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Continuous Calculation of Intratracheal Pressure in Tracheally Intubated Patients

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Background: Intratracheal pressure (P_{trach}) should be the basis for analysis of lung mechanics. If measured at all, P_{trach} is usually assessed by introducing a catheter into the trachea *via* the lumen of the endotracheal tube (ETT). The authors propose a computer-assisted method for calculating P_{trach} on a point-by-point basis by subtracting the flow-dependent pressure drop $\Delta P_{ETT}(\dot{V})$ across the ETT from the airway pressure (P_{aw}), continuously measured at the proximal end of the ETT.

Methods: The authors measured the pressure-flow relationship of adult endotracheal tubes with different diameters (ID, 7–9 mm) at different lengths and of tracheostomy tubes (ID, 8–10 mm) in the laboratory. The coefficients of an approximation equation were fitted to the measured pressure-flow curves separately for inspiration and expiration. In 15 tracheally intubated patients under volume-controlled ventilation and spontaneous breathing, the calculated P_{trach} was compared with the measured P_{trach}.

Results: The authors present the coefficients of the "nonlinear approximation": $\Delta P_{ETT} = K1 \cdot \dot{V}^{K2}$, with ΔP_{ETT} being the pressure drop across the ETT and K1 and K2 being the coefficients relating $\dot{V}$ to ΔP_{ETT}. An important result was an inspiration/expiration asymmetry: the pressure drop caused by the inspiratory flow exceeds that of the expiratory flow. A complete description of the pressure-flow relationship of an ETT, therefore, requires a set of four coefficients: K1I, K2I, K1E, and K2E. The reason for this asymmetry is the abrupt sectional change between ETT and trachea and the asymmetric shape of the swivel connector. Comparison of calculated and measured P_{trach} in patients gives a correspondence within ± 1 cmH_2O (mean limits of agreement). The mean root-mean-square (rms) deviation is 0.55 cmH_2O.

Conclusions: P_{trach} can be monitored by combining our ETT coefficients and the flow and airway pressure continuously measured at the proximal end of the ETT. **(Key words: Anesthetic equipment: endotracheal tube; tracheostomy tube. Measurement techniques: flow-dependent pressure drop. Trachea: intubated.)**

ANALYSIS of respiratory system mechanics is based on measured flow, volume, and pressure at the airway opening. In the tracheally intubated patient, there is a considerable difference between the pressure at the proximal end of the endotracheal tube (ETT), usually called airway pressure (P_{aw}), and the pressure at the distal end of the ETT, called tracheal pressure (P_{trach}). This pressure difference equals the pressure drop across the ETT. The ETT acts as an additional flow resistance connected in series with the patient's conductive airways. At flow rates and respiratory frequencies usually observed in adults whose lungs are mechanically ventilated, the flow within the ETT is predominantly turbulent. The ETT is, therefore, a nonlinear, flow-dependent resistive element strongly influencing the analysis of patient respiratory system mechanics.[1–4]

Assessment of P_{trach} is, consequently, a prerequisite for mechanics analysis. If measured at all, P_{trach} is usually assessed by introducing a catheter into the trachea *via* the lumen of the ETT.[1,5,6] As an alternative, P_{trach} can be continuously calculated as the difference of continuously measured airway pressure minus flow-dependent pressure drop $\Delta P_{ETT}(\dot{V}(t))$ across the ETT:

$$P_{trach}(t) = P_{aw}(t) - \Delta P_{ETT}(\dot{V}(t)). \qquad (1)$$

Application of this method requires information about the flow-dependent pressure drop $\Delta P_{ETT}(\dot{V}(t))$ across the ETT, which has already been investigated by several authors, either in the laboratory or in patients in whom the trachea was intubated. Unfortunately, published data show wide variability.[1,3,6–16] If one focuses on a single flow value, for example 1 l/s, and on

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a single ETT diameter, for example 8.0 mm, the corresponding pressure drop values published demonstrate a variability from 2 to 10 cmH_2O (table 1), which may be explained mainly by the considerable differences in the equipment used.

It is the purpose of this study, first, to systematically investigate in the laboratory the pressure-flow relationship of ETT and tracheostomy tubes of different sizes and lengths usually used in adults, and, second, to evaluate the method of continuously calculating tracheal pressure in patients under a variety of clinical conditions by comparing P_{trach} calculated with P_{trach} measured by the catheter technique.

Materials and Methods

Figure 1 shows the equipment setup. An LS4000 lung simulator (Drägerwerk, Lübeck, Germany) driven by an external sine wave oscillator was used to generate a sinusoidal flow of room air with ± 2 l/s amplitude at 14 cycles/min. The flow was measured with a Fleisch no. 2 pneumotachograph (PT, Metabo, Epalinges, Switzerland) connected to an FC040 differential pressure transducer (Furness Controls, Bexhill, UK). The flow was directed through a standard 15-mm swivel connector (SC, No. 100/250/001, Portex Ltd, Hythe, Kent, U.K.), the ETT under test, and an artificial trachea consisting of a lucite tube of 21 mm ID open to atmosphere (AT). Pressure P1 was taken from a separate opening located in the wall of the connecting diffuser

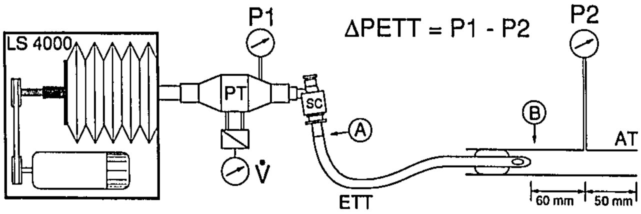

Fig. 1. Equipment needed to make measurements. LS4000 = lung simulator used to generate sinusoidal flow; PT = pneumotachograph; SC = swivel connector; AT = artificial trachea; circled "A" and "B" = demarcations for ETT length, see text for explanation; and ΔP_{ETT} = pressure difference measured across ETT.

