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Regional lung derecruitment after endotracheal suction during volume- or pressure-controlled ventilation: a study using electric impedance tomography

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Abstract *Objective:* To assess lung volume and compliance changes during open- and closed-system suctioning using electric impedance tomography (EIT) during volume- or pressure-controlled ventilation. *Design and setting:* Experimental study in a university research laboratory. *Subjects:* Nine bronchoalveolar saline-lavaged pigs. *Interventions:* Open and closed suctioning using a 14-F catheter in volume- or pressure-controlled ventilation at tidal volume 10 ml/kg, respiratory rate 20 breaths/min, and positive end-expiratory pressure 10 cmH₂O. *Measurements and results:* Lung volume was monitored by EIT and a modified N₂ washout/-in technique. Airway pressure was measured via a pressure line in the endotracheal tube. In four ventral-to-dorsal regions of interest regional ventilation and compliance were calculated at baseline and 30 s and 1, 2, and 10 min after suctioning. Blood gases were followed. At disconnection functional

residual capacity (FRC) decreased by $58 \pm 24\%$ of baseline and by a further $22 \pm 10\%$ during open suctioning. Arterial oxygen tension decreased to $59 \pm 14\%$ of baseline value 1 min after open suctioning. Regional compliance deteriorated most in the dorsal parts of the lung. Restitution of lung volume and compliance was significantly slower during pressure-controlled than volume-controlled ventilation. *Conclusions:* EIT can be used to monitor rapid lung volume changes. The two dorsal regions of the lavaged lungs are most affected by disconnection and suctioning with marked decreases in compliance. Volume-controlled ventilation can be used to rapidly reconstitute lung aeration and oxygenation after lung collapse induced by open suctioning.

Keywords Acute Lung Injury · Electrical impedance tomography · Functional residual capacity · Monitoring · Suctioning · Lung recruitment

Introduction

The purpose of endotracheal suctioning is to remove secretions from the airways of intubated and mechanically ventilated patients, and this procedure must be carried out as safely and efficiently as possible [1, 2]. Patients with acute lung injury (ALI) or acute respiratory distress syndrome (ARDS) are especially sensitive to derecruitment of the lungs [3], and research has therefore focused on evaluating and minimizing adverse side effects of open-system suc-

tioning (OSS), such as lung collapse and desaturation [4, 5, 6]. Side effects of suctioning can be monitored by arterial blood gas analysis and airway pressure-volume curves reflecting global lung function, but little is known about regional effects on ventilation during suctioning induced lung collapse. Closed-system suctioning (CSS) has fewer side effects than OSS [7, 8, 9, 10, 11, 12, 13, 14], but its efficacy may be low [15, 16]. Thus in patients with respiratory insufficiency and viscous secretions there may still be an indication for open suctioning. Lung collapse follow-

ing open suctioning can be reversed by a recruitment maneuver [17], but in clinical practice these procedures are regarded as cumbersome [18] and may be associated with hemodynamic and respiratory complications [19].

In a study on healthy pigs Almgren et al. [20] have shown that oxygenation and lung volumes after open suctioning are better preserved during volume-controlled ventilation (VCV) than pressure-controlled ventilation (PCV). This study on lung injured pigs assessed the time course of lung collapse with special reference to regional effects on ventilation of suctioning and disconnection during VCV and PCV using electric impedance tomography (EIT) [21, 22]. The results were presented in part during the 2004 ESA meeting in Lisbon and the 2004 ESICM meeting in Berlin.

Material and methods

The study was approved by the Committee for Ethical Review of Animal Experiments at Gothenburg University and performed in accordance with the NIH guidelines [23]. Nine pigs of either gender (25–29 kg) were studied. Other data from these animal experiments have been presented previously [24].

Anesthesia

Premedication with 15 mg/kg ketamine and 0.3 mg/kg midazolam intramuscularly was followed by a bolus of 6 mg/kg sodium pentobarbital and subsequent infusion of 4 mg/kg per hour and 25 μ g/kg fentanyl per hour. Muscle relaxation was achieved by a bolus of 0.15 mg/kg pancuronium followed by an hourly infusion of 0.3 mg/kg during the experiment. The pigs were tracheotomized and mechanically ventilated through an 8-mm endotracheal tube using a Servo 300 ventilator (Siemens-Elma,

Sweden). Fluid balance was maintained by infusion of Ringer's solution at 10 ml/kg per hour. Body temperature was kept at 38–39 °C by heating pads. Animals were placed in supine position.

