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A fibre optics system for the evaluation of airway pressure in mechanically ventilated patients

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Abstract. *Objective:* The present study was intended to evaluate the "in vivo" endotracheal (ET) tube resistance and respiratory mechanics in mechanically ventilated patients with respiratory failure by using fiber optic catheters. *Design:* Two fiber optic catheters, consisting of a thin probe with a pressure transducer on the tip, were used. The first was placed at the proximal side of the ET tube and the second was positioned distally beyond the end. A low compliant air-filled catheter connected to a traditional pressure transducer was placed close to the proximal fiber optic device to compare the pressure values obtained with both systems. *Setting:* The study was performed in the General Intensive Care Unit of Rome "La Sapienza", University Hospital. *Patients and participants:* Seven patients admitted for the management of acute respiratory failure of different etiologies were included in the protocol. All the patients were intubated and mechanically ventilated for at least 48 h prior to the investigation. *Measurements and results:* The endotracheal tube resistance was obtained both by the end-inspiratory occlusion method and measuring pressure proximally and distally to the ET tube. The measurement of respiratory mechanics was obtained proximally and distally to the ET tube. Different flows and tidal volume changes were performed. The results showed that the fiber optic device gives an adequate evaluation of airway pressure and the possibility for an easy detection of obstructions and/or deformations of the ET tube. The area described by inspiratory and expiratory pressure recorded at both sides of the ET tube showed a positive relationship between the surface and flows while no surface changes were shown when the tidal volumes were modified. Thoraco-pulmonary compliance measured proximally and distally to the ET tube gave rise to a small and statistically insignificant difference. *Conclusion:* This study confirms that 48 h after the positioning of ET tubes the airflow resistance is significantly higher than might be expected from the "in vitro" data. The presence of the endotracheal tube can interfere with the evaluation of thoraco-pulmonary mechanics, particularly in dynamic conditions. The fiber optic system represents an interesting and simple tool for the evaluation of ET tube resistance and pulmonary mechanics in patients undergoing mechanical ventilation.

Key words: Endotracheal tube resistance – Thoraco-pulmonary mechanics – Fiber optic catheter – Mechanical ventilation

Mechanical ventilation offers the ideal conditions for the non-invasive evaluation of respiratory mechanics using simple and readily available instruments such as a pneumotachograph, a flow integrator (usually incorporated in the ventilator) and one or more pressure transducers [1]. Pressure is usually measured through a transducer located outside the patient and connected to the tube at different points, by means of a small low compliant air-filled catheter. The pressure signal is normally monitored in the internal circuit of the ventilator and either at the proximal and/or distal side of the endotracheal (ET) tube, if it has a proper channel. The reliability of the pressure reading measured with the transducer (P_{out}) depends on the elastance (1/C) of the transmission line and on the compressibility and inertia of the transmission volume. Consequently, the real pressure (P_{in}) corresponds to the measured value ($P_{in} = P_{out}$) only in near-static conditions and the accuracy of the data obtained is in relation to the internal diameter and length of the small channel connecting the transducer to the patient [2].

When a constant flow is maintained throughout inspiration a close relationship is formed between the airway pressure (P_{aw}) and the volume delivered by the mechanical ventilator, so that the slope of the corresponding pressure-volume curve estimates the elastance of the respiratory system (E_{rs}). Sudden interruption of the airway flow during inspiration has been shown to be useful in measuring pulmonary airway resistance [3]. Use of the end-inspiratory occlusion technique permits evaluation of the elastic and resistive properties of the lung [4–5]. While extremely useful in evaluating the mechanics of the respiratory system, the pressure gradients generated by controlled mechanical ventilation reflect only the global resistance of patients, without distinguishing the possible resistance due to interference from "in vivo" factors such as secretions, tube deformation and/or neck positioning.

In 1898, Grunbaum first underlined the importance of measuring pressure by means of a transducer placed directly at the recording site (e.g. a blood vessel). Various types of fiber optic catheter with a pressure sensor in or close to the tip are commercially available, but to date these devices have been applied only for intravascular and/or intracranial pressure measurements.

