Intensive Care Med (2001) 27: 1496–1503
DOI 10.1007/s001340101046

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Aspiration of dead space allows isocapnic low tidal volume ventilation in acute lung injury. Relationships to gas exchange and mechanics

Received: 25 September 2000
Final revision received: 30 May 2001
Accepted: 29 June 2001
Published online: 17 August 2001

The study was supported by the Swedish Medical Research Council (02872) and the Swedish Heart Lung Foundation

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Abstract *Objective*: In acute lung injury (ALI) mechanical ventilation damages lungs. We hypothesised that aspiration and replacement of dead space during expiration (ASPIDS) allows normocapnic ventilation at higher end-expiratory pressure (PEEP) and reduced tidal volume (V_T), peak and plateau pressures (Paw_{peak}, Paw_{plat}), thus avoiding lung damage.
Setting: University Hospital.
Patients: Seven consecutive sedated and paralysed ALI patients were studied.
Interventions and measurements: Single breath test for CO_2 and multiple elastic pressure volume (Pel/V) curves recorded from different end-expiratory pressures guided ventilatory setting at ASPIDS. ASPIDS was studied at respiratory rate (RR) of 14 min^{-1} and then 20 min^{-1} with minute ventilation maintaining stable CO_2 elimination.
Results: Alveolar and airway dead spaces were 24.3 % and 31.3 % of V_T, respectively. Multiple Pel/V curves showed a shift towards lower volume at decreasing PEEP, thus indicating that patients required a higher PEEP. At ASPIDS, PEEP was increased from 8.9 cmH_2O to 12.6 cmH_2O and V_T reduced from 11 ml/kg to 8.9 ml/kg at RR 14 min^{-1} and to 6.9 ml/kg at RR 20 min^{-1}. A significant decrease in Paw_{peak} (36.7 vs 32 at RR 14 min^{-1} and 28.7 at RR 20 min^{-1}) and Paw_{plat} (29.9 vs 27.3 at RR 14 min^{-1} and 24.1 at RR 20 min^{-1}) were observed. $PaCO_2$ remained stable. No intrinsic PEEP developed. No side effects were noticed.
Conclusions: ASPIDS allowed the use of higher PEEP at lower V_T and inflation pressure and constant $PaCO_2$. Multiple Pel/V curves gave insight into the tendency of lungs to collapse.

Keywords ARDS · Pressure volume curve · Lower inflexion point · Single breath test · Lung protective ventilation

Introduction

Mechanical ventilation can contribute to the progression of pulmonary disease by generating a "ventilatory-induced lung injury" (VILI) [1, 2]. VILI may contribute to morbidity and mortality in acute respiratory distress syndrome (ARDS). The mechanisms behind VILI are probably multiple. Trauma resulting from high airway pressure and over-distention may lead to air leakage [3]. Repeated lung collapse and re-expansion leads to very important shear forces [4]. Consequently, to avoid lung damage, a respiratory pattern should open up closed units and maintain aeration and stability throughout the respiratory cycle [5]. Several modes of ventilation prevent lung collapse during expiration, such as pressure-controlled ventilation with a high I/E ratio [6, 7], high frequency jet ventilation [8], and an adequately high positive end-expiratory pressure (PEEP) [9].

Table 1 Patients' characteristics. (*M* male, *F* female, *DIC* disseminated intravascular coagulation, *COPD* chronic obstructive pulmonary disease, *LIS* lung injury score, C_{RS} quasi-static compliance of the respiratory system)

Patient No.	Sex	Age Years	Weight Kg	Cause of acute respiratory failure	Underlying disease	LIS	PaO_2/FiO_2	CRS ml/cmH_2O
1	M	54	60	Pneumonia	Acute renal failure	2.25	161	51.9
2	M	60	70	Septic shock	Abdominal surgery	2.75	125	46.8
3	M	79	80	Pneumonia	Guillain-Barrè	3.25	91	27.1
4	M	79	70	Alveolar hemorrhage	DIC	3	143	51
5	F	59	110	Pneumonia	COPD	3	141	51
6	M	33	45	Aspiration	Chorea	2.75	100	45.4
7	F	69	70	Pneumonia	None	3.25	78	24.9
Mean		61.8	72.1			2.89	120	42.6
± SD		16	19.9			0.35	30.6.	11.6

