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Improved determination of static compliance by automated single volume steps in ventilated patients

M. Sydow, H. Burchardi, J. Zinserling, H. Ische, Th. A. Crozier and W. Weyland

Zentrum für Anaesthesiologie, Rettungs- und Intensivmedizin, Georg-August-University, Göttingen, FRG

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Abstract. A new method for determination the static compliance of the respiratory system is described ("static compliance by automated single steps" – SCASS). In 12 ventilated patients pressure/volume (P/V) curves were determined by automated repetitive occlusion (6 s) at single volume steps and compared to the conventional syringe method (SM). All measurements were corrected for effects of temperature, humidity and pressure (THP). SM was found to be significantly influenced by intrapulmonary gas exchange causing an effective mean volume deficit of 217.4±65.7 ml (BTPS) at the end of the deflation. In contrast to that, the short duration of occlusion in SCASS minimize the gas exchange effects. The methodical differences between both methods result in overestimation of the inflation compliance in the uncorrected SM (SM_{uncorr}: 83.4±12.6; SCASS: 76.0±11.9 ml/cmH_2O. $p<0.01$) and underestimation of the deflation compliance resp. (SM_{uncorr}: 58.3±7.5; SCASS: 79.1±15.0 ml/cmH_2O. $p<0.005$). In contrast to the P/V curves by SM no significant hysteresis was found by SCASS. Gas exchange seems to be the main reason for the hysteresis. Even after correcting gas exchange and THP effects a significant hysteresis remained. The SCASS method avoids these problems and allows furthermore an accurate checking of leaks.

Key words: Static compliance – Pressure volume curve – Pulmonary mechanics – Acute respiratory failure – Adult respiratory distress syndrome

Static compliance as a parameter of the elasticity of the total respiratory system (lung and thorax) or of the lung itself can be determined by various methods. The procedure most used is the continuous step by step inflation and deflation with a super syringe [1–6]. At the end of each step with short pauses (1.5–2 s) static conditions are assumed. A similar method uses inflation/deflation with a very slow continuous flow of 1.7 l/min [7].

Determination of the static compliance with these procedures results in pressure/volume (P/V) curves that are often different during inspiration and expiration, so called hysteresis. The degree of hysteresis depends on the lung history and on other dynamic factors, for instance gas exchange which goes on during the time required for the measurement (60–90 s). With P/V curves properly corrected for gas exchange effects and changes in temperature, pressure and humidity on lung volume hysteresis is significantly less than with uncorrected loops [8]. However, complicated correction procedures make determination of static compliance a very complex method. It seems that respiratory inductive plethysmography allows correction of the net effect of gas exchange during the syringe inflation/deflation cycle more adequately as has been shown by Dall'Ava-Santucci et al. [9]. However, this procedure still remains combersome and, probably, less accurate (volume error compared with spirometer up to 13% [9]).

In order to avoid these artefactual influences we used a different methodical approach for automated, computer controlled measuring the P/V relationship in ventilated patients ("static compliance by automated single steps" – SCASS).

Hereby static compliance is determined during mechanical ventilation without altering the ventilatory pattern. The short occlusion phases for measurement of the different single volume steps minimizes the influence of gas exchange and of altered "lung history".

We compared the results of this method with those obtained by the conventional syringe method (SM) in mechanically ventilated patients. We also attempted to analyze if the methodical errors of SM could be eliminated by meticulous corrections for gas exchange, temperature, humidity and pressure changes.

Patients and methods

P/V curves were determined in 12 patients with acute respiratory failure of different degree and different etiologies (table 1), first by SCASS and immediately thereafter by continuous step by step inflation and deflation with a syringe. All patients were heavily sedated, completely paralyzed with pancuronium bromide or norcuronium, and mechanically ventilated during the measurement. ZEEP was applied 15 min before starting the measurements and continued until these were completed. A controlled mechanical ventilation mode with constant flow and inspiration/expiration ratio of 1 : 2 to 1 : 1 was selected, and the ventilator settings were kept constant during the whole procedure according to the patients need. The study protocol was approved by the Ethical Committee of our Medical Faculty.

Table 1. Patient data and results for the functional residual capacity (FRC), the oxygen uptake (delta $\dot{V}O_2$), the CO_2 input into the lungs (delta $\dot{V}CO_2$), the net effect of gas exchange during the *whole* syringe maneuvre [in ml BTPS]; compliance was determined with SCASS during inspiration (C_i) and expiration (C_d) including their correlation coefficients ($Corr._i$ and $Corr._d$, resp.). Mean values and standard deviation (SD) are calculated

