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Changes in lung volume with three systems of endotracheal suctioning with and without pre-oxygenation in patients with mild-to-moderate lung failure

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Abstract *Objective:* To compare changes in lung volume, oxygenation, airway pressure, and hemodynamic effects induced by suctioning with three systems in critically ill patients with mild-to-moderate lung disease, and also to evaluate the effects of hyperoxygenation applied prior to the maneuver as suggested by some guidelines. *Design:* Prospective crossover study. *Setting:* General intensive care department of a university-affiliated hospital. *Patients:* Ten mechanically ventilated patients with mild-to-moderate acute respiratory failure. *Interventions:* Patients were ventilated in volume control mode with a mean tidal volume of 490 ± 88 ml, PEEP 7 ± 4 cmH₂O and FiO₂ 0.36 ± 0.05 . Suctioning was performed sequentially with a quasi-closed system, with an open system 10 min later, and finally with a closed system. Thereafter, pure oxygen was applied for 2 min and the whole suctioning sequence was repeated in reverse order. *Measurements and main results:* Patients' mean PaO₂/FiO₂ ratio was 273 ± 28 mmHg. The

reductions in lung volume during suctioning were similar with the quasi-closed (386 ± 124 ml) and closed system (497 ± 338 ml), but significantly higher with the open system (1281 ± 656 ml, $P=0.022$). We found no significant hemodynamic adverse effects, and no significant SpO₂ reductions with all the studied suctioning techniques. Pre-oxygenation with pure oxygen did not induce additive effects in lung volume changes. With and without pre-oxygenation, lung volume returned to baseline in every patient within 10 min. *Conclusions:* Suctioning with closed and quasi-closed systems reduces the substantial losses in lung volume observed with the open system. Nevertheless, in patients without severe lung disease these changes were transient and rapidly reversible.

Keywords Endotracheal suctioning · Mechanical ventilation · Acute respiratory failure · Health technology assessment

Introduction

Endotracheal suctioning is routinely required in mechanically ventilated (MV) patients to clear bronchial secretions. Tracheal intubation and mechanical ventilation markedly impair airway secretion clearing [1]. Moreover, the use of sedative drugs, impaired glottis closure, high cuff pressure, and tracheal mucosal damage

are reported to depress cough reflex and mucociliary clearance [2]. Suctioning is therefore warranted in MV patients not only to prevent airway obstruction but also to decrease the work of breathing caused by retained secretions. Nevertheless, each step of this maneuver is potentially harmful and may lead to serious and even life-threatening complications. Arterial hypoxemia is the most commonly reported complication, while atelectasis,

bronchospasm, tracheal mucosal damage, cardiac arrhythmia, intracranial hypertension, and even cardiac arrest have been described [3, 4, 5, 6, 7].

Previous studies on this subject have been focused on the prevention and treatment of suctioning-induced impairment of arterial oxygenation. Several preventive maneuvers, such as pre-oxygenation [7], have been proposed. Nevertheless, ventilation with pure oxygen has been reported to increase atelectasis and shunt, even in the short term [8]. Furthermore, recent studies have shown that alveolar collapse is harmful to the lung and should be avoided by means of a targeted ventilation strategy [9]. Accordingly, some authors suggest performing a recruitment maneuver after endotracheal suctioning in order to re-expand atelectasis and to decrease pulmonary shunt [10].

The most frequent procedure for suctioning consists of disconnection from mechanical ventilation, followed by insertion of a suction catheter into the trachea while negative pressure is generated. Disconnection itself results in an airway pressure drop and loss of lung volume, but a further volume decrease is observed during suctioning due to the generation of negative pressure in the airway [4]. Several studies have taken these considerations into account and the authors propose the use of a special suction adapter to avoid disconnecting the patient from the ventilator [11, 12]. Finally, closed suctioning systems, with a catheter continuously placed between the endotracheal tube and the Y-piece of the ventilator's circuit, are an alternative. While their advantages have been reported in patients with severe lung failure [13, 14, 15], in the present scenario of limitation of resources, it will be of value to know whether closed systems have any beneficial effects in the majority of critically ill MV patients, i.e., patients with mild-to-moderate lung injury.

The objectives of our study were: 1) to compare changes in lung volume, oxygenation, airway pressure, and hemodynamic effects induced by suctioning with open, closed, and quasi-closed systems in critically ill patients with mild-to-moderate lung disease; and 2) to evaluate the preventive effects of hyperoxygenation before suctioning.

