Gradual Reduction of Endotracheal Tube Diameter during Mechanical Ventilation via Different Humidification Devices

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Background: Limited data suggest that increased resistance to flow within endotracheal tubes (ETT) may occur in patients whose lungs are mechanically ventilated for more than 48 h, especially when airway humidification is inadequate. This could lead to sudden ETT obstruction or induce excessive loading during spontaneous breathing.

Methods: Twenty-three such patients were randomly assigned to three types of airway humidifier based on three different working principles: a Fisher Paykell hot water system (n = 7), a Pall BB2215 heat and moisture exchanger (HME) hydrophobic filter (n = 8), and a Dar Hygrobac 35254111 HME hygroscopic filter (n = 8). The decrease in internal pressure along the ETT and the flow rate were measured in each patient every 2 days. An "effective inner diameter" was derived from these measurements and allowed the inner ETT configuration to be monitored.

Results: On the first day of intubation, the mean diameter was similar in the three groups, and was slightly smaller than the *in vitro* diameter (mean ± SD: 7.6 ± 0.6 mm for Fisher-Paykell, 7.7 ± 0.4 for Pall, and 7.5 ± 0.4 for Dar). The mean diameter tended to decrease from day to day. At the end of the study, the overall reduction in mean diameter was significantly greater with the hydrophobic HME (Pall) than with the two other systems (Pall: −6.5 ± 4% vs. −2.5 ± 2.5% for Dar and −1.5 ± 3% for Fisher-Paykell; P < 0.01 with analysis of variance). The same was true of the mean reduction in effective inner ETT diameter expressed per day of ventilation (−1.6 ± 1.5% per day for Pall vs. −0.5 ± 0.4% for Dar and −0.2 ± 0.4% for Fisher-Paykell; P < 0.01). In four patients, the ETT became obstructed and emergency repeated tracheal intuba-

tion was required. The Pall HME and the Fisher-Paykell system were being used in three and one patient, respectively. Before obstruction, the reduction in ETT diameter was significantly greater for these four patients than for the remaining 23 patients (7.8 ± 1.4% vs. 3.1 ± 4.1%; P < 0.01).

Conclusions: During prolonged mechanical ventilation, significant alterations in inner ETT configuration occur frequently and are influenced by the type of humidification device used. *In vivo* monitoring of ETT mechanical properties might be clinically useful. (Key words: Endotracheal tube, airway humidification, acute respiratory failure, mechanical ventilation.)

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MAINTAINING the patency of an endotracheal tube (ETT) is vital when caring for patients whose lungs are mechanically ventilated. Partial obstruction of an ETT may have two important consequences: First, it may promote a sudden occlusion of the tube, leading to emergency repeated tracheal intubation.[1-4] Second, during spontaneous or assisted breathing through an ETT, the load imposed on the respiratory muscles may increase considerably.[5-8] Airway humidification greatly affects mucus composition, and inadequate humidification could lead to the deposit of viscous secretions on the internal tube wall.[9] During mechanical ventilation, airway humidification is most frequently performed using hot water humidifiers. Heat and moisture exchangers (HME), also called "artificial noses," have been more recently proposed to replace conventional humidifiers. They can be combined with a bacterial filter and thus offer several attractive advantages, including small size, reasonable cost, and reduced circuit contamination. The efficiency of these devices in providing adequate humidification, however, has been questioned, and a greater incidence of ETT occlusion than with hot water humidifiers has been reported.[4] Several recent studies suggested that hygroscopic HME may perform better than the hydrophobic HME initially proposed.[10-13] However, data are lacking on the efficiency

of such devices to provide adequate humidification during prolonged mechanical ventilation.

The resistance of an ETT is frequently described by the nonlinear Rohrer equation, using constants related to laminar and turbulent flow patterns.[14,15] In addition to having no significance in terms of fluid mechanics, this equation does not allow the computation of a single parameter characterizing internal ETT geometry, because the pressure decrease in a nonlinear system is, by definition, nonlinearly related to the flow rate.[16] We recently analyzed the fluid dynamic flow in ETT under standard conditions of mechanical ventilation[17] and proposed a method, derived from the Blasius resistance formula, of estimating ETT geometry from pressure and flow measurements. The method was based on a formula designed to obtain the "effective inner diameter" of an ETT, taking into account the type of fluid dynamic flow encountered in ETT under usual conditions, the possible nonhomogeneous distribution of mucus deposits, and the presence of a catheter to measure the distal pressure. Thus this "effective inner diameter," a flow-independent parameter, could be used to monitor ETT geometry. The aims of our study were (1) to monitor *in vivo* ETT geometry in patients whose lungs were mechanically ventilated over prolonged periods (*i.e.,* more than 48 h), and (2) to compare, using this method, three types of airway humidifiers, including the two different types of HME.

