

The Effects of Closed Endotracheal Suction on Ventilation During Conventional and High-Frequency Oscillatory Ventilation

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ABSTRACT: In newborn infants, closed endotracheal tube (ETT) suction may reduce associated adverse effects, but it is not clear whether ventilation is maintained during the procedure. We aimed to determine the effect of ETT size, catheter size, and suction pressure on ventilation parameters measured distal to the ETT. Suction was performed on a test lung, ventilated with conventional (CMV) and high-frequency oscillatory ventilation (HFOV) using ETT sizes 2.5–4.0 mm, catheter sizes 5–8 French gauge (Fr), and suction pressures 80–200 mm Hg. Tracheal and circuit peak inspiratory pressure, positive end-expiratory pressure, and tracheal tidal volume (V_T) were recorded for each suction episode. During both CMV and HFOV, tracheal pressures and V_T were considerably reduced by suctioning; this reduction was dependent on the combination of ETT, catheter, and suction pressure. Loss of V_T , inflation pressure (CMV), and pressure amplitude (HFOV) occurred primarily with insertion of the catheter, and loss of end-expiratory pressure (CMV) and mean tracheal pressure (HFOV) occurred with the application of suction. Circuit pressures were reduced to lesser degree. We conclude that airway pressures and V_T are not maintained during closed endotracheal suction with either CMV or HFOV, and choice of equipment and settings will affect the degree of interruption to ventilation. (*Pediatr Res* 66: 400–404, 2009)

Endotracheal tube (ETT) suction is performed periodically on infants receiving mechanical ventilation to clear secretions from the ETT and airway. Although necessary, it is associated with adverse effects including atelectasis, hypoxemia, and cardiovascular instability, partly attributable to loss of airway pressure and interruption of ventilation (1–5). Closed suction, performed without disconnection from respiratory support, has been shown to reduce adverse effects (6–8), but whether ventilation is maintained during closed suction has not been demonstrated in a neonatal population.

With adult-sized ETTs, airway pressure has been shown to decrease during closed suction and concerns have been raised about the potential for very large negative airway pressures during the procedure (4,9,10). However only one study has quantified pressure and tidal volume (V_T) changes during

closed suction with neonatal equipment (11). Using an *in vitro* model, a considerable reduction in airway pressures and V_T was demonstrated, particularly when a large catheter relative to the ETT was used. However, the authors did not report results using 5 or 7 French gauge (Fr) suction catheters, nor did they measure the effect of varying the suction pressure.

Airway pressures during closed suction are influenced by ventilation mode in adult models (4,10), but this effect has not been studied using neonatal ventilators. Of particular interest is the performance of closed suction catheters during high-frequency oscillatory ventilation (HFOV), because closed suction is generally recommended for patients receiving this ventilation mode (12,13).

This study aimed to determine the effect of ETT size, catheter size, and suction pressure on tracheal pressure and V_T with closed suction of a neonatal lung model during conventional mechanical ventilation (CMV) and HFOV. Additionally, we aimed to measure ventilator circuit pressures during the procedure.

MATERIALS AND METHODS

Experimental model. The experimental arrangement is shown in Figure 1. An uncuffed ETT (Mallinckrodt, Rowville, Victoria, Australia) was connected to the trachea of an infant test lung (model 560li; MI Instruments, Grand Rapids, MI) with an ETT adaptor and sealed with silicon to prevent leak. A Ballard Trachcare in-line suction catheter (Kimberly-Clark, Roswell, GA) was placed between the ventilator circuit and ETT. Test lung compliance was set to 1 mL/cm H₂O to represent an average compliance in our patient population, and no extra resistance was added to the airway.