Material and methods

Inclusion criteria

Over a 1-month period, we enrolled all patients who required MV for more than 48 h due to mild-to-moderate respiratory failure ($\text{PaO}_2/\text{FiO}_2 > 200$ mmHg), and who were under continuous sedation, orally intubated with 8.5-mm I.D. tubes, and in stable clinical condition. The investigation was conducted in accordance with our Hospital Ethics Committee and written informed consent was obtained from the patients' next of kin.

Exclusion criteria

These were suctioning-induced bronchospasm, intracranial hypertension (intracranial pressure > 20 mmHg), and hemodynamic instability (mean arterial pressure < 70 mmHg). Patients were in 45°-Fowler position, whereas MV was supplied as volume assist-controlled mode by commercial ventilators (Servo Ventilator 900 C, Siemens Elema, Solna, Sweden, and Evita 2 and 4, Draeger, Lubeck, Germany) with a standard circuitry. No changes in individual ventilatory settings were made for the purpose of the study. Patients were already under continuous sedation with midazolam or propofol, and morphine to a Ramsay score of 2 to 3 points, and up to the point that no triggering activity was detectable.

Patients were continuously monitored with our standard ICU equipment (Hewlett Packard M1166A, Palo Alto, Calif., USA): ECG, blood pressure (measured either non-invasively or by means of an indwelling arterial catheter), and pulse oximetry. Exhaled CO_2 (ETCO_2) was measured by capnography (HP78556A, Palo Alto, Calif., USA), and airway opening pressure by pressure transducer (MP45, Valyline, Calif., USA). End-expiratory lung volume (EELV) was measured by inductive plethysmography with thoracic and abdominal strips (NIMS, Miami Beach, Fla., USA). Plethysmographic intrathoracic volume was zeroed at end-expiration and was calibrated by using the tidal volume supplied by the ventilator as reference value, with electronic correction of the drift. Five tidal volumes were averaged to take into account the possible effect of respiratory muscles activity. The analog output port of each monitor was connected to a data acquisition system (Windaq 200, Data Q) that allowed analog to digital conversion and storage of signals sampled at 100 Hz.

We performed endotracheal suctioning in sequential order with three different systems: 1) the quasi-closed system places a 14-Fr suction catheter (Vigon, Ecouen, France) through a rubber-sealed swivel connector placed between the endotracheal tube and the Y-piece of the circuitry; 2) the open system consists of the total disconnection of the patient from the mechanical ventilator and the insertion of a 14-Fr suction catheter into the trachea; and 3) the closed-system (Hi-Care, Mallinckrodt, Mirandola, Italy) has a 14-Fr suction catheter continuously placed between the ET tube and the Y-piece that can be advanced into the trachea through a firmly sealed ring.

The catheter was fully inserted, allowing the tip to reach the airways 20–30 mm away from the end of the ET tube. Negative suctioning pressure at 150–200 mmHg was continuously applied for 10–15 s while the catheter was rotated and gradually removed. The insertion of the suction catheter reduced the cross-sectional area of the 8.5-mm I.D. endotracheal tube from 56.7 mm² to 38.6 mm², i.e., a 30% reduction. Ventilator trigger sensitivity remained set at -2 cmH₂O, allowing the ventilator to respond to gas aspiration during closed and quasi-closed aspiration with triggered-cycling and increasing respiratory rate (Fig. 1).

The study had two parts. In the first, we performed suctioning without changes in ventilatory settings, whereas in the second, pure oxygen was applied for 2 min before suctioning.

Each suction maneuver was performed at 10-min intervals allowing the respiratory system to recover baseline conditions. Therefore, 10 min after the first suctioning with the quasi-closed system (our routine method), suctioning was performed again with the open system. The closed system was then attached to the circuit and suctioning was performed 10 min later.

In the second part of the study, an inspired oxygen fraction of 1 was supplied for 2 min and suctioning was performed under hyperoxygenation. The sequence was in reverse order, i.e., closed, open and finally the quasi-closed system separated by 10-min intervals. The techniques were not randomized so as to minimize the number of disconnections from mechanical ventilation.

