Intensive Care Med (1999) 25: 1084–1091

ORIGINAL

G. Mols
I. Brandes
V. Kessler
M. Lichtwarck-Aschoff
T. Loop
K. Geiger
J. Guttmann

Volume-dependent compliance in ARDS: proposal of a new diagnostic concept

Received: 29 October 1998
Final revision received: 7 April 1999
Accepted: 5 July 1999

G. Mols (✉) · I. Brandes · V. Kessler · T. Loop · K. Geiger · J. Guttmann
Department of Anesthesiology and Critical Care Medicine, University of Freiburg, Hugstetterstrasse 55, 79106 Freiburg, Germany
Tel.: + 49 (761) 2702329
Fax: + 49 (761) 2702396
email: mols@ana1.ukl.uni-freiburg.de

M. Lichtwarck-Aschoff
Department of Anesthesiology and Surgical Intensive Care, Zentralklinikum, Augsburg, Germany

Abstract *Objective:* Adaptation of ventilator settings to the individual's respiratory system mechanics requires information about the pressure-volume relationship and the change of compliance which is dependent on inflated volume. Unfortunately, established methods of obtaining this information are invasive and time-consuming, and, therefore, not well suited for clinical routine. We propose a new standardized diagnostic concept based on the recently developed slice method. This multiple linear regression method (MLR) determines volume-dependent respiratory system compliance (C_{SLICE}) within the tidal volume (V_T) during ongoing mechanical ventilation. The impact of a ventilator strategy, recommended by a consensus conference, on the course of compliance within V_T was investigated in patients with the acute respiratory distress syndrome (ARDS) or acute lung injury (ALI).
Design: Prospective observational study.
Setting: Intensive care unit of a university hospital.
Patients: 14 ARDS patients, 2 patients with ALI.
Interventions: None.
Measurements and results: After measurement of flow and airway pressure and calculation of tracheal pressure, C_{SLICE} was determined. The resulting course of C_{SLICE} within V_T was estimated using a mathematical algorithm. C_{SLICE} data were compared to those obtained by standard MLR. We found decreasing C_{SLICE} mainly in the upper part of V_T in all patients. In 7 patients, we found an additional increasing C_{SLICE} mainly in the lower part of V_T.
Conclusions: C_{SLICE} was not constant in patients with ARDS/ALI whose lungs were ventilated according to consensus conference recommendations. The proposed diagnostic concept may serve as a new tool to obtain a standardized estimation of respiratory system compliance within V_T non-invasively without interfering with ongoing mechanical ventilation.

Key words Compliance · Overinflation · Recruitment · Derecruitment · Alveolar collapse · Slice method

Introduction

Optimal respiratory therapy for patients suffering from severe acute respiratory distress syndrome (ARDS) or acute lung injury (ALI) remains one of the most difficult tasks in intensive care medicine. The physician at the bedside faces at least two major problems. First, pulmonary gas exchange is severely impaired. Second, respiratory system mechanics are changed to a great extent, accompanied by the risk of pulmonary trauma because of too high [1] or too low [2] inspiratory pressure and volume. Consequently, the former strategy aiming at normal arterial blood gas tensions has been replaced by a strategy aiming at the prevention of alveolar collapse and overdistension [3]. This strategy has found its way into different ventilatory regimens [4–8]; some of them adjusting positive end-expiratory pressure (PEEP) according to the lower inflection point on the static pressure-volume curve [6], others setting the ventilator based on empirical data [7, 8]. Only one of these trials demonstrated a benefit [6]. The disappointing results of the two other trials [7, 8] "may be related to the lack of individual titration of ventilation", as stated by Brochard et al. referring to their own work [8]. Obviously, the maneuvres needed for such an adaptation are cumbersome and time-consuming. Consequently, simpler methods to describe respiratory mechanics may be useful. In this context, we propose a new diagnostic concept based on the recently developed slice method [9], which is an enhancement of the standard multilinear regression analysis (MLR), modeling a passive respiratory system [10, 11]. The concept has three features: (1) The course of compliance is determined not for large volumes but within the tidal volume (V_T). (2) The non-invasive analysis is done without change or interruption of mechanical ventilation. (3) The resulting course of compliance is processed with a mathematical algorithm yielding standardized estimations free from observer bias.

We evaluated the impact of a ventilatory strategy recommended by a consensus conference in 1993 [4] on the course of compliance within V_T (C_{SLICE}) in 16 patients with ARDS or ALI. For reference, compliance was also determined using standard MLR (C_{MLR}) [10, 11].