Materials and Methods

Patients

Patients in the intensive care unit whose lungs were being mechanically ventilated were selected for the study. We excluded patients with hemorrhagic disorders, those in whom the trachea was intubated for more than 24 h before arrival, and those whose intubation was expected to be of short duration, such as patients after operation and persons who took a drug overdose.

Informed consent was obtained from the participants or their next of kin, and the protocol was approved by the ethics committee of our institution. Patients were randomly assigned to one of three types of humidifier: a hot water MR 310 humidifier (Fisher-Paykell, Auckland, New Zealand); a hydrophobic HME, the BB-2215 filter (Pall, Portsmouth, England); and a hygroscopic HME, the Hygrobac 352/5411 filter (Dar, Mirandola, Italy). Hygroscopic HMEs chemically adsorb a proportion of the expired vapor onto the humidifier element: this is
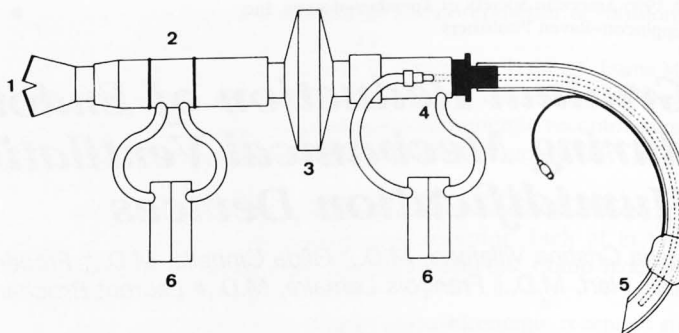
Fig. 1. The experimental setup used in this study inserted between the Y piece of the ventilator circuit and the endotracheal tube. 1 = Y piece of the ventilator circuit; 2 = pneumotachograph; 3 = heat and moisture exchange filter; 4 = entry or proximal pressure; 5 = exit or distal pressure measured with a catheter placed within the endotracheal tube; 6 = pressure transducer.

collected by the dry inspired gases.[9] These HMEs are therefore made of two independent elements, the humidifier and the bacterial filter. The hydrophobic HMEs are made of a single element and rely on the low thermal conductivity of its element to allow a temperature gradient to develop within the humidifier as the latent heat of vaporization is taken from the fresh gas. Hot water humidifiers were filled daily and the temperature of the water was set at 32°C. Heat and moisture exchangers were replaced every 24 h.

All ETTs were made of inert polyvinyl chloride and were equipped with a low-pressure cuff (HI-LO, Mallinckrodt, Athlone, Ireland, and Blue-line, Portex, Berck-sur-Mer, France). The internal diameter (ID) of the ETT ranged from 7.5 to 18.5 mm.

Measurements and Equipment

To determine the exact diameter of the ETT, the internal diameter of each size of ETT was calculated *in vitro* by volumetric water displacement. For this purpose, the ETT was cut above the Murphy's eye, occluded and filled with water. Water content of the ETT and of the exact length allowed were measured to calculate the diameter.

In patients, effective internal diameters of the ETT were measured *in vivo* as follows: the pressure decrease along the ETT was measured during constant-flow ventilation. Although one flow rate would have been sufficient for the calculation, two or three flow rates were selected to ensure the independence of the calculation for flow rate (approximately 0.5, 0.75, and 1.00 l/s, depending on the initial ventilatory settings). The experimental setup is shown in figure 1. The venti-

lator was connected to a calibrated and heated pneumotachograph (Fleisch #2) coupled with a differential pressure transducer (Validyne MP 45, $\pm$ 2 cm H_2O, Northridge, CA). The pressure decrease along the ETT was obtained between the entry or proximal pressure and the exit or distal pressure, the difference being measured with a differential pressure transducer (Validyne MP 45, ±100 cm H_2O). Because the flow was nearly constant, the pressure decrease along the ETT was also nearly constant. We selected graphically the zone of plateau for flow and pressure.

