

Estimation of inspiratory pressure drop in neonatal and pediatric endotracheal tubes

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Jarreau, Pierre-Henri, Bruno Louis, Gilles Dassieu, Luc Desfrere, Perre W. Blanchard, Guy Moriette, Daniel Isabey, and Alain Harf. Estimation of inspiratory pressure drop in neonatal and pediatric endotracheal tubes. *J. Appl. Physiol.* 87(1): 36–46, 1999.—Endotracheal tubes (ETTs) constitute a resistive extra load for intubated patients. The ETT pressure drop (ΔP_{ETT}) is usually described by empirical equations that are specific to one ETT only. Our laboratory previously showed that, in adult ETTs, ΔP_{ETT} is given by the Blasius formula (F. Lofaso, B. Louis, L. Brochard, A. Harf, and D. Isabey. *Am. Rev. Respir. Dis.* 146: 974–979, 1992). Here, we also propose a general formulation for neonatal and pediatric ETTs on the basis of adimensional analysis of the pressure-flow relationship. Pressure and flow were directly measured in seven ETTs (internal diameter: 2.5–7.0 mm). The measured pressure drop was compared with the predicted drop given by general laws for a curved tube. In neonatal ETTs (2.5–3.5 mm) the flow regime is laminar. The ΔP_{ETT} can be estimated by the Ito formula, which replaces Poiseuille's law for curved tubes. For pediatric ETTs (4.0–7.0 mm), ΔP_{ETT} depends on the following flow regime: for laminar flow, it must be calculated by the Ito formula, and for turbulent flow, by the Blasius formula. Both formulas allow for ETT geometry and gas properties.

fluid mechanics; laminar flow; turbulent flow; Ito formula; Blasius formula

PRECISE KNOWLEDGE of the resistance to flow in endotracheal tubes (ETTs) is important for a rational approach to the clinical management of critically ill patients under mechanical ventilation, because of the pressure drop inside the ETT; this drop means that the pressure measurement given by the ventilator does not indicate the pressure at the distal end of the ETT. ETT resistance increases total airway resistance and must be taken into account when the patient's respiratory system resistance is being evaluated (16, 18, 23). Furthermore, this additional resistance increases the patient's work of breathing (WOB) (3, 6). This is particularly important for spontaneous ventilatory cycles, which may constitute most of the respiratory cycles during

the intermittent mandatory ventilation generally used for neonates.

For adult ETTs, a mechanical approach has been used, to allow precise characterization of the relationship among ETT pressure drop, flow, inner geometry, and the physical properties of gas (17). It was found that the flow regime can be considered as turbulent and described with the Blasius equation, in which ETT pressure drop is proportional to $V^{1.75}$, with V representing flow. To our knowledge, such an approach is lacking in the neonatal and pediatric fields. Although resistance measurements are available from the literature (6, 15, 22, 26), they have so far been interpreted with empirical equations, generally Rohrer equations, the coefficients of which must be computed for each ETT and that are altered by any change in ETT length, diameter, or other parameters (22). We propose to establish a general law, based on the conventional adimensional fluid mechanical approach to analysis of the pressure-flow relationship (20).

We found that flows encountered in clinical practice can be considered as laminar for neonates intubated with ETTs that have an internal diameter (ID) of 2.5, 3.0, or 3.5 mm. Under these conditions, the ETT pressure drop cannot be estimated by the Poiseuille formula, because it does not take the curvature of the tube into account, but with the Ito formula, the dimensional form of which defines pressure drop as a polynomial function of $V^{-0.5}$, $V^{0.5}$, and $V^{1.5}$. For larger ETTs, 4.0- to 7.0-mm ID, the clinical range of flows includes both the laminar and turbulent flows: the Ito formula applies to laminar flows, and the Blasius formula to turbulent flows.

These general laws relate the ETT pressure drop to flow, inner geometry, and gas physical properties and can be applied to any ETT without changing the coefficients of the equation. Evaluating the pressure drop in neonatal and pediatric ETTs makes it possible to predict the part played by the ETT in total airway resistance, as well as the additional WOB imposed on the patient. Furthermore, this evaluation could be used to compensate for the ETT pressure drop with new types of assisted ventilatory modes.

THEORY

In the fluid dynamic theory, it is usual to divide the pressure drop in a duct into two components. The first

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is reversible and is caused by the changes in kinetic energy between two distinct cross sections of a tube during a steady incompressible flow. The second component is the friction pressure drop or viscous dissipation term generated by the friction between the gas and the wall. Accordingly, $\Delta P = \Delta P_{ke} + \Delta P_{vd}$, where ΔP is pressure drop and ΔP_{ke} and ΔP_{vd} are pressure drop due to changes in kinetic energy and to viscous dissipation, respectively.

The pressure drop in a tube caused by the viscous dissipation, ΔP_{vd} , has been extensively studied (4, 9, 11, 12, 18, 20, 21, 27). It depends on whether the flow is laminar or turbulent, on the geometry of the tube, i.e., its ID, curvature diameter and length, and on the thermodynamic characteristics of the gas. In all cases, the transition between laminar and turbulent flow depends on the value of the Reynolds number, an adimensional number representing fluid velocity. Below a critical Reynolds number value, the flow is laminar, and above it the flow is turbulent. For curved tubes, the critical value of the Reynolds number is higher than for straight tubes and depends on the ratio of the curvature diameter to the ETT ID.

Both adult and neonatal ETTs are curved, to permit adaptation to the normal morphology of the upper airways. Under conditions of laminar flow in a straight tube, the pressure drop is given by the well-known Poiseuille's law, whereas in a curved tube it is given by the Ito formula, which indicates a larger pressure drop. Under conditions of turbulent flow in a straight tube, ΔP_{vd} is given by the Blasius formula, whereas other formulas such as the one proposed by White (27) describe ΔP_{vd} for curved tubes. However, as demonstrated below (see APPENDIX), we found that, in the clinical range of flows and ETT geometry, the pressure drop computed with the White formula is virtually the same as that computed with the Blasius formula.

In clinical practice, flow in the ETT is oscillatory. However, under certain conditions, oscillatory flow can be considered to be quasi-steady, i.e., it behaves instantaneously like steady flow. Criteria for quasi-steady-flow conditions in airways have already been extensively reported (10, 20) and are described in detail in the APPENDIX. For the purposes of this study, we can consider breathing flow in the ETT to be quasi-steady.

All equations and details of the formulas are given in the APPENDIX.

METHODS

Experimental Setup

Neonatal- and pediatric-size ETTs, with an ID ranging from 2.5 to 7.0 mm, were tested with their natural curvature. This curvature was measured by comparing the natural curvature with calibrated circles drawn on a sheet of paper. ETT ID and length were systematically checked by the acoustic reflection method, already validated for adult ETTs (19, 25) as well as for neonatal ETTs (13). This method gives the area of the inner cross section, which was converted into diameter assuming a pure circular geometry. Table 1 indicates the characteristics of the different ETTs used.

The pressure-flow relationship was studied for the ranges of flow rates used in clinical practice, as well as for higher flow rates (Table 1), so as not to exclude any clinical situation. The range of flow studied therefore included and extended beyond the entire clinical range for each ETT. Pressure drop and flow were measured by using *setups A* and *B* (Fig. 1).

