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TECHNICAL NOTE

Passive partitioning of respiratory volumes and time constants in ventilated patients

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ABSTRACT: If the thoracoabdominal partitioning of volumes in the mechanical respiratory apparatus was constant, one transducer of indirect spirometry should be sufficient to measure volume variations.

To verify this hypothesis we used respiratory inductive plethysmography (RIP) in 16 paralysed patients, of whom eight had normal lungs and 8 had not, to measure: 1) the thoracoabdominal partitioning of volumes (400–1,200 ml) insufflated from either a syringe (Syr) or a ventilator (Vent); and 2) thoracic (Tho) and abdominal (Abd) time constants ($T_{0.368}$) on spontaneous deflation to barometric pressure. In eleven additional subjects with normal lungs we measured only the time constants.

1) Correlation coefficients of the calibration lines were in all but one subject >0.98. In all patients the error of volume was <±10% when either one of two coils alone was used to assess volumes with no difference between the two coils; 2) Partitioning varied little with volumes (4±2%), but widely between subjects, with no group average significant difference between Syr and Vent; 3) $T_{0.368}$ were identical for Tho and Abd except in one patient; 4) Partitioning and $T_{0.368}$ were volume size independent.

We conclude that, to measure volume variations and time constants in ventilated, paralysed patients, the use of either a thoracic or abdominal single coil RIP is justified. We also provide the normal range for time constant in 19 subjects (0.73±0.29 s).

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Thoracoabdominal partitioning of respiratory volumes has been studied in various physiological [1–4] and pathological [5–7] situations, since the pioneer study of KONNO and MEAD in 1967 [8] and the introduction, in 1978, of respiratory inductive plethysmography (RIP). The observed breath-by-breath variation in partitioning during spontaneous breathing in normal subjects [3], as well as in patients [5], is probably due to active muscular activity and renders necessary the use of two coils and the establishment of the corresponding motion/volume coefficients.

Several authors made the assumption [9], or suggested [10, 11], that if partitioning was constant, the thoracoabdominal system would move with one degree of freedom and one coil would suffice to define volume changes. It has been assumed that this situation exists when muscles are pharmacologically paralysed. To our knowledge, this assumption has never been verified, except in a preliminary study of three patients [12].

Indeed, a small subgroup of ventilated patients in intensive care units are continuously paralysed for adaptation to the ventilator, especially to avoid barotrauma, and during extracorporeal CO_2 extraction with apnoeic oxygenation [13]. More often curarization is transitory in ventilated patients, in order to evaluate passive mechanical properties of the respiratory system.

With increasing use of RIP for noninvasive clinical assessment of the respiratory system [5–7, 14–16], simplified methods would be helpful. Therefore, we undertook to verify the hypothesis of the constancy of partitioning of tidal volume, in both static and dynamic conditions, in paralysed patients, to give a rational basis for the use of a single coil RIP.

We measured, in paralysed patients with normal or diseased lungs: 1) the characteristics of the thoracic and abdominal calibration lines of a double coil RIP; 2) the partitioning of volumes insufflated either with a syringe (Syr) or a ventilator (Vent); 3) the thoracic (Tho) and abdominal (Abd) time constants ($T_{0.368}$) of full relaxation to barometric pressure.

Methods

Patients

Sixteen patients admitted to the intensive care unit, who needed mechanical ventilation, were included in the study. Patients with an overt mechanical cause of limitation of the expansion of the respiratory system, *e.g.* thoracic or abdominal surgery, pleural effusion or pneumothorax, were excluded. Eight were comatose patients with normal lungs (Nos 1–8). They were ventilated because of central ventilatory depression, due to self-poisoning in seven cases. They had normal chest X-ray and normal blood gases on conventional ventilation with air and no known history of pulmonary disease. The others were patients (Nos 9–16) with various pulmonary diseases, whose characteristics and main diagnosis, as well as initial ventilator settings chosen by the attending physician are presented in table 1.

Patients were studied in supine horizontal position with one coil placed around the chest, just below the axilla, ("thoracic coil") and the other around the abdomen, just above the iliac crest, ("abdominal coil"). Patients were sedated when needed with flunitrazepam (Narcozep) and then paralysed with pancuronium bromide (Pavulon), both injected intravenously. Curarization was first obtained with 4 mg of pancuronium bromide and further injections of 1 mg of pancuronium bromide were given when necessary. Curarization was documented by both constancy of end-expiratory volume and absence of inspiratory movements during the short periods of withdrawal of the ventilator. Patients were ventilated with fractional inspiratory oxygen (F_{IO_2}) = 1 during the protocol to prevent hypoxia. Patients were systematically monitored by the usual clinical set up, including transcutaneous arterial oxygen saturation (Sa_{O_2}). Each step of the protocol that involved disconnection from the ventilator or the syringe lasted only a few seconds (15–30 s). Partial data, *i.e.* calibration and static partitioning for patients Nos. 8, 10 and 11 appeared in a previous paper [12].