Materials and methods

Patients

Between February 1997 and May 1998 we investigated 16 consecutive adult patients mechanically ventilated for ARDS or ALI (defined in Bernard et al. [12]). All patients studied were transferred to our institution from other hospitals for advanced life support. Patients with intracranial trauma, chronic obstructive pulmonary disease, or leakage of the respiratory system were excluded. The study was conducted according to the principles established in Helsinki. Patients were studied after we obtained approval of the institutional ethical committee and written informed consent of the patient's relatives as early as possible after admission. During measurement, all patients except 1 (patient E) were in the supine position. Patients were treated for clinical reasons not related to this study with flunitrazepam, piritramid, and pancuronium bromide. Muscular relaxation was checked by train of four stimulation. Patients' lungs were ventilated according to consensus conference recommendations [4], similar to other studies [7]. The strategy implements the concept of permissive hypercapnia [5]. We did not target a specific arterial carbon dioxide tension, but rather we tried to avoid severe respiratory acidosis (pH below 7.25). The aspired minimum arterial oxygen tension (PaO_2) was 60 mm Hg. We used a Servo 900C ventilator (Siemens-Elema, Solna, Sweden) set by the attending physician to the pressure-controlled mode. The ratio of inspiratory to expiratory time was set to 2 : 1. PEEP was elevated in small steps until the fractional inspired oxygen (FIO_2) was reduced to or below 0.5. If this target was not reached with a PEEP of 18 mbar (1.8 kPa), FIO_2 was increased for adequate oxygenation. Hemodynamic side effects of PEEP were treated by volume expansion and/or by dobutamine infusion.

To prevent severe respiratory acidosis, patients' lungs were ventilated with a respiratory rate up to 26 breaths/min, while the plateau pressure (P_{plat}) was limited to 30 mbar (3 kPa). If pH fell below 7.25, P_{plat} was increased up to 40 mbar (4 kPa). If PaO_2 could not be elevated or stabilized at 60 mm Hg (~ 8 kPa), even with high FIO_2 in the first few hours after admission, patients were treated with venovenous extracorporeal lung assist (ECLA). The extracorporeal circuit resembled that described by Gattinoni et al. [13]. The need for a high FIO_2 above 0.5 for several days with no improvement was a second indication for ECLA. In the patients treated with ECLA, P_{plat} and respiratory rate were reduced if possible.

Since we were interested in the effects of the given ventilator settings on the course of compliance within V_T, neither were the settings changed nor recruitment maneuvers performed preceding the measurement.

Determination of compliance: volume-dependent C_{SLICE} and C_{MLR}

In 2 patients, we measured the gas flow rate with a heated pneumotachograph (Fleisch No. 2, Metabo, Epalinges, Switzerland) at the proximal end of the endotracheal tube, calibrated with a syringe of 1000 ± 1 ml (Calibration-Syringe 54500460, Jaeger, Würzburg, Germany). Flow proportional pressure difference was measured by a differential pressure transducer (SPS1, Hoffrichter, Schwerin, Germany). Airway pressure was measured at the site of the pneumotachograph by a transducer (1210A, ICSensors, Milpitas, Calif., USA) previously tested for linearity between ± 80 mbar (± 8 kPa) and calibrated (Calibrator, Revue Thommen, Waldenburg, Switzerland). The measured signals were digitized with 100 Hz (12-bit resolution, SDM863, Burr Brown, Tucson, Ariz., USA) and stored on a computer hard disk. In the remaining patients, we used a CP-100 pulmonary monitor (Bicore Monitoring Systems, Irvine, Calif., USA). The CP-100 monitor was calibrated according to the manufacturer's instructions. The raw data sampled with 50 Hz were transmitted to a standard laptop computer.

After measurement, the raw data of both systems were transmitted to a workstation (SparcStation 4, Sun Microsystems, Palo Alto, Calif., USA) for calculation of volume-dependent respiratory system compliance using the slice method [9] (also described in Lichtwarck-Aschoff et al. [14]). In brief, V_T is subdivided into six consecutive volume slices of equal size. For each volume slice, one value of dynamic compliance (C_{SLICE}) is determined by MLR using the simple linear RC model within each slice [15]. The method is based on the continuously calculated tracheal pressure, with a good correspondence of ± 1 mbar to measured tracheal pressure [16]. The slice method considers intrinsic PEEP [17] and resistance. The plot of C_{SLICE} over the corresponding volume gives volume-dependent compliance within V_T. Data from the first 15 breaths of each measurement were averaged (mean ± SD). The same data set was used for calculation of standard C_{MLR} [10].

