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Evaluation of respiratory system resistance in mechanically ventilated patients: the role of the endotracheal tube

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Abstract. *Objective:* To investigate the role played by the endotracheal tube (ETT) in the correct evaluation of respiratory system mechanics with the end inflation occlusion method during constant flow controlled mechanical ventilation.
Setting: General ICU, university of Rome "La Sapienza".
Patients: 12 consecutive patients undergoing controlled mechanical ventilation.
Methods: We compared the values of minimal resistance of the respiratory system (i.e. airway resistance) (RRS min) obtained: i) subtracting the theoretical value of ETT resistance from the difference between P max and P1, measured on airway pressure tracings obtained from the distal end of the ETT; ii) directly measuring airway pressure 2 cm below the ETT, thus automatically excluding ETT resistance from the data.
Results. The values of RRS min obtained by measuring airway pressure below the ETT were significantly lower than those obtained by measuring airway pressure at the distal end of the ETT and subtracting the theoretical ETT resistance (4.5 ± 2.8 versus 2.5 ± 1.6 cm $H_2O/l/s$, $p < 0.01$).
Conclusion: When precise measurements of ohmic resistances are required in mechanically ventilated patients, the measurements must be obtained from airways pressure data obtained at tracheal level. The "in vivo" positioning of ETT significantly increases the airflow resistance of the ETT.

Key words: Mechanical ventilation – Endotracheal tube – Respiratory system resistance – Airway resistance

Measurements of respiratory mechanics in mechanically ventilated ICU patients are commonly used to asses the severity and the evolution of the disease.

Particularly, during controlled mechanical ventilation (CMV) with constant inspiratory flow it is a relatively common practice to evaluate the resistance of the respiratory system with the end inflation occlusion method [1–7]. This allows separation of ohmic and visco-elastic resistances of the respiratory system.

The minimal resistance of the respiratory system, generally called RRS min, measures the ohmic or instantaneous resistance of the respiratory system, mainly representing the airway resistance [2, 4, 5].

RRS min is generally obtained by measuring airway pressure at the distal end of the endotracheal tube (ETT); thus it includes also the airflow resistance of the ETT; therefore this measure is generally corrected by subtracting the value of ETT "in vitro" resistance at the administered flow [1, 6].

However, Wright and co-workers elegantly demonstrated that "in vitro" measurements of ETT resistance significantly differ from "in vivo" values, showing a constant underestimation of the ETT resistance compared to the "in vitro" values [8].

These data have been confirmed recently by our group [9] by measuring airway pressure with a thin fiber optic airway transducer to influence minimally the ETT resistance.

Also in this study the "in vivo" values of ETT resistance were constantly higher than the values obtained "in vitro", although the measurements were performed in patients with a recently positioned ETT (24 h). It was therefore suspected that RRS min values obtained with the end inflation occlusion method by subtracting the "in vitro" values of ETT resistance, overestimate the true value of RRS min by erroneously attributing a part of the resistive load represented by the ETT to the ohmic resistance of the respiratory system.

The aim of this study was to compare, in a group of ICU patients undergoing mechanical ventilation, the values of RRS min obtained by subtracting the "in vitro" values of the ETT resistances with RRS min values obtained by directly measuring the airway pressure at the tracheal level (thus excluding the ETT resistive load) [10, 11].

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Patients and Methods

Twelve consecutive patients admitted to our general ICU for management of acute respiratory failure of various etiologies were studied. Main patient data are shown in Table 1. The protocol was approved by our Institutional Ethics Committee and informed consent was obtained from patients or families.

All patients were nasotracheally intubated with Portex cuffed ETT: 9 patients had an 8 mm I.D. tube, 2 had an 8.5 mm I.D. tube and one a 7.5 mm I.D. tube. The ETT were cut to a 32 cm length.

All patients were mechanically ventilated with a SERVO 900C Siemens Ventilator (Sweden) for a period ranging 1–3 days preceeding the study and were in stable clinical conditions. All were sedated with flunitrazepam as a continuous infusion and were well adapted to the ventilator.

In all patients, at the time of the study, the ETT had been replaced within 12 h, and the absence of lumen obstruction with secretions had been checked by fiberoptic bronchoscopy in 7 out of 12 patients. Just before the study each patient was carefully suctioned.

Ventilator settings were as follows: respiratory rate 14–18 cycles/min; FI O_2 0.35–0.4; V_t 10 ml/kg; I.E. ratio 1:2; ZEEP in 10 patients, PEEP 6 and 4 cm H_2O in the remaining two patients; a square flow wave was used with mean airflow values ranging between 0.37 and 1 l/s. (Individual values in Table 1).

The patients were studied in supine position with the head in a median position; during the whole procedure a physician not involved in the study was present to take care of the patient. Airflow was measured with a pneumotachograph (Fleish n°2) connected to the ETT via a cone, and to a Valydine MP 45 differential pressure transducer; volume was obtained by airflow signal electrical integration (Gould Integrator). The hold button of the ventilator was used to obtain an end-inspiratory and end-expiratory 2 s airway occlusion [2, 5]. All corrections for the finite occlusion time of the occlusion valve were made according to Kochi and co-workers [12].