In eleven additional paralysed subjects with normal lungs ventilated for self-poisoning we measured only time constants with a single coil RIP, placed at mid-distance between the axilla and the iliac crest, in order to propose normal values.

Protocol

The experimental set up was identical to that described previously [12]. Briefly, a two-way stopcock allowed the operator to connect the patient either to the ventilator or to a 2 *l* syringe. RIP thoracic and abdominal output were recorded as a function of time on a 2YT Sefram recorder (Velizy, France), with initially the same electrical gain for both channels of the recorder. The calibration of the coils was then performed with the syringe to obtain volume/motion coefficients and volumes. The protocol, including calibration, consisted of insufflations of known volumes with the syringe or with the ventilator. Thoracoabdominal RIP output was taken as representative of partitioning of thoracoabdominal volumes [17].

Insufflation of syringe volumes (calibration, static partitioning and time constants). Six volumes ranging from 200–1,200 ml of ambient air were randomly used to inflate the lungs with the technique described previously for non-cumulative calibration [12], *i.e.* disconnection of the ventilator, full relaxation at barometric pressure, insufflation of the selected volume, with the desired inflation maintained for 15 s, followed by full relaxation (fig. 1).

Table 1. – Characteristics of the patient

Patients No.	Diagnosis	Drugs ingested	Sex	Age yrs	Weight kg	V_T ml	I/E	RR $c \cdot min^{-1}$	PEEP cmH_2O
1	Poisoning	BB	M	45	75	620	0.28	17	0
2	Poisoning	BZ BB	F	31	55	500	0.33	17	0
3	Poisoning	BZ NL	F	20	54	400	0.35	18	0
4	Poisoning	BZ AT	M	37	70	560	0.33	19	0
5	Poisoning	BZ BB	M	29	75	540	0.50	17	0
6	Poisoning	BZ OP	M	26	58	520	0.33	19	0
7	Poisoning	BZ AL	M	24	70	460	0.33	15	0
8	Meningitis	None	M	73	75	800	0.40	20	5
9	Aspiration	BZ AT	M	21	65	700	0.55	16	0
10	Near drowning	None	M	35	75	800	0.25	20	5
11	ARDS	None	M	29	65	860	0.25	16	14
12	Aspiration	None	M	24	65	700	0.23	20	6
13	Septic shock	None	M	50	77	650	0.33	20	5
14	Septic shock	None	M	75	80	750	0.50	20	6
15	Septic shock	None	F	56	88	580	0.33	18	0
16	COPD	None	M	56	49	600	0.25	14	0

ARDS: adult respiratory distress syndrome; COPD: chronic obstructive pulmonary disease; BB: barbiturates; BZ: benzodiazepines; NL: neuroleptics; AT: antidepressants; AL: alcohol; OP: opiates. V_T: tidal volume; I/E: inspiratory/expiratory time RR: respiratory rate; PEEP: positive end-expiratory pressure, refer to pre-study ventilator settings. Patients 1–8 had normal lungs.