Ventilation. The test lung was ventilated using both CMV and HFOV modes. CMV was delivered using a Dräger Babylog 8000 (Dräger, Lübeck, Germany) in time-cycled pressure-limited mode with the following settings: 20 cm H₂O positive inspiratory pressure (PIP); 5 cm H₂O positive end-expiratory pressure (PEEP); rate 60 per minute; inflation time 0.4 s; circuit gas flow 8 L/min; and fraction of inspired oxygen 0.4. HFOV was delivered using a Sensormedics 3100A oscillator (Sensormedics, Yorba Linda, CA) at mean airway pressure (P_{aw}) 20 cm H₂O, pressure amplitude (ΔP) 30 cm H₂O, frequency 15 Hz, I:E ratio 1:2, circuit gas flow 20 L/min, and fraction of inspired oxygen 0.4. These settings were chosen to represent those commonly used in clinical practice.

Abbreviations: ΔP , pressure amplitude during HFOV; CMV, conventional mechanical ventilation; ETT, endotracheal tube; Fr, French gauge; HFOV, high-frequency oscillatory ventilation; P_{aw} , mean airway pressure during HFOV (measured in the ventilator circuit); MTP, mean tracheal pressure; PEEP, positive end-expiratory pressure; PIP, peak inspiratory pressure; V_T , tidal volume

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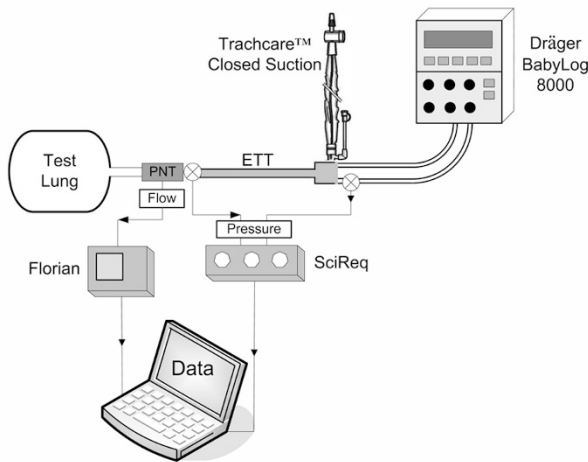


Figure 1. Diagram of the experimental design. ETT, endotracheal tube; PNT, pneumotachograph.

Suction procedure. Experiments were performed with all practicable combinations of neonatal ETT (sizes 2.5, 3.0, 3.5, and 4.0 mm internal diameter), suction catheter (5, 6, 7, and 8 Fr, which have external diameters of 1.7, 2.0, 2.3, and 2.7 mm, respectively), and suction pressure (80, 120, 160, and 200 mm Hg), to cover the range used in clinical practice. A suction regulator (PM3000, Precision Medical Inc., Northampton, PA) was attached to wall suction, and pressure was set with the tubing occluded using a manometer (model RT-200; Timeter, St Louis, MO).

Before each suction episode was performed, a period of baseline ventilation (≥ 6 s in all cases) occurred to allow ventilation parameters to stabilize. For each suction episode, a catheter was passed to the tip of the ETT and held there for 6 s without suction. Suction was then applied for 6 s, and then the catheter was withdrawn. The procedure was repeated six times with each combination of ETT, catheter size, and suction pressure during both ventilation modes.

Measurements. Ventilator circuit pressure was measured proximal to the ETT and tracheal pressure was measured 1 cm distal to the ETT. Both measurements were recorded using pressure transducers and signal amplifiers (SciReq, Montreal, PQ, Canada), which were calibrated against the Timeter manometer before the study. Tracheal gas flow was measured using a hot wire anemometer (Florian respiration monitor, Acutronic Medical Systems, Zug, Switzerland), calibrated to zero flow, placed distal to the ETT, and 1 cm distal to the tracheal pressure measurement port (Fig. 1). All pressure and flow signals were acquired at 200 Hz (CMV) or 1000 Hz (HFOV) using LabVIEW 6.0 (National Instruments, Austin, TX).

Data analysis. Proximal and distal PIP and PEEP and V_T (calculated by integrating the flow wave signal) were determined for each inflation. From these measurements, inflation pressure (CMV) and ΔP (HFOV) were calcu-

lated as the difference between PIP and PEEP. P_{aw} (measured in the ventilator circuit) and mean tracheal pressure (MTP) during HFOV were calculated as the mean pressure during each ventilation cycle.

