Endotracheal Suction
a Reopened Problem

BIRGITTA ALMGREN
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Abstract

During mechanical ventilation, patients are connected to the ventilator by an endotracheal tube. The tube needs to be cleaned from mucus by suction, which can cause negative effects such as lung collapse, hypoxemia and desaturation. These can be avoided by preoxygenation, change of ventilator settings, use of closed suction systems and recruitment manoeuvres. The aim of the study was to investigate the effects of endotracheal suction during different ventilator settings and by different suction methods. A method to reverse side effects was investigated.

In anaesthetized pigs, the effect of suction during volume and pressure-controlled ventilation was investigated, and the effect of different suction systems and catheter sizes were compared. Suction efficacy was investigated in a bench study. The effect of recruitment manoeuvre added after suction, i.e. post-suction recruitment manoeuvre was evaluated.

Endotracheal suction causes lung volume loss leading to impaired gas exchange, an effect that is more severe in pressure-controlled ventilation than in volume-controlled ventilation. When 14 French suction catheters were used more side effects were found compared to 12 French catheters, but no difference was found between open and closed suction system in pressure-controlled ventilation. Open suction system was more effective to remove mucus compared to closed system. Post-suction recruitment manoeuvre restored the side effects after the first recruitment when it was applied directly after suction.

In conclusion, open endotracheal suction causes impairment in gas exchange and lung mechanics, and more so in pressure-controlled than in volume-controlled mode. These changes can be minimized if smaller suction catheters are used. A post-suction recruitment manoeuvre applied directly after suction restores lung function. It is obvious that the recruitment manoeuvre should be added directly after suction, because if the manoeuvre is delayed and the lung is collapsed and left collapsed, it will be more difficult to recruit the lung.

Keywords: Mechanical, ventilation, endotracheal, suction, lung, volume, loss, gas, exchange

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To my daughter Elin
Original papers

The thesis is based on the following papers, which will be referred to in the text by their roman numerals:


II. Almgren B, Strid N, Wickerts CJ, Hogman M. Negative pressure during suction differs between suction systems and catheter sizes. *Submitted*


# Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ARDS</td>
<td>Acute respiratory distress syndrome</td>
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<tr>
<td>ARF</td>
<td>Acute respiratory failure</td>
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<tr>
<td>CO</td>
<td>Cardiac output</td>
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<tr>
<td>CPAP</td>
<td>Continuous Positive Airway Pressure</td>
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<tr>
<td>Crs</td>
<td>Compliance of the respiratory system</td>
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<tr>
<td>CSS</td>
<td>Closed suction system</td>
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<tr>
<td>CVP</td>
<td>Central venous pressure</td>
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<tr>
<td>EELV</td>
<td>End-expiratory lung volume</td>
</tr>
<tr>
<td>ET</td>
<td>Endotracheal</td>
</tr>
<tr>
<td>ETCO₂</td>
<td>End-tidal carbon dioxide concentration</td>
</tr>
<tr>
<td>Fr</td>
<td>French (size)</td>
</tr>
<tr>
<td>FRC</td>
<td>Functional residual capacity</td>
</tr>
<tr>
<td>HR</td>
<td>Heart rate</td>
</tr>
<tr>
<td>i.d.</td>
<td>Inner diameter</td>
</tr>
<tr>
<td>MAP</td>
<td>Mean systemic arterial pressures</td>
</tr>
<tr>
<td>MPAP</td>
<td>Mean pulmonary arterial pressures</td>
</tr>
<tr>
<td>N₂</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>OSS</td>
<td>Open suction system</td>
</tr>
<tr>
<td>o.d.</td>
<td>Outer diameter</td>
</tr>
<tr>
<td>PaCO₂</td>
<td>Arterial carbon dioxide partial pressure</td>
</tr>
<tr>
<td>PaO₂</td>
<td>Arterial oxygen partial pressure</td>
</tr>
<tr>
<td>PCV</td>
<td>Pressure-controlled ventilation</td>
</tr>
<tr>
<td>PEEP</td>
<td>Positive end expiratory pressure</td>
</tr>
<tr>
<td>PEEPi</td>
<td>Intrinsic PEEP</td>
</tr>
<tr>
<td>Pplat</td>
<td>Plateau pressure</td>
</tr>
<tr>
<td>PS-RM</td>
<td>Post-suction recruitment manoeuvre</td>
</tr>
<tr>
<td>SpO₂</td>
<td>Arterial oxygen saturation from pulsoximetry</td>
</tr>
<tr>
<td>SvO₂</td>
<td>Mixed venous oxygen saturation</td>
</tr>
<tr>
<td>VCV</td>
<td>Volume-controlled ventilation</td>
</tr>
<tr>
<td>V₁</td>
<td>Tidal volume</td>
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</table>
Introduction

Patients being mechanically ventilated are often connected to the ventilator by an endotracheal (ET) tube. The ventilator can be set in different ventilation modes, e.g. volume-controlled mode (VCV) or pressure-controlled mode (PCV). In acute respiratory distress syndrome (ARDS), there is no difference in in-hospital morbidity and mortality, if the patient is ventilated with VCV or PCV, as long as there are no differences in pressure limitation settings (1). Both ventilation modes are commonly used, as found in a cohort study in Sweden, Denmark and Iceland (2). This study was carried out to determine incidence of and mortality due to acute respiratory failure (ARF) and ARDS, and among ARF patients 48% were ventilated with VCV compared to 23% PCV, and among ARDS patients 34% were ventilated with VCV compared to 28% in PCV. The third most common mode was pressure-regulated volume-controlled mode. Lung protective ventilation has been shown to improve survival rate in intensive care patients. This strategy keeps the lung open with positive end-expiratory pressure (PEEP), and high airway pressures are minimized by using small tidal volumes ($V_T$) (3,4). By keeping the lung open lung damage due to high shear forces is prevented (5).

The ET tube and the airways occasionally need to be cleared of mucus by suction, because the normal coughing mechanism is disrupted. If the patient is disconnected from the ventilator during ET suction, there is a risk of lung volume loss. Moreover, suction can negatively affect the patient by causing additionally lung volume loss, hypoxemia and arrhythmias (6-8). Already after 24 hours use, the ET tube narrows because of mucus buildup and the intraluminal diameter will be reduced (9,10). The number and severity of negative effects resulting from ET suction is related to both ventilator settings and suction method. Therefore, various methods have been proposed to limit the risks, e.g. different ventilator settings, closed suction systems, preoxygenation and recruitment.

Suction methods

Different ET suction systems are used, i.e., open, quasi-closed and closed systems. When an open suction system (OSS) is used, the ET tube is disconnected at the Y-piece and the suction catheter is inserted into the ET
tube before suction. The disconnection allows airway pressure to fall to atmospheric pressure before the suction starts. Since the disconnection itself results in pressure drop, a quasi-closed system consisting of a suction adaptor can be used. By this adaptor, the suction catheter can be passed through a side hole, and disconnection of the patient from the ventilator is avoided. By the usage of a quasi-closed system, lung volume loss due to ET suction can be reduced (11). The closed suction system (CSS) has a catheter continuously placed between the ET tube and the Y-piece of the ventilator. The suction catheter is introduced into the trachea without the ET tube being disconnected (12). Different studies have described both advantages and disadvantages to the use of CSS. The system limits the incidence of nosocomial infection and exposure of personnel in the surrounding area (13-15). Less desaturation was found when CSS was used in patients with positive PEEP settings exceeding 8 cmH₂O (16). In contrast, suction with CSS without any breaths delivered during suction and with a PEEP of 10 cmH₂O influenced the cardiovascular system more than suction with OSS (17). The use of CSS has also been shown to prevent arterial and systemic venous oxygen desaturation as well as lung collapse during VCV (18). Yet, there is a risk of intrinsic positive end-expiratory pressure (PEEPi) caused by insertion of the suction catheter in VCV (19). When closed, quasi-closed (suction adaptor) and open suction were compared in patients without severe lung disease, lung volume loss was rapidly reversed (i.e. within 10 minutes) in every patient (11).