Setup A allowed pressure and flow measurements under conditions close to clinical conditions. A ventilator circuit was connected via a standard ETT connector to the ETT studied, the tip of which was open to the atmosphere. Compressed air was used to deliver a predetermined steady flow to the inspiratory line of standard ventilator circuits. These comprised a neonatal circuit for 2.5- to 3.5-mm ETTs (Electro Medical Equipment, Brighton, UK), a pediatric circuit (Siemens, Erlangen, Germany) for 4.0-mm ETTs, and an adult circuit for 5.0- to 7.0-mm ETTs (DAR SPA, Mirandola, Italy). The predetermined flows were measured with a screen pneumotachograph (PT 180/10, Jaeger, Würzburg, Germany), which was linear up to flows of 500 ml/s. For larger flows, we used a Fleisch no. 1 pneumotachograph (SensorMedics, Marne-La-Vallée, France), linear up to flows of 1,350 ml/s. Both pneumotachographs were placed on the inspiratory line and connected to a differential pressure transducer (Validyne DP-45, ± 2 cmH₂O, Validyne, Northridge, CA). The expiratory line was obstructed. Pressure was measured at two sites with two differential pressure transducers (Validyne DP-45, ± 22.5 cmH₂O, Validyne) connected to a hole 1 mm in diameter drilled, first, in the inspiratory line 2 cm upstream of the Y piece for the neonatal and pediatric circuits and 3 cm for the adult circuit, and, second, in the ETT connector.

To assess the effect of the Y piece, we used *setup B*, in which the pneumotachograph was directly linked to the ETT connector. It allowed pressure drop measurement through a standard ETT connector and the studied ETT, the tip of which was

Table 1. Characteristics of the endotracheal tubes studied, maximal flows studied and their corresponding Reynolds numbers, and values of critical Reynolds numbers for each ETT

	ETT ID, mm						
	2.5	3	3.5	4	5	6	7
Diameter, mm	2.55	2.99	3.53	3.94	4.79	5.79	6.81
Diameter of curvature, mm	330	240	260	360	300	320	240
Length, mm	151	174	196	210	250	294	304
Maximal flow studied, ml/s	100	150	200	410	600	750	1,060
Reynolds number for the maximal flow studied	3,338	4,270	4,822	8,857	10,661	11,025	13,247
Critical Reynolds number	4,219	4,916	5,053	4,716	5,322	5,539	6,397
Flow value for critical Reynolds number, ml/s	126	173	210	220	300	377	512

ETT, endotracheal tube; ID, inner diameter. Maximal flows and their respective Reynolds nos. as well as values of critical Reynolds nos. for each ETT were analyzed by using *Eqs. 3 and 8* in the APPENDIX, respectively.

open to the atmosphere. Compressed air was used to deliver a predetermined steady flow measured with the same pneumotachographs as above, which were placed upstream of the ETT connector. Pressure was measured with the same differential pressure transducer as above, connected to a hole 1 mm in diameter drilled in the standard ETT connector.

To assess the effect of curvature diameter on pressure drop and to validate our general laws, we studied the pressure-flow relationship with *setup B* for various curvature diameters of a 2.5-mm ETT, ranging from 6 to 20 cm. To determine the diameter, the ETT was gently curved and fixed on a circle of known diameter drawn on a sheet of paper. The curvature was constant over the entire length of the ETT.

Analysis

The relationship between pressure drop and flow was obtained by direct measurement. Once the kinetic energy calculated by Eq. 1 (see APPENDIX) had been subtracted, we compared the resulting pressure drop to the predicted pressure drop given by the Blasius formula (Eq. 4) or the Ito formula (Eq. 6). Both formulas are given in the APPENDIX. Flow rate was expressed as a normalized value, represented by the Reynolds number (Eq. 3) for turbulent flow and by the Dean number (which includes the Reynolds number and curvature, Eq. 5 in the APPENDIX) for laminar flow. Pressure drop was normalized by the equivalent pressure drop given by Poiseuille's law (Eq. 2) for laminar flow and by the equivalent pressure drop given by the Blasius formula for

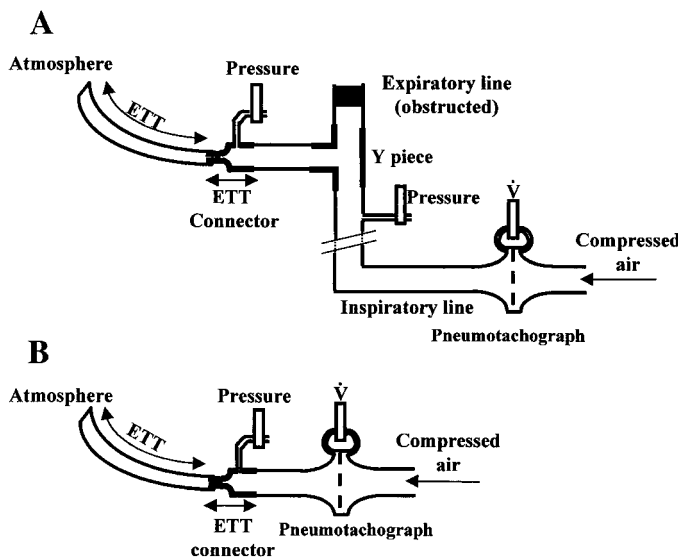


Fig. 1. Schematic representation of setups used to measure pressure drop-flow relationship. *A: setup A* allowed pressure-flow measurement under conditions close to clinical reality. Ventilator circuit was connected to an endotracheal tube (ETT), the tip of which was open to the atmosphere, through a standard ETT connector. Compressed air was used to deliver a predetermined steady flow (\dot{V}), which was measured with a pneumotachograph placed on inspiratory line, to inspiratory line of standard ventilator circuit. Expiratory line was obstructed. Pressure was measured at 2 sites with 2 differential pressure transducers connected to holes 1 mm in diameter drilled in inspiratory line upstream of Y piece and in ETT connector. *B: setup B* allowed pressure drop measurement through a standard ETT connector and ETT, the tip of which was open to the atmosphere. Compressed air was used to deliver a predetermined steady \dot{V} measured with a pneumotachograph placed just upstream of ETT connector. Pressure was measured with a differential pressure transducer connected to a hole 1 mm in diameter drilled in standard ETT connector.

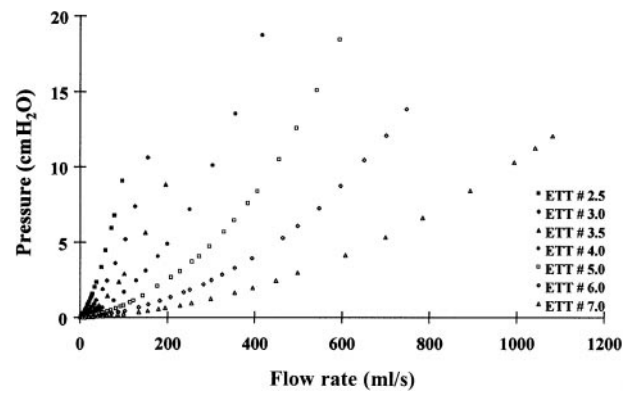


Fig. 2. Dimensional representation of pressure drop-flow relationship. Pressure drop was measured by using *setup A*. Unlike adimensional representation, this conventional representation led to construction of 7 curves with 7 equations, each corresponding to 1 ETT in 1 given geometry comprising inner diameter (ID), curvature diameter, and length, and for physical properties of 1 gas. #, ID (mm).

turbulent flow. To separate the laminar from the turbulent flow, the criterion used was the critical Reynolds number, defined in Eq. 8 (see APPENDIX).

Statistics

The pressure drop obtained by direct measurements and the predicted pressure drop given by Eq. 4 or 6 in the APPENDIX were compared by plotting the difference between the two values against the mean of the two values, as recommended by Bland and Altman (2).