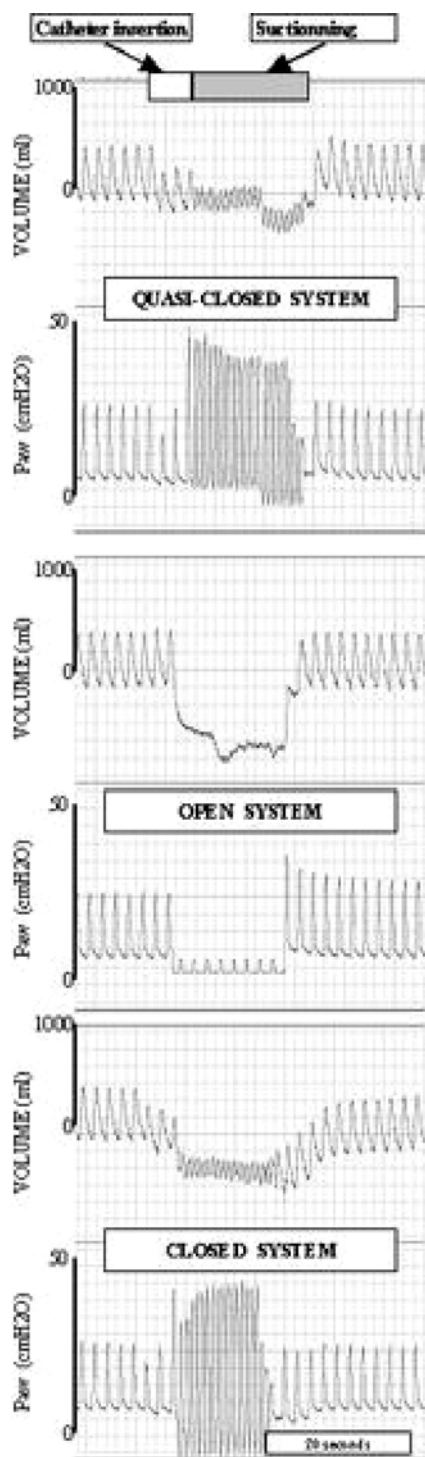


Fig. 1 Lung volume and airway pressure in a representative patient (#4) with the three suctioning systems. Note that the volume loss was higher during catheter insertion with open system due to PEEP loss. Airway pressure with open system shows an artifact due to disconnection from the ventilator circuit, whereas in quasi-closed and closed systems shows negative pressure inside the circuit that triggers the ventilator reducing EELV loss.

Statistical analysis

The crossover design of the study forced us to check for any time effect and any residual effect of previous treatment. These assumptions were rejected if the baseline values differed less than 10%. For each step, we analyzed the more abnormal values within ten breaths before suctioning was begun (pre) and within the ten breaths after suctioning (post). Data are expressed as mean+SD. The response for each variable before, during, and after suctioning with each system was compared with the nonparametric Wilcoxon analysis, the values just before each studied technique being considered as the baseline for that specific experimental step. The same variables were compared before and after preoxygenation. Sample size calculation to detect a change >30% in EELV between closed and quasi-closed systems and the open system as the control condition with a power of 80% and an error of 0.05 was eight patients. A difference was considered statistically significant when the *P* value was below 0.05.

Results

Demographic data of the ten patients enrolled in the study are summarized in Table 1. No patient was excluded from the study for safety reasons. Indeed, we found no deleterious hemodynamic effects such as hypotension or cardiac arrhythmia in any of the ten patients in any of the study conditions. Reductions in SpO₂ during suctioning on basal FiO₂ did not achieve statistical significance (Table 2), while SpO₂ remained constant at 99–100% during suctioning with pure oxygen. We found a weak correlation between SpO₂ drop and PEEP, but even at PEEP >6 cmH₂O the lower values of SpO₂ never reached 88%, i.e., an accepted safety threshold value in important clinical trials [9].

We found changes in lung volume measured by inductance plethysmography related to the suction system used. Lung volume loss with quasi-closed and closed systems was very similar (386 ml + 124 ml and 497 ml + 338 ml, respectively), whereas suctioning with the open system induced the greatest loss in lung volume (1281 ml + 656 ml). These clinically significant differences in lung volume during suctioning were rapidly reversible, and the EELV after 10 min did not differ from the pre-manuever values (Fig. 2). Looking at patients with low versus moderate PEEP levels, we found greater EELV loss at higher PEEP only with the open system (1357±371 vs 1105±349 ml), mainly due to the volume loss just after disconnection (see Fig. 1), but the differences did not reach statistical significance due to the small sample size.

Hyperoxygenation before suctioning showed similar effects to those observed without pre-oxygenation in terms of oxygen saturation and lung volume losses. Oxygen saturation was 99–100% with pure oxygen and it did not change during suctioning. The amount of lung volume loss and the rate of volume recovery after suctioning were similar to values at basal FiO₂ (Table 3).

Table 1 Clinical characteristics of the patients. PaO₂/FiO₂ was calculated at the PEEP and FiO₂ shown in the table.