Patient	Age	Sex	Diagnosis	Pulmonary status	F_IO_2	FRC	delta $\dot{V}O_2$	delta $\dot{V}CO_2$	Net effect of gas exchange	C_i [SCASS] [ml/cm H_2O]	$Corr._i$ [SCASS]	C_d [SCASS] [ml/cm H_2O]	$Corr._d$ [SCASS]
						ml BTPS							
1	68	m	Severe head injury	Normal	0.25	1668	241[a]	103	138	85.4	0.9994	99.0	0.9982
2	48	f	Ruptured cranial aneurysm	Mild atelectasis	0.3	1862	280[a]	90	190	65.0	0.9993	73.0	0.9996
3	60	m	Pharynx carcinoma	Pneumonia, COPD	0.45	3251	259[a]	84	175	96.0	0.9999	98.3	0.9996
4	44	f	Ruptured cranial aneurysm	Mild atelectasis	0.3	1796	261[a]	96	155	84.1	0.9990	84.3	0.9997
5	72	m	Multiple trauma	Lung contusion	0.5	1385	260[a]	89	171	75.6	0.9997	74.8	0.9993
6	39	f	Multiple trauma	Lung contusion	0.5	1811	337[a]	106	231	64.1	0.9997	60.8	0.9997
7	58	f	Ruptured cranial aneurysm	Pneumonia	0.7	1577	364[a]	76	288	65.8	0.9998	69.6	0.9991
8	26	m	Severe head injury	Normal	0.21	2495	474[a]	107	367	78.8	0.9998	84.9	0.9967
9	84	m	Multiple trauma	Pneumonia	0.4	1178	359[a]	88	271	58.2	0.9994	55.0	0.9992
10	54	m	Severe head injury	Pneumonia, COPD	0.5	2424	360[b]	117	243	69.8	0.9993	68.7	0.9989
11	54	m	COPD	Pneumonia	0.7	2136	285[b]	84	201	94.4	0.9994	104.2	0.9997
12	74	m	Multiple trauma	Lung contusion	0.3	1900	288[a]	119	169	81.8	0.9998	83.6	0.9996
Mean	56.8					1956.7	314.0	96.9	217.4	76.0		79.1	
SD	±16.3					±558.9	±67.1	±13.7	±65.7	±11.9		±15.0	

[a] 72 s
[b] 60 s

Respiratory flow was measured with a heated pneumotachometer (Fleisch no. 2, Fleisch, Lausanne, Switzerland. Linearity: ±1% for 0 to 2,5 l/s) directly connected to the proximal end of the endotracheal tube and a differential pressure transducer (Dr. Fenyves & Gut, Basel, Switzerland). At the same position tracheal pressure was measured by another differential pressure transducer (same producer). The data were sampled on-line by an analog/digital-converter (DT 2801-A, Data Translation, Marlboro MA, USA) at a rate of 20/s and processed by an IBM AT compatible personal computer. The data acquisition and processing software was programmed with a commercially available software program (Asyst® 3.0, Asyst Software Technologies, Rochester NY, USA). Volume was obtained by numerical integration of the flow signal. The pneumotachometer was calibrated with the patient's collected expired gas mixture which was supplied by a motor driven pump delivering 1 l of gas volume with sinusoidal flow pattern. The FRC was determined at the beginning and at the end of the measurements using the argon dilution method [10, 11]. The analysis of argon and CO_2 was carried out by mass-spectrometry (MGA 1100, Perkin-Elmer, Pomona CA, USA).

Additionally, the P/V curves of three patients with moderate and severe ARDS (definition see [12]) were also determined by SCASS alone without comparison with SM.

Static compliance by automatic single step (SCASS)

A general diagramm of the apparatus is shown in Fig. 1. For each single measuring step airways are totally occluded during controlled mechanical ventilation at various inspiratory and expiratory volume levels. The occlusion onsets are taken as delay times after beginning of inspiration and expiration respectively. The different volume steps are defined by varying the delay time for occlusion. The opening and closing of the occluding pneumatic valve is automatically controlled by the computer program. The duration of the occlusing procedure (electronical control inclusive pneumatic occlusion) takes 125 ms. This delay time is automatically compensated by the software. Volume is taken as the actually measured volume at the moment of the effective complete occlusion (flow = zero). Airway pressure is taken as the mean value between the 4th and the 6th second. Each pre-defined volume step is independent of the others. Between each measurement step normal ventilation (5 breath cycles) is continued without disconnecting the patient from the ventilator. The same procedure can be done separately for expiration.

Values for barometric pressure, ambient and patient temperatures are entered into the computer for automatically correcting the intrapulmonary volume into BTPS. At the end of the measuring procedure the determined P/V values are plotted in a P/V diagramm. The static compliance of the respiratory system is calculated by regression analysis of the linear part of the inspiratory and the expiratory slope resp. A single measurement performed during inspiration is shown in Fig. 2.

The measurement for one P/V data pair lasts six seconds. All volume steps are within the applied tidal volume. Correction of the intrapulmonary volume due to the gas exchange during the short occlusion time was not made. In these series 10-12 P/V data pairs for each in- and expiratory compliance curve were determined starting at end expiratory volume at ZEEP (at ambient pressure).