The pressure volume curve of the respiratory system has been suggested as a guideline in setting ventilation to reduce the risk associated with mechanical ventilation. Tidal ventilation should be confined to the segment within which the Pel/V curve is linear in order to avoid lung collapse below this zone and hyperinflation above it [10, 11, 12]. Recently a "protective ventilatory strategy" with a PEEP of 2–3 cmH_2O above the lower inflection point of the P/V curve, combined with low tidal volumes (V_T), was shown to attenuate cytokine response induced by mechanical ventilation [13] and to reduce 28-day mortality in ARDS [14]. Furthermore, the NIH multicenter randomised trial on ventilation in ARDS was stopped earlier since the first 861 enrolled patients showed approximately 25 % fewer deaths among those receiving a low V_T of 6 ml/kg of body weight (BW) compared to a relatively large V_T of 12 ml/kg BW [15]. However, low V_T is in general accompanied by some degree of hypercapnia that may be harmful to the patient [16].

We have recently shown that aspiration of the dead space (ASPIDS) allows the use of low V_T at reduced airway pressures while maintaining isocapnic condition in healthy pigs [17] and in humans ventilated for neurological pathologies [18]. In ASPIDS, gas in ventilator tubing, Y-piece, filter, and the tracheal tube is – during the late part of the expiration – aspirated from the tip of the tracheal tube and replaced with fresh gas through the ordinary inspiratory line of the ventilator. Thus, by reducing the airway dead space, ASPIDS augments alveolar ventilation.

In the present study we tested the hypothesis that ASPIDS may allow isocapnic lung ventilation at low V_T, thus allowing the use of a higher PEEP level in combination with lower inflation pressures. We examined whether, at ASPIDS, the elastic pressure variations could be restricted to the pressure range between the lower and upper inflection points (LIP and UIP, respectively) of the elastic pressure volume (Pel/V) curve. A comprehensive exploration of dead space and Pel/V curves recorded from different levels of PEEP was performed.

Materials and methods

Patients

The Ethical Committee of the University of Napoli "Federico II" approved the study, conducted according to the Helsinki principles. Informed consent was obtained from patient's next of kin.

During the period of the study, patients requiring mechanical ventilation with an FiO_2 equal to or greater than 0.5 for more than 24 h and fulfilling the criteria for acute lung injury (ALI) [19] were regarded as potential candidates. Exclusion criteria were: age less than 18 years, signs of intracranial hypertension, presence of chest tube, and contra-indication for sedation and paralysis. Seven patients were studied (Table 1). The lung injury score (LIS) was computed as described by Murray and co-workers [20]. All patients were transorally intubated with cuffed endotracheal tubes with an inner diameter of 8–8.5 mm. The cuff was inflated and frequently tested for air leakage. Volume controlled ventilation at a constant inspiratory flow pattern was given with a Servo Ventilator 900 C (Siemens-Elema, Sweden). On average minute ventilation (V_E) was 10.9 ± 1.8 l/min, respiratory rate (RR) 14 breaths/min. Inspiratory time was 33 %, postinspiratory pause time 5 %, and the fraction of inspired oxygen (FiO_2) 0.7. PEEP level was chosen according to standard protocol based on clinical criteria and was 8.9 ± 0.9 cmH_2O. A moisture exchanger and bacterial/viral filter and a connector to the Y-piece were used.

Patients were studied in supine position, sedated by a continuous infusion of propofol, 2 mg/kg per hour, and paralysed with pancuronium bromide, 0.1 mg/kg. Monitoring comprised electrocardiogram, invasive arterial blood pressure, central venous pressure, and temperature. Treatment according to the standard protocol was maintained stable during the experimental period.