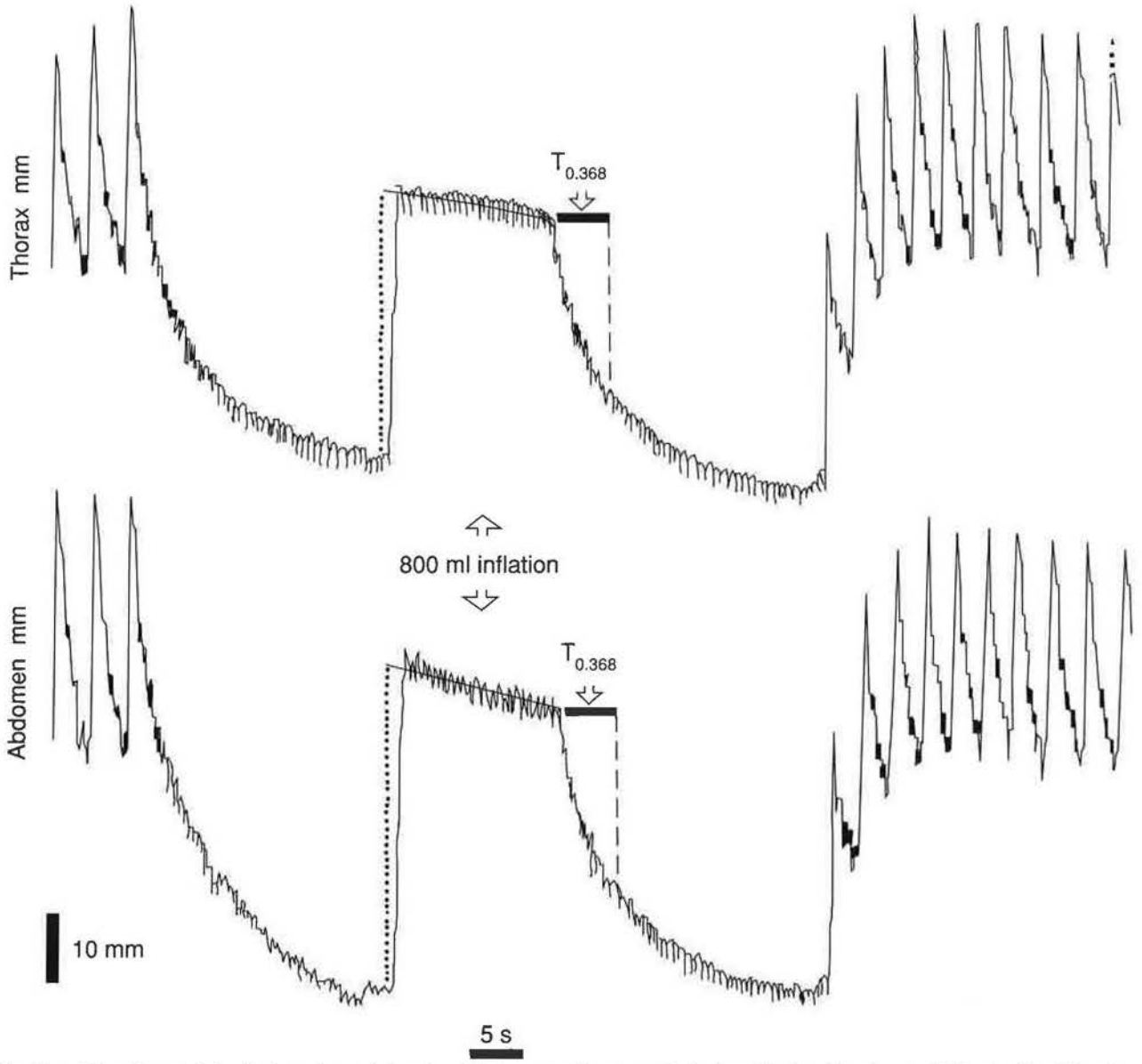

Fig. 1. – Thoracic and abdominal respiratory inductive plethysmographic outputs during insufflation of a volume of 800 ml with a 2 *l* syringe between two full passive relaxations at barometric pressure (patient No. 15, with septic shock and COPD). Left vertical dashed lines indicate the deflections after correction for gas exchange by backward extrapolation. $T_{0.368}$ is the time constant (6.9 s), *i.e.* the time taken by lung volume to fall from end-insufflation to 0.368 of the total volume fall. (NB. In this patient, with the highest time constant there was a dynamic hyperinflation of 600 ml above FRC). COPD: Chronic obstructive pulmonary disease; FRC: functional residual capacity.

Mechanical ventilation was resumed for 20 cycles before each step to standardize for volume history. These steps had three purposes: firstly, calibration of coils (fig. 2A); secondly, measurement of partitioning of volume in static conditions (fig. 2B); and thirdly, measurement of thoracic and abdominal time constants (fig. 1) at each step. The 15 s plateau also allowed checking for leaks [12].

Insufflation of ventilator volumes (dynamic partitioning). Five volumes from 400–1,200 ml were randomly selected on the ventilator settings and applied to the patients for 10 cycles. Each experimental volume was followed by the resumption of the pre-experimental tidal volume (VT) for 20 cycles.

The study was approved by the Ethics Committee of our institution. Since patients were unconscious before the beginning of the study, informed consent was obtained from the family, following the recommendations of the French Speaking Society of Intensive Care Medicine [18] and the French law No. 88-1138, December 20, 1988. The protocol lasted approximately one hour with no adverse effects for the patients.

Data processing and statistical analysis

Calibration lines. Calibration technique was detailed in a previous paper [12]. For each insufflated syringe

volume, RIP output was corrected for gas exchange during apnoea by retrograde extrapolation as described previously (fig. 1). All data points including zero volume were used to construct calibration lines of RIP output as a function of insufflated syringe volume (fig. 2). The slopes of the calibration lines are the motion/volume coefficients and the final gains or volume/motion coefficients are the inverse of the slopes.

