

OPEN AND CLOSED ENDOTRACHEAL SUCTIONING

Experimental and human studies

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Göteborg 2007

Printed by Intellecta Docusys AB
Göteborg, Sweden, 2007
ISBN 978-91-628-7115-4

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*Till mina föräldrar
Per och Margareta;
farfar*

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Abstract

Background: The practice of endotracheal suctioning of ventilator treated patients is necessary to remove secretions to prevent obstruction of the endotracheal-tracheal tube and lower airways. This very common procedure creates a large variety of heart-lung interferences. The closed system enables ventilation during suctioning, avoiding disconnection from the ventilator. Thus, the lesser side-effects of the closed suction system have been thoroughly evaluated rather than its effectiveness of secretion removal. Qualitative and semi-quantitative studies have indicated that the effectiveness of the closed system is inferior to the open one. Optimising the side-effects and effectiveness of the suction procedure is essential to preserve oxygenation in critically ill patients. This also requires adequate monitoring techniques. Suctioning through a fiberoptic bronchoscope (FOB) via a tight seal connector is another form of closed suctioning. The aim of this thesis was to evaluate the effectiveness and side-effects of open and closed suctioning manoeuvres, using novel lung-monitoring techniques.

Methods: Studies were performed in mechanical lung models, an experimental model of acute lung injury (ALI) in pigs and in ALI patients. Effectiveness of secretion removal was evaluated by weighing the suction system before and after suctioning of gel in a transparent trachea. In ALI model and patients, airway pressure and lung mechanics were measured via a tracheal catheter. A modified N₂ wash-out/wash-in method was used for functional residual capacity (FRC) measurements. Electric impedance tomography (EIT) was used to monitor global and regional lung volume changes during different suction manoeuvres.

Results: In a mechanical lung, closed suction during volume control ventilation caused high intrinsic PEEP levels at insertion of the catheter. Pressure control ventilation (PCV) produced less intrinsic PEEP. The continuous positive airway pressure (CPAP) mode offered the least intrinsic PEEP during insertion of the catheter and least sub-atmospheric pressure during suctioning. Open suctioning and closed suctioning during CPAP of 0 cmH₂O was about five times more effective in regaining gel from an artificial trachea than closed suctioning during PCV or CPAP of 10 cmH₂O. In lavaged lungs side-effects were considerable less during closed suction with positive pressure ventilation than during open suction. Closed system suctioning during CPAP of 0 cmH₂O caused side-effects similar to open suctioning. At disconnection FRC decreased with about 50 % of baseline value and further 20 % during open suctioning. Regional compliance deteriorated most in the dorsal parts of the lavaged lung. Post-suction restitution of lung volume and compliance was somewhat slower during pressure controlled - than during volume controlled ventilation, both in experimental lung injury and in some ALI patients. Bronchoscopic suction through a tight seal connector in a mechanical lung and in ventilator treated ALI patients caused marked lung volume reduction, especially if the endotracheal tube was too small in relation to the thickness of the bronchoscope.

Conclusions: New monitoring strategies such as continuous, bedside FRC measurements with EIT technique and the nitrogen washout/washin method could contribute to a better understanding of the suctioning induced lung collapse and give us knowledge on how to minimize its negative effects, hence develop better clinical routines for handling them. The largest loss of lung volume takes place already at disconnection of the ventilator prior to suctioning. The dorsal regions of lavaged lungs are most affected by disconnection and suctioning. Closed system suctioning prevents lung collapse but is less efficient in removing secretions. Volume control ventilation in the post-suctioning period is a way of recruiting collapsed lung tissue. Bronchoscopic suctioning can cause severe lung collapse, although considered a closed system.

Key words: Suctioning, endotracheal, closed system suctioning, monitoring, lung volume, airway pressure, lung recruitment, bronchoalveolar lavage, acute lung injury

ISBN 978-91-628-7115-4

Göteborg 2007

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ABBREVIATIONS AND SYMBOLS

∅	diameter
⊙	inner cross sectional area
●	outer cross sectional area
ANOVA	analysis of variance
ΔEELV	end-expiratory lung volume change
ΔF	change in fraction
ΔPtrach	difference between end-inspiratory and expiratory tracheal pressure
ΔZ	impedance change
ΔZ _{GLOB}	global impedance change
ΔZ _{ROI}	regional impedance change
ALI	acute lung injury
ARDS	acute respiratory distress syndrome
ARF	acute respiratory failure
BAL	bronchoalveolar lavage
Ch	Cherrier
CPAP	continuous positive airway pressure
Crs	compliance of the respiratory system
CSS	closed system suctioning
CT	computed tomography
CVP	central venous pressure
FOB	fiberoptic bronchoscope/bronchoscopy
EELV	end-expiratory lung volume
EIT	electric impedance tomography
ETT	endotracheal tube
FiO ₂	inspiratory fraction of oxygen
F _{N2}	fraction of nitrogen
Fr	French
FRC	functional residual capacity
HR	heart rate
I:E	inspiratory-to-expiratory ratio
ICU	intensive care unit
ID	inner diameter
MAP	mean arterial pressure
MPAP	mean pulmonary arterial pressure
N ₂	nitrogen
OD	outer diameter
OSS	open system suctioning
PaCO ₂	arterial carbon dioxide tension
PaO ₂	arterial oxygen tension
PCV	pressure controlled ventilation
PRVC	pressure regulated volume controlled ventilation
PEEP	positive end expiratory pressure
PEEPi	intrinsic PEEP
Ptrach	tracheal pressure
Ppeak	peak tracheal pressure
Pexp	end-expiratory tracheal pressure
ROI	region of interest
RR	respiratory rate
SaO ₂	arterial oxygen saturation
SD	standard deviation
SpO ₂	arterial oxygen saturation by pulse-oximetry
SvO ₂	mixed venous oxygen saturation
VAP	ventilator associated pneumonia
VCV	volume controlled ventilation
VILI	ventilator induced lung injury
Vt	tidal volume

LIST OF PUBLICATIONS

This thesis is based on the following papers, which will be referred to in the text by their Roman numerals. The papers are appended at the end of the thesis.

- I** **Warning! Suctioning. A lung model evaluation of closed suctioning systems.**
Stenqvist O, Lindgren S, Karason S, Sondergaard S, Lundin S
Acta Anaesthesiol Scand 2001 45:167-172
- II** **Effectiveness and side effects of closed and open suctioning: an experimental evaluation.**
Lindgren S, Almgren B, Hogman M, Lethvall S, Houltz E, Lundin S, Stenqvist O
Intensive Care Med 2004 30:1630-1637
- III** **Regional lung derecruitment after endotracheal suction during volume- or pressure-controlled ventilation: a study using electric impedance tomography**
Lindgren S, Odenstedt H, Olegård C, Söndergaard S, Lundin S, Stenqvist O
Intensive Care Med 2007 33:172-180
- IV** **Bronchoscopic suctioning may cause lung collapse: A lung model and clinical evaluation**
Lindgren S, Odenstedt H., Erlandsson K, Grivans C, Lundin S, Stenqvist O
Manuscript

*“As with electric hand-dryers public acceptance
does not always mean demonstrable efficacy”*

INTRODUCTION

HISTORICAL BACKGROUND

The birth of long-term artificial ventilation took place in the beginning of the 20th century when the whole body negative pressure respirator known as the “iron lung” was developed at Harvard Medical School by Philip Drinker and the smaller “cuirass respirator” generating negative pressure in a corset placed around the chest also came into use. At about the same time, development of thoracic “open chest” surgery and longer surgical procedures created the need for manual and mechanical positive pressure ventilation in the operating theatre, but the negative pressure ventilation dominated long-term ventilation treatment during the first half of the 20th century. It was not until the 1950’s during the polio epidemic in Copenhagen that positive pressure ventilation became an obvious requirement for long-term ventilator treatment as the negative pressure respirators were too few and also insufficient to prevent carbon dioxide accumulation and acidosis, resulting in mortality rates of up to 90% [1, 2]. Other events during the first half of the 20th century, such as longer and more complicated surgical procedures and an increasing number of barbiturate self-poisoning, led to the development of artificial airways. The technique to perform a tracheostomy and a tracheal intubation was well known amongst surgeons and anaesthesiologists in Scandinavia in the 1950’s [3]. With the use of artificial airways and long term positive pressure ventilator treatment came the possibility and need of clearing the patients’ lower airways from accumulating secretions - endotracheal suctioning.

The Copenhagen poliomyelitis epidemic in 1952 was the most severe since the first cases diagnosed in Denmark 1905 and probably one of the worst in Europe of all times. During one week in late August, Blegdams hospital, which was the polio-centre for the Copenhagen area, admitted 335 patients with polio. About 30 of them were suffocating or “drowning in their own secretions” [4]. The epidemiologists soon discovered that the overwhelming amount of patients with respiratory muscular and bulbar paralysis, as well as proceeding airway obstruction because of accumulating secretions, created the need for extraordinary actions. At the time the general belief was that most of the patients died from the consequences of a disseminated virus infection, but since the respiratory paralysis with swallowing impairment seemed to be more lethal, Dr Bjørn Ibsen, a Danish anaesthesiologist educated in Boston was consulted [1, 5, 6]. His analysis was that the patients died from the consequences of inadequate gas exchange in the lungs and not from the virus infection itself and that the negative pressure ventilators were not sufficient to eliminate carbon dioxide from the blood.

In patients with bulbar paralysis and impaired swallowing there was also no effective way to clear the lower airways of accumulating secretions. Suctioning could only be performed in the oropharynx, which contributed to airway obstruction, aspiration pneumonia and atelectasis of the lungs. Ibsen proposed that a tracheostomy during local anaesthesia and insertion of a suction tube would allow removal of secretions obstructing the lower airways. After this procedure a cuffed, rubber breathing tube was inserted through the tracheostomy to prevent aspiration of upper airway secretions into the lungs, and enable manual positive pressure ventilation using a connected rubber bag. The breathing tube would be equipped with a rubber stopper at the connection with the ventilation bag and by removing it, endotracheal suction could be performed through the breathing tube during treatment [7]. Later on the patients were intubated during cyclopropane anaesthesia and then a tracheostomy was performed. Repeated suction of the trachea and the main bronchi sometimes in combination with bronchoscopy kept the airways clear from secretions. Frequent changing of position and squeezing of the thorax contributed to mobilisation of secretions from the lower airways. With the help of about 250 medical students

who managed the ventilation in shifts, the manual positive pressure ventilation proposed by Ibsen lowered the mortality rates from 90 to 25% within some weeks [4]. Manual ventilation was later replaced by the novel Engström positive pressure ventilator, built in Sweden by Carl-Gunnar Engström in 1950. It was manufactured in larger scale based on the Copenhagen experience and when the polio-epidemic hit Stockholm in 1953 there was no need for the medical students to perform manual ventilation [2]. The Scandinavian practice and technology was then spread throughout Europe [8, 9].

This period was the beginning of the positive pressure ventilation era and practice of modern clinical respiratory physiology [1]. Not surprisingly, there are very few reports on experiences of endotracheal suctioning equipment or side-effects in long-term positive pressure ventilated patients from the early fifties. Dr Bjørn Ibsen himself, who still has a very good remembrance, has told us that the suction catheters used in 1952 were made of rubber with one side-hole and were not disposable (Personal communication with Ibsen Oct. 2006). For repetitive suctioning, Tiemann catheters were used according to Lassen [4, 6]. The most common suction apparatus for anaesthesia and operating theatre use at this time was of the ejector type, using compressed gas to produce a vacuum (the venturi principle). It did not require electricity to function, which in the forties and fifties was a great advantage since the anaesthetic gases in the operating room could create an explosive atmosphere [4, 6, 10]. In the decades to come, increasing use of circulatory and respiratory monitoring equipment during anaesthesia and in the care for the critically ill resulted in suction-research mainly focusing on the heart-lung interactions of endotracheal suctioning and developing suction-procedures and suction systems limiting these unwanted side-effects.

VENTILATOR INDUCED LUNG INJURY (VILI)

Currently around 7000 patients in Sweden every year require invasive ventilator treatment for more than 24 hours and furthermore about 3000 patients receive short-term ventilatory support (Swedish Intensive Care Registry). Acute lung injury (ALI) and acute respiratory distress syndrome (ARDS) are the main reasons for long term mechanical ventilation and is caused by a variety of conditions such as sepsis, trauma and airway infections [11]. Mechanically ventilated patients suffer from accumulation of tracheobronchial secretions due to increased mucus production, impaired cough reflex and depressed mucociliary clearance. To avoid tube occlusion, impairment of gas exchange and increased work of breathing and pulmonary infections, repeated endotracheal suctioning is performed 8-13 times per 24 hours [12, 13].

The positive pressure ventilator treatment is life saving but invasive and several animal and human studies imply that it can cause substantial harm to the lung tissue [14-16]. The lung injury can be described by three different pathologic definitions: high-permeability type pulmonary edema, mechanical distortion/overinflation of lung structures and lung inflammation or biotrauma [17]. If the volume and pressure delivered with each tidal volume is too high the positive pressure ventilator treatment in itself can cause repetitive baro –and/or volutrauma to the smaller airways. This leads to over distension of the alveoli with release of inflammatory mediators causing oedema and fibrosis [18, 19]. Emphysematic lesions predominate in nondependent and caudal lung regions [20, 21]. Repetitive endotracheal suctioning induces alveolar collapse and formation of atelectasis which could augment lung injury [22]. If a ventilator treated patient is subjected to approximately 10 suctioning procedures every 24 hours, possibly over 120,000 endotracheal suctioning procedures are performed each year in Sweden.

LUNG PROTECTIVE VENTILATION

To reduce the release of inflammatory mediators during positive pressure ventilation several concepts has been proposed. In 1987 Gattinoni described the ARDS lung as the “baby lung”, meaning that the adult lung should be ventilated with very small tidal volumes, minimising over-distension of the diseased lung tissue [23, 24]. Several studies have confirmed this and shown that a low tidal volume reduces mortality in ventilator treated patients [25, 26]. The “open lung” concept was presented in an editorial of 1992 [27, 28], and proposed a treatment strategy to open up the lung with high inspiratory pressures during a short period of time and the keep the lung open with sufficient PEEP-levels afterwards. The goal was to optimise functional residual capacity (FRC) and prevent atelectasis and hence reduce stress from repetitive alveolar collapse during tidal volume variations [28-30]. Disconnection and suctioning induced lung collapse stand in contrast to these concepts. In the editorial Lachmann expresses his concerns: *“this raises the question whether one should disconnect patients from the ventilator for routine bronchial toilet and thus allow total lung collapse”*. Limiting cardiopulmonary side-effects of suctioning could be considered as part of a lung protective ventilation strategy and the closed suction system has been advocated for this reason [22, 31-33].

SIDE-EFFECTS OF SUCTIONING

“The not-infrequent occurrence of cyanosis during endotracheal suctioning and an occasional death attributable to the procedure have prompted studies on the subject”

Azmy R Boutros M.D. *Anesthesiology* 1970

DEATH BY SUCTIONING

The first reports on the serious side-effects of endotracheal suctioning came from thoracic surgeons, probably because they were the first to use positive pressure ventilation, suction and oxygen saturation monitoring on a routine basis during anaesthesia. In 1948 in the Journal of Thoracic Surgery, Kergin et al presented a number of patients undergoing thoracotomy and stated that *“The sudden profound fall in arterial oxygen saturation associated with bronchial suction is probably due not only to sucking out oxygen, but also to a temporary increase in the atelectasis by negative intra-bronchial pressure....Our anaesthetists now watch the oximeter and apply positive pressure as indicated.”* In the same journal in 1950 Shumacker et al described several deaths occurring during thoracic surgery with particular reference to aspiration through the endotracheal tube. Not until 1960, in the British Journal of Anaesthesia, did Rosen and Hillard describe endotracheal suctioning from an anaesthesiologists point of view. They thoroughly explained what occurred when a suction catheter was introduced into the trachea via the endotracheal tube (ETT) and suctioning applied with reference to pressure drop and air flow. They stated that *“...gas is drawn from the lungs and this is replaced by air drawn from the atmosphere through the space left round the catheter.”* They also pointed out the fact that *“The exact fraction of the total pressure drop from atmosphere to suction apparatus that develops in the lungs depends on how closely the suction catheter fits into the trachea or endotracheal tube.”* They meant that if the fit was exact the suction system would become closed and theoretically the pressure in the lungs would fall until it equalled the maximum negative pressure of the suction apparatus. This could of course produce substantial harm to the patient subjected to endotracheal suctioning. They recommended that the outer diameter of the suction catheter should not exceed half of the inner diameter of the tube (see Table 1).

Table 1.
Tube and suction catheter sizes. The catheter sizes are given in French (Fr). 1 Fr = 0.33 mm. 12 Fr = 12 x 0.33 mm = 4.0 mm. Rest area is the area remaining between tube and catheter with the catheter inserted.