Equipment

A Servo Ventilator was linked, through a Computer/Ventilator Interface (CVI), to an IBM compatible computer equipped with a card for A/D and D/A conversion and digital in- and outputs (PC-30, Eagle Technology, South Africa). The CVI was used for computer control of the ventilator during mechanics measurements [21, 22] and of the solenoid valves of the ASPIDS system [18]. Signals from the ventilator transducers representing airway pressure in the expiratory line, inspiratory and expiratory flow in the ventilator, and the CO_2 signal from a mainstream CO_2 analyzer (CO_2 Analyzer 930, Siemens Elema, Sweden) were A/D converted at

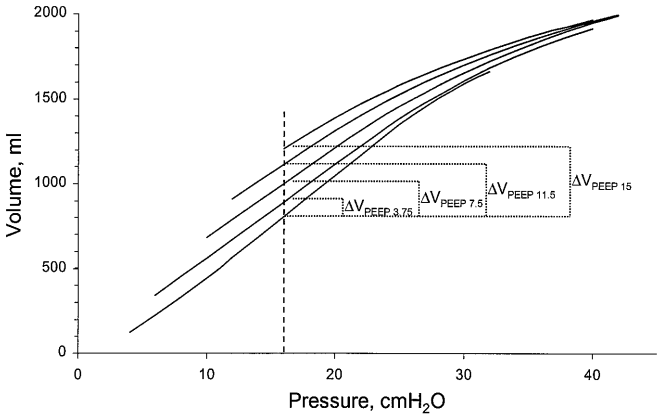

Fig. 1 Typical multiple Pel/V curve recording obtained in patient 2. Lung volume difference, at Paw 16 cmH_2O, between the Pel/V curve recorded from ZEEP (the lowest one) and each of the other Pel/V curves recorded from four PEEP levels ($\Delta V_{PEEP\ 3.5}$ to $\Delta V_{PEEP\ 15}$) are indicated

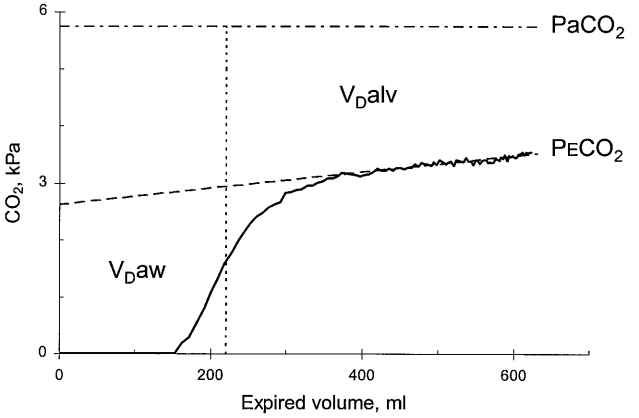

Fig. 2 The single breath test for CO_2 recorded in patient 6. CO_2 partial pressure in expirated gas ($PECO_2$) and $PaCO_2$ are plotted against expired lung volume. Airway and alveolar dead space ($V_D$aw and $V_D$alv, respectively) are indicated

50 Hz. The system was constructed and programmed at the Department of Clinical Physiology, University of Lund, Sweden.

Recording and analysis of mechanics

After increasing PEEP to 15 cmH_2O, Pel/V curves of the respiratory system were recorded during constant low flow inflation of the lung after a 6-s long expiration according to a previously reported principle [21]. A target volume, which during an insufflation preceded by an expiration to zero end-expiratory pressure would cause a pressure of 45 cmH_2O, was estimated from compliance observed during an ordinary tidal volume. For safety reasons the insufflation is always automatically arrested at 45 cmH_2O. A modification of the method allowed the computer to automatically perform a pre-defined sequence of insufflations [23]. The first insufflation was recorded after a prolonged expiration at a PEEP of 15 cmH_2O. The subsequent insufflations were recorded after expirations at progressively decreasing PEEP levels in steps of 3.75 cmH_2O. Four breaths of ordinary V_T and at PEEP of 15 cmH_2O separated the five insufflations. Immediately after the recording, data of flow and pressure from the insufflations were automatically analysed in order to construct the corresponding Pel/V curves that were plotted at the bedside on the computer screen on a common volume axis according to known principles [22]. After the study a complete analysis was performed. Each of the five Pel/V curves was mathematically defined according to the sigmoid model of Svantesson et al. [21]. According to the same model, LIP and UIP were mathematically determined from the Pel/V curve recorded from zero end-expiratory pressure (ZEEP).