During each suction episode, three phases were identified from the tracheal pressure signal: baseline (normal ventilation), catheter insertion (before suction was applied), and during suction. For each parameter, mean values for the last 3 s (CMV, equal to 3 inflations) or 1 s (HFOV, equal to 15 inflations) of each phase were calculated and used in the analysis.

The effect of ETT size, catheter size, and suction on each of the measured parameters was determined using multiple linear regressions with the method of least squares, with p values < 0.05 considered statistically significant. Statistical analyses were performed using Stata (Version 9.0, Stata Corporation, College Station, TX). Values in text and figures are mean \pm SD.

RESULTS

CMV: Tracheal measurements. Changes from baseline in PEEP, inflation pressure, and V_T during catheter insertion are shown in Table 1. Minimal changes in PEEP occurred, however, considerable reduction in inflation pressure and V_T were observed, with greater reduction in these parameters associated with increasing catheter size ($p < 0.05$ in all cases).

During suction, tracheal PEEP fell by up to 110 cm H₂O, depending on the combination of ETT, catheter and suction pressure (Fig. 2). V_T (Fig. 3) was also reduced, and this reduction was greatest where a large catheter relative to the ETT was used. Inflation pressure followed a similar pattern to V_T , with reduction being greatest with large catheters and being relatively unaffected by suction pressure. With a 4.0 ETT, an 8 Fr catheter, and either 160 or 200 mm Hg suction pressure, the ventilator stopped delivering inflations; thus inflation pressure and V_T were reduced to zero.

Multiple linear regression analyses demonstrated that ETT and catheter size had significant independent effects in determining PEEP, inflation pressure and V_T during suction ($p < 0.001$ in all cases). Suction pressure had no independent effect on PEEP ($p = 0.858$), but was independently significant in determining inflation pressure and V_T ($p < 0.001$ in each case). Interaction between variables was observed with each combination of independent variables ($p < 0.001$ in each case), except between ETT and catheter size during regression of V_T ($p = 0.424$). The multiple linear regression models used accurately described PEEP ($R^2 = 0.83$), inflation pressure ($R^2 = 0.79$) and V_T ($R^2 = 0.91$).

Table 1. Suction catheter insertion—change in ventilation parameters from baseline during insertion of a closed suction catheter (no suction applied)

ETT, mm ID	Catheter, Fr	CMV			HFOV		
		Δ PEEP, cm H ₂ O	IP, %	V_T , %	Δ MTP, cm H ₂ O	Trach ΔP , %	V_T , %
2.5	5	0.7 \pm 0.1	62 \pm 2	59 \pm 4	0.2 \pm 0.0	50 \pm 1	35 \pm 1
	6	2.8 \pm 0.1	24 \pm 2	21 \pm 2	0.4 \pm 0.0	22 \pm 1	10 \pm 1
3.0	5	0.0 \pm 0.0	92 \pm 1	90 \pm 1	0.1 \pm 0.0	70 \pm 1	55 \pm 1
	6	0.3 \pm 0.1	73 \pm 1	70 \pm 2	0.0 \pm 0.0	53 \pm 1	35 \pm 1
	7	1.8 \pm 0.1	39 \pm 2	36 \pm 2	0.2 \pm 0.0	31 \pm 1	15 \pm 1
3.5	5	0.0 \pm 0.0	98 \pm 1	98 \pm 1	0.1 \pm 0.0	80 \pm 0	69 \pm 1
	6	0.0 \pm 0.0	94 \pm 1	93 \pm 1	0.1 \pm 0.1	70 \pm 1	54 \pm 1
	7	0.2 \pm 0.1	79 \pm 3	76 \pm 3	0.1 \pm 0.1	56 \pm 1	38 \pm 1
	8	1.7 \pm 0.2	42 \pm 2	40 \pm 2	0.1 \pm 0.0	30 \pm 1	14 \pm 1
4.0	5	0.0 \pm 0.0	99 \pm 1	99 \pm 1	0.1 \pm 0.1	88 \pm 1	84 \pm 1
	6	0.0 \pm 0.0	98 \pm 1	98 \pm 1	0.1 \pm 0.0	82 \pm 0	75 \pm 1
	7	0.0 \pm 0.0	98 \pm 1	98 \pm 1	0.2 \pm 0.0	76 \pm 1	65 \pm 1
	8	0.1 \pm 0.2	96 \pm 2	95 \pm 3	0.2 \pm 0.0	22 \pm 0	55 \pm 0