of the pneumotachograph (diameter at the measuring site 20 mm, diffuser angle 10°). The tip of the ETT was inserted centrally into the artificial trachea. The tracheal near field flow pattern of the ETT is highly asymmetric because of the special shape of its tip (our own observations in the physical model). The P2 was, therefore, taken by means of a ring channel connected to the artificial trachea through 12 equally distributed small radial holes, 60 mm from the tip of the ETT and 50 mm from the end of the artificial trachea (fig. 1). All positions of the pressure-measuring sites and the geometry of the artificial trachea were optimized in preliminary laboratory investigations. The P1 and P2 were measured using two SZ75120 relative pressure transducers (Sensym, Milpitas, CA). The flow signal and the pressure difference signal, $\Delta P = P1 - P2$, were sampled at a rate of 60 Hz and digitized 12 bits wide for subsequent numeric analysis.

Table 1. Pressure Drop across an Endotracheal Tube (ETT) of 8 mm ID at 1 l/s Calculated from Published Data

Reference	Year	Physical Model	Patient	ETT Length (cm)	Pressure drop across the ETT at 1 l/s (cmH_2O)
Sahn *et al.*[14]	1976	X		?	1.9
Sullivan *et al.*[3]	1976	X		30.5	6.1
Behrakis *et al.*[8]	1983	X		35	9.8*
Gottfried *et al.*[12]	1985	X		24	5.9
Rossi *et al.*[13]	1985	X		24	5.9
Weissman *et al.*[15]	1986	X		25	4
Wright *et al.*[1]	1989	X		32	4.1
Wright *et al.*[1]	1989		X	22–28	5.3†
Prezant *et al.*[11]	1990	X		24	5.5
Berg van den *et al.*[10]	1991	X		?	11.1‡
Pesenti *et al.*[6]	1991		X	?	8.9
Bhatt *et al.*[16]	1992	X		22	5.4

* Assessed with 70% N_2O/30% O_2.

† Linear interpolation between ETT resistance values given at 50 l/min and at 80 l/min.

‡ Pressure drop across ETT, ventilator tubing, and pneumotachograph.

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Endotracheal tubes sized from 7 to 9 mm ID in ½-mm increments (107-70, 107-90 intermediate endotracheal tube; Mallinckrodt Laboratories, Athlone, Ireland) were measured. One tube of each size was measured in its original length and was cut to different lengths ranging from 20 to 30 cm, measured from the tip (point B, fig. 1) to the lower end of the 15-mm connector (point A, fig. 1). We also measured the pressure differences of the 122-70, 122-80, and 122-90 hi-lo jet ETT and the 100-80, 100-90, and 100-10 tracheostomy tubes. We tied the tracheal tubes to a test fixture designed to approximate the typical curvature of the ETT obtained from radiologic measurement of a roentgenogram of a lateral view of the cervical region of a mechanically ventilated patient in the ICU.

Further preliminary laboratory investigations have shown that there is no significant influence of the oxygen concentration on the results.

Mathematic Procedure

During laboratory measurements, ten consecutive sinusoidal cycles were recorded for each ETT. The data were subdivided into ten arrays, each containing one cycle. The arrays were then averaged.

We applied three different mathematic models to the averaged data arrays to approximate the measured pressure-flow dependence, using the standard Marquardt least-squares fit technique.[17] The three models were as follows.

The first model was combined linear and nonlinear pressure-flow dependence, which we introduce here and call "3-coefficient approximation":

$$\Delta P_{ETT} = K1 * \dot{V}^{K2} + K3 * \dot{V}. \qquad (2)$$

The second model was combined linear and quadratic pressure-flow dependence (Rohrer[18]), here called "quadratic approximation":

$$\Delta P_{ETT} = K1 * \dot{V}^2 + K3 * \dot{V}. \qquad (3)$$

The third model was pure nonlinear pressure-flow dependence (Gottfried *et al.*[12]), here called "nonlinear approximation":

$$\Delta P_{ETT} = K1 * \dot{V}^{K2}. \qquad (4)$$

The first model (equation 2) relates to the quadratic approximation (equation 3) in that K2 differs from 2, and relates to the nonlinear approximation (equation 4) in that K3 differs from 0. We used this model to test whether there is an optimal way of going between the quadratic approximation and the nonlinear approximation. To consider inherent inspiration/expiration (I/E) asymmetry of the airflow within the ETT and trachea, the Marquardt procedure was followed separately for inspiration and expiration. This gives four coefficients with equations 3 and 4, and six coefficients with equation 2, to completely describe the flow-resistive properties of an ETT being used in a patient.

Investigation in Patients

We studied 15 tracheally intubated patients admitted to the Basel University Clinics. Patients were studied in the ICU as well as in the operating theater. Clinical conditions (basic disease, type of ventilator, ventilatory mode, and inspiratory gas mixture) are listed in table 2. To measure tracheal pressure, we introduced a catheter with two side holes (at 8 and 13 mm distance from the tip) without end hole and 2.2 mm OD (K-31; Baxter, Trieste, Italy). During the measurement, the catheter was introduced by wire guide through the ETT with its tip protruding 3 cm beyond the tip of the ETT; the catheter tip was, thus, completely outside the ETT but safely prevented from entering a main bronchus (in patients 1–6, investigated immediately after intubation, the ETT was minimally introduced under visual inspection to be safely blocked; in patients 7–15, the distance between ETT tip and carina was verified to be greater than 3 cm from roentgenograms of the thorax). Simultaneously, airway pressure was measured at the same location as taken for the laboratory measurements (P1, fig. 1). The flow and pressure signals were sampled and digitized (12 bit) at a rate of 60 Hz and stored digitally for offline analysis. The measurement was approved by the Ethical Committee of our institution.