Syringe method

A 1 l plexiglass super-syringe carefully checked for air tightness was filled with 100% dry oxygen, and volume steps of 200 ml were applied up to a volume of 1000 or 1200 ml (depending on maximum airway pressure). Inflation of the lung started at FRC at ZEEP after visual control that airway pressure had reached ambient pressure. Deflation, also with steps of 200 ml, was carried out until ambient pressure was reached. Each volume step was hold 6 s, airway pressure was taken as the mean value between the 4th- and 6th- second. The whole procedure lasted 60-72 s depending of the maximum inflated volume (see Table 1).

Correction factors in the syringe method

The P/V relationship is usually evaluated assuming that the volume displaced from the syringe is equal to the volume change in the lung. However, this assumption is invalid because of the influences of oxygen up-

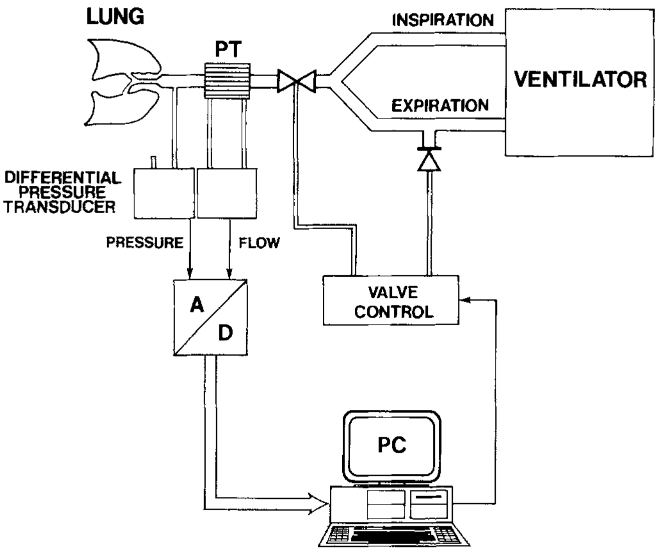

Fig. 1. General diagramm of the SCASS system for computer-controlled, automated measurements of static compliance (for details see text). *a*, pneumatic driven valve occluding the main airway; *b*, pneumatic driven valve releasing the ventilatory circuit during occlusion; *PT*, pneumotachometer; *A/D*, analog/digital converter; *PC*, personal computer

take and CO_2 production and changes in temperature, pressure and humidity. To eliminate these influences we applied the following correcting calculations.

Temperature, humidity and pressure

For each inflation step the syringe volume in ATPD conditions was corrected to BTPS conditions in the lung. For each deflation step the lung volume in BTPS conditions was corrected to ATPS conditions in the syringe. The gas temperature was determined twice (at the beginning and the end of the measuring procedure) by measuring the gas temperature in the syringe. The oxygen collected in a bag and the syringe were stored at constant ambient temperature before and during the measuring procedure. The patient's rectal temperature was monitored continuously. The humidity of the oxygen prior to inflation was supposed to be zero percent, the humidity of the gases in the lungs was taken as 100%, as was the humidity of the deflated gas in the syringe (coming saturated out of the lung and converted to ambient/syringe temperature). Correction was made for the increasing and decreasing airway pressures according to Boyle-Marriotte's law.

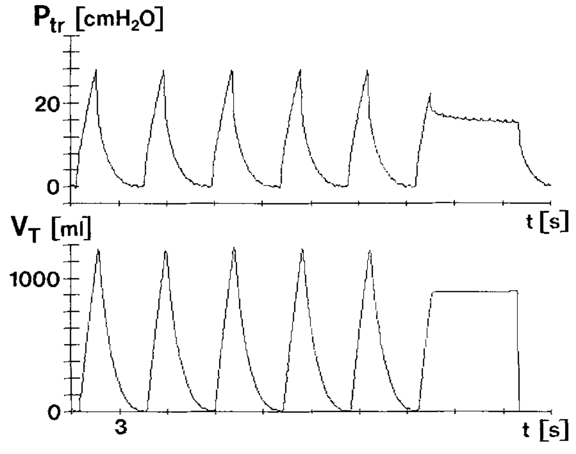

Fig. 2. Original tracing of a single occlusion step with five normal ventilatory cycles preceeding the occlusion maneuver at a preset inspiratory volume level. P_{tr}, tracheal pressure in cm H_2O, V_T, ventilated volume above FRC in ml (BTPS) integrated from the flow signal by pneumotachometry; *t*, time in seconds

Inflation (ATPD → BTPS):

$$V_{BTPS} = V_{ATPD} \times (273.15+T_p)/(273.15+T_s) \times P_b/(P_b - P_{H_2O}(T_p))$$

Deflation (BTPS→ATPS):

$$V_{ATPS} = V_{BTPS} \times (273.15+T_s)/(273.15+T_p) \times (P_b - P_{H_2O}(T_p))/P_b - P_{H_2O}(T_s))$$