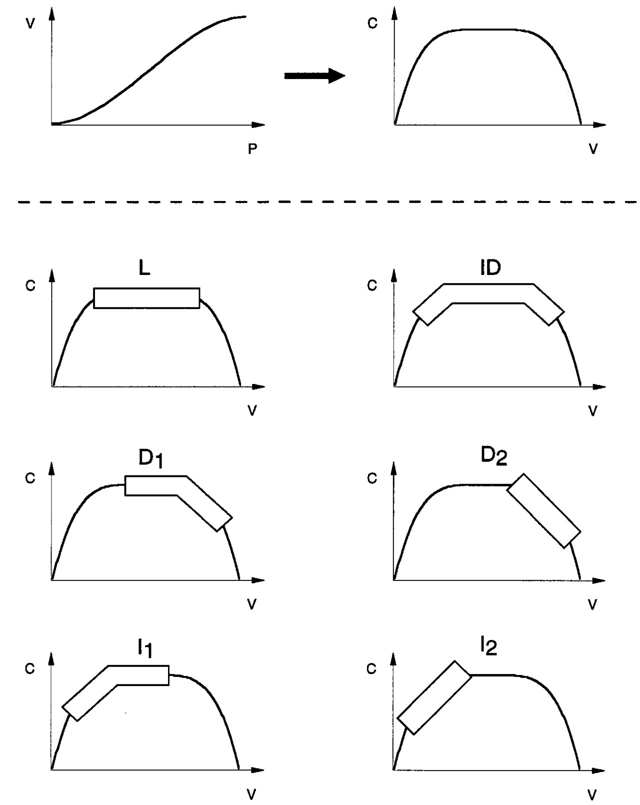

Fig. 1 **Above** The S-shaped pressure-volume curve is translated to the trapeziform compliance-volume curve. **Below** Six shape categories, each reflecting a partial "view" on the compliance-volume curve. *L* linear part with constant C_{SLICE}, *ID* increasing and decreasing C_{SLICE}, $I_{1,2}$ and $D_{1,2}$ moderately and severely increasing or decreasing C_{SLICE}

Shape categories

To avoid observer bias in the interpretation of the C_{SLICE}-volume curve, we prospectively defined six shape categories for its standardized interpretation based on preliminary measurements and on the following considerations. The slope of the respiratory system's S-shaped pressure-volume curve is defined as compliance. Therefore, the pressure-volume curve can be translated into volume-dependent compliance, which is its derivative (Fig. 1). As a differential value, compliance is very sensitive to changes in the shape of the volume-pressure curve. The compliance-volume curve has a trapeziform appearance [18].

During mechanical ventilation, the V_T is only a small part of total lung capacity. Consequently, only a small part of the S-shaped pressure-volume curve or the trapeziform compliance-volume curve can be seen. We prospectively defined six shape categories depicted schematically as symbols in Fig. 1, each representing a partial "view" on the trapeziform compliance-volume curve. Their exact definition is given in the appendix. *L* is ventilation in the steepest, linear part of the S-shaped pressure-volume curve with maximal and constant compliance; *ID* is increasing and decreasing compliance within the V_T; D_1 is moderately decreasing compliance; D_2 is severely decresing compliance; I_1 is moderately increasing compliance; and I_2 is severely increasing compliance.

Results

Patients' age, sex, diagnoses, outcome, PaO_2/FIO_2, lung injury score (LIS) [19], ECLA therapy, and ventilator settings are outlined in Table 1. All but two patients (B and F) suffered from ARDS (LIS $\geq$ 2.5); patient K improved from an LIS of 3 the day before the measurement to an LIS of 2.25 during the investigation.

The compliance-volume curves and the corresponding shape categories are presented in Fig. 2: C_{SLICE} data are marked as mean ± SD; shape categories are drawn schematically over the compliance data. Ventilator settings resulted in decreasing compliance in all patients (shape category D_1, D_2, or ID); additional increasing compliance was seen in 7 patients (shape category ID). C_{MLR} is drawn as a horizontal line within each graph and its absolute value and SD are given.

Discussion

In this study, we propose a new diagnostic concept to assess volume dependency of respiratory system compliance within V_T during ongoing and unchanged mechanical ventilation. The proposed estimation of the resulting compliance-volume curve is free of observer bias. In all 16 patients suffering from ARDS or ALI, whose lungs were ventilated in accordance with consensus recommendations [4], compliance decreased mainly in the upper part of V_T. In 7 patients, compliance increased as well in the lower ranges of V_T.

Methodological considerations

The slice method is based on standard MLR [10, 11], which does not require maneuvers or changes of the ventilatory pattern. For standard MLR, data on the whole breath are used. Consequently, the volume dependency of compliance cannot be detected within the breath itself. For that purpose, standard MLR has been extended to the slice method [9]. With this method, V_T is subdivided into six small portions (slices); then each slice is analyzed separately using MLR. This preserves the simplicity and robustness of the MLR algorithm.

Volume-dependent C_{SLICE} is based on data obtained during ongoing mechanical ventilation, hence, under dynamic conditions. Consequently, standard MLR was chosen as a reference for dynamic compliance. Comparison of our data with static compliance is not appropriate. However, the principal difference between dynamic and static methods should be addressed. Since the lungs are not allowed to rest with the dynamic methods, C_{MLR} and C_{SLICE} not only represent the respiratory system's elastic recoil pressure, they also contain a viscoelastic component and the effects of inhomogeneities, depend-

Table 1 Patient characteristics and ventilatory parameters (*LIS* lung injury score, *ECLA* extracorporeal lung assist, P_{plat} end-inspiratory plateau pressure, *PEEP* positive end-expiratory pressure, *CPR* cardiopulmonary resuscitation, *HELLP* hemolysis, elevated liver enzymes, low platelet count, *SIRS* systemic inflammatory response syndrome, *MOF* multiple organ failure)