Because the pressure-measuring catheter reduces the free cross-sectional area of the ETT, it strongly influences the pressure-flow relationship. The respective coefficients for equation 4 were, thus, determined from a special data set obtained from laboratory measurements of the ETTs with the same pressure-measuring catheter in place. These coefficients were used to calculate tracheal pressure using equation 1.

Statistical Analysis

To test the quality of fit of the three approximations (equations 2–4), the differences between all pairs of measured and fitted sample points were evaluated. To

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Table 2. Clinical Situation of the Patients Preceding the Investigation and Ventilatory Treatment during the Investigation

Patient No.	Age (yr)	Sex	Location	Clinical Situation	Ventilatory Mode	Ventilator Type	FI_{O_2}	N_2O	Volatile Anesthetic
1	61	M	OPTH	General anesthesia for endarterectomy of both common iliac arteries with claudication	IPPV	Ventilog*	0.53	0.47	Isoflurane
2	40	M	OPTH	General anesthesia for cholecystectomy (recurrent cholecystitis) in a patient with traumatic paraplegia	IPPV	Ventilog	0.50	—	Isoflurane
3	32	F	OPTH	General anesthesia for resection of goiter (hyperthyroid adenoma)	IPPV	Ventilog	0.53	0.47	Enflurane
4	37	M	OPTH	General anesthesia for staging laparotomy in Hodgkin's disease	IPPV	Ventilog	1.00	—	—
5	51	F	OPTH	General anesthesia for laparoscopic cholecystectomy for recurrent cholecystitis in a patient with traumatic paraplegia	IPPV	Ventilog	0.56	—	Isoflurane
6	36	M	OPTH	General anesthesia for laparascopic ligation of the left spermatic vein (painful varicocele)	IPPV	Ventilog	0.98	—	Enflurane
7	62	M	GSICU	After abdominal aortic aneurysm surgery; 8 weeks after myocardial infarction; chronic hemodialysis for renal failure	CPPV	SV 900 C†	0.40	—	—
8	66	F	MICU	Acute respiratory failure in pneumonia (COLD) after severe hemorrhage from esophageal varices; hemodialysis for acute renal failure	CPPV	Bennett 7200‡	0.50	—	—
9	45	M	CSICU	After open heart procedure (3 CABG: 2 VG, 1 IMA)	CPPV	EV-A§	0.64	—	—
10	46	M	CSICU	After open heart procedure (4 CABG: 3 VG, 1 IMÁ) atelectasis: PEEP 5 before extubation	CPPV	SV 900 C	0.60	—	—
11	63	M	CSICU	After open heart procedure (3 CABG: 2 VG, 1 IMA); 1 h before rethoracotomy for surgical bleeding and hypovolemia	IPPV	SV 900 C	0.40	—	—
12	30	M	CSICU	After open heart procedure (replacement of aortic valve and ascending aorta for dissecting aneurysm type B with severe aortic regurgitation; Marfan's Syndrome)	IPS	EV-A	0.40	—	—
13	47	M	CSICU	After open heart procedure (4 CABG: 3 VG, 1 IMA)	IPS	EV-A	0.40	—	—
14	73	F	CSICU	After open heart procedure (4 CABG: 3 VG, 1 IMA)	SIMV	EV-A	0.40	—	—
15	29	M	MICU	Acute respiratory failure due to pneumonia after aspiration during cardiopulmonary rescuscitation in acute heroin intoxication; HIV positive	IPPV	Bennett 7200	0.30	—	—

ICU = intensive care unit; CSICU = cardiosurgical intensive care unit; MICU = medical intensive care unit; OPTH = operating theater; GSICU = general surgical intensive care unit; CABG = coronary artery bypass graft; VG = venous graft; IMA = internal mammarian graft; IPPV = mechanical ventilation with intermittent positive pressure; CPPV = mechanical ventilation with continuous positive pressure; SIMV = synchronized intermittent mandatory ventilation; IPS = spontaneous breathing with inspiratory pressure support.

* Bag-in-bottle anesthesia ventilator (Drägerwerk, Lübeck, Germany).

† Siemens-Elema, Solna, Sweden.

‡ Puritan-Bennett, Carlsbad, CA.

§ Drägerwerk.

obtain one representative value that is unaffected by the sign of the individual differences, we calculated the root-mean-square (rms) deviation. For each approximation, and for each tube in table 3, one inspiratory and one expiratory rms-value was calculated separately.

To compare the catheter and the calculation methods, the differences between all inspiratory and expiratory pairs of measured and calculated P_{trach} sample points were evaluated. The limits of agreement of both methods were determined using the bias and precision analysis according to Bland and Altman.[19] Furthermore, rms deviation was calculated. For statistical analysis, the data of a sequence of 2 min were used, *i.e.*, 7,200 sample points in each patient. This includes 9–33 breaths (18 ± 8, mean ± SD) analyzed, depending on the respiratory frequency.