Boyle-Marriotte's law:

$$V_{corr} = V_{uncorr} \times P_b/(P_b - \mathrm{delta}\, P_{L,b})$$

T_p = patient temperature
T_s = syringe temperature
P_b = barometric pressure
$P_{H_2O}(T_p)$ = partial pressure of H_2O at patient temperature
$P_{H_2O}(T_s)$ = partial pressure of H_2O at syringe temperature
$\mathrm{delta}\, P_{L,b}$ = differential pressure between barometric pressure and pressure in the lung

Oxygen uptake: volume removal from the lung (delta $\dot{V}O_2$)

We assumed a constant oxygen removal from the lung (delta $\dot{V}O_2$) caused by uptake during the measurement. The oxygen uptake of the sedated and relaxed patient was measured by indirect calorimetry (Deltatrac^R, Datex Instrumentarium, Helsinki, Finland) [13] in a steady state 15 min before and after the compliance measurements. If both values were in good accordance (less than 10% difference) the mean value was taken for the correcting calculation during the entire procedure. In case of poor accordance the whole measurement was excluded from the study.

Correction for oxygen uptake for each step was calculated by the following formula:

$$V_i^{corr} = V_i^{uncorr} - i \times t \times \dot{V}O_2$$

i = "ith" volume step of 200 ml
V_i^{corr} = corrected volume (for $\dot{V}O_2$)
V_i^{uncorr} = uncorrected volume
t = time for one volume step in minutes
$\dot{V}O_2$ = oxygen consumption [ml BTPS/min]

CO_2 production: volume addition to the lung (delta $\dot{V}CO_2$)

Baseline CO_2 content of the lung was calculated by measuring the end-tidal CO_2 concentration with mass spectrometry at the predetermined FRC.

For the *inflation* procedure we used the CO_2 concentration difference between the beginning and the end (taken at the end of first deflation step) of inflation. We assumed a linear increase of the amount of CO_2 between these values (volume steps). From that we calculated the increasing CO_2 volume difference ($\mathrm{delta}\dot{V}_{CO_2}$) for each inflation step with the following formula:

$$(\mathrm{delta}\dot{V}_{CO_2} = \{(\%CO_{2,e} \times 10^{-2} \times (FRC + k \times 200\ [ml])) - (\%CO_{2,b} \times 10^{-2} FRC)\} \times k^{-1}$$

$$V_{infl,i}^{corr} = V_{infl,i}^{uncorr} + i \times \mathrm{delta}\dot{V}_{CO_2}$$

$\mathrm{delta}\dot{V}_{CO_2}$ = added intrapulmonary volume of CO_2 per volume step
$\%CO_{2,b}$ = % endtidal CO_2 concentration before inflation
$\%CO_{2,e}$ = % endtidal CO_2 concentration at the end of inflation (taken at the end of first deflation step)
i = "ith" volume step of 200 ml
k = numbers of inflation steps
$V_{infl,i}^{corr}$ = corrected volume (for CO_2 at "ith" inflation step
$V_{infl,i}^{uncorr}$ = uncorrected volume (for CO_2) at "ith" inflation step

During *deflation* we measured the endtidal CO_2 concentrations at the end of each deflation step. From these the additional CO_2 volume for each deflation step was again calculated.

$$V^{corr}_{defl,i+1} = V^{uncorr}_{defl,i+1} + V^{uncorr}_{defl,i+1} \times ((\%CO_{2,i+1} - \%CO_{2,i}) \times 10^{-2}) + k \times delta\dot{V}_{CO_2}$$

$\%CO_{2,i}$ = % endtidal CO_2 concentration at "ith" deflation step
$\%CO_{2,i+1}$ = % endtidal CO_2 concentration at "ith" +1 deflation step
k = numbers of inflation steps
$V^{corr}_{defl,i+1}$ = corrected volume (for CO_2) at "ith" +1 deflation step
$V^{uncorr}_{defl,i+1}$ = uncorrected volume (for CO_2) at "ith" +1 delfation step

Correction was carried out step by step for each volume. The corrections are performed in different consecutive steps.

The correlation between the volume effect of gas exchange and the trapped volume was calculated by linear regression analysis.

Parameters of the P/V curves

The following parameters form the pressure-volume data of the SCASS and SM (uncorrected and corrected) were derived and compared:

1. *Inflation compliance (C_i):* regression line of the inflation P/V data pairs of the linear part of the slope.
2. *Deflation compliance (C_d)*: regression line of the deflation P/V data pairs of the linear part of the slope.
3. *Trapped volume* (= unrecovered volume): volume deflated by the syringe procedure but not recovered by deflation to barometric pressure (P_B). For SCASS: the volume difference between the inspiratory and expiratory P/V curve at the point of intersection of the inspiratory P/V curve with the y-axis (P_B).
4. *Hysteresis area or hysteresis ratio* [14] was only calculated for uncorrected and corrected syringe P/V values. Hysteresis area was calculated as the area within the inflation and deflation limbs of the P/V curve. Hysteresis ratio was calculated as the ratio of the hysteresis area and the product of maximum pressure and volume. For the SCASS method hysteresis and hysteresis area cannot be correctly defined because of the open upper part of the inspiratory/expiratory P/V curves. Here, alternatively inflation/deflation pressure differences were calculated.
5. *Inflation/deflation pressure differences* (dP) at 25%, 50% and 75% of the maximum insufflation volume were taken as a measure for the hysteresis of the P/V curves in SM and SCASS.