This is illustrated on figure 2 for patient No. 10. For this patient the slopes of the calibration lines for thorax and abdomen are, respectively, 0.056 and 0.117 mm·ml^{-1} (table 2) and the corresponding volume/motion coefficients are 1/0.056 or 17 ml·mm^{-1} and 1/0.117 or 8.5 ml·mm^{-1}. The partitioning of syringe volumes is 0.333, *i.e.* for each inflated volume 0.333 for thorax and 0.667 for abdomen. On the tracings, thoracic and abdominal deflections are 40 and 75 mm, respectively. Thus, tidal volume (V_T) on mechanical ventilation on this portion of the tracing is the sum of thoracic and abdominal volumes, each of which is obtained by the multiplication of 3 terms, *i.e.* fraction of partitioning, volume/motion coefficient and tracing deflection:

$$V_T \text{ (ml)} = (0.333 \times 17 \times 40) + (0.667 \times 8.5 \times 75) = 226 + 425 = 651$$

Thoracoabdominal partitioning for both insufflated syringe and ventilator volumes was expressed for each volume step as the ratio: thorax/(thorax + abdomen) on the tracings (figs 1 and 2). Intra-patient variation was expressed by the coefficient of variation, *i.e.* SD expressed as a percentage of the mean value of partitioning. RIP volumes during artificial ventilation were averaged over 10 ventilator cycles.