Since the diameter of fiber optic catheters fits small sites we used these devices in the airways of mechanically ventilated patients with respiratory failure in order to evaluate the "in vivo" resistance of the ET tube and respiratory mechanics distally to it. A fiber optic catheter has the advantage that it can measure the airway pressure "in situ" and is thus not subject to possible interferences due to transmission volume, connectors or size. The measurements obtained using the fiber optic device and a traditional air filled catheter-transducer system on the proximal side of ET tube were compared in order to verify the reliability of the new system.

Materials and methods

Seven patients admitted to our general intensive care unit for the management of acute respiratory failure of different etiologies were included in the protocol (Table 1). The investigation was approved by the institutional ethic committee and informed consent was obtained from patients or their relatives. All the patients were intubated (Portex cuffed ET, 7.5–8 mm I.D. with a length of 24 cm) and mechanically ventilated in the intermittent mandatory ventilation mode (Servo Siemens 900 C) for at least 48 h prior to the investigation. During the period of measurement the mandatory ventilation rate was set until the patients' spontaneous breathing was interrupted. The flow was maintained constant throughout inspiration. Therapeutic and ventilatory management was prescribed by the primary physician according to each patient's requirements and therapy was unaltered during the investigation period.

Airflow (V) was measured by the flow transducer incorporated in the Servo 900 C ventilator and tidal volume (Vt) was obtained by integration of the flow signal. A pneumatic cuff valve was used for a rapid occlusion of the airway. The airway pressure was evaluated using a fiber optic pressure monitoring system (Camino 420 XP).

The optic device basically consists of a fiber optic catheter (∅ = 1 mm, 4F) with a pressure transducer at the tip, connected to an opto electronic module at the proximal end of the catheter. A low-power electrical connection links this point to a pre-amp cable that amplifies the low level signal and delivers it to a digital pressure monitor. The catheter measures frequencies up to 50 Hz with a frequency response that is flat to 20 Hz. The fiber optic system is suitable for the measurement of absolute pressure (related to atmospheric pressure, taken as 0) and measurements range from −10 to +250 mmHg with a signal linearity of ±2 mmHg in the range of −10 to 50 mmHg. In the present study two fiber optic catheters were used; the first was placed, through the connection joint, at the proximal side of the endotracheal tube; the second was inserted in the ET tube and moved distally to 3 cm beyond the end.

A traditional low compliant air filled catheter with linear lateral holes on the tip (I.D. = 1.8 mm, 100 cm length), was connected to a pressure transducer (Statham P50) and placed at the connection joint close to the fiber optic device to compare the pressure values obtained with both systems.

Table 1. Characteristics of patients

Subject no.	Sex	Age (yr)	Weight (kg)	Tube ID (mm)	PaO_2 (mmHg)	Baseline (pH)	Diagnosis
1	F	35	50	7.5	71	7.38	Cerebral ischemia
2	M	46	75	7.5	89	7.53	Skull trauma
3	M	63	65	7.5	64	7.34	Cerebral infection
4	M	65	63	8	61	7.34	COPD pneumonia
5	F	62	55	7.5	65	7.33	COPD, CPE
6	M	53	78	8	80	7.43	Cerebral hemorrhage
7	M	52	150	8	78	7.35	Pickwick Sdr.

PaO_2, partial pressure of arterial O_2; COPD, chronic obstructive pulmonary disease; CPE, cardiogenic pulmonary edema

The measurement systems were connected to a four-channel pen recorder (Kontron polygraph 304) and at the same time to an X–Y plotter (Linseis LY18100).

After a 5 min observation period the pressure measurements were recorded. The endotracheal tube resistance was obtained by dividing the difference between the distal and proximal peak pressure (P_{max}) by the inspiratory constant flow. The total and minimal thoraco-pulmonary resistances were measured proximally to the ET tube as described by Bates et al. [4]. The airway was rapidly occluded by a pneumatically operated valve (Rudolph 4200, Hans Rudolph, MO) at the end of a relaxed inflation until a stabilized pressure was reached (Fig. 1). The ohmic resistance of the respiratory system (minimal resistance) and total respiratory resistance (maximal resistance) are obtained dividing the sudden drop in Paw following inspiratory occlusion ($P_{max}-P_1$: R_{es},min) and the difference between peak inflation pressure and the end-inspiratory "plateau" pressure ($P_{max}-P_2$: $R_{es,}$max) by the constant flow immediately preceding occlusion [5].