ETT no	ID \odot	\odot	Catheter no	OD \odot	\bullet	Rest area	
						$\odot - \bullet$	% of \odot
■ 7	7,0 mm	38 mm ²	12	4,0 mm	13 mm ²	25 mm ²	66 %
			14	4,6 mm	17 mm ²	21 mm ²	55 %
			16	5,3 mm	22 mm ²	16 mm ²	42 %
■ 8	8,0 mm	50 mm ²	12	4,0 mm	13 mm ²	37 mm ²	75 %
			14	4,6 mm	17 mm ²	33 mm ²	66 %
			16	5,3 mm	22 mm ²	28 mm ²	56 %
■ 9	9,0 mm	64 mm ²	12	4,0 mm	13 mm ²	51 mm ²	79 %
			14	4,6 mm	17 mm ²	47 mm ²	73 %
			16	5,3 mm	22 mm ²	42 mm ²	66 %

ID \odot = inner diameter
 OD \odot = outer diameter
 \odot = inner cross sectional area
 \bullet = outer cross sectional area

CARDIO-PULMONARY INTERACTIONS

In the beginning of the 1950's the described cardiac arrests and sudden deaths during tracheal suctioning was thought to be caused by respiratory tract reflexes [34]. As better ways of monitoring oxygen saturation, blood-pressure variations and lung volumes were developed the circulatory and respiratory side-effects of suctioning could be observed. It became obvious that the suctioning induced lung collapse was the primary reason for these cardio-pulmonary effects. In 1959 Rigler showed with chest radiographs taken during suctioning that both domes of the diaphragm were higher and that there was a marked dilatation of the superior vena caval shadow and of the pulmonary artery. There was also an enlargement of the diameter of the heart, indicating an increased venous return to the heart. In the same year, Boba et al studied the effects of endotracheal suctioning in paralysed patients. Using manometric methods they reported severe hypoxia resulting from one minute of suctioning [10]. Increased venous return in combination with anoxia in the myocardium was explained by Rosen and Hillard in 1960 to be the real cause of these sudden deaths during suctioning. In 1970 Boutros showed in 22 lung healthy patients that hyperinflation following suctioning resulted in a significantly smaller relative decrease in PaO₂. The use of pre-oxygenation before, and hyperinflation after endotracheal suctioning came into practise in the 1960's and 70's but not routinely [35].

In 1977 Naigow et al examined the effect of different suction procedures on arterial blood gases in healthy anaesthetised dogs. They listed the suction-procedure variables that were thought to affect the degree of hypoxemia during open endotracheal suctioning: a) Magnitude of suction pressure and flow, b) Ratio of suction catheter size to endotracheal tube size and c) Duration of suctioning. In addition, the following patient related variables were listed: a) Initial arterial oxygen tension, b) Magnitude of pulmonary shunt and c) Susceptibility to suction-induced small airway closure. They concluded that fifteen seconds of endotracheal suctioning in spontaneously breathing dogs resulted in a sustained five minutes fall in arterial oxygen tension. Giving 100% oxygen before suctioning prevented suction-induced hypoxemia during and directly after

suctioning, but not five minutes after suctioning. Mechanical hyperinflation after suctioning quickly raised arterial oxygen tension. With suctioning performed via a tight seal connector and mechanical ventilation maintained with 100% oxygen (i.e. closed suctioning) during the whole suction procedure the arterial oxygen level remained high. These interventions were aimed at minimising the suctioning induced lung collapse and its effects.

Several other studies during the 70's and 80's showed that disconnection of the breathing apparatus and the negative pressure application during suctioning resulted in atelectasis, pulmonary shunting and increased venous return producing hypoxemia, lung compliance changes, arterial blood-pressure variations (both drops and rises), brady- and tachy-arrhythmias and pulmonary hypertension [36-48] (see Table 2). These studies partly contributed to the development of closed suction systems, to allow suction during ongoing ventilation and prevent lung collapse.

Table 2. Known complications and side-effects of endotracheal suctioning

Lung collapse	Bronchoconstriction	Pulmonary shunting
	<ul style="list-style-type: none"> ▪ Decrease of lung compliance ▪ Decrease of arterial oxygen tension and saturation ▪ Increase of arterial carbon dioxide tension ▪ Decrease in mixed venous oxygen saturation ▪ Increase in mean pulmonary arterial pressure ▪ Systemic blood pressure variations ▪ Heart rate variations ▪ Cardiac output variations ▪ Increase of intracranial pressure 	
Infection	<ul style="list-style-type: none"> ▪ Environmental contamination ▪ Bacterial colonisation of the lower airways ▪ Pneumonia 	
Other	<ul style="list-style-type: none"> ▪ Pneumothorax ▪ Damage and granulomas of the respiratory tract epithelium 	

NEW MONITORING STRATEGIES

The clinical possibility to routinely monitor pulse-oximetry and volume-pressure loops during mechanical ventilation was developed during the last part of the 20th century and has in itself changed the suctioning management from routinely suctioning every two hours to a more strict “on indication” suctioning procedure [49, 50]. During the nineties, as research began to focus on describing the course of the suctioning induced lung collapse, new monitoring techniques were becoming available including continuous online blood-gases, body plethysmography,

computerised tomography (CT), and electric impedance tomography (EIT). In 2000, in a study on anaesthetised sheep, Lu et al used computed tomography to describe the bronchoconstriction and volume loss caused by endotracheal suction. In 2003 Maggiore et al used body plethysmography to do the same on ALI patients. They concluded that the largest lung volume loss had already taken place at the disconnection of the ventilator, prior to suctioning. The aim of a large number of studies during this period and up to now has been to compare side-effects between closed and open suctioning (see Table 3). Side-effects of suctioning can be monitored by arterial blood gas analysis, pulse oximetry and airway pressure-volume curves, reflecting global lung function, but little is known about regional effects on ventilation during suctioning induced lung collapse. EIT is a potential tool for monitoring rapid lung de-recruitment bedside as well as regional distribution of ventilation [51, 52]. Monitoring of FRC changes during suctioning could be essential for ventilator optimisation in the post-suctioning period.

VENTILATOR ASSOCIATED PNEUMONIA (VAP)

Ventilator associated pneumonia is a nosocomial infection and complication of long-term respirator treatment. Among critically ill patients it may contribute to increased morbidity, mortality and health care costs [53, 54]. Different risk factors have been associated with the condition such as prolonged immobility, frequent disconnection of ventilator circuit, use of heated moisturisers and pooling of secretions above the inflated ETT cuffs [53]. Patients suffering from ALI/ARDS, chronic obstructive pulmonary disease, burns, neurosurgical conditions and patients in need of reintubation and administration of muscle relaxants are at high risk of developing VAP [55]. The closed suction system has been proposed as part of a strategy to prevent ventilator associated pneumonia. This is based on assumed advantages such as lower frequency of disconnections and decreased microbial contamination, thus lower risks for cross-infections. However the closed suction system catheters often become colonised by patients' own respiratory tract microbial flora which could contribute to auto-contamination [56, 57]. In two recent meta-analyses there is no evidence supporting the closed suction systems' supposed ability to prevent VAP [13, 58] (see Table 3).

CLOSED SUCTION SYSTEMS

"Most clinicians are aware that it is dangerous to attach the tubing directly on to the endotracheal tube as this makes the system a closed one"

Rosen and Hillard

British Journal of Anaesthesia 1960

During the USA's AIDS epidemic in the early eighties the closed suction system was originally introduced by Dale H. Ballard in 1983 to prevent environmental and airway contamination, and to reduce the unwanted side-effects of endotracheal suctioning. In agreement with the "open lung concept", the closed system enables suctioning to be performed without disconnection of the patient or interrupting mechanical ventilation, to prevent lung collapse. Several studies during the last 15 years support the fact that the closed system, if used correctly, minimises side-effects and environmental contamination [32, 33, 38, 59-64] (see Table 3). However, there is a potential to create large negative pressures if the suction flow exceeds ventilation or secretions lining the inside surface of the tube creates a too high tube resistance, preventing adequate ventilation [65]. In a closed system, this would not only harm the patient but could also cause ventilator dysfunction.

In the late nineties, the Swedish National Board of Health and Welfare received reports from ventilator manufacturers on ventilator dysfunction due to excessive negative pressures during closed system suctioning. At this time the intensive care nurses had a clinical impression, supported by a large Canadian survey [66, 67], that the closed systems were inefficient in clearing the patients' airways from secretions. This drove the manufacturers of the closed suction systems to recommend use of higher vacuum levels and thicker catheters that could contribute to development of large negative pressure levels in the lungs and/or ventilator. There are few quantitative data on secretion removal but two patient studies from 1991 and 2006 compare the weight of recovered secretion during open and closed suctioning. The first study was performed on 25 ICU patients and did not find any difference between open and closed suctioning [68]. The second study was performed on 18 ICU patients and found that open suctioning was about 4-5 times more effective in regaining secretions than closed suctioning [64] (see Table 3). In the last 15 years the use of closed suction systems has increased and in an American survey from 2000 it was found that 58% of ICU wards use them exclusively. However, 61% of the nurses reported that they disconnected the ventilator tubing to perform open suctioning some or most of the time [69]. In consideration of this, there are few large outcome studies comparing open and closed suctioning systems and in two recent meta-analyses no difference was found in mortality, morbidity or length of ICU stay (see Table 3).

Fiberoptic bronchoscopy (FOB) has been used as a "controlled" and directed suctioning manoeuvre in intensive care patients since the 1970's. When it is performed through a tight seal connector, it is considered a form of closed suctioning [70]. Few patient data exist on the subject but several studies indicate that the procedure has the potential to create an unwanted lung collapse with respiratory and circulatory side-effects comparable to an open suctioning procedure [71-73].

Table 3. Studies comparing open and closed suction systems

	No. pat.	Cost	Side-effects	Environment contamination	Airway colonisation	VAP	Morbidity /Mortality	Secretion removal
		OSS/CSS	OSS/CSS	OSS/CSS	OSS/CSS	OSS/CSS	OSS/CSS	OSS/CSS
Brown et al 1983 [60]	22		more/less					
Ritz et al 1986 [74]	30				no diff.			
Carlton et al 1987 [61]	20	less/more	more/less					
Clark et al 1990 [38]	127		more/less					
Deppe et al 1990 [56]	84				less/more	no diff.	no diff.	
Cobley et al 1991[59]	11			more/less				
Witmer et al 1991[68]	25							no diff.
Johnson et al 1994[62]	35	more/less	more/less			no diff.		
Adams et al 1997[75]	20	less/more			no diff.	no diff.		
Combes et al 2000[76]	104					more/less		no diff.
Cereda et al 2001[33]	10		more/less					
Maggiore et al 2003 [32]	9		more/less					
Zeitoun et al 2003 [77]	47					no diff.		
Rabitsch et al 2004 [78]	24					more/less		
Topeli et al 2004 [57]	78				less/more	no diff.	no diff.	
Lorente et al 2005 [79]	443	less/more				no diff.	no diff.	
Lorente et al 2006 [80]	457	more/less				no diff.	no diff.	
Lasocki et al 2006 [64]	18		more/less					more/less
Total no pat.	1544							
Reviews/Surveys/Meta-analyses								
Noll et al 1990 [81]	Rev.	no consensus	adv. CSS	adv. CSS		no consensus		adv. OSS
Cook et al 1998 [53]	Rev.					no consensus		
Blackwood et al 1998 [67]	Surv.							adv. OSS
Vonberg et al 2006 [58]	Meta.	no consensus		adv. CSS	adv. OSS	no diff.		
Jongerden et al 2007 [13]	Meta.	no consensus	adv. CSS	adv. CSS		no diff.		adv. OSS
Overall conclusions		no consensus	adv. CSS	adv. CSS	adv. OSS	no diff.	no diff.	adv. OSS

Open system suctioning (OSS); Closed system suctioning (CSS); More than OSS or CSS (more); Less than OSS or CSS (less); No difference (no diff.); Advantage (Adv.); Review (Rev.); Survey (Surv); Meta-analysis (Meta); Number of patients (No. pat.)

MAIN ISSUES

- a “simple” and common clinical routine such as endotracheal suctioning has a wide series of well known side-effects and complications that stand in contrast to the lung-protective ventilation strategies
- the closed suction system, proposed as a part of a lung-protective ventilation strategy has the potential of creating a severe lung collapse and
- in a large North-American survey from 1998 the nurses that performed suctioning manoeuvres had an impression that the closed system was not sufficient in removing secretions in 50% of the cases, furthermore
- there are few quantitative data on the effectiveness of secretion removal
- a general clinical practice of post-suctioning recruitment does not exist and
- few data exist on the effects of fiberoptic bronchoscopic suctioning through a tight seal connector, a method commonly used in our intensive care wards and another form of closed suctioning.

AIM OF THESIS

The principal objective of this thesis was to evaluate the endotracheal suction systems and suction methods available today in order to contribute to the development of a safe and efficient clinical intervention by assessing:

- respiratory and circulatory side-effects during suctioning with open and closed suctioning catheters or fiberoptic bronchoscopes
- the effectiveness of secretion removal during open and closed system suctioning
- the impact of different ventilation modes, catheter/bronchoscope sizes, suction duration and vacuum levels during these procedures

...in mechanical lung models, experimental lung injury and patients suffering from acute lung injury by using novel lung-monitoring techniques.

METHODS

ANIMALS AND PATIENTS

ANIMALS (II, III)

In the animal studies, Swedish landrace pigs (25-35 kg) of either gender were used and taken care of in accordance with the National Institute of Health guidelines for the use of laboratory animals [82] and with approval from the Committee for Ethical Review of Animal Experiments at Gothenburg University. Educated personnel were present at all times before and during the experimental procedures. The animals were fasted over night with free access to water. Anaesthesia was initiated with an intramuscular bolus injection of ketamin and midazolam followed by an intravenous infusion of α -chloralose and fentanyl (II) or by pentobarbital and fentanyl (II, III). An open airway was established by intubation in prone position in Study II and by tracheotomy in supine position in Study III. During the studies all animals were placed in supine position and connected to a Servo 900 C (II) or Servo 300 (III) ventilator. Muscle relaxation was achieved by pancuronium infusion. Fluid balance was maintained by infusion of Ringer's solution at 10ml/kg per hour. Body temperature was kept at 38–39°C by heating pads. Femoral arteries and internal jugular veins were cannulated. In study II a pulmonary artery catheter was inserted via the right jugular vein and in Study III a continuous blood gas sensor was inserted in one of the femoral lines and an electric impedance tomography (EIT) electrode belt placed around the thorax of the pigs. Baseline data are presented in Table 4.

PATIENTS (IV)

13 patients suffering from ALI were recruited from an adult, general intensive care unit and included after consent was obtained from next of kin. The study protocol was approved by the local ethics committee of Gothenburg. The need for intensive care treatment was caused by major surgery in 5 patients, pneumonia in 6 patients, multiple trauma in 1 patient and sepsis in 1 patient. ALI was caused by primary lung injury in 7 patients (bacterial pneumonia, aspiration pneumonia and lung contusion) and secondary lung injury in 6 patients (sepsis and major surgery). Patients with intracranial lesions were excluded. Baseline data are presented in Table 4.

Table 4. Summary of animals and patients in Studies II, III and IV.

Paper	Animals (II, III) and Patients (IV)							
	no	male/ female	P/F ratio at BL, mmHg	body weight, kg	age, yr	intubated/ tracheotomised	orally/nasally intubated	ETT no 7/8
II	12	-	197±55	31±3	-	12/0	12/0	12/0
III	9	-	165±30	27±1	-	0/9	-	0/9
IV	13	8/5	194±33	87±15	62±12	13/0	11/2	9/4

P/F ratio = arterial oxygenation (PaO₂) in mmHg/fraction of inspired oxygen (FiO₂); BL = base line, ETT = endotracheal tube, yr = years, no = number, mean±SD

EXPERIMENTAL MODELS

MECHANICAL LUNG MODELS (I, II, IV)

For assessment of lung mechanics and effectiveness of secretion removal during open and closed suctioning a Biotek ventilator tester, model VT-1 (Bio-Tek Instruments Inc, Vermont, USA), was used as lung model (I, II) and compliance was set at 50 ml/cmH₂O. The lung model was fitted with a rigid plastic “trachea” and intubated with a cuffed endotracheal tube 7 or 8 mm ID. A 12 or 14 Fr Trach Care closed suctioning system (CSS) catheter with an outer diameter (OD) of 4.0 or 4.6 mm was connected to an ejector vacuum device with an interposed suction bottle. The test lung was ventilated with a Servo 900C (I,II) or a Servo 300 (I) ventilator (Siemens, Solna, Sweden) and a side stream spirometer was connected between the distal end of the plastic trachea and the alveolus of the lung model. A disposable pressure monitoring set was connected to the alveolus (I). Secretion removal was studied by applying 15 ml of a soap gel in the “trachea” 2 cm below the endotracheal tube tip (II) (see Figure 1).