Intrinsic positive end-expiratory pressure (PEEPi) was calculated as the difference between the Paw read at end of expiration and Paw read after 3 s of an end-expiratory pause. The latter pressure represents total PEEP (PEEPtot). Peak airway pressure (Paw_{peak}), postinspiratory plateau pressure (Paw_{plat}), and mean airway pressure (Paw_{mean}) were read from the digital display of the ventilator. To evaluate patients' clinical status and effects of ASPIDS, the quasi-static compliance (C_{RS}), measured as V_T divided by Paw_{plat} minus PEEPtot, was used.

Dynamic compliance (C_{RSdyn}) was measured as the slope of the Pel/V curves at a Pel of 16 cmH_2O recorded from a PEEP of 15–0 cmH_2O. The volume recruited by different levels of PEEP was estimated measuring the volume difference between the Pel/V curve that was recorded from ZEEP and each of the other Pel/V curves ($\Delta V_{PEEP\ 3.5}$ to $\Delta V_{PEEP\ 15}$). These measurements were made at 16 cmH_2O as shown in Fig. 1.

Single breath test for CO2

Signals for flow and CO_2 from the unperturbed breath preceding the recording of the Pel/V curve were analyzed to yield the single breath test for CO_2 (SBT-CO_2) (Fig. 2) [24]. CO_2 partial pressure in expired gas ($PECO_2$) and $PaCO_2$ were plotted against volume obtained by integration of flow. Airways dead space from the Y-piece to and including the conducting airways ($V_D$aw) and alveolar dead space ($V_D$alv) were computed from the SBT-CO_2 according to Fletcher et al. [25].

ASPIDS circuit

ASPIDS comprises aspiration of dead space gas from the distal end of the tracheal tube and injection of compensatory fresh gas in the inspiratory limb of the ventilator tubing during the late part of expiration. The computer controlled the two 100% oxygen-safe solenoid valves of the ASPIDS system (Fig. 3). Aspiration was performed through a polyethylene end-hole catheter (ID 2 mm; OD 3 mm). This was inserted into the tracheal tube through a swivel adapter connecting the tube to the ventilator circuit. The tip of the catheter was positioned 2 cm proximal to the tip of the tracheal tube. At activation of the aspiration solenoid valve the catheter was connected to a 3 liter damping reservoir coupled to the central hospital vacuum source. In order to achieve a suitable flow rate of aspirated gas, the degree of negative atmospheric pressure in the reservoir was adjusted by a leakage valve to the atmosphere.

The injected fresh gas was delivered directly from the bellows reservoir in the ventilator. The injection line further comprised a solenoid valve, a variable resistor valve, and a tube connected to the inspiratory line of the ventilator circuit. The compensatory flow rate was adjusted with a resistor valve.

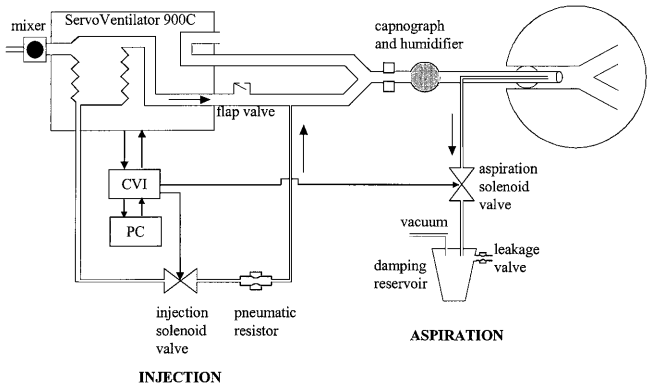

Fig. 3 ASPIDS equipment. When the solenoid valves for aspiration and injection open under control of the personal computer (PC) and the computer/ventilator interface (CVI), ASPIDS is performed as described in the text

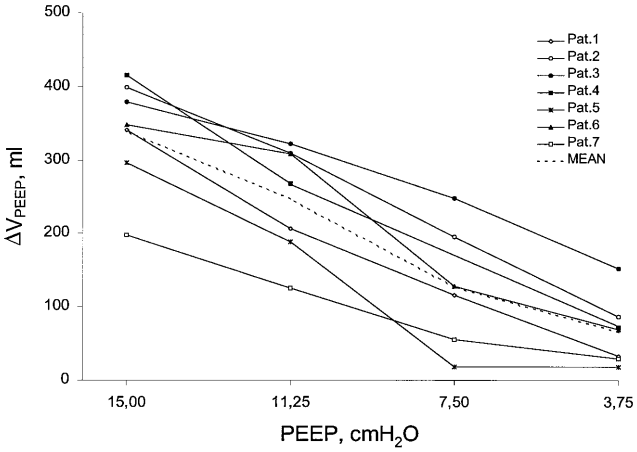

Fig. 4 Lung volume recruited by PEEP (ΔV_{PEEP}). ΔV_{PEEP} was measured, at a pressure of 16 cmH_2O (as shown in Fig. 1.)

