A comprehensive review of pediatric endotracheal suctioning: Effects, indications, and clinical practice*

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Objective: **To provide a comprehensive, evidence-based review of pediatric endotracheal suctioning: effects, indications, and clinical practice.**

Methods: **PubMed, Cumulative Index of Nursing and Allied Health Literature, and PEDro (Physiotherapy Evidence Database) electronic databases were searched for English language articles, published between 1962 and June 2007. Owing to the paucity of objective pediatric data, all reports dealing with this topic were examined, including adult and neonatal studies.**

Results: **One hundred eighteen references were included in the final review. Despite the widespread use of endotracheal suctioning, very little high-level evidence dealing with pediatric endotracheal suctioning exists. Studies of mechanically ventilated neonatal, pediatric, and adult patients have shown that suctioning causes a range of potentially serious complications. Current practice guidelines are not based on evidence from controlled clinical trials. There is no clear evidence that endotracheal suctioning improves respiratory mechanics, with most studies pointing to the detrimental effect it has on lung mechanics. Suctioning should be performed when obstructive secretions are present rather than routinely. There is no clear evidence for the superiority of closed- or open-system suctioning, nor is there clear evidence for appropriate vacuum pressures and suction catheter size. Sterility does not seem to be necessary when suctioning. Preoxygenation has short-term benefits, but the longer-term impact is unknown. Routine saline instillation before suctioning should not be performed. Recruitment maneuvers performed after suctioning have not been shown to be useful as standard practice.**

Conclusions: **Endotracheal suctioning is a procedure used regularly in the pediatric intensive care unit. Despite this, good evidence supporting its practice is limited. Further, controlled clinical studies are needed to develop evidence-based protocols for endotracheal suctioning of infants and children, and to examine the impact of different suctioning techniques on the duration of ventilatory support, incidence of nosocomial infection, and length of pediatric intensive care unit and hospital stay. (Pediatr Crit Care Med 2008; 9:465–477)**

KEY WORDS: endotracheal suction; pediatric; mechanical ventilation; suction catheter

Infants and children with life-threatening conditions frequently require admission to the pediatric intensive care unit (PICU), where they may be intubated and mechanically ventilated. Globally, respiratory tract infections contribute significantly to morbidity and mortality in the pediatric population (1).

Intubated patients are unable to clear secretions effectively, as glottic closure is compromised and normal mucociliary function is impaired (2). Inadequately humidified inspired gas and the presence of the endotracheal tube (ETT) may cause irritation of the airways and increased secretion production (3). In addition, many children with respiratory tract infections have increased sputum volume and altered sputum rheology, which further impedes secretion clearance. Therefore, all infants and children with an artificial airway require endotracheal (ET) suctioning to remove secretions and prevent airway obstruction (4, 5).

ET suctioning is known to have many complications. Despite this, the practice of ET suctioning continues without adequate evidence for the different techniques used (6). Although recommendations and clinical guidelines have been made regarding suction pressures, depth of insertion of the suction catheter, and catheter size (5, 7–11) few of these have been objectively shown to be appropriate or safe. The available guidelines do not address any dimensions of the suction catheters other than the cross sectional diameter, and do not factor in variation in mucus characteristics; nor do they seem to consider the relationships between ETT and catheter size (length and diameter) and suction pressures; and the potential effects these may have on the pediatric lung. Surveys conducted in clinical settings suggest that practice guidelines and protocols vary widely and are not, in general, based on sound evidence (12, 13).

This article presents a comprehensive review of the pediatric ET suctioning literature, including precautions and contraindications; effects (clinical and mechanical); frequency of suctioning; open- and closed systems; preoxygenation; saline instillation; catheter size selection; vacuum pressure; sterility; duration of suction application; depth of catheter insertion; and postsuction recruitment maneuvers (RM). Clinical recommendations are made on the basis of these results.

METHODS

Electronic literature searches for articles published between January 1962 and June 2007 were conducted using PubMed, Cumulative Index of Nursing and Allied Health Literature and PEDro (Physiotherapy Evi-

***See also p. 539.**

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dence Database) databases. The references listed in the publications so identified were also reviewed. The search terms used were *suctioning, suction, tracheal suction,* and *endotracheal suction,* in various combinations with modifiers such as *children, pediatric, infant, complications,* and *effects*. The search was initially limited to randomized controlled trials (RCTs) and systematic reviews, in the English language, of infants and children from birth to 18 yrs.

Considering the lack of studies focusing on pediatric ET suctioning, and the small number of controlled clinical trials generally available on the subject, the scope of the review was subsequently extended and all articles investigating or discussing ET suctioning were considered for inclusion; where RCTs specific to the pediatric age group were not identified, studies of lower evidence levels were sourced. Studies pertaining to neonatal care were included in the data synthesis as these patients are often managed in PICUs; where insufficient evidence was available on infants and children, adult data were considered for inclusion. When insufficient human clinical trials were identified, *in vitro* and animal studies were discussed.

The physiologic and anatomical differences among the three age groups (neonates, infants and children, and adults), and the different disease spectra were taken into account in the development of clinical recommendations.

RESULTS

Forty-three clinical trials and systematic reviews were identified, of which 14 were initially excluded as they either did not evaluate suctioning specifically or they concerned the adult age group (14–27). A further four studies were excluded as they addressed perinatal suctioning of meconium-stained neonates (28–31). Of the remaining studies, 17 dealt specifically with neonates (6, 32–47) and eight clinical trials pertained to infants and children (48–55). One hundred eighteen articles were included in the final review.

Data Synthesis

Precautions and Contraindications to ET Suctioning. Considering that all intubated and ventilated patients may require ET suctioning to maintain a patent airway, there can be no absolute contraindications to the procedure (9).

Special care should be taken with patients who have raised intracranial pressure, as this can be exacerbated by ET suctioning and coughing (23, 54, 56, 57) as can pulmonary hypertension. Patients with pulmonary edema and pulmonary hemorrhage should only be suctioned when absolutely necessary, as it has been suggested that these conditions may be exacerbated by suctioning (58, 59).