Proximal pressure was measured upstream of the ETT in the enlarged cross-sectional area of an adapter (diameter, 12 mm). Because a change in cross-sectional area generates a longitudinal gradient in lateral pressure resulting from kinetic energy variations and, to a lesser extent, frictional losses, the pressure measured upstream required correction to obtain a reliable value for the proximal pressure in the tube itself. We derived the equations of corrections of the measured pressures, obtained *in vivo*, from experimental *in vitro* data by comparing pressures measured at the adapter to pressures measured at the level of the ETT using a special connector, whose internal diameter was identical to that of the ETT. In addition, we also derived theoretical equations using the Bernoulli equation, and accounting for the local frictional losses (see appendix 1). We observed an excellent correlation between the pressure measured experimentally in the ETT and the theoretical pressure (that measured in the adapter and subsequently corrected) (y [cm H_2O] = 1.03 $\times$ [cm H_2O] $-$ 0.245; r^2 = 1.00; $P < 0.001$), with a mean bias of -0.11 cm H_2O and a mean precision of 0.68 cm H_2O, indicating that the pressure can be reliably estimated using the correction formula.

Distal pressure was measured using a small-caliber polyethylene catheter (internal diameter, 1.5 mm; effective diameter, 2 mm). To obtain lateral pressure only and avoid any interference from dynamic phenomena, several holes were made in the last centimeter of the catheter while the tip was occluded. Knowing the exact length of the ETT, we inserted the catheter such that the distal part was at the tip of the ETT, and not in the trachea, to avoid any Bernoulli phenomenon due to changes in cross-sectional area in the passage from the ETT to the trachea. The presence of a catheter inside the ETT reduces the cross-sectional area and increases the resistive pressure decrease in the tube. Accordingly, application of the Blasius formula with the Bernoulli equation correction was extended to the annular flow

formed by the ETT and a catheter characterized by its external diameter (see appendix 1). This correction was experimentally confirmed.[17] The effective inner diameter was thus computed from this modified Blasius formula. Simultaneous flow and pressure signals were recorded on a strip chart recorder (Gould TA550, Cleveland, OH).

The "effective diameter" was calculated by applying the Blasius law to the measurements and computing the mean internal diameter of a homogeneous ETT, which would give the same pressure–flow relation. This mode of presentation offers the advantage of being independent of the flow rate at which it is measured and of being easy to put into perspective for the physician. It can be measured from a single pressure measurement obtained at any flow rate in a physiologic range[17] (unlike the usual pressure–flow curves), but assumes that the real reduction in caliber is more or less even, at least on a portion of the tube, or is equivalent to a homogeneous reduction.

Protocol

Pressure and flow measurements were obtained in the first 24 h after intubation and then every day or every 2 days until 6 to 8 days of mechanical ventilation. To ensure comparable duration of the study in the three groups, using the different humidifiers, no measurements were made after the eighth day. Data from patients in whom the lungs were ventilated for less than 72 h were retrospectively excluded from the analysis.

The routine nursing care of these patients included tracheal suctioning performed at least once every 2 h. When nurses thought that insertion of the suction catheter was difficult, 3 to 5 ml saline solution was instilled. Tracheal suctioning was also performed before each series of measurements.

Analysis

For each patient, effective diameter was computed each time from at least two different flow rates measured on the same day. Because, theoretically, no change should be observed among different flow rates, the difference between these effective diameter values based on different flow rates was used as a means to validate the reliability of measurements.

The results obtained with each type of airway humidifier were compared as follows: Because, inside the three groups, the patients had different numbers of measurements, performed at different days over different periods of time, we simply compared the reduction in ETT

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diameter at the end of the study period expressed as a percentage of the first-day value (calculated from the difference between the measurements obtained on the first and last days) among the three groups; to ensure that the individual differences in duration of the study period did not affect the results, we also calculated the mean reduction in diameter divided by the number of days of the study period. The change in effective diameter was thus expressed in the percentage of *in vitro* values and in the percentage of the first-day value, and was compared among the groups. All data are means $\pm$ SD. Multiple analysis of variance was used for intergroup comparisons, and Tukey's test was used for two-by-two comparisons. Qualitative variables were compared using the chi squared test with Yates correction for small samples. Probability values less than 0.05 were considered significant.