The recommendation is to use a suction catheter with an outer diameter (o.d.) not exceeding half the ET tube inner diameter (i.d.). Conversion from i.d. to o.d. is done by multiplying the i.d. by 3 and then divide the product by 2. An example for ET tube 8 mm i.d. requires a 12 French (Fr) suction catheter (20). Suction catheters with larger o.d. and higher suction pressure create more negative pressure (21). Moreover, short suction catheters (30 cm) give rise to more negative pressure than longer catheters (50 cm). For comparison, an investigation of short and long suction catheters with open suction technique showed that use of shorter catheters reduced side-effects (22).

In clinical practice, it is recommended to set the vacuum pressure between –100 to –125 mmHg (12,20). But in studies of ET suction, different vacuum pressures have been used. Moreover, suction flow is the main factor that influences the amount of gas removed from the lungs. The suction flow depends on level of vacuum and diameter and length of the suction catheter (12). Table 1 summarizes vacuum levels in mmHg, kPa, cmH₂O and flow used in different studies of endotracheal suction.
Table 1. Vacuum pressures and flowrate; mmHg, kPa, cmH₂O, L/min used in studies of endotracheal suction.

<table>
<thead>
<tr>
<th>mmHg</th>
<th>kPa</th>
<th>cmH₂O</th>
<th>L/min</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>–100</td>
<td>- 13.3</td>
<td>- 136</td>
<td></td>
<td>(18,23)</td>
</tr>
<tr>
<td>–120 (CSS)</td>
<td>- 16</td>
<td>- 163.2</td>
<td></td>
<td>(23)</td>
</tr>
<tr>
<td>–150 to –200</td>
<td>20 to - 26.6</td>
<td>204 to - 272</td>
<td></td>
<td>(11)</td>
</tr>
<tr>
<td>–400 occlusion pressure</td>
<td>- 53.2</td>
<td>- 544</td>
<td></td>
<td>(24)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>16 L/min</td>
<td>(17)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13-18 L/min</td>
<td>(19)</td>
</tr>
<tr>
<td>- 105</td>
<td>- 14</td>
<td>- 142.8</td>
<td></td>
<td>Paper I, III-V</td>
</tr>
<tr>
<td>- 150 and - 300</td>
<td>20 and - 40</td>
<td>204 and - 408</td>
<td></td>
<td>Paper II</td>
</tr>
</tbody>
</table>

Negative pressure during suctioning might also cause tracheobronchial trauma, as a correlation has been observed between such trauma and the magnitude of negative pressure applied (25). Pressure changes were investigated in a study performed in a “bag-in-a-box” model. The negative effects of endotracheal suction might be caused by the large amount of negative pressure applied during suction, but the negative pressure is desirable to clear away mucus.

One method to prevent desaturation is to increase inspired oxygen (preoxygenate) before ET suction (26). However, 100% oxygen can contribute to absorption atelectasis, as shown in a study comparing 40 and 100% oxygen during recruitment manoeuvre in general anaesthesia (27). For preoxygenation, it has been suggested that the oxygen concentration should be increased by 20% compared to the maintenance oxygen level in order to minimize absorption atelectasis and further lung volume loss (28).

**Ventilator settings**

Different settings of the ventilator have been suggested during ET suction to limit the side-effects due to the negative pressure in trachea. A constant flow of air delivered by the ventilator during ET suction has been shown to prevent desaturation (29). The ventilator can be set so that high pressure supported breaths can be triggered during closed suctioning, and loss of lung volume can be avoided (30). Negative effects after ET suction during VCV have been described, but no study we have found that compares the effects of suctioning during VCV and PCV. Modifications in timing of the breath, such as short expiration time or increased respiratory rate and large VT, might produce PEEPi. The time allowed for expiration is cut short before next inspiration and the lung becomes hyperinflated (31,32). When a CSS is used, trigger sensitivity is important, and the sensitivity can be set so that breaths can be triggered due to suction (18). But if the CSS catheter is left in
malposition, i.e. not withdrawn completely, inappropriate triggering can occur due to air leak (33).

Respiratory monitoring

During mechanical ventilation, airway pressures and volumes are monitored continuously in modern ventilators. In clinical practice, airway pressure and tidal volume are the most common values for assessment of lung mechanics (34). In most modern ventilators, respiratory mechanics, e.g. compliance and resistance can be measured in order to facilitate the adjustment of the ventilator. The measurement can either be made inside the ventilator or at the airway opening (35). Compliance reflects volume change per unit pressure change. Airway resistance is the pressure difference between alveoli and the mouth divided by a flow rate (36). With an ET tube in place, the airway resistance is increased (37). Functional residual capacity (FRC) is the volume of gas remaining in the lung after a normal expiration. Recently, a simple method for FRC monitoring has been described (38,39). End expiratory lung volume was measured with nitrogen washout/washin method and the end-tidal gas concentrations were used for calculation of end-expiratory lung volume (EELV). The end-tidal concentrations of nitrogen were used for calculation of FRC with an N2-washout/in method.

Lung recruitment

During lung protective ventilation, small VT are used, and therefore there is a risk of derecruitment. The lung is kept open with PEEP, but recruitment manoeuvres are also used to regain lung volume (40). In patients with ARDS, without impairment of chest wall mechanics, treated with a protective ventilatory strategy for 1-2 days, non-aerated lungs can be recruited by applying a pressure of 40 cm H2O for 40 s (41). During anaesthesia, a recruitment manoeuvre can be used to restore atelectasis by different methods, such as vital capacity manoeuvre and step-wise increases of PEEP (42,43). High-pressure of 40 cm H2O repetitive recruitment manoeuvres were necessary in an animal study when recruitment was tested in a lung injury model (44). However, the increase in airway pressure by recruitment manoeuvres might affect hemodynamics. High-pressure recruitments by vital capacity manoeuvres involving lung inflation at pressures of 40 cmH2O during one minute are associated with more hemodynamic depression compared to recruitment during ongoing ventilation in PCV with 40/20 cm H2O in endotoxinemic animals (45). Repeated derecruitments might accentuate lung injury, expressed in histopathology from bronchiolar epithelium (46). Lung volume loss after
endotracheal suction is greater in patients with lung damage compared to patients with normal lungs. Moreover, lung volume loss is greater with OSS than with CSS. The most significant lung volume loss is associated with ventilator disconnection (18,23). After ET suction with OSS, a lung recruitment manoeuvre by repetitive airway pressure peaks of 45 cmH₂O for 20 seconds has been shown to regain lung volume and oxygenation (24). Preoxygenation before suction combined with a postsuction recruitment manoeuvre by 20 VT breaths each of 20 mL kg⁻¹ volume immediately after suction reverses side-effects (47).

Strategies for mechanical ventilation have changed, but the endotracheal procedures are not yet harmonized to these new strategies. Moreover, not only ventilator settings, but also suction methods, suction systems, catheter sizes, and vacuum levels have large impact, and sometimes negative effects. The present study aimed to investigate suction procedures and their effect on hemodynamics and gas exchange.
Aims

The overall aim of this thesis was to investigate the negative effects of endotracheal suction and evaluate a method to limit side-effects. The aim was also to investigate the effects when different ventilation modes, suction systems and suction catheter sizes were used. In particular the aims of the study were to:

- compare the efficacy of ET suction with open and closed systems and with 12 Fr and 14 Fr catheter sizes in different ventilation modes.

- investigate whether there is a difference in side-effects on hemodynamics and gas exchange after open ET suction in pressure-controlled and volume-controlled mode.

- find out if negative side-effects on hemodynamics and gas exchange can be avoided after ET suction with open system by adding a post-suction recruitment in pressure-controlled and volume-controlled mode.

- investigate when in time a post-suction recruitment should be performed after open suction pressure-controlled mode.

- determine whether there is a difference in side-effects on hemodynamics and gas exchange during ET suction with open and closed systems and with 12 Fr and 14 Fr catheter sizes in pressure-controlled mode.

- compare tracheal pressure during suction with open and closed systems and with 12 Fr and 14 Fr catheter sizes in pressure-controlled mode.
Materials and Methods

Animals

Healthy anaesthetised pigs of mixed breed (Hampshire, Yorkshire and Swedish Landrace) with a body weight ranging from 17.5 to 35 kg were investigated. The experimental protocol was examined and approved by the local Ethics Committee for Animal Experiments, Uppsala, Sweden. The study was performed in accordance with the recommendations of the Swedish National Board for laboratory animals.