RESULTS

Laminar Flow

We first analyzed the data obtained under laminar flow conditions, i.e., for the Reynolds number below the critical Reynolds number, which represent all the flows encountered in clinical practice for 2.5- to 3.5-mm ETTs and the lower flows for 4.0- to 7.0-mm ETTs (Table 1).

With *setup A* for laminar flow, no significant difference was observed between the pressures measured upstream of the Y piece and those measured in the ETT connector. The mean difference between the two measurements was 0.02 cmH₂O with an SD of 0.06 cmH₂O, which corresponds to a mean of 3.1% of the pressure measurement at the ETT connector.

Figure 2 gives a dimensional representation of the pressure-flow relationship.

The pressures we measured were extremely close to those predicted by the Ito formula (Fig. 3). Figure 3A shows the measured and predicted data expressed as normalized values (see METHODS). The actual pressure measurement curve was close to the curve corresponding to the pressure drop values predicted by the Ito formula. The difference between the measured and predicted values vs. the mean of both gave a mean of -0.04 cmH₂O with an SD of 0.15 cmH₂O (Fig. 3B). The coefficient of correlation (r) between the two methods was 0.997.

In *setup B*, the measured values were also not different from the theoretical values, with mean differ-

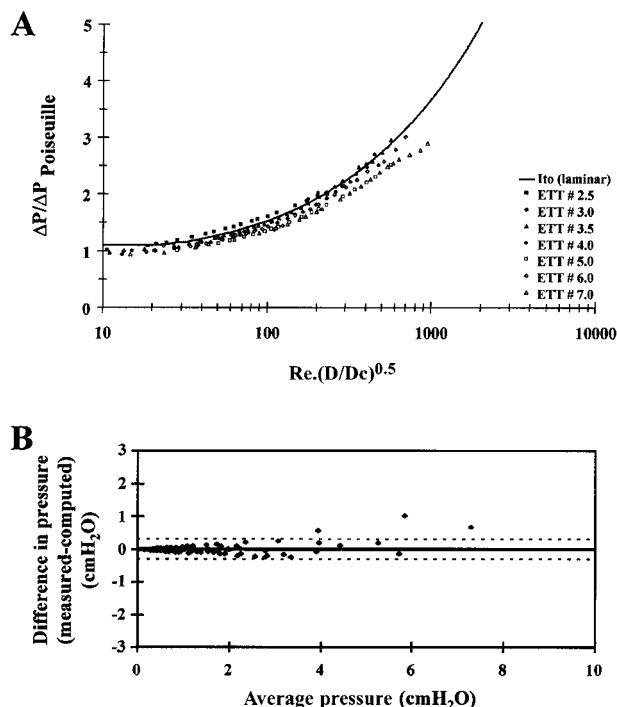


Fig. 3. A: plot of adimensional pressure-flow relationship by using *setup A* for 7 ETTs studied in range of laminar flow. Criterion used to separate laminar from turbulent flow was critical Reynolds number (Eq. 8 in APPENDIX). Neonatal ETTs were in laminar flow throughout entire flow range. Once kinetic energy had been subtracted, pressure drop (ΔP) was normalized by equivalent pressure drop in Poiseuille flow ($\Delta P_{\text{Poiseuille}}$; Eq. 2) and compared with predicted pressure drop given for a curved tube by Ito equation (solid line). Flow rate was normalized in terms of the Dean number $[Re \cdot (D/D_c)^{0.5}]$, where Re is Reynolds no. and D and D_c are diameter of tube and curvature, respectively. Note that ratio of actual and Ito-predicted ΔP to $\Delta P_{\text{Poiseuille}}$ was much higher than 1, indicating that $\Delta P_{\text{Poiseuille}}$ greatly underestimates ETT pressure drop. All formulas and equations are in APPENDIX. B: comparison of pressure drop values minus pressure drop due to kinetic energy changes obtained from direct pressure measurement, using *setup A*, with predicted pressure drop given for a curved tube by Ito formula. As recommended by Bland and Altman (2), differences between 2 values were plotted against mean of 2 values. Mean of differences between 2 methods was $-0.04 \text{ cmH}_2\text{O}$, with SD of $0.15 \text{ cmH}_2\text{O}$.

ence of $-0.04 \text{ cmH}_2\text{O}$, SD of $0.08 \text{ cmH}_2\text{O}$, and $r = 0.996$ (figure not shown).

As shown in Fig. 4A, the measured pressure drops for different curvature diameters were very close to those predicted by the Ito formula. Figure 4B shows the variation of pressure drop curves for different curvature diameters in a dimensional representation of the pressure-flow relationship and emphasizes the influence of curvature diameter on this relationship.

Turbulent Flow

The conditions of turbulent flow, i.e., for the Reynolds number exceeding the critical number, were only present for the higher flows studied for 4.0- to 7.0-mm ETTs.

In *setup A*, a small insignificant difference was observed between the pressure recorded upstream of the Y piece and the pressure recorded in the ETT connector (mean difference between the 2 measure-

ments = $0.32 \text{ cmH}_2\text{O}$, SD = $0.24 \text{ cmH}_2\text{O}$). This difference constituted a mean of 3.4% of the pressure measured in the ETT connector.

Our results are in agreement with the Blasius formula, as we found that, throughout the entire flow range studied, the difference between the actual measurements and those predicted by this formula vs. the mean of the two methods gave a mean of $0.02 \text{ cmH}_2\text{O}$ and an SD of $0.50 \text{ cmH}_2\text{O}$ (Fig. 5). The r between the two methods was 0.99.

In *setup B*, we found that the Blasius formula slightly overestimates our experimental results. Throughout the entire range of clinical values for flow, the mean difference between the measured and predicted values was $-0.20 \text{ cmH}_2\text{O}$, with an SD of $0.18 \text{ cmH}_2\text{O}$ and $r = 0.99$.

DISCUSSION

Our laboratory previously demonstrated that, in adult ETTs, the inspiratory pressure drop can be satisfactorily estimated by the Blasius formula, which, for turbulent flows, relates ETT geometry and gas properties to the pressure drop (17). In the present study, we used an identical approach for neonatal and pediatric ETTs. Our main observation was that, for neonatal ETTs 2.5–3.5 mm in diameter, 1) the flow is laminar; and 2) because of the curvature of the tube, the pressure drop is higher than predicted by the

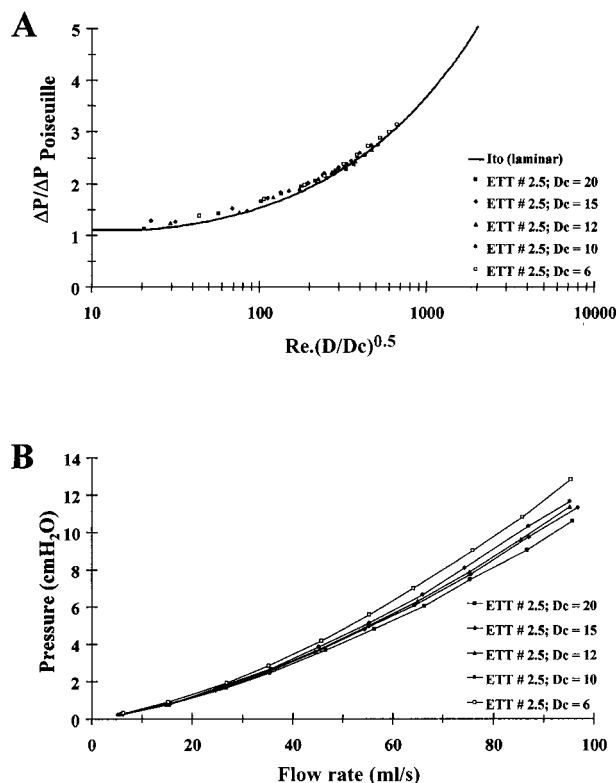


Fig. 4. Effect of D_c on pressure-flow relationship in a 2.5-mm-ID ETT. A: adimensional plot. Measured pressure drops for different curvature diameters were very close to those predicted by Ito formula. B: dimensional representation of pressure-flow relationship. Pressure drop increase with decreasing value of curvature.