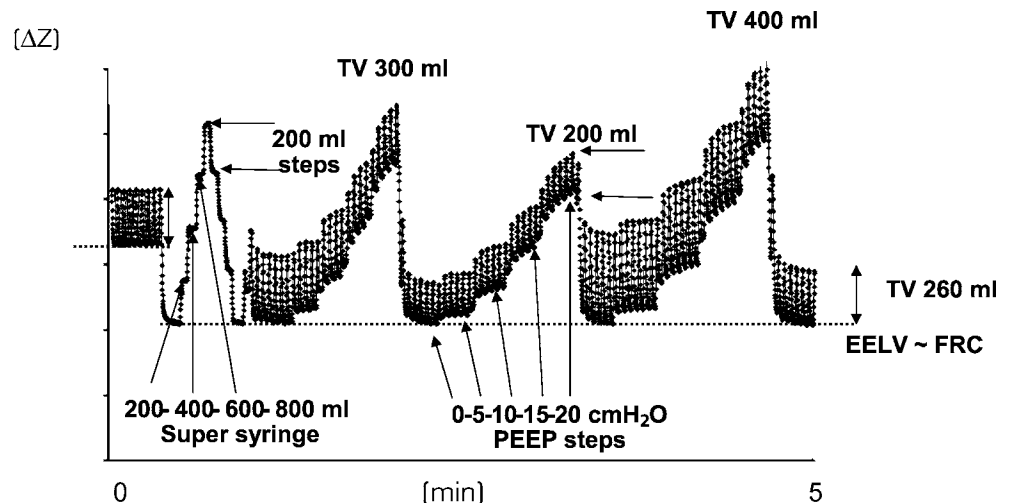
Preparation

Femoral arteries and internal jugular veins were cannulated. A continuous intravascular blood gas sensor (Trend-CareMonitor 6000, Diametrics Medical) was inserted into one of the femoral arterial lines. After preparation positive end-expiratory pressure (PEEP) was set to 10 cmH₂O, tidal volume (V_t) 10 ml/kg, respiratory rate 20 breaths/min and inspiratory fraction of oxygen (FIO₂) to 1.0. Repeated bronchoalveolar lavage with body warm saline was performed [25]. Total amount of saline ranged from 9 to 12 l. The procedure was continued until pO₂ was lower than 26 kPa at FIO₂ 1.0 and PEEP 5 cmH₂O.

Electric impedance tomography

Sixteen standard electrocardiographic electrodes (Red Dot, 3M) were placed around the thorax at the fifth–sixth parasternal intercostal space and connected to the EIT monitor (Dräger/GoE MFII, Göttingen, Germany). EIT data were generated by applying an electrical current of 5 mA and 50 kHz. Voltage differences between neighboring electrode pairs were measured in a sequential rotating process which obtained a scan every 72 ms (13 Hz). The scan slice in the EIT device used in this study has a radius-dependent estimated thickness of 5 cm [26]. Global and regional impedance changes were analyzed by prototype software for measuring ventilation induced impedance changes (Dräger Medical, Lübeck, Germany). Before and after lavage calibrations of global electrical

Fig. 1 Calibration of impedance changes (ΔZ) to lung volume changes (ΔV) in one animal. End-expiratory lung volume (EELV) is indicated. Animals were ventilated with tidal volume of 10 ml/kg b.w. at baseline. Lung volume changes from stepwise inflation with the super syringe were plotted against impedance changes and the equation of the curve used to calculate lung volume changes during the experimental protocol



impedance changes against known lung volume changes were performed using a super syringe. In steps of 200 ml, 800 ml was inflated and then deflated. Ventilation was resumed with V_t of 200, 300, and 400 ml and PEEP increased from 0 to 20 cmH₂O in steps of 5 cmH₂O at each V_t (Fig. 1). Lung volume changes were plotted against impedance changes and the slope was calculated for each animal.