Statistical analysis

Statistical evaluation was performed with the Wilcoxon signed rank test for paired data [15]. A p-value less than 0.05 was defined as significant.

Results

Correction factors

FRC, changes of lung volume by oxygen uptake and CO_2 input into the lung (delta $\dot{V}O_2$ and delta $\dot{V}CO_2$ resp.) of the patients are shown in Table 1.

The corrections for temperature and humidity (ATPD →BTPS during inflation and BTPS→ATPS during deflation) caused a mean increase of the lung volume of 56 ± 3.7 ml at the end of the syringe measurement (during inflation each volume step was increased by 12.5%, and during deflation progressively increasing up to 28%).

According to Boyle-Mariotte's law the intrapulmonary gas volume compressed during inflation because of the increasing intrapulmonary pressure. The maximal pressure-related reduction of the intrapulmonary gas volume was an average of 31 ml at the end of inflation. This effect decreased during deflation with decreasing pressure, and the difference between corrected and uncorrected intrapulmonary volumes was only 1 ml at the end of deflation.

The effective volume change calculated by alveolar O_2 uptake from the lung and CO_2 addition into the lung (in BTPS) during the syringe procedure depends on the duration of the measuring process. The duration of SM varied between 60 and 72 s depending on the insufflated volume. It must be taken into consideration that this influence varied considerably for each different volume step. The relative changes of the intrapulmonary gas volume was more marked during deflation as the increasing volumes during inflation diminish the effects of gas exchange.

P/V curves

Table 2 summarizes the differences in inflation compliance (C_i) and deflation compliance (C_d), trapped volume and inflation/deflation pressure differences (Pd) at 25%, 50% and 75% of the maximum insufflation volumes between the SCASS, and the uncorrected and corrected SM values.

Table 2. P/V curve parameters (mean values and standard deviation) syr_{uncorr} = syringe uncorrected; syr_{corr} = syringe corrected for temperature, pressure, humidity, gas exchange; SCASS = static compliance by automated single step

	syr_{uncorr}	syr_{corr}	SCASS	Unit
C_i	83.4 ± 12.6^{b,c}	76.4 ± 13.0	76.0 ± 11.9	ml/cmH_2O
C_d	58.3 ± 7.5^{b,d}	67.9 ± 8.0^{c}	79.1 ± 15.0	ml/cmH_2O
Trapped volume	436.2 ± 112.0^{b,d}	188.8 ± 125.0^{d}	−34.7 ± 44.3	ml
Hysteresis area	449.5 ± 219.3^{b}	210.8 ± 125.9	n.c.	mJ
Hysteresis ratio	22.3 ± 7.9^{b}	11.6 ± 6.1	n.c.	%
dP 25% V_T	4.5 ± 0.9^{a,d}	1.9 ± 0.9^{d}	−0.3 ± 0.3	cmH_2O
dP 50% V_T	3.4 ± 0.8^{b,d}	2.0 ± 0.7^{d}	−0.0 ± 0.5	cmH_2O
dP 75% V_T	2.0 ± 0.6^{d}	1.9 ± 0.6^{d}	−0.0 ± 0.4	cmH_2O

C_i, inflation compliance; C_d, deflation compliance; dP 25% (50%, 75%) V_T, pressure difference at 25%, 50% and 75% of the maximum insufflation volume (tidal volume) ; n.c., not calculated

[a] $p < 0.01$ vs syr_{corr}
[b] $p < 0.005$ vs syr_{corr}
[c] $p < 0.01$ vs SCASS
[d] $p < 0.005$ vs SCASS