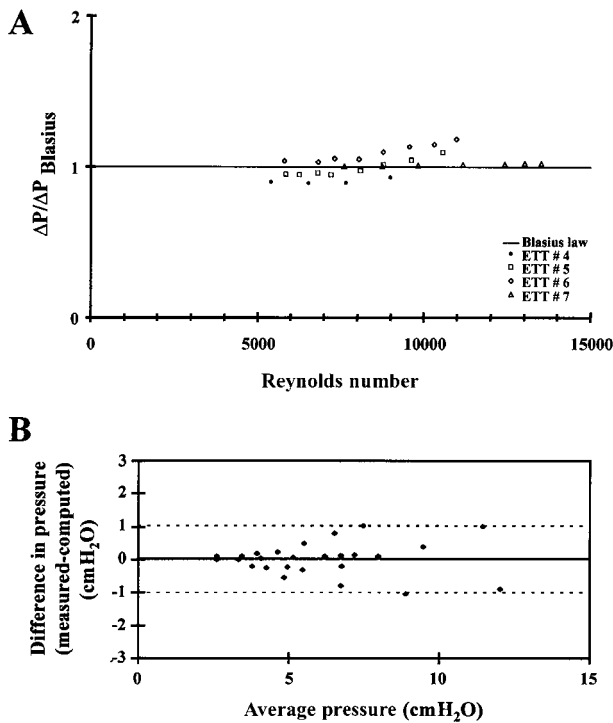


Fig. 5. *A*: plots of adimensional pressure-flow relationship by using *setup A* for ETTs with 4.0- to 7.0-mm ID in range of turbulent flow. Pressure drop and flow were obtained by direct measurement. Once pressure drop due to kinetic energy change had been subtracted, it was compared with predicted pressure drop given by Blasius formula (Eq. 4 in APPENDIX). Pressure drop was normalized by equivalent pressure drop given by Blasius formula ($\Delta P_{\text{Blasius}}$). Criterion used to separate laminar from turbulent flow was critical Reynolds number (Eq. 8). Solid line, values predicted by Blasius formula. *B*: comparison of values for pressure drop minus pressure drop due to kinetic energy changes obtained from direct pressure measurements by using *setup A* and predicted pressure drop given by Blasius formula. As recommended by Bland and Altman (2), differences between 2 values were plotted against mean of 2 values. Mean of differences between 2 methods was 0.02 cmH₂O, with SD of 0.50 cmH₂O.

Poiseuille flow. We found that, in neonatal ETTs, the pressure drop can be estimated by the Ito formula, in which the ETT pressure drop is a polynomial function of $V^{-0.5}$, $V^{0.5}$, V , and $V^{1.5}$. In pediatric ETTs (4.0- to 7.0-mm ID), we observed that physiological flows are successively laminar and turbulent during inspiration, and consequently the ETT pressure drop can be estimated by the Ito formula for laminar flows and by the Blasius formula for turbulent flows.

Flow Regimes

Laminar flow. By calculating the critical Reynolds number (Eq. 8 in the APPENDIX), we found that the flow regime in neonatal ETTs was laminar for a curved tube. The excellent agreement (Fig. 3) observed in the physiological flow range between our pressure drop measurement and the values predicted by the Ito formula (Eq. 6 in the APPENDIX) indicates that the flow in neonatal ETTs was laminar for a curved tube. At first sight, this result seems to disagree with the findings of several groups (22, 23, 30) who used empirical equations such as the Rohrer equation ($\Delta P = K_1 \cdot V + K_2 \cdot V^2$) to

describe the resistive properties of neonatal ETTs. The Rohrer constants K_1 and K_2 are indeed generally assumed to refer to the factors determining laminar and nonlaminar flow, respectively (24). However, this interpretation of the significance of the Rohrer equation coefficients might indicate that the neonatal flow is not only laminar, which would be erroneous. The laminar flow in a curved tube is a good example of the fact that laminar flow does not mean that there is a linear relationship between pressure drop and flow. Furthermore, our results clearly show that laminar flow is not synonymous with Poiseuille flow, and the use of the conventional Poiseuille equation (Eq. 2) does not account for the pressure drop due to the ETT curvature. Figure 4 clearly illustrates the influence of curvature on pressure drop, and, obviously, in Fig. 3, the ratio $\Delta P / (\Delta P_{\text{Poiseuille}})$ is far above one, except for flows close to zero, where $\Delta P_{\text{Poiseuille}}$ is the Poiseuille pressure drop. The use of the Poiseuille flow (Eq. 2) would have underestimated the pressure drop by a factor that can reach three for the larger flows (Fig. 3). Moreover, compared with the Rohrer equation, the Ito formula has the advantage of taking into account the circular inner geometry of the ETT (diameter and length), its curvature, and the gas properties. The ETTs we studied had in vitro curvatures. In clinical situations, this curvature varies with the position of the patient's head. Furthermore, this curvature is probably not constant along the tube. Because all these variations along the tube cannot be integrated, we propose to use a mean curvature diameter. We tried to evaluate this curvature diameter on 20 magnetic resonance imaging scans of children, from premature newborn infants to 10-yr-old children. In a first approximation, the mean range of curvature diameter encountered in clinical situations can be estimated as 8–18 cm. The difference in pressure drop between these two extremes (variation of up to 100%) is <16%. This difference can be disregarded in clinical practice, especially when it is compared with the error induced by Poiseuille's law (see Fig. 3A). This slight difference induced by the curvature diameter variation, therefore, allows the use of a mean curvature diameter for calculation of the pressure drop.

Given the flows usually used in clinical practice, and the flow values for the critical Reynolds number for curved tubes (Table 1), the laminar flow in a curved pipe predicted by the Ito formula (Eq. 6) applies to neonatal ETTs, the diameters of which range from 2.5 to 3.5 mm. For pediatric ETTs (4.0- to 7.0-mm ID), the Ito formula can be applied as long as the Reynolds number is below the critical Reynolds number, i.e., as long as the flow does not exceed the flow corresponding to this critical number. We therefore noted the value of this flow for a given ETT geometry (Table 1).

Turbulent flow. We previously found that, in adult ETTs, turbulent flow is observed during most of the inspiration and that the pressure drop along the ETT is proportional to $V^{1.75}$, as predicted by the Blasius formula (17, 25). In the present study, computation of the critical Reynolds numbers showed that turbulent flow

is only present in ETTs with an ID above 4.0 mm under the flow conditions chosen for study.

In contrast to laminar flow, we found that, for turbulent flows, the calculated effect of the curvature was negligible. In the range of geometric curvatures and flows tested, the ΔP_{vd} value predicted by White (27) for turbulent flows in curved tubes was indeed extremely close to the value given by the Blasius formula (see APPENDIX). It can therefore be concluded that the effect of the ETT curvature on the pressure drop is slight and can be disregarded. In adult ETTs the pressure drop along the tube can be estimated by the Blasius formula. In this study, we extended the results for turbulent flows to ETTs with an ID of 4.0–7.0 mm.