Results

Patients

Twenty-three patients were included in the study. In thirteen, the trachea was intubated orally, and in 11 the trachea was intubated nasally. Twenty of the ETTs used were HI-LO tubes (Mallinckrodt) and three were blueline tubes (Portex). Endotracheal tube diameters ranged from 7.5 to 18.5 mm (4 ETTs of 8.5 mm, 15 ETTs of 8 mm, and 4 ETTs of 7.5 mm). When diameters were measured *in vitro* by water displacement, they were found to be slightly smaller than those specified by the manufacturer. Thus, for ETTs with diameters of 8.5, 8, and 7.5 mm, the diameters measured *in vitro* were 8.30, 7.98, and 7.34 mm, respectively. *In vivo* reduction of ETT diameter thus will also be expressed as a percentage of the diameter measured *in vitro*.

Reliability of the In Vivo Measurements

Effective inner diameters were calculated for each patient at different flow rates. There was no systematic difference in these calculated values when the flow rate was increased from 500 to 1,000 ml/s (for each individual, the differences among the two or three measurements of diameter varied from 0.05 to 3% of the mean value). Figure 2 illustrates the type of pressure-flow relation found from day to day in several patients.

Comparison of the Three Types of Airway Humidifier

Seven patients were assigned to the Fisher-Paykell hot water humidifier, and eight each were assigned to the Pall and Dar HMEs.

The three groups were similar in terms of age, simplified acute physiologic score,[18] duration of the study, fractional concentration of oxygen in inspired gas, minute ventilation throughout the study, site of intubation, and incidence of chronic obstructive pulmonary disease (table 1).

On the first day of intubation, mean ETT internal diameters were similar in the three groups (7.6 $\pm$ 0.6 mm for Fisher-Paykell, 7.7 $\pm$ 0.4 mm for Pall, and 7.5 $\pm$ 0.5 mm for Dar) and tended to be smaller than the diameter sizes measured *in vitro* (8.2 mm for Fisher-Paykell, 8 mm for Pall, and 7.9 mm for Dar), as illustrated in figure 3 (*in vivo* diameter = [0.94 *in vitro* diameter] + 0.15; r = 0.72; $P < 0.001$). The mean reduction compared with *in vitro* values amounted to 3.85 $\pm$ 3.6%.

At the end of the study period, the mean reduction in effective inner ETT diameter was significantly greater with the hydrophobic HME (Pall) than with the two other systems (−6.5 $\pm$ 4% for Pall *vs.* −2.5 $\pm$ 2.5% for Dar and −1.5 $\pm$ 3% for Fisher Paykell; $P < 0.01$ with analysis of variance). When expressed as the mean reduction in diameter divided by the number of days of the study period, it was still significantly larger with the hydrophobic HME (Pall) than with the two other humidifiers (−1.6 $\pm$ 1.5% per day for Pall *vs.* −0.5 $\pm$ 0.4% per day for Dar, and −0.2 $\pm$ 0.4% per day for Fisher Paykell; $P < 0.05$). Compared with the *in vitro* values, the respective reductions were −10 $\pm$ 4% for Pall, −7.4 $\pm$ 2.5% for Dar, and −8.7 $\pm$ 3% for Fisher Paykell ($P < 0.05$).

Four patients experienced sudden ETT obstruction (three using the Pall hydrophobic HME and one using a Fisher Paykell humidifier). The difference in the incidence of obstruction observed with Pall *versus* the two other systems was not significant (37.5% *vs.* 4.3%; $P = 0.08$). Emergency reintubation of the trachea was indicated because of a sudden increase in peak airway pressure, making ventilation difficult and hazardous. Although no measurements were possible just before extubation, reductions in the last measurement of effective inner diameter obtained before extubation were, respectively, 6.8%, 6.5%, and 9.7% for the three cases of obstruction that occurred in the Pall group and 8.2% for the case in the Fisher Paykell group. Although three other patients presented similar or greater degrees of ETT diameter reduction (respectively, 8.7%, 12.4%, and 12%), the reduction in ETT diameter observed in these four patients necessitating repeated tracheal intubation was significantly larger than the modification observed for the 19 remaining patients (7.8 $\pm$ 1.4% *vs.* 3.1 $\pm$