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Table 3. Nonlinear Approximation Coefficients for Endotracheal and Tracheostomy Tubes of Different Size and Length (Ambient Conditions)

Specification 21 mm Trachea			Inspiration				Expiration			
Type Diameter (mm)	Status	Length (cm)	K1I (cmH_2O*s/L)	K2I	rms (cmH_2O)	N*	K1E (cmH_2O*s/L)	K2E	rms (cmH_2O)	N*
Mallinckrodt 107 intermediate										
7.0	Original	30.8	11.12	1.99	0.27	120	11.69	1.85	0.36	126
7.0	Cut	30.0	11.00	2.02	0.28	120	11.74	1.84	0.36	126
7.0	Cut	28.0	11.77	2.11	0.33	120	12.21	1.78	0.36	126
7.0	Cut	26.0	10.20	2.08	0.27	120	10.24	1.80	0.30	126
7.0	Cut	24.0	10.72	2.06	0.26	120	10.73	1.75	0.31	126
7.0	Cut	22.0	10.08	2.09	0.39	120	10.09	1.76	0.28	126
7.0	Cut	20.0	9.62	2.06	0.25	120	9.44	1.77	0.32	126
7.5	Original	31.2	8.41	1.96	0.21	121	9.28	1.81	0.31	125
7.5	Cut	30.0	8.52	1.98	0.32	121	9.19	1.77	0.24	125
7.5	Cut	28.0	8.35	2.01	0.31	121	8.45	1.77	0.28	125
7.5	Cut	26.0	7.87	2.03	0.21	121	7.92	1.79	0.30	125
7.5	Cut	24.0	7.86	1.95	0.26	121	7.63	1.77	0.30	125
7.5	Cut	22.0	7.20	1.98	0.23	121	7.11	1.79	0.27	125
7.5	Cut	20.0	7.35	2.01	0.25	122	6.88	1.76	0.24	124
8.0	Original	32.3	6.57	1.94	0.23	122	7.50	1.75	0.24	124
8.0	Cut	30.0	6.41	1.93	0.25	121	7.59	1.68	0.20	125
8.0	Cut	28.0	6.47	1.92	0.20	122	7.03	1.69	0.16	124
8.0	Cut	26.0	6.34	2.03	0.25	122	6.34	1.74	0.18	124
8.0	Cut	24.0	6.14	2.02	0.23	122	6.15	1.78	0.24	124
8.0	Cut	22.0	5.95	2.06	0.24	122	6.34	1.79	0.19	124
8.5	Original	32.7	5.17	1.94	0.20	122	5.12	1.88	0.28	124
8.5	Cut	30.0	4.83	1.96	0.19	122	5.48	1.71	0.19	124
8.5	Cut	28.0	4.69	1.97	0.19	122	5.30	1.79	0.17	124
8.5	Cut	26.0	4.97	2.00	0.18	123	4.78	1.72	0.14	123
8.5	Cut	24.0	4.88	2.01	0.19	123	4.50	1.74	0.19	123
8.5	Cut	22.0	4.64	1.99	0.18	123	4.49	1.79	0.17	123
9.0	Original	33.8	4.29	1.94	0.16	122	4.28	1.88	0.24	124
9.0	Cut	30.0	4.10	1.95	0.17	123	4.21	1.77	0.15	123
9.0	Cut	28.0	4.02	1.96	0.16	123	4.10	1.74	0.14	123
9.0	Cut	26.0	4.14	1.99	0.16	123	4.00	1.70	0.16	123
9.0	Cut	24.0	3.92	2.00	0.15	123	3.74	1.71	0.15	123
9.0	Cut	22.0	3.74	1.93	0.13	123	3.56	1.71	0.16	123
Mallinckrodt 122 hi-lo jet										
7.0	Original	30.5	10.59	2.03	0.29	119	11.25	1.82	0.45	127
8.0	Original	32.0	5.84	1.89	0.19	123	5.74	1.77	0.17	123
9.0	Original	32.0	3.85	1.90	0.14	123	3.79	1.78	0.18	123
Mallinckrodt 100 hi-lo tracheostomy										
8.0	Original	9.0	4.50	2.03	0.14	125	3.70	1.74	0.12	120
9.0	Original	10.0	2.95	2.00	0.10	124	2.24	1.79	0.15	121
10.0	Original	10.5	2.05	1.98	0.06	125	1.77	1.82	0.11	121

rms = root-mean-square deviation.

* Number of analyzed samples.

Results

Laboratory Investigation

Figure 2 shows measured pressure difference ΔP_{ETT} *versus* flow from a laboratory measurement in a 7.5-mm ID ETT of 30 cm length, with the three approximation curves according to equations 2–4. The central part of figure 2 is marked and expanded to give figure

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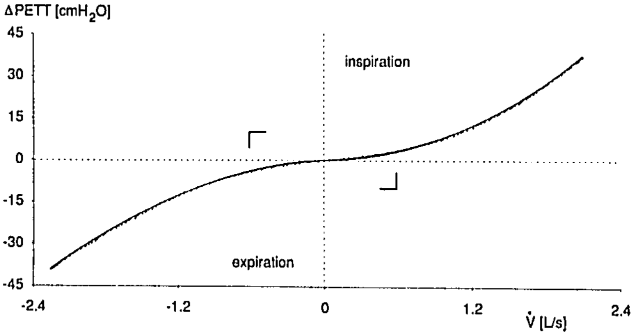

Fig. 2. Pressure difference ΔP_{ETT} measured across ETT *versus* flow through ETT (7.5 mm ID, 30 cm long). Measured sample points are averaged from ten consecutive sinusoidal flow cycles of the lung simulator. Approximation curves of approximation equations 2–4 are superimposed on measured sample points. Note that all three curves are nearly identical, except for small deviations near the origin. This small region is marked with brackets and expanded in figure 3.

3. Figure 3 shows that part where the three approximation curves display the largest differences in pressure-up to a flow of approximately 600 ml/s. At flows greater than 1,000 ml/s, the differences are smaller. The pressure difference between the three approximation curves is nowhere larger than 0.5 cmH_2O, indicating that the three equations are nearly equivalent in terms of approximation quality. The rms deviations calculated for the three types of approximation are all very small and quite similar. Table 4 lists, for each approximation, the rms values averaged from 38 tube investigations. Because the rms values did not differ significantly, the quality of fit did not "favor" one of the three approximations. We decided to use the nonlinear approximation (equation 4) because of the theoretical considerations described below.