All patients should be continuously monitored to assess clinical and physiologic changes in response to ET suctioning.

Adverse Clinical Effects. Although considered essential to prevent airway obstruction from accumulation of secretions, it is recognized that severe adverse events may result from suctioning.

Respiratory complications include: hypoxia, which has been reported in neonatal (32, 60–63) and pediatric (54, 55) studies; pneumothorax has been observed in neonates as a result of the suction catheter perforating a bronchus (64, 65); deep ET suctioning has been shown to cause mucosal trauma in animal models (2, 66) and in neonates (64, 67, 68); atelectasis has been reported in neonatal (69) and pediatric (8, 51, 70) subjects; and loss of ciliary function has been observed in animal models (2).

Cardiovascular complications include bradycardia (60, 62, 71, 72), other cardiac arrhythmias (62), and increases in systemic blood pressure (57, 62), which have been reported in neonatal studies. The pulmonary vasoconstriction, occurring in response to ET suctioning-induced hypoxia may predispose neonates to persistent pulmonary hypertension or patent ductus arteriosus (62).

Neurologic sequelae of suctioning include raised intracranial pressure, which has been observed in preterm infants (56, 57), in pediatric patients (54), and in adult traumatic brain-injured patients (23). Cerebral blood volume has been shown to increase significantly in mechanically ventilated preterm neonates (73) during ET suctioning, with the cerebral blood volume changes occurring in relation to changes in carbon dioxide tension (61). Marked decreases in cerebral blood oxygen concentration and, thus, decreased cerebral oxygen availability have been observed in neonates (60, 73). It has been suggested that the hypoxia induced by suctioning in neonates may contribute to the development of intraventricular hemorrhage (60) and hypoxic-ischemic encephalopathy (74).

ET suctioning has been implicated in nosocomial bacteremia, attributed to the introduction of pathogens by the suction catheter (2).

ET suctioning has also been shown to cause behavioral pain responses in low birth weight infants (75). In a prospective observational study of 151 neonates, it was shown that patients were subjected to an average of 14 painful procedures per day (measured as pain scores >4 on a 10-point scale), of which suctioning accounted for almost 64%. However, <35% of neonates received preemptive analgesia (76). In a randomized, placebo-controlled study of 84 ventilated neonates, it was shown that administration of opioids before ET suctioning significantly reduced the duration of hypoxemia and the level of distress, as quantified by a behavioral scoring method (42).

ET suctioning has also been shown to cause pain in critically ill adults (77, 78) and the discomfort caused by suctioning is frequently recalled upon discharge from the intensive care unit (79).

Some of the above adverse events may be due to vagal nerve stimulation (71), coughing, or catheter trauma (2, 65, 74) and others may be directly related to the physical effects of suctioning on the lungs (68, 80–85). Atelectasis has been attributed to the aspiration of intrapulmonic gas (81), mucosal edema (8), or bronchial obstruction as a result of mucosal trauma (67).

In infants and young children where functional residual capacity is close to the closing volume, glottic closure on expiration is used as a natural mechanism to maintain lung volume. The ETT prevents glottic closure, predisposing the patient to atelectasis. Therefore, even in intubated children with normal lungs, positive end-expiratory pressure may be necessary to maintain lung volume. Disconnection from the ventilator results in a decrease in airway pressure with loss of lung volume, and further lung volume loss occurs with the application of a negative suction pressure (70, 84, 86).

The effects ET suctioning have on patient outcome, length of PICU and hospital stay, and patient mortality and morbidity are currently not known and this requires further investigation.

Effect of Suctioning on Lung Mechanics. Main et al. (49) found that overall there were no significant changes in tidal volume or respiratory system compliance after ET suctioning in 100 pediatric patients with variable lung disease. It was noted, however, that individual responses were variable with some patients showing a marked improvement although others deteriorated. Patients received different repetitions of suctioning; catheter size and suction pressures were not reported;

variable amounts of saline were instilled before suctioning; and some patients received hyperinflation maneuvers after the procedure. The duration, method, and amount of positive pressure applied during these maneuvers were not documented. The lack of standardization of the suctioning technique among patients resulted in this study having limitations in interpretation, application, reliability, and reproducibility.

In an observational study prospectively investigating the effects of a standardized suctioning procedure in 78 critically ill pediatric patients, ET suctioning was shown to reproducibly result in a decrease in dynamic compliance and tidal volume, attributable to a loss of lung volume, which returned to presuction levels again within 10 mins of being reconnected to the ventilator (70). This recurrent derecruitment and subsequent rerecruitment on reconnection to the ventilator may exacerbate lung injury (84, 86, 87). This study was limited by the lack of a control group. Choong et al. (51) also showed that ET suctioning resulted in loss of lung volume in 14 pediatric patients receiving conventional ventilation.

Using inductive plethysmography, it was shown that open-ET suctioning of newborn infants (n = 7) receiving high-frequency oscillatory ventilation caused a significant loss of lung volume, which was in all but one patient rapidly regained on reconnection to the ventilator without further intervention (88). Similar studies related to suctioning and high- frequency oscillatory ventilation have not been conducted in older infants and children.

End-expiratory lung volume, measured by inductive plethysmography, decreased during ET suctioning of adults (n = 9) with acute lung injury (ALI), regardless of the suctioning technique performed: open-suction, through swivel adaptor or through a closed-suction system (84). This study confirmed that both loss of airway pressure because of disconnection and the application of negative pressure were implicated in suction-induced alveolar collapse. This may suggest that patients receiving high positive end-expiratory pressure levels are at increased risk of volume loss during open-ET suctioning.

Theoretically, removal of secretions from the airways should reduce airway resistance (63), but this has not been clinically demonstrated. The reduction in resistance caused by clearing the large airways could be negated if suctioning-induced volume loss occurred, with an associated increase in airway resistance (11). "Routine" suctioning, performed in the absence of secretions, would not be expected to drop airways resistance, as demonstrated clinically in a pediatric study (70).