Protocols

Paper I

The effects of open endotracheal suction were compared in two ventilation modes, VCV and PCV. Suction was done with an open suction catheter 14 Fr (n=8). The effects of open and closed endotracheal suction were compared during PCV. Suction was done with OSS and CSS and different catheter sizes, 12 Fr and 14 Fr (n=4). A recruitment manoeuvre was used to standardize lung volume.

Paper II

Tracheal pressure was measured during endotracheal suction with CSS and OSS with suction catheters no 12 Fr and no 14 Fr in PCV (n=5). Tracheal pressure was also measured at 5 and 10 seconds after insertion of 12 Fr CSS catheter during VCV. Respiratory rate was set to 10, 15, 20 or 25 min⁻¹ in random order (n=5). Suction flow measurements were performed in a bench model. Open suction catheters 12 Fr and 14 Fr were used at vacuum levels of –15 kPa and –20 kPa.

Paper III

In a lung model, a standardised soap gel emulsion was applied and suction efficacy was evaluated. The amount of gel recovered by suctioning was quantified by weighing the suctioning systems. CSS was performed during VCV, PCV and CPAP (Continuous Positive Airway Pressure) mode (0 or 10 cmH₂O), and vacuum level was set at –20 or –40 kPa. Open suction was performed by disconnection the CSS from the Y-piece. ET tube 7 and 8 mm
i.d., and suction catheters 12 and 14 Fr (4.0 and 4.6 o.d.) were used. In random order, suctioning system and ventilator settings were repeated six times.

Paper IV
The effects of a recruitment manoeuvre, performed directly after open endotracheal suction was compared to suction without the recruitment manoeuvre in VCV and PCV, with a \( V_T \) setting of 14 or 10 mL·kg\(^{-1}\). An OSS 14 Fr catheter was used (n=5).

Paper V
The effects of open endotracheal suction directly followed by a Post-suction recruitment manoeuvre (PS-RM, n=6) or without PS-RM (n=6) were compared in PCV. Endotracheal suction was repeated four times, once per hour with a 14 Fr catheter.

The effects of open endotracheal suction directly followed by a PS-RM at different time periods after suction; 1 (n=5), 30 (n=6), 120 (n=6) and additional 30 (n=6) minutes after the 120 minute period were compared in PCV. The first PS-RM was done by an increase in airway pressure to 15 cm H\(_2\)O above plateau pressure (Pplat) or inspiratory pressure by using the inspiratory hold key on the ventilator. If baseline \( V_T \) was not reached by the first PS-RM, the following PS-RM’s were done with an increased pressure level in steps of 2 cm H\(_2\)O above the 15 cm H\(_2\)O inspiratory pressure. The same order a-b-c-d, were repeated in each animal (Figure 1). Recording of measurements were made before suction, after suction, after PS-RM and 10 and 30 minutes thereafter. EELV was measured before and after suction, before and after PS-RM and 30 minutes thereafter.
Figure 1. In paper V comparison of open endotracheal suction followed by a Post-suction recruitment maneuver (PS-RM) at a = 1 minute (n=5), b = 30 minutes (n=6), c = 120 minutes (n=6) and d = 30 minutes (n=6, additional) were made. Arrows indicate measurement recordings.

Anaesthesia

Before transport to the laboratory, the pigs were premedicated with 40 mg azaperon (Stresnil®, Janssen Pharmaceutical, Beerse, Belgium), given by intramuscular injection. Anesthesia was induced with 0.5 mg atropine (Atropin®, NM Pharma AB, Stockholm, Sweden) and a mixture of 100 mg tiletamin (comparable to ketamine) and 100 mg zolazepam (benzodiazepine derivative, Zoletile® forte vet, Virbac Laboratories, Carros, France) dissolved in 5 mL of a solution of medetomidin (a selective alpha2-adrenoceptor agonist, Domitor®, 1 mg mL⁻¹; Orion Corporation, Farmos, Finland); 1 mL per 20 kg body weight was injected intramuscular. The animals were placed in supine position on a heating pad and intubated with a cuffed ET tube, 6.0 mm i.d (Paper I, II, IV, V). A bolus injection of 0.2 mg fentanyl (Fentanyl®, Antigen Pharmaceuticals, Roscrea, Ireland) was given intravenous. Anesthesia was maintained by infusion of 5 mL kg⁻¹ h⁻¹ of a solution containing 4 g ketamin (Ketamin® Veterinaria, Zürich, Switzerland), 1 mg fentanyl in 1000 mL of a glucose electrolyte solution, Rehydrrox with glucose (Pharmacia and Upjohn, Stockholm, Sweden). Bolus doses of 1-2 mg pancuron (Pavulon®, Organon, Netherlands) were given before suction.
Ventilation

The pigs were mechanically ventilated (Evita 4, Dräger Medical, Lübeck, Germany) in either a volume-controlled (Intermittent Positive Pressure Ventilation) or a pressure-controlled (Biphasic Positive Airway Pressure) mode Paper I, II, IV. In Paper III and paper V, Servo 900 C (Siemens-Elema, Solna, Sweden) was used. Ventilator settings were inspired oxygen fraction 0.3, PEEP 3 cm H₂O. Tidal volume was either set to 14 mL kg⁻¹ or inspiration pressure level was set to achieve Vₜ 14 mL kg⁻¹ (paper I, II, IV, V). In paper IV, Vₜ 10 mL kg⁻¹ was also used. Respiratory rate was adjusted to achieve a stable end-tidal CO₂ (ETCO₂) close to 5 kPa. Auto flow was off, and trigger level set to minimum. In paper III, ventilator settings were: Vₜ 450 mL, PEEP 5 cm H₂O, respiratory rate 20, inspiration expiration ration 1:3 and trigger -2 cm H₂O.

Suction

No preoxygenation was used before or after endotracheal suction. During the suction procedure, the catheter was inserted into the ET tube and suction with a −14 kPa vacuum was performed for 10 seconds with a standard vacuum device. Immediately after suction, the catheter was removed. Suction systems CSS (Trach Care®, Ballard Medical Products, USA) and OSS (UNO, Maersk Medical A/S, Denmark) with catheters 12 Fr (o.d. 4.0 mm) and 14 Fr (o.d. 4.6 mm) were used.

Recruitment

In paper I, a recruitment manoeuvre was used to standardize lung volume. Directly after suction, a 10-s recruitment manoeuvre was done, involving an increase in airway pressure to 15 cm H₂O above Pplat or inspiratory pressure by using the inspiratory hold key on the ventilator (paper IV, V). Additionally, in paper V, the first PS-RM was done by an increase in airway pressure to 15 cm H₂O above Pplat or inspiratory pressure by using the inspiratory hold key on the ventilator. If baseline Vₜ was not reached by the first PS-RM, the following PS-RM’s were done with an increased pressure level in steps of 2 cm H₂O above the 15 cm H₂O inspiratory pressure.

Measurements and Monitoring

A catheter was inserted in the carotid artery for blood pressure measurements and blood sampling. A balloon thermodilution catheter was
introduced in the external jugular vein and advanced to the pulmonary artery. A central venous catheter was inserted in the same vein as the balloon thermodilution catheter. Measurements consisted of arterial and venous blood gases (ABL 5, Radiometer, Copenhagen, Denmark; tonometric correction for pig blood was made), heart rate (HR), mean systemic arterial pressures (MAP), mean pulmonary arterial pressures (MPAP), central venous pressure (CVP), cardiac output (CO) measured by thermodilution technique, arterial oxygen saturation from pulsoxymetry (SpO₂) and mixed venous oxygen saturation (SvO₂). A D-lite™ flow sensor (Datex-Ohmeda, Instrumentarium Corp., Helsinki, Finland) was connected at the Y-piece for dynamic gas monitoring. Inspired and expired oxygen fractions, respiratory rate, V₁, ETCO₂, compliance of the respiratory system (Crs), airway pressure and Pplat were measured. All measurements were recorded using a CS/3 CCM™ critical care monitor (Datex-Ohmeda). The monitor was connected to a computer and data was collected continuously (S5 Collect, Datex-Ohmeda), paper I,II,IV and V.