Data mean \pm SD.

ID, inner diameter; IP, inflation pressure; %, percent of baseline value measured; trach ΔP , pressure amplitude measured in the trachea.

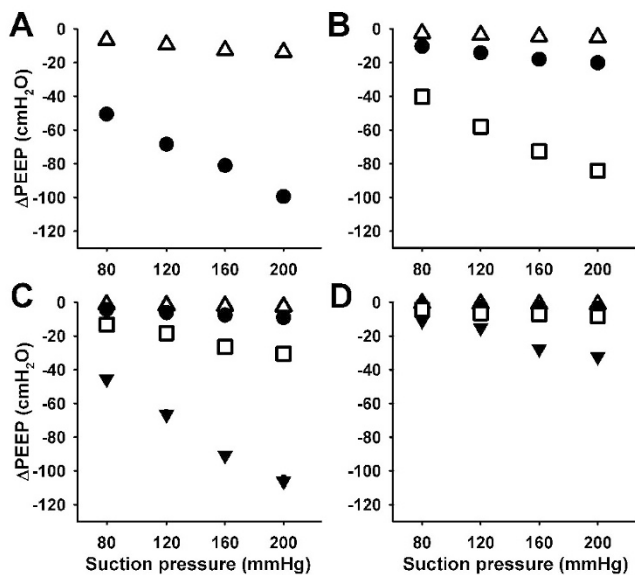


Figure 2. A–D, change in tracheal PEEP (cm H₂O) from baseline during CMV for suction of ETT internal diameters 2.5 mm (A), 3.0 mm (B), 3.5 mm (C), and 4.0 mm (D) with catheter sizes 5 Fr (Δ), 6 Fr (\bullet), 7 Fr (\square), and 8 Fr (\blacktriangledown).

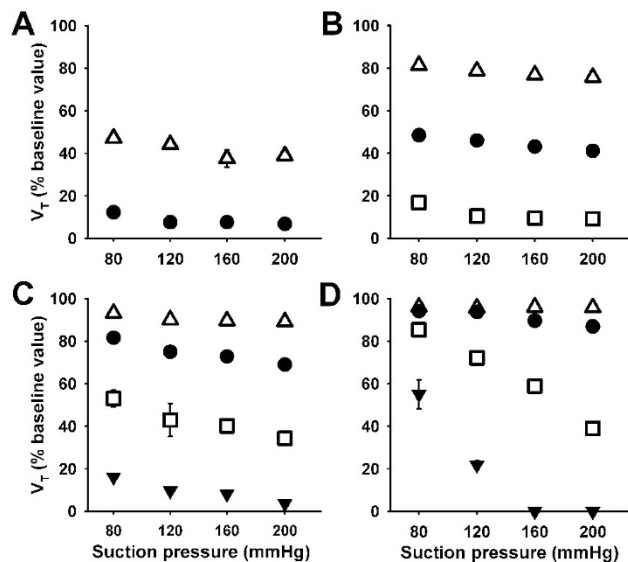


Figure 3. A–D, delivered V_T (expressed as percent of baseline) during CMV for suction of ETT internal diameters 2.5 mm (A), 3.0 mm (B), 3.5 mm (C), and 4.0 mm (D) with catheter sizes 5 Fr (Δ), 6 Fr (\bullet), 7 Fr (\square), and 8 Fr (\blacktriangledown).