Evaluation of the thoraco-pulmonary elasticity was performed by dividing the expiratory volume (Vt) by the end-inspiratory "plateau" pressure (P_2) minus positive end-expiratory pressure (PEEP) and/or intrinsic-PEEP if present, as proposed by Rossi et al. [5]. A further evalu-

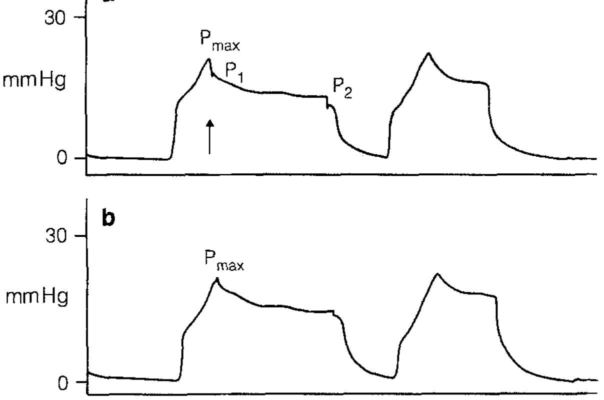

Fig. 1a, b. Representative records of the airway pressure measured by the fiber optic system. End-inspiratory occlusion was signed by the arrow. **a** proximal side of the ET tube. The sudden drop in P_{aw} following the occlusion ($P_{max}-P_1$) and the end-plateau pressure ($P_{ax}-P_2$) are used to compute respectively the ohmic and the total respiratory resistance. **b** distal side. No drop in P_{aw} was shown ation of the static thoraco-pulmonary compliance was obtained by dividing the tidal volume (Vt) by the inspiratory "plateau" pressure (P_2) measured at the distal side of the ET tube subtracted from PEEP and/or PEEPi.

Different flows were achieved at constant volume (VT) either by changing the inspiratory-time/pause ratio at constant minute volume or by varying the minute volume and respiratory rate. Tidal volume changes were achieved by modifying the respiratory rate at constant flow.

The results were statistically evaluated using one-way analysis of variance (ANOVA), paired *t*-test and least-square regression analysis.

Results

The comparison of pressure values recorded by the traditional air-filled and the fiber optic catheters, positioned at the proximal level of the endotracheal tube, is shown in Fig. 2. The linearity of the signals is clearly evident for all measurements and the regression coefficient of the measurements was not lower than 0.99.

As expected from in vitro data [6, 7], at constant flow a non linear relationship between airway pressure and flow has been shown to vary according to the diameter of the tube. The resistance of the ET tubes was obtained dividing the difference between the peak pressures, recorded by the fiber optic catheters at both sides of the ET tube, by the constant flow. The result was related to flow. The values were then compared with the "in vitro" measurements performed by Wright et al. [8]. The "in vivo" ET tube resistance was on average higher than the measurement obtained "in vitro" for both tube sizes, but the difference is not statistically significant. The linear regression between our flow and resistance values gives a different slope to that obtained "in vitro" (Fig. 3).

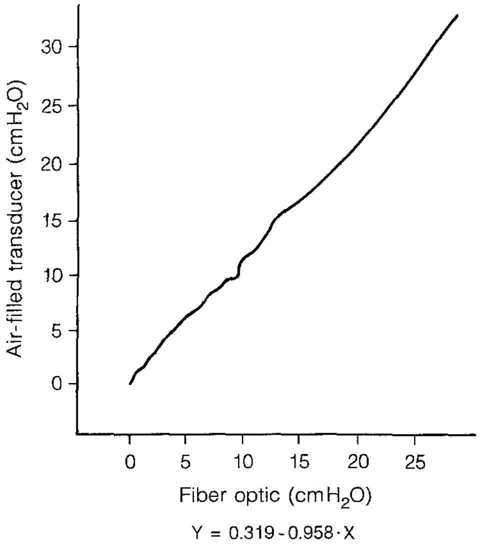

Fig. 2. A representative X–Y plot of a patient's airway pressure recording using two transducers placed at the proximal side of the ET tube. The signals from a fiber optic and traditional air-filled catheter are compared. The linearity of the signal was clearly evident and the regression coefficient of these data pressure was 1.0