Pressure measurements
Pressure was measured in the trachea with a Pressure-wire system™ (Radi Medical Systems, Uppsala, Sweden). The pressure-wire was positioned at the end of, but outside, the ET tube. The pressure-wire has an o.d. of 0.36 mm, and a sensor head size of 0.1x0.15x1.3 mm. The pressure range is –130 to 200 cmH₂O, and the accuracy is ± 2.6 cmH₂O. The frequency range is 0 to 200 Hz and the measurement principle is piezoresistive. The pressure-wire was connected to a separate computer for data recording. At the beginning of each experiment the system was calibrated and the zero level was checked before each sampling period.

End-expiratory lung volume
EELV was measured with nitrogen (N₂) washout/washin method and the end-tidal concentrations were used for calculation. In this method, inspired oxygen fraction was first increased from 0.3 to 0.5, and once the end-tidal concentrations had achieved a new steady state value, reduced back to 0.3. The N₂ concentration was calculated from O₂ and CO₂ concentrations. The change in lung N₂ volume divided by the change in N₂ concentration gives the EELV. The reported final value was calculated as average of the successive N₂ wash-out and wash-in measurements (38,39).

Bench experiments
Suction efficacy
A Biotek ventilator tester, model VT-1 (Bio-Tek Instruments Inc, Vermont, USA) was used as a lung model. Crs was set at 50 mL cmH₂O⁻¹. The lung
model was fitted with a plastic “trachea”, with an i.d. of 18 mm, which was intubated with a cuffed ET tube 7 or 8 mm o.d. A 12 or 14 Fr CSS catheter was attached between the endotracheal tube and a standard breathing system connected to a Servo 900C ventilator. A standard ejector vacuum device was used and the vacuum level was set at –20 or –40 kPa. Before intubation, 15 mL of a standardized soap gel emulsion was applied, density 1.0 g mL⁻¹, (Hudosil, Stockholms Analytiska Lab AB, Sweden) in the “trachea”, 2 cm below the endotracheal tube tip with the “trachea” clogged with gel. Open suctioning was performed by disconnecting the CSS from the Y-piece.

Suction flow measurement
Suction flow measurements (4040 C TSI Inc, USA) were performed in a bench model. Peak and steady flow was measured at the tip of the suction catheter. The suction device was set at -15 kPa and -20 kPa. Open suction catheters no 12 Fr and no 14 Fr were used. The measurements were repeated three times.

Statistical analysis
Analysis of variance (ANOVA) and repeated measurement ANOVA were used to compare data both between and within the groups, at different times. The Tukey honest significant difference test was used for post hoc comparisons and probability values were calculated (paper I, II, IV, V). Mann-Whitney U-test was used to compare data between 12 Fr and 14 Fr OSS and CSS groups, at different study times (paper I). Student’s t-test was used to compare data between 12 Fr and 14 Fr OSS and CSS groups (paper II). Kruskal-Wallis test and Mann-Whitney U-test were used for comparisons in the benchtest (paper III). For correlations, the Spearman rank order correlations were used (paper IV). For all statistical calculations the Statistica/w 5.0 software package (StatSoft Inc.,Tulsa, OK, USA) was used. Results are given as mean values ± SD. In figures, results are given as mean values ± SEM. In the analyses the probability p<0.05 was regarded as significant.
Results

The results show that not only ventilator settings, but also suction methods involving different suction systems, catheter sizes as well as vacuum levels can have a large impact in terms of negative side-effects of endotracheal suction. A post-suction recruitment manoeuvre was found to be effective to reverse these negative side-effects.

Ventilator settings

From paper I, results show that in VCV, 1 minute after open suction, MPAP, and Pplat were increased. After 10 and 30 minutes, the variables had returned to baseline values except Pplat (Table 2).

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>1 min</th>
<th>10 min</th>
<th>30 min</th>
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<tr>
<td>MPAP mmHg</td>
<td>20 ± 1</td>
<td>22 ± 2*</td>
<td>21 ± 2</td>
<td>21 ± 2</td>
</tr>
<tr>
<td>SpO₂ %</td>
<td>98 ± 1</td>
<td>97 ± 2</td>
<td>98 ± 2</td>
<td>97 ± 2</td>
</tr>
<tr>
<td>ETCO₂ kPa</td>
<td>5.4 ± 0.3</td>
<td>5.3 ± 0.3</td>
<td>5.4 ± 0.4</td>
<td>5.3 ± 0.4</td>
</tr>
<tr>
<td>V₇ mL</td>
<td>389 ± 26</td>
<td>388 ± 24</td>
<td>391 ± 26</td>
<td>390 ± 29</td>
</tr>
<tr>
<td>Pplat cm H₂O</td>
<td>15 ± 2</td>
<td>19 ± 3*</td>
<td>19 ± 2*</td>
<td>19 ± 2*</td>
</tr>
</tbody>
</table>

Data are mean values ± SD. * Different from baseline, repeated measurement ANOVA, p<0.05.

In PCV, 1 minute after open suction, MPAP was increased, and V₇ was decreased. After 10 and 30 minutes, these changes were still significant, and in addition, ETCO₂ had increased (Table 3).
Table 3. Open suction, side-effects of endotracheal suction during PCV with 14 Fr suction catheter (n=8).

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>1 min</th>
<th>10 min</th>
<th>30 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPAP mmHg</td>
<td>19 ± 1</td>
<td>22 ± 3*</td>
<td>24 ± 4*</td>
<td>24 ± 4* †</td>
</tr>
<tr>
<td>SpO2 %</td>
<td>97 ± 1</td>
<td>90 ± 11</td>
<td>95 ± 3</td>
<td>95 ± 4</td>
</tr>
<tr>
<td>ETCO2 kPa</td>
<td>5.4 ± 0.3</td>
<td>6.1 ± 0.6</td>
<td>7.0 ± 1.2*</td>
<td>7.4 ± 1.6* †</td>
</tr>
<tr>
<td>VT mL</td>
<td>395 ± 28</td>
<td>291 ± 81*</td>
<td>291 ± 75*</td>
<td>290 ± 73*</td>
</tr>
<tr>
<td>Pplat cm H2O</td>
<td>17 ± 1</td>
<td>17 ± 1</td>
<td>17 ± 1</td>
<td>17 ± 1</td>
</tr>
</tbody>
</table>

Data are mean values ± SD. * Different from baseline, repeated measurement ANOVA, p<0.05. † Different from VCV, repeated measurement ANOVA, p<0.05.

Comparison of VCV and PCV 30 minutes after suction, shows that in PCV, MPAP and ETCO2 were significantly increased (Table 3). One minute after suction, a significant decrease of SvO2 was found in PCV (p<0.05) but not in VCV (Figure 2).

![Figure 2. SvO2 changes due to open endotracheal suction with 14 Fr suction catheter (n=8). Data are mean values ± SEM. * Different from baseline, repeated measurement ANOVA. • =volume controlled mode ▲ = pressure controlled mode.](image-url)
Compliance was significantly decreased one minute after open suction in both VCV and PCV, and this remained at 10 and 30 minutes in both VCV and PCV (p<0.05), but there was no significant difference between VCV and PCV (Figure 3).

Figure 3. Compliance changes due to open endotracheal suction with 14 Fr suction catheters (n=8). Data are mean values ± SEM. * Different from baseline, repeated measurement ANOVA. ● = volume controlled mode ▲ = pressure controlled mode.

One minute after open suction, a significant decrease of PaO₂ was found in VCV and PCV, and at 10 and 30 minutes in PCV. There was a significant difference between VCV and PCV after 30 minutes (Figure 4).
Figure 4. PaO₂ changes due to endotracheal suction with 14 Fr suction catheter (n=8). Data are mean values ± SEM. * Different from baseline, † PCV different from VCV, repeated measurement ANOVA. ● = volume controlled mode ▲ = pressure controlled mode.

One minute after open suction, a significant increase of venous admixture was found in VCV and PCV, and at 10 and 30 minutes in PCV. There was a significant difference between VCV and PCV after 30 minutes (Figure 5).

Figure 5. Venous admixture changes due to open endotracheal suction with 14 Fr suction catheter (n=8). Data are mean values ± SEM. * Different from baseline, †, different from VCV, repeated measurement ANOVA. ● = volume controlled mode ▲ = pressure controlled mode.
Suction systems and catheter sizes

In paper I, the results comparing 12 Fr OSS and CSS in PCV, no significant difference in hemodynamics and gas exchange measured 30 minutes after suction was found. Nor could any significant differences be found between 14 Fr OSS and CSS (Table 4). Comparison of the effects of OSS in PCV with 12 and 14 Fr catheters showed a significant difference when 14 Fr was used in terms of higher MPAP, Arterial carbon dioxide partial pressure (PaCO₂) and venous admixture and lower VT and Arterial oxygen partial pressure (PaO₂) after 30 minutes (Table 4).