Total lung mechanics and volumes

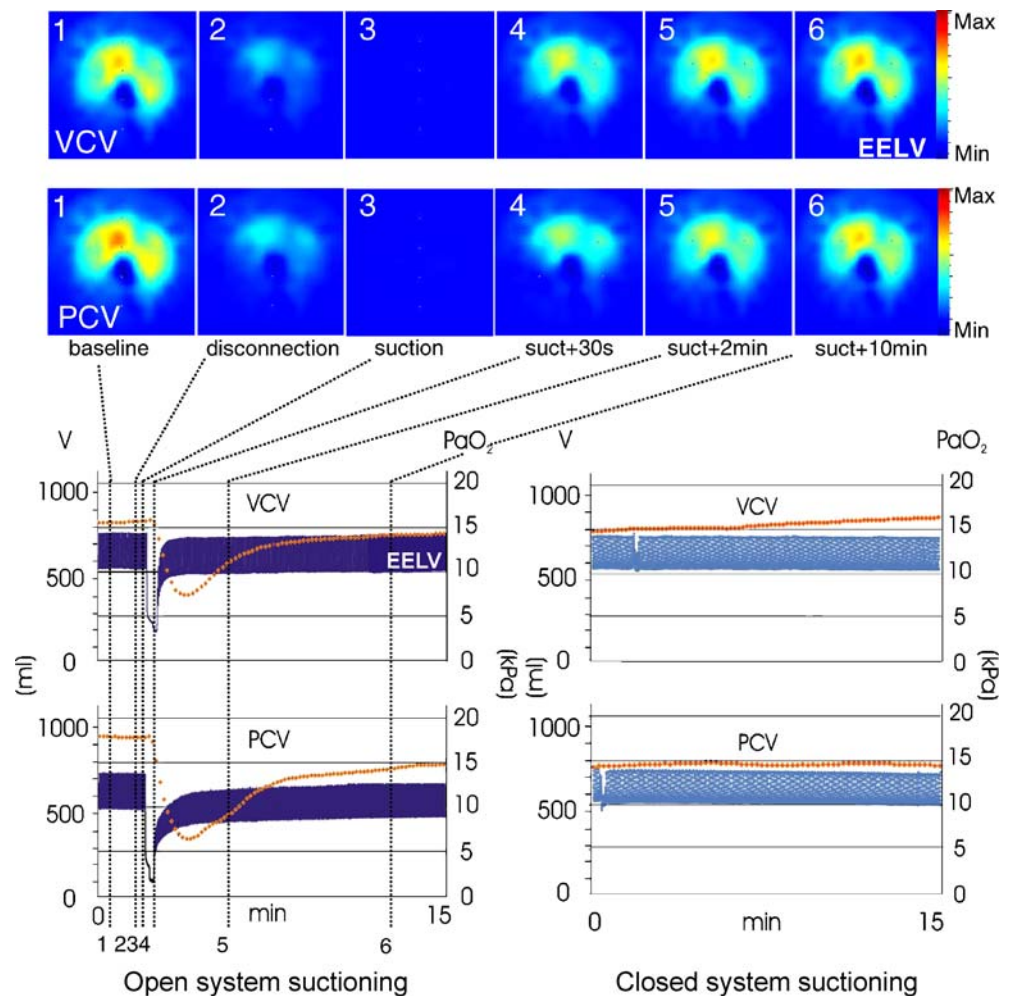
Tracheal pressure was measured with a pressure line inserted into the tracheal tube and positioned 2 cm below the tip of the endotracheal tube [27, 28]. The pressure sensor was placed so that the tracheal pressure was equal to the ventilator pressure during a prolonged end-expiratory pause. Respiratory rate, lung volume, and pressures were measured using a Pitot type D-lite flow/airway pressure sensor (Datex-Ohmeda/GE) connected at the Y-piece [29].

Total respiratory compliance was calculated as the V_t divided by the difference between end-inspiratory and end-expiratory tracheal pressure. Inspiratory and expiratory fractions of carbon dioxide and oxygen were measured breath-by-breath with side-stream infrared and paramagnetic technology (AS/3, Datex-Ohmeda). A modified technique of nitrogen washout/washin by a stepwise change in FIO_2 was used to measure FRC [30]. These FRC measurements (FRC_{N_2}) provided the absolute value of the EIT baseline volume, and from this baseline changes in end-expiratory lung volume (FRC_{EIT}) were calculated by using EIT super syringe calibrated volumes described above.

Regional lung mechanics and volumes

The EIT software can give both global and regional aeration-related impedance variations and, together with tracheal pressure, regional lung mechanics data [31].

Fig. 2 Above In a typical experiment EIT scans before, during, and after open suction, representing the end-expiratory lung volume (EELV). Below Numbers 1–6 indicate position of corresponding EIT scan in time. After OSS, restoration of PaO_2 (red dotted lines) is slower with PCV than VCV. CSS has minimal effect on lung volume (blue lines) and oxygenation compared to OSS



Four regions of interest (ROI) were chosen from off-line EIT analysis: ventral, midventral, middorsal, and dorsal. The regional V_t values (V_{tROI}) were calculated as: $V_{tROI} = (\Delta Z_{ROI} / \Delta Z_{GLOB}) \times V_t$, where the ΔZ_{ROI} is the regional impedance change for a ROI and ΔZ_{GLOB} is the sum of all impedance changes in the ROIs (= global impedance changes). Regional compliance was obtained by dividing V_{tROI} by tracheal pressure changes assuming no flow at end of inspiration and expiration.