Initial deterioration in resistance as a result of transient bronchoconstriction has been described after suctioning, and it is notable that even after this bronchoconstriction had resolved, patients still did not show any improvement in airway resistance (4). Main et al. (49) found that ET suctioning did not affect respiratory resistance, although chest physiotherapy and suctioning combined caused a decrease in resistance. This may suggest that chest physiotherapy combined with ET suctioning improves secretion clearance more effectively than ET suctioning alone; however, the lack of standardization of study intervention makes interpretation difficult and confirmation is required from further standardized controlled trials.

There is still no clear evidence that ET suctioning improves respiratory mechanics (4). However, many available studies are limited by small sample sizes, patient heterogeneity, lack of intervention standardization, and the absence of a suitable control group. Although in most studies the overall effect was found to be negative or of no benefit, individual patients have seemed to improve their lung mechanics. Predictive factors for a positive effect were unable to be identified statistically.

Frequency of ET Suctioning. It is generally accepted that suctioning should not be performed as a routine intervention, but rather as indicated after a thorough clinical assessment (89). Observational studies of clinical practice have suggested that the identification of the need for ET suctioning is a complex issue, involving changes in both clinical signs and patient behavior (90).

Previous guidelines based on expert consensus have suggested that clinical indications for suctioning include audible or visible secretions in the ETT, or coarse breath sounds on auscultation (9); coughing; increased work of breathing (9); arterial desaturation and/or bradycardia as a result of secretions; decreased tidal volume during pressure-controlled ventilation (9); the need for a tracheal aspirate culture (9); and after chest physiotherapy to clear mobilized secretions. If ventilators are equipped with flow-volume loop displays, changes in graphics (9) or a saw-toothed pattern may indicate the presence of secretions in the ETT (91). Patients receiving high-frequency oscillatory ventilation should be observed with regard to the amount of chest wall oscillation; if this changes it may indicate the presence of secretions.

Many of these indications are very subjective, and closer monitoring of, for example, transcutaneous Pco_2 levels, may provide a more objective indication for suctioning. This requires investigation.

Open vs. Closed-System Suctioning. Commonly used suctioning systems are open-ET suctioning (OES) and closed-system suctioning (CSS). OES involves first disconnecting the patient from the ventilator and then suctioning the ETT before reconnecting the patient to the ventilator circuit. CSS allows mechanical ventilation to continue during ET suctioning, and may be performed using special adaptors that allow partial mechanical ventilation to continue during the insertion of the suction catheter (35). However, the method frequently used clinically is the inline multi-use suction catheter system, in which catheters are encased in a plastic sleeve on insertion, providing a seal that maintains a closed system (92).

Neonates have been shown to maintain better physiologic stability during CSS (33, 93). In a crossover study of 11 preterm infants, it was found that the magnitude and duration of desaturation and bradycardia were significantly reduced with CSS. In addition, OES caused a greater decrease in cerebral blood volume than CSS (94). Rieger et al. (95) found that the suctioning system did not influence cerebral blood flow velocity in extremely low birth weight infants.

Use of CSS may prevent ET suction-induced hypoxia and decreases in lung volume in pediatric (51) and adult (92) patients. CSS may limit aerosolization of infectious mucus particles; thereby preventing the spread of infection between patients and from patients to staff (96). It has been suggested that CSS should reduce the risk of ventilator-associated pneumonia by eliminating environmental contamination of the catheter before introduction into the ETT (96).

The drawbacks of CSS include the risk of producing high negative pressures (97) if the amount of air suctioned exceeds the gas flow delivered to the patient by the ventilator (98); and reduced efficiency in clearing thick secretions from the airways (99). Practically, there is also a risk

of not withdrawing the catheter completely after the suctioning event and, thus, partially occluding the ETT and increasing airway resistance.

In a bench test evaluation of a neonatal closed-suction system, Monaco and Meredith (100) found that CSS did not preserve continuity of volume or pressure delivery during suctioning; therefore, this was unlikely to be the reason for the reported reduction in suction-related hypoxia (71, 72, 101).

Two randomized crossover studies in adults have compared sputum weight with OES and CSS. The first study did not find any difference between the suctioning systems (102), whereas the second study found that OES was four to five times more effective in removing secretions than CSS (103). These studies are difficult to interpret, as the mass of secretions suctioned could have been affected by simultaneous aspiration of condensed water (104).

In an *in vitro* study using adult-sized ETT and suction catheters (99), it was found that OES was significantly more efficient than CSS during three different ventilation modes. Auto-triggering of the ventilator was observed during all CSS procedures. In addition, during CSS with positive pressure ventilation, the triggered inspiratory gas flow actually forced secretions away from the catheter tip. It seemed that pulmonary secretions could not be effectively removed without causing lung collapse and affecting gaseous exchange. OES was presented as the system of choice, in the presence of clear indications for suctioning. Similarly, Copnell et al. (105) demonstrated in an animal lung injured model that CSS was less effective in clearing both thin and thick secretions, regardless of the mode of ventilation.

In 175 low birth weight infants, randomized to CSS or OES, CSS did not affect the rate of bacterial airway colonization, frequency of ET suctioning and reintubation, duration of mechanical ventilation, length of hospitalization, incidence of nosocomial pneumonia or neonatal mortality. However, CSS was preferred by most nurses because of ease of use, time efficiency, and the perception that it was better tolerated by the patients (39).

Freytag et al. (106) showed that not changing the closed-system catheter for 72 hrs in adult patients significantly increased microbial growth on the catheters and led to a significant increase in colonization of the lower respiratory tract.

Three meta-analyses have concluded that there were no significant differences between OES and CSS on the incidence of ventilator-associated pneumonia and mortality in adults (107–109). Although CSS was associated with a significant reduction in fluctuations of heart rate and mean arterial blood pressure, no conclusions could be drawn with regard to oxygenation or secretion removal, and CSS was associated with increased colonization (108). Based on these meta-analyses, there is no evidence to support the use of CSS over OES, in the adult intensive care unit population.