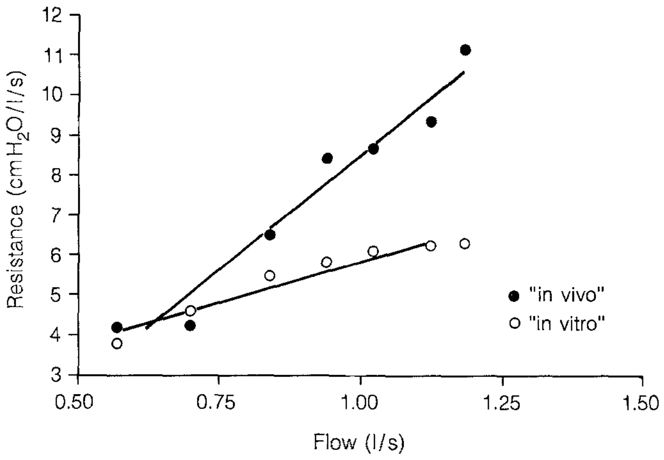

Fig. 3. Linear regression between flow and resistance on "in vivo" and "in vitro" [8] values for 7.5 I.D. tubes. The slope is different. When the flow was increased the "in vivo" resistance values showed a steeper increase than the "in vitro" measurements

When the flow was increased the "in vivo" resistance values showed a steeper increase than the "in vitro" measurements.

When the airway resistance was measured by the end-inspiratory occlusion method there was no difference between minimal resistance (P_{min}) and the "in vivo" ET tube resistance measured by the fiber optic device (Table 2).

The airway pressures measured during the inspiratory and expiratory phases by the fiber optic catheters positioned at both sides of the ET tube were plotted against each other. When the inspiratory flow was varied at constant volume the area circumscribed in the plot was changed, while it remained unchanged when the tidal volume was varied at constant flow (Fig. 4). There was thus a dose relationship between area (cm^2) and flow, not between area and volume (Fig. 5) on the four patients evaluated.

The thoraco-pulmonary compliance recorded proximally and distally to the ET tube side is showed in the Fig. 6. Intrinsic PEEP was measured in COPD patients and cerebral infarction patient with values ranging from 4 to 8. The mean value obtained at the ET connection joint was 55.87 ml/cmH_2O (SD±12.76) and that at the distal side was 51.61 ml/cmH_2O (SD±11.87) showing only a small and statistically insignificant difference when the paired *t*-test was applied.

Table 2. ET tube resistance measured by proximally and distally positioning two fiber optic catheters (dP_{max}) and minimum ($P_{max} - P_1$) and total airway resistance ($P_{max} - P_2$) measured proximally by the end-inspiratory occlusion method [3]

	dP_{max}	$P_{max} - P_1$	$P_{max} - P_2$
Mean (cmH_2O/l/s)	5.959^a	7.971^b	$14.23^{a,b}$
SD	2.396	2.869	5.88