Comparison of the effects of CSS in PCV with 12 and 14 Fr catheters showed that after 30 minutes PaO₂ was lower, PaCO₂ was higher, venous admixture was higher and VT was lower when catheter size 14 Fr was used (Table 4).
Table 4. Comparisons of open and closed system suction (OSS and CSS, respectively) with catheter size 12 and 14 Fr in PCV (n=4).

<table>
<thead>
<tr>
<th></th>
<th>OSS 12 Fr</th>
<th>CSS 12 Fr</th>
<th>OSS 14 Fr</th>
<th>CSS 14 Fr</th>
<th>Baseline</th>
<th>30 min</th>
<th>Baseline</th>
<th>30 min</th>
<th>Baseline</th>
<th>30 min</th>
<th>Baseline</th>
<th>30 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPAP mmHg</td>
<td>18 ± 2</td>
<td>18 ± 2</td>
<td>19 ± 4</td>
<td>19 ± 1</td>
<td>19 ± 1</td>
<td>24 ± 4*†</td>
<td>19 ± 1</td>
<td>24 ± 4*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PaO2 kPa</td>
<td>19 ± 2</td>
<td>18 ± 2</td>
<td>19 ± 2</td>
<td>18 ± 1</td>
<td>20 ± 1</td>
<td>15 ± 4*†</td>
<td>19 ± 1</td>
<td>14 ± 7*†</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PaCO2 kPa</td>
<td>4.8 ± 0.5</td>
<td>4.9 ± 0.6</td>
<td>4.9 ± 0.4</td>
<td>5.2 ± 0.8</td>
<td>4.8 ± 0.1</td>
<td>6.9 ± 1.3*†</td>
<td>4.9 ± 0.1</td>
<td>7.3 ± 1.7*†</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Venous admixture %</td>
<td>4 ± 2</td>
<td>6 ± 1</td>
<td>5 ± 1</td>
<td>5 ± 1</td>
<td>5 ± 2</td>
<td>13 ± 9*†</td>
<td>5 ± 2</td>
<td>17 ± 14*†</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crs mL/cmH2O</td>
<td>33 ± 6</td>
<td>30 ± 7</td>
<td>32 ± 8</td>
<td>29 ± 8</td>
<td>33 ± 3</td>
<td>24 ± 6*</td>
<td>33 ± 4</td>
<td>23 ± 5*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vt mL</td>
<td>418 ± 48</td>
<td>394 ± 49</td>
<td>410 ± 47</td>
<td>380 ± 53</td>
<td>395 ± 28</td>
<td>290 ± 73*†</td>
<td>406 ± 32</td>
<td>290 ± 84*†</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Data are mean values ± SD. * Different from baseline, repeated measurement ANOVA, p<0.05. † Different from 12 Fr, Mann-Whitney, p<0.05.
Tracheal pressure during suction

In paper II, it was found that with larger catheters, more negative pressure was produced in the trachea. Tracheal pressure during suctioning with 12 Fr catheter OSS was significantly lower (–11±1 cmH₂O) than CSS (–5±1 cmH₂O). When 14 Fr catheters were used, tracheal pressure was as low as –52±27 cmH₂O with OSS, and –70±32 cmH₂O with CSS. There was no significant difference between OSS and CSS 14 Fr. Examples of pressure tracings for both catheter sizes and systems are shown in Figure 6.

![Figure 6](image-url)

Figure 6. Examples of pressure tracings from the same animal a) 12 Fr and b) 14 Fr systems, note different scales. Dotted line open system, solid line closed system.

During suction with CSS, a PEEP was induced during volume-controlled ventilation. During insertion of the catheter in the ET tube, the pressure had increased after 5 s and continued increasing after 10 s (Table 5, Figure 7). When respiratory rate was set higher, the PEEP increased with higher rate.
Table 5. Comparisons of tracheal pressure during insertion of 12 Fr closed suction system at different respiratory rates during volume controlled ventilation

<table>
<thead>
<tr>
<th>Respiratory Rate breaths min⁻¹</th>
<th>Change in tracheal pressure, cmH₂O 5 s</th>
<th>10 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.3 ± 0.4</td>
<td>2.6 ± 0.7*</td>
</tr>
<tr>
<td>15</td>
<td>3.1 ± 0.8†</td>
<td>6.3 ± 1.5*†</td>
</tr>
<tr>
<td>20</td>
<td>4.4 ± 1.1‡</td>
<td>8.7 ± 2.1*‡</td>
</tr>
<tr>
<td>25</td>
<td>5.3 ± 0.8</td>
<td>10.2 ± 1.8*</td>
</tr>
</tbody>
</table>

* Different from 5 seconds, † different from respiratory rate 10, ‡ different from respiratory rate 20, p<0.05 repeated measurement ANOVA.

Figure 7. Tracheal pressure during insertion of closed suction system. Example from one animal.

Suction flow

Peak flow at the tip of the suction catheter size 14 Fr was 40% higher and the steady flow was 16% higher than with catheter size 12 Fr at a suction pressure of −15 kPa. The corresponding values for −20 kPa are 78% and 40% (see Table 6).
Table 6. The flow rate at the tip of the catheter Fr 12 and Fr 14 in the bench test.

<table>
<thead>
<tr>
<th>Suction pressure –15 kPa</th>
<th></th>
<th>Suction pressure –20 kPa</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Catheter size Fr 12 Fr 14</td>
<td>Fr 12 Fr 14 Fr 12 Fr 14</td>
<td>Fr 12 Fr 14 Fr 12 Fr 14</td>
<td>Fr 12 Fr 14 Fr 12 Fr 14</td>
</tr>
<tr>
<td>Suction pressure –15 kPa</td>
<td>Peak Plateau Peak Plateau</td>
<td>Peak Plateau Peak Plateau</td>
<td>Peak Plateau Peak Plateau</td>
</tr>
<tr>
<td>Flow rate L·min⁻¹</td>
<td>16 ± 1 7 ± 0 22 ± 1 8 ± 0</td>
<td>17 ± 1 8 ± 0 30 ± 3 11 ± 1</td>
<td></td>
</tr>
</tbody>
</table>

Suction efficacy

In paper III, the results show that open system suctioning was significantly more efficient than closed system suctioning with 12 Fr catheter in VCV, PCV and CPAP +10 cm H₂O with regards to mucus removal. In contrast, the efficacy of closed system suctioning at CPAP 0 cm H₂O was similar to that of open system suctioning. With CSS at CPAP +10 cmH₂O, suction at vacuum level –20 kPa was compared to –40 kPa, and the greater suction level did not increase mucus removal (Figure 8).

Figure 8. Suction efficacy quantified as weight difference of the suctioning system before and after suctioning. Suction with open and closed systems, catheter sizes 12 and 14 Fr, during different ventilation modes were compared. Data are mean values ± SEM. * Different from 12 Fr catheter. † Different from CPAP +10 cmH₂O.
Limiting side-effects

In paper IV, it was found that a recruitment manoeuvre after suction reversed physiological changes due to suction in both volume-controlled and pressure-controlled ventilation, $V_T$ setting of 14 mL kg$^{-1}$. No side-effects were observed in MAP, CO, HR or CVP (see Table 7).

Table 7. Effects of recruitment manoeuvre after endotracheal suctioning in volume-controlled (VCV) and pressure-controlled ventilation (PCV), n=5.