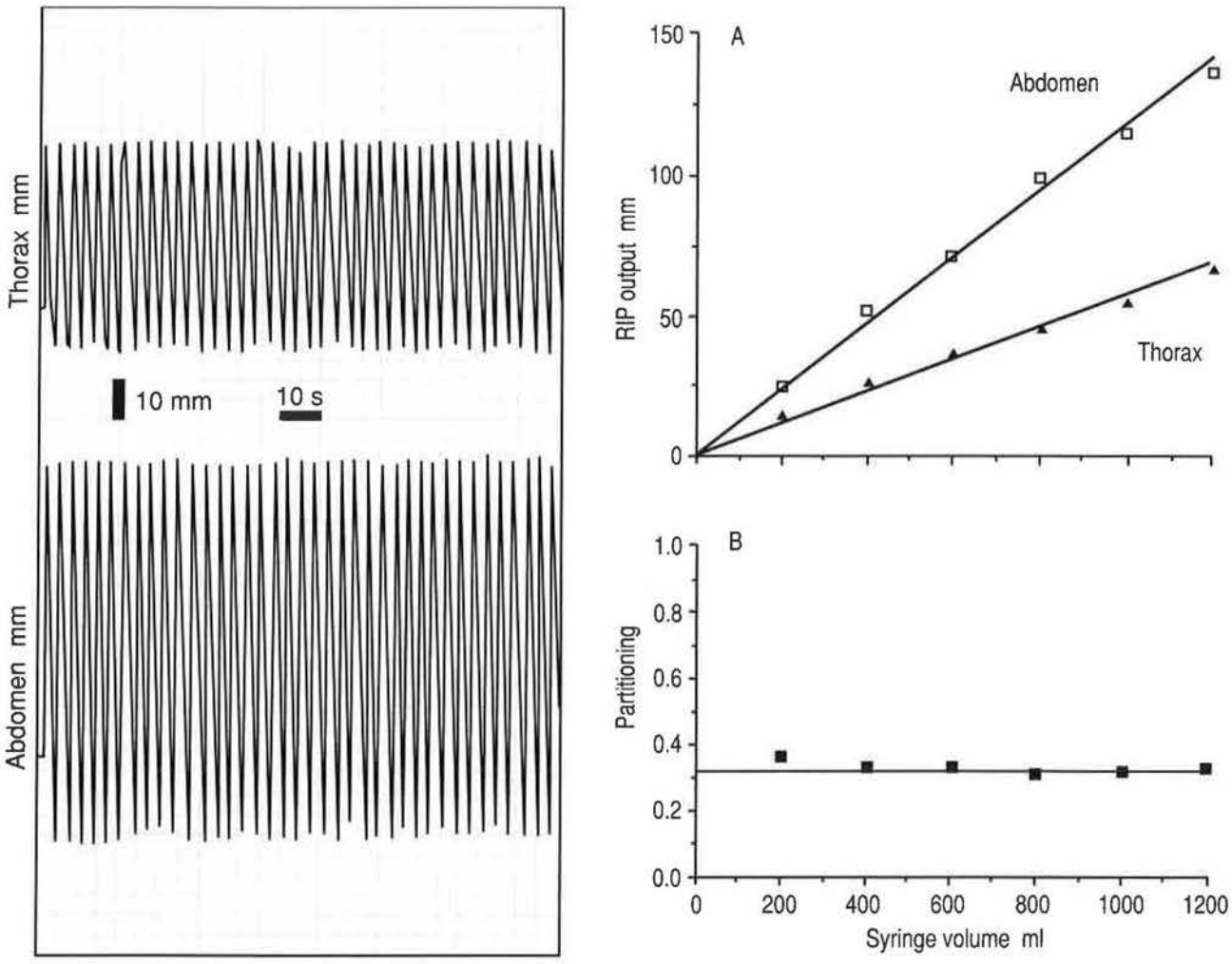

Fig. 2. – Left: original uncalibrated deflections of the respiratory inductive plethysmographic coils on patient 10 on mechanical ventilation, recorded with the same electrical gain. Right: A) abdominal (r=0.997) and thoracic (r=0.995) calibrations lines; and B) syringe volume partitioning as a function of insufflated volume. Tidal volume (V_T) can be obtained using the original tracings (deflections of 40 and 75 mm for thorax and abdomen, respectively, in this example), the two calibration lines with volume/motions coefficient (here 17 and 8.5 ml·mm^{-1}) and the partitioning of syringe volume (here 0.333). V_T (ml)=(0.333×17×40) + (0.667×8.5×75) = 226+425 = 651. If only one coil is used, tidal volume can be calculated without using the partitioning coefficient, either wih the thoracic (17×40=680 ml) or abdominal deflection (8.5×75=637 ml) in this portion of the tracing with an acceptable error <±5%.

Table 2. – Calibration lines for thoracic and abdominal RIP coils

Pt No.	Thorax r	Thorax slope mm·ml^{-1}	Thorax Error of volume %	Abdomen r	Abdomen slope mm·ml^{-1}	Abdomen Error of volume %
1	0.997	0.084	-9.7	0.997	0.084	-3.8
2	0.999	0.108	1.3	0.995	0.106	3.6
3	0.957	0.110	-2.3	0.997	0.080	9.5
4	0.998	0.128	0.0	0.997	0.159	6.2
5	0.985	0.147	5.7	0.982	0.189	-3.0
6	0.997	0.089	8.3	0.992	0.095	-5.7
7	0.995	0.103	8.8	0.999	0.087	2.5
8	0.997	0.023	-2.3	0.997	0.026	1.3
9	0.996	0.091	3.3	0.990	0.095	4.5
10	0.992	0.056	0.0	0.995	0.117	5.8
11	0.993	0.080	1.9	0.995	0.087	-6.3
12	0.993	0.050	-2.4	0.985	0.122	6.3
13	0.997	0.053	1.3	0.995	0.086	-2.5
14	0.999	0.095	5.2	0.996	0.083	-0.4
15	0.986	0.073	7.3	0.983	0.067	9.1
16	0.999	0.063	1.1	0.999	0.112	1.0
Mean	0.993		1.7	0.993		1.8
±SD	0.010		4.8	0.005		5.0

r and slope refer to the regression of RIP output as a function of volume insufflated with a 2 *l* syringe. Error of volume is the value of $(V_{Rip}-V_{Syr})/V_{Syr}$. RIP: respiratory inductive plethysmography.

Time constant was measured on each passive relaxation curve to functional residual capacity (FRC) with the patient disconnected from the ventilator (fig. 1). Time constant ($T_{0.368}$) was defined, as usual, as the time taken by RIP output to fall from end-insufflated volume to 0.368 of the total fall in volume.

Statistics. Calibration lines were obtained by linear regression. All comparisons between two sets or three sets of data were assessed by Wilcoxon's and Friedman's non-parametric comparison tests, respectively. Intra-subject or group averages are given as mean±SD. Volume dependence of syringe or ventilator partitioning, as well as of time constants was tested by a Spearman non-parametric correlation test, with syringe volume the independent variable. Except for calibration, data from syringe volumes of 200 ml were not used in the calculations, since such small volumes are in the range of deadspace.

Level of significance was $p \leq 0.05$, for all statistics.

Results

Characteristics of calibration lines are reported in table 2. All coefficients of regression of calibration lines, except one, (patient No. 3 on thorax) were ≥0.98 with no difference between thorax and abdomen (0.993 ±0.01 and 0.993±0.005, respectively). The calibration lines were used to calculate the percentage error of RIP volumes, with syringe volume as the reference, *i.e.* $(V_{Rip} - V_{Syr})/V_{Syr}$. This error was calculated for all patients and both coils in the range of pre-experimental inspiratory volume above the volume of full relaxation, *i.e.* pre-experimental VT (patients No. 1–13) or pre-experimental VT plus dynamic hyperinflation when present (patients No. 14, 15, 16). For all patients and both coils this error was <±10% (table 2). The group average value of the error was not statistically different between thorax and abdomen (1.7±4.8 and 1.8±5.0%, respectively, $p>0.05$).