$^{a,b}P < 0.01$. The one-way Anova test was performed

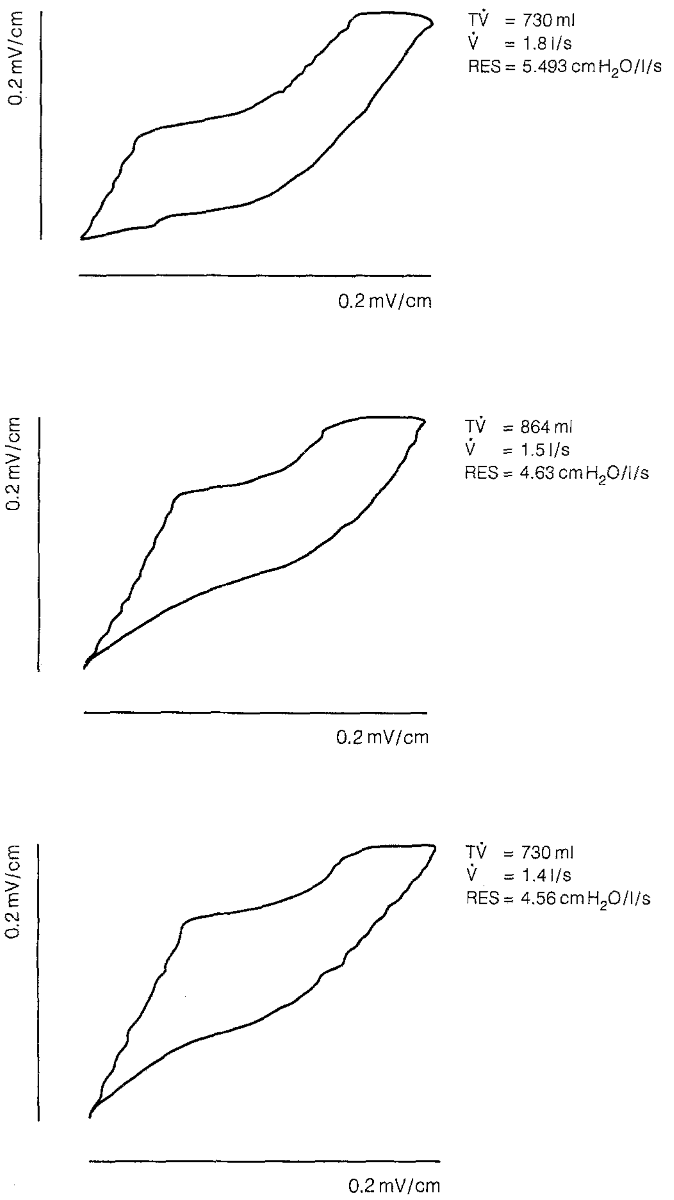

Fig. 4. Plot recording of pressure measured at the proximal (*x-axis*) and distal (*y-axis*) sides of the ET tube by two fiber optic catheters. The rates of flow and volume were varied

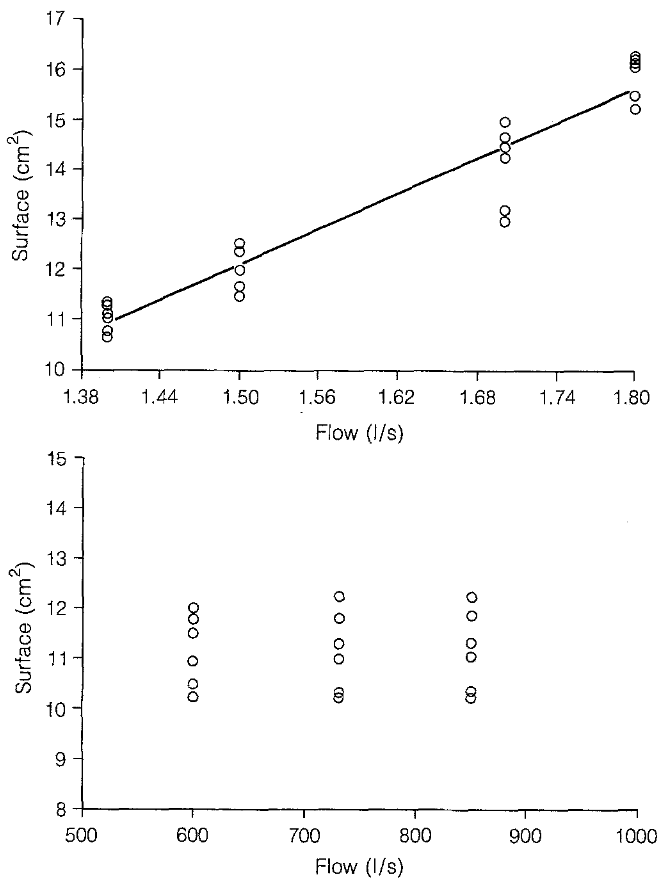

Fig. 5. Area described by inspiratory and expiratory pressure, recorded at both sides of the ET tube, and with different volumes and flows. A close positive relationship was found between the areas and flows (*upper panel*) while there are no area changes when the tidal volumes were modified (*lower panel*)