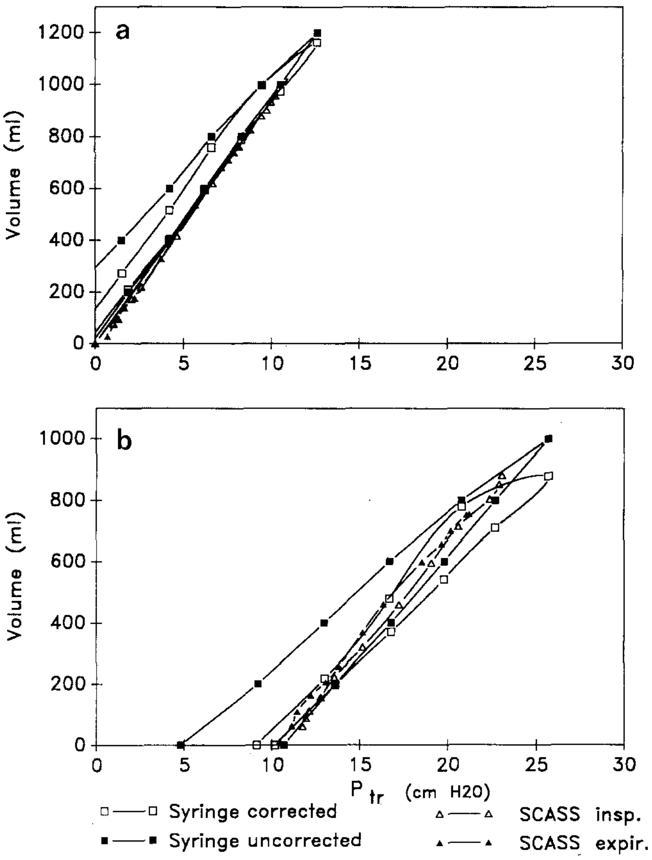

Fig. 3a, b. P/V curves of 2 patients determined by SCASS and the syringe method (uncorrected and corrected) plotted into the same diagram: With the SCASS determination there is no or nearly any hysteresis between the inspiratory and the expiratory slope. Whereas, with the SM determination a large hysteresis is obvious which only can be partly reduced by corrections for effects of gas exchange, temperature, pressure, and humidity. P_{tr}, tracheal pressure in cmH_2O, Volume above FRC in ml. **a** Measurement in a 27-years-old patient with a healthy lung (patient no. 3) C_i: $SM_{uncorrected}$ 93.6, $SM_{corrected}$ 89.3, SCASS 96.0; C_d: $SM_{uncorrected}$ 73.0, $SM_{corrected}$ 84.5, SCASS 97.7 [ml/cm H_2O]. **b** Measurement in a 54-years-old patient with COPD (patient no. 10). C_i: $SM_{uncorrected}$ 66.4, $SM_{corrected}$ 56.5, SCASS 69.9; C_d: $SM_{uncorrected}$ 48.9, $SM_{uncorrected}$ 58.3, SCASS 68.2 [ml/cmH_2O] (inspiratory syringe curves superimposed on the SCASS curve)

There was no significant difference between C_i and C_d as determined by SCASS, however, this difference was highly significant ($p<0.005$ resp. $p<0.01$) when measured with SM even after correction. The significant difference of C_i between SCASS and SM could be eliminated by the correction for gas exchange, temperature, pressure and humidity; however, this was not true for C_d. This means that the hysteresis of the P/V curves determined by SM could be reduced but not totally eliminated by the correction procedure. In contrast to this the SCASS curves had no hysteresis. Consequently Pd at 25%, 50% and 75% of the maximum inflation volume was considerable with SM (whether corrected or not) but non-existent with SCASS (Table 2).

In our studies there was no correlation between the amount of the gas exchange volume effect and the trapped volume ($r = -0.15$; $p = 0.64$).

The original P/V curves of two patients determined by SCASS and SM (uncorrected and corrected) are shown in Fig. 3a-b. One was a patient with normal lungs (a) who was mechanically ventilated because of severe head injury; the other was a patient with decompensated COPD (b). Additionally, the P/V curves of three further patients with ARDS are shown, which were determined only by SCASS (Fig. 4a-c). In contrast to previous investigations [3–5] all P/V curves had only very small or no hysteresis.