<table>
<thead>
<tr>
<th></th>
<th>VCV</th>
<th>PCV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>1 min after</td>
</tr>
<tr>
<td>MPAP mmHg</td>
<td>20 ± 2</td>
<td>25 ± 3*</td>
</tr>
<tr>
<td>PaO$_2$ kPa</td>
<td>20 ± 1</td>
<td>16 ± 5</td>
</tr>
<tr>
<td>PaCO$_2$ kPa</td>
<td>5.0 ± 0.2</td>
<td>4.9 ± 0.2</td>
</tr>
<tr>
<td>Venous admixture</td>
<td>6 ± 3</td>
<td>5 ± 1</td>
</tr>
<tr>
<td>Crs mL/cmH$_2$O</td>
<td>34 ± 6</td>
<td>38 ± 6*</td>
</tr>
<tr>
<td>$V_T$ mL</td>
<td>392 ± 24</td>
<td>393 ± 25</td>
</tr>
<tr>
<td>Pplat cm H$_2$O</td>
<td>15 ± 1</td>
<td>15 ± 4</td>
</tr>
<tr>
<td>MAP mmHg</td>
<td>84 ± 14</td>
<td>82 ± 18</td>
</tr>
<tr>
<td>CO L/min</td>
<td>3.2 ± 0.8</td>
<td>3.0 ± 1.1</td>
</tr>
<tr>
<td>HR min$^{-1}$</td>
<td>99 ± 20</td>
<td>99 ± 20</td>
</tr>
<tr>
<td>CVP mmHg</td>
<td>10 ± 2</td>
<td>10 ± 2</td>
</tr>
</tbody>
</table>

Data are mean values ± SD. * Different from baseline, repeated measurement ANOVA, $p<0.05$.

A recruitment manoeuvre after suction also reversed the physiological changes due to suction in both volume-controlled and pressure-controlled ventilation, at a $V_T$ setting of 10 mL kg$^{-1}$.

As shown in Figure 9, the compliance correlated positively with PaO$_2$ in PCV, $V_T$ setting 10 and 14 mL kg$^{-1}$ ($r=0.77$) but the correlation was absent in VCV ($r=0.46$).

In paper V, it was found that with PS-RM after open suction, HR decreased after 60 minutes. Without PS-RM after open suction, Crs and $V_T$ were decreased, and ETCO$_2$ increased after 10 minutes. After 30 minutes, HR, Crs, $V_T$ were decreased, and ETCO$_2$ was increased. After 60 minutes, HR, Crs, $V_T$ were decreased and ETCO$_2$ was increased (Table 8).

Comparing the effect of endotracheal suction directly followed by a PS-RM or not, showed a significant lower Crs and $V_T$ and higher ETCO$_2$ in the suction without PS-RM protocol compared to the suction with PS-RM protocol at 60 minutes.
Figure 9. Correlation between compliance and PaO2 in pressure-controlled (PCV) and volume-controlled (VCV) mode (n=5). Each animal is represented by a symbol and the lines indicate correlation for each animal.
Table 8. Open endotracheal suction with and without Post-suction recruitment manoeuvre (PS-RM) in pressure-controlled mode. Results are from before suction, 10, 30 and 60 minutes after suction. Note the increase in ETCO₂, the decrease in compliance and VT when a PS-RM is not given after suction.

<table>
<thead>
<tr>
<th></th>
<th>Endotracheal suction with PS-RM (n=6)</th>
<th>Endotracheal suction without PS-RM (n=6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before suction</td>
<td>10 min</td>
</tr>
<tr>
<td>MPAP, mmHg</td>
<td>20 ± 3</td>
<td>20 ± 3</td>
</tr>
<tr>
<td>PaO₂, kPa</td>
<td>22 ± 1</td>
<td>21 ± 2</td>
</tr>
<tr>
<td>ETCO₂, kPa</td>
<td>5.1 ± 0.4</td>
<td>5.1 ± 0.3</td>
</tr>
<tr>
<td>Crs, mL/cmH₂O</td>
<td>27 ± 3</td>
<td>27 ± 3</td>
</tr>
<tr>
<td>VT, mL</td>
<td>343 ± 31</td>
<td>343 ± 43</td>
</tr>
<tr>
<td>MAP, mmHg</td>
<td>81 ± 10</td>
<td>80 ± 9</td>
</tr>
<tr>
<td>CO</td>
<td>2.6 ± 0.8</td>
<td>2.7 ± 0.7</td>
</tr>
<tr>
<td>HR</td>
<td>91 ± 17</td>
<td>91 ± 15</td>
</tr>
</tbody>
</table>

Data are mean values ± SD. * Different from before suction, *p<0.05 **p<0.001. † Different from with PS-RM p<0.05, repeated measurement ANOVA.
Hourly open suction, without PS-RM resulted in significant differences compared to open suction with PS-RM 60 minutes after each suction in $V_T$, (Figure 10) Crs (Figure 11), and ETCO$_2$ (Figure 12).

Figure 10. Hourly open suction in PCV, ▲=with and ●=without PS-RM resulted in significant differences in $V_T$, 60 minutes after each suction. Arrows indicating suction.

Figure 11. Hourly open suction in PCV, ▲=with and ●=without PS-RM resulted in significant differences in compliance, 60 minutes after each suction. Arrows indicating suction.
Figure 12. Hourly open suction in PCV, ▲=with and ▼=without PS-RM resulted in significant differences in ETCO₂, 60 minutes after each suction. Arrows indicating suction.

In paper V, the results show that when PS-RM was added 1 minute after open suction, there was a significant decrease of $V_T$ and $Crs$, and EELV (Figure 13) before PS-RM, but no significant difference after PS-RM compared to before suction. When PS-RM was added 30 minute after open suction, there was a significant decrease of $V_T$ and $Crs$ before PS-RM, but no significant difference was found after PS-RM compared to before suction. When PS-RM was added 120 minute after open suction there was a significant decrease of $V_T$, $Crs$ and EELV before PS-RM, and $Crs$ was still significantly decreased after the first PS-RM compared to before suction. When PS-RM was added additionally 30 minute after open suction, there was a significant decrease of $V_T$, $Crs$ and EELV before PS-RM, and EELV was still significantly decreased after the first PS-RM compared to before suction (Table 9).
Table 9. Post-suction recruitment manoeuvre (PS-RM) applied 1, 30, 120 and additionally 30 minutes after suction. Results are from before suction, before PS-RM (after suction) and directly after the first PS-RM.

<table>
<thead>
<tr>
<th></th>
<th>1 minute (n=5)</th>
<th>30 minutes (n=6)</th>
<th>120 minutes (n=6)</th>
<th>Additional 30 minutes (n=6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VT mL</td>
<td>354 ± 52</td>
<td>310 ± 62*</td>
<td>354 ± 52</td>
<td>354 ± 65</td>
</tr>
<tr>
<td>Crs mL cm H2O</td>
<td>29 ± 5</td>
<td>23 ± 4*</td>
<td>28 ± 5</td>
<td>23 ± 4*</td>
</tr>
<tr>
<td>EELV mL</td>
<td>617 ± 104</td>
<td>511 ± 190*</td>
<td>579 ± 57</td>
<td>517 ± 75</td>
</tr>
</tbody>
</table>

Data are mean values ± SD. * Different from before suction, repeated measurement ANOVA, p<0.05.
Figure 13. End Expiratory Lung Volume after open suction in PCV. Post-suction recruitment manoeuvre has been added one minute after suction, by an increase in airway pressure to 15 cm H₂O above inspiratory pressure by using the inspiratory hold key on the ventilator. Data are mean values ± SEM.

There was no significant difference between mean pressure levels used for the recruitment in order to return to baseline $V_t$, Crs and EELV. Pressures were; in the 1 minute period 16±4 cmH₂O, in the 30 minute period 19±4 cmH₂O, in the 120 minute period 22±5 cmH₂O and in the additional 30 minute period 20±3 cmH₂O. Repeated recruitment manoeuvres were needed two times in both 30 minute periods and up to four times in the 120 minute period.
Discussion

Endotracheal suction causes impairments in lung function such as desaturation, compliance decrease and CO₂ increase due to lung volume loss. The severity of these negative changes, as well as the efficacy of mucus removal are related to ventilator settings, but also to suction methods: suction systems, catheter sizes, and vacuum levels. Adding a post-suction recruitment manoeuvre the lung function can be restored, and it is beneficial to apply this manoeuvre as soon as possible after suction. During artificial ventilation, it is important to prevent lung volume loss and thus minimize the risk of ventilator-induced lung injury. The results from the present study show the importance of including strategies for endotracheal suction into lung protective ventilation.

Suction methods

During endotracheal suction, tracheal pressure variations are dependent on factors such as suction system, catheter size, catheter insertion time, vacuum level and respiratory rate. Closed suction systems have been found to prevent lung collapse during VCV in patients with acute lung injury (18). The results from paper II shows that the negative pressure created during suction contributed to lung volume loss and gas exchange impairment that remained long after completed suction. During PCV, suction with 14 Fr catheters in an ET tube, 6.0 mm i.d. caused severe side-effects irrespective of whether CSS or OSS was used.