Table 3. – Thoracoabdominal partitioning of syringe and ventilator volumes

Pt No.	Syringe Tho/Tho+Ab mean±SD	Syringe Variation %	Ventilator Tho/Tho+Ab mean±SD	Ventilator Variation %
1	0.50±0.00	0	0.51±0.01	2
2	0.51±0.02	4	0.53±0.02	4
3	0.57±0.03	5	0.62±0.01*	2
4	0.45±0.01	2	0.44±0.01	2
5	0.45±0.03	7	0.40±0.02*	5
6	0.47±0.02	4	0.48±0.01	2
7	0.54±0.02	4	0.55±0.01	2
8	0.46±0.02	7	0.46±0.01	2
9	0.48±0.01	2	0.46±0.02*	4
10	0.33±0.01	3	0.36±0.03	8
11	0.48±0.02	4	0.48±0.00	0
12	0.28±0.03	11	0.33±0.04*	12
13	0.39±0.01	3	0.39±0.02	5
14	0.53±0.02	4	0.51±0.02	4
15	0.53±0.02	4	0.47±0.04*	9
16	0.36±0.01	3	0.44±0.01*	2
Mean	0.46	4	0.46	4
±SD	±0.08	±2	±0.07	±3

Variation is the coefficient of variation, *i.e.* SD/mean. *: significant difference compared to syringe partitioning ($p<0.05$).

Partitioning of syringe volumes differed widely between subjects (table 3 and fig. 3), ranging 0.28–0.57 (mean±SD: 0.46±0.08). Most patients had a predominant abdominal compartment, since 10 out of 16 patients had a partition ratio <0.5. The partitioning was stable in a given patient: with the exception of patient No. 12 the coefficient of variation was <±10% (range 0–12%) with a group average value of 4±2%.

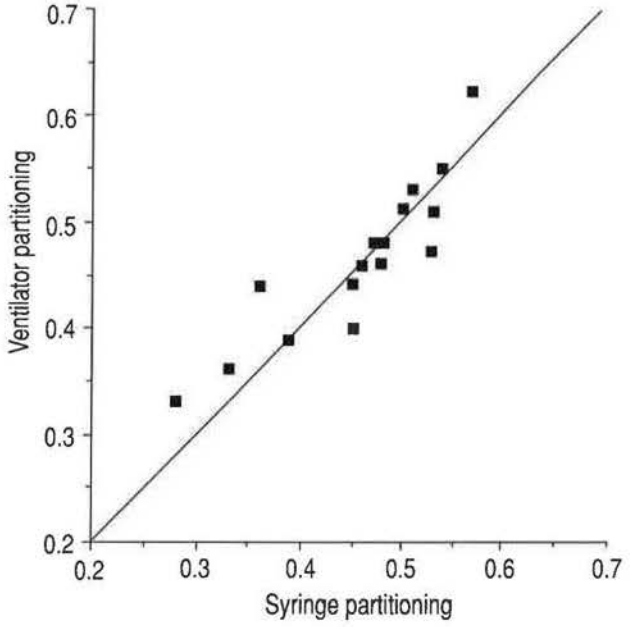

Fig. 3. – Partitioning of volumes insufflated with the ventilator and with the syringe and line of identity. Each point is the mean of 5 volumes ranging from 400–1,200 ml. Note the wide variation of partitioning between subjects. The mean partitioning was 0.46±0.8 and 0.46±0.07 ($p>0.05$) for syringe and ventilator, respectively.

Furthermore, no volume dependence of the partitioning was observed, *i.e.* partitioning was not related to the size of the insufflated volume, since all Spearman's correlation coefficients between partitioning and volume were nonsignificant ($p\geq0.05$).

Partitioning of ventilator volumes was similar to that of syringe volume partitioning. Only patient No.12 had a coefficient of variation >±10% (table 3). For the entire group, the mean coefficient of variation was 4±2% (*vs* 4±3% with the syringe). Again this partitioning was not correlated to the size of insufflated volumes. For a given insufflated volume, the variability of partitioning across the 10 ventilator cycles used was <±1% for all patients (data not reported) and ranged 0.33–0.62 across subjects (fig. 3).

Individual values of syringe and ventilator partitioning differed significantly from one another in six individuals out of 16. However, this difference was not systematically in favour of thorax or abdomen and there was no statistical difference between the group-average values of syringe and ventilator partition ratio (0.46±0.08 and 0.46±0.07, respectively).

Time constants. For each patient there was no statistical difference between thoracic and abdominal measurements (fig. 4), in all but one patient (No. 14). The group difference between mean thoracic and mean abdominal time constant was lower than the standard deviation of one or both of these two variables. The mean group time constant ranged 0.49–7.12 s and 0.47–6.62 s for thorax and abdomen, respectively. As for partitioning, there was no correlation between time constant and insufflated volume, either for the thorax or for the abdomen (Spearman's correlations, p values ≥0.05).