Entry effects. The formulas used in the present study (Ito, Poiseuille, White, and Blasius) assume a fully developed flow. This means that the velocity profile remains the same from the entry to the exit of the ETT. When this profile is not verified, a pressure drop (ΔP_{ent}) must be added to the kinetic energy term and to the viscous dissipation term to account for the entry flow effect. Many formulas have been proposed to describe this additional pressure drop, which is due to fluid contraction (9, 18). This drop can be rendered by the equation

$$\Delta P_{ent} = \epsilon \cdot (0.5 \cdot \rho \cdot \bar{u}^2)$$

where ϵ is a coefficient that depends on the flow regime, on the ratio of the area before contraction to the area after contraction, and, above all, on the shape of the passage from the upper to the lower section of the ETT connector (rough, smooth, and so on), ρ is the fluid density, and \bar{u} is the average velocity. If we apply the formula proposed by Idel'cik (9) for a conical curvilinear connector with an angle close to 60° to the ETT connector, the ratio of ΔP_{ent} to the pressure drop due to the ETT is between 3 and 14%. Our results, which are in agreement with this approximate analysis, suggest that ΔP_{ent} is negligible. We also observed in *setup A* that the pressures measured upstream and downstream of the Y piece were identical, suggesting the Y piece is designed to reduce the pressure drop to a minimum. This last point is clinically important, because it suggests that the pressure measurement in the Y piece of the neonatal circuit is well adapted to estimating the real pressure at the entry of the ETT connector.

Kinetic energy. The use of the Ito or Blasius formula alone implies that the pressure drop due to kinetic energy has been subtracted from the measured drop in the ETT plus the connector. Therefore, direct comparison of the measured pressure drop to the predicted value makes it necessary to add the drop due to kinetic energy to the drop calculated with the Ito or Blasius formula. The drop due to kinetic energy is due to the fact that the section at the top of the ETT connector is larger than the section at the bottom. Whereas the diameter at the top of the connector is always the same, the diameter of the lower section, i.e., of the ETT, varies. Here, we observed that the pressure drop due to kinetic energy was between 13 and 37% of the mean

total pressure drop, which includes the ETT plus the connector.

Exit effect. Because of the area difference between the end of the ETT and the trachea, an exit effect associated with a variation of kinetic energy is observed. The resulting pressure drop is always positive (18) and close to

$$\Delta P = \rho \cdot \left(\frac{\dot{V}}{A_1} \right)^2 \cdot \frac{A_1}{A_2} \cdot \left(1 - \frac{A_1}{A_2} \right)$$

It is difficult to use this formula without a precise knowledge of the tracheal area, A_2 . Use of the Ito (or Blasius) formula may therefore slightly overestimate the ETT pressure drop with the ETT in situ. In this study, we considered that the pressure drop due to the abrupt expansion between the ETT and the trachea is not a specific effect of the ETT but is included in the pressure drop due to the patient's airways.

Dimensional forms of the equations for practical estimation of the pressure drop in a clinical situation. The use of either the adimensional or the dimensional form of the Ito formula (see APPENDIX) to compute the pressure drop may represent a hard challenge for the clinician outfitted with only a pocket calculator. It is possible to propose a simpler formula. Taking into account the gas properties of air with 100% relative humidity at 37°C , and with a barometric pressure of 76 mmHg, and assuming a curvature diameter of 14 cm, a simplified and dimensional form of the Ito formula can be written to estimate the pressure drop (cmH_2O)

$$\Delta P_{vd} = L \cdot (0.0203 \cdot D^{-4.25} \cdot \dot{V}^{1.5} + 0.0319 \cdot D^{-4} \cdot \dot{V})$$

where \dot{V} is the flow (ml/s), D is the ID of the ETT (mm), and L is its length (cm). Note that this polynomial function of \dot{V} and $\dot{V}^{1.5}$ is derived from *Eq. 7* in the APPENDIX by neglecting the terms in $\dot{V}^{0.5}$, \dot{V}^0 , and $\dot{V}^{-0.5}$. Because the introduction of oxygen instead of air does not substantially modify the physical properties of gas, this formula can be used to estimate the pressure drop when oxygen is added to the respiratory gas. However, this formula must not be used when the respiratory gas has very different physical properties, like heliox.

The flow becomes turbulent for a Reynolds number exceeding the critical number. Taking into account the gas properties of air and assuming a curvature diameter of 14 cm, this number is reached when

$$\dot{V} \cdot 10^{-6} \cdot D^{-1.32} > 0.441$$

This means that, under the simplified conditions already defined above, the flow for a standard ETT becomes turbulent when it exceeds the following flows

ETT ID, mm	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
Flow, ml/s	250	300	350	405	460	515	570	630

Note that these flows are indicative. They correspond to the manufacturer's values of ETT ID instead of the values given in Table 1, which correspond to the measurement of ETT ID by the acoustic reflection method.

When a Reynolds number is above the critical Reynolds number, i.e., for turbulent flows, the Blasius formula must be used. Taking into account the gas properties of air, the pressure drop can be estimated (cmH_2O) with the following dimensional form

$$\Delta P_{\text{vd}} = 0.0104 \cdot L \cdot D^{-4.75} \cdot \dot{V}^{1.75}$$

To evaluate the pressure drop due to the ETT connector plus the ETT, the pressure drop due to kinetic energy must be added to both the Ito and Blasius formulas. This drop can be written in a simplified form, assuming a standard ETT connector with a diameter of 1.15 cm at the top

$$\Delta P_{\text{ke}} = -0.98 \cdot \dot{V}^2 \cdot (D^{-4} - 5.72) \quad \text{when } D \geq 3 \text{ mm}$$

$$\Delta P_{\text{ke}} = -0.98 \cdot \dot{V}^2 \cdot (1.5 \cdot D^{-4} - 5.72) \quad \text{when } D = 2.5 \text{ mm}$$

Prediction of the ETT Pressure Drop, ETT Resistance, and WOB Due to ETT (ETT WOB) in Clinical Practice

The formulas proposed in the present study (see APPENDIX) allow calculation of the pressure value required to overcome ETT resistance for a given flow and calculation of the pressure at the distal end of the ETT, under any conditions where ETT geometry (ID, curvature diameter, and length) and gas properties are known. This means that calculation of the pressure drop due to the ETT gives the minimal level of inspiratory pressure required to overcome ETT resistance, as shown below.

ETT pressure drop and resistance estimation. Our results indicate that, in any clinical situation, knowledge of ETT geometry and of the flow regime allows accurate evaluation of the pressure drop specifically due to the ETT. In the neonatal range, there is no easy way of measuring this pressure drop. The catheter technique for measuring tracheal pressure, used for adult ETTs (8, 17), is hardly applicable routinely during the neonatal period, even though its use has been attempted (5). If the catheter is too large, it will dramatically reduce the permeability of the ETT and may render ventilation difficult or hazardous and may also modify the flow regime, thus affecting the measurement. If the catheter is very thin, there is a high risk of its being partially or totally obstructed, which also impedes correct measurement.