Patient	Age (years)	Sex	Diagnoses	PaO_2/FIO_2	LIS[a]	ECLA[b]	Survived	No. of days of mechanical ventilation	PEEP[c] (mbar)	P_{plat}[c] (mbar)	V_T (ml)
A	31	M	Aspiration	160	2.75	–	Yes	20	11	30	750
B	18	M	After CPR (Romano-Ward-syndrome)	193	1.75	–	No	1	12	28	560
C	48	F	Pneumonia	102	2.75	–	No	16	11	37	390
D	45	M	Pneumonia and sepsis	153	3	(+)	Yes	4	14	31	690
E	24	F	Malaria tropica	233	2.5	–	Yes	4	10	28	500
F	40	M	Stab wound injury of pericardium and liver	188	2	–	Yes	3	10	28	640
G	36	F	HELLP syndrome	118	3.75	–	Yes	6	15	29	500
H	30	M	Blunt chest trauma with rupture of diaphragm	126	3	–	Yes	2	10	35	290
I	26	M	Pneumonia and sepsis after multiple trauma	45	3.75	+	No	5	14	40	280
J	37	M	Pneumonia	122	3.5	+	No	15	13	30	470
K	75	M	Pneumonia, SIRS, MOF	175	2.25	–	No	6	8	27	590
L	40	M	Blunt chest trauma, multiple trauma	113	2.75	–	Yes	3	17	33	500
M	23	F	Aspiration	57	3.5	(+)	Yes	2	12	35	650
N	24	M	Multiple trauma	110	3.5	+	No	10	14	34	400
O	24	M	Blunt chest trauma	140	3.5	–	Yes	10	14	38	250
P	42	F	Peritonitis	160	3.75	+	Yes	17	14	37	120

[a] Modified during ECLA: despite a PaO_2 of about 60 mm Hg (~ 8 kPa) with an FIO_2 of 0.4, 4 points for the severity of gas exchange impairment were given because patients' blood was saturated with oxygen mainly by the extracorporeal oxygenators
[b] (+) before or after ECLA therapy
[c] Conversion to kPa: 0.1

ing on gas flow, respiratory rate, and inflated volume [20]. In other words, dynamic methods describe the respiratory system's behavior during ongoing mechanical ventilation. In contrast to this, static methods describe the respiratory system's behavior under the conditions of zero flow [21–26], neither encountered in mechanical ventilation or during normal breathing. Later on, based on these static measurements, predictions are made about the behavior of the respiratory system under the dynamic conditions of ongoing mechanical ventilation. However, it is not clear which information such static data provide for the description of a dynamic system. Therefore, dynamic parameters may be more relevant than static ones for setting the ventilator [27]. This has been shown recently in an animal model [28].

Interpretation of volume-dependent C_{SLICE}

It is often recommended that V_T should be placed on the steepest linear part of the static pressure-volume curve, where compliance is maximal and constant (e.g., see Dreyfuss and Saumon [29]). PEEP should be titrated above the lower inflection point (LIP) [22, 30] in order to prevent alveolar trauma due to cyclical closing and reopening of alveoli [2]. On the other hand, V_T and P_{plat} should be limited so as not to exceed the upper inflection point (UIP) to prevent alveolar overinflation [29]. However, the validity of LIP and UIP as markers of tidal recruitment and overinflation has been questioned recently [18, 31]. In fact, the LIP may just mark the beginning of recruitment rather then its endpoint [27].

These considerations could also be applied to the interpretation of the course of C_{SLICE} within V_T. Ventilation at low lung volumes with ongoing tidal recruitment would be indicated by an increasing C_{SLICE}. Ventilation at high lung volumes with alveolar overdistension would