Experimental protocol

Before EIT calibration the ventilator was set in VCV with V_t 10 ml/kg, respiratory rate 20/min, PEEP at 10 cmH₂O, inspiration-to-expiration ratio (I:E) of 1:2, and FIO₂ of 0.5. During the suctioning procedure either VCV or PCV was used with 10 cmH₂O PEEP, I:E 1:2, triggering level -2 cmH₂O, respiratory rate 20/min, and V_t 10 ml/kg b.w. (titrated by changing the pressure level

Fig. 3 Global changes in lung volume ($\Delta EELV_{EIT}$), functional residual capacity (FRC_{EIT}), tidal volume (V_t), peak tracheal pressure (P_{trach}), compliance (Crs), arterial oxygen tension (PaO_2), saturation (SaO_2), and arterial carbon dioxide tension ($PaCO_2$) during open suctioning with either volume- or pressure-controlled ventilation (VCV, PCV). Mean \pm SD ($n=9$). # $p < 0.05$ baseline vs. 30 s; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ VCV vs. PCV

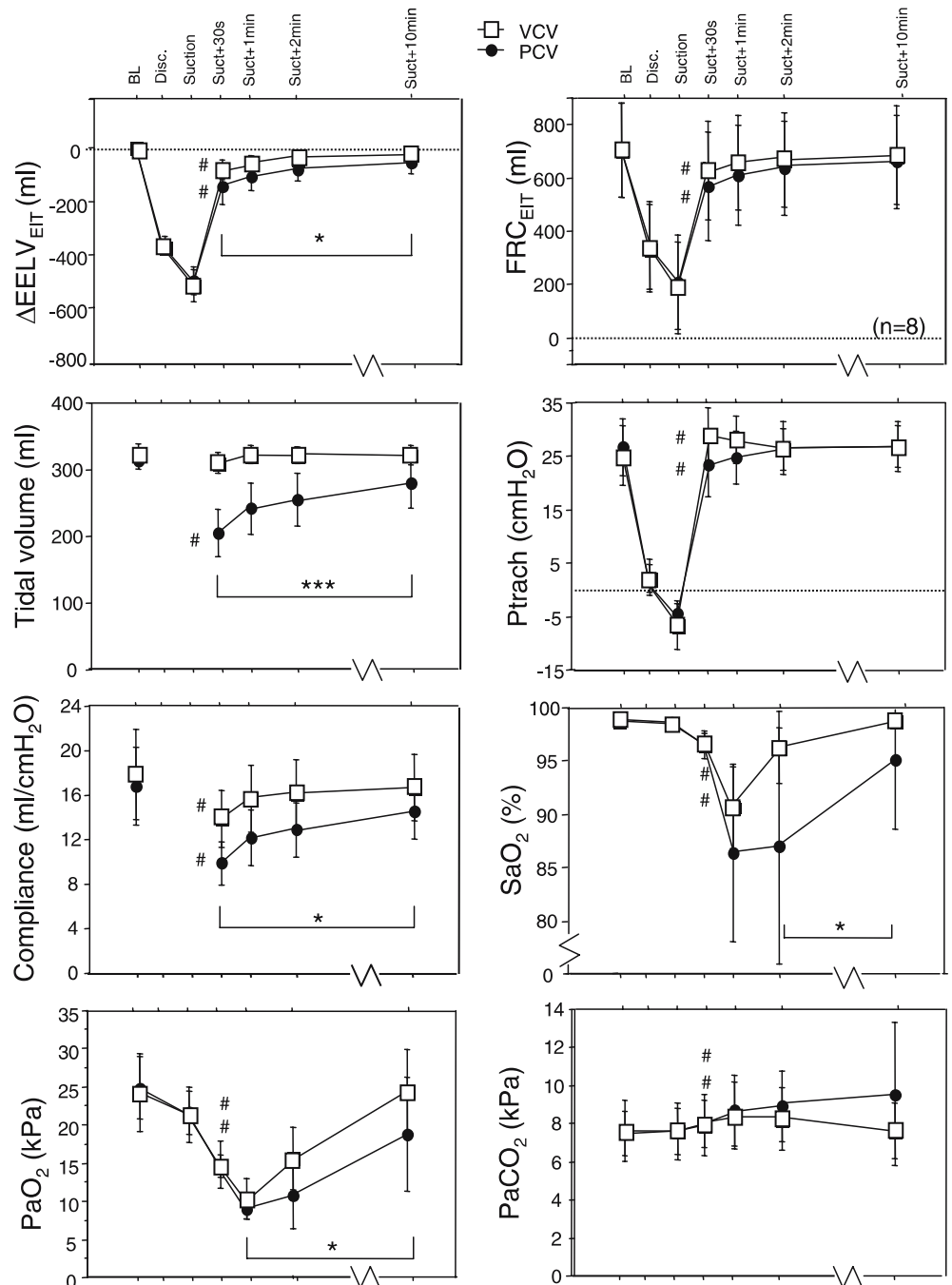


Fig. 4 Regional distribution of lung volume reduction relative to baseline (BL) in ventral (V), midventral (MV), middorsal (MD), and dorsal (D) region of interest (ROI). Dorsal regions are most affected by open system suctioning and postsuctioning ventilatory mode, volume- or pressure-controlled ventilation (VCV, PCV). Mean \pm SD ($n=8$). * $p < 0.05$, VCV vs. PCV