There is a paucity of evidence relating to the merits of CSS or OES in the pediatric critical care population. Choong et al. (51) found that total lung volume loss was significantly greater with OES than CSS in pediatric patients aged 6 days to 13 yrs. In addition, patients suctioned with the open method experienced greater levels of desaturation. These authors suggest that CSS is preferable to the open technique, especially in patients with significant lung disease requiring high levels of positive end-expiratory pressure, to avoid alveolar derecruitment and hypoxia during ET suctioning.

ET suctioning provides an abundant opportunity for the spread of infections (110), and this would seem to be more so with the open technique. Although CSS has not been shown to reduce the incidence of ventilator-associated pneumonia, the importance of this measure in preventing patient-to-patient or patient-to-staff transmission of infectious diseases has not been adequately studied.

Preoxygenation. Although it is accepted that oxygen should generally be provided to prevent ET suction-induced hypoxia, the optimal degree and duration of preoxygenation is currently not known (111).

In preterm neonates, brain oxygenation was shown to decrease in parallel with arterial oxygen saturation (Sa_{O_2}) during suctioning, but the decreases in both were ameliorated by increasing the fraction of inspired oxygen (F_{IO_2}) by 10% before suctioning (61). In a systematic review of neonatal trials, Pritchard et al. (34) reported that although preoxygenation decreased hypoxemia at the time of suctioning, other clinically important outcomes, including the adverse effects of hyperoxia, were not known. Owing to the poor quality of the one study (46) qualifying for inclusion in the above review, no recommendations for clinical practice could be made.

In an observational study of neonates (n = 17), providing 10% F_{IO_2} above baseline for 2 mins before suctioning and manually ventilating with 100% O_2 in between suction passes reduced the incidence of hypoxemia, bradycardia, and apnea associated with suctioning (112). In a prospective, crossover study of 15 ventilated newborn infants, those who received a 10% increase in F_{IO_2} before suctioning, had significantly better postsuctioning Sa_{O_2} than those in the control group (32).

Kerem et al. (55) examined ways of preventing hypoxia during ET suctioning in a prospective randomized crossover trial of 25 hemodynamically stable pediatric patients. Patients underwent one of four suctioning approaches: a control with no treatment; preoxygenation; hyperinflation presuction; and hyperinflation postsuction. The significant fall in Sa_{O_2} and Pa_{O_2} occurring as a result of suctioning was completely prevented by delivering 100% inspired O_2 for 1 min before the procedure.

A meta-analysis of 15 adult trials (111) showed that the occurrence of hypoxia was 32% lower when preoxygenation was applied. In a crossover study of 30 adults undergoing CSS (113), it was found that although oxygenation was significantly higher in patients who were preoxygenated with 100% O_2, patients who were not preoxygenated did not experience significant hypoxia during suctioning. Based on this data, it was recommended that the decision on whether or not to preoxygenate adults undergoing CSS should be determined on an individual basis according to the patients' clinical condition.

Branson et al. (9) suggested that adults and children should receive 100% inspired O_2 for >30 secs before suctioning. Hodge (74) suggested increasing the F_{IO_2} by 10%–20% higher than the F_{IO_2} for about 1 min before suctioning neonates. Neither of these recommendations is supported by high-level evidence.

In all age groups, hyperoxia causes free-radical damage and absorption atelectasis, associated with major morbidity. The issue of what level of oxygenation one should deliver is, however, likely to be most relevant in the neonatal population where hyperoxia has been implicated in the development of periventricular

leukomalacia, retinopathy of prematurity, and chronic lung disease, with the potential for major long-term sequelae (114, 115).

Because of the known risks of hyperoxia, it is recommended that F_{IO_2} be returned to presuctioning levels as soon as the Sa_{O_2} has stabilized.

Use of Saline. Instillation of isotonic saline (sodium chloride) has been a widespread practice in PICUs for many years, under the impression that the fluid aided in the removal of pulmonary secretions by lubricating the catheter, eliciting a cough, and diluting secretions. This practice may have been necessary historically, before the use of humidifying systems. However, mucus and water in bulk form are immiscible and maintain their separate phases even after vigorous shaking (116). Thus, the function of saline as a secretion dilutant is doubtful. Instillation of normal saline in conjunction with ET suctioning may cause additional dispersion of contaminated adherent material in the lower respiratory tract, with the subsequent increased risk of nosocomial infection (106).

Adult studies have consistently reported the adverse effect of saline instillation on arterial oxygenation (117–120).

In infants, routine saline instillation before suctioning was only found to be of benefit in maintaining ETT patency with 2.5 mm internal diameter ETT, but no benefit was found in using saline for a 3.0 or a 3.5 mm ETT (43). Shorten et al. (44) randomly assigned 27 clinically stable neonates to two orders of suctioning methods, one with and one without saline instillation (0.25–0.5 mL). These authors found no significant difference in oxygenation, heart rate or blood pressure between the groups. Beeram and Dhanireddy (121) performed suctioning with and without saline in 18 neonates, acting as their own controls. Although there was no difference in lung compliance or resistance, there was a significant, albeit transient, deterioration in Sa_{O_2} from baseline in those infants who received saline before suctioning.

In a randomized controlled trial of 24 pediatric patients, for 104 suctioning episodes, it was shown that patients who received between 0.5 and 2 mL of normal saline before or during suctioning, experienced significantly greater oxygen desaturation than patients who did not receive saline instillation. There were no cases of ETT occlusion in either group (52).

Despite the body of knowledge indicating that instillation of saline is unlikely to be beneficial and may in fact be harmful, there is still limited evidence in the pediatric population, and many clinicians continue to be concerned about adequately clearing thick secretions from the small ETTs used for infants and children (52). Hodge (74) suggested that in the case of tenacious secretions, 0.1–0.2 mL/kg body weight of 0.9% saline could be instilled before suctioning. Shorten et al. (44) showed that clinically stable newborn infants tolerated 0.25–0.5 mL saline instilled before suctioning.

To ensure that pulmonary secretions are easily manageable with suctioning, it is essential to ensure adequate humidification of inspired gas (9, 52).