We simultaneously measured airway pressure at the proximal end of the ETT, trachea at a distance of 2 cm from the ETT tip, and at the distal end of the ETT (Spectramed pressure transducers). The tracheal Paw signal was obtained with an air filled non-compliant catheter provided with multiple sides holes and an occluded hole [9–11]. All signals were recorded on a 4 channel pen recorder (Roche 3000).

In each patient respiratory mechanics were obtained by the end-inspiratory and end-expiratory airway occlusion technique [2]; in detail, the value of ohmic resistance of the respiratory system (RRS min) was obtained as described previously [2, 5] with an end-inspiratory airway occlusion.

From the airway pressure tracing recorded at the distal ETT end during and end-inspiratory occlusion we obtained the values of peak inspiratory pressure (Pmax) and elastic recoil of the respiratory system (Pel rs). As the decay of pressure from Pmax to Pel rs was biphasic a pressure value at the end of the initial rapid Paw drop was observed (P 1) [1]; the ohmic resistance of the respiratory system was calculated as (Pmax–P 1)/$\dot{V}$i–ETT "in vitro" resistance for $\dot{V}$i obtained from Wright et al [8].

A similar procedure, according to Pesenti [10] and Eissa [11] was used with the tracheal pressure signal to evaluate RRS min trach, i.e. the values of RRS min obtained directly from tracheal pressure (Pmax trach–P 1 trach)/$\dot{V}$i. As this measure excludes the ETT no subtraction for ETT resistance was necessary.

A tele-expiratory airway occlusion was maintained for 2 s, obtaining a plateau; the difference between end-inspiratory and end-expiratory occlusion airway pressure was divided by the expired tidal volume to calculate the elastance of the respiratory system (Ers).

The total resistance of the respiratory system (RRS max) was calculated as (Pmax–Pel rs)/$\dot{V}$i. RRS max represents RRS min, plus the additional respiratory impedance generated by stress relaxation and/or time constant inhomogeneities in the respiratory circuit. The difference between RRS max and RRS min allows the measurement of this additional respiratory impedance (DRRS).

For the purposes of this study the difference between RRS max and RRS min (DRRS) was evaluated both as described above and by subtracting RRS min trach from RRS max trach (DRRS trach). RRS max trach was obtained as (Pmax trach–Pel rs)/$\dot{V}$i.

Finally, the ETT "in vitro" resistance at the applied airflow was evaluated by dividing the values of P max obtained simultaneously at the proximal end of the ETT and at tracheal level by the inspired flow (Pmax–P max trach)/$\dot{V}$i. No correction for the resistance represented by the carinal catheter was made, as this was not significant for the ETT diameters used in this study [8]. In all patients no time delay was observed between Pmax and Pmax trach.

The values of RRS min and RRS min trach, DRRS and DRRS trach and those of "in vitro" and "in vivo" resistances have been compared using Student's *t*-test for paired data. RRS min and DRRS values were plotted versus RRS min trach and DRRs trach, respectively; all data are presented as mean ± SD; *p*-values < 0.05 were considered as statistically significant.

Table 1. Main patient data (age: years; weight: kg; total static elastance (cmH_2O/l); ETT I.D.: endotracheal tube internal diameter; $\dot{V}$: inspired flow l/s)

Patient	Sex	Age	Weight	Est	$\dot{V}$	ETT I.D.	Diagnosis
1	M	57	84	0.016	1	8.5	Brain haemorrhage
2	M	70	80	0.018	0.6	8	Multiple trauma
3	F	66	50	0.031	0.4	8	Guillain Barré syndrome
4	M	70	59	0.030	0.47	8.5	COPD
5	M	50	70	0.023	0.56	8	Brain haemorrhage
6	F	60	58	0.030	0.46	8	Post op ARF
7	F	63	60	0.031	0.41	8	Post op ARF
8	F	45	57	0.033	0.37	7.5	ARDS
9	M	63	60	0.030	0.6	8	Post op ARF
10	F	19	65	0.025	0.6	8	Post op ARF
11	M	63	58	0.033	0.5	8	Trauma
12	F	60	68	0.026	0.6	8	Head trauma

Results

The individual values of RRS min obtained by subtracting from (Pmax–P 1)/$\dot{V}$i the "in vitro" values of ETT resistance, those of RRS min trach and the values of DRRS and DRRS trach are shown in Table 2. Figure 1 shows the comparison of the ETT resistance obtained "in vitro" and "in vivo" for the same value of flow. We observed also a significant difference between RRS min and RRS min trach ($p < 0.01$, Fig. 2); this was due to the significant difference between "in vitro" and "in vivo" ETT resistance values ($p < 0.01$). DRRS and DRRS trach were not significantly different.