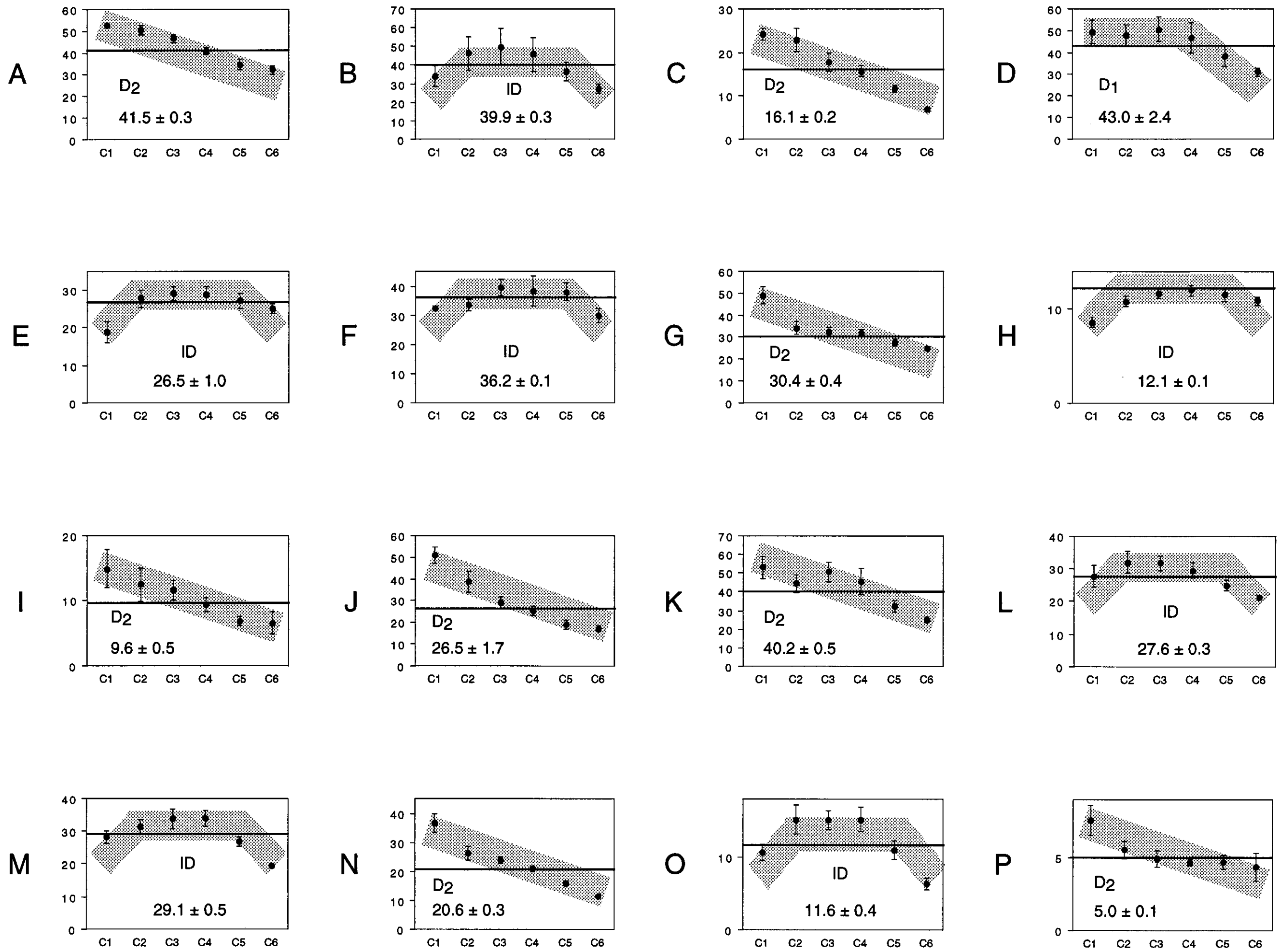

Fig. 2 C_{SLICE} data (mean ± SD, ml/mbar, conversion to l/kPa: 0.01). Volume increases from *left to right, C1–6.* C_{MLR} of the same breaths are plotted as a *straight line,* mean values (± SD) are given. The letters correspond to patients in Table 1. Shape categories are labeled and schematically drawn over the C_{SLICE} data for each patient

be indicated as a decreasing C_{SLICE}. In contrast, ventilation in the middle part of the pressure-volume relationship would be indicated by an almost unchanged C_{SLICE}. However, considering the above, almost constant C_{SLICE} does not necessarily exclude alveolar recruitment during inspiration and alveolar collapse during expiration. The interpretation of mechanical data obtained by the slice method or other methods is further complicated by the fact that a diseased lung may not have uniform mechanical properties [32]. With a given PEEP, V_T, and P_{plat}, some alveoli may be recruited during inspiration, while others may be already overdistended. Consequently, mechanical data should be used carefully, regardless of which method is used. Further investigations, like that of Muscedere et al. [2], are needed to clarify the relationship between respiratory mechanics and structural damage to the lung.

For the interpretation of C_{SLICE}, another aspect should be addressed. The slice method describes the mechanical behavior of the respiratory system in a given ventilatory situation. The resulting data cannot be used to predict respiratory system mechanics in other situations. For example, it is not clear from a decreasing course of C_{SLICE} whether a recruitment maneuver might be useful. Maybe the course of compliance would change after such an intervention. Our measurements were performed without a preceding recruitment maneuver. Consequently, the respiratory system was on the "inflation limb" of the pressure-volume relationship of total lung capacity. A recruitment maneuver preceding the measurement would have resulted in shifting V_T to the respiratory system's "deflation limb", at least immediately after the recruitment maneuver. The inflation and deflation limb of a static pressure-volume curve may differ substantially [33]. Such a hysteresis, which is in part explained by recruitment during inflation and collapse during deflation, may be reduced with the elevation of PEEP [31, 33]. After the recruitment, a shift back to the inflation limb could be expected. Data about the time needed for this shift are conflicting [14, 34]. Therefore, it is unclear if a recruitment maneuver preceding the measurements would have caused different results. Notwithstanding these considerations, we were interested in the impact of the actual ventilatory pattern without any intervention. However, the slice method continuously applied may be a useful tool to record the short- and long-term effects of a recruitment maneuver.