Suction Catheter Size. If a catheter largely or completely occludes an artificial airway or bronchus, the full suction pressure may be transmitted to that airway leading to massive atelectasis (80, 122). To avoid this, the recommendation has been made that the suction catheter size should be no more than half the internal diameter of the ETT (8, 11). This is not possible when suctioning infants with small diameter ETTs ($<$3.5 mm).

The amount of gas that can be removed from the thorax through the catheter will largely be determined by the cross sectional area of the catheter. With a partially occluded ETT, gas would be able to flow into the thorax, largely replacing the gas removed during suctioning. The amount of gas able to flow into the thorax through the ETT would depend on the available space between the ETT and the catheter. Morrow et al. (122) suggested, therefore, that lung volume loss would be related to the catheter area: area difference ratio (where area difference is the difference between the internal ETT area and the external catheter area). This hypothesis was subsequently confirmed in a prospective observational clinical study with the suction-induced change in dynamic compliance being directly related to the catheter area: area difference ratio (70). This suggests that the most severe lung volume changes are likely to occur during ET suctioning of neonates and young infants intubated with small internal diameter ETT, as in these patients the catheters used will always be relatively large compared with the ETT size. Similar changes in lung volume loss would also occur in older children if the catheters selected were inappropriately large relative to ETT size.

The catheter sizes recommended for pediatric use by Shann (7) range from 55% to 100% of the corresponding ETT's internal diameter. Morrow (123) demonstrated that for ETTs $\leq$3.5 mm internal diameter, the recommended catheters all occluded the ETT by more than 75%. Potentially low intrapulmonary and intrathoracic pressures could be generated in this situation.

In a prospective study of 17 ventilated pediatric patients, it was found that catheter diameter did not influence the magnitude of change in Sa_{O_2}, heart rate, and intracranial pressure (54). When using a catheter with outer diameter:ETT inner diameter of 0.4, repeated suction passes were required to adequately clear the airway, and catheters with an outer diameter:inner diameter ratio $>$0.7 were difficult to insert into the ETT. These authors found that using a suction catheter with outer diameter:inner diameter of 0.7 was easiest to introduce into the ETT and was most effective in clearing secretions.

The selection of catheter size should be made considering both the ETT size and the secretion consistency, as small diameter catheters will not effectively clear thick secretions (122). The recommendation for catheter size selection presented in Table 1 was developed by the authors from the findings of an *in vitro* study (122) and has not been subjected to rigorous testing by means of a prospective controlled clinical trial. It is recommended that this be used as a guideline until stronger evidence is available.

The suction catheter should be large enough to effectively suction thick secretions but not so large that it traumatizes or occludes the ETT, which would lead to greater negative pressure accumulation (122) and lung volume loss (70).

Vacuum Pressure. The issue of selecting suction pressures relates to the balance between effective suctioning of secretions and potential risk to the patient. The suction pressure should be high enough to be effective in removing secretions, but not so high that it causes mucosal damage or lung volume loss. There is still no high-level evidence supporting a maximum, safe, and effective suction level.

Negative pressure in the lungs produced during suctioning would only occur while air was flowing through the suction catheter. As soon as secretions are drawn into the catheter, the pressure in the lungs would return to that of the

Table 1. A proposed guideline for suction catheter selection based on *in vitro* investigations by Morrow et al. (122)

Age	Weight (kg)	ETT (mm ID)	Mucus Consistency, Catheter Size (FG)		
			Liquid	Medium	Thick
Newborn	<1	2.0	5	5	5
Newborn	1	2.5	5	5	6
Newborn	2	3.0	5	6	6
Newborn	3.5	3.5	5	6	7
3 months	6	3.5	5	6	7
1 year	10	4.0	6	7	7
2 years	12	4.5	6	7	8
3 years	14	4.5	6	7	8
4 years	16	5.0	7	8	8
6 years	20	5.5	7	8	8
8 years	24	6.0	8	10	10
10 years	30	6.5	8	10	12
12 years	>30	7.0	8	10	12

ETT, endotracheal tube; mm ID, mm internal diameter; FG, French gauge.

atmosphere (80). An observational study of pediatric patients suggested that suctioning in the presence of ETT secretions may not result in loss of lung volume (70). However, routine suctioning, which often occurs in the absence of secretions, is likely to cause significant atelectasis. Repeating suctioning maneuvers after mucus has been removed is also likely to cause loss of lung volume. Therefore, although suction pressures should be limited, the issue may not be as critical when suctioning only when indicated to do so in the presence of secretions.

Results of an animal study, in which the suction catheter was passed to the carina, showed that mucosal trauma occurred when using suction pressures of both 100 mm Hg and 200 mm Hg; however, damage was greater at the higher suction level (66). This study also suggested that efficiency of aspiration was not affected by the suction pressure used. Conversely, in an *in vitro* study, it was shown that suction pressures up to 360 mm Hg measured at the vacuum source were more effective in removing secretions than using vacuum pressures of 200 mm Hg (122). These suction pressures were the lowest two options on the commercially available suction units in use at the time of these investigations.

In two pediatric ET suction studies, Morrow et al. (48, 70) used suction pressures of approximately 360 mm Hg measured at the source with the tubing clamped. Although not measured, much lower suction pressures would actually have been delivered at the distal end of the catheter than were indicated on the gauge because of the resistance offered by the suction tubing and suction catheter (123).

These suction pressures are higher than those recommended by most authors, who advocate a range between 70 and 150 mm Hg (74, 124). Young (11) suggested that these pressures may be increased up to 200 mm Hg to aspirate thick secretions. In a neonatal study, suction pressures between 200 and 300 mm Hg were used (60). Singh et al. (54) did not show any difference in the change of physiologic parameters when suctioning children using vacuum pressures of 80 mm Hg, 100 mm Hg or 120 mm Hg. Clinical studies have not investigated comparatively the effects of higher suction pressures on physiologic changes, efficacy of secretion removal, or patient outcome.

The potential impact of high suction pressures (potential mucosal damage and lung volume loss) needs to be weighed against the potential damage that may occur with repeated suction passes when using a lower vacuum level. This warrants investigation.