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Fig. 2. Example of repeated pressure and flow measurements obtained from four representative patients mechanically ventilated *via* the three different humidification devices. Note that the pressure scale on the Y axis is different among patients. Some data have not been shown for clarity.
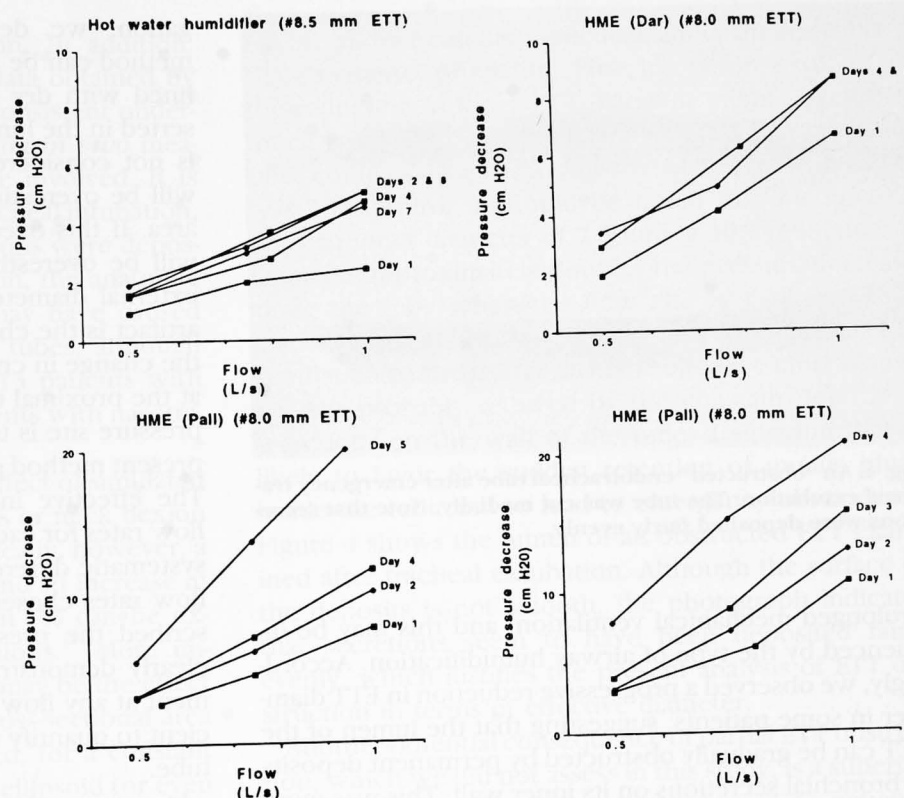
4.1%; $P < 0.01$). The ETT removed from these patients presented dry adherent secretions lining the inner wall of the tube, suggesting a relatively homogeneous reduction of the mean diameter. An example of such ETT obstruction is illustrated in figure 4.

Discussion

The main finding of this study is that the patency of artificial airways can be modified in the course of

Table 1. Characteristics of the Patients Mechanically Ventilated *via* Three Types of Airway Humidifier

	DAR	PALL	Fisher-Paykell
No.	8	8	7
Age (yr)	59 ± 18	67 ± 5	60 ± 9
SAPS	16 ± 6	17 ± 7	17 ± 5
Duration of study (days)	6 ± 3	6 ± 3	6 ± 2
Fi_{O_2}	51 ± 10	52 ± 10	53 ± 15
VE (L·min⁻¹)	10.8 ± 2.4	11.6 ± 1.5	10.2 ± 3.4
COPD (no.)	1	1	1
Orotracheal intubation (no.)	5	4	4

SAPS = simplified acute physiological score[18]; Fi_{O_2} = fraction of inspired oxygen; VE = minute ventilation (averaged values during the study); COPD = chronic obstructive pulmonary disease.
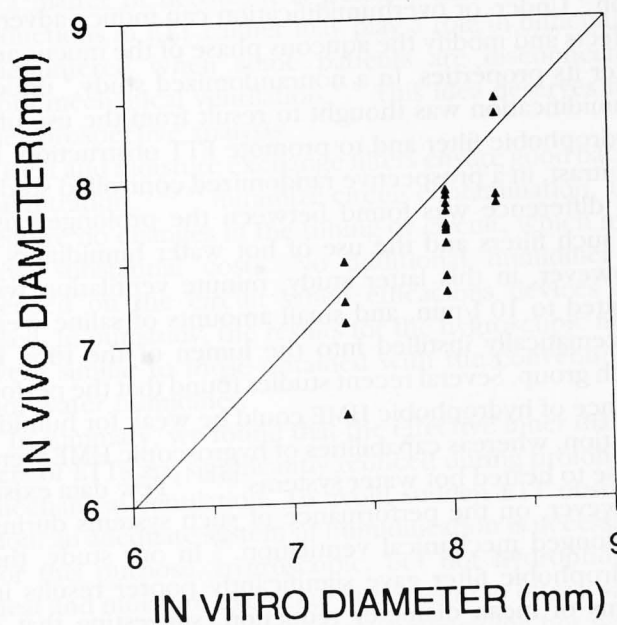