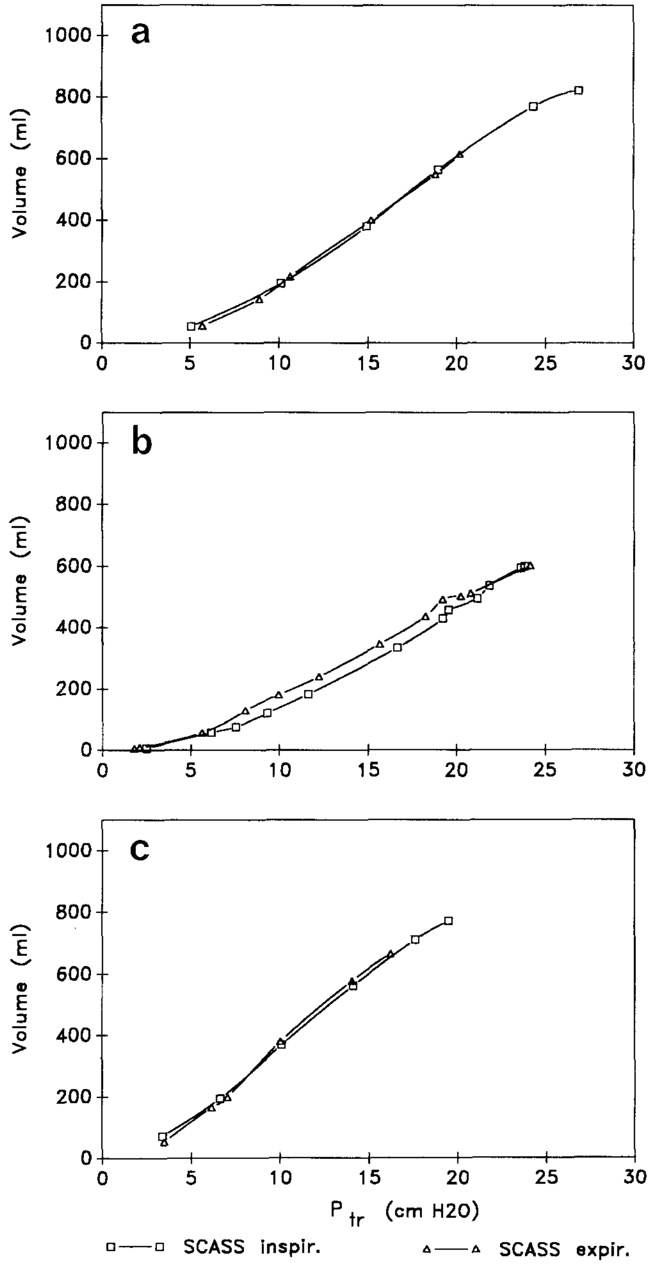

Fig. 4a–c. P/V curves determined by SCASS of 3 ARDS patients. Note the nearly complete lack of hysteresis in the slightly S-shaped curves. P_{tr}, tracheal pressure in cmH_2O, Volume above FRC in ml. P/V values during inspiration (*SCASS inspir*) and during expiration (*SCASS expir.*). **a** 28-years-old female, HELLP-syndrom; C_i 40.9, C_d 41.1 [ml/cmH_2O]; trapped volume: −27.9 ml (SCASS); **b** 42-years-old female, aspiration pneumonitis; C_i 33.3, C_d 28.1 [ml/cmH_2O]; trapped volume: 49.0 ml (SCASS); **c** 83-years-old male, aspiration pneumonitis; C_i 47.1, C_d 53.4 [ml/cmH_2O]; trapped volume: −38.0 ml (SCASS)

As all measurements were performed without external PEEP the positive pressure of the deflation curve determined with SCASS at zero volume is effected by an intrinsic PEEP at this ventilatory situation. We found intrinsic PEEP commonly present in patients with COPD, but it has also been noticed in patients with pneumonia and ARDS patients.

Discussion

Static compliance has proved useful for staging and determining the prognosis of acute respiratory failure and especially ARDS. It seems also to be an important parameter for optimizing ventilation, for example the level of PEEP [16]. Principally, the static compliance should only reflect the elastic properties of the lung and should not be influenced by dynamic factors. However, in practice, the elastic properties of the rib cage are always part of the measurement in paralyzed patients, if the measurement is not based on the transpulmonary pressure difference (via esophageal pressure). Also, dynamic influences (like insufficient pressure equilibration, ongoing gas exchange effects, alveolar recruitment etc.) will still play an important role in the conventional measuring procedures, even if performed meticulously.

Conventional methods for measuring static compliance are cumbersome, and are therefore not routinely used in clinical practice. The static compliance by automated single step (SCASS) described in this report avoids a number of these handicaps.

Both SCASS and SM must be corrected for pressure, temperature and humidity. Pressure causes only minor volume changes (1% to maximal 3% during inflation, decreasing to 0.05% at the end of deflation). If the inflation is performed with dry gases (ATPD condition) the intrapulmonary volume must be converted into BTPS. In our study this amounted to an average of 12.5% for each volume step during inflation. During deflation the BTPS conditions must be converted into ATPS, since the expired gas is no longer dry but water vapor saturated.

The syringe maneuver normally takes between 60 and 90 s. This is inherent to the method, since zero-flow conditions must be fulfilled after each volume step. It is obvious that gas exchange would be an important factor during this time [8]. This was confirmed by our study.

Furthermore, the lung is often hyperinflated during the syringe measurement. This certainly affects the "lung history" and probably also the fluid content of the lung. Here, dynamic factors (for instance alveolar recruitment) may also influence the measurement and lead to artefacts. Altogether, this maneuver has little in common with a normal ventilatory pattern.

With SCASS on the other hand only one P/V data pair is determined during an normal breath cycle interrupted only by an additional hold. The single determination lasts only 6 s. Between each measurement normal ventilation is continued. In contrast to the marked influence in the syringe method the effect of gas exchange (and perhaps also of the changed "lung history") in the SCASS method is only small (in our study approximatively 15 ml) and (under stable conditions) identical at all measured volume steps. As static compliance is calculated from the slope of the linear part of the P/V curve this systemical artifact does not influence the result.