Sterility. There is a risk of introducing pathogens into the respiratory tract during ET suctioning, largely as a result of environmental exposure of the suction catheter (96). Therefore, it has been suggested that a strictly aseptic technique be used during ET suctioning (9, 125). During suctioning, however, the catheter is passed into the ETT through an unsterile port which may be colonized with potentially pathogenic organisms. This will occur regardless of operator sterility. In a randomized controlled trial of 486 intubated children and infants, it was found that reusing a disposable suction catheter in the same patient over a 24-hr period did not affect the incidence of nosocomial pneumonia (53).

The increased prevalence of community-acquired infections among young children who have not yet become immune either by vaccination or natural exposure, results in more patients presenting with transmissible infections, especially during seasonal epidemics (e.g., respiratory viruses, measles, varicella, rotavirus, and pertussis). The emergence of multidrug-resistant organisms in the PICU setting and the spread among patients poses the threat of outbreaks of untreatable infectious diseases associated with significant mortality and morbidity. Use of infection control precautions to prevent transmission among patients is, therefore, a top priority (110). Considering that transmission of infectious organisms from patient to patient frequently occurs on the hands of healthcare workers (110), hand washing before and after patient contact is essential despite the wearing of gloves, and regardless of suctioning method (open or closed).

There are reports of nursing staff acquiring tuberculosis from children requiring ET suctioning (126, 127), implying a potential risk of infection to the person performing the procedure. With exposure to respiratory secretions, pregnant healthcare workers are at risk of exposing their fetuses to potentially damaging pathogens such as hepatitis C, cytomegalovirus, and parvovirus B19. Standard and transmission-based precautions are the only preventive measures for minimizing this risk (110).

Therefore, it is essential to adhere to strict infection control procedures, particularly in developing countries, where there is a higher incidence of infectious diseases such as tuberculosis (1, 128, 129). More research into the influence of different suctioning techniques on the occurrence of nosocomial pneumonia is needed.

The recommended contact and standard precautions for patients with presumed infectious diseases include the use of gloves (either "clean" or sterile); face protection (face masks and goggles) for open ET suctioning, which is likely to cause splashes or sprays of secretions; washing hands before and after donning gloves; and wearing a gown to protect the skin and prevent contamination of the clothes (110, 130).

Although the same suction catheter may be used for several suction passes

(53), external environmental contamination should be limited. The suction catheter should be immediately discarded if it comes into contact with any surfaces, and should not be used to suction the nose or mouth before introduction into the ETT.

Although strict sterility in the suctioning process may be unnecessary, adherence to standard infection control procedures is mandatory.

Duration of Suctioning. Increasing the duration of suction application has been shown to significantly increase the amount of negative pressure within a lung model (122) and has been implicated in the degree of hypoxia induced clinically (69, 80). Although there is currently no strong evidence supporting an appropriate duration of suctioning, most authors recommend between 10 and 15 secs (9, 11). Runton (10) suggests that the actual time of negative pressure application during suctioning of children be limited to ≤5 secs.

Depth of Catheter Insertion. The depth of insertion of the suction catheter during ET suctioning varies according to institutional practice (6). Although the definitions of deep and shallow suctioning are inconsistent in the literature, in most cases shallow ET suctioning refers to passing the catheter to the tip of the ETT, whereas in deep ET suctioning the catheter is passed beyond the ETT into the trachea or bronchi, usually until resistance is felt.

In two randomized crossover studies of high-risk neonates (36, 37), it was shown that there were no significant differences in Sa_{O_2} or heart rate responses between shallow and deep ET suction (37). During deep suctioning more fresh clustered columnar cells were detached from the respiratory epithelium, although shallow ET suction caused less tracheal epithelial loss and inflammation. Deep suctioning was not superior in sampling from the lower respiratory tract (36).

No studies met the inclusion criteria for a systematic review of deep vs. shallow ET suctioning of ventilated infants (6) and, it was therefore, concluded that there was insufficient concerning the benefits or risks of the respective techniques despite some anecdotal evidence regarding possible airway damage.

In an animal model, inserting the catheter to 1 cm beyond the ETT tip resulted in significantly less mucosal necrosis and inflammation than with deeper suctioning (2).

Mucosal inflammation as a result of deep ET suctioning could cause squamous metaplasia, ulceration, and formation of obstructive granulation tissue (67). Cases of pneumothorax have been reported after deep ET suctioning (64, 65).

In specific situations, such as following surgical repair of tracheo-esophageal fistulas, deep suctioning may be hazardous as the surgical site may be compromised by direct catheter trauma.

Recruitment Maneuvers Performed After ET Suctioning. RM have been suggested as a method of reversing suctioning-induced lung volume loss and improving arterial oxygenation, by reinflating the collapsed lung segments before resuming ventilation (87, 99, 131). A RM refers to the application of a sustained inflation pressure to the lungs for a specified duration to return the lung to normal volumes and distribution of air.

Collapsed alveoli are subject to Laplace's law and a high inspiratory pressure is required to expand these atelectatic lung units. Laplace's law, however, also implies that, in the presence of normally aerated or hyperinflated alveoli together with collapsed alveoli, there is a risk that the RM would preferentially overdistend the aerated units before expanding collapsed areas.

In lung-injured rabbits, a RM (inflation pressure of 30 cm H_2O sustained for 30 seconds) resulted in a significant sustained increase in end-expiratory lung volume, Pa_{O_2} and dynamic compliance despite equal positive end-expiratory pressure levels used before and after the maneuver (132). Cakar et al. (133) concluded that responses to RMs differed among different models of ALI, using dogs as experimental subjects.

In anesthetized sheep, airway narrowing and atelectasis caused by ET suctioning was completely reversed by hyperoxygenation and a RM (85). Similarly, a timed re-expansion inspiratory maneuver successfully reversed apnea-induced decreases in dynamic compliance in anesthetized lambs (134). In a porcine lung model ventral lung regions re-expanded faster than dorsal regions after suctioning irrespective of ventilation mode. In the dorsal regions, however, where loss of volume and compliance were most pronounced, recruitment was significantly faster with volume-controlled compared with pressure-controlled ventilation (135).