The computer and the CVI together performed continuous tests of proper system functioning. The ASPIDS valves could only be opened during expiration. A flap valve in the inspiratory line served as a safety measure against accidental development of a negative pressure in the circuit. Importantly, all alarm functions of the ventilator were continuously in function during treatment with ASPIDS.

The computer was set to simultaneously open both valves from 50 % until 100 % of the expiratory time. This period is denoted the ASPIDS phase. The volume of gas needed to replace the dead space down to the tip of the tracheal tube during each breath (V_{ASPIDS}) comprises dead space of the tubing (VD_{tubing}) and the volume of gas expired by the patient during the ASPIDS phase (VE_{late}):

$$V_{ASPIDS} = VD_{tubing} + VE_{late} \quad (1)$$

VD_{tubing} is the dead space of the connections comprising Y-piece, capnograph, humidifier, connectors, and the tracheal tube. It was in vitro determined to be 145–150 ml depending upon the size of the tracheal tube. VE_{late} is the volume expired during the ASPIDS phase. VE_{late} was measured before ASPIDS was started as the integral of flow rate during a period corresponding to the ASPIDS phase. To set the ventilator and the ASPIDS system the subsequent procedure was followed.

Minute ventilation (V_E) was reduced by ($VD_{tubing}\times$ RR). The tidal volume to be used during ASPIDS ($V_{TASPIDS}$) was then read from the ventilator display. VE_{late} was measured to calculate V_{ASPIDS} according to Eq. 1. The injection solenoid valve was activated and injection flow adjusted until expiratory tidal volume (V_{TE}), read on the ventilator, was equal to ($V_{TASPIDS}+V_{ASPIDS}+V_{extra}$). V_{extra} (extra volume), which was about 10 ml, served to provide a slight surplus of compensatory gas over aspirated gas. Then, the aspiration solenoid valve was activated. The leakage valve was adjusted until the V_{TE} read on the ventilator was brought back to ($V_{TASPIDS}+V_{extra}$).

Procedure

Patients were studied when they were stable with respect to clinical and hemodynamic condition and body temperature. As a preparation for the studies of Pel/V curves, basal clinical PEEP level was increased to 15 cmH_2O. Some minutes later the multiple Pel/V curve recording was performed. Clinical PEEP was re-instituted. Ten minutes later a blood gas sample was taken and the SBT-CO_2 was performed. Pressures and V_T were read from the ventilator as described. The multiple Pel/V curve should be used in order to guide the PEEP and V_T setting at the bedside. Accordingly, at ASPIDS PEEP should be set above the level at which a clear de-recruitment is observed from a loss of volume compared to curves recorded from higher levels of PEEP. Clinical rules in the department limited the PEEP to 15 cmH_2O.

ASPIDS was then started at reduced V_E and increased PEEP. After 30 min, when changes in blood gas parameters should have stabilised [26], data collection was repeated. ASPIDS was stopped and basal ventilation restored.

RR was increased to 20. V_E was increased so as to maintain a stable CO_2 elimination in millilitres per minute, which was monitored with the capnograph. After establishment of a new steady state, the ASPIDS procedure was repeated at the higher frequency and, following the same above-mentioned procedure, at reduced V_E and increased PEEP.

Statistical analysis

Data are expressed as mean ± SD. Two-tailed Student's *t*-test was used to compare findings from different study periods. Linear regression was employed.

Results

Seven consecutive patients were studied. All of them had a PaO_2/FiO_2 lower than 200 mmHg and fulfilled criteria for ARDS (Table 1). All patients remained hemodynamically stable through the experimental period (Table 2). No side effects of ASPIDS were noticed.