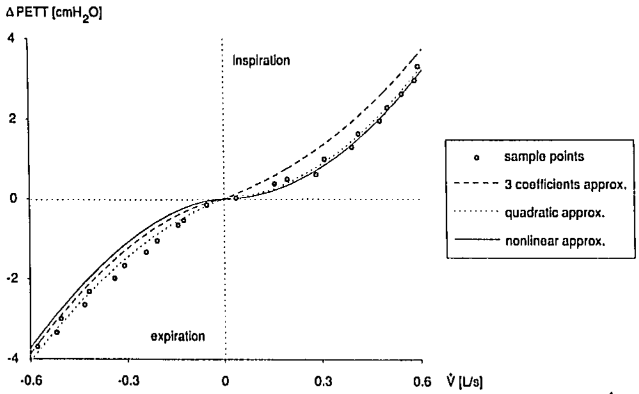

Fig. 3. Expanded view of the bracketed region of figure 2.

Table 4. Root-Mean-Square (rms) Deviation Calculated for the Three Types of Approximation

Approximation	Equation	rms Inspiration* (cmH_2O)	rms Expiration* (cmH_2O)
Three coefficients approximation	2	0.15	0.20
Quadratic approximation	3	0.23	0.21
Nonlinear approximation	4	0.22	0.23

* Each value is averaged from 38 tube investigations.

Table 3 lists the coefficients of the nonlinear approximation (equation 4) separately for inspiration and expiration determined in all ETTs investigated, along with the corresponding rms deviation in pressure and the number of samples used for calculations. The coefficients are related to ambient conditions.

Figure 4 shows approximation curves according to the nonlinear approximation (equation 4) for ETT from 7 to 9 mm ID and of 30 cm length. A strong dependence of pressure difference on diameter is observed, resulting in a pressure difference of the 7-mm ETT being three times that of the 9-mm ETT at 1 l/s.

Dependence of pressure difference on length is shown in figure 5 in an ETT of 7.5 mm ID. Although pressure difference increases, as expected, with length in expiration, no corresponding tendency can be observed in inspiration. Inspiratory pressure differences seem to be essentially less dependent on length than expiratory pressure differences. This highlights the marked asymmetry between spatial flow distributions in inspiration and expiration.

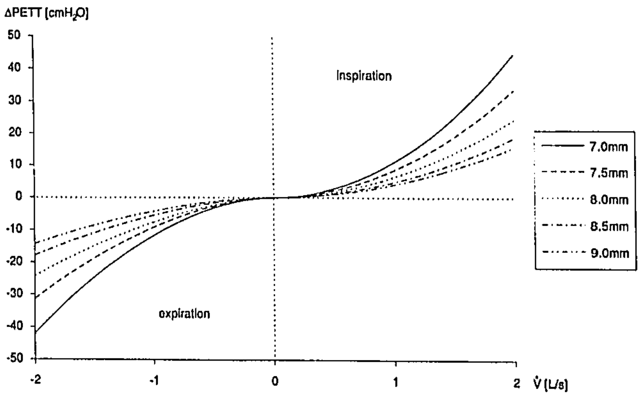

Fig. 4. Pressure differences across ETT of 30 cm length and of different diameters. Solid line = 7 mm; broken line = 7.5 mm; dotted line = 8 mm; dash-dot = 8.5 mm; and dash-dot-dot = 9 mm ID. Approximation curves are according to nonlinear approximation (equation 4).

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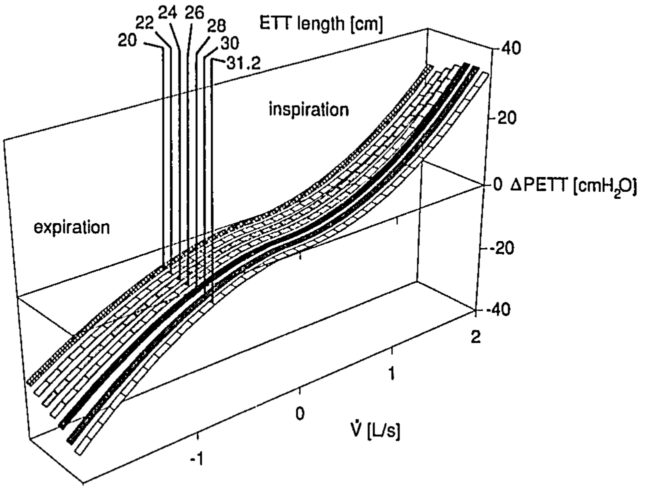

Fig. 5. Pressure differences across ETT of 7.5 mm ID and of different lengths. Three-dimensional view of the curves according to the nonlinear approximation (equation 4). The ETT lengths are 20–30 cm in 2-cm increments, and the original length of 31.2 cm, giving seven curves in all.

Finally, we compared pressure differences observed in an 8-mm ID ETT with those observed in cuffed tracheostomy tubes of 8 and 10 mm ID (fig. 6). Besides having lower flow resistance than the ETT, tracheostomy tubes display more I/E asymmetry. After tracheotomy, a tracheostomy tube can be inserted with an ID exceeding, usually by 2 mm, the ID of the ETT initially used. To compare a 10-mm tracheostomy tube with an 8-mm ETT, again at a flow of 1 l/s, the 10-mm tracheostomy tube accounts for less than one-third of the resistive pressure difference of the 8-mm ETT.

Patient Investigation

The results of the quantitative comparison between calculated and measured tracheal pressure and the ETT specifications are given in table 5. The lower/upper limit of agreement indicates how much calculated P_{trach} may be below/above measured P_{trach}. The confidence intervals of the limits of agreement are narrow, reflecting the small variations of the differences. The low rms deviations ranging from 0.27 to 0.99 cmH_2O (0.55 ± 0.24 cmH_2O, mean ± SD) show that the mean difference between measured and calculated P_{trach} is less than 1 cmH_2O. No systematic changes were observed with increasing duration of intubation up to 2 days.