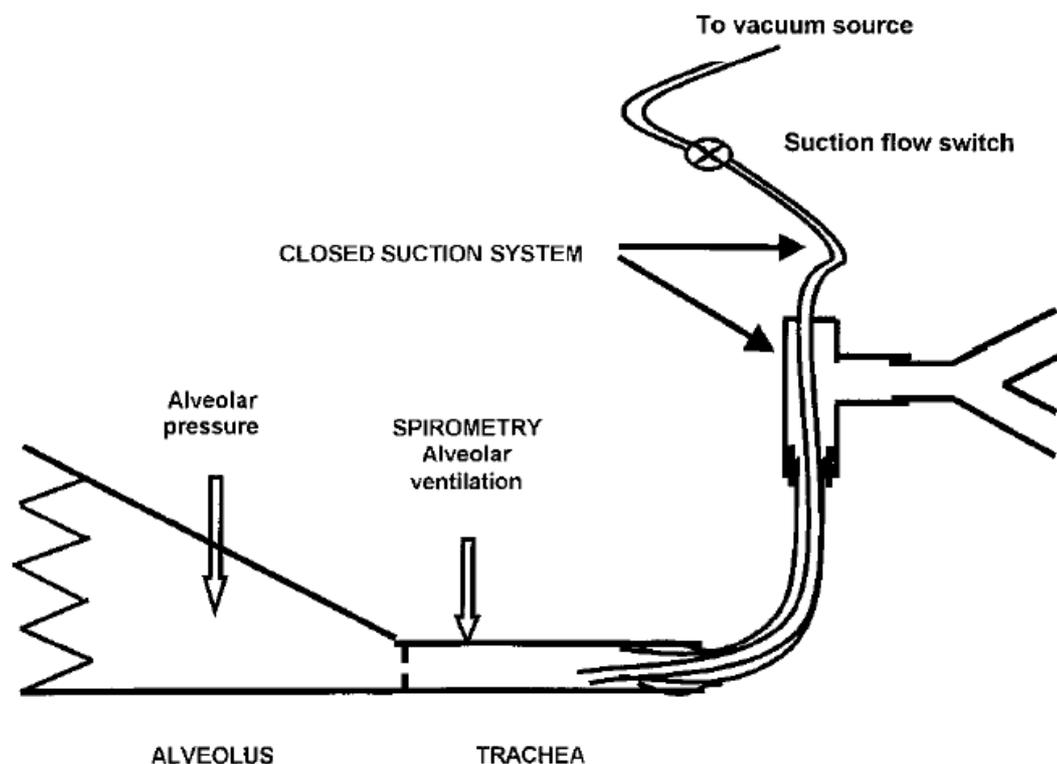


Figure 1. Mechanical test lung used in bench tests from Study I and II. Airway pressure was measured in the “alveolus” of the lung and ventilation was measured in the “trachea” distal to the ETT tip and suction catheter.

For assessment of changes in FRC, tidal volume (V_t) and tracheal pressure (P_{trach}) during bronchoscopic suctioning a lung model constructed of two water filled U-pipes with a liquid compliance of about 80 ml/cmH₂O was connected to a plastic trachea and two main bronchi (IV). The trachea was intubated with an ETT no 7 or 8 and ventilated with a Servo 300 ventilator. Each main bronchus was connected to a pressure monitoring set. A 12 or 16 Fr bronchoscope with an OD of 4.0 or 5.2 mm was inserted through a tight seal connector into the tube and suctioning performed in trachea and left main bronchus. The volume above the surface represented FRC that together with tidal volumes could be read off a scale on the water pipes (see Figure 2).

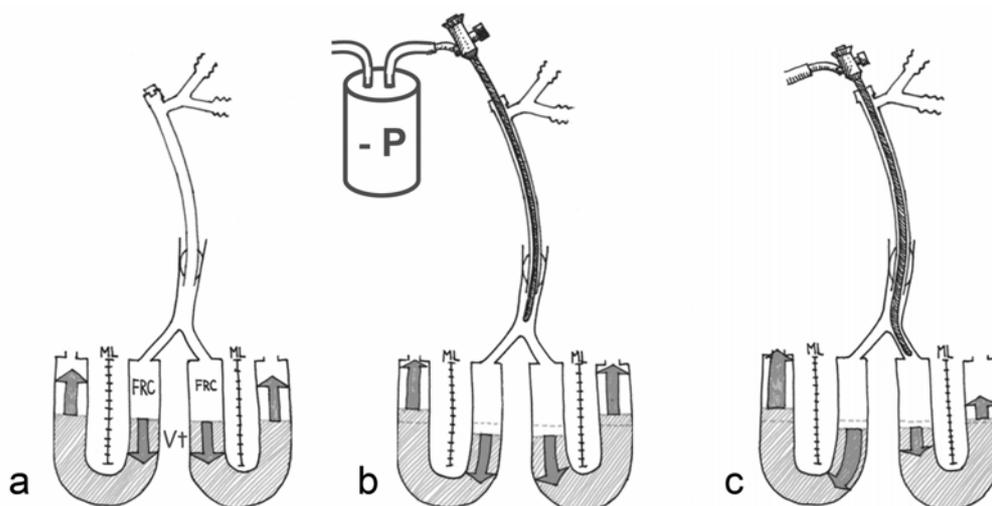


Figure 2. The lung model used in the bench test from Study IV consisting of two water filled U-pipes: a) without bronchoscope b) with bronchoscope inserted into the “trachea” and c) left main “bronchus”. Airway pressure was measured in the two main “bronchi”.

LUNG INJURY MODEL (II, III)

An experimental model of acute lung injury (ALI) was established by repeated bronchoalveolar lavage (BAL) with body warm saline of 9 mg/ml, 30 ml/kg in each wash, resulting in surfactant depletion and lung tissue prone to collapse [30, 83, 84]. Total amount of saline ranged 6-14 l. During the procedure the animals were ventilated with pressure (II) -or volume (III) controlled ventilation (PCV or VCV) at a tidal volume of 10 ml/kg, respiratory rate (RR) 20 breaths/min, FiO_2 1.0 and positive end expiratory pressure (PEEP) of 5-15 cmH₂O. BAL was continued until there were no visual signs of surfactant in the fluid exchanged from the lungs and PaO_2 was less than 10 kPa (75 mmHg) or oxygen saturation was below 90% at FiO_2 1.0. The animals were allowed to stabilise for one hour and if needed, additional BAL was performed.

SUCTION SYSTEMS (I, II, III, IV)

The suction systems used consist of a suction catheter or fiberbronchoscope connected to an ejector device via an interposed suction bottle of 1.0 l (bench tests I, II, IV) or 2.5 l (animal and patient studies II, III, IV). The ejector device has the capacity to produce a maximum vacuum effect of about -80 kPa (-600 mmHg).

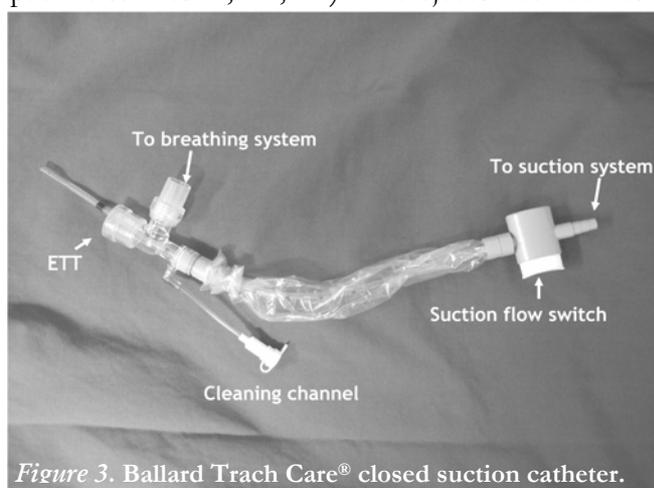


Figure 3. Ballard Trach Care® closed suction catheter.

Open suctioning (OSS) was performed either by using standard disposable suction catheters or by disconnecting the closed suction system from the Y-piece. Closed system suctioning is defined as suctioning through a tight-fitting device on the endotracheal tube that allows the ventilator to be connected and working during suctioning. The suctioning system used in Study I, II and III (Trach Care®, Ballard Medical Product, USA) has a manually operated suction flow switch and a plastic sheath surrounding the catheter (Figure 3).

Fiberbronchoscopic suctioning was performed through a tight seal connector placed between the tube and the Y-piece, hence considered a form of closed suctioning.

EXPERIMENTAL INTERVENTIONS AND STUDY PROTOCOLS

Table 5. Summary of interventions in Studies I-IV.

Paper	ETT no	Suction system	Bench studies				Animal/Patient studies			
			catheter FOB Fr	suction duration s	vacuum kPa	ventilation mode	catheter FOB Fr	suction duration s	vacuum kPa	ventilation mode
I	7/8	open/closed	12/14	20-30	-50	VCV/PCV; CPAP 10	-	-	-	-
II	7	open/closed	12/14	10	-20/-40	VCV/PCV; CPAP 0/CPAP 10	12/14	5, 10, 20	-20	PCV; CPAP 0/CPAP 10
III	8	open/closed	-	-	-	-	14	10	-20	VCV/PCV
IV	7/8	FOB closed	12/16	20-30	-60	VCV/PCV	16	10	-60	VCV/PCV

ETT = endotracheal tube, no = number, FOB = fiber optic bronchoscope (Paper IV), Fr = French, s = seconds, VCV = volume controlled ventilation, PCV = pressure controlled ventilation, CPAP = continuous positive airway pressure.

PAPER I

Steady state volumes and pressures were registered at baseline and after introduction of the suction catheter into the endotracheal tube and finally during suctioning. The Servo 900 C was used with PCV and VCV and with continuous positive airway pressure (CPAP). The Servo 300 was tested in pressure regulated volume control (PRVC) mode and CPAP. All tests except the CPAP were performed with a minute ventilation (MV) of 10 l and a RR of 20/min. The inspiration-to-expiration (I:E) ratio varied between 1:2, 1:1 and 2:1 and PEEP was set at 0 or 10 cm H₂O. To imitate the effect of secretions on the interior surface of the endotracheal tube, 1 ml of gel (Xylocain 2% gel, Astra Ltd, Södertälje, Sweden) was injected into the middle part of the tube and allowed to disperse on the inner surface of the tube during ventilation. The same suction catheter test as described above was then performed. Vacuum level was set at -50 kPa (-375 mmHg).

PAPER II

Suction effectiveness

Before open or closed suctioning, the suction catheter was inserted 2 cm below the tip of the tube. Suction was applied for 10 s without moving the catheter with a vacuum level of either -20 or -40 kPa (-150 or -300 mmHg). The amount of gel recovered by suctioning was quantified by weighing the suctioning systems on a precision scale (Sauter RC 1631, August Sauter, Germany). CSS was performed during VCV, PCV and CPAP mode (0 or 10 cmH₂O). Ventilator settings during PCV and VCV mode were: MV 9.0 l, PEEP 5, RR 20, I:E 1:2, triggering level -2 cmH₂O. The suctioning system and ventilator settings chosen were performed randomly and each intervention repeated six times.

Side-effects

One group of six animals were subjected to four interventions in random order: (1) OSS with 12 Fr catheter; (2) OSS with 14 Fr catheter; (3) CSS with 12 Fr catheter; and (4) CSS with 14 Fr catheter during PCV. For each of the four modes, suctioning was applied for 5, 10 and 20 s consecutively. Measurements were made at baseline, during the first minute after the start, at the point when the most extreme (worst) value was registered and at 5 min. Between manoeuvres the animals were allowed to stabilise and a new baseline was registered when SpO_2 and $ETCO_2$ reached steady state, which took 4–10 min. CSS was performed during PCV 26–28 cmH_2O , PEEP 9 ± 3 cmH_2O , I:E 1:2, RR 20 and triggering sensitivity -2 cmH_2O . A second group of six animals were subjected to three interventions in random order: (1) OSS with 12 Fr catheter (2) CSS with 12 Fr catheter during CPAP 0 cmH_2O (3) CSS with 12 Fr catheter during CPAP 10 cmH_2O . Suctioning and measurement procedures were performed as above.

PAPER III

During preparation and stabilisation after lavage and between suctioning procedures the Servo 900 C ventilator was set in VCV with V_t 10 ml/kg, respiratory rate 20/min, PEEP at 10 cmH_2O , I:E of 1:2, and FiO_2 of 0.5. Before starting the experimental protocol ventilation induced changes in electric impedance were calibrated against known lung volumes using a super syringe [85, 86]. 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 cmH_2O in steps of 5 cmH_2O at each V_t (see Figure 4). During the suctioning procedure either VCV or PCV was used with 10 cmH_2O PEEP, I:E 1:2, triggering level -2 cmH_2O , RR 20/min, and V_t 10 ml/kg body weight (titrated by changing the pressure level in PCV). Suctioning was applied for 10 seconds with vacuum level -20 kPa (-150 mmHg) and a 14 Fr catheter. Four different suctioning procedures were tested in random order: (1) OSS with VCV, (2) OSS with PCV, (3) CSS during VCV, and (4) CSS during PCV. Data collection was started at baseline before suctioning and continued for 15 min after each suctioning procedure. Animals were allowed to stabilise, and a new baseline was established before proceeding.

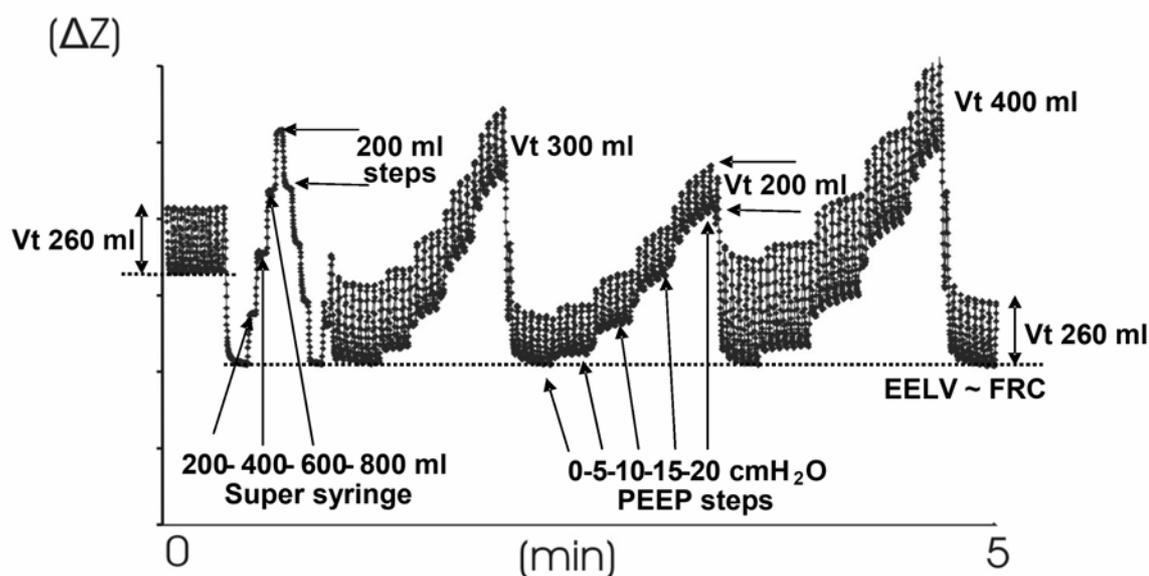


Figure 4. EIT recordings from one animal during stepwise volume inflation with super syringe, tidal volume changes and increasing PEEP-levels (Paper III).

PAPER IV

Before starting the experimental protocol the ventilator was set in VCV with the patients' baseline tidal volume, RR and PEEP. I:E was set to 1:2 and triggering sensitivity -2 cmH₂O and volume calibration for EIT tidal changes performed by stepwise changing the tidal volume by 100 ml at three levels [87]. During the suctioning procedure, either VCV or PCV was used with patient's baseline tidal volume, RR and PEEP. I:E was set to 1:2 and triggering level to -2 cmH₂O. A 16 Fr bronchoscope was introduced through a tight seal connector into the trachea or main bronchi. Suctioning was applied for 10 s with vacuum level -60 kPa (-450 mmHg). Data collection was started at baseline before suctioning and continued for 10 minutes after each suctioning procedure. Patients were then allowed to stabilise and a new baseline established before proceeding.

MONITORING/MEASUREMENTS

SUCTION FLOW AND TUBE RESISTANCE (I, IV)

In Study I the suctioning capacity was measured by connecting the distal tip of the suctioning catheter directly to a pressure flow meter (Calibration analyzer RT-200, Timeter™ Instrument Corporation, Lancaster, USA) at vacuum level -50 kPa (-375 mmHg). In Paper IV the suctioning flow through the bronchoscope's suctioning channel was measured with a gas flow analyzer (Fluke VT Plus Bio-Tek™, Winooski, USA) at vacuum levels of -20 to -80 kPa (-150 to -600 mmHg). Tube resistance during fiberbronchoscopy was assessed by placing either a 12 or 16 Fr bronchoscope in an ETT no 7 or 8, measuring pressure (Calibration analyzer RT-200 Timeter™ instrument corp. Lancaster, USA) at five different flow levels 10, 20, 30, 40 and 50 l/min through the tube (Gas flow analyzer Fluke VT Plus Bio-Tek™, Winooski, USA). Each measurement was repeated three times (IV). The resistance of the system was measured and the tube resistance was calculated as the total resistance minus system resistance (see Figure 5).