$V_D$aw varied between 190 ml and 260 ml and was 31.3 ± 5 % of V_T. $V_D$alv was on average as large as 187 ml, or 24.3 ± 8.3 % of the V_T. A SBT-CO2 is shown in Fig. 2.

Table 2 Ventilatory, gas exchange, and hemodynamic variables. (*RR* respiratory rate, V_E minute ventilation, V_T tidal volume, *BW* body weight, Paw_{peak} peak pressure, Paw_{plat} plateau pressure, Paw_{mean} mean airway pressure, $PEEP_{total}$ total positive end-expiratory pressure, *PEEPi* intrinsic positive end-expiratory pressure, C_{RS} quasi-static compliance of the respiratory system, *HR* heart rate, *mABP* mean artery blood pressure)

	Basal RR: 14		RR: 20	
	Baseline	ASPIDS	Baseline	ASPIDS
RR, breaths/min	14.1 ± 1.2	14.1 ± 1.2	20	20
V_E, l/min	10.9 ± 1.8	8.8 ± 1.7***	12.5 ± 1.8	9.6 ± 1.8***
V_T, ml/kg BW	11.1 ± 2.0	8.9 ± 1.6***	9.1 ± 2.0	6.9 ± 1.5***
Paw_{peak}, cmH_2O	36.7 ± 9.9	32.0 ± 7.7***	35.2 ± 7.7	28.7 ± 6.4***
Paw_{plat}, cmH_2O	29.9 ± 8.5	27.3 ± 5.9*	28.0 ± 7.6	24.1 ± 5.6**
Paw_{mean}, cmH_2O	16.9 ± 3.2	18.0 ± 2.6*	16.9 ± 2.6	17.3 ± 2.4
$PEEP_{tot}$, cmH_2O	10.0 ± 1.3	13.6 ± 1.2***	10.5 ± 1.1	14.4 ± 1.2***
PEEPi, cmH_2O	1.11 ± 0.99	1.03 ± 0.27	1.69 ± 0.87	1.85 ± 0.79
C_{RS}, ml/cmH_2O	42.6 ± 11.6	50.0 ± 14.0**	39.3 ± 10.9	58.1 ± 19.6**
$PaCO_2$, mmHg	45.9 ± 8.9	45.2 ± 5.9	44.0 ± 8.9	47.4 ± 7.0
pH	7.40 ± 0.10	7.41 ± 0.09	7.41 ± 0.11	7.38 ± 0.08
PaO_2/FiO_2, mmHg	117 ± 34	137 ± 61	137 ± 62	144 ± 65
HR, beats/min	107 ± 21	102 ± 15	100 ± 15	107 ± 14
mABP, mmHg	69 ± 11	68 ± 8	70 ± 8	79 ± 10

In comparison between baseline and ASPIDS: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

Table 3 Dynamic compliance (ml/cmH_2O) calculated at a distending pressure of 16 cmH_2O. *R* is the correlation coefficient between compliance and PEEP

Patient No.	Pel/V from PEEP 15	Pel/V from PEEP 11.25	PeIN from PEEP 7.5	Pel/V from PEEP 3.7	PelfV from PEEP 0	*R*
1	56	63	69	75	82	–1.00
2	49	51	53	55	60	–0.97
3	28	27	32	32	38	–0.91
4	53	54	–	71	81	–0.98
5	49	51	56	65	62	–0.92
6	34	44	48	52	53	–0.94
7	18	19	20	29	31	–0.94
Mean	41	44	46	54	58	–0.95
± SD	15	16	18	18	19	0.03

In each patient the multiple Pel/V curves showed a shift towards lower volumes when PEEP during the preceding expiration was stepwise lowered (Fig. 1). The volume loss observed when PEEP was reduced, ΔV_{PEEP}, showed a nearly linear relationship to the change of PEEP (Fig. 4). Dynamic compliance, determined as the slope of the Pel/V curve at 16 cmH_2O, was always higher for Pel/V curves recorded from lower PEEP values (Table 3).

In six patients the mathematically identified LIP varied from 3.8 cmH_2O to 14.5 cmH_2O (average 9.2). In one patient no LIP was identified. The transition from the lower sigmoid segment to the linear part of the Pel/V curves defining LIP was in general smooth to the eye (Fig. 1). No relationship was found between LIP and ΔV_{PEEP}. UIP ranged from 20 cmH_2O to 26 cmH_2O (average 23.8).

