction expressed per day of MV was 2 in 441 for HH and 1 in 285 for HME. For those three patients, only the first episode of MV was used in the analysis.

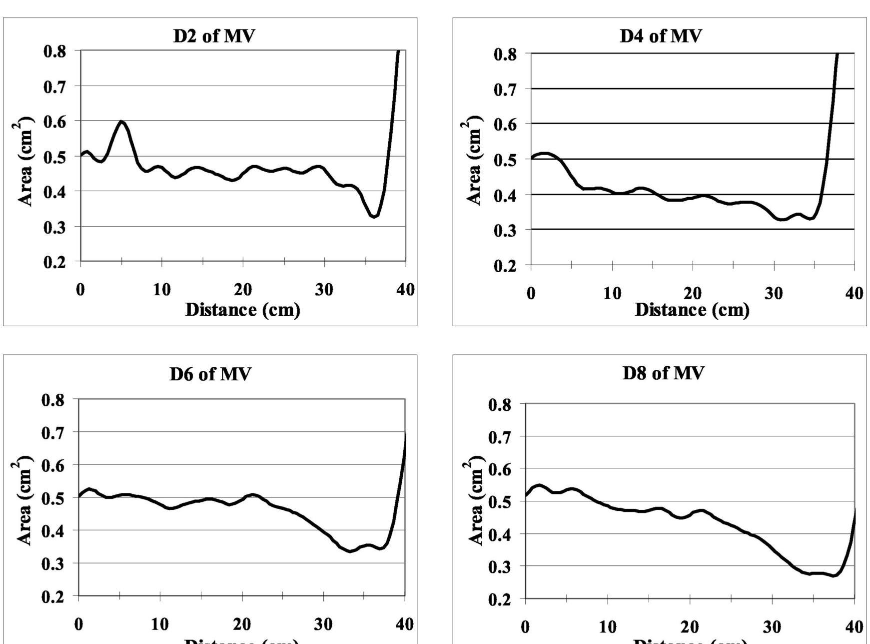

Fig. 1. Longitudinal area profile measured with the acoustic method in patient 25. The area is plotted in square centimeters on the vertical axis *versus* the longitudinal distance plotted in centimeters on the horizontal axis. Measurements were performed on days 2, 4, 6, and 8 of mechanical ventilation (MV). A gradual reduction of endotracheal tube diameter was observed during MV.

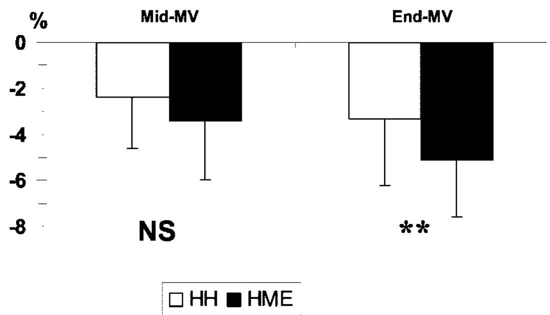

Fig. 2. Reduction in endotracheal tube (ETT) volume. Relative variations in the volume of the ETT, shown as mean ± SD. Comparisons between the two groups (heated humidifier [HH] *vs.* heat and moisture exchanger [HME]) were performed three times a week during the course of mechanical ventilation (MV). The mean volume reduction was significantly greater with the HME than with the HH. * $P < 0.05$. ** $P < 0.01$. NS = not significant.

ETT Volume and ETT Blasius Resistance Variations

At mid duration of the study period of MV, no statistical difference was observed in volume reduction between the two devices. At the end of the study period, the mean reduction in ETT volume was significantly greater in the HME group than in the HH group (−5.1 ± 2.5 *vs.* −3.3 ± 2.9%; $P = 0.008$; fig. 2). Expressed as a mean daily reduction in ETT volume, the difference was also significant (−0.4 ± 0.3 *vs.* −0.8 ± 0.8%/day; $P = 0.008$).

Similar results were observed in the progressive increase of the ETT Blasius resistance during MV. No significant difference was observed between the two groups at mid duration of MV. At the end of the study period, the mean increase in ETT Blasius resistance was significantly greater in the HME group than in the HH group (8.4 ± 12.2 *vs.* 19.4 ± 17.7%; $P = 0.001$; fig. 3). When expressed as the mean daily increase in ETT resistance, it was also significant (1.0 ± 1.4 *vs.* 3.2 ± 3.7%/day; $P = 0.002$).