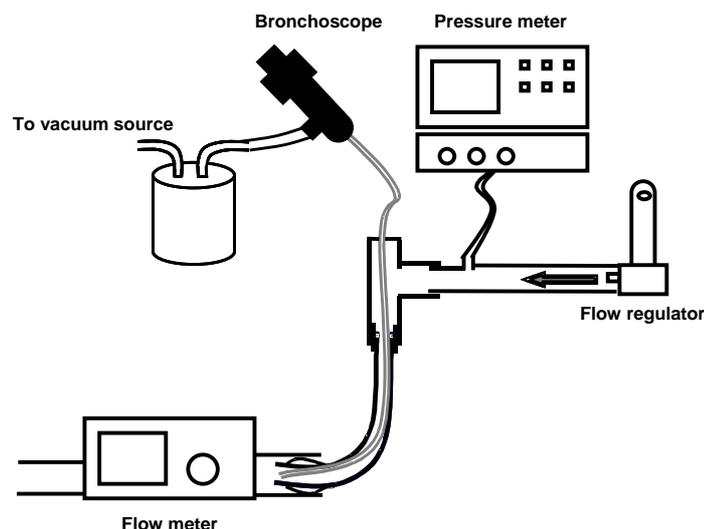


Figure 5. Set up used for suction flow and tube resistance measurements (IV).

BLOOD AND AIRWAY GAS ANALYSES (II, III, IV)

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, Finland). Oxygen saturation (SpO_2) was monitored by pulse-oximetry and in Study II oxygen tension (PaO_2) was calculated from SpO_2 values using a standard oxygen dissociation curve [88]. Arterial and mixed venous blood gases were analyzed in multi-parameter analyzers placed in the animal lab (ABL 5[®], Radiometer A/S, Copenhagen, Denmark) and in the intensive care unit (COBAS[®] b 221, Roche Diagnostics, Basel, Switzerland).

CONTINUOUS BLOOD GAS MEASUREMENTS (II, III)

Continuous monitoring of mixed venous oxygen saturation (II) was obtained from a fibre-optic catheter system using reflectance spectrophotometry, which was inserted into the pulmonary artery (7.5 Fr Swan-Ganz thermodilution catheter CCO/SvO₂, Edward Life Sciences, California, USA). A continuous intravascular Paratrend 7+ fibre-optical blood gas sensor (Diametrics Medical Inc. UK) was inserted into a femoral arterial line for measurement of arterial blood gases and connected to a TrendCare Monitor 6000[™] (III).

LUNG MECHANICS (I, II, III, IV)

Respiratory rate, lung volume/pressures and respiratory compliance (Crs) were measured using a Pitot type D-lite[™] flow and airway pressure sensor (Datex-Ohmeda/GE, Finland) connected at the Y-piece [89]. “Alveolar” and “bronchial” pressure in the mechanical lung models (I, IV) was measured using a standard disposable pressure receptor set (PVB Medizintechnik, Germany). Tracheal pressure in the animal studies (II, III) was measured with a fluid filled pressure line inserted into the tracheal tube and positioned 2 cm below the tip of the tube. In patients, the pressure line was inserted in the same way but filled with air (IV) [90, 91]. All transducers were connected with the AS/3 (I, II, III) or S5 (IV) modular monitor (Datex-Ohmeda/GE, Finland). Total respiratory compliance in Study III was calculated as the V_t divided by the difference between end-inspiratory and end-expiratory tracheal pressure (ΔP_{trach}). Regional ventilation and compliance could be calculated from the EIT data (III), see below.

FRC/EELV MEASUREMENTS (III, IV)

A modified technique of nitrogen (N_2) washout/washin by a stepwise change in FiO_2 was used to measure FRC [92]. By increasing FiO_2 by 10 % and then by lowering it again, an FRC value was obtained by dividing the washout/washin volume of N_2 with the change in fraction (ΔF) of N_2 (FRC_{N_2}). Trend data on metabolism, end-tidal O_2 , CO_2 , and tidal volumes were sampled at one-second intervals in a data collection program, S/5 Collect 4.0 (Datex-Ohmeda, Finland). In Study III data for FRC calculations was analyzed in a dedicated software application, TestPoint[®]. In Paper IV, this application was integrated with the S/5 Collect program. Ventilation induced impedance changes were monitored using 16 electrodes placed around the chest wall at the level of the fifth intercostal space, connected to an EIT monitor (Dräger/GoEMF II, Paper III and Dräger EIT Evaluation Kit 2, Paper IV). An EIT scan or image representing the impedance variations within a ~5 cm wide slice of the thorax was created every 77 (III) or 20 msec (IV). FRC_{N_2} provided the absolute value of the EIT baseline volume. By using the EIT super syringe or tidal volume calibration described above (Figure 3) lung volume changes were plotted against impedance changes and the slope was calculated for each subject. From the baseline volume, absolute changes in end-expiratory lung volume (FRC_{EIT}) could then be determined.

REGIONAL VENTILATION AND COMPLIANCE (III)

The EIT software could give both global and regional aeration-related impedance variations and, together with tracheal pressure, regional lung mechanics data [85, 93]. Four regions of interest (ROI) were chosen from off-line EIT analysis: ventral (V), mid ventral (MV), mid dorsal (MD), and dorsal (D) (See Figure 6). The regional $V_{t_{ROI}}$ values were calculated as: $V_{t_{ROI}} = (\Delta Z_{ROI} / \Delta Z_{GLOB}) \times V_t$, 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 $V_{t_{ROI}}$ by tracheal pressure changes assuming no flow at end of inspiration and expiration. (see Figure 13)

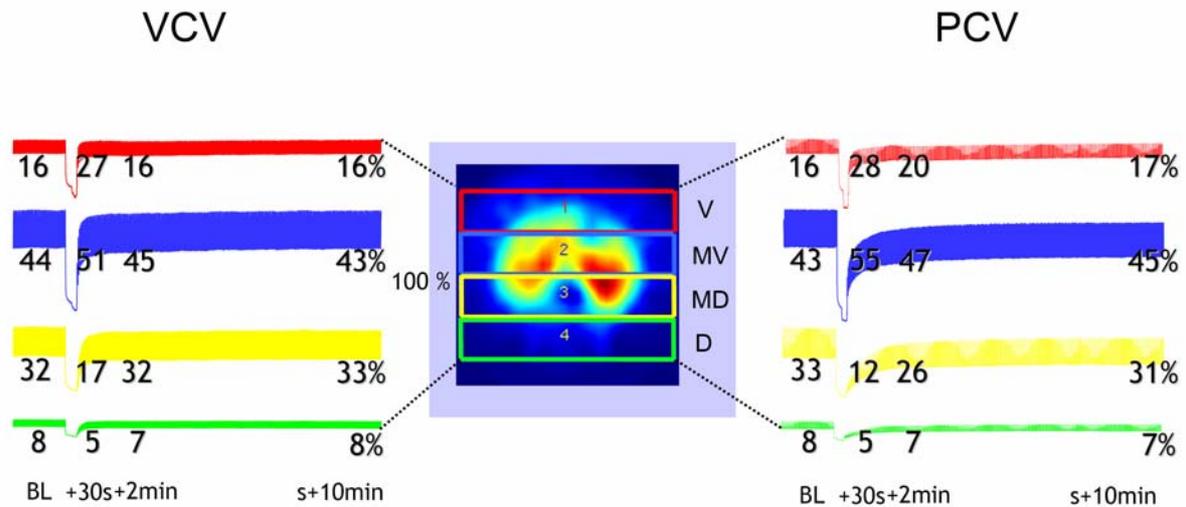


Figure 6. Regional EIT tracings (four ventral to dorsal regions of interest) from one animal during open suctioning with either VCV or PCV (III). The mid-dorsal (MD) region is nearly emptied and the ventilation re-distributed to the ventral regions. Post-suctioning recruitment is slower in PCV-mode.

BLOOD PRESSURES (II, III, IV)

Mean arterial pressure (MAP) was measured by an intra arterial line in a. femoralis in the animal studies (II, III) and by catheters already in place in a. radialis in patients (IV). Mean pulmonary arterial pressure (MPAP) was measured with a pulmonary artery catheter inserted via v. jugularis interna (II). The catheters were connected to the monitors via standard disposable pressure transducer sets (PVB Medizintechnik, Germany).

STATISTICS

For comparison of effectiveness of secretion removal in the bench test in Study II, non-parametric tests were used, Kruskal-Wallis and Mann-Whitney U, for pair-wise comparisons between interventions. In the first animal study (II) the two groups of subjects were analysed separately. Within each group the effects of OSS versus CSS were compared between interventions using a two-way analysis of variance (ANOVA) for repeated measures. In the case of a significant ANOVA finding, dependent variables (baseline vs 1 min values) were compared using single degree of freedom contrast analysis [94]. In Study III and IV the two-way ANOVA and the unpaired t test were used for post-suctioning comparison between interventions (VCV or PCV). The paired t test was used to evaluate changes between base line and selected measuring points. Probability values less than 0.05, after Bonferroni correction for multiple comparisons, were considered significant. The values in text, tables and figures are presented as mean \pm SD.

RESULTS

PAPER I

SUCTION FLOW THROUGH CATHETERS

Initial suctioning flow of a 14 and 12 Fr catheter was 43 and 23 l/min respectively. After 3–5 seconds of suctioning the steady state vacuum had decreased from the initially set level of -50 kPa (-500 cm H₂O) to -5.6 (-56 cmH₂O) and -11.6 kPa (-116 cm H₂O) respectively and the flow to 18 and 13 l/min respectively. (see Figure 7)

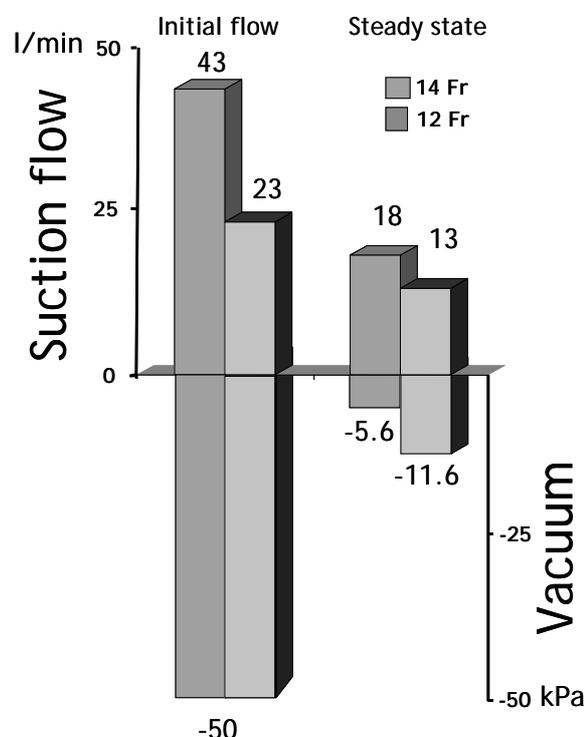


Figure 7. Suction flow measurements through 12 and 14 Fr suction catheters (l).

“ALVEOLAR” PRESSURE AND LUNG VOLUMES DURING SUCTIONING

Open suctioning

Suctioning using a 12 Fr catheter through an ETT of 7 mm ID resulted in an initial “alveolar” pressure of -7 cm H₂O, which increased to -4 cm H₂O at steady state suctioning, measured in the “alveolus” of the model lung. The corresponding values for a 14 Fr catheter were -24 and -15 cm H₂O respectively. Open suctioning through an ETT of 8 mm ID showed a similar but less pronounced effect on airway pressure.

Closed system suctioning

When using closed system suctioning during volume control ventilation, insertion of the catheter through the tube caused an increase in end-expiratory pressure measured in the “alveolus” of the model lung (See Figure 8). A 14 Fr catheter introduced through a 7 mm ID ETT at an I:E ratio of 1:2 resulted in an end-expiratory pressure increase of 7 cm H₂O over set extrinsic PEEP with preserved minute ventilation. In pressure control ventilation the increase in PEEP over set value was considerable less, 2 cm H₂O but the minute ventilation decreased with approximately 50% when the catheter was introduced. During steady state suctioning with a 14 Fr catheter through a 7 mm ID ETT during VCV the lowest airway pressure was -2 cmH₂O with I:E 1:2 and corresponding value in PCV was -8 cmH₂O. Suctioning in steady state decreased the minute ventilation during VCV from 9.1 at a respiratory rate of 20 to 7.0 l/min with a respiratory rate of 41 due to triggering of the ventilator caused by suctioning. In PCV the minute ventilation decreased to around 2 l/min with a ventilation frequency of 30–55.

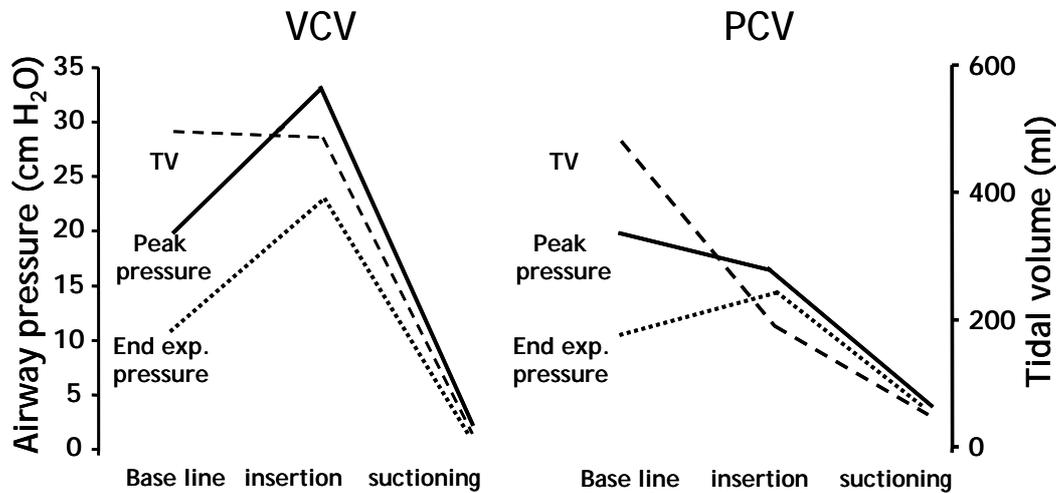


Figure 8. Airway pressure and tidal volume changes during closed suctioning with a 14 Fr catheter in ETT no 7 in the test lung from Paper I. Ventilator settings were MV 10 l, RR 20/min, PEEP 10 cmH₂O and I:E 1:2.

Increasing the inspiratory time aggravated these findings and suctioning in VCV with I:E of 2:1 resulted in a negative pressure of -80 cmH₂O. When gel was injected into the endotracheal tube to imitate the effect of secretions, there was a marked increase in intrinsic PEEP during insertion of a catheter in VCV. In PCV the resistance of the gel, tube and inserted catheter led to very small tidal volumes being delivered to the model lung and suctioning created sub-atmospheric pressures down to -15 cm H₂O. PRVC mode was equal to VCV mode in the aspect of producing intrinsic PEEP and CPAP produced less intrinsic PEEP of all modes.

PAPER II

EFFECTIVENESS OF SECRETION REMOVAL DURING OPEN AND CLOSED SUCTIONING

In the model lung, suctioning without ongoing ventilation, i.e. open system suctioning and closed system suctioning with CPAP 0 cmH₂O, was about 4-5 times as effective in removing secretions as closed suctioning during ongoing ventilation with VCV, PCV or CPAP 10 cmH₂O, irrespective of catheter size or vacuum pressure (see Figure 9). Suctioning was performed with 12 Fr suction catheters in ETT no 7 and 14 Fr catheters in ETT no 8.