Several groups (22, 23, 30) have provided empirical equations such as the Rohrer equation ($\Delta P = K_1 \cdot \dot{V} \cdot K_2 \cdot \dot{V}^2$) in which the coefficients K_1 and K_2 are both computed from the fitting of the data for a single ETT. Such empirical equations lack physical significance. They describe the pressure drop-flow relationship for a particular curvature of one specific ETT but do not account for variations in ETT ID, length, or curvature or for changes in gas composition. The use of such dimensional pressure-flow relationships in the present study would have led to seven distinct curves to describe the ETTs tested (Fig. 2), thus introducing seven distinct pairs of Rohrer coefficients. It is true that the

report by Sly et al. (22) takes into account the diameters and lengths of the ETTs, but the results cover a full page of the study, and the large number of multiple coefficient pairs given cannot easily be used in clinical practice. By contrast, the formulas proposed in the present work are applicable to all neonatal and pediatric ETTs. For example, we compared the results given by Sly et al. to the values obtained with the Ito formula, to which we added the pressure drop due to kinetic energy, and found that differences between the pressure drops were <15%. Note that, because entry effects and other nonlinear processes were disregarded, the formulas we propose do not provide the exact pressure drop, but they do give an estimation that is very close to the measured values.

In addition, it must be emphasized that the general formulas we propose apply to gases other than air. For instance, using pure oxygen instead of air slightly raises the resistance, whereas the use of a low-density gas mixture like heliox is known to reduce it (26, 28). In view of this, we use the Ito formula to calculate ETT resistance with air and heliox for an ETT with a diameter of 2.5 mm, a length of 14.8 cm, and a curvature diameter of 33 cm. For air, we predicted a resistance of $89 \text{ cmH}_2\text{O} \cdot \text{l}^{-1} \cdot \text{s}$ and for heliox a resistance of $73 \text{ cmH}_2\text{O} \cdot \text{l}^{-1} \cdot \text{s}$. These values are very close to the 90 and $68 \text{ cmH}_2\text{O} \cdot \text{l}^{-1} \cdot \text{s}$, respectively, measured by Wall (26) for the effect of gas density on ETT resistance at a flow of 100 ml/s.

ETT WOB. The pressure drop calculated according to the Ito formula (or the Blasius formula when appropriate) augmented by the pressure drop due to kinetic energy changes allows estimation of the ETT pressure drop and therefore the ETT WOB. WOB can be calculated from pressure drop and flow as

$$\text{WOB} = \oint P dV$$

where V is the volume and P is the pressure drop

The importance of the ETT WOB has already been studied (3, 6). It was clearly demonstrated that reducing the ETT diameter increased the WOB. On the basis of a flow pattern recorded in an infant, we simulated the inspiratory pressure drop and calculated the theoretical ETT WOB for physiological flow patterns in neonatal and pediatric ETTs. Flow was simulated, assuming a tidal volume for boys with mean French weight-for-age values and a normal respiratory rate (7), with intubation by using an ETT of standard size (1). Pressures were estimated from the physiological flow by using the laws that we have described in THEORY. WOB was computed by numerical integration. Figure 6 shows the ETT WOB simulation for ETTs, assuming a tidal volume of 7 ml/kg, whereas Fig. 7 shows the ETT WOB simulation for a tidal volume of 12 ml/kg and a 25% increase in the respiratory rate. In the first case (Fig. 6), the pressure drop is due to kinetic energy and laminar flow. For all ETTs, the ETT WOB normalized for tidal volume is relatively constant (between 0.09 and 0.17 mJ/ml), and the increase in work is mainly due to the pressure drop due to kinetic energy (from 17% of the total ETT WOB for the 2.5-mm ETT to 28%

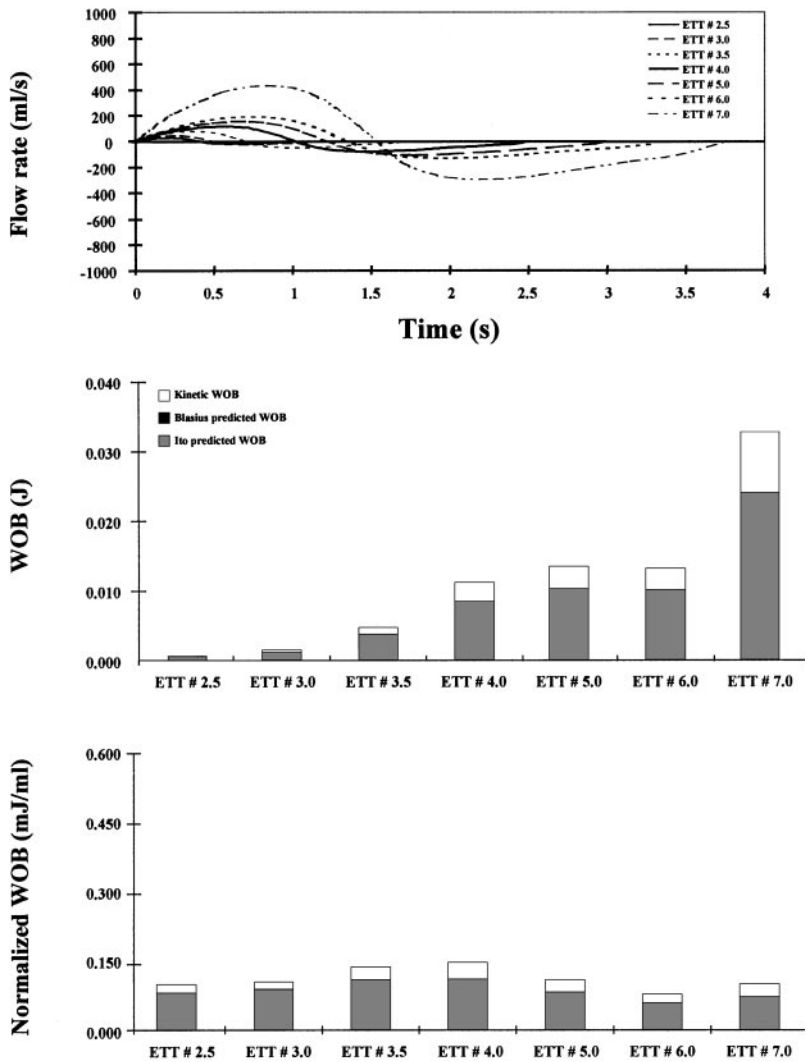


Fig. 6. Simulated flow (*top*), theoretical total work of breathing (WOB) due to ETT (ETT WOB; *middle*), and that normalized by tidal volume (V_T ; *bottom*). Pressure drop was computed from flow rate by using Ito or Blasius formula, depending on Reynolds number, plus pressure drop due to kinetic energy changes (see APPENDIX). ETT WOB was calculated by assuming a V_T of 7 ml/kg, a physiological respiratory rate (RR) with an inspiratory-to-expiratory ratio of 1/2.75. ETT #2.5: $V_T = 7$ ml, RR = 60 breaths/min; ETT #3.0: $V_T = 14$ ml, RR = 50 breaths/min; ETT #3.5: $V_T = 35$ ml, RR = 35 breaths/min; ETT #4.0: $V_T = 77$ ml, RR = 24 breaths/min; ETT #5.0: $V_T = 126$ ml, RR = 20 breaths/min; ETT #6.0: $V_T = 172$ ml, RR = 18 breaths/min; ETT #7.0: $V_T = 333$ ml, RR = 16 breaths/min.

for the 7.0-mm ETT). In the second case (Fig. 7), the turbulence occurs in the pediatric ETTs (4.0- to 7.0-mm ID). In these ETTs, the WOB is mainly due to the turbulent flow (between 43 and 56% of the total ETT WOB).