Fig. 3. Values of the effective inner diameter measured on the first day of mechanical ventilation (*in vivo* diameter) plotted against the true endotracheal tube diameter measured *in vitro* by volumetric water displacement (*in vitro* diameter).
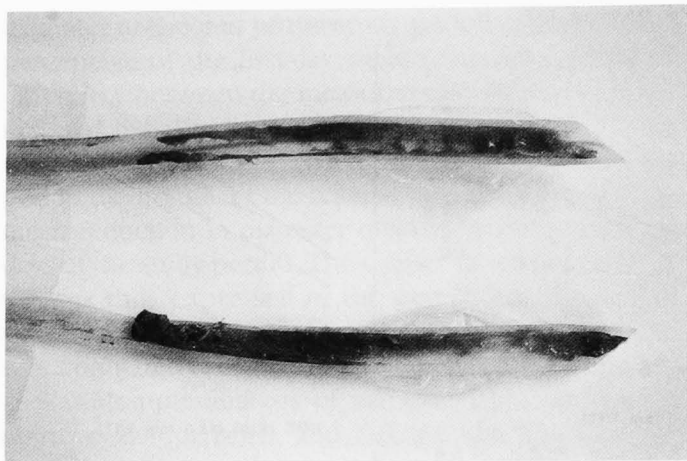
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Fig. 4. An "obstructed" endotracheal tube after emergency tracheal extubation. The tube was cut medially. Note that secretions were deposited fairly evenly.

prolonged mechanical ventilation, and this may be influenced by the type of airway humidification. Accordingly, we observed a progressive reduction in ETT diameter in some patients, suggesting that the lumen of the ETT can be gradually obstructed by permanent deposits of bronchial secretions on its inner wall. This was more frequent with hydrophobic HME than with other systems.

Airway humidification greatly affects mucus composition.[9] Under- or overhumidification can induce adverse effects and modify the aqueous phase of the mucus and alter its properties. In a nonrandomized study,[4] underhumidification was thought to result from the use of a hydrophobic filter and to promote ETT obstruction. In contrast, in a prospective randomized controlled study, no difference was found between the prolonged use of such filters and the use of hot water humidifiers.[19] However, in this latter study, minute ventilation was limited to 10 l/min, and small amounts of saline were systematically instilled into the lumen of the tube in each group. Several recent studies found that the performance of hydrophobic HME could be weak for humidification, whereas capabilities of hygroscopic HME were close to heated hot water systems.[10,12,13] Few data exist, however, on the performance of such systems during prolonged mechanical ventilation.[20] In our study, the hydrophobic filter gave significantly poorer results in terms of mean diameter reduction, suggesting that a significant degree of underhumidification resulted from its prolonged use.

The method we used to calculate the effective internal diameter was previously validated. In a previous investi-

gation, we demonstrated experimentally that this method can be applied to both unused ETTs and ETTs lined with dry mucus secretions, with a catheter inserted in the lumen.[17] When the presence of a catheter is not considered, the pressure decrease in the tube will be overestimated because of the reduced surface area. If this overestimation is ignored, tube resistance will be overestimated to a degree depending on the external diameter of the catheter. Another important artifact is the change in lateral pressure resulting from the change in cross-sectional area. This can occur both at the proximal tip of the ETT and in the trachea if the pressure site is too distal. Our results indicate that the present method gave reliable data for the ETT diameter. The effective inner diameters calculated at different flow rates for each set of measurements did not exhibit systematic differences, suggesting that in the range of flow rates chosen, the Blasius equation accurately described the pressure–flow relation. In addition, this clearly demonstrates that a simple pressure measurement at any flow rate, in a physiologic range,[17] is sufficient to quantify the pressure–flow relation within the tube.