in PCV). Suctioning was applied for 10 s with vacuum level -20 kPa (approx. -150 mmHg, -200 cmH₂O) and a 14-F catheter. Four different suctioning procedures were tested in random order: (a) OSS with VCV, (b) OSS with PCV, (c) CSS during VCV, and (d) CSS during PCV. Data collection was started at baseline before suctioning and continued for 15 min after each suctioning procedure. Animals were allowed to stabilize, and a new baseline was established before proceeding. During the recovery and stabilization periods the ventilator was set at VCV, PEEP10 cmH₂O, I:E 1:2, respiratory rate 20/min, and Vt 10 ml/kg.

Data collection

Data from the AS/3 monitor for FRC calculations were collected at a sample frequency of 1 Hz (S/5 Collect 4, Datex-Ohmeda), exported to and analyzed in a dedicated software application (Testpoint, Capital Equipment, USA) [30]. Data from spirometry and invasive pressures were collected at sample frequencies of 25 and 100 Hz, respectively.

Statistical analysis

Values are presented as mean \pm SD. Two-way analysis of variance and the unpaired t test were used for postsuctioning comparison between interventions (VCV or PCV). The paired t test was used to evaluate changes between baseline and selected measuring points. A p value less than 0.05 was considered statistically significant. Bonferroni's correction for multiple comparisons was performed. One animal was excluded from the FRC calculations due to missing values.

Results

Changes in global impedance and lung volume obtained by the stepwise super syringe inflation were well correlated ($R^2 > 0.95$). A good correlation was also found between tidal electrical impedance and volume variations ($R^2 > 0.90$). FRC_{N2} before suctioning was 715 ± 171 ml ($n=8$) and had not changed significantly 10 min after