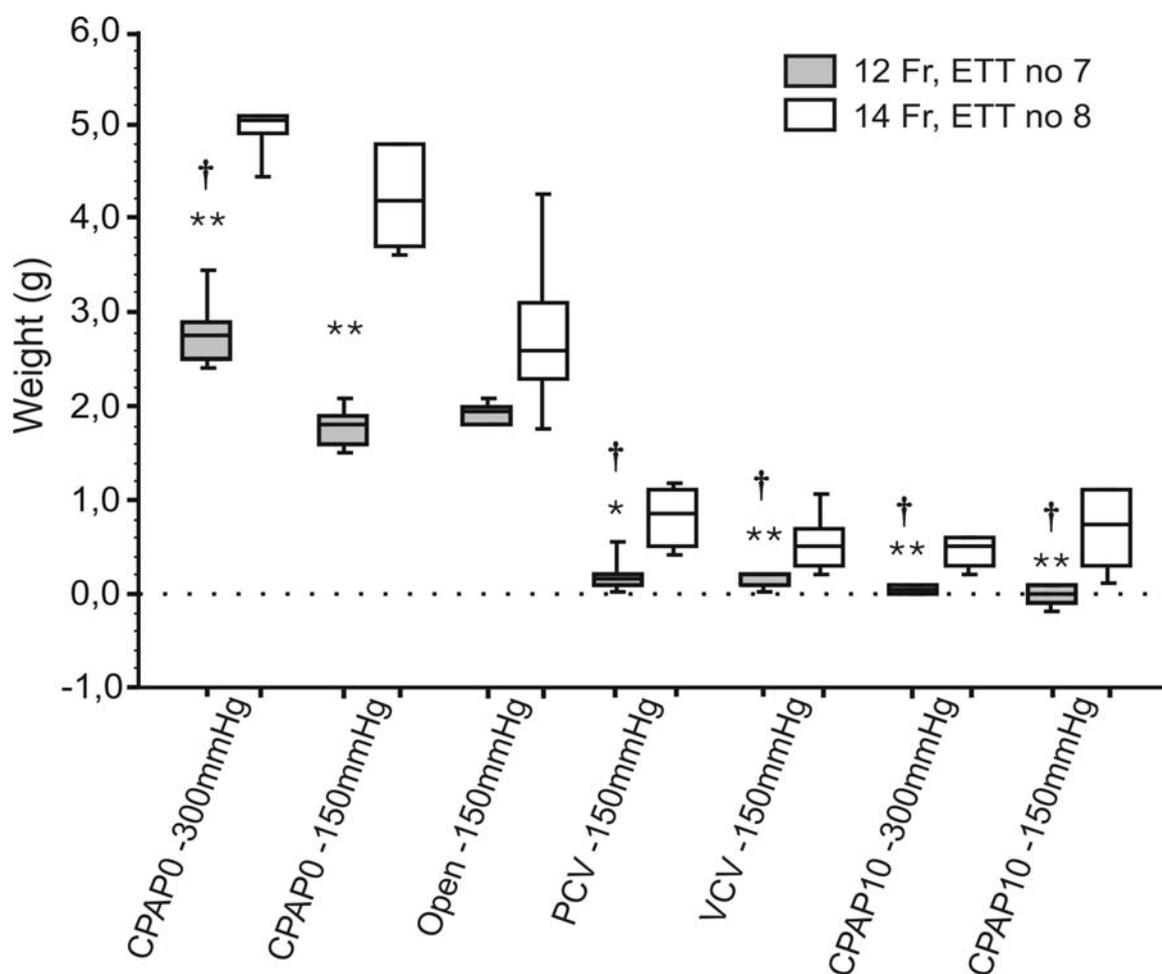


Figure 9. Weight difference of the suction system before and after open and closed suctioning for 10 s with 12 and 14 Fr catheters. Open suctioning and closed suctioning with CPAP 0 is 4-5 times more effective in regaining soap gel from an artificial trachea (Paper II). Box plot showing median, 25th to 75th percentile and 10th to 90th percentile. 12 vs. 14 Fr catheters * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; open vs. closed suctioning † $p < 0.01$. (Paper II)

EFFECT OF OPEN AND CLOSED SUCTIONING ON RESPIRATORY AND CIRCULATORY PARAMETERS IN EXPERIMENTAL LUNG INJURY

Suctioning without ongoing ventilation, i.e. open suctioning and closed suctioning during CPAP 0 cmH_2O significantly decreased arterial and mixed venous oxygen saturation irrespective of suction catheter size. Tracheal pressure became sub-atmospheric and static respiratory compliance and tidal volumes were markedly reduced. In contrast, closed suctioning during ongoing ventilation with PCV and CPAP 10 cmH_2O caused less ventilatory side-effects (see Figure 10). All respiratory parameters differed marginally with suction duration of 5, 10 or 20 seconds or catheter size.

Mean pulmonary arterial pressure was significantly raised during open suctioning for 10 s with a 14 Fr catheter from baseline value of 29 ± 5 mmHg to 34 ± 9 mmHg 1 min after suctioning ($p < 0.05$). Heart rate and mean arterial pressure were not significantly affected by the suctioning procedures and the circulatory parameters differed marginally with suction duration of 5, 10 or 20 seconds or catheter size.

Irrespective of open or closed suctioning, variables returned to baseline within 5 minutes after suctioning (see Figure 10).

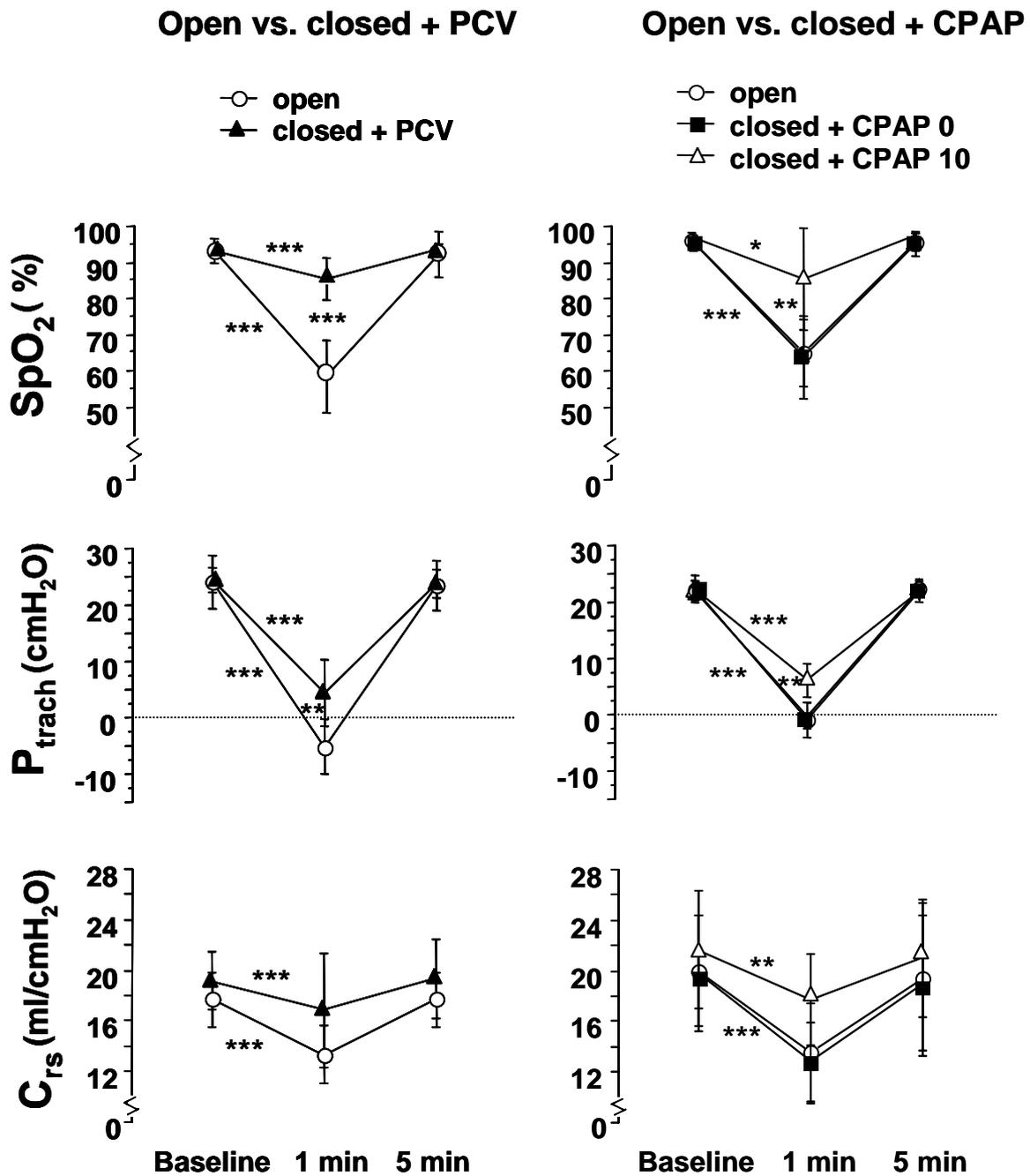


Figure 10. Effect on oxygen saturation (SpO₂), peak tracheal pressure (P_{trach}) and compliance (C_{rs}) during and after suctioning 10 s with 12 Fr catheters in a lavaged lung. In the left column CSS during PCV compared to OSS (n=6). In the right column CSS during CPAP of 0 or 10 cmH₂O (n=6). Baseline vs. 1 min value and open versus closed system * p<0.05, ** p<0.01, *** p<0.001. (Paper II)

PAPER III

EFFECT OF OPEN AND CLOSED SUCTIONING ON FRC AND GAS EXCHANGE IN EXPERIMENTAL LUNG INJURY

Changes in impedance and lung volume obtained by the stepwise super syringe inflation were well correlated, $R^2 > 0.95$. Baseline FRC before suctioning was 715 ± 171 ml and did not change significantly 10 min after suctioning. Disconnection before open suctioning induced an instant decrease in FRC by $54 \pm 14\%$ and suctioning $74 \pm 20\%$. VCV in the postsuction period recruited lost lung volume somewhat faster than PCV and this also was reflected in a faster restoration of arterial oxygenation and saturation in VCV mode compared to PCV (See Figure 11 and 19). There were minimal, transient effects on FRC and oxygenation during closed suctioning irrespective of ventilatory mode.

EFFECT ON TOTAL LUNG MECHANICS

At insertion of the closed suctioning catheter in VCV, peak tracheal pressure increased from baseline pressure of 24 ± 3 to 28 ± 3 cmH₂O ($p < 0.001$). This increase was not seen in PCV. During closed system suctioning tracheal pressure decreased in both VCV and PCV but not below zero. During open suctioning, peak tracheal pressure decreased to sub-atmospheric pressures of -6 ± 5 cmH₂O (range -23 to 0 cmH₂O). Directly after open suctioning when the ventilator was started with VCV, tracheal pressure was slightly increased from base line 25 ± 6 to 29 ± 5 cmH₂O ($p < 0.01$) and this increase was not seen in PCV (See Figure 11).

Compliance could not be measured during open suctioning as there was no tidal ventilation. At the first registration after reconnection and ventilation 30 seconds after suctioning compliance showed a significant decrease using either VCV or PCV but the decrease was more pronounced in PCV mode ($p < 0.05$). VCV maintained Vt in contrast to PCV ($p < 0.05$). (see Figure 11)

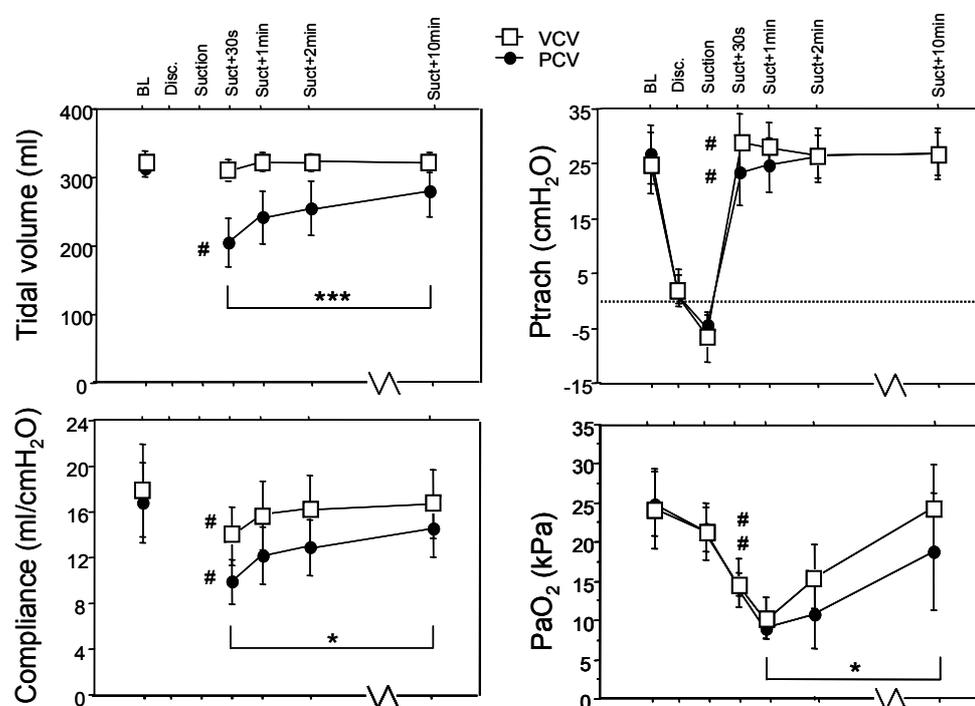


Figure 11. Effect on peak tracheal pressure (Ptrach), tidal volume, compliance and arterial oxygen tension (PaO₂) during open suctioning with either VCV or PCV in a lavaged lung. Baseline vs. 30 s # $p < 0.05$; VCV vs. PCV

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. (Paper III)

REGIONAL EFFECTS OF OPEN SUCTIONING

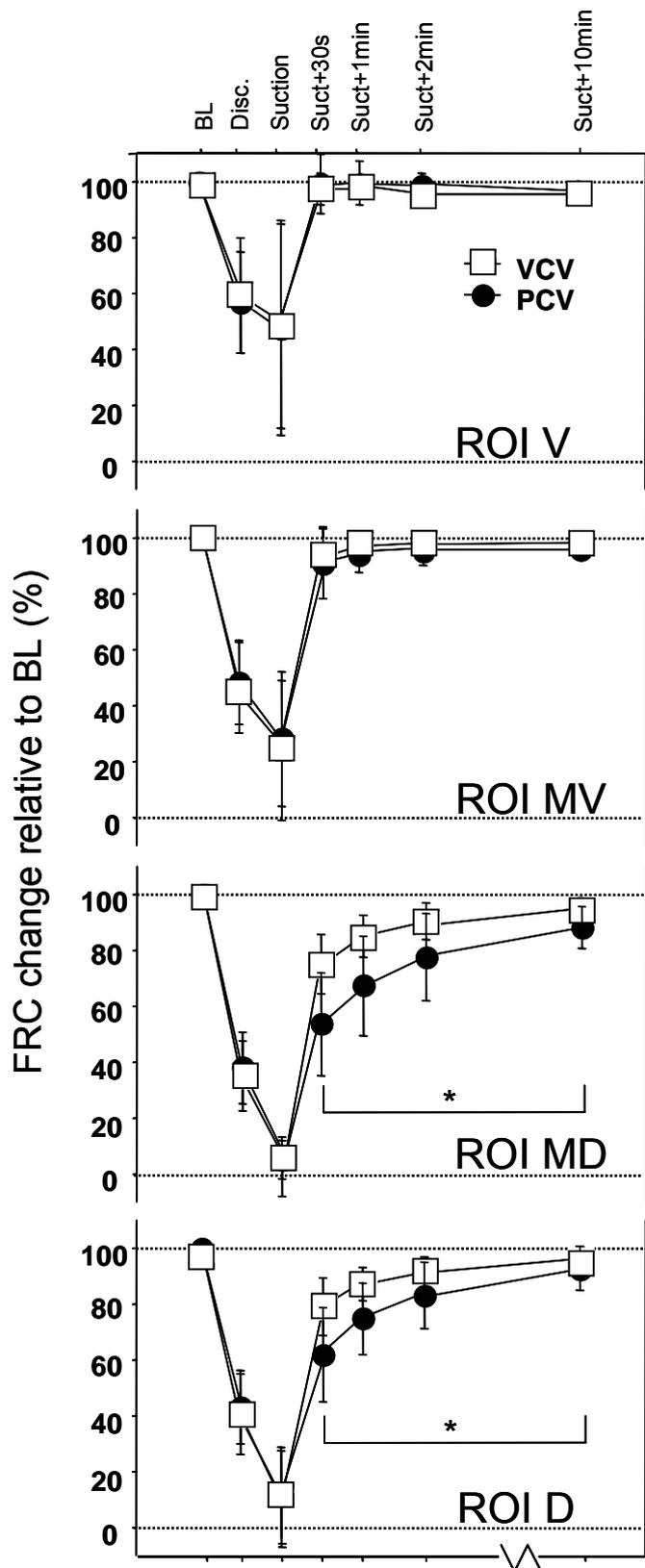
At disconnection before suctioning and during suctioning, loss of volume and compliance was more pronounced in the two dorsal regions of interest. At disconnection approximately 65% of baseline FRC was lost in the mid-dorsal and dorsal regions and during suctioning they were nearly “emptied”. Volume restitution after suctioning was faster in the two ventral regions irrespective of ventilation mode. In the two dorsal regions there was a significantly faster recruitment with VCV compared to PCV (see Figure 12). Compliance recovered more slowly during PCV than during VCV and the difference was observed primarily in the two dorsal regions (see Figure 13).