Figures 7 and 8 show the calculated and measured tracheal pressure presented as V/P_{trach}-loops superposed on each other. Simultaneously, airway pressure measured at the proximal end of the ETT is drawn as a V/P_{aw}-loop. Figure 7 shows the V/P-loops obtained from patient 10 during volume-controlled ventilation. Figure 8 shows the V/P-loops obtained from patient 12 during spontaneous breathing. The difference in pressure between the V/P_{aw}-loop and the V/P_{trach}-loop equals the flow-dependent pressure drop across the ETT.

Discussion

In the current study, we analyzed the relationship between pressure drop across the endotracheal tube (ΔP_{ETT}) and flow by means of a laboratory setup tailored to mimic a realistic clinical situation. The setup includes the swivel connector, the anatomically curved ETT, and an artificial trachea. We investigated tracheal tubes and tracheostomy tubes having different ID. We also investigated all ETT of variable lengths. The coefficients of the approximation equations were fitted separately to the measured $\Delta P_{ETT}/\dot{V}$ curves for inspiration and expiration. The $\Delta P_{ETT}/\dot{V}$ curves are described by the fit coefficients of the approximation equation used.

The mean velocity of gas flow in an ETT of 8 mm ID is about seven times the mean velocity in a trachea of 21 mm ID. Thus, at a flow of 1 l/s, the mean velocity of flow in a 8-mm ETT approximates 2 m/s. The corresponding Reynolds number (Re) is 10,570, indicating turbulent flow (Re > 2,300 indicates turbulence). As a consequence of the turbulent gas flow, the $\Delta P_{ETT}/\dot{V}$ relationship of an ETT is nonlinear and, therefore,

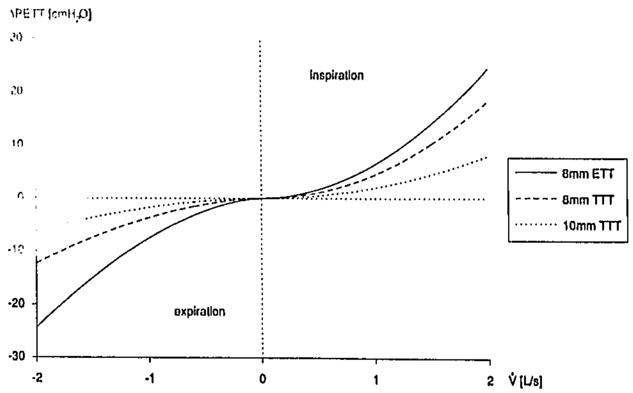

Fig. 6. Pressure differences across ETT and tracheostomy tubes. Solid line = 8-mm ID ETT, 30 cm long; broken line = 8-mm ID tracheostomy tube (TTT); and dotted line = 10-mm ID tracheostomy tube (TTT). Curves are according to the nonlinear approximation (equation 4).

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Table 5. Numeric Description of Difference of Calculated *Versus* Measured Tracheal Pressure and Specification of Endotracheal Tubes (ETT)

Patient No.	rms (cmH_2O)	Bias: Lower Limit of Agreement (cmH_2O)	Bias: Upper Limit of Agreement (cmH_2O)	95% Confidence Interval for the Lower Limit of Agreement (cmH_2O)		95% Confidence Interval for the Upper Limit of Agreement (cmH_2O)		ETT ID (mm)	ETT Length (cm)	Duration of Intubation (h)
1	0.67	−1.28	1.28	−1.31	−1.25	1.25	1.31	8.5	25	1
2	0.68	−1.36	1.28	−1.39	−1.33	1.25	1.31	8.5	25	1
3	0.65	−1.12	1.40	−1.15	−1.09	1.37	1.43	7.5	25	1
4	0.28	−0.57	0.51	−0.58	−0.56	0.50	0.52	8.5	25	1
5	0.31	−0.47	0.69	−0.48	−0.46	0.68	0.70	7.5	25	1
6	0.27	−0.45	0.59	−0.46	−0.44	0.58	0.60	8.5	25	1
7	0.68	−1.41	1.23	−1.44	−1.38	1.20	1.26	8.5	33	3
8	0.67	−1.20	1.44	−1.23	−1.17	1.41	1.47	7.5	25	8
9	0.93	−1.89	2.07	−1.93	−1.85	2.03	2.11	8.0	32	8
10	0.38	−0.79	0.69	−0.80	−0.78	0.68	0.70	8.5	26	9
11	0.47	−0.91	0.89	−0.93	−0.89	0.87	0.91	8.5	26	9
12	0.33	−0.58	0.78	−0.59	−0.57	0.77	0.79	8.5	26	17
13	0.27	−0.55	0.49	−0.56	−0.54	0.48	0.50	8.0	26	17
14	0.62	−1.07	1.29	−1.09	−1.05	1.27	1.31	7.5	25	32
15	0.99	−1.79	1.97	−1.83	−1.75	1.93	2.01	8.0	32	53
Mean	0.55	−1.03	1.11							
SD	0.24	0.47	0.50							

rms = root-mean-square deviation.

should be described by a power function. We have described the measured $\Delta P_{ETT}/\dot{V}$ function by means of three different approximation equations. To determine which is best, we can check the quality of the fit or the physical relevance of the approximation equation itself. The first derivative of the most common quadratic approximation (equation 3), $d(\Delta P_{ETT})/d\dot{V}$, gives a linear relationship between resistance of the endotracheal tube (R_{ETT}) and flow, whereas the first derivative of the three-coefficient approximation (equation 2) and of the nonlinear approximation (equation 4) give a nonlinear relationship between R_{ETT} and $\dot{V}$. From the physical point of view, the linearity of the $R_{ETT}/\dot{V}$ relationship may be a certain restriction of the quadratic approximation. However, the degree of correspondence between the measured data and the approximation equation, *i.e.*, the quality of fit, has been quantified by means of the rms deviation. The three-coefficient approximation (equation 2) does not give a smaller rms compared to the simpler quadratic (equation 3) and nonlinear (equation 4) approximation (table 4). This indicates that only two degrees of freedom are necessary for a good approximation. Furthermore, there is no need for a linear term, as in the three-coefficient approximation (equation 2), because flow separation and turbulence prevail over laminar flow throughout the investigated flow range. We, therefore, chose the nonlinear approximation (equation 4) for further considerations. (Coefficient tables based on quadratic approximation [equation 2] and the three-coefficient approximation [equation 3] are available from the authors on request.)