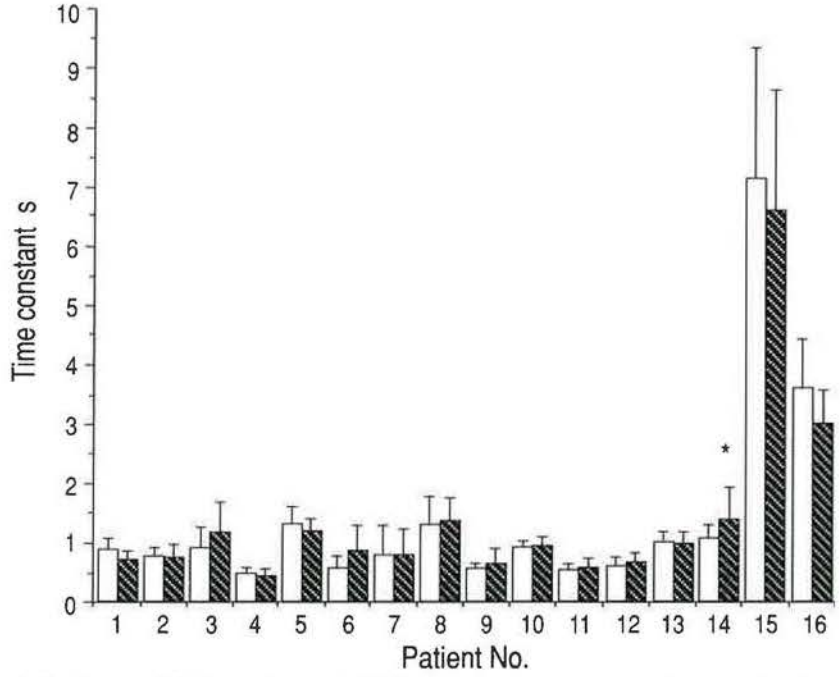

Fig 4. – Time constants for thoracic (□) and abdominal (▨) compartments measured during full relaxation at barometric pressure after the inflation steps of 400 to 1,200 ml. Each bar represents the mean+SD of 5 measurements. Patients No. 1 to 8 are patients with normal lungs. *: significant difference ($p<0.05$).

For the group of patients with normal lungs (patients No. 1–8) the mean time constants were 0.89±0.28 and 0.92±0.29 s, for thorax and abdomen, respectively, (NS, mean 0.91±0.29). In the eleven additional patients with normal lungs, the time constant measured with a single coil was 0.63±0.22 s. Pooling these results yielded a normal time constant of 0.73±0.29 s.

Discussion

The main findings of this study in ventilated, paralysed patients are (1) intra-patient stability of partitioning of insufflated volumes (2) identity of thoracic and abdominal time constants and (3) volume independence of both partitioning and time constants.

Both thoracic and abdominal calibration lines showed a very close correlation between the RIP measured volume and the actual insufflated volume. The error of volume measurement was <±5% in 9 out of 16 patients with thoracic RIP coil, and in 10 out of 16 patients with abdominal RIP coil and always <±10%. Therefore, either the abdominal or the thoracic coil can be used to measure volume variations in paralysed subjects.

For patient No. 10, taken as an example (fig. 2), tidal volume calculated with both coils was 651 ml. (see calibration lines in Methods). If only one coil is used, tidal volume can be calculated without using the partitioning coefficient of syringe volume either with thoracic or abdominal deflection. Tidal volume equals volume/motion coefficient × thoracic or abdominal deflection *i.e.* 17×40=680 ml or 8.5×75=637 ml, respectively, with an acceptable error of <±5% on this portion of tracing.

These results also suggest that the potential confounding effect of the non-linearity of compliance was negligible in the range of volumes used. However, at volumes 1,200 ml the flat upper part of the compliance curve would probably have been reached, resulting in distortion of the calibration lines. In clinical practice such breathing in the upper flat part of the compliance curve has to be avoided to prevent barotrauma [19, 20].

The syringe volume partitioning was stable, independent of the volume in any given subject. Since the diaphragm was relaxed, the change in pressure during each 15 s insufflation plateau, was probably the same in the two compartments [21]. Therefore, the partitioning of volumes in an individual subject reflects the ratio of compartmental compliance. In seven patients, thoracic compliance was higher since partition ratio was >0.5, whereas the reverse was true in the other nine patients. One would have expected changes in partitioning if high volumes had been used because of the shape of the upper part of the compliance curves and the change in the ratio of compartmental compliance. This was not the case in this study.

We do not know what the partitioning of our subjects would have been with spontaneous breathing, but our group average value (0.46±0.08) was similar to those found by Tobin *et al.* [3] in supine, spontaneously breathing normal and diseased subjects [5]. These authors found that pulmonary disease did not change the normal mean partitioning significantly (0.46±0.14 and 0.48±0.13), except in asthmatic patients in whom the thoracic compartment is predominant. However, partitioning variability in spontaneous breathing was higher than in our paralysed patients. Therefore, thoracic and abdominal elastic characteristics are probably major determinants of mean partitioning, whereas muscular activity plays a major role in superimposing breath-by-breath variations of partitioning during spontaneous breathing.