CMV: Ventilator circuit measurements. Circuit PEEP was maintained during CMV with all combinations tested, with the exception of 4.0 mm ETT, 8 Fr catheter, and either 160 or 200 mm Hg suction pressure, where the ventilator ceased delivering inflations. In this circumstance, ventilator circuit pressure stabilized at -4.2 cm H₂O. Circuit PIP was reduced by ≥ 3 cm H₂O only with the following combinations of ETT/catheter/suction pressure: 3.5 mm/8 Fr/200 mm Hg; 4.0 mm/7 Fr/160 or 200 mm Hg; 4.0 mm/8 Fr/120 or 160 or 200 mm Hg. With these combinations, circuit PIP was reduced by up to 10.9 cm H₂O. In addition, PIP was equal to PEEP when the ventilator stopped delivering inflations as described earlier.

HFOV: Tracheal measurements. Minimal changes in MTP were recorded during catheter insertion. There was marked

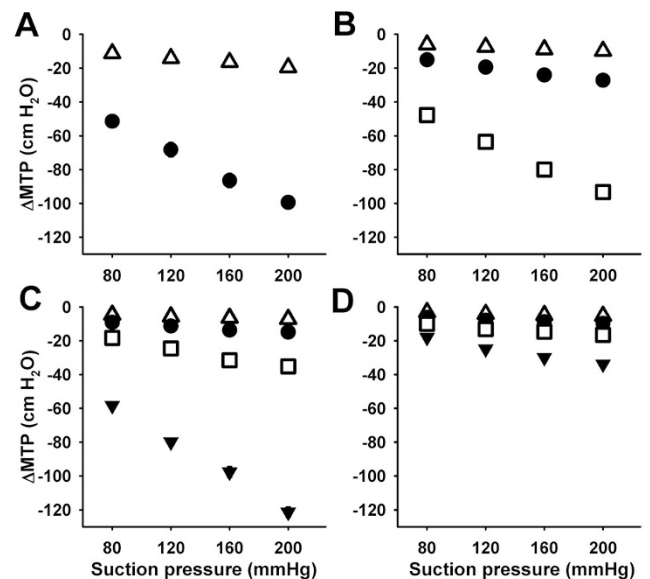


Figure 4. A–D, change in MTP (cm H₂O) from baseline during CMV for suction of ETT internal diameters 2.5 mm (A), 3.0 mm (B), 3.5 mm (C), and 4.0 mm (D) with catheter sizes 5 Fr (Δ), 6 Fr (\bullet), 7 Fr (\square), and 8 Fr (\blacktriangledown).

reduction in both ΔP and V_T during catheter insertion and considerable variation between combinations of ETT and catheter, with an increase in catheter size resulting in reduction in these parameters in all circumstances ($p < 0.001$; Table 1).

Reduction in MTP during suction was between 3 and 121 cm H₂O from the baseline value of approximately 20 cm H₂O (Fig. 4). Delivered V_T was reduced to 16–83% of baseline depending on the combination of ETT and catheter (Fig. 5). Tracheal ΔP was reduced to 15–20% of baseline where the largest catheter for ETT sizes 2.5, 3.0, and 3.5 were used. Suction pressure had little influence on tracheal ΔP .

ETT and catheter size both had significant independent effects on determining MTP, tracheal ΔP , and V_T during suction ($p < 0.001$), as determined by multiple regression analyses. Suction pressure had no independent effect on any of the outcome variables ($p > 0.6$ in all cases). Interaction between each of the three predictor variables was significant in determining MTP ($p < 0.001$ in each case). Interaction was observed between ETT and catheter size for both ΔP and V_T ($p < 0.001$ in each case), whereas no interaction was seen between suction pressure and either of the other variables ($p > 0.3$ in each case). The independent variables included in the model accurately predicted MTP ($R^2 = 0.83$), ΔP ($R^2 = 0.97$) and V_T ($R^2 = 0.99$) during suction with HFOV.