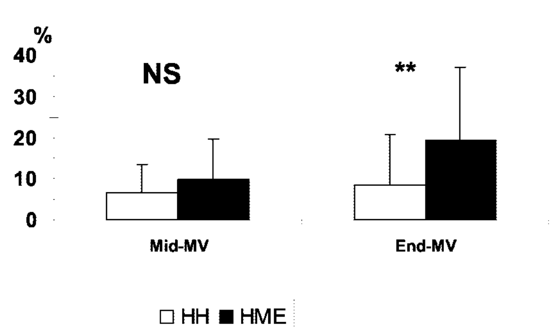

Fig. 3. Increase in endotracheal tube (ETT) Blasius resistance. Relative variations in the Blasius ETT resistance, shown as mean ± SD. Comparisons between the two groups (heated humidifier [HH] *vs.* heat and moisture exchanger [HME]) were performed three times a week during the course of mechanical ventilation (MV). *Numbers in brackets* are the numbers of patients in each group included for the analysis. Beginning at D6, the mean resistance increase was significantly greater with the HME than with the HH. * $P < 0.05$. NS = not significant.

Discussion

The main finding of this study is that during long-term MV, *i.e.*, after more than 4 or 5 days, the type of humidification system used may significantly modify the ETT patency. Accordingly, we observed after 9 or 10 days of MV a significantly greater reduction in ETT volume and a greater increase in Blasius resistance with the HME than with the HH.

These results confirm that permanent deposits of bronchial secretions on the inner wall of the ETT can gradually obstruct the lumen of the ETT. This deposit was less pronounced with the HH than with the HME. The HH system is an active device during all phases of the respiratory cycle and can deliver heated humidity to the airway. By contrast, the HME device is a passive device that keeps humidity and heat in the airway. Mucociliary transport can be altered by changes in ciliary function or physical properties of the mucus, which depend in part of the gas conditioning in mechanically ventilated patients. Konrad *et al.*[23] showed that mucociliary transport can be altered after 3 days of MV in intubated patients and suggested that several weeks of MV of patients with severe respiratory insufficiency would have more pronounced effect on ultrastructural changes. Recently, Nakagawa *et al.*[24] reported in a randomized controlled trial that the type of humidification device influenced mucociliary transport by cough. In this study, the authors[24] studied the transportability by cough *in vitro* and found that it was diminished after 72 h of MV in the HME group. These data[23,24] support the fact that the impact of the humidification device on the mucosal structure and function can exist and may need several days of MV to be detected.[5]

Endotracheal tube patency was evaluated because its status can be influenced by progressive deposit of secretions, the quality of which is influenced by gas conditioning. ETT patency thus indirectly reflects the quality of gas conditioning in the patient airways. Several studies presented in table 2 have already shown the presence of partial obstruction of the ETT after few days of MV.[9,16,21,25–29]

Villafane *et al.*,[9] reported that during prolonged MV (after 6 ± 3 days of MV), the patency of artificial airways can be affected by the type of airway humidification. In this study,[9] the overall reduction in ETT mean diameter evaluated by the hydraulic method was significantly greater with a hydrophobic HME than with an HH (−6.5 *vs.* −1.5%; $P < 0.01$). Contrary to the current study, in the study of Villafane *et al.*,[9] no significant difference was observed in the overall reduction in ETT mean diameter between a hygroscopic HME and the HH (−2.5 *vs.* −1.5%; not significant). We hypothesize that the reason for such a discrepancy between the two studies is the mean duration of MV. The current study looked at prolonged periods of MV (10 ± 6 days), greater than in

Table 2. ETT Obstruction in Mechanically Ventilated Patients Observed by Different Investigators

Author	Year	Number of Patients	Duration of MV	Humidification Device	Estimated ETT Obstruction	Methods Used to Estimate the ETT Obstruction
Wright *et al.*[25]	1989	10	NG	NG	NG	*In vitro* and *in vivo* measurements of ETT airflow resistance
Lofaso *et al.*[26]	1992	8	2 weeks	NG	12 ± 3%	Hydraulic method and pressure–flow relation (Blasius)
Van Surell *et al.*[16]	1994	10	12 h to 25 days	NG	13 ± 10% (2–36%)	Hydraulic method and acoustic reflection method
Heyer *et al.*[21]	1996	5	11 ± 11	NG	5–10%	Acoustic reflection method
Villafane *et al.*[9]	1996	8	6 ± 3	Hydrophobic HME	6.5 ± 4.0%	Hydraulic method with pressure–flow relation
		8	6 ± 3	Hygroscopic HME	2.5 ± 2.5%	
		7	6 ± 2	HH	1.5 ± 3.0%	
Guttmann *et al.*[27]	1998	10	NG	NG	NG	Computer-assisted method with measurement of expiratory flow
Rumbak *et al.*[28]	1999	37	21 days (2–4 weeks)	NG	NG	Bronchoscopy
Diehl *et al.*[29]	1999	8	31 ± 19	NG	Resistive WOB increased by 28% compared with a new ETT	*In vitro* measurements of ETT airflow resistance

ETT = endotracheal tube; HH = heated humidifier; HME = heat and moisture exchanger; MV = mechanical ventilation; NG = not given; WOB = work of breathing.

the study of Villafane *et al.*[9] (6 ± 3 days). Indeed, in the current study, we did not find any difference between the two devices at mid duration of the study period of MV (5 ± 3 days), this duration being quite similar to the total duration of the study of Villafane *et al.*[9] Both studies suggest that there is no substantial difference between the two types of humidification devices used, as long as the patients are mechanically ventilated for a short duration (5 or 6 days).