PAPER IV

SUCTION FLOW AND TUBE RESISTANCE DURING FIBER-BRONCHOSCOPY

Suction flow through a 16 Fr bronchoscope (OD 5.2 mm) at vacuum level -20, -40, -60 and -80 kPa was 5, 8, 11 and 17 l/min. Corresponding values for a 12 Fr bronchoscope (OD 4.0 mm) were 3, 4, 4 and 5 l/min. Tube resistance increased linearly with flow, $R^2 > 0.99$. When a 16 Fr bronchoscope was introduced in an ETT no 8, tube resistance increased about eight times and in an ETT no 7 thirty times. Corresponding values for a 12 Fr bronchoscope were three and seven times (see Figure 14).

Figure 12. Regional distribution of lung volume reduction relative to base line (BL) in ventral (V), midventral (MV), middorsal (MD) and dorsal (D) region of interest (ROI). Dorsal regions of lavaged lungs are most affected by open system suctioning and post-suctioning ventilation mode, VCV or PCV. * $p < 0.05$ ($n=8$). (Paper III)



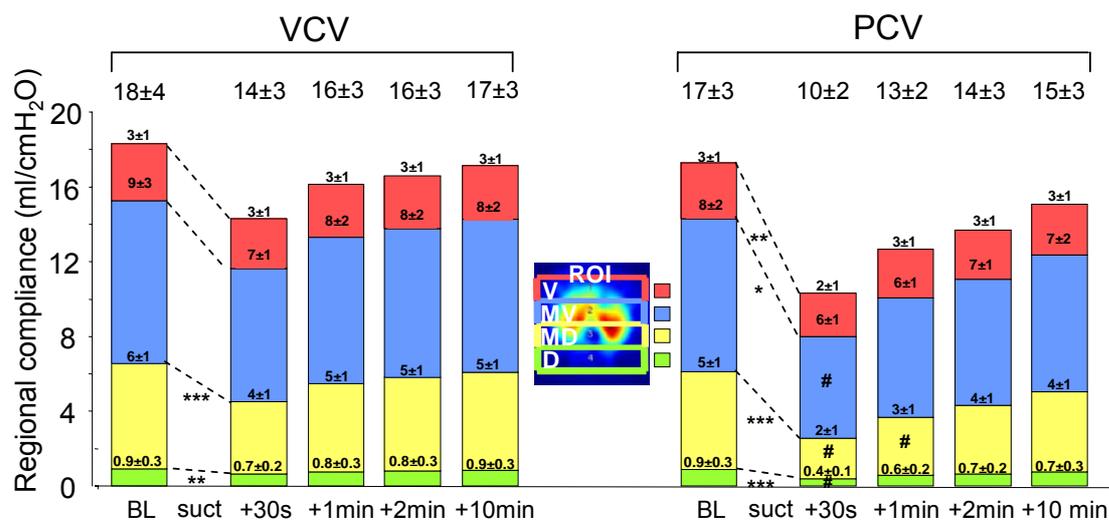


Figure 13. Regional distribution of compliance reduction during open suctioning in lavaged lung. Restitution of compliance was significantly slower during PCV than during VCV ($p < 0.05$) primarily in the midventral (MV), middorsal (MD) and dorsal ROIs. VCV vs. PCV # $p < 0.05$; Baseline vs. measuring points * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ (Paper III).

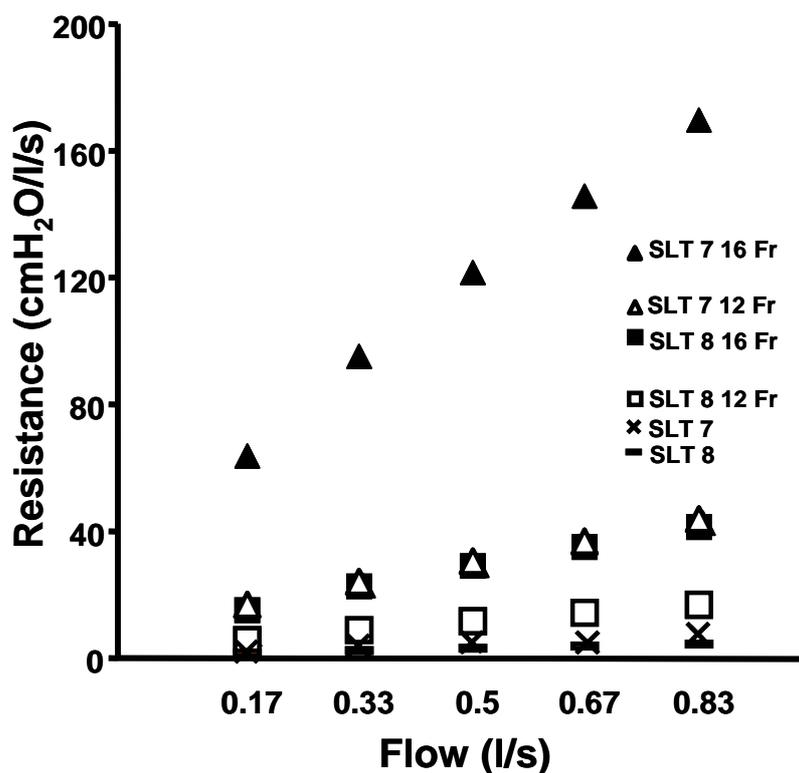


Figure 14. Tube resistance increases linearly with flow. When a 16 Fr bronchoscope was inserted into an ETT no 7 tube resistance increased approximately 30 times (IV).

EFFECT OF FIBER BRONCHOSCOPIC SUCTIONING ON “BRONCHIAL” PRESSURE, TIDAL VOLUME AND FRC CHANGES IN A WATER LUNG MODEL

Insertion of a 16 Fr bronchoscope in an ETT 7 during VCV raised the peak airway pressure (P_{peak}) measured in the “bronchi” with approximately 10 cmH₂O and the end-expiratory pressure (P_{exp}) with about 5 cmH₂O bilaterally. This was accompanied by a 50% increase in FRC from baseline and a unchanged tidal volume distribution. In PCV the airway pressures and FRC were not affected by insertion of the bronchoscope but tidal volume was reduced with 80%. Suctioning with – 60kPa during VCV reduced the tidal volume in the left “lung” with 80%. During suctioning and PCV the ventilator was not able to deliver any tidal volume at all to the lung. FRC was reduced with approximately 50% in both lungs and the peak and end-expiratory pressure reached sub-atmospheric levels irrespective of tube size or ventilator mode (see Figure 15).

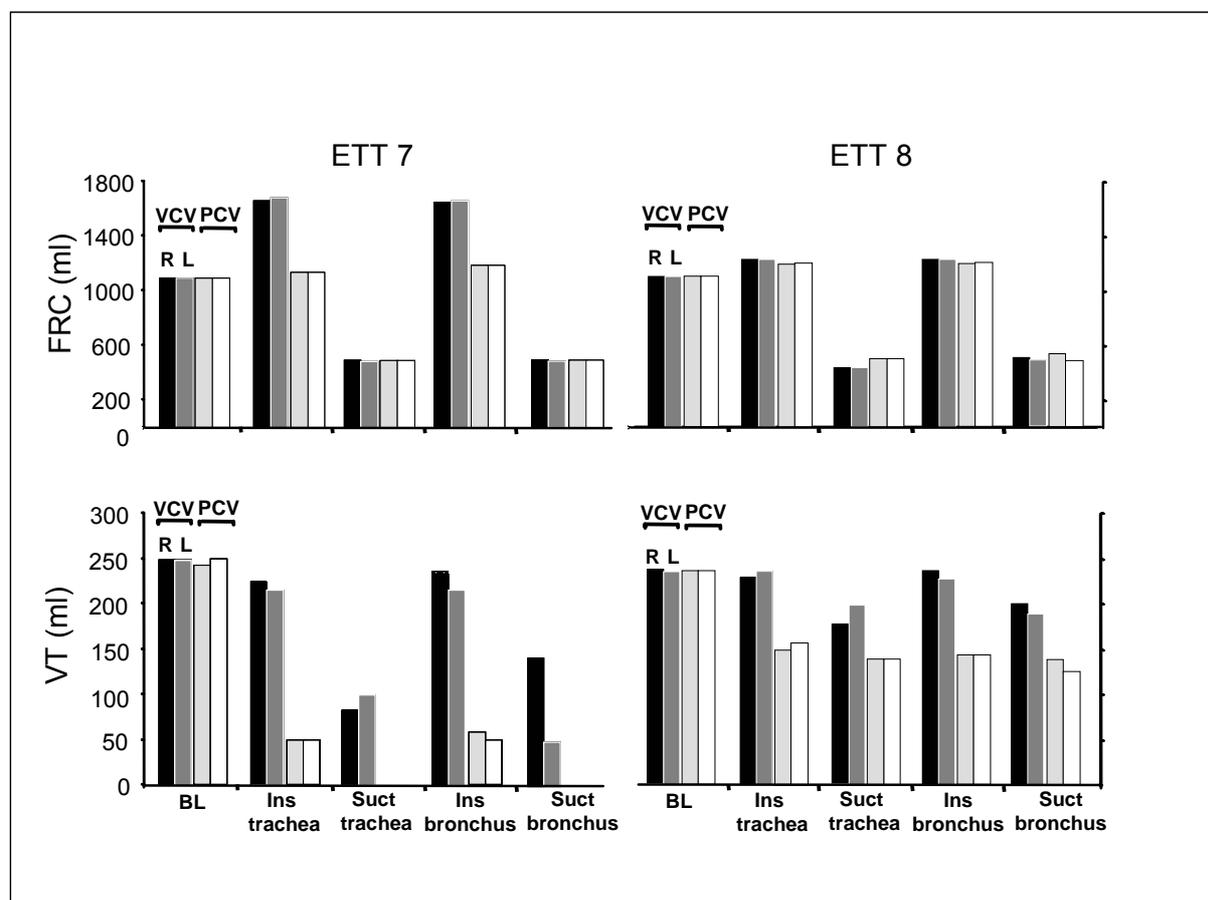


Figure 15. Changes in FRC and tidal volume during closed bronchoscopic suctioning in the water lung model (Paper IV). During insertion of the bronchoscope in an ETT no 7 with VCV, there was a marked increase in FRC and during PCV a marked reduction of tidal volume. During suctioning FRC decreased with 50% irrespective of ventilation mode but tidal volume was better preserved in VCV. Insertion (ins) and suction (suct).

..AND IN ALI PATIENTS

Changes in tidal electrical impedance and tidal volume variations were well correlated, $R^2 > 0.95$. In coherence with the findings in the water lung model, fiberbronchoscopic suctioning in ALI patients resulted in a marked reduction of tidal volume, FRC and tracheal pressure. In the worst cases this was accompanied by desaturation. In Figure 16, eight EIT recordings are presented showing the course of the FOB suctioning induced lung collapse in 4 patients.

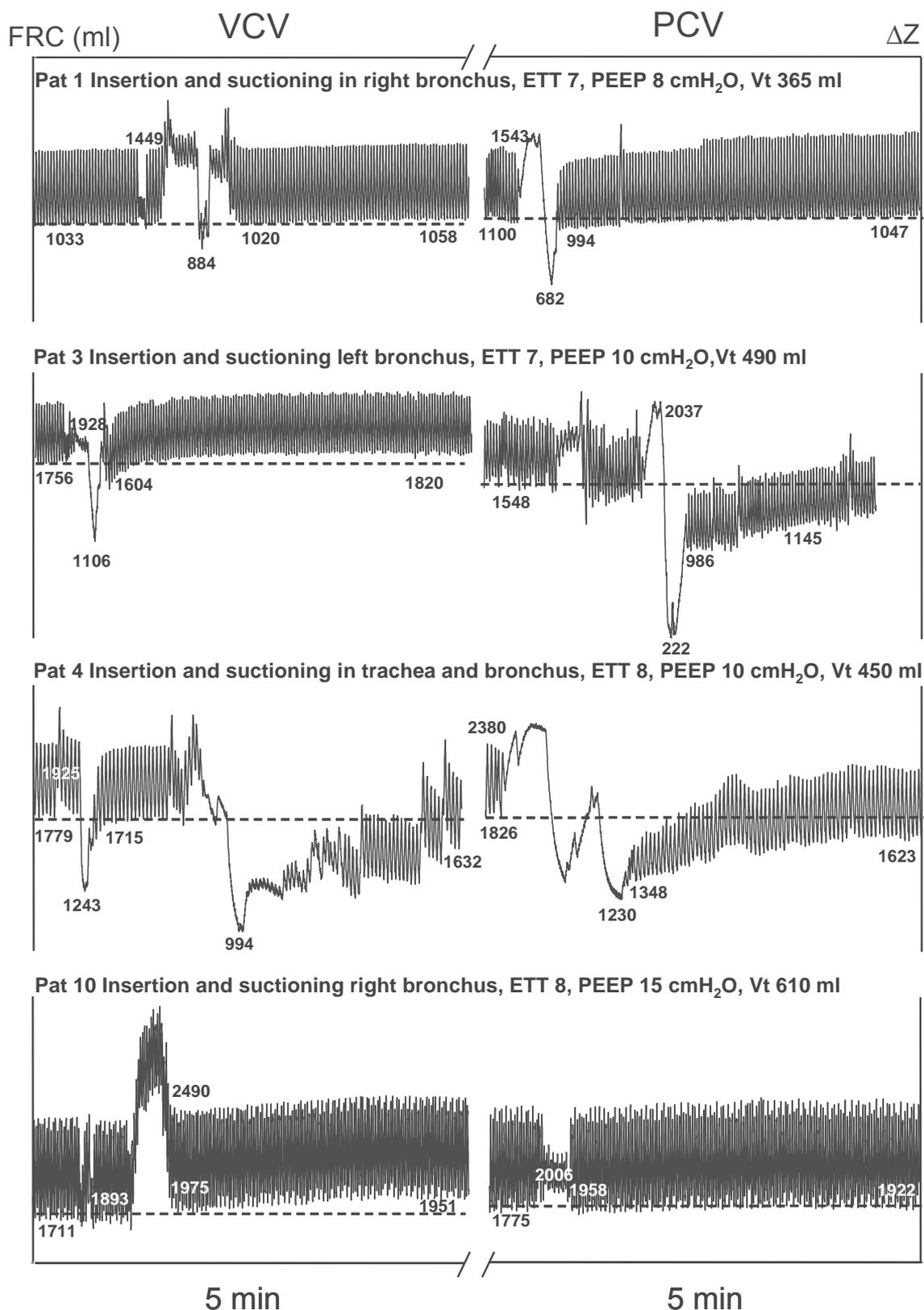


Figure 16. EIT recordings from four ALI patients during closed suctioning with a 16 Fr bronchoscope in either VCV or PCV. In patient no 3 there was a marked difference between VCV and PCV mode post-suctioning. In patient no 4 a large lung collapse was induced by suctioning in the trachea and then by advancing the bronchoscope into one of the main bronchi, in spite of ETT no 8 and a PEEP-level of 10 cmH₂O. (Paper IV)

During insertion of the bronchoscope in VCV, P_{peak} increased from baseline value 27±6 cmH₂O with 6±5 cmH₂O (p<0.01). This increase was not seen in PCV (p<0.05). P_{exp} increased similarly in both modes from baseline 11±5 cmH₂O with 7±5 cmH₂O in VCV and 5±3 cmH₂O in PCV (p<0.01). In contrast to the findings in the water lung model, FRC increased during insertion irrespective of ventilation mode, from baseline value of 1392±403 ml with 297±233 ml in VCV and 324±184 ml in PCV. Tidal volumes were better preserved in VCV where the decrease from base line value 508±93 ml was -236±158 ml compared to -358±94 ml in PCV (p<0.05 VCV vs. PCV). During suctioning V_t decreased further from baseline with -272±110 ml in VCV and -405±88 ml in PCV (p<0.01 VCV vs. PCV). FRC decreased from baseline with -497±481 ml in VCV and -496±483 ml in PCV. P_{peak} and P_{exp} decreased below set PEEP or below zero in several of the patients irrespective of ventilation mode (see Figure 17). In the post-suctioning period a short increase of peak tracheal pressure was seen in VCV, 7±9 cmH₂O (range -7 to 40 cmH₂O) in several of the patients. This was not the case with PCV where the P_{peak} was -4±1 cmH₂O below baseline 30 seconds after suctioning (p<0.01 VCV vs PCV). Consequently the tidal volume was faster restored with VCV than with PCV, 416±121 ml vs. 274±144 ml 30 seconds after suctioning (p<0.01 VCV vs. PCV). There was also a tendency towards a faster recruitment of FRC during VCV than with PCV, 1340±397 ml vs. 1127±503 ml 30 seconds after suctioning. Corresponding values 1 min after suctioning were 1356±397 and 1176±523 respectively. Crs decreased during insertion and suctioning in both modes, in VCV from BL 32±9 to 17±10 ml/cmH₂O and in PCV from BL 30±7 to 16±10 ml/cmH₂O. Corresponding values during suctioning were 20 (1-76) and 14 (1-39) ml/cmH₂O, mean (range).