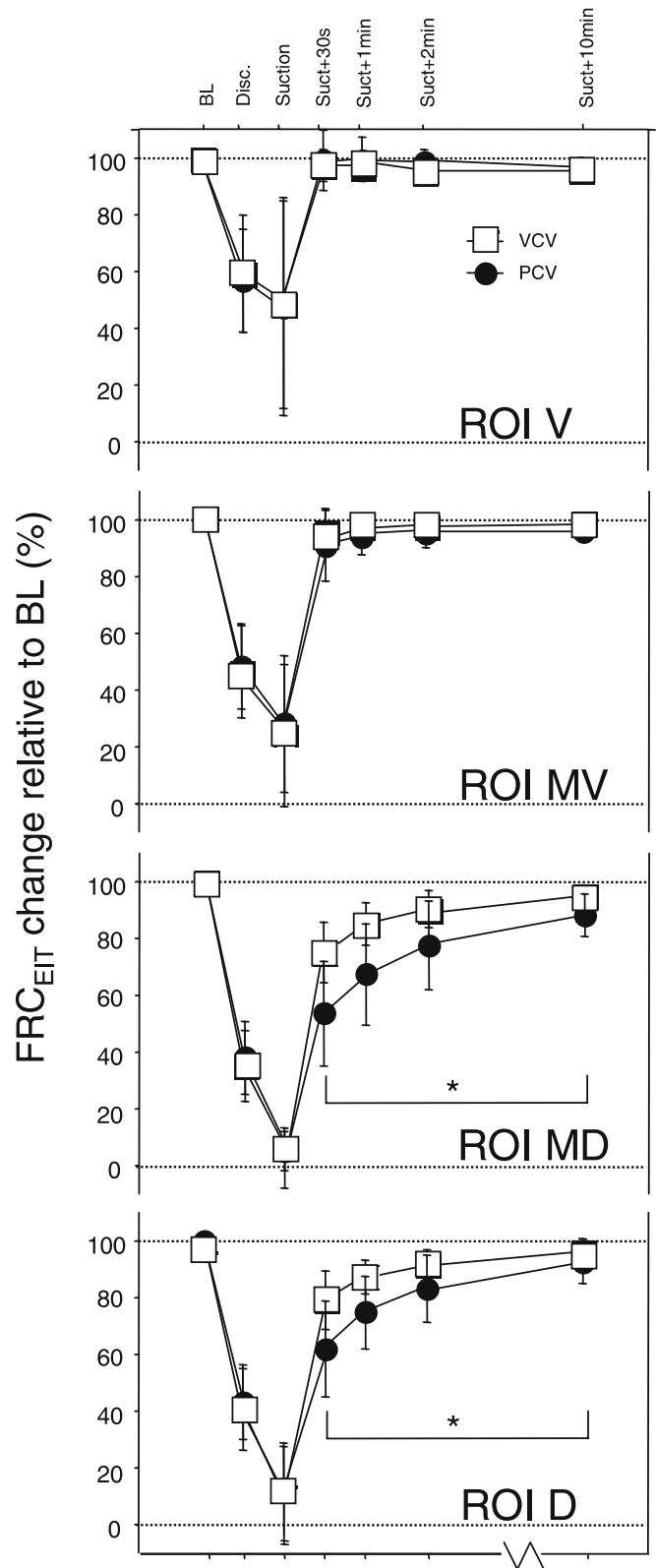


Fig. 5 Regional distribution of compliance reduction during open suctioning. Four regions of interest (ROI) were chosen ventral (V), midventral (MV), middorsal (MD), and dorsal (D). Restitution of compliance was significantly slower during PCV than during VCV ($p < 0.05$) primarily in the MV and D ROIs. Mean \pm SD ($n = 9$). # $p < 0.05$ VCV vs. PCV; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ baseline vs. measuring points

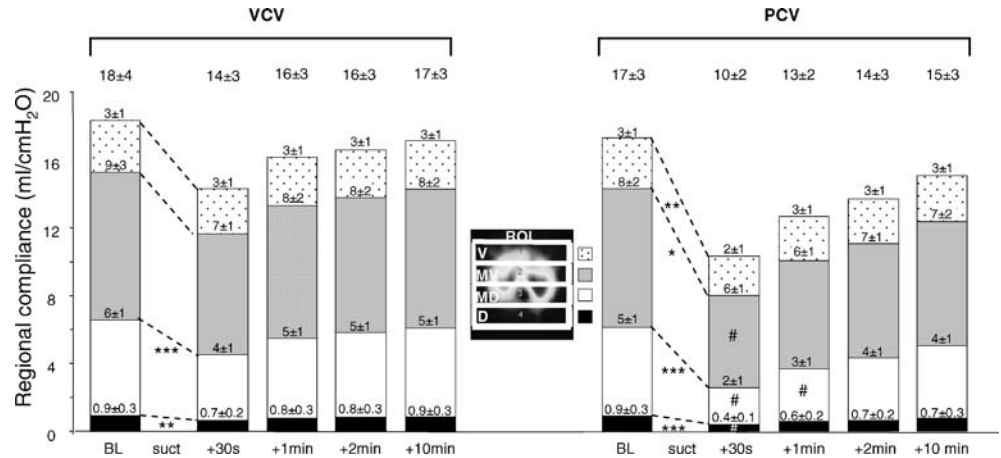
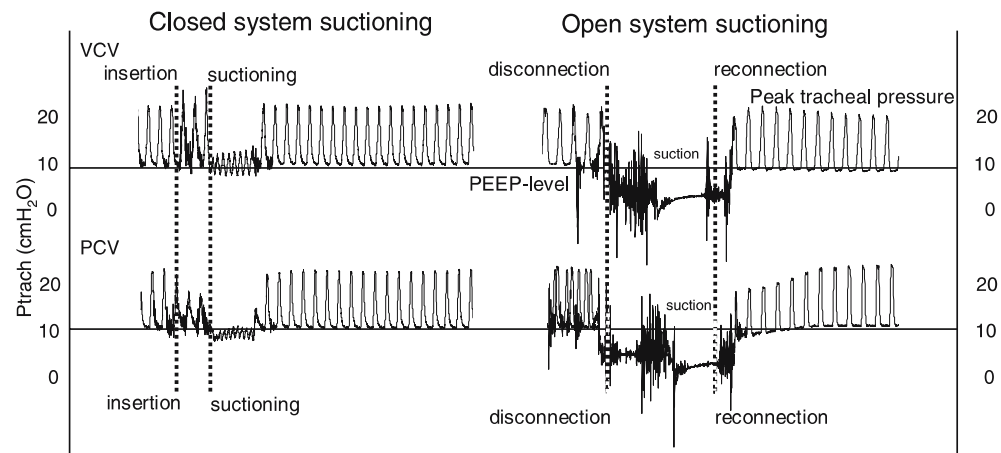