To evaluate the physiological significance of ETT WOB, we also calculated it from flow recordings obtained in two infants intubated with an ETT of 2.5-mm ID and who were breathing spontaneously in the continuous positive airway pressure mode. The data were taken from a previous study in which we assessed total WOB by using the esophageal catheter technique (14). In these two patients, the ETT WOB, calculated from the Ito formula plus the pressure drop due to kinetic energy value, was found to amount to 13 and 20% of total WOB, respectively (Table 2). The differences observed between these two infants were due to the differences in the flow spontaneously generated. The greater the weight and flow rate, the higher the ETT WOB. In view of these results, it would have been wise to use a larger ETT for the infant with a body weight of 1.9 kg if the patient's cricoid cartilage was large enough to accept it.

ETT WOB cannot be disregarded, particularly for small premature infants ventilated under intermittent

mandatory ventilation, and perhaps under synchronized intermittent mandatory ventilation, at a slow frequency. In these ventilatory modes, the portion due to spontaneous ventilatory cycles may exceed the portion due to mechanical ventilatory cycles. In these infants, we indeed demonstrated that the WOB in the continuous positive airway pressure mode was not different from the WOB necessary in the intermittent mandatory mode at slow frequency (14). In any case, the additional ETT WOB, better defined as unjustified, could have been compensated for by an adequate mode of ventilation with a low level of inspiratory pressure. In adults, it has been shown that the pressure support level compensating for the increase in ETT WOB varies between 3.4 and 12.4 cmH₂O (3). This additional WOB may be important, as it can lead to underestimation of an infant's ability to withstand extubation, and it is therefore important to be able to calculate it. This additional WOB may at least be taken into account in the process of weaning.

In summary, the pressure drop due to the ETT may be evaluated by general formulas that take account of flow, ETT geometry, and gas properties. When the ETT pressure drop is known, ETT resistance can be sepa-

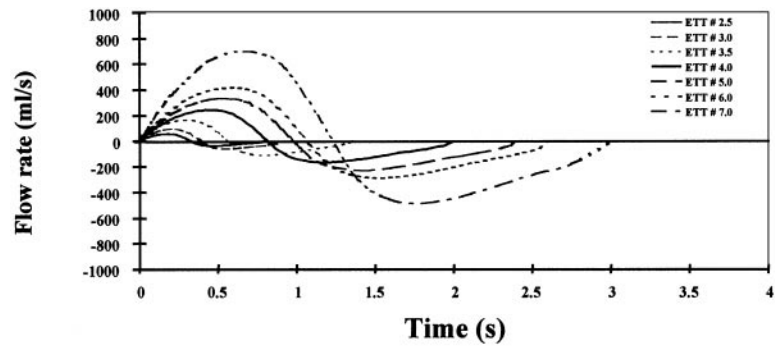
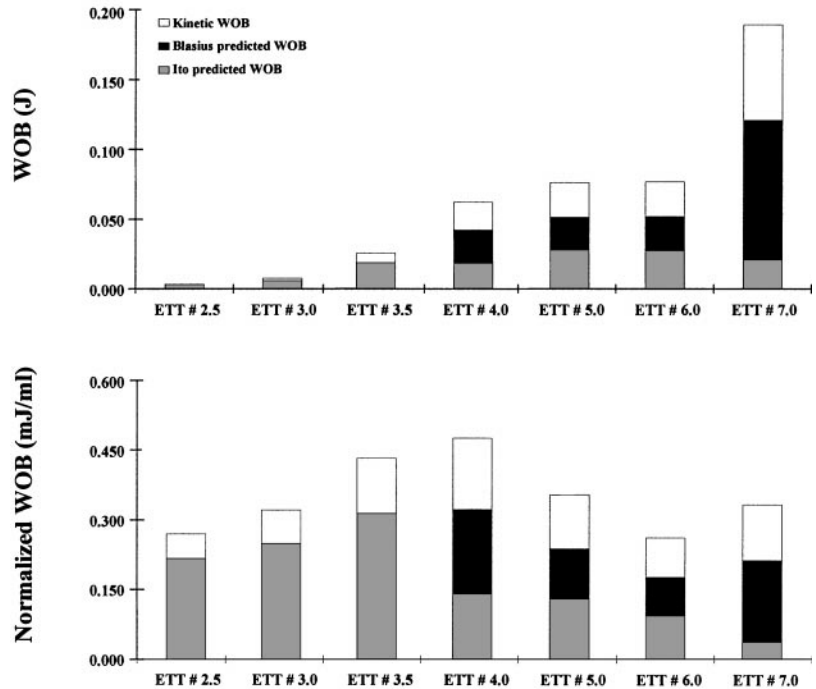


Fig. 7. ETT WOB was calculated from same formulas as in Fig. 6, assuming a V_T of 12 ml/kg and an increase in RR of 25%. ETT #2.5: $V_T = 12$ ml, RR = 75 breaths/min; ETT #3.0: $V_T = 24$ ml, RR = 63 breaths/min; ETT #3.5: $V_T = 60$ ml, RR = 44 breaths/min; ETT #4.0: $V_T = 131$ ml, RR = 30 breaths/min; ETT #5.0: $V_T = 216$ ml, RR = 25 breaths/min; ETT #6.0: $V_T = 295$ ml, RR = 23 breaths/min; ETT #7.0: $V_T = 570$ ml, RR = 20 breaths/min. Note that scale in *middle* panel is different from that in *middle* panel in Fig. 6. Total ETT WOB is much larger than that computed for conditions specified in Fig. 6. Note also appearance of turbulent flow for 4.0- to 7.0-mm ETTs and large amount of related WOB.



rated from total resistance, and the ETT WOB can easily be calculated from the measurement of the inspiratory flow. All these formulas can be easily used with a pocket calculator, thus allowing fast calculation of these different parameters in clinical practice.

APPENDIX

ETT Pressure Drop

The pressure drop in the region between two distinct cross sections of a tube during a steady incompressible flow can be

estimated from the Cotton-Fortier formula (also called the generalized Bernoulli formula) (4). When the hydrostatic pressure gradient is disregarded, which is usual when the fluid is a gas, this formula is used to calculate the pressure drop between the two cross sections S_1 and S_2 and becomes

$$\underbrace{(p_2 - p_1)}_{\Delta P} = \underbrace{\frac{-D_p}{\dot{V}}}_{\Delta P_{vd}} + \underbrace{-0.5 \cdot \rho \cdot (\alpha_2 \cdot \bar{u}_2^2 - \alpha_1 \cdot \bar{u}_1^2)}_{\Delta P_{ke}} \tag{1}$$

Table 2. *Work of breathing due to the ETT in 2 patients spontaneously breathing in the continuous positive airway pressure mode*

Patient No.	Wt, kg	Mean Tidal Volume, ml	Mean Maximal Flow, ml/s	Total WOB, mJ/ml	ETT WOB, mJ/ml	%ETT WOB
1	1.13	9.1	28.6	0.77	0.10	13.4
2	1.92	11.5	39.9	0.81	0.16	19.4

ETT WOB, work of breathing (WOB) due to ETT. The total WOB of these patients was measured by using the esophageal catheter technique and is the mean of 5 recordings (14). The %ETT WOB is the mean of the percentages computed for each recording.

where \dot{V} is the flow rate, D_p is the rate of energy dissipation in the region between the cross sections S_1 and S_2 , ρ is the fluid density, \bar{u}_i is the average velocity of section i defined by $\bar{u}_i = \dot{V}/A_i$, where A_i designates the cross-sectional area, α_i is the coefficient of the kinetic energy associated with section i , and p_i is the pressure in section i .