When CSS is used, the ventilator can deliver breaths even though the suction catheter has been inserted into the endotracheal tube, provided that the catheter is narrow enough, leaving enough flow path for ventilator gas. This illustrates how important it is to choose a catheter of the correct size, one that will allow the ventilator to continue ventilation and maintain PEEP when CSS is used. Maintained PEEP could explain why less desaturation was found in patients with PEEP settings > 8 cm H₂O when CSS was used (16). It is always a risk that presence of mucus can reduce the ET tube lumen when CSS is used (9).
In the present studies, more severe side-effects were found when 14 Fr catheters were used compared to 12 Fr regardless of whether OSS or CSS was used. However, if smaller catheters are used, this might necessitate frequently repeated ET suctions, if not all mucus is removed. Depending on the patients, it might either be better to remove as much mucus as possible to avoid repeated suction procedures, or reduce negative pressure by using smaller suction catheters.

Suction in the ET tube causes negative pressures within the lung that can contribute to lung volume loss and gas exchange impairment. Paper II shows that when a catheter with a smaller lumen was used, the negative pressures were less extreme. Furthermore, suction flow is increased by larger suction catheters (Table 6). In view of the recommendation not to use a catheter larger than half the size of the ET tube i.d. it is clearly difficult to select the right size of catheter if the ET tube is narrowed by mucus. Glass et al. showed that mucus might collect in the ET tube, especially when CSS is used (9), and the ET tube narrowing is common already after 24 hours (10). With mucus narrowing the ET tube, also smaller catheters can be harmful. Application of vacuum under such circumstances might cause large negative pressure and the negative pressure created in the trachea might be one of the explanations for the difference in side-effects between suction catheters of different sizes.

It has been shown that less desaturation occurs when CSS is used during VCV (18). But an increase in PEEPi can potentially be achieved, and the lung pressure is built up in the lung during insertion of the suction catheter (Figure 7). The explanation for the milder desaturation might be the production of PEEPi, with the resulting extension of the lung before suction. However, when suction is applied the PEEPi will be removed. In contrast, if a large catheter CSS is used, the negative side-effects are the same as with open system. Furthermore, if suction is stopped before withdrawing of the catheter as in the study from Cereda et al. (18), there is again a risk of PEEPi. The authors excluded PEEPi development, since there was no increase of lung volume during the procedure. The clinical recommendation is to maintain suction while withdrawing the catheter from the ET tube (12). Cereda et al. do not state why this nonstandard procedure was used in their study (18), but it seems not to be clinically applicable, since the purpose of suction is to remove mucus from the ET tube.

In papers I-V, suction has been applied during 10 seconds according to guidelines (12,37). In other studies, different suction periods have been used, 5 seconds (24), 10 seconds (17), 10-15 seconds (11) and 20 seconds (18). Results in paper III show that SpO₂ and compliance did not differ between suction time 5, 10 and 20 seconds. In contrast, paper II shows that insertion
time of CSS during VCV is important, because of the risk of PEEPi. Furthermore, suction has been done once (paper I-V), the same as in (11,17,18). In (23,24) suction was done three times. In the recommendations, nothing is stated about repetition of suction, and that might be because this is dependent on whether the removal of mucus was successful or not. In clinical practice, breathing sounds are used to verify that all mucus has been removed. There are no available methods to evaluate the need for and success of suction, but one recent study has measured intraluminal ET tube diameter after the removal of the ET tube (10). There is a clinical need of evaluation methods before and after ET suction.

Suction efficacy

The main objective for endotracheal suctioning is to remove mucus. The rationale for using closed suctioning technique was originally to limit bacterial contamination and ventilator-associated pneumonia (13-15). Maggiore et al. recently evaluated the influence of different suctioning techniques on lung volume and respiratory mechanics (30). They conclude that open suctioning is more harmful in terms of lung recruitment in ARDS patients. However, suctioning efficacy was not assessed in that study. In paper III, open suction techniques were efficient in terms of removal of secretions in the bench tests, whereas closed system suctioning during positive pressure ventilation or CPAP was ineffective. One reason is that during closed system suctioning with positive pressure ventilation, including CPAP, mucus is pushed away from the tip of the suctioning catheter during inspiration. Furthermore, when gas is aspirated from the lung during open suctioning, this gas flow will facilitate movement of secretions towards the suctioning catheter. Therefore, when CPAP was set to 0 cm H\textsubscript{2}O, CSS was effective. Increase of vacuum level from −20 to −40 kPa with 12 Fr and 14 Fr closed suction system at CPAP +10 cmH\textsubscript{2}O, did not improve mucus removal (Figure 8). Suction flow was increased both by larger catheters and by increase of vacuum when open suction systems were measured. The largest increase was found when vacuum was increased with 14 Fr catheters (Table 6). Increase of vacuum level improves mucus removal with open suction system, but not with closed suction system if ventilation is ongoing during suction.

Ventilator settings

Both VCV and PCV are ventilation modes that are commonly used (2). Different ventilation modes have been used in studies of endotracheal suction, but no previous study compares the different side-effects on
hemodynamics and gas exchange. Volume-controlled ventilation is a commonly used ventilation mode in other studies of endotracheal suction (11,17,18) and this probably reflects that VCV is common use in clinical practice.

In paper I, results showed that gas exchange and lung mechanics were more negatively affected by open endotracheal suction in PCV than in VCV. One minute after suction, decreased oxygenation was found in both VCV (increased MPAP and venous admixture and decreased PaO$_2$) and PCV (increased MPAP and venous admixture, decreased PaO$_2$ and SvO$_2$), although most pronounced in PCV. The changes remained in PCV after 10 minutes, but were reversed in VCV. The observation of desaturation is also known from other studies (18,23,24). The desaturation is one reason for the use of preoxygenation before and after suction. Also lung volume loss was observed in both VCV (decreased Crs and increased Pplat) and PCV (decreased Crs and V$_T$) already one minute after suction. Most of the negative effects of suction remained after 30 minutes in PCV, but this was different from VCV (Figure 3). One possible explanation is that in VCV, where the volume of each breath is the same, there is a small recruitment with each successive breath because of the increase of inspiratory pressure to maintain V$_T$. However, in VCV, the changes in both compliance and plateau pressure remained 30 minutes after suction, and this may indicate partial lung collapse. Given that tidal volume was not changed, pulmonary collapse might lead to over-distention of those parts of the lung that remained open. In PCV we found a positive correlation between compliance and PaO$_2$. This indicates that compliance could be one evaluation method in PCV. But in VCV there was no such correlation. This might be explained by different ventilation–perfusion relationships of the lung (V$_A$/Q) in the different ventilation modes. This can be compared to a decrease in Crs that was found in a study comparing different PEEP-levels in PCV and VCV (48). The Crs decrease was higher in PCV at PEEP 5 cmH$_2$O, than in VCV. The conclusion was that the Crs decay was due to lung collapse.

**Limiting side-effects**

In paper IV, it was found that the recruitment manoeuvre restored lung mechanics and reversed gas exchange impairment induced by suction in volume- and pressure-controlled ventilation. Manual hyperinflations sometimes are recommended before and after endotracheal suction together with preoxygenation to prevent adverse side-effects (49). How hyperinflations (or recruitment manoeuvres) can be used in relation to the suction procedure is unclear, especially at different ventilator settings. Lung volume could be regained after open ET suction by a recruitment manoeuvre
in ARDS patients (24). In that study both pressure-controlled and volume-controlled ventilation were used without any comparisons. A pressure of 45 cmH2O was applied twice during 20 seconds to recruit the lung. We included a recruitment manoeuvre involving an increase of airway pressure to 15 cm H2O above plateau pressure directly after suction, without hyperoxygenation during different ventilation modes and different Vt settings. The animals were healthy, and we could reverse the side-effects. In the literature, recruitment of the lung generally refers to a diseased lung that has collapsed gradually over time. By allowing the ventilator to trigger a pressure supported breath, lung volume loss can be avoided in volume-controlled ventilation, but the effectiveness of suction was never evaluated (30). Since the pressure-supported breath will create a positive pressure against the negative suction-pressure, it will probably result in very little negative pressure and therefore little suction effect.