Morrow et al. (48) conducted a prospective randomized controlled trial investigating the effect of a postsuctioning RM in 34 infants and children (after excluding patients with large ET leaks) with variable lung pathology, who were receiving conventional pressure-limited, time-cycled mechanical ventilation. The RM was performed by manually applying a sustained inflation pressure of 30 cm H_2O for 30 secs. The RM may have improved airway resistance and oxygenation, but generally had no effect on dynamic compliance as compared with the control group. In both patient groups, pulmonary compliance dropped significantly after open-ET suctioning, indicating a loss of lung volume. However, in most cases pulmonary compliance had returned to baseline levels within 10 mins of the suctioning procedure, regardless of whether a RM was applied or not. The efficacy of the RM may have been influenced by the manual nature of the technique. Most of the patients studied had acute respiratory distress syndrome (ARDS) or ALI by definition, but these were all cases of pulmonary (primary) lung injury. It has previously been found, in adults, that patients with extrapulmonary ARDS showed a greater increase in Pa_{O_2} after RM than those with pulmonary ARDS (136). In the study by Morrow et al. (48), there was a variable response to the RM among different patients, with two patients with severe lung disease experiencing a compliance increase of >100%. This suggests that postsuctioning RM may be effective under certain conditions, and warrants further investigation.

In a prospective randomized controlled study using eight adults with ALI or ARDS (137), patients received open-ET suctioning with or without a RM performed after the suctioning procedure. The RM consisted of two hyperinflations of 45 cmH_2O sustained for 20 secs. The RM was well tolerated and produced a rapid recovery in end-expiratory lung volume, respiratory system compliance, and Pa_{O_2}. The study was limited by the small sample size.

Other adult studies have investigated the use of RM in various situations, using different techniques, and with variable results. In adults with ARDS, an "extended sigh" as a RM resulted in a sustained increase in both Pa_{O_2} and static respiratory compliance. In addition, no major hemodynamic or respiratory com-

plications were noted (136). Similarly, when a sustained positive pressure was applied to adults with severe ARDS after first being turned prone, there were significant, sustained improvements in oxygenation index, $Pa_{O_2}/F_{I_{O_2}}$ and alveolar-arterial O_2 difference (138). The ARDS Clinical Trials Network (2003) (139) found a variable response to RM, with some patients experiencing a drop in Sa_{O_2} although others' increased markedly. The RM caused greater decreases in systolic blood pressure compared with controls, and respiratory system compliance did not increase more after RM than sham RM. RMs were terminated early in a few cases because of hypotension or desaturation. This group concluded that more information regarding efficacy and safety is needed from clinical studies before RMs can be recommended as part of standard ventilator management in patients with ALI or ARDS.

Other studies investigating the use of RM in pediatric patients have involved small sample sizes and used subjects with normal lungs (140, 141). Tingay et al. (88) reported that term infants receiving high-frequency oscillatory ventilation experienced a significant but transient loss of lung volume which, in most cases, had resolved within 1 min without the need for a recruitment maneuver. These authors noted that in one patient postsuction lung volume was higher than at baseline and that, in this case, performing a RM would have placed the lung at the risk of overdistension. Conversely, one infant still had a deficit in lung volume at the end of the study period, and may have benefited from a RM.

Physiotherapists working in adult intensive care units often use manual hyperinflation techniques in conjunction with other manipulations to expand the lung (142, 143). These maneuvers are usually repeated short manual inflations reaching a predetermined set pressure or volume with a brief inspiratory hold. Studies reporting the efficacy and safety of manual hyperinflation have been conflicting with some reporting improvements in atelectasis, lung compliance, and gas exchange (142, 144, 145), although others have found no change (146). Care should be taken when applying adult hyperinflation studies to pediatric practice. In infants and children, performing hyperinflation maneuvers (as opposed to recruitment/inflation maneuvers aiming to normalize lung volumes) may be dangerous because of the high risk of baro- or volutrauma.

A pediatric crossover study found that hyperinflation (five breaths over 10 secs administered at approximately twice the patient's tidal volume) performed after suctioning immediately restored Pa_{O_2} to presuction levels (55). Considering that preoxygenation alone completely prevented the fall in Pa_{O_2} with suctioning, one needs to question the recommendation made by the authors to use postsuction hyperinflation maneuvers in addition to preoxygenation (as this approach was not compared with others in this study), especially when one considers the potential risks of hyperinflation in the pediatric population.

Although further investigation is clearly necessary, the routine practice of performing RM after ET suctioning in children does not seem to be beneficial (and may in fact be harmful) and is therefore not recommended for clinical use.

Limitations. Because of the paucity of high-level pediatric evidence, a broad range of studies were included in this review, including those outside the targeted age group and those of all evidence levels. This constitutes a limitation of this article, but was deemed necessary to present a comprehensive review of the ET suctioning literature, much of which may be able to be extrapolated to the pediatric population or at least stimulate further research in this neglected group. Furthermore, only published articles in the English language were considered, which might bias the review's findings.

Recommendations. Table 2 summarizes the recommendations derived from this literature review. The evidence is graded according to the system described by Harbour and Miller (147), as summarized below:

Levels of Evidence

1++ High quality meta-analyses, systematic reviews of RCTs or RCTs with a very low risk of bias.

1+ Well-conducted meta-analyses, systematic reviews of RCTs, or RCTs with a low risk of bias.

1− Meta-analyses, systematic reviews or RCTs, or RCTs with a high risk of bias.

2++ High quality systematic reviews of case-control or cohort studies, or high-quality case-control, or cohort studies with a very low risk of confounding and bias, and a high probability that the relationship is causal.

2+ Well-conducted case-control or cohort studies with a low risk of confounding, bias, or chance and a moderate probability that the relationship is causal.

2− Case-control or cohort studies with a high risk of confounding, bias, or chance and a significant risk that the relationship is not causal.