The observed Pel/V curve recorded from ZEEP started at a positive pressure in six out of seven patients (Fig. 1). This was partly due to technical truncation. However, in five patients expiratory flow continued at a rate of 0.04–0.16 l/s even at the end of the prolonged expiration preceding the recording of the Pel/V curve from ZEEP. Accordingly, some degree of intrinsic PEEP existed. This contribution by PEEPi is less than the observed value of total PEEP (Table 2).

ΔV_{PEEP} read from multiple Pel/V curves displayed during the procedure at the bedside, contrary to our expectations, did not allow a definition of an expiratory pressure at which lung collapse started. However, they clearly indicated that all patients required a higher PEEP to keep the lung open. At ASPIDS, PEEP was reset from 8.9 ± 0.9 to 12.6 ± 1.1 cmH_2O. At RR 14 breaths/min, V_T was at ASPIDS decreased from 11.1 to 8.9 ml/kg BW. $PaCO_2$ remained stable, as intended. Paw_{peak} and Paw_{plat} decreased significantly. Paw_{mean} and C_{RS} increased significantly. The increase in PaO_2 was not significant (Table 2).

Baseline blood gases at RR 20 breaths/min were similar to those at RR 14 and did not change significantly at ASPIDS (Table 2). At ASPIDS, V_T was reduced to 6.9 ml/kg BW. Notably, the tendency of increase in $PaCO_2$ was insignificant ($P = 0.3$). Paw_{plat} and Paw_{peak} were reduced to lower values than at ASPIDS at RR 14 breaths/min ($P < 0.001$ and $P < 0.01$, respectively). C_{RS} increased significantly.

During ASPIDS, PEEPi did not change either at the lower or at the higher RR.

Discussion

Lung protection is a key issue in mechanical ventilation in ALI. VILI may be caused by barotrauma inflicted by high inflating pressure, volutrauma caused by large tidal volume, shear caused by repeated collapse and recruitment [2]. The study of Amato et al. [14] showed that low V_T and high PEEP may reduce mortality in ARDS. Ranieri et al. demonstrated that mechanical ventilation may lead to an increase in cytokine levels if a protective strategy is not used [13]. With ASPIDS, isocapnia can be maintained at reduced V_T [17, 18]. If the benefits of a low V_T should preferably be used to increase lung inflation by a high PEEP or to decrease peak and plateau pressures is unknown. Our hypothesis that isocapnia could be maintained at higher PEEP and lower distending pressures was confirmed. Accordingly, ASPIDS allows a pattern of ventilation that may reduce VILI. How the benefits of ASPIDS should be utilised in an optimal way remains an open question.

Based upon theories by Mead et al. [4] and observations by Reynolds [6] and Lachmann et al. [7, 8], in 1982 a concept was formulated: "a respiratory pattern should open up closed units and maintain aeration and stability throughout the respiratory cycle" [5]. The Pel/V curve may be a guide to reach this goal [10, 11, 12, 14]. Previous problems related to clinical recording of the Pel/V curve [27] are solved [21, 22, 28] and by modifying the low flow inflation method we could perform automated multiple Pel/V recording [23]. Roupie et al. [11] suggested that tidal ventilation should be confined to the linear segment between LIP and UIP of the Pel/V curve recorded from ZEEP. At basal ventilation, a Paw_{plat} higher than UIP indicated lung overdistension in our subjects. At ASPIDS, Paw_{plat} approached UIP at RR 14 and reached UIP at RR 20 breaths/min. Our multiple Pel/V curves showed a progressive volume loss indicating instant de-recruitment when PEEP was lowered. The linear relationship between PEEP and ΔV_{PEEP} (Fig. 4) indicates a wide distribution of the pressure at which lung units closed. During insufflation C_{RSdyn} was higher for curves recorded from low PEEP values. Theoretical analysis [29, 30] and observations in healthy pigs and humans [31, 32] and in patients with ALI [22] show that these higher values of C_{RSdyn} reflect continuing recruitment starting below LIP and proceeding far above it. This confirms observations based on CT by Gattinoni et al. [33]. The multiple Pel/V curves rather than LIP indicated that ASPIDS should be used so as to allow a higher PEEP.