In an experimental study, Wright and coworkers[21] measured ETT pressure–flow relations in patients with adult respiratory distress syndrome whose lungs were mechanically ventilated. They found higher values than those expected from the Rohrer equation, although the scatter of the values was large. However, their measurements were not corrected for the Bernoulli effect. In addition, the insertion of a catheter could have contributed to the large dispersion between their *in vivo* and *in vitro* data. On the whole, our results correspond with theirs with regard to the observation that *in vitro* values are poor predictors of the *in vivo* values measured in the course of mechanical ventilation. When the first-day results of the present study were compared with the *in vitro* assessments of ETT diameter, values of the effective diameter were found to be slightly less (mean reduction, $3.85 \pm 3.6\%$). This could result from a systematic overestimation of the pressure decrease in the tube by *in vivo* measurements, and we cannot eliminate a problem in methodology.

This question, however, has been assessed extensively in a previous study[17] using *in vitro* the exact setup used *in vivo* and showing that measurements performed in obstructed or in clean ETTs gave reliable results compared with the water-displacement method. Good correlation ($r = 0.93$) was found between these *in vivo* values and measurements performed on the

tubes shortly after tracheal extubation. In addition, these results are consistent with the data obtained by Wright and coworkers.[21] We found a consistent underestimation of *in vitro* values when using *in vivo* measurements, and several factors may be involved. It is possible that, even a few hours after tracheal intubation, sufficient amounts of bronchial secretions were deposited on the wall of the tube; in addition, the anatomic configuration of the upper airways may have caused deformations in the geometry of the tubes, although no difference was found among the 13 patients with orotracheal intubation and the 11 patients with nasotracheal intubation.

A previous *in vitro* study found no effect of simulated anatomic oral and nasal conformations or neck flexion on pressure–flow relations.[22] Theoretically, however, a slight effect of curvature is possible, and an increase in pressure drop reaching no more than 7% can be expected based on theoretical calculations.[17] More important than the curvature, however, may be the effect of the changes in the shape of the cross-sectional area induced by tube deformations. Indeed, for a constant perimeter, if a circle is changed to an ellipsoid (or even to a less-regular structure), its surface area will decrease. Consequently, the pressure decrease induced by this new structure will be greater, resulting in an underestimation of the mean hydraulic diameter. We can estimate that a 5% increase in pressure decrease will be induced when a circle is modified into an ellipsoid in which the longest radius is 1.3 times the smallest radius. These phenomena of deformation probably played an important role in the *in vivo* diameter reduction found shortly after tracheal intubation. In any case, the changes in ETT diameter over time were also consistent with the duration of mechanical ventilation in our previous study[17] and with the pathophysiologic hypothesis concerning the type of airway humidification in this study. We decided to monitor ETT diameter by also comparing it with the first-day value rather than just with the *in vitro* value, because subsequent changes did not depend on the anatomic configuration.

In the four patients in whom emergency extubation and repeated intubation were required, the last values measured indicated a significant reduction of the effective inner ETT diameter, of 6.5%, 6.8%, 8.2%, and 9.7%, respectively. Although the reductions may appear relatively small, the fact that they were of greater magnitude than in the other patients strongly suggested that they were associated with a high risk for ETT obstruction. We could not obtain any measurement just before extubation, and we can only speculate about the reasons for this emergency procedure. First, just before extubation, the reduction in inner ETT diameter might have been much larger than the values indicated previously. Second, compared with the *in vitro* value, the reduction was 15%. Third, it should be noted that for an ETT with an inner diameter of 7.5 mm, a 10% reduction in diameter approximately doubles the pressure decrease along the tube when the flow rate is 1 l/s and thus markedly increases the peak pressure, which makes ventilation hazardous. Fourth, the effective inner diameter was probably reduced by the constant deposit of secretions on the wall of the tube, a situation that is likely to favor the sudden retention of mucus plugs inside the tube and to lead to emergency obstruction. Figure 4 shows the lumen of an obstructed ETT examined after tracheal extubation. Although the surface of the deposits is not smooth, the photograph indicates that secretions seem to have been deposited fairly evenly, which justifies the present analysis of ETT obstruction in terms of effective diameter.

Another potential consequence of partial ETT obstruction, which we did not assess in this study, is a superimposed workload to spontaneously breathing patients. Although the relative importance of the work of breathing due to a clean ETT in mechanically assisted patients is a matter of debate, it is possible that unsuspected reductions in ETT caliber may play a role in difficulties encountered when some patients are disconnected from mechanical ventilation.[5-8] This idea deserves further prospective analysis.