Diehl *et al.*[29] evaluated the changes in the work of breathing induced by tracheotomy in eight ventilator-dependent patients and compared the characteristics of the removed ETT with those of a new clean ETT. The authors observed significant extra work of breathing induced by the removed ETT, which had been left in place for 31 ± 19 days of MV. There was an increase in resistive work of breathing of 28% over the work measured with a clean new ETT. These studies suggest that the mean diameter or volume of ETT trended downward from day to day, and a marked difference was observed after a long-term period of MV. Progressive reduction in the ETT diameter accompanies permanent mucus deposition. Until the hydraulic[9] and acoustic methods,[16,19] no accurate method was available to monitor its accumulation (table 2). Peak airway pressure, which has frequently been used as an index of gas flow resistance in the ventilated patient, does not allow one to distinguish the contribution of the ETT resistance to the overall resistance and is highly dependent on flow pattern and patient spontaneous activity.[22,25,26]

The current investigation is the first study to directly assess the effects of HME and HH *in vivo* on the patency of the ETT in patients undergoing prolonged MV. The mean values for volume reduction for the period of the study were moderate (< 10%), though in some patients a reduction greater than 15% was observed (n = 1 in the HH group, n = 6 in the HME group; $P = 0.02$). Similarly, an increase in Blasius resistance by more than 30% was observed in several patients (n = 3 in the HH group, n = 7 in the HME group; $P = 0.06$). ETT patency reduction can increase the mechanical load of respiration in ventilated patients and may markedly reduce the efficiency of pressure-targeted modes because part of the ventilatory assistance is used to overcome the resistive load due to the ETT. As shown in a previous study by Heyer *et al.*,[21] a correct estimation of the ETT-related work of breathing may be especially important when patients are weaned from MV. Indeed, the level of pressure support and the tolerance of a T piece trial are among the main predictors used to determine whether tracheal extubation is feasible. Also, the use of an HME increases dead space and adds an elastic load to respiratory work.[10,30–32] HMEs are increasingly employed because they are easy to use, require less manipulation, and may be less expensive than HHs.[14,33] Uncertainties have persisted regarding the efficacy and the potential risks of HMEs. Indeed, tracheal obstruction with the first generation of HMEs exhibiting only hydrophobic properties[6–8] occurred in some studies because of inadequate airway humidification. The low incidence of obstruction expressed per day of MV observed in our study (3 in 726) confirms that this risk is no longer a major concern with the new HMEs. HMEs provide bacterial filtration[34] and minimize circuit contamination. They may need to be changed only every 5 or 7 days,[14,33] without any adverse effects for the patients, which may reduce costs. Our study, however, raises concern about their efficacy over prolonged periods of MV, *i.e.*, more than 4 or 5 days. The heated-wire circuits with the HH eliminate condensation in the circuit and the need for water traps and their maintenance, which has been considered as a major shortcoming of this type of system, but increase their cost. For the HH, the 40°C setting ensures a 37°C gas temperature when the gas reaches the patient because cooling occurs across the 8- to 10-cm flexible catheter mount and the 6 cm of protruding ETT. This follows the recommendation of the manufacturer and is supported by the literature as mimicking normal upper airway function.[5] This study shows that obstruction still exists with HHs, however, and it may be worthwhile to explore the causes of this process.

The current study also indicates that the acoustic reflection method can be performed in routine clinical practice to monitor the ETT patency. In one patient, the acoustic measurement prompted the decision for reintubation, to avoid a risk of emergency obstruction. A similar technique has recently been proposed for checking the ETT placement.[35]

One limitation of this study is its nonrandomized nature. To assess the respective efficacy of the two systems, performing a randomized study design was first considered. However, ventilating patients with the two types of humidification systems in the department at the same time was a source of confusion for the personnel and made the necessary training for HH manipulation more difficult. Therefore, we decided against performing a randomized controlled trial and preferred to study two successive periods. No changes in the policy of MV or in the prevention, diagnosis, or management of nosocomial pneumonia occurred during this period. The only concern could be that two different periods of the year may be associated with different climatic conditions. Although this has not been demonstrated, one could imagine that this may influence the two types of humidification systems. The two periods, however, included a similar duration of cold periods (winter season) and warm periods (summer season). Several recent reports have suggested that such a study design could give results similar to those of randomized controlled trials.[36]

Our results confirm the findings of Villafane *et al.*,[9] who reported that during prolonged MV, the patency of artificial airways can be affected by the type of airway humidification. More importantly, the results of this study suggest that during long-term MV (*i.e.*, around 9 or 10 days), HH should be the technique of choice for adequate humidification. For a short period of MV, HME may be used safely.

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