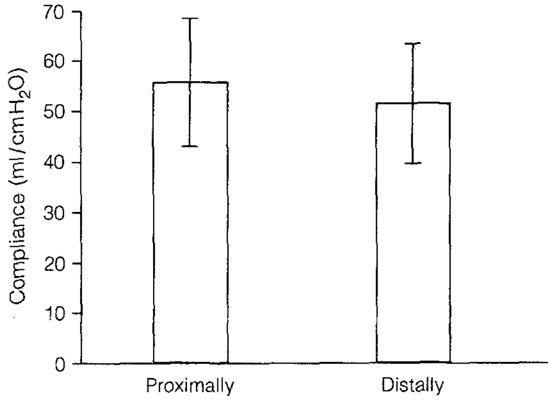

Fig. 6. Thoraco-pulmonary compliance measured proximally and distally to the ET tube during end-inspiratory occlusion. Only a small and statistically insignificant difference is shown

Discussion

The evaluation of respiratory mechanics requires the accurate measurement and recording of pressure, volume and flow signals. In experimental and mechanical models pressure measurements can be obtained easily at different sites. In clinical practice invasive procedures of measuring pressure could result in a bias during the routine collection of data.

Mechanical ventilatory support is usually discontinued when the patient is able to breathe spontaneously through the endotracheal tube. In this regard it is well known that during T-piece trials patients with chronic obstructive pulmonary disease (COPD) may need to increase the effort of breathing and that this can lead to failure of weaning [9]. The resistance to airflow is not influenced only by the internal diameter or length of the tube, but also by the flow regime [10]. "In vitro" studies of different sized endotracheal (ET) tubes subjected to flow rate changes suggest the presence of non-laminar or turbulent flow throughout the tested range [10]. The same phenomenon is considered to be present in the human's airways [13]. Moreover, the presence of secretions and possible deformations can enhance the resistance of the ET tube and condition the weaning.

The endotracheal tube can interfere with the evaluation of respiratory mechanics. It is well known [6] that the ET tube can interfere in the correct measurement of dynamic compliance, flow resistance and breathing.

The problem can be solved by the introduction of a catheter in the ET tube for the distal P_{aw} measurement, although the diameter and length of the catheter, together with the connecting joint, can interfere with signal reproduction.

The "in vitro" value of the resistance of the ET tube to flow changes is often used in literature [11, 12] to correct the valuation of respiratory mechanics even though this could result in a technical bias.

In this study we first obtaind P_{aw} measurements proximally and distally to the ET tube using a very thin fiber optic tipped catheter to minimize interference.

The difference between the "in vitro" and "in vivo" ET tube resistance values is due to the dissipation of kinetic energy and to convective-accelerative changes [13], so that the pressure in an isolated tube would be expected to exceed the "in vivo" value [14].

Our results are consistent with those of Wright [8], i.e. ET tube resistance is on average higher "in vivo" than "in vitro". This confirms the presence of additional flow resistance, probably due to the presence of deformations and/or variable amounts of secretions already 48 h after positioning of the ET tube.

The fiber optic device also represents a useful system for the interpretation of respiratory mechanics using the end-inspiratory occlusion method. A comparison between the values of airway resistance recorded with the fiber optic catheter outside the patient by the occlusion method ($P_{max} - P_1$) and those obtained by positioning two fiber optic catheters proximally and distally to the ET tube (dP_{max}) (Fig. 1) shows that minimal resistance (P_{min}) is due mainly to the presence ET tube (Table 2). Further, the measurement of thoraco-pulmonary compliance performed at the end of the ET tube shows values comparable to those obtained outside the patient with the inspiratory occlusion method. The contrast with Wright's results of higher values for dynamic compliance at the level of the trachea, is probably due to the near static conditions under which our study was performed.

The time course measurements of airway pressure recorded proximally and distally to the ET tube could permit a morphological and quantitative evaluation of additional airflow resistance and respiratory mechanics.

In conclusion, 48 h after their positioning, ET tubes contribute to airflow resistance significantly more than might be expected from the "in vitro" data. The presence of the endotracheal tube can interfere with the evaluation of thoraco-pulmonary mechanics, particularly in dynamic conditions. Finally, the fiber optic system represents an interesting and simple tool for the measurement airway and ET tube resistance in patients undergoing mechanical ventilation.

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