HFOV: Ventilator Circuit measurements. During HFOV, circuit P_{aw} was reduced in all circumstances during closed suction (Table 2). Larger reductions in P_{aw} were observed with increasing catheter size, ETT size, and suction pressure. Circuit ΔP was minimally affected by the procedure, being raised by up to 1.9 cm H₂O when the largest catheter for each ETT size was used.

DISCUSSION

This bench test, by investigating a practical and clinically relevant range of suction apparatus for newborn infants, is the

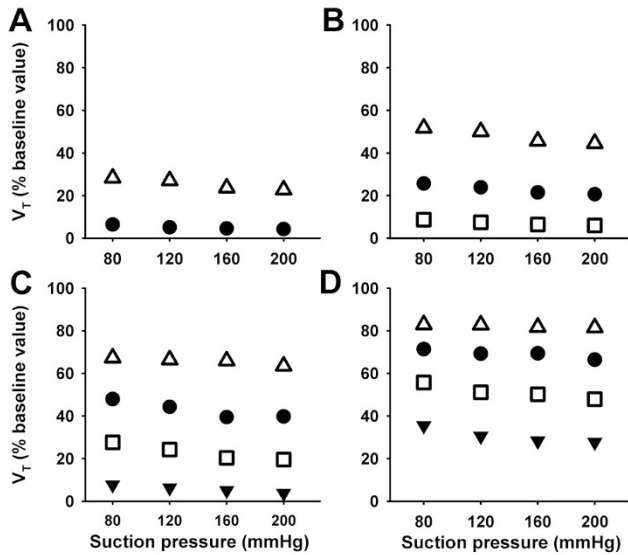


Figure 5. A–D, delivered V_T (expressed as percent of baseline) during HFOV for suction of ETT internal diameters 2.5 mm (A), 3.0 mm (B), 3.5 mm (C), and 4.0 mm (D) with catheter sizes 5 Fr (Δ), 6 Fr (\bullet), 7 Fr (\square), and 8 Fr (\blacktriangledown).

Table 2. High frequency oscillatory ventilation—reduction in circuit P_{aw} from baseline during the application of suction (cm H_2O)

ETT, mm ID	Catheter, Fr	Suction pressure (mm Hg)			
		80	120	160	200
2.5	5	2.0	2.6	3.0	3.3
	6	2.8	3.6	4.1	4.6
3.0	5	2.1	2.6	3.0	3.4
	6	3.5	4.3	5.0	5.6
3.5	7	4.2	5.3	6.3	6.9
	5	2.1	2.6	3.0	3.3
	6	3.6	4.4	5.1	5.6
	7	5.1	6.3	7.2	7.9
4.0	8	5.5	6.9	8.0	8.8
	5	1.9	2.6	3.0	3.3
	6	3.4	4.4	5.1	5.6
	7	4.9	6.4	7.3	8.1
	8	6.7	8.6	9.8	10.7

ID, inner diameter.

first to report the effect of closed system suction on ventilation pressure and V_T delivered to a test lung during CMV and HFOV. We found that tracheal pressures and V_T were affected by the combination of the ETT and catheter dimensions, and also the suction pressure applied to the catheter, with larger catheters and higher suction pressures associated with lower tracheal pressures and delivered V_T .

Comparison between the ‘catheter insertion’ and ‘suction’ phases shows that during both CMV and HFOV, ventilation is interrupted by simply inserting the catheter, and that distending pressure (tracheal PEEP or MTP) is lost only after suction is applied. This finding is significant because it has previously been proposed that the time taken to perform the entire suction procedure is less important with closed suction than open, because ventilation is assumed to be maintained (14). We also found that when the largest catheter for a given ETT is used, delivered V_T is reduced to <10% with both CMV and HFOV,

and distending pressure becomes extremely negative when suction is applied. However, circuit pressures are only minimally affected, therefore, clinicians may be unaware of the magnitude of negative pressure occurring within the airways. Even with catheter sizes currently recommended for neonatal airways (15,16), pressure was dramatically reduced: tracheal PEEP during CMV was reduced by up to 60 cm H_2O , and during HFOV, MTP was reduced by 17–70 cm H_2O . In clinical practice, even a small drop in pressure may be significant (17), and a large reduction in pressure may result in mucosal damage, airway collapse, and significant atelectasis (6,18,19).