Implications

Applying the proposed diagnostic concept yielded a non-constant C_{SLICE} within the V_T in patients with ARDS or ALI whose lungs were ventilated according to accepted recommendations [4]. Without disregarding the considerations above, decreasing C_{SLICE} may suggest alveolar overinflation and increasing C_{SLICE} may indicate ongoing recruitment during tidal inflation and alveolar collapse during tidal deflation. These findings are in line with the results of a recent study by Roupie et al. using static pressure-volume curves in 25 ARDS patients [24].

Because the course of C_{SLICE} varies largely from patient to patient, ventilator settings should be adapted to the actual mechanical state of the individual's respiratory system. Until now, various attempts based on static or quasi-static methods have been undertaken in this direction without gaining widespread acceptance or clinical application [24, 30, 35, 36]. Our diagnostic concept may facilitate future attempts, since it focuses on the actual V_T in the dynamic situation of ongoing mechanical ventilation, and it is easier to use in the clinical setting than other methods. Since this method dos not require hardware additional to that needed for standard MLR, it may be incorporated easily into ventilators or devices for respiratory monitoring. This has already been done for tracheal pressure calculation (Evita 4, Dräger, Lübeck, Germany) and for C_{MLR} (Galileo, Hamilton, Rhäzünz, Switzerland).

Limitations

Using tracheal pressure for the calculation of compliance, we cannot distinguish between alterations in compliance caused by the lung itself or by the chest wall, or both. Only a measurement of pleural pressure would allow this. Since pleural pressure is not easily accessible, esophageal pressure is often used as a substitute. Unfortunately, esophageal pressure measurements are subjects to artifacts in the supine position [23], due to the weight of the mediastinum. However, numerous studies of ARDS have used esophageal pressure, yielding conflicting results about its relevance. Not only lung compliance but also chest wall compliance seems to be diminished in ARDS [23, 37]. LIP, especially, is often caused by the chest wall and not by the lung [38], while UIP always seems to be caused by the lung [24, 38]. This understanding led to the distinction of a direct insult to the lung and extrapulmonary disease causing ARDS [39]. The authors showed that decreased respiratory system compliance in pulmonary ARDS was predominantly caused by mechanical alterations of the lung itself. In contrast, in extrapulmonary ARDS both the lungs and the chest wall contributed to a decrease of respiratory system compliance [39]. A similar distinction was made by Ranieri et al. [23], differentiating between surgical (abdomen) and medical ARDS. Furthermore, in some of their patients suffering from surgical ARDS, the elastic properties of the chest wall and the lungs grossly changed after abdominal decompression [23]. Given this background, it seems desirable to include esophageal pressure measuring in the proposed diagnostic concept. However, while this could easily be done technically, measuring esophageal pressure would change this concept to an invasive technique, no longer suited for routine clinical use.

In conclusion, the new diagnostic concept can be used to detect variable compliance within V_T. This is done non-invasively and without intervention into the respiratory pattern. The estimation of the resulting course of compliance is standardized mathematically and, therefore, free from observer bias. Increasing compliance within V_T may be an indicator of ongoing tidal recruitment; decreasing compliance within V_T may indicate alveolar overdistension. However, constant compliance within V_T may not indicate optimal ventilator settings, since recent studies have questioned the former interpretation of mechanical data of the respiratory system. Therefore, an "optimal" ventilatory pattern needs to be established in the future. This cannot be done based on respiratory system mechanics alone. However, the proposed diagnostic concept may provide a part of its methodological basis. The application of the diagnostic concept to 16 ARDS/ALI patients whose lungs were ventilated following consensus conference recommendations revealed a decreasing C_{SLICE} in all of them and an increasing C_{SLICE} in some of them.

Acknowledgements The authors are indebted to Professor Heike Pahl and Professor Rüdiger Bittner for critical revision of the manuscript.