Patient	Apache II	Sex	Age years	Diagnosis	V _T ml/kg	RR b/min	PEEP cmH ₂ O	FiO ₂	PaO ₂ /FiO ₂ mmHg
1	23	M	37	Subarachnoidal hemorrhage	9.1	19	0	0.35	314
2	18	F	86	Pneumonia	6.5	22	10	0.40	232
3	17	M	33	Trauma	8.0	14	8	0.30	291
4	19	F	69	Intracranial hemorrhage	7.3	19	6	0.35	288
5	25	F	88	Coma	8.2	16	5	0.35	274
6	14	M	70	Pneumonia	7.8	19	8	0.40	220
7	21	F	87	Septic shock	6.8	15	4	0.35	267
8	22	F	80	Abdominal surgery	7.6	18	4	0.30	280
9	16	F	72	Multiple trauma	6.6	22	10	0.45	276
10	11	M	23	Multiple trauma	7.8	18	10	0.35	285
Mean±SD	19±4		64±2		7.6±.8	18±2	7±4	0.36±0.05	273±28

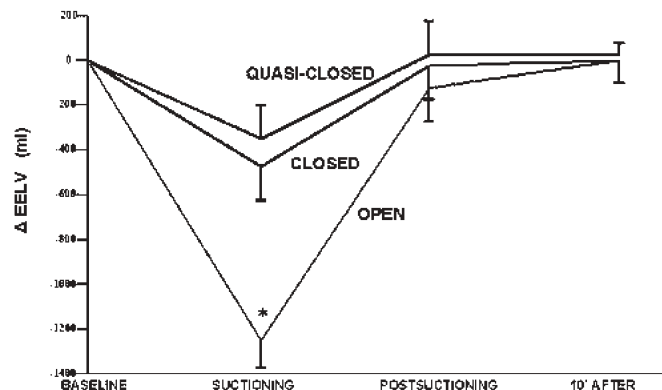
Table 2 Hemodynamic, capnometric, and oxygenation parameters with each suctioning system at baseline FiO₂. Data show the more abnormal values either during suctioning or within the 10-min post-suctioning period. Differences did not achieve statistical significance.

	Baseline	Quasi-closed	Open	Closed
MAP (mmHg)	81±8	82±8	84±6	81±7
HR (beats/min)	91±11	90±12	94±14	90±10
ETCO ₂ (mmHg)	33±3	32±3	31±4	33±2
SpO ₂ (%)	95±1	95±3	93±2	94±3

Discussion

Results from this study indicate marginal advantages with the closed and quasi-closed systems versus the open system for endotracheal suctioning in patients with mild-to-moderate lung failure. However, although lung volume loss induced by suctioning is reduced with the former systems, from a clinical viewpoint, differences in oxygen saturation, heart rate, and hemodynamics are minimal and do not justify the routine substitution of the open system in favor of closed and quasi-closed suctioning. Whether the avoidance of transient lung volume losses may have any impact on the long-term outcome remains an issue of debate. Comparison of our results with previous studies are mainly modulated by duration of suctioning, patient selection, and previous ventilatory strategy, and are addressed in the next paragraphs.

First, the duration and mode of suctioning could play a determinant role in side effects. In mechanically ventilated patients, endotracheal suctioning induces a substantial loss in lung volume if it is performed when the patient is totally disconnected from the ventilator. This

**Fig. 2** Changes in end-expiratory lung volume during endotracheal suctioning and 10 min after suctioning with each method and without preoxygenation. **P* <0.05 compared to closed and quasi-closed systems.

maneuver could induce the appearance of atelectatic lung areas as suggested by several studies. In an animal model, Lu et al. showed that long suctioning (60 s) reduced the bronchial area and increased respiratory resistance, impaired arterial oxygenation, and promoted atelectatic lung areas [8]. In a medium-duration suctioning clinical study, Cereda et al. performed endotracheal suctioning for 20 s [13] and suggested that their patients could have lost a greater lung volume because of the continuous application of negative pressure. Similarly, Maggiore et al. [14] applied intermittent suctioning for 25–30 s and found severe lung volume losses, but significant oxygen desaturation only appeared with the open system. In our study, the duration of suctioning was only 10–15 s and aspiration was continuously applied according to the AARC clinical

Table 3 Changes in lung volume with each suctioning system with preoxygenation.

	Quasi-closed	Open	Closed
Δ volume during suctioning (ml)	-352±91	-1218±403*	-449±370
Δ volume 1 min. after suctioning (ml)	-27±35	-12±48	-9±31
Δ volume 10 min. after suctioning (ml)	-6±15	-13±39	-4±12

**P* <0.05 compared to closed and quasi-closed systems

practice guidelines [16] and our clinical experience, but our results may be difficult to extrapolate to clinical scenarios with longer suctioning-time protocols.