ΔP , the pressure drop in the region between the two cross sections, is divided into two components: the first one is ΔP_{vd} , representing viscous dissipation, which is always negative, and the second is ΔP_{ke} , representing the pressure drop due to changes in kinetic energy.

The kinetic energy term, ΔP_{ke} , is given by the second term of Eq. 1 above, in which

$$\alpha_i = \iint_{S_i} \left(\frac{u}{\bar{u}} \right) \cdot \frac{\partial S}{A_i}$$

and u is the fluid velocity. The coefficient α_i depends on the velocity profile and varies between one (flat profile) and two (parabolic profile). In view of the entry length generally

When flow is laminar and D_c is the diameter of the curvature, the Ito formula (12) gives ΔP_{vd} as

$$\frac{\Delta P_{vd}}{0.5 \cdot \rho \cdot \bar{u}^2} \cdot \frac{D}{L} = 64 \cdot \text{Re}^{-1} \cdot [0.103 \cdot \text{De}^{0.5} \cdot (1 + 3.945 \cdot \text{De}^{-0.5} + 7.782 \cdot \text{De}^{-1} + 9.097 \cdot \text{De}^{-1.5} + 5.608 \cdot \text{De}^{-2} + \dots)] \quad (6)$$

if $30 < \text{De} < 2,000$

In its dimensional form, the Ito formula can be written

$$\Delta P = \dot{V}^{1.5} \cdot (4.736 \cdot \rho \cdot L \cdot D_c^{0.25} \cdot D^{-4.25} \cdot \nu^{0.5}) + \dot{V} \cdot (16.556 \cdot \rho \cdot L \cdot D^{-4} \cdot \nu) + \dot{V}^{0.5} \cdot (28.942 \cdot \rho \cdot L \cdot D_c^{0.25} \cdot D^{-3.75} \cdot \nu^{1.5}) + (29.984 \cdot \rho \cdot L \cdot D_c^{0.5} \cdot D^{-3.5} \cdot \nu^2) + \dot{V}^{-0.5} \cdot (16.381 \cdot \rho \cdot L \cdot D_c^{0.75} \cdot D^{-3.25} \cdot \nu^{2.5}) \quad (7)$$

accepted in fluid mechanics, ~ 10 – 15 diameters for laminar flow and the respective length of the ETT, for calculation of kinetic energy we considered that the flow was flat in the ETT, as the entry length was larger than the ETT length, except for the 2.5-mm-ID ETT for which the ETT length was close to the entry length. We therefore considered α_{ETT} to be equal to 1, except for the 2.5-mm-ID ETT, for which α_{ETT} was considered to be equal to 1.5. This analysis, which can also be interpreted as a larger entry effect in the 2.5-mm-ID ETT connector and is confirmed by the fact that the ETT pressure drop, corrected for kinetic energy measured for various diameters of the curvature (D_c), i.e., when ΔP_{ETT} varies but not ΔP_{ke} , in 2.5- and 3.0-mm-ID ETTs perfectly agrees with the pressure drop predicted by the Ito formula.

The viscous dissipation term, ΔP_{vd} , depends on the flow regime.

In a long straight tube in laminar flow (Poiseuille flow), ΔP_{vd} is given by the well-known formula (4, 21)

$$\frac{\Delta P_{vd}}{0.5 \cdot \rho \cdot \bar{u}^2} \cdot \frac{D}{L} = \frac{64}{\text{Re}} \quad (2)$$

with

$$\text{Re} = \frac{\bar{u} \cdot D}{\nu} \quad (3)$$

as the Reynolds number. D is tube diameter, L is tube length, and ν is the kinematic viscosity ($\nu = \mu/\rho$, where μ is the dynamic viscosity). This formula is valid as long as the Reynolds number is $< 2,300$.

For larger Reynolds numbers ($> 2,300$) the flow becomes turbulent, and Eq. 2 is no longer valid. For a hydraulically smooth tube, Eq. 2 should be replaced by the Blasius formula (4, 21)

$$\frac{\Delta P_{vd}}{0.5 \cdot \rho \cdot \bar{u}^2} \cdot \frac{D}{L} = 0.316 \cdot \text{Re}^{-0.25} \quad (4)$$

In a curved tube, the presence of centrifugal forces makes ΔP_{vd} larger than in a straight tube. The characteristic dimensionless variable that determines the effect of the curvature is the Dean number (De)

$$\text{De} = \text{Re} \cdot \left(\frac{D}{D_c} \right)^{0.5} \quad (5)$$

and is a polynomial function of $\dot{V}^{1.5}$, \dot{V}^1 , $\dot{V}^{0.5}$, \dot{V}^0 , and $\dot{V}^{-0.5}$.

The critical Reynolds number, i.e., the number for which the flow becomes turbulent, is larger in a curved tube than in a straight tube. It depends on the ratio D/D_c . Ito proposed the following formula

$$\text{Rec} = 20,000 \cdot \left(\frac{D}{D_c} \right)^{0.32} \quad (8)$$

where Rec is the critical Reynolds number.

For turbulent flow, Ito showed that the dimensionless variable is

$$\text{Re} \cdot \left(\frac{D}{D_c} \right)^2 \quad (9)$$

For this flow, different empirical formulas were proposed to compute ΔP_{vd} . White proposed (27)

$$\frac{\Delta P_{vd}}{0.5 \cdot \rho \cdot \bar{u}^2} \cdot \frac{D}{L} = (0.316 \cdot \text{Re}^{-0.25}) \cdot \left\{ 1 + 0.075 \cdot \left[\text{Re} \cdot \left(\frac{D}{D_c} \right)^2 \right]^{0.25} \right\} \quad (10)$$

For low $\text{Re} \cdot (D/D_c)^2$ values, the pressure drop given by the White formula is approximated by the Blasius formula (Eq. 4), which is simpler to use. In the clinical range, $\text{Re} \cdot (D/D_c)^2$ does not exceed 10, and discrepancy between the two formulas does not exceed 12% at the maximal flow rate.

Oscillatory Flow

In clinical practice, flow in the ETT is oscillatory. However, under certain conditions, oscillatory flow can be considered to be quasi-steady, i.e., it behaves instantaneously like steady flow. Criteria for quasi-steady flow conditions in airways have already been extensively discussed (10, 20).

Steady or unsteady conditions depend on the balance between 1) the viscous force added to the convective acceleration, which alone causes the fluid to respond instantaneously; and 2) the inertial forces, which cause the fluid to lag. For fully developed laminar oscillating flow in a straight tube (29), the balance between viscous and inertial forces is given by the Womersley parameter $\alpha = D/2 \sqrt{\omega/\nu}$, where D is the diameter, ω is the pulsation, and ν is the kinematic viscosity. It is only when α is much greater than one that the unsteadiness of flow cannot be neglected. It has been shown (10, 29) that an increase in resistance over the entire flow occurs only for $\alpha \geq 4$. Such a criterion applied to the ETT introduces a higher

bound of frequency (f_{\max}) to ensure the quasi-steady condition. In air, this higher bound is roughly

D (mm)	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
f_{\max}	24	17	12.5	9.5	7.5	6	5	4.2	3.6	3.1

The presence of curvature in the tube or singular losses (for example entry phenomena), as in our study, increase convective accelerations and viscous loss in contrast to inertial forces. They therefore tend to increase the higher bound of frequency. In summary, for the purposes of our study, flow in the ETT can be considered to be quasi-steady.

This work was performed while P. W. Blanchard was on sabbatical from the Université de Sherbrooke, Québec, Canada.

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Received 23 September 1998; accepted in final form 18 February 1999.

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