The individual values of RRS min trach (the true value of ohmic resistance of the respiratory system, not influenced by the ETT resistance) was, in some cases, lower than 30% of the value of RRS min obtained in the same patients by subtracting the theoric ETT resistance.

The identity plot between RRS min and RRS min trach, and the values of ETT "in vitro" and "in vivo" resistances (Figs. 1, 2) showed significantly different measurements.

Discussion

The end inspiratory airway occlusion technique during constant flow ventilation has been widely used to obtain a simple and non-invasive measurement of the ohmic re-

Table 2. Modifications of RRS min and RRS evaluated at the proximal and distal end of the ETT

PT	RRS min	RRS min trach	DRRS	DRRS trach
1	1.3	1	2	1.5
2	1.5	1.5	6.3	6.3
3	6.5	2	2.8	2
4	8.8	6.7	8	10.1
5	4.5	2	4.8	7.3
6	5.9	4.1	14.7	16.3
7	2.4	1.6	4.9	7.6
8	1.2	0.8	11.2	11.7
9	9	2.3	3	2
10	6.6	3.3	2.7	1.7
11	4.5	3	3.5	3
12	2.4	1.4	3.8	4.3
Mean	4.5*	2.5*	5.6	6.1
SD	2.8	1.6	3.8	4.6

*$p<0.01$

RRS min, Minimal resistance of the respiratory system; RRS min trach, minimal resistance of the respiratory system evaluated from tracheal pressure tracing; DRRS, viscoelastic resistance of the respiratory system; DRRS trach, viscoelastic resistance of the respiratory system evaluated from tracheal pressure tracing

All measurements are expressed in $cmH_2O/l/s$

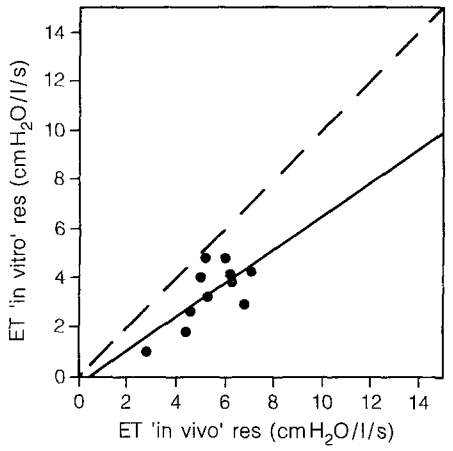

Fig. 1. Identity plot between ETT "in vivo" and "in vitro" resistances [8]. All data are expressed in $cmH_2O/l/s$

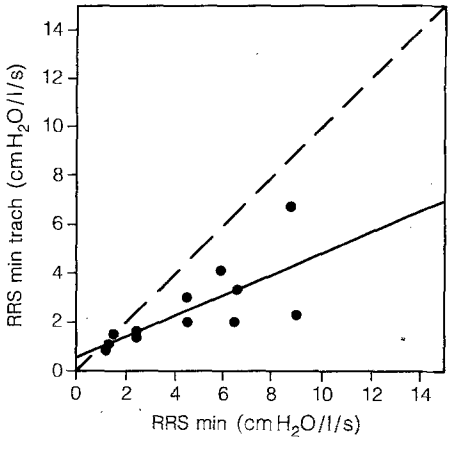

Fig. 2. Identity plot between RRS min and RRS min trach. All data are expressed in $cmH_2O/l/s$

sistance of the respiratory system in mechanically ventilated relaxed patients [1, 7]. This technique can be useful both for a better comprehension of the functional behaviour of the respiratory system [1, 2, 4, 10, 11] or to asses the efficacy of therapeutic manoeuvres [3, 5]. In order to simplify the measurements of respiratory mechanics airway pressure has often been measured at the distal end of the ETT, thus including the ETT resistance in the value of resistance obtained. This problem has generally been solved by subtracting the ETT resistance measured "in vitro" assuming that "in vitro" and "in vivo" measurements for the same flow are similar.

However, our results do not support this view in a group of unselected mechanically ventilated patients, showing a significant difference between theoretical and "in vivo" values of ETT resistance. Our data are in line with other previous observations [8, 9]. The main consequence of this difference is that RRS min values computed by recording Paw at the distal end of the ETT are often inprecise, sometimes artifactually doubling the values of ohmic resistance of the respiratory system.

In this study the ETT were recently positioned [< 12 h] and patients' heads were positioned in order to avoid neck flexion. Moreover tracheobronchial toilet was adequate and, in many cases, a recent fibrobronchoscopy confirmed the absence of secretions plug.

Therefore our data support the view that the simple "in vivo" positioning of the ETT particularly with the nasal route, increases significantly the ETT resistance [8, 9], and this affects largerly the values of RRS min obtained from distal Paw signal.

In conclusion we suggest that when precise measurement of ohmic respiratory system resistances is required the measurement is based on tracheal pressure recording, although this represents a more invasive and complicated procedure.

On the contrary, the value of respiratory system elastance can be correctly obtained from Paw values recorded at the distal end of ETT.

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