The function $\Delta P_{ETT}(\dot{V})$ is influenced by the properties of the ETT, *i.e.*, by its length, shape, diameter, and sectional shape.[20,21] $\Delta P_{ETT}(\dot{V})$ is also reported to be influenced by the properties of the gas flow, its velocity, respiratory frequency, and the composition of the gas.[20–22] In addition, the pressure drop depends on the flow direction.[7] Inspiratory gas flow causes a greater pressure drop than expiratory gas flow. The values of the coefficients K2 (exponents) reflect this I/E asymmetry: K2I > K2E. From the basic work of Loring *et al.*[23] and Chang *et al.*,[22] we know the reason for this I/E asymmetry. At the tip of the ETT, there is an abrupt change in cross-sectional area from ETT to trachea. For example, the ratio of cross-sectional area between a trachea of 21 mm ID and an 8-mm ETT is about 7 (3.5 cm^2/0.5 cm^2). At regions with an abrupt area change, kinetic energy dissipates by flow separation, leading to additional pressure loss. This additional pressure loss is greater when the gas flow passes an abrupt sectional expansion, as in inspiration, than when the gas flow passes a contraction, as in expiration. The greater the step in cross section, the greater the pressure drop be-

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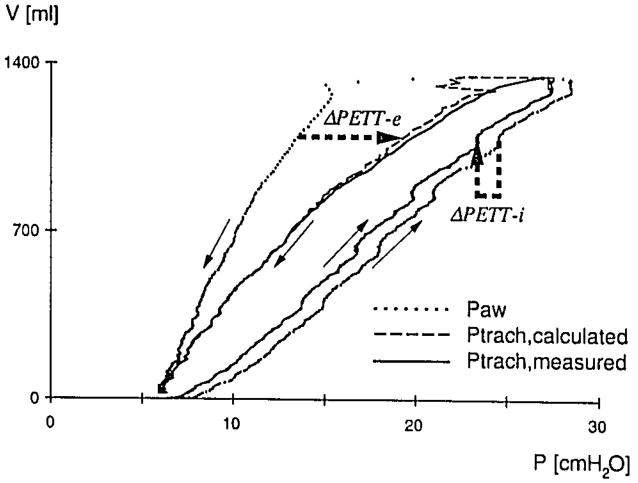

Fig. 7. Volume/pressure diagram in a tracheally intubated patient (patient 10) during volume-controlled mechanical ventilation (V_T = 1,280 ml-BTPS, RR = 7/min, $\dot{V}_I$ = 300 ml/s, and PEEP = 5 cmH_2O). Dotted line = V/P_{aw}-loop measured outside the ETT; solid line = V/P_{trach}-loop measured by means of the catheter (2.2 mm OD) introduced through the ETT; and broken line = V/P_{trach}-loop calculated using equation 5 with coefficients determined in a laboratory measurement of the ETT with the catheter in place. The pressure drop across the ETT (ΔP_{ETT}) is indicated both in inspiration and in expiration by a broken arrow. The direction of the arrow points from airway pressure to tracheal pressure.

cause of flow separation. To get a realistic change in cross section, we used a tracheal model with an ID in the upper range of the normal human trachea.[24,25] The swivel connector takes the form of a bent tube (ca. 90°) with side arms of different ID; it is another element contributing to the I/E asymmetry.

To consider I/E asymmetry of the ETT, any laboratory setup must, first, include the geometry of both its ends and, second, the flow-dependent pressure drop must be analyzed separately for inspiratory and expiratory flow. This necessitates two sets of fit coefficients for complete description of the pressure-flow relationship of an ETT: an inspiratory set and an expiratory set.

P_{trach} can be calculated point-by-point using our fit coefficients (summarized in table 3) for the ETT or the tracheostomy tube applied in the individual patient. To this end, equation 1 can be rewritten:

$$P_{trach}(t) = P_{aw}(t) - K1 * \dot{V}(t)^{K2}. \qquad (5)$$

In inspiration, the coefficients K1 and K2 are replaced by K1I and K2I; in expiration, K1 and K2 are replaced by K1E and K2E, respectively. Equation 5 shows that calculation of P_{trach} only requires airway pressure and flow, both measured at the proximal end of the ETT. The excellent correspondence between measured and calculated P_{trach} found in patients under a variety of clinical situations clearly demonstrates the general applicability of our fit coefficients (table 3).

Wright *et al.*[1] have compared the flow resistance of an ETT 8.0 measured in a laboratory setup with that measured in patients. Their resistance values "measured *in vivo* were generally higher than those derived from *in vitro* measurements." However, the coefficients determined by our laboratory setup are completely different from those of Wright *et al.*[1] Using our fit coefficients for an ETT 8.0 of original length (32 cm), we calculate a resistance of 6.2 $cmH_2O \cdot s/l$ (average of inspiratory and expiratory ETT resistance) at a flow of 50 l/min instead of 4.8 $cmH_2O \cdot s/l$, and 8.9 $cmH_2O \cdot s/l$ at a flow of 80 l/min instead of 6.3 $cmH_2O \cdot s/l$, respectively. These discrepancies emphasize that the details of the geometry of the physical model are decisive for the transferability of laboratory data to the patient. Clearly, a variation of head or neck position with concomitant tube deformation (*e.g.*, kinking) or obstructing secretions may increase the tube resistance compared with the resistance obtained from a laboratory setup.[26,27] Any change in flow resistance of an ETT occurring *in situ* is, therefore, an increase.