Fig. 6 Variations in tracheal pressure during open and closed suctioning in one animal. PEEP 10 cmH₂O, tidal volume of 10 ml/kg b.w., respiratory rate 20 bpm, I:E 1:2, suction catheter 14-F, and endotracheal tube no. 8. During closed-system suctioning and pressure-controlled ventilation (PCV) the tidal breaths triggered by the ventilator have smaller pressure amplitudes than during volume-controlled ventilation (VCV). After open suctioning there is a transient increase in peak tracheal pressure with VCV, in contrast to PCV. The disturbances seen in measurements are due to movement artifacts



the suctioning procedure. During an open suctioning procedure FRC_{EIT} instantly decreased by $54 \pm 14\%$ at disconnection ($p < 0.01$). Suctioning caused a further decrease, and the total lung volume loss was $74 \pm 20\%$ of baseline FRC. When VCV was used after suctioning, the FRC_{EIT} increased rapidly and was $12 \pm 6\%$ below baseline after 30 s. The corresponding value for PCV was $20 \pm 9\%$ ($n = 8$). VCV recruited lost lung volume more efficiently than PCV during the postsuctioning period of 10 min ($p < 0.05$, $n = 9$; (Figs. 2, 3). At disconnection, before suctioning, volume loss was more pronounced in dorsal regions of the lung: in the ventral ROI approx. 40%, midventral ROI 55%, and middorsal and dorsal ROIs 65% of regional baseline FRC was lost. During suctioning the two dorsal regions were nearly emptied. Consequently the volume restitution was rapid in the two ventral ROIs but slower in the dorsal ROIs, with a significant difference between PCV and VCV ($p < 0.05$; Fig. 4). During closed suctioning the decrease in FRC_{EIT} was 37 ± 17 and 26 ± 17 ml during PCV and VCV, respectively ($n = 7$). These minimal decreases in lung

volume were regained immediately when the suctioning catheter was removed.

Compliance could not be measured during open suctioning as there was no tidal ventilation. At the first registration after reconnection and ventilation 30 s after suctioning compliance showed a significant decrease using either VCV or PCV. The decrease was more marked with PCV than with VCV ($p < 0.05$; Fig. 3). Regional compliance deteriorated most in the dorsal parts of the lung ($p < 0.05$), but during PCV there was also a decrease in compliance in the ventral parts of the lung, however to a smaller extent. Compliance recovered more slowly during PCV than during VCV, and the difference was observed primarily in the middorsal and dorsal regions ($p < 0.05$; Fig. 5). Thirty seconds after closed suctioning there was a small decrease in respiratory compliance during PCV from baseline 18 ± 5 to 15 ± 4 ml/cmH₂O ($p < 0.05$; $n = 7$), which was not seen during VCV. V_t immediately after suctioning was 268 ± 16 ml in VCV and 162 ± 35 ml in PCV. Ten minutes after suctioning V_t values were 279 ± 14 and 237 ± 36 ml, respectively

($p < 0.01$; Fig. 3). During open suctioning tracheal pressure decreased to sub-atmospheric levels -6 ± 5 cmH₂O (range -23 to 0 cmH₂O). Thirty seconds after open suctioning tracheal pressure was slightly increased during VCV from baseline 25 ± 6 to 29 ± 5 cmH₂O ($p < 0.01$), but not during PCV. At insertion of the CSS catheter in VCV peak tracheal pressure increased significantly from baseline pressure of 24 ± 3 to 28 ± 3 cmH₂O ($p < 0.001$), which was not seen in PCV, where it instead decreased slightly from 26 ± 4 to 24 ± 2 cmH₂O. During CSS in VCV the peak tracheal pressure decreased from 24 ± 3 to 13 ± 2 cmH₂O ($p < 0.001$) and in PCV from 26 ± 5 to 12 ± 3 cmH₂O ($p < 0.001$, $n = 7$; Figs. 3, 6). Arterial oxygenation decreased immediately after OSS from a baseline value of 23 ± 4 kPa and reached its minimum 1 minute after the suctioning procedure at 9 ± 1 kPa. Restoration of oxygenation was slower during PCV than during VCV during the postsuction period ($p < 0.01$). A slight postsuctioning increase in PaCO₂ remained in PCV (Fig. 3).

Discussion

In surfactant depleted pigs open suctioning induced collapse of the lung, especially in the dorsal parts, which were deaerated. Approximately one-half of FRC was lost instantly at disconnection and another 20% during suctioning. When ventilation was resumed, lung volume was recruited more rapidly and effectively with VCV than with PCV, as Vt was preserved in spite of decreased compliance during suctioning. Restoration of oxygenation following open suctioning was also slower during PCV than during VCV. Insertion of the suction catheter during closed suctioning resulted in a slightly increased tracheal pressure during VCV but not during PCV. There were minimal, transient effects on FRC and oxygenation during CSS, irrespective of ventilatory mode.

Methodological considerations

The lung model used in this study is prone to collapse and the inflammatory reaction is comparatively mild. It can be regarded as a model of early acute respiratory distress syndrome and is easier to recruit than more inflammatory types of lung injury, like the oleic acid and pneumonia induced models [32, 33]. The EIT device used measures impedance changes in a ~ 5 cm thick slice of the thoracic cavity. The thickness of the slice is radius dependent [26] but also electrode size dependent. Movements of the lung could result in different parts of the lung being measured during a respiratory cycle. However, the close correlation between impedance changes and stepwise inflations of the lung implies that at least in a homogenous lung injury model, the EIT slice may be representative for

the whole lung [34]. A software, low-pass filter, minimizes stroke volume induced impedance changes.