Ventilator volume partitioning was remarkably constant for a given inflated volume (except in the same patient No. 12), and the variation was volume independent, as with syringe volumes. On average, partitioning was not statistically different with the ventilator and with the syringe. However, in six patients (table 3), the difference between syringe and ventilator partitioning was significant. It could be due to complex dynamic interactions between thoracic, abdominal and apparatus compliance and resistance, since syringe partitioning corresponds to static variations, whereas ventilator partitioning reflects dynamic variations. Indeed the highest difference was observed in patients No. 15 and 16, who also had the longest time constant (6.9 and 3.3 s, respectively). However, we do not exclude other unrecognized factors that may explain this difference, because it was also found in some patients with normal lungs.

Time constants were also volume independent in the range of volumes used. It is probable that a volume dependence would have been found had we used larger inflated volumes. It may seem paradoxical to use a single time constant, implying mono-exponential passive expiration, since we and others have shown that passive expiration in paralysed patients with normal or diseased lungs is better described by a two exponential linear model [22–24). However, this does not preclude the use of a simple time index, $T_{0.368}$, called for simplicity "time constant" in the present study. Firstly, this time index only varied by a few percent with volumes in the range of usual inflated volumes and was reproducible, whereas it can be increased sevenfold in patients with chronic obstructive pulmonary disease (COPD) as shown in figure 4. Secondly, this "time constant", related as it is to numerous variables, *e.g.* total compliance, resistance of airways, and of the endotracheal tube, and intrinsic positive end-expiratory pressure (PEEP), gives global, simple and useful information about expiration of ventilated patients, as recently indicated by Smith and Marini [25]. Thirdly, this time index is able to detect effects of bronchodilators in ventilated patients: for example in a patient with asthma it decreased from 7 to 4 s with an aerosol of beta-agonist (unpublished data).

All expiratory time constants measured so far in normal and diseased paralysed patients [13, 25, 26] are

overestimated, due to the resistance of the endotracheal tube [27, 28]. To our knowledge, no attempt has been made to correct for this effect, probably partly because of the uncertainty of such a correction in terms of time constant and partly because data which includes tracheal tube are useful. Other possible causes of error due to the equipment were negligible since the recorder and the RIP had a time constant of 0.01 and 0.005 s, respectively.

Thoracic and abdominal time constants, except in one subject were almost identical (fig. 3). If we accept that time constant is the product of compliance and resistance, this result, combined with the fact that compliances where different, suggests that resistances were also different, although both compartments empty through the same resistance of the tracheal tube.

Time constants are known to be normal in patients with adult respiratory distress syndrome (ARDS) [13] and high in patients with obstructive disease [25]. Time constant of patient No. 15 with septic shock was very high (6.9 s), due to an underlying obstructive disease. In this patient the corresponding dynamic hyperinflation may be seen on figure 1 as the difference between ventilated and relaxed end-expiratory volume. There are very few data in the literature on normal time constants. On the basis of our measurements in 19 paralysed patients with normal lungs we propose normal values for time constant: 0.73±0.29 s.

These values are in accordance with those established by BERGMAN [26] (0.63±0.14 s) with direct spirometry.

Degrees of freedom. Two degrees of freedom, *i.e.* thoracic and abdominal displacements are generally necessary to describe the behaviour of the respiratory system [8, 21]. However, when body posture changes or when forces applied are large enough to distort the configuration of the system, additional degrees of freedom are necessary [21, 29], which is not the case in our study.

Passive properties of the lung have initially been studied in conscious subjects with voluntary relaxation or with only partial curarization. With voluntary relaxation only trained subjects produce reproducible results. In either case, residual muscular activity is a cause of artifacts, so that results in most conscious subjects at best approximate the relaxed state of the system [29].

In ventilated, sedated or anaesthetized patients, passive properties of the respiratory system including pressure-volume curves, have been extensively studied using curare. In the present study, we used a two coil RIP and demonstrated that in paralysed patients only one coil, either thoracic or abdominal, allows the measurement of volume changes and of time constants. In other words, the system acts with one degree of freedom. This is probably an oversimplified model but our results show that it satisfactorily fits with reality in the range of volumes and in the type of patients studied. This further validates the use of this model for obtaining pressure-volume curves in paralysed patients.

In conclusion, this study shows that in paralysed, intubated patients, without thoracoabdominal surgery or X-ray asymmetry, the respiratory system moves with a single degree of freedom during passive ventilation, with no variation in partitioning over a large volume range for any given patient. In consequence, volume variations and time constants can be reliably measured in paralysed patients with a single coil respiratory inductive plethysmograph. This conclusion cannot be extrapolated to non-paralysed patients.

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