To correct the influence of gas exchange for SM the FRC must be determined, which per se is troublesome. Furthermore the $\dot{V}O_2$ must be determined either by the inverse Fick principle or by indirect calorimetry. All this makes SM more laborious and sometimes even more invasive (for example in those cases in which a Swan-Ganz-catheter is necessary). It has to be stated that even with these correction procedures the real situation can only be estimated within limited accuracy. In our opinion this is a strong argument for non accumulative methods like SCASS. Only the respiratory inductive plethysmography avoids these effects of gas exchange and therefore do not require determination of FRC nor determination of oxygen consumption and CO_2 removal into the lungs.

In the syringe method, even after applying elaborate corrections, we were not able to eliminate the hysteresis of the P/V curves. Also other investigators still found a residual hysteresis in spite of proper corrections [8], and even in studies on cadavers [8] or in isolated lungs [14, 17], e.g. without gas exchange.

This indicates that there may be other factors which must be taken into consideration. Apart from gas exchange and changes in temperature, pressure and humidity, hysteresis may be partially explained by other dynamic effects (like stress relaxation) as viscoelastic and plastic elements of lung tissue properties. The hyperinflation often employed by SM will influence the static compliance [18] during deflation more than during inflation, as previously closed alveoli may be opened by the inflation maneuver. P/V curves determined by respiratory inductive plethysmography which principally avoids gas exchange problems still seem to demonstrate hysteresis, although of a lesser degree [9]. But also here the inflation/deflation maneuvre is continuously performed with a syringe and will therefore alter the "lung history" at the different volume levels.

Furthermore, fluid displacement (blood and interstitial fluid) out of the thorax during inflation may possibly alter the P/V relationship. However, simultaneous measurements of the thoracic and abdominal volume by inductive plethysmography indicate that thoraco-abdominal blood displacement only may play a minor role [9].

Of course, the measurements are only reliable if during the occlusion maneuver leaks can be definitively ruled out. In SCASS this can, indeed, be excluded by subtle control of the pressure behavior during occlusion. Control of leaks seems us to be a main advantage of our method since gas exchange and leaks normally are the major causes of artefactual hysteresis. During occlusion the loss of pressure due to gas exchange is independent of the volume at which the occlusion is performed, while the loss of volume due to leaks increases with the pressure.

One main result of our study is the lack of a significant hysteresis, even in severely diseased lungs. It seems that the pronounced hysteresis phenomenons found with the conventional methods for determining static compliance are mainly due to methodical errors caused by effects of gas exchange, different gas conditions, and possibly altered "lung history". Even with measurements using large tidal volumes up to 2.4 l in moderately diseased lungs we were unable to demonstrate a significant hysteresis with SCASS (data not shown).

Other authors, who used for instance different PEEP levels [19] or different inspiration volumes [20] to determine static compliance, also came to the conclusion, that a hysteresis could not be detected [19] or seems to be much smaller than previously assumed [20]. This is also confirmed by compliance measurements using respiratory inductive plethysmography [9].

Principally, artifactual formation of hysteresis will result from every difference in volume estimation between the inflation and the deflation, e. g. overestimation of the intrapulmonary volume during deflation or underestimation of the expired volume resp.. Theoretically there are two possibilities for underestimating the expired gas volume with the SCASS procedure:
1) The sampling frequency of 20 Hz may introduce errors namely for the measurement of the expired volume of upto 50 ml (in our study the expiratory flow was maximal 1 l/s). This leads to an underestimation of the volume. However, the mathematical procedure of flow integration to volume in our calculation program defines zero flow by assuming the inspired volume to be equal expired volume. Consequently, this will underestimate the inspiratory and the expiratory compliances equally. It cannot cause missing a hypothetically existing hysteresis.
2) Accordingly, the effect of R (expired volume less than inspired volume at $R<1$) is also equally partitioned between inspiration and expiration by the integration procedure. In contrast to the possible errors by sampling frequency expired volumes may hereby be slightly overestimated and, respectively, the inspired volume uneresti-mated (approximatively maximal 8 ml per total tidal volume for ventilatory rate $= 10 \times \text{min}^{-1}$, $R = 0.7$ and $\dot{V}O_2 = 270$ ml/min). Therefore, this may only lead to an small overestimation of the inspiratory and expiratory compliance but not to an underestimation of hysteresis.
Conclusions: Conventional methods for determining static compliance are influenced by factors, not related to the elastic properties of the lung. The correction of these side-effects is laborious and probably insufficient. Our automated, computer-controlled method measuring single steps repetitively avoids these problems. Furthermore, it allows accurate checking of leaks. With this method static compliance can be easily determined in all paralyzed and mechanically ventilated patient (independent of the type of ventilator). In contrast to conventional methods hysteresis is negligible even in severely diseased lungs. If these results can be confirmed in a larger number of patients, especially in pathological conditions, the discussion concerning the phenomenon of hysteresis has to be reviewed.

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Dr. M. Sydow
Zentrum für Anaesthesiologie,
Rettungs- und Intensivmedizin
der Universität
Robert-Koch-Strasse 40
W-3400 Göttingen
FRG