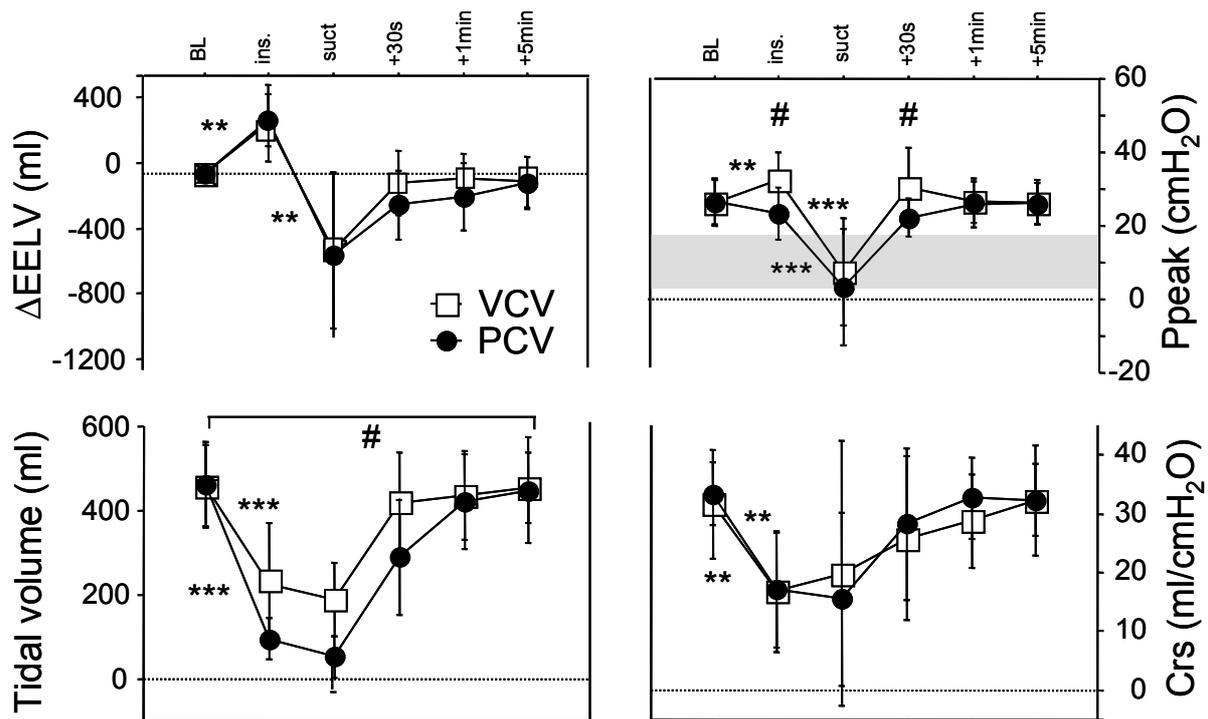


Figure 17. Changes in end-expiratory lung volume (Δ EELV), compliance (Crs), tidal volume and peak tracheal pressure (P_{peak}) during closed bronchoscopic suctioning in thirteen ALI patients. Grey area in tracheal pressure measurements represents range of base line end expiratory pressure (3-18 cmH₂O). VCV vs. PCV # p<0.05; Baseline vs. measuring points * p<0.05, ** p<0.01, *** p<0.001 (IV).

Oxygen saturation (SpO₂) decreased during FOB suctioning from baseline value of 96±2 to 94±4% (range 87-99%) in VCV (p<0.05) and from 97±2 to 94±4% (range 86-99%) in PCV (p<0.05). Arterial oxygen and carbon dioxide tension was at base line levels 10 minutes after FOB suctioning both in VCV and PCV.

DISCUSSION

MAIN FINDINGS

- In a mechanical lung, insertion of a closed suction catheter during volume control ventilation caused high intrinsic PEEP levels, a finding not seen during pressure control ventilation or CPAP.
- The steady state suction flow through suction catheters was more than twice the normal minute ventilation provided by the ventilator in the ICU.
- Closed system suctioning had the potential to induce lung collapse if thick suction catheters in narrow tubes and high vacuum levels were used.
- In lavaged porcine lungs, closed system suctioning during positive pressure ventilation prevented lung collapse induced by disconnection and suctioning, but open suctioning was about five times more effective than closed system suctioning in removing secretions from an artificial trachea.
- Closed system suctioning during CPAP of 0 cmH₂O caused side-effects similar to open suctioning and was equally effective.
- Open system suctioning in experimental lung injury induced a large loss of FRC already at disconnection of the ventilator prior to suctioning.
- The dorsal regions of lavaged lungs were predominantly affected by disconnection and suctioning.
- After open suctioning restitution of lung volume and compliance were slower during pressure controlled vs. volume controlled ventilation in experimental lung injury.
- Restitution of lung volume and compliance after bronchoscopic suction through a tight seal connector showed a more varying pattern in ALI patients but the worst situation occurred during pressure controlled ventilation.
- Large increases in tube resistance occurred when wide bronchoscopes were inserted into standard sized endotracheal tubes.

METHODOLOGICAL AND EXPERIMENTAL CONSIDERATIONS

ETHICAL ISSUES

Mechanically ventilated patients with ALI or ARDS have a high mortality. It is therefore important to improve respiratory care of these patients [11, 25, 95, 96]. Animal studies play an important part in expanding our knowledge in this research area, leading to better clinical routines to minimize the risks associated with mechanical ventilation. Still it can be questioned whether animals should be sacrificed for medical and experimental reasons. We feel that animals can be used for this reason provided that they are treated correctly. The pigs used in our studies (Paper II and III) were taken care of by educated personnel and treated according to the NIH guidelines for the care and use of laboratory animals [82]. There are also several ethical issues concerning research on patients with an impaired autonomy, i.e. sedated and ventilator treated patients (Paper IV) as they can not give informed and written consent. However if we exclude this patient category i.e. acute critically ill patients from research we will also exclude this group of patients from advancement in medical treatment, which is unfair. We have used informed and written consent, from next of kind, in accordance with the ethical directives of the European Union [97, 98], based on the Helsinki declaration [99] and with permission from the local ethical committee of Gothenburg. If possible patients were informed later in order to be able to give consent.

LUNG MODELS AND STUDY DESIGN

In the bench tests performed with a mechanical lung (Paper I and II) we could not study any effects of diaphragmatic movements when the ventilator was disconnected. These effects can only be studied in patients and animals and the effects will vary with sedation level and end-expiratory lung volume. The water lung model used in Study IV gave an approximate simulation of compliance and the volume changes were read visually off a scale. In the animal studies (II and III) we used a relatively small number of animals and an easily recruitable lung injury model frequently used in research to mimic ALI/ARDS. The lung model is prone to collapse and the inflammatory reaction is comparatively mild. It can be regarded as a model of early ARDS and is easier to recruit than more inflammatory types of lung injury, such as the oleic acid and pneumonia induced models [100, 101]. We are aware of that this model may only represent subsets of ALI/ARDS patients thus not the whole spectrum of the ALI/ARDS disease. Due to the relatively small number of patients in our most recent study (Paper IV), it could be considered as observational.

MEASUREMENTS OF FUNCTIONAL RESIDUAL CAPACITY AND EELV

The nitrogen washout/washin method for FRC measurements used (Papers III and IV) is new but promising and evaluated in a number of studies [87, 92]. It is computerized and currently in clinical use, incorporated into modern ventilators and therefore suitable for our studies. The EIT technique has been evaluated in research for 15 years but only as a modern application the last 3-4 years. The EIT device used (Papers III and IV) for continuous FRC evaluation measures impedance changes in a ~ 5 cm thick slice of the thoracic cavity. The thickness of the slice is radius dependent [86] but also electrode size dependent. Movements of the lung could result in different parts of the lung being measured during a respiratory cycle. The devices used in Study III and IV are research prototypes. They have been evaluated a few studies [85, 87, 102]. It is at present the only radiation free, bedside tool for continuous monitoring of global and regional changes in EELV in contrast to the CT technique.

PRESSURE AND CALIBRE UNITS

At present the terminology regarding pressure and calibre units is somewhat confusing both in the clinical situation and in publications on mechanical ventilation and endotracheal suction. The manometers' vacuum pressure is often given in kilopascals (kPa) or millimetres of mercury (mmHg) and the airway pressure is measured and displayed in cmH₂O on the ventilators and monitors. It is not clear to all users that when the vacuum source is set on -40 kPa or -300 mmHg that is equal to -400 cmH₂O and in a worst case scenario this could actually be the negative pressure generated in the lungs during suctioning. The endotracheal tubes' inner diameter is given in millimetres (mm) and the suction catheters outer diameter is given in French (Fr). 1 Fr equals 0.33 mm, thus 12 Fr equals an outer diameter of 4 mm. This makes it less easy to see the relationship between the size of the tube and the catheter and whether the catheter is too thick in relation to the tube. To make it even more confusing another calibre unit is also frequently used, Chierri (Ch). 1 Ch is equal to 1 Fr.

SUCTION FLOW AND TUBE RESISTANCE

In the mechanical lung (Paper I), using a vacuum level of -50kPa (-375 mmHg, -500 cmH₂O), the initial suction flow through a 12 Fr (Ø 4.0 mm) catheter, when the switch was opened, was around 18 l/min for some seconds. The duration of this "high flow period" depends on the size of the suction bottle and will be shorter with a small one than for a large one. The flow reaches a steady state at 13 l/min. The corresponding values for a 14 Fr (Ø 4.6 mm) catheter was 43 and 23 l/min. It is noteworthy that changing catheter diameter with 0.6 mm results in a large increase in flow, especially the initial flow. When closed system suctioning was started with a 14 Fr catheter, 670 ml is suctioned during the first second and if the trigger function of the ventilator is deactivated or secretions inside the tube prevent ventilation during suctioning, this volume will be removed from the lungs. This could also be applied to bronchoscopic suctioning which has been proposed as an alternative as it enables a directed, closed suctioning manoeuvre. However, suction flow through a bronchoscope has the potential to empty the lungs efficiently as a 16 Fr (Ø 5.2 mm) bronchoscope can produce a high flow of 17 l/min at steady state when using a vacuum level of -80 kPa (-450 mmHg, -800 cmH₂O), shown in the bench test of Study IV. This in combination with a thick bronchoscope in a small tube, creating a high tube resistance and can produce a severe lung collapse as shown in the bench test and in the ALI patients (Paper IV).

MONITORING OF ENDOTRACHEAL SUCTIONING

Several experimental and patient studies have shown that lung collapse induced by disconnection and/or suctioning can result in hypoxemia, increased pulmonary shunt and bronchoconstriction [36-48]. By adequate on-line respiratory monitoring during suctioning manoeuvres the patients most susceptible to disconnection and suctioning can be identified. In our present studies (II, III and IV) we have used tracheal pressure catheters to measure airway pressure, not in the ventilator but in the trachea, avoiding the tube resistance influence on airway pressure measurements [103]. This catheter also provides the possibility to continuously follow dynamic changes in compliance and the technique is currently available for clinical use [104]. In Study III, tracheal pressure measurements were used to calculate global and regional compliance changes during suctioning assuming no flow at the end of inspiration and expiration. This was accomplished by using N₂ wash out/in FRC technique [92] and EIT measurements that gave us valuable information on which regions of the lavaged lungs were mostly affected by open suctioning. Interestingly, the volume loss was unevenly distributed and the greatest deterioration of FRC and compliance took place in the dorsal regions. The dorsal lung collapse was followed by a rapid decrease of arterial oxygen tension and an increase in arterial carbon dioxide tension measured by on-line intra

arterial blood gas analysis. This is probably explained by the fact that the superimposed pressure makes the dorsal parts, where perfusion is highest, more prone to collapse [105-107]. The rapid de-oxygenation could be interpreted as an indirect sign of an increased pulmonary shunt in the dorsal regions of the lungs. It has been proposed that monitoring of tube resistance or airway flow curves could be used as an indication “trigger” for suctioning [108]. We have not assessed this in our present studies. Reliable, non-invasive, bedside monitoring techniques is essential to adequately handle suctioning procedures and suctioning induced lung collapse in the ICU. As shown in ALI patients (Paper IV) some were affected far more by the FOB suctioning procedure. By identifying these patients, individual evaluations and adjustments of ventilator treatment can be made to minimize the risks associated with suctioning procedures.

OPEN VERSUS CLOSED SYSTEM SUCTIONING

The practice of endotracheal suctioning of ventilator treated patients is necessary to remove secretions to prevent obstruction of the endotracheal/tracheal tube and lower airways. The risk of serious side-effects increases with the severity of the patients’ disease. The higher the PEEP level needed, the greater the risk of severe heart/lung interactions, especially loss of end expiratory lung volume and hypoxemia, and already at disconnection of the ventilator [32]. Regarding this, it seems preferable that suctioning should be performed on strict indications such as the presence of bubbling secretions in the trachea or increasing airway resistance [49]. The closed system was introduced in the early eighties as it permits ventilation during suctioning, avoiding disconnection from the ventilator. Several studies including our present findings (Paper II and III) have shown that closed system suctioning preserves lung volumes, airway pressure and oxygenation in contrast to open suctioning (Table 3). However, closed system suctioning is no guarantee for avoidance of negative pressures or loss of lung volume during suctioning, as we have shown during steady state suctioning (Paper I) and during bronchoscopic suctioning (Paper IV). The lesser side-effects of closed system suctioning are highly dependent on how the suctioning procedure is handled. As shown in Study I the use of large suction catheters, high vacuum levels or disadvantageous ventilator settings can result in similar or worse side-effects than an open suctioning procedure. There is also a possibility to create a completely closed system if the resistance in the tube cannot be overcome by the ventilator, when the interior surface is lined with thick secretions[65, 109] and/or a very thick catheter is used, and/or the trigger function of the ventilator is deactivated. In such a situation the suctioning flow will empty the lungs rapidly and if the suctioning procedure has sufficient duration the pressure in the lungs will be the same as the vacuum level in the suctioning system. This could lead to damage to both patient and ventilator.

Research has previously been focused on the side-effects, rather than the effectiveness of secretion removal. Thus only a few qualitative, semi-quantitative or quantitative studies are available (Table 3). The results from the three patient studies are disparate. In a quantitative study from 1991 Witmer et al showed that the mass of recovered secretions was the same comparing open and closed suctioning by weighing the suction systems before and after suctioning. In 2000 a semi-quantitative study by Combes et al showed the same result. However, the amount of aspirate was estimated according to a four-point scale and the quantity of secretions available for suctioning was unknown. In vivo, condensed water accumulates in the breathing system, the connected closed suction catheter and its protective sleeve [110]. Thus, the mass of secretions aspirated with a closed system could be increased due to water. The bench test in Study II circumvented these problems by determining the efficacy in vitro, which allows the deposition of a standardised volume of “secretions” at a fixed position in the trachea and observation of the suctioning catheter tip as well as movement of the “secretions” during suctioning. In our mechanical model open suctioning and closed suctioning during CPAP of 0

cmH₂O was 4-5 times more effective in removing “secretions” (Figure 9). In 2006 Lasocki et al assessed the mass of secretions aspirated in 18 patients by weighing and in this study open suctioning also removed about 4-5 times more secretions than closed suctioning (Table 3).

Resistance to flow through the endotracheal tube, with the inserted suction catheter or bronchoscope, is high (Paper IV). This increased resistance to flow from ambient air towards the suction catheter tip in the trachea is larger than the resistance from the lungs, because the cross-sectional area of the trachea is about 250 mm² and the area between the inner surface of a 7 mm inner diameter (ID) endotracheal tube and a 12 Fr suction catheter (4 mm outer diameter) is 38–13 mm² = 25 mm² (Table 1). Thus, during open suctioning, gas is aspirated from the lungs rather than from room air. During closed system suctioning and ongoing mechanical ventilation, with normal trigger sensitivity sub-atmospheric lung pressures are avoided as the ventilator interpret the suction flow as a start of a breath by the patient. It responds by delivering a tidal volume which helps overcome the resistance of the endotracheal tube and feeds the suction catheter with gas, minimising suction from the airway below the suction catheter tip. During the bench test the triggered inspiratory gas inflow could be seen to push secretions away from the catheter tip and there was less likelihood of movement of the secretions from the lungs (Paper II). Conversely, during open suctioning, gas aspirated from the lung will probably facilitate the movement of secretions towards the suction catheter. Finally, the rapid change in lung volume following disconnection of the ventilator for open suctioning may initiate a cough; moving secretions towards the suction catheter (see Figure 18).