3 Nonanalytic studies, e.g., case reports, case series.

4 Expert opinion.

Grades of Recommendations

A. At least one meta-analysis, systematic review, or RCT rated as 1++ and directly applicable to the target population, or a systematic review of RCTs, or a body of evidence consisting principally of studies rated as 1+ directly applicable to the target population and demonstrating overall consistency of results.

B. A body of evidence including studies rated as 2++ directly applicable to the target population and demonstrating overall consistency of results or extrapolated evidence from studies rated as 1++ or 1+.

C. A body of evidence including studies rated as 2+ directly applicable to the target population and demonstrating overall consistency of results or extrapolated evidence from studies rated as 2++.

D. Evidence level 3 or 4 or extrapolated evidence from studies rated as 2+.

Considering the physiologic and anatomical differences between different age groups, where recommendations have been based on extrapolations from neonatal or adult studies, this is explicitly stated in Table 2.

CONCLUSION

ET suctioning, although necessary to maintain patency of the airways, is not a benign procedure. All staff performing the procedure should be aware of the positive and negative effects of ET suctioning, and methods to prevent or min-

Table 2. Clinical recommendations for endotracheal suctioning of infants and children

Clinical Practice	Recommendation	Grade of Recommendation
Analgesia	ET suctioning is a frequently performed procedure that causes pain and discomfort. As the procedure is often performed immediately after secretions are detected, there may be insufficient time to administer analgesia and allow it to take full effect. Therefore, it is recommended that all ventilated patients receive regular or infused analgesia for the duration of ventilation.	B. Extrapolated from neonatal RCT (42).
Frequency of suctioning	Routine suctioning should be avoided (64, 137), with the possible exception of paralyzed patients. Suctioning should be performed only when clinically indicated (9).	D. No experimental evidence.
Suctioning system	Although there may be short-term benefits of closed-system suctioning in terms of reduced lung volume loss and hypoxia (51), there is no clear benefit for the use of closed- or open-system suctioning, and practitioners should continue with the method at which they are proficient (33, 107–109).	B. Extrapolated from adult (107–109) and neonatal (33, 39) systematic reviews.
Monitoring	Considering the known complications of ET suctioning, the patient's heart rate, blood pressure, and oxygen saturation should be carefully monitored at all times during the procedure. Clinical observations should include patient color (to detect early cyanosis); signs of respiratory distress (such as sweating, tachypnea, marked costal recessions); and signs of pain or anxiety. Where possible, respiratory mechanics should be monitored to detect lung volume changes.	D. No experimental evidence.
Preoxygenation	Considering the short-term effects of hyperoxygenation in reducing hypoxia (34, 55), patients should receive increased inspired oxygen levels for a brief period (≤60 secs) before suctioning (9, 55). The optimal level of preoxygenation is not known, but can be individually determined by the patient's clinical condition and response to handling. The clinical context should be taken into consideration, as some pathological processes may make an individual more susceptible to the adverse effects of hypoxemia (e.g., severe pulmonary hypertension).	B. One pediatric randomized cross-over trial (55); recommendation extrapolated from neonatal (34) and adult (111) systematic reviews, and neonatal randomized cross-over trials (32, 61).
Suction catheter size	Table 1 can be used as a guideline for suction catheter selection. Doubling the ETT internal diameter gives an indication of which FG catheter size to use for efficacy and safety (e.g., with a 3.5-mm internal diameter ETT, a size 6 or 7 FG catheter could be used).	D. *In vitro* studies (122) and anecdotal evidence (7, 8, 11).
Vacuum pressure	Medical and paramedical staff should use the lowest pressure that effectively removes the secretions with the least adverse clinical reaction. Suction pressures should be at least ≤360 mm Hg.	D. *In vitro* studies (122) and expert opinion (70, 74, 124).
Sterility	A strictly sterile technique is not necessary (53), but staff should adhere to strict infection control measures to protect themselves and other patients (110, 126).	A. Large RCT of infants and children (53).
Duration of suctioning	To limit the adverse effects of lengthy duration of suctioning and to minimize airway trauma, the catheter should be inserted in the absence of vacuum pressure, and suction only applied on catheter withdrawal. The application of suction should be limited to ≤10 secs (9, 10, 11). Patients should be reconnected to the ventilator, and given several recovery breaths before repeating the suctioning procedure if secretions have not been adequately cleared by the previous suctioning event.	D. *In vitro* studies (122) and expert opinion (9, 10, 11).
Depth of catheter insertion	Considering that there are no known benefits to performing deep ET suctioning, and there is an increased risk of direct trauma (36) and vagal nerve stimulation with deep rather than shallow suctioning (37), the catheter should only be passed to the end of the ETT. The depth of insertion can be determined by direct measurement.	C. Extrapolated from randomized cross-over studies in high-risk neonates (36, 37).
Use of saline	Saline should never be used routinely for suctioning.	B. Pediatric RCT (52).
When to discontinue suctioning	Suggested that suctioning be discontinued if there are no more secretions in the large airways; if the child desaturates to ≤80% (assuming baseline Sa_{O_2} ≥90%); if the child experiences a cardiac arrhythmia or bradycardia; or if the child becomes extremely agitated (respiratory signs of distress, anxiety, or pain responses). Where possible, suctioning should be discontinued if the child has acute pulmonary hemorrhage or pulmonary edema. At all times, however, a patent airway must be ensured. In the event of hypoxia or bradycardia, the appropriate pediatric life support measures should be implemented.	D. No experimental evidence.
Recruitment maneuvers	Recruitment maneuvers should not be performed routinely after endotracheal suctioning (48).	B. Pediatric RCT (48).

ET, endotracheal; ETT, endotracheal tube; FG, French gauge; RCT, randomized controlled trials.

imize its complications. Currently, objective evidence in support of clinical practice recommendations is limited, particularly, in the pediatric population (Table 2). Further controlled clinical trials are necessary to develop an evidence-based protocol for ET suctioning of infants and children, as well as to examine the impact of different suctioning techniques on the duration of mechanical ventilatory support, incidence of nosocomial infections and length of PICU and hospital stays.

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