When a positive pressure is added after aspiration, the lung volume can be regained. How this positive pressure postsuction recruitment manoeuvre should be given is not clear. We showed that an increase of 15 cm H2O above plateau pressure for 10 s was enough to reverse the venous admixture and restore compliance in the lungs of healthy pigs. But different pressures might be necessary, as Dyhr et al. showed (24). It might be easier to reopen the lung directly after endotracheal suction than it is to open a diseased lung that has collapsed over a longer period of time. This can be compared to the re-expansion of atelectasis during anaesthesia, where a shorter recruitment time is needed (42). The hemodynamics was not affected during or after the recruitment (Table 7), which also has been shown in other studies (24,50). In other conditions the hemodynamic effects have to be considered (45). Furthermore, Grasso et al. showed a 20-30% reduction of MAP and cardiac output in patients with acute respiratory distress syndrome, who did not respond to the recruitment manoeuvre (41).

During suction with open suction system, the oxygen supply from the ventilator is interrupted during the disconnection period, and if the patient requires supplementary oxygen, this can be a problem. The interruption of oxygen can be avoided by using a closed suction system. Another solution is to compensate for the loss by using hyper-oxygenation before and after endotracheal suction. However, studies have shown that pure oxygen can produce reabsorption atelectasis in the lung during anesthesia (42). Sometimes, there is a need to use preoxygenation, but the amount of oxygen needs to be evaluated for each patient, so that high levels are avoided. If a lung collapses due to suction and causes desaturation, the lung can be recruited instead of using supplementary oxygen.
In paper V, repeated endotracheal suction once per hour combined with a post-suction recruitment manoeuvre was compared to suction without the post-suction manoeuvre. It was possible to open up the lungs as shown by restored VT and Crs during the first three hours in the recruitment group, but in the fourth hour, a tendency to a decrease in VT and Crs was seen, although we had added a post-suction recruitment manoeuvre. One explanation might be that not enough recruitment pressure was applied. We repeated the same recruitment pressure level all four times, and this shows the importance of evaluation and adjustment of recruitment pressure. Another explanation might be that there is an ongoing lung collapse over time during mechanical ventilation, seen as a tendency to a decrease in compliance (48). When we recruited the lungs, the recruitment was standardized by a set level of recruitment pressure, and the results might have been different if pressure level adjustment had been done. Comparison of these results to those obtained when suction was repeated during four hours without recruitment, showed that most of the changes occurred during the first hour, and continued the following hours. When patients are treated with lung protective ventilation, recruitment manoeuvres are used to open up the lung. The rationale is to keep the lung open in order to avoid repetitive collapse – reopening. These patients are probably more sensitive to suction, and it seems obvious that the lung should be reopened by a post-suction recruitment.

A post-suction recruitment manoeuvre applied at different times after suction was also investigated in paper V. The goal was to repeat the recruitment until VT, Crs and EELV returned to the same values as before suction. The results showed that when recruitment was given directly after suction, the first PS-RM reversed side-effects. If the PS-RM was delayed and the lung was kept collapsed 120 minutes after suction, all side-effects could not be reversed by the first PS-RM, and up to four repeated recruitment manoeuvres were needed. If the recruitment was delayed 30 minutes, side-effects could be reversed. In contrast, if a collapse period of 30 minutes (the additional protocol) was repeated after the 120 minutes period, also this recruitment became more difficult. The amount of total lung tissue that is possible to recruit varies between patients, and this has been shown in both experimental and clinical studies (51,52). If lung volume is lost during endotracheal suction, that lost lung volume is possible to regain if the recruitment manoeuvre is done directly after suction.

Endotracheal suction is probably one of the most common procedures that can cause lung collapse during mechanical ventilation. The loss of lung volume primarily occurs during disconnection of the ventilator (23). But disconnection is also required during other procedures, such as nebulization, transportation and changes of ventilator or tubings. Therefore a general
understanding of the problem and methods to evaluate lung volume are needed. Our results show the importance of a prompt reopening after suction and also the need of individualization. When a quick reopening after suction is done, repeated recruitments can be avoided.

Study limitations

In this study, the pigs were healthy and this might be a limitation since most of the patients that are mechanically ventilated are not healthy. The PEEP settings of only 3 cmH₂O were used, because this was a healthy lung model. The results might have been different if a higher PEEP had been used, since higher PEEP has been shown to prevent loss of compliance in patients with ARDS (40).
Clinical implications

Even in healthy, mechanically ventilated animals, endotracheal suction causes large negative effects on gas exchange due to lung volume loss.

If a large suction catheter e.g. 14 Fr is used in an ET tube 6 mm i.d. or if mucus is narrowing the ET tube a large negative pressure might be created in trachea.

If suction is repeated hour by hour, these negative effects are worsened for each repetition.

The lung will not restore by itself, a reopening by a recruitment manoeuvre is needed.

It is obvious that the recruitment manoeuvre should be added directly after suction, because if the manoeuvre is delayed and the lung is collapsed and left collapsed, it will be more difficult to recruit the lung. Higher pressures might be needed, that can become harmful for the lung and also affect hemodynamics.
Conclusions

- Open suction systems are more effective to remove mucus compared to closed suction system during VCV, PCV and CPAP 10 cm H₂O. The efficacy of closed suction system is similar to open system at CPAP 0 cm H₂O. Suction catheter 14 Fr is more effective of mucus removal, but there is no difference between open or closed suction systems.

- In healthy animals, open endotracheal suction causes more severe gas exchange changes in pressure-controlled mode than in volume-controlled mode, without severe hemodynamic side-effects.

- Negative side-effects after open suction can be avoided by a post-suction recruitment manoeuvre in both pressure-controlled and volume-controlled mode in healthy animals.

- The post-suction recruitment manoeuvre should be applied directly after suction.

- In pressure-controlled mode, suction with catheter 14 Fr causes more severe side-effects compared to 12 Fr both with open and closed suction system, without severe hemodynamic side-effects.

- In pressure-controlled mode, suction with 12 Fr open system creates more negative tracheal pressure than with 12 Fr closed system. Suction with 14 Fr catheters creates very low tracheal pressure for both open and closed systems, but there is no difference between the systems.
Vid mekanisk ventilation är patienten ansluten till ventilatorn via en tub i trachea. Tuben behöver rengöras från sekret med sugning, vilket i sin tur kan orsaka negativa effekter såsom lungkollaps, syrebrist och försämrad syresättning. Dessa sidoeffekter kan undvikas genom att öka syrgastillförseln, förändrade ventilatorinställningar, använda slutna sugsystem och blåsa upp lungan med rekryteringsmanövrar. Syftet med denna studie var att undersöka effekten av sugning vid olika ventilatorinställningar och med olika metoder för sugning. En metod att återställa negativa effekter undersöktes.

Effekt av sugning undersöktes på sövda grisar vid volym och tryckkontrollerad ventilation och effekten av olika katetersystem och storlekar jämfördes. Effektivitet av sugning utvärderades i en bänkstudie. Effekten av en rekryteringsmanöver given efter sugning utvärderades.

Rensugning av luftvägarna orsakade minskning av lungvolymen som i sin tur ledde till störningar i gasutbytet, mer uttalat i tryckkontrollerad ventilation än i volymskontrollerad ventilation. När 14 French sugkateter användes, uppstod mer sidoeffekter jämfört med 12 French sugkateter, men det fanns ingen skillnad mellan öppet och slutet system i tryckkontrollerad ventilation. Öppet sugsystem var mera effektivt att suga bort sekret jämfört med slutet system. Rekryteringsmanövern återställde sidoeffekter efter den första rekryteringen när den utfördes direkt efter sugning.

Sammanfattningsvis, öppen sugning orsakar störningar i gasutbyte och lungmekanik, mer uttalat i tryckkontrollerad än volymskontrollerad ventilationsmod. Dessa förändringar kan minskas om tunnare sugkatetrar används. En rekryteringsmanöver utförd direkt efter sugning återställer lungfunktionen. Det är uppenbart att rekryteringsmanövern skall utföras direkt efter sugningen, för om rekryteringen görs senare och lungan får vara sammanfallen blir det svårare att öppna upp lungan igen.
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