References

1. Dreyfuss D, Saumon G (1982) Barotrauma is volutrauma, but which volume is the one responsible? Intensive Care Med 18: 139–141
2. Muscedere JG, Mullen JBM, Gan K, Slutsky AS (1994) Tidal ventilation at low airway pressures can augment lung injury. Am J Respir Crit Care Med 149: 1327–1334
3. Suntharalingam G, Evans TW (1999) Current trends in the management of acute respiratory distress syndrome. Curr Opin Crit Care 5: 1–8
4. Slutsky AS (1994) Consensus conference on mechanical ventilation, January 28–30, 1993 at Northbrook, Illinois, USA. Part 2. Intensive Care Med 20: 150–162
5. Hickling KG, Henderson SJ, Jackson R (1990) Low mortality associated with low volume pressure limited ventilation with permissive hypercapnia in severe adult respiratory distress syndrome. Intensive Care Med 16: 372–377
6. Amato MBP, Barbas CSV, Medeiros DM, Magaldi RB, Schettino GPP, Filho GL, Kairalla RA, Deheinzelin D, Munoz C, Oliveira R, Takagaki TV, Carvalho CRR (1998) Effect of a protective-ventilation strategy on mortality in the acute respiratory distress syndrome. N Engl J Med 338: 347–354
7. Stewart TE, Meade MO, Cook DJ, Granton JT, Hodder TV, Lapinsky SE, Mazer CD, McLean RF, Rogovein TS, Schouten BD, Todd TRJ, Slutsky AS, the Pressure- and Volume-limited Ventilation Strategy Group (1998) Evaluation of a ventilation strategy to prevent barotrauma in patients at high risk for acute respiratory distress syndrome. N Engl J Med 338: 355–361
8. Brochard L, Roudot-Thoraval F, Roupie E, Delclaux C, Chastre J, Fernandez-Mondéjar E, Clémenti E, Mancebo J, Factor P, Matamis D, Ranieri M, Blanch L, Rodi G, Mentec H, Dreyfuss D, Ferrer M, Brun-Buisson C, Tobin M, Lemaire F, the Multicenter Trial Group on Tidal Volume Reduction in ARDS (1998) Tidal volume reduction for prevention of ventilator-induced lung injury in acute respiratory distress syndrome. Am J Respir Crit Care Med 158: 1831–1838
9. Guttmann J, Eberhard L, Fabry B, Zappe D, Bernhard H, Lichtwarck-Aschoff M, Adolph M, Wolff G (1994) Determination of volume-dependent respiratory system mechanics in mechanically ventilated patients using the new SLICE method. Technol Health Care 2: 175–191
10. Iotti GA, Braschi A, Brunner JX, Smits T, Olivei M, Palo A, Veronesi R (1995) Respiratory mechanics by least square fitting in mechanically ventilated patients: applications during paralysis and during pressure support ventilation. Intensive Care Med 21: 406–413
11. Brunner JX, Wolff G (1988) Pulmonary function indices in critical care patients. Springer, Berlin Heidelberg New York, pp 18–26
12. Bernard GR, Artigas A, Brigham KL, Carlet J, Falke K, Hudson L, Lamy M, Legall JR, Morris A, Spragg R, the Consensus Committee (1994) Report of the American-European consensus conference on ARDS: definitions, mechanisms, relevant outcomes and clinical trial coordination. Intensive Care Med 20: 225–223
13. Gattinoni L, Pesenti A, Rossi GP, Vesconi S, Fox U, Kolobow T, Agostini A, Pelizzola A, Langer M, Uziel L, Longoni F, Damia G (1980) Treatment of acute respiratory failure with low-frequency positive pressure ventilation and extracorporal removal of CO_2. Lancet II: 292–294
14. Lichtwarck-Aschoff M, Guttmann J, Eberhard L, Fabry B, Birle J, Adolph M (1997) Delayed derecruitment after removal of PEEP in patients with acute lung injury. Acta Anaesthesiol Scand 41: 675–684
15. Guttmann J, Eberhard L, Wolff G, Bertschmann W, Zeravik J, Adolph M (1992) Maneuver-free determination of compliance and resistance in ventilated ARDS patients. Chest 102: 1235–1242
16. Guttmann J, Eberhard L, Fabry B, Bertschmann W, Wolff G (1993) Continuous calculation of intratracheal pressure in tracheally intubated patients. Anesthesiology 79: 503–513
17. Eberhard L, Guttmann J, Wolff G, Bertschmann W, Minzer A, Kohl HJ, Zeravik J, Adolph M, Eckart J (1992) Intrinsic PEEP monitored in the ventilated ARDS patient with a mathematical method. J Appl Physiol 73: 479–485
18. Svantesson C, Sigurdsson S, Larsson A, Jonson B (1998) Effects of recruitment of collapsed lung units on the elastic pressure-volume relationship in anaesthetized healthy adults. Acta Anaesthesiol Scand 42: 1149–1156
19. Murray JF, Matthay MA, Luce JM, Flick MR (1988) An expanded definition of the adult respiratory distress syndrome: Am Rev Respir Dis 138: 720–723
20. Eissa NT, Ranieri VM, Corbeil C, Chassé M, Robatto FM, Braidy J, Milic-Emili J (1991) Analysis of behaviour of the respiratory system in ARDS patients: effects of flow, volume and time. J Appl Physiol 70: 2719–2729
21. Bates JHT, Baconnier P, Milic-Emili J (1988) A theoretical analysis of the interrupter technique for measuring respiratory mechanics. J Appl Physiol 64: 2204–2214
22. Matamis D, Lemaire F, Harf A, Brun-Buisson V, Ansquer JC, Atlan G (1984) Total respiratory pressure-volume curves in the adult respiratory distress syndrome. Chest 86: 58–66
23. Ranieri VM, Brienza N, Santostasi S, Puntillo F, Mascia L, Vitale N, Giuliani R, Memeo V, Bruon F, Fiore T, Brienza A, Slutsky AS (1997) Impairment of lung and chest wall mechanics in patients with acute respiratory distress syndrome: role of abdominal distension. Am J Respir Crit Care Med 156: 1082–1091
24. Roupie E, Dambrosio M, Servillo G, Mentec H, el Atrous S, Beydon L, Brun-Buisson C, Lemaire F, Brochard L (1995) Titration of tidal volume and induced hypercapnia in adult respiratory distress syndrome. Am J Respir Crit Care Med 152: 121–128
25. Putensen C, Baum M, Hörmann C (1993) Selecting ventilator settings according to variables derived from the quasi-static pressure/volume relationship in patients with acute lung injury. Anesth Analg 77: 436–447
26. Sydow M, Burchardi H, Zinserling J, Ische H, Crozier TA, Weyland W (1991) Improved determination of static compliance by automated single volume steps in ventilated patients. Intensive Care Med 17: 108–114
27. Jonson B, Svantesson C (1999) Elastic pressure-volume curves: what information do the convey? Thorax 54: 82–87