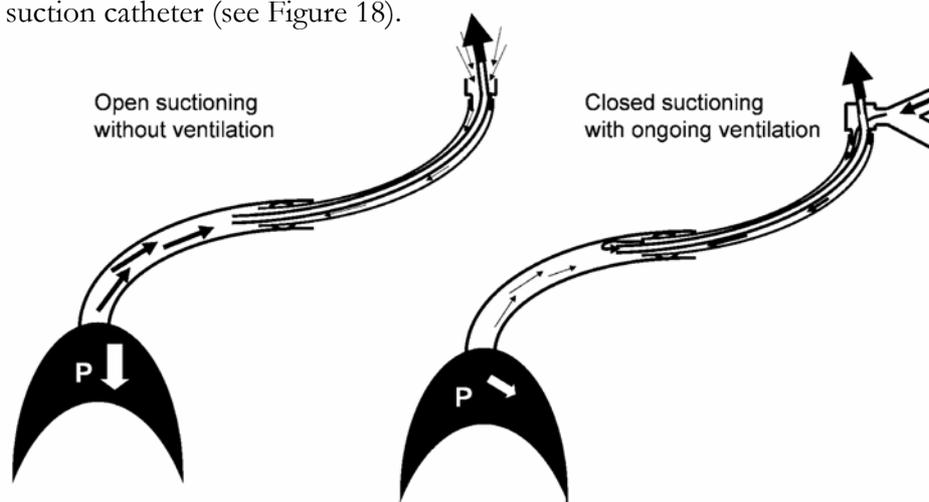


Figure 18. Lung mechanical explanation of the different flow conditions during open and closed suction.

When handled correctly, closed system suctioning has less side-effects than open suctioning, but the suctioning procedure may have to be repeated several times in order to reach the same degree of secretion removal as during an open suctioning procedure.

Fiberbronchoscopic suctioning has been suggested as an alternative to blind endotracheal suctioning as it offers a more directed intervention supposedly limiting the traumatic effect on the airways. Preferably it is performed through a tight seal connector allowing mechanical ventilation during suctioning. However the few bench and patient studies that exist suggest that these manoeuvres produce side-effects comparable to an open suctioning [71-73]. These findings were confirmed in the water lung model and patient study (Paper IV) as FOB suctioning induced marked decreases in lung volume, compliance and tracheal pressure. Hence FOB suctioning can not be regarded as a “safe” alternative to standard endotracheal suctioning.

VENTILATION MANAGEMENT AND ENDOTRACHEAL SUCTIONING

Choice of preoxygenation method, suction system, ventilator settings and lung recruitment has been addressed in several studies. Desaturation caused by suctioning procedures is a sign of loss of FRC, decrease of compliance and increased pulmonary shunt. Preoxygenation is effective in preventing suctioning induced decrease of PaO_2 [50]. However, preoxygenation does not prevent lung collapse but simply conceals its' consequences. Preoxygenation with 100% of oxygen could even contribute to formation of atelectasis [111]. Some models of modern ventilators have a preoxygenation function where the FiO_2 level is elevated with 0.3 for a couple of minutes which seems a more physiologic alternative. In our animal and patient studies protocols (Paper II, III and IV) we have chosen not to preoxygenate in order to be able to follow the time course of the arterial oxygenation during suctioning. (see Figure 19)

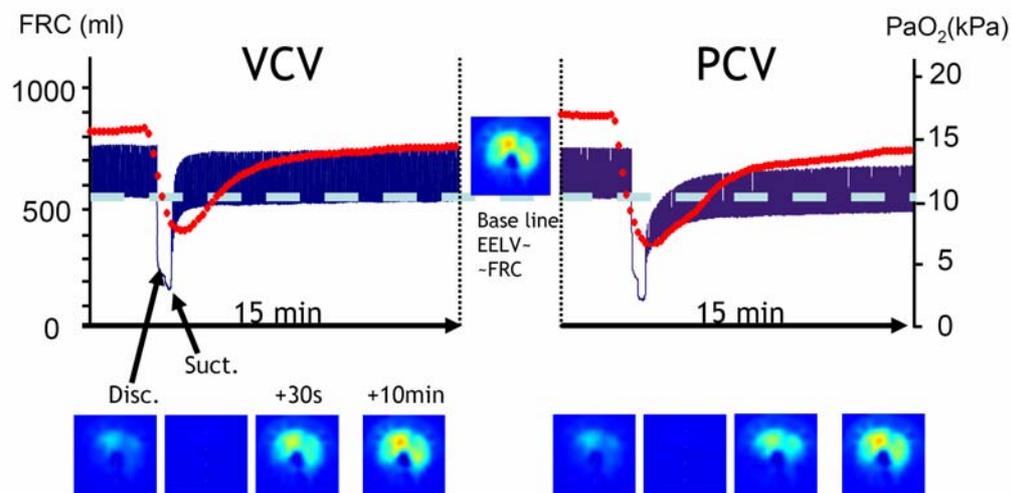


Figure 19. Time course of changes in FRC and PaO_2 in one animal (III) during disconnection (Disc.) and open suctioning (Suct.) with VCV or PCV. Red dotted line = PaO_2 ; dark blue dotted line = lung volume changes;

When using closed system suctioning disconnection of the breathing apparatus is avoided and mechanical ventilation maintained. This reduces the side-effects of suctioning, provided that adequate ventilator settings, catheter sizes and vacuum pressure are used (see above). In a bench test by Taggart et al 1988 negative airway pressures occurred during closed system suctioning [112]. Our results in the bench tests (Paper I and IV) confirm this. Additionally insertion of the closed system catheter or bronchoscope during VCV resulted in high intrinsic PEEP-levels, with maintained tidal volume. In PCV the intrinsic PEEP effect was not seen but tidal volumes were reduced. During suctioning a marked reduction of lung volume was seen in both modes in spite of a closed system. The intrinsic PEEP effect during closed suctioning could be considered a type of uncontrolled recruitment manoeuvre and there are case reports of pneumothorax when using closed suction catheters on paediatric patients [48]. As shown in the bench tests of Study I and IV and in some of the patients (Paper IV) the positive effects of avoiding disconnection of the breathing system without warning may be turned into a negative event with high intrinsic PEEP levels as well as marked negative pressure levels. In 1991 Brochard et al showed in seven mechanically ventilated patients that constant flow insufflation of oxygen during endotracheal suctioning maintained airway pressure around 10 cmH_2O and prevented fall in lung volume and desaturation [113]. In Study I closed suctioning during CPAP mode of 10 cmH_2O prevented intrinsic PEEP and sub-atmospheric pressures. In Study II closed suctioning in experimental lung injury during CPAP of 10 cmH_2O resulted in modest changes of circulatory and respiratory variables comparable to closed suctioning with PCV. Interestingly closed suctioning during CPAP of 0 cmH_2O resulted in similar side-effects as compared to open suctioning. The reason for this is that suctioning in a completely closed system without ongoing ventilation creates a

large lung collapse as the negative pressure in the lungs has the possibility to reach the vacuum pressure generated by the suction apparatus. This is probably the reason why the secretion removal during closed suctioning and CPAP of 0 cmH₂O was comparable to open suctioning. Closed suctioning with CPAP of 10 cmH₂O was about 4-5 times less effective. Closed system suctioning during continuous positive pressure ventilation with a moderate pressure level could be a tolerable compromise to optimize efficiency and side-effects. Another alternative is to convert to open suctioning combined with a subsequent recruitment manoeuvre [114, 115]. However, some recruitment manoeuvres are considered clinically cumbersome and potentially harmful procedures [22, 64, 85, 116].

When using open system suctioning, an easy way of recruiting diseased and collapsed lung tissue is proposed in Study III based on findings from Almgren et al 2003. Healthy pigs recovered gas exchange and lung volume faster with volume control ventilation than with pressure control ventilation in the post-suctioning period of 30 min [117]. In the lung lavaged pigs, suctioning induced hypoxemia was significantly faster reversed when VCV instead of PCV was used during the post-suctioning period of 10 min (Paper III). 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 tidal volumes, approximately one-half of baseline, which was not sufficient to recruit the lung. During VCV tidal volume 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 after 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 tidal volume resulted in higher recruiting pressures. Increasing the set pressure and/or PEEP when using pressure control in the post-suctioning period of 10 to 20 min would probably recruit the collapsed lung tissue in the same way, but this was not tested. Further studies are needed.

Two recent meta-analyses on open and closed endotracheal suctioning with special reference to ventilator associated pneumonia and impact on morbidity/mortality found no difference in outcome between the two methods [13, 58] (Table 3). Within the same patient there is often a mix between closed and open suctioning procedures [69] and one possible explanation could be that closed suction is converted to open suctioning due to problems with secretion removal. Thus in patients with respiratory insufficiency and viscous secretions there may still be an indication for open suctioning, preferably with a subsequent recruitment manoeuvre, which positive effects on ventilation and gas exchange has been described by Dyhr et al in 2003 and by Almgren et al in 2004. There is a recommendation in existing evidence based clinical guidelines to recruit the lungs after open suctioning [22, 50] but no consensus or algorithm describing exactly how to perform this recruitment. Preferably this would have to be an easy manoeuvre, performed with only a few adjustments of the ventilator settings and cautiously done, aimed at not worsen the cardiopulmonary side-effects of the suctioning procedure. One easy way is to use volume controlled ventilation as described in Paper III or perhaps use a slow low pressure recruitment manoeuvre [85] based on a moderate elevation of PEEP in combination with repeated end-expiratory pauses every other minute during 15 to 20 minutes. Keeping in mind the lung collapse that could follow after bronchoscopic suctioning (Paper IV) these recommendations could be extended to concern these procedures as well (see Figure 20).

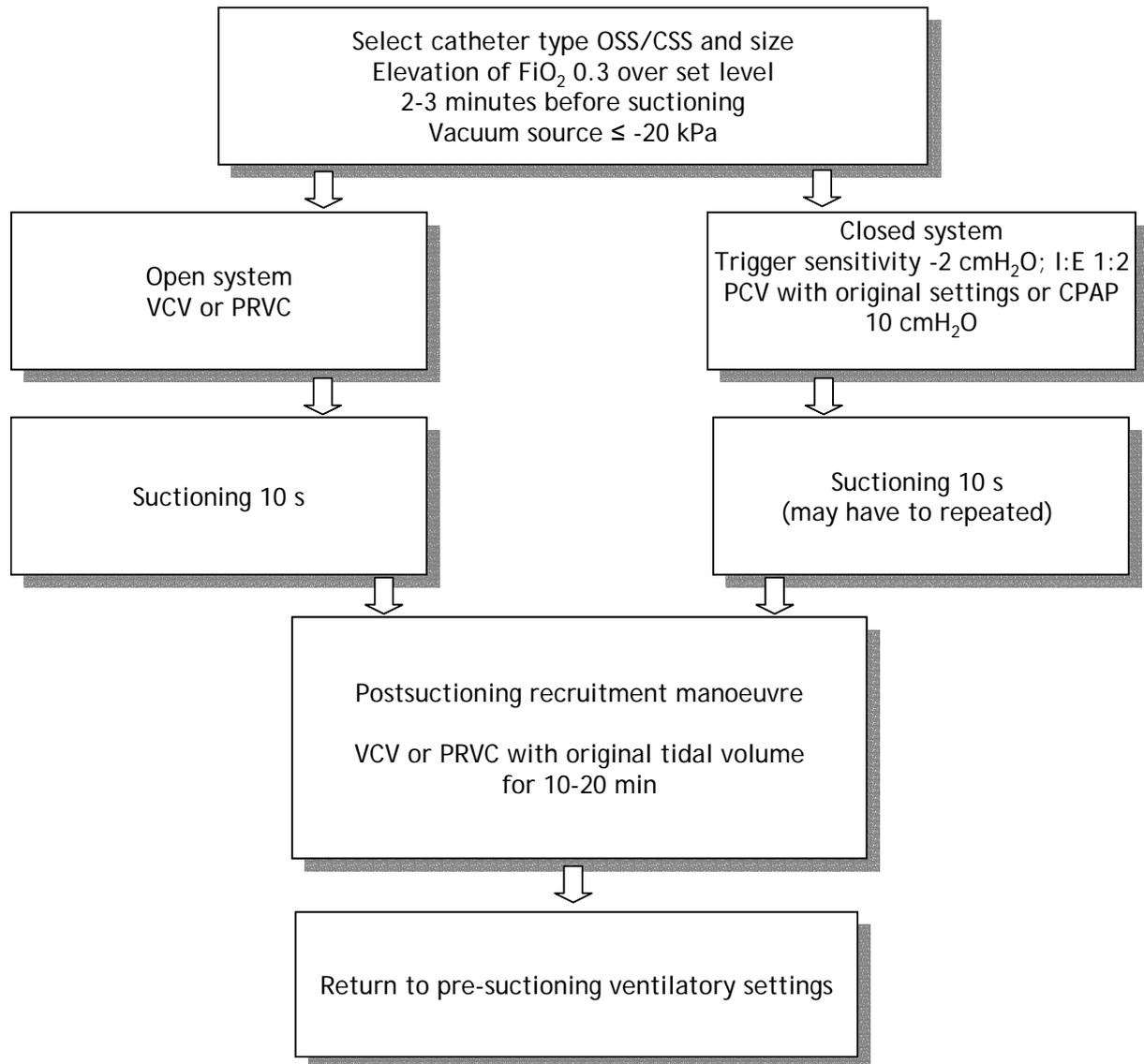


Figure 20. Suggestion of ventilation management during open or closed suctioning in ALI/ARDS patients based on studies discussed in this thesis.

CONCLUSIONS

- New monitoring strategies such as bedside FRC measurements with the nitrogen washout/washin method and continuous lung volume measurements with EIT technique could contribute to a better understanding of suctioning induced lung collapse and give us knowledge on how to minimize its negative effects to develop better clinical routines for handling them.
- Open suctioning induces a large loss of FRC at the time of disconnection of the ventilator prior to suctioning but is more effective than closed system suctioning in removing secretions.
- The dorsal regions of lavaged lungs are predominantly affected by disconnection and suctioning but volume control ventilation after open suctioning is an easy way to recruit diseased collapsed lung tissue.
- Closed system suctioning prevents lung collapse induced by disconnection and suctioning but has the potential to induce lung collapse if thick suction catheters in narrow tubes and high vacuum levels are used.
- Bronchoscopic suctioning can cause severe lung collapse, despite being a closed suction procedure.

ACKNOWLEDGEMENT

“Liksom en god sås reder en bra doktorand sig själv”

I wish to express my sincere gratitude to all those who have contributed to this work. In particular I want to thank:

My tutor, Professor **Ola Stenqvist**, for his energetic guidance and constant encouragement in the progress of this thesis. Without his ideas and enthusiasm, this work would have been impossible to complete. My co-tutor, Assistant Professor **Stefan Lundin**, for always being helpful and optimistic, and for giving valuable advice on how to manage in the world of clinical science (and what shoes not to wear at work).

Dr **Heléne Seeman-Lodding**, Head of Dept. of Anaesthesia and Intensive Care-Sahlgrenska University Hospital and Professor **Björn Biber**, Head of Dept. of Anaesthesiology and Intensive Care - Sahlgrenska Academy for financial and personal support, making it possible for me to finish this work.

My co-authors Dr **Sigurbergur Karason** and Dr **Sören Söndergaard**, spirodynamics experts, **Birgitta Almgren** and Assistant Professor **Marianne Högman**, introducing me to the pigs and to the hills of Nepal and Dr **Erik Houltz**, statistics wizard, for giving invaluable contributions to my first two papers.

My co-authors and friends Dr **Helena Odenstedt**, Dr **Cecilia Olegård** and Dr **Karin Erlandsson** for invaluable support during experiments and never ending data analysis sessions as well as good company in congress halls around Europe, during shopping tours or in the ski slopes.

Dr **Annette Nyberg** for valuable assistance during experiments and for friendship over cups of coffee and during rabbit maintenance ☺ (sorry about Titti though). Professor **Anders Åneman**, for sharing his view on science and life in general, and for introducing me and Ola to the field of power analysis. Dr **Sven “el Medico” Lethvall**, for good assistance during experiments and salsa lessons. **Marita Ahlqvist** for providing excellent help with tubes and samples. Assistant professor **Kai Knudsen** for continuous computer support and Dr **Christina Grivans** for helping me out in the basement lab. **All the staff at the MTA-lab, EBM-lab and in the ICU** at Sahlgrenska for good assistance and secretaries **Jenny Ström** and **Linda Innala-Nyberg** at the Dept. for always fixing the details.

All dear colleagues and friends. Without your support and inspiration during working days and nights as well as outside the hospital walls, taking me to “mellofester”, fantastic dinners, tennis, sailing in the Adriatic Sea, skiing in the French Alps, reggae festivals, strange hip hop clubs and so on, this process would have been much more difficult to endure.

All members of my large and loud family, here and abroad. Farfar **Göte**, because you stayed alive just as you promised. My god-parents **Helén** and **Torsten** for best back-up family ever. My brother **Fredrik** and his wife **Anna** and little **Nora**, for pure joy and for help with layout and graphics. My parents, **Per** and **Margareta**, for bringing me up with unconditional love, always being there for me and giving me the tools in life to manage a thing like this.

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