Second, the role of patient selection is also of importance. In an animal model of severe lung failure, Neumann et al. [17] studied the dynamics of lung collapse and recruitment. They observed that lung collapse and re-opening occurred as early as within the first 4 s during breath-holding procedures. The referenced clinical studies were also focused on severe lung failure, with PaO₂/FiO₂ of 192 mmHg in Cereda's study and 143 mmHg in Maggiore's study. The value of our study is the inclusion of patients with less severe lung failure (PaO₂/FiO₂ 273 mmHg), though our results in terms of lung volume losses closely mirrored those of the above-mentioned authors.

Finally, the ventilatory strategy applied may be a key determinant. In a pioneering study, Carlon et al. [15] described oxygen deterioration only in patients receiving over 10 cmH₂O of PEEP, and found that changes were statistically, but not clinically, significant. In Newman's study, an aggressive ventilatory pattern (V_T of 15 ml/kg and no PEEP) that could promote unstable lung regions prone to collapse was used. In the clinical scenario, both Cereda and Maggiore used a protective lung ventilation (V_T 6–8.8 ml/kg and 11–12 cmH₂O PEEP) and both showed lung derecruitment. Interestingly, even in the most severe patients in Maggiore's study, lung volume was almost completely recovered within 1 min, except with the open system. Similarly, our patients were already ventilated with a protective lung approach that supposedly maintains a more stable lung structure. With a similar ventilatory strategy in ARDS patients, we have reported no significant effects of recruitment maneuvers, suggesting that the lungs have few unstable areas prone to collapse and reopening [18, 19].

The level of sedation may also account for the loss in lung volume. It has been estimated that in healthy adults as much as 15% of the entire lung becomes atelectatic under general anesthesia and paralysis. Our patients received continuous, but lighter, sedation with a mean Ramsay scale score of 2–3, allowing some of them to cough during suctioning.

Ventilator malfunctioning during closed suctioning due to high negative pressures in the circuit has been reported, but in our study we did not observe any damage to the ventilator sensors.

Limitations of the study

In a crossover study like this, the issue of how long the period of time between interventions should be is a matter of convenience and a risky decision. Longer intervals allow for better restoring to baseline conditions, but reduce the likelihood of being in a comparable state because of

the changing nature of diseases. The advantage of shorter intervals is that the patient is less likely to improve/deteriorate, while the risk is the possibility that baseline conditions are not yet achieved. Therefore, any crossover study must check how good the return to baseline conditions was, and in our study every patient returned to baseline conditions in the 10-min period between each suctioning in terms of EELV, SpO₂ and hemodynamics.

Several studies have postulated that arterial oxygen desaturation with open systems occurs as a result of disconnecting the patient from the ventilator and using a manual resuscitation bag, which delivers less predictable oxygenation and hyperinflation breaths [20]. In the present study, we did not use resuscitation bags and hyperinflation breaths before suctioning. As this may lead to more stable lung conditions, comparisons with previous studies might be difficult to interpret. Because of the nonlinear relationship between PaO₂ and SpO₂, the use of SpO₂ as a surrogate of oxygenation cannot exclude wide variations in PaO₂, mainly at SpO₂ >90–92%, and clearly at SpO₂ >98–99%. From a physiological point of view these changes in oxygenation have great interest, whereas from a clinical point of view the target is to avoid life-threatening hypoxemic episodes. Accordingly, in our moderate lung failure patients, even without pre-oxygenation, SpO₂ was never <88%, which was an acceptable target value in some important trials in ARDS patients [9]. Oxygen desaturation may occur not only during suctioning, but also after suctioning, while our continuous SpO₂ recordings allow us to avoid this bias. The possible role of active inspiratory muscles in restoring EELV may be real, but our study design does not allow for any speculation about the possible differences in paralyzed patients.

The impact of the different techniques in terms of secretion removal was outside the scope of this study. Very recently, a relationship between loss of lung volume and efficacy of secretion removal has been suggested [21], but in our study, the short time elapsed between each suctioning precluded comparison in the amount of secretions obtained. Additionally, our design was unable to offer any information about other suggested advantages of closed systems in terms of ventilator-associated pneumonia or cross-contamination.

Conclusion

Airway suctioning with open systems appears to induce substantial losses in lung volume that can be reduced by using closed and quasi-closed systems. The rapid reversibility of these changes and the lack of significant arterial oxygen desaturation suggest that the open system may be a safe procedure in patients with mild-to-moderate lung disease, although these findings must not be extrapolated to patients with more severe lung failure.

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