The increase in C_{RS} at ASPIDS may be caused by a combination of less overdistension at lower Paw_{plat} values and better recruitment at higher PEEP levels. As PaO_2 was not significantly higher with ASPIDS, less overdistension appears to be the more important factor. Oxygenation reflects mean airway pressure in ARDS. Paw_{mean} increased only slightly at ASPIDS at RR 14 and not even significantly at RR 20. Higher mean and peak airway pressure may not be dangerous, according to Dreyfuss et al. [1, 3]. Accordingly, a more aggressive way to take advantage of ASPIDS may be to increase PEEP more than we did. Amato et al. [14], who increased PEEP to a higher extent than we did, observed a significant improvement in oxygenation, which may be related to the important increase in Paw_{mean}.

Physiological dead space, comprising airway and alveolar dead space, was at basal ventilation on average 55 % of V_T. ASPIDS will primarily only reduce $V_D$aw. The high $V_D$alv reflects uneven ventilation/perfusion of the lungs. In ALI, thrombosis of small pulmonary vessels is important and will contribute to $V_D$alv in a similar way as does lung embolism [24]. Right-to-left shunt will also contribute to $V_D$alv by increasing $PaCO_2$ (Fig. 2). In principle, ASPIDS might reduce alveolar dead space if applied in such a way that shunt fraction is decreased, i.e., by increasing PEEP sufficiently to recruit a larger part of the lung. As PaO_2/FiO_2 remained stable during ASPIDS, shunt fraction did not change significantly at ASPIDS. The elucidation of the effect of ASPIDS upon dead space fractions is hampered by the fact that SBT-CO_2 cannot be measured at ASPIDS.

Tracheal gas insufflation (TGI) through an additional catheter or lumen of the tracheal tube is an alternative way to reduce dead space ventilation [34, 35, 36]. The efficiency of TGI reflects different mechanisms [35, 36, 37, 38, 39]. TGI applied during inspiration implies that dead space is by-passed. When performed during expiration, TGI dilutes the CO_2 present in the dead space at the end of expiration thus inducing an expiratory washout (EWO). Furthermore, if TGI is delivered as expiratory pulses it may even have an effect analogous to high-frequency ventilation [2, 35]. TGI is associated with some recognised drawbacks [2, 36]. Warming and humidification of compressed gas used for TGI constitutes a problem. Jet streams into the trachea may possibly be harmful. TGI increases the intratracheal pressure, augments PEEPi, and impedes expiration [38, 39]. When expiratory flow rate continues throughout expiration TGI may only dilute and not flush the dead space free from CO_2. ASPIDS is a new form of EWO that circumvents most problems associated with previous systems.

Since ASPIDS primarily reduces $V_D$aw, results in the same direction could be expected by eliminating the heat and moisture exchangers [39]. Such an approach could be useful in dramatic conditions but remains to be tested. During mechanical ventilation with heated humidifiers, substantial condensation occurs in the tubing, which rapidly becomes contaminated and may increase the risk of pneumonia. Although the potential of heat and moisture exchangers to reduce the incidence of ventilator induced pneumonia is not verified, the use

of the latest generation of heat and moisture exchangers has been recommended [40]. The reasons for this are easily obtained proper humidification and a reduced micro-organism contamination of ventilator circuit.

Taking all these aspects into account, ASPIDS appears advantageous. However, the present system should still be regarded as experimental. It should be used only under the surveillance of a well-informed operator. A system for routine clinical use would need to be modified. The pressure at the tip of the tracheal tube should be monitored to further increase the safety of the system and to allow patient triggering, which is now hindered by the flap valve.

In conclusion, by reducing dead space ventilation, ASPIDS allows ventilation of ALI patients with small V_T at isocapnic conditions and with higher PEEP levels. This should increase the feasibility of lung protective ventilation. The optimal way to apply ASPIDS remains to be explored. Multiple Pel/V curves may be useful to evaluate lung collapse and to guide setting of PEEP.

Acknowledgements The authors wish to thank Björn Drefeldt and Gerth-Inge Jönsson for the generous and helpful technical assistance. Salvatore Boccieri gave valuable help.

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