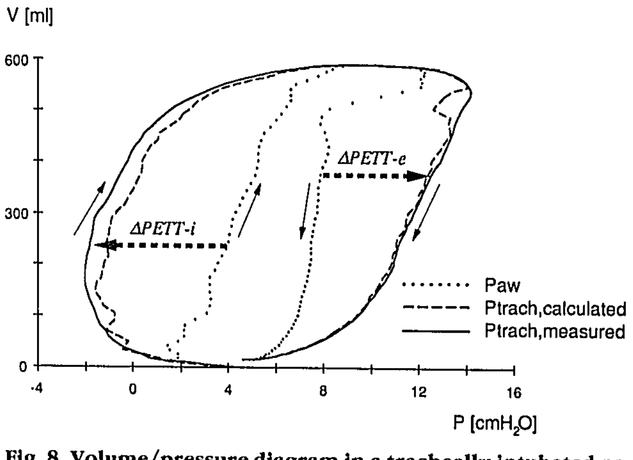

Fig. 8. Volume/pressure diagram in a tracheally intubated patient (patient 12) during spontaneous breathing with inspiratory pressure support (PEEP = 5 cmH_2O, IPS = 5 cmH_2O). Inspiratory pressure support was applied with a slope of 4 cmH_2O/s. P_{trach} is calculated using the same ETT coefficients as in figure 7. The pressure drop across the ETT (ΔP_{ETT}) is indicated both in inspiration and in expiration by a broken arrow. The direction of the arrow points from airway pressure to tracheal pressure.

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Table 6. Benefits and Disadvantages of the Catheter Method and of the Calculation Method

	Catheter Method	Calculation Method
Main benefits	Measures P_{trach} reliably even with major obstruction or deformation of the ETT	Enables continuous P_{trach} monitoring Could be applied in children
Limiting factors	Obstruction of the pressure-measuring catheter	Partial obstruction or deformation of the ETT
General disadvantages	Catheter is difficult to introduce Catheter increases ETT resistance Catheter changes P_{trach} Catheter disturbs clinical routine (endotracheal suction) Exact localization of the catheter tip is not possible	Needs a flow probe Needs a computer

ETT = endotracheal tube.

As a test of the mathematic method in practical application, we compared calculated tracheal pressure with tracheal pressure measured by means of a catheter introduced through the ETT. The test was performed in 15 tracheally intubated patients under a variety of clinical conditions. Patients were investigated during volume-controlled ventilation and spontaneous breathing.

The results of the test reveal an excellent correspondence between measured and calculated tracheal pressure. The rms deviations were smaller than 1 cmH_2O throughout all patient investigations, regardless of the duration of tracheal intubation (the maximum duration of tracheal intubation in our patients was 53 h). Figures 7 and 8 show that measured and calculated V/P_{trach}-loops are practically identical, both in volume-controlled ventilation and in spontaneous breathing. The method was found to be reliable under quite different clinical conditions.

Deviations between calculated and measured P_{trach} larger than 1 cmH_2O were observed at the very start of inspiration and expiration, where the flow signal shows fast oscillations. The calculated P_{trach} reflects these flow oscillations. These flow oscillations are damped out along the ETT's length because of the inertial properties of the gas within the ETT[3] and within the air-filled catheter. This renders the measured V/P_{trach}-loop smoother than the calculated V/P_{trach}-loop.

Table 6 lists the relative benefits and disadvantages of both the catheter method and the calculation method. The main benefit of the catheter method is its reliability at partial ETT obstruction, whereas the main benefit of the calculation method is its suitability for continuous P_{trach} monitoring without disturbing clinical routine. To profit from the benefits of both methods, they should be combined; the calculation method should be used for continuous monitoring, and the catheter method should be used for spot-check measurements performed either periodically or, at least, if partial ETT obstruction is suspected. It is important to note that the ETT, with the pressure-measuring catheter in place, needs a different set of four coefficients for description than the ETT without catheter.

The volume/pressure-loops (figs. 7, 8) make it obvious that our method can be used for P_{trach} monitoring. Using the same continuously measured parameters as in the past, namely airway pressure and flow, the tracheal pressure can be continuously calculated and the even more informative V/P_{trach}-loop can be monitored. In volume-controlled ventilation, as well as in spontaneous breathing, the V/P_{trach}-loops differ considerably in shape from the V/P_{aw}-loops. In volume-controlled mechanical ventilation, the V/P_{trach}-loop is inside the V/P_{aw}-loop (fig. 7). If it is insufflated with constant inspiratory flow rate, as in our example, the inspiratory curve is shifted in parallel, but expiration begins with a huge flow peak and the expiratory curve, therefore, shows a marked change of form. Inspiratory and expiratory segments of the V/P_{trach}-loop are nearly parallel, and the loop is narrow. Considering P_{aw} in isolation, the inspiratory pressure drop across the ETT leads to the patient's risk of barotrauma being overestimated. The ETT reduces expiratory flow and may even contribute to dynamic hyperinflation. In spontaneous breathing, the V/P_{trach}-loop is far outside the V/P_{aw}-loop (fig. 8), which indicates that the patient, although receiving inspiratory pressure support, has to contribute appreciable additional work in overcoming ETT resistance in inspiration, and that exhalation is impaired.

We conclude that intratracheal pressure can be continuously determined by combining the pressure-flow characteristics of the ETT obtained from a laboratory

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setup and the flow and airway pressure continuously measured at the proximal end of the ETT. This proved sufficiently reliable for continuous monitoring of tracheal pressure under clinical conditions.

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