In accord with earlier studies [26, 35] we also found that tidal impedance variations were well correlated to variation in Vt, which implies that in a clinical situation impedance variations can be calibrated merely by changing Vt, making the super syringe obsolete. Regional lung mechanics calculations were based on regional lung volume, but tracheal pressure data, as regional pressures could not be measured. This should not affect the adequacy of the regional compliance values as the tracheal pressure was measured during no-flow conditions during end-inspiration and end-expiration. We chose a 14-F catheter (4.7 mm OD) as the pigs were intubated with an 8-mm ID endotracheal tube. The vacuum level was -20 kPa (approx. -200 cmH₂O, -150 mmHg) which was lower than in most other studies [16, 17] but well in accordance with guidelines [1].

Open-system suctioning

This and previous studies have shown a marked decrease in lung volume and arterial oxygenation following open suctioning [13, 17, 20]. Disconnecting the breathing system could be expected to have more adverse effects, the higher the PEEP level. All animals in the present study had a PEEP level of 10 cmH₂O, and the main fall in end-expiratory lung volume (EELV) occurred already at disconnection of the breathing system, which is well in accordance with the findings of Maggiore et al. [13]. Regional EIT shows that EELV loss was most pronounced in the dorsal regions, and when suctioning was applied, these regions seemed to be nearly deaerated. This is probably explained by the fact that the superimposed pressure increases down the vertical axis of the lung, making the dorsal parts more prone to collapse [36, 37, 38]. In ventral regions of the lung the negative pressure applied during suctioning did not suffice to deaerate, as the superimposed pressure was too low. If the 80% lung volume loss had been evenly distributed through the lungs, the magnitude of desaturation would have been less than in the present situation, with a nearly total lung collapse in the dorsal parts, where perfusion is highest.

A previous study found that the negative effects of open suctioning remained after 30 min in PCV, but this was not the case when VCV was used [20]. In the present study hypoxemia recovered significantly faster when VCV instead of PCV was used during the postsuctioning period of 10 min. The reason for this difference was that the suctioning procedure resulted in a significant decrease in compliance, which in the case of PCV resulted in low Vt, approx. one-half of baseline, which was not sufficient to recruit the lung. During VCV Vt remained stable at 10 ml/kg, resulting in a transient increase in peak tracheal pressure, which returned to baseline within the first five to ten breaths af-

ter reconnecting the breathing system. Thus compliance was restored almost immediately in VCV as a sign of recruitment of the lung volume lost during suctioning. The pressure needed to open collapsed alveoli, especially in the dorsal regions, is higher than the set pressure during PCV. This resulted in a slower restoration of lung volume during PCV than during VCV, where the maintained Vt resulted in higher recruiting pressures.

Closed-system suctioning

There was no decrease in oxygenation during a closed-suctioning procedure, which is explained by the minimal decrease in EELV, irrespective of ventilatory mode. However, in a recent report [16] 44% of patients subjected to CSS showed a deterioration in PaO₂ by 5–26%. This may be explained by secretions lining the interior surface of the endotracheal tube, which in combination with a 16-F catheter causes a resistance to inspiratory flow that may be high enough for CSS to result in partial lung collapse. In the present study during insertion of the suction catheter peak tracheal pressure increased in VCV but not in PCV as the ventilator was capable of inflating the same Vt during VCV in spite of the increased resistance of the tube with the catheter inserted. In contrast, during PCV the increased resistance resulted in lowered Vt. This is well in accordance with earlier reports [2] in which both peak tra-

cheal pressure and intrinsic PEEP increased when a suction catheter was introduced through a tube during VCV.

Clinical considerations

EIT is a potential tool for monitoring rapid lung derecruitment bedside. In a surfactant depleted lung model, prone to collapse, disconnection of the breathing system resulted in marked loss of lung volume, predominantly in the dorsal regions with the highest superimposed pressure. Open suctioning seemed nearly to deaerate dorsal lung regions, causing instantaneous desaturation. Repetitive open suctioning could contribute to this focal distribution, especially if the patient is ventilated with PCV [39]. After suctioning lung volume was readily restored by using VCV. In PCV Vt was lowered as a result of the decrease in compliance after suctioning, and this low Vt did not recruit the lung fully. Thus it may be advisable to use VCV after open suctioning to restore lung volumes rapidly. The same effect may be achieved by increasing the pressure level in PCV.

This study confirms that CSS causes modest side effects irrespective of ventilatory mode.

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