Morrow and Argent (20) recently recommended smaller catheter sizes than previous recommendations for pediatric and neonatal patients, with the choice of catheter depending on the consistency of secretions. According to our results, catheter selection using these recommendations based on thin secretions would avoid subatmospheric airway pressures if used with ≤ 200 mm Hg suction pressure. However, a 6-Fr catheter recommended for a 2.5 ETT in the presence of thick secretions could result in large subatmospheric airway pressures if suction continued once secretions were cleared, and V_T is likely to be significantly reduced during the procedure. Furthermore, such secretions may adhere to the ETT inner surface and increase resistance (21,22), which may lead to airway pressures lower than have been recorded in this study.

The only other study to measure ‘intratracheal’ pressure during closed suction with neonatal apparatus was performed using a similar test lung and compliance setting to this study, but used only a single suction pressure of 100 mm Hg (11). Despite different ventilator settings, PEEP was within 3 cm H_2O and delivered V_T was within 20% of our findings for all comparable combinations of ETT and catheter, when our data are interpolated to 100 mm Hg suction pressure.

Airway pressures during closed suction in this study were considerably lower than we have previously described during open suction, particularly when using larger sized catheters in relation to the ETT (23). Airway pressures during open suction are a function of catheter size, and the difference in cross-sectional area between the ETT and the catheter (23–25). Flow between the ETT and catheter is predominantly laminar during open suction (23), but during closed suction, the dynamic circuit pressure and gas flow may lead to turbulent flow within this space increasing resistance and resulting in reduced tracheal pressures. This effect may be particularly important with infant ETTs, as this space is relatively small. Studies comparing airway pressures during open and closed suction using adult-sized equipment have reported higher pressures with closed suction than with open, at least under similar conditions to our study (4,10). These findings suggest that the larger area between the adult ETT and catheter may allow for flow to be predominantly laminar despite the dynamic flow conditions of closed suction, and therefore pressure loss to be less than with ETTs used for infants.

Our study has several limitations. In the clinical setting, airway pressure and V_T are likely to be influenced by the volume and consistency of mucus. Secretions adhering to the ETT can cause considerable narrowing of the ETT lumen

(21,22), which could result in greater loss of pressure and V_T during suction, whereas secretions entering the catheter will tend to inhibit a fall in pressure (26). However, suction in the absence of secretions can occur in clinical practice (26) and may occur toward the end of the procedure when secretions have been cleared, especially with multiple passes of the catheter. This experiment was conducted at a single compliance setting and excluded any effect from patient effort. In clinical practice, spontaneous breathing might affect ventilation during suction, while the collapsible lungs of infants with respiratory distress might cause greater reduction in delivered V_T than was observed with the constant compliance lung used in this experiment. Leak around the ETT was similarly excluded, as its variable magnitude would make testing complicated. Although leak occurs primarily during the higher-pressure conditions of inflation (27) and might therefore be less likely to occur during suction, the effect of leak on airway pressure during the procedure is yet to be determined. Finally, investigating the effects of suction using other ventilator settings and modes commonly used in neonatal practice, such as V_T -targeted ventilation, would increase understanding of the interaction between closed suction and ventilation.

In conclusion, this study demonstrates that, *in vitro*, airway pressures and V_T are not maintained during closed suction with either CMV or HFOV. Major determinants of loss in tracheal PEEP and MTP are the combination of ETT size, suction catheter size, and suction pressure. The major determinants of tracheal ΔP , inflation pressure, and V_T are ETT and catheter size. During ETT suction, the magnitude of subatmospheric tracheal pressure generated is potentially large and may cause atelectasis or airway collapse. Therefore, choice of catheter size and suction pressure has important clinical implications.

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