28. Lichtwarck-Aschoff M, Kessler V, Guttmann J, Hedlund AJ, Mols G, Rubertsson S, Marktstrom AM, Sjostrand UH (1998) Static or dynamic respiratory mechanics for setting the ventilator (abstract). Chest 114 [Suppl]: 4S
29. Dreyfuss D, Saumon G (1988) Ventilator-induced lung injury: lessons from experimental studies. Am J Respir Crit Care Med 157: 294–323
30. Suter PM, Fairley HB, Isenberg MD (1975) Optimum end-expiratory airway pressure in patients with acute pulmonary failure. N Engl J Med 292: 284–289
31. Hickling KG (1998) The pressure-volume curve is greatly modified by recruitment: a mathematical model of ARDS lungs. Am J Respir Crit Care Med 158: 194–202
32. Gattinoni L, Pesenti A, Avalli L, Rossi F, Bombino M (1987) Pressure-volume curve of total respiratory system in acute respiratory failure: computed tomography scan study. Am Rev Respir Dis 136: 730–736
33. Dall'Ava-Santucci J, Armaganidis A, Brunet F, Dhainaut J-F, Nouira S, Morisseau D, Lockhart A (1990) Mechanical effects of PEEP in patients with adult respiratory distress syndrome. J Appl Physiol 68: 843–848
34. Neumann P, Berglund JE, Mondejar EF, Magnusson A, Hedenstierna G (1998) Dynamics of lung collapse and recruitment during prolonged breathing in porcine lung injury. J Appl Physiol 85: 1533–1543
35. Brunet F, Jeanbourquin D, Monchi M, Mira JP, Fierobe L, Armaganidis A, Renaud B, Belghith M, Nouira S, Dhainaut JF, Dall'Ava-Santucci J (1995) Should mechanical ventilation be optimized to blood gases, lung mechanics, or thoracic CT scan? Am J Respir Crit Care Med 152: 524–530
36. East TD, Andriano KP, Pace NL (1986) Computer-controlled optimization of positive end-expiratory pressure. Crit Care Med 14: 792–797
37. Pelosi P, Cereda M, Foti G, Giacomini M, Pesenti A (1995) Alterations of lung and chest wall mechanics in patients with acute lung injury: effects of positive end-expiratory pressure. Am J Respir Crit Care Med 152: 531–537
38. Mergoni M, Martelli A, Volpi A, Primavera S, Zuccoli P, Rossi A (1997) Impact of positive end-expiratory pressure on chest wall and lung pressure-volume curve in acute respiratory failure. Am J Respir Crit Care Med 156: 846–854
39. Gattinoni L, Pelosi P, Suter PM, Pedoto A, Vercesi P, Lissoni A (1988) Acute respiratory distress syndrome caused by pulmonary and extrapulmonary disease: different syndromes? Am J Respir Crit Care Med 158: 3–11

Appendix

Shape categories

The shape categories are calculated from the compliance-volume data using simple algorithms. In the first step, several characteristic values are derived from the compliance-volume curve:

C_{max}: maximal C_{SLICE}
C_{min}: minimal C_{SLICE}
C_{ampl}: $C_{max} - C_{min}$
the amplitude of C_{SLICE}

MDS_{xy} $\quad MDS_{xy} = \dfrac{C_y - C_x}{(y - x) \cdot V_{SLICE}}$ $, x < y$ and $1 \leq x \leq 5$ and $2 \leq y \leq 6$
as the mean differential compliance between C_x and C_y, V_{SLICE} is the volume of one slice, x and y are the numbers of the slices

The shape categories are checked sequentially by a computer program (Pascal for Apple Macintosh):
L: If $C_{ampl}/C_{max} < 0.2$
ID: If $(MDS_{56}/C_{max} < -0.5)$ and $(MDS_{12}/C_{max} > 0.5)$ and (C_{max} between C_2 and C_5)
I_1: If $(MDS_{16} > 0)$ and $(MDS_{13} > 1.5 \cdot MDS_{46})$
I_2: If not I_1 and (tf $(MDS_{16} > 0)$ and $(MDS_{16}/C_{max} > 0.5)$)
D_1: If $(MDS_{16} < 0)$ and $(MDS_{46} < 1.5 \cdot MDS_{13})$
D_2: If not D_1 and ((if $(MDS_{16} < 0)$ and $(MDS_{16}/C_{max} < -0.5)$))