Heat and moisture exchange filters ensure good bacterial filtration,[11,23,24] minimize circuit contamination, and require no changes in the tubing or circuit, which may save substantial costs. No additional humidifier is needed on the circuit when efficacious devices are used. In our study, the results for the hygroscopic filter were similar to those obtained with the conventional hot water humidifier.

In summary, we found that the effective inner diameters of ETTs are significantly reduced during prolonged mechanical ventilation. To avoid sudden ETT obstruction, an adequate system of humidification is necessary; for this purpose, hygroscopic, but not hydrophobic, heat and moisture exchange filters seem to offer a satisfactory alternative to the more cumbersome hot water humidifiers.

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Appendix 1

Blasius Formula

For air flowing in a long tube with smooth walls, the pressure–flow relation is nonlinear and can be described by the Blasius formula

$$\Delta P = 1.83 \cdot 10^{-7} \cdot L \cdot \left(\frac{1}{D^{4.75}}\right) \cdot \dot{V}^{1.75}$$

where ΔP is the pressure decrease in centimeters of water, L is the length in centimeters, D is the diameter in centimeters, and $\dot{V}$ is flow rate expressed in cubic centimeters per second.

This formula was used to describe the pressure decrease in adult ETTs, as proposed by Lofaso and associates[17] in a previous study. The Blasius formula was modified, as indicated below, to account for the annular shape of the ETT cross-section when a catheter with an external diameter "d" is inserted in the ETT:

$$\Delta P = 1.83 \cdot 10^{-7} \cdot L \cdot \left(\frac{1}{(D-d)^{1.25} \cdot (D^2 - d^2)^{1.75}}\right) \cdot \dot{V}^{1.75}$$

Generalized Bernoulli Equation[25]

The generalized Bernoulli equation allows us to relate the ETT entry pressure (P_2) to the pressure P_1 measured in the connecting cannula of a larger cross section (A_1) than the tube cross section (A_2):

$$P_1 - P_2 = \Delta P_k + \Delta P_{res}$$

In the system presently used ($A_1 > A_2$), the above equation means that pressure P_1 overestimates P_2 by an amount equal to the sum of kinetic energy change, $\Delta P_k = 1/2 \cdot \rho \cdot \dot{V}^2 [1/A_2^2 - 1/A_1^2]$, and frictional pressure decrease, $\Delta P_{res} = \epsilon \cdot 1/2 \cdot \rho \cdot (\dot{V}/A_2)^2$.

ϵ depends on the local geometry of the connection between two tubes ($\epsilon = 0.09 - 0.14$ for $D = 8.5 - 7$ mm). ρ is the gas density and $\dot{V}$ is the flow rate.

These equations show that the expression giving the pressure difference ($P_1 - P_2$) remains proportional to $1/2 \cdot \rho \cdot \dot{V}^2$.

Taking a constant value for A_1 (1.13 cm²) and the actual values of A_2 measured by water displacement for each ETT tested, it is possible theoretically to estimate (from values obtained in standard textbooks[25] on pressure decrease) the expression relating P_1 and P_2 in air:

ETT 8.5 mm (actual diameter: 8.3 mm): $P_1 - P_2 = 1.81 \cdot \dot{V}^2$

ETT 8.0 mm (actual diameter: 7.9 mm): $P_1 - P_2 = 2.24 \cdot \dot{V}^2$

ETT 7.5 mm (actual diameter: 7.4 mm): $P_1 - P_2 = 3.37 \cdot \dot{V}^2$

ETT 7.0 mm (actual diameter: 6.9 mm): $P_1 - P_2 = 4.59 \cdot \dot{V}^2$

where $P_1 - P_2$ is expressed in centimeters of water and $\dot{V}$ in liters per second.

Experimental estimates of the coefficients for different ETTs tested in air gave the following values (the pressure tap used to obtain P_2 was located about 1 cm downstream from the cross-sectional reduction):

ETT 8.5 mm: $P_1 - P_2 = 1.86 \cdot \dot{V}^2$

ETT 8.0 mm: $P_1 - P_2 = 2.29 \cdot \dot{V}^2$

ETT 7.5 mm: $P_1 - P_2 = 3.49 \cdot \dot{V}^2$

ETT 7.0 mm: $P_1 - P_2 = 4.72 \cdot \dot{V}^2$

These experimental values differ from theoretical values by only 2.3–3.6%, which fully justified the proposed corrections. These expressions were used to recompute P_2 from the measured P_1.

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