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Effect of Closed Endotracheal Tube Suction Method, Catheter Size, and Post-Suction Recruitment During High-Frequency Jet Ventilation in an Animal Model

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Summary. Rationale: High-frequency jet ventilation (HFJV) is often used to treat infants with pathologies associated with gas trapping and abnormal lung mechanics, who are sensitive to the adverse effects of suction. Objective: This study aimed to investigate the effect of closed suction (CS), catheter size, and the use of active post-suction sighs on tracheal pressure (P_{trach}), and global and regional end-expiratory lung volume (EELV) during HFJV. Methods: Six anaesthetized and muscle-relaxed adult rabbits were stabilized on HFJV. CS was performed using all permutations of three CS methods (*Continual* negative pressure, negative pressure applied during *Withdrawal*, and HFJV in *Standby*) and 6 French gauge (6FG) and 8 French gauge (8FG) catheter, randomly assigned. The sequence was repeated using post-suction sighs. P_{trach}, absolute (respiratory inductive plethysmography) and regional (electrical impedance tomography; expressed as percentage of vital capacity for the defined region of interest, $\%Z_{VCroi}$) EELV were measured before, during and 60 sec post-suction. Results: CS methods exerted no difference on ΔP_{trach}, $\Delta EELV_{RIP}$ or $\Delta\%Z_{VCroi}$. 8FG catheter resulted in a mean (95%CI) 20.0 (17.9,22.2) cm H_2O greater loss of P_{trach} during suction compared to 6FG (Bonferroni post-test). Mean ($\pm$SD) $\Delta EELV_{RIP}$ was $-6(\pm3)$ and $-2(\pm1)$ ml/kg with the 8 and 6FG catheters ($P < 0.0001$; Bonferroni post-test). ΔEELV was 31.7 (21.1,42.4) $\%Z_{VCroi}$ and 24.8 (10.9,38.7) $\%Z_{VCroi}$ greater in the ventral and dorsal hemithoraces using the 8FG. Only after 8FG CS was post-suction recruitment required to restore EELV. Conclusions: In this animal model receiving HFJV, ΔP_{trach}, ΔEELV, and need for post-suction recruitment during CS were most influenced by catheter size. Volume changes within the lung were uniform.
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Key words: infant; newborn; high-frequency ventilation; endotracheal tube suction; electrical impedance tomography; lung volume.

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INTRODUCTION

All infants receiving mechanical ventilation require endotracheal tube (ETT) suction to remove secretions and maintain airway patency. Cardiorespiratory instability is common during ETT suction and is partially attributed to alveolar derecruitment with loss of lung volume.[1–3] Maintenance of lung volume is essential to optimize gas exchange and protect the lungs from ventilator-induced injury.[4,5] Closed suction (CS), which avoids breaking the ventilator circuit and, theoretically, allows tidal ventilation to continue throughout suction, is often advocated as a technique for minimizing lung volume loss.[2,6] Despite this, lung volume loss can occur during CS.[3,7] The magnitude of this lung volume loss is related to catheter size and applied suction pressure,[8,9] highlighting the complexity of the interaction between suction technique, lung mechanics, and disease state.[8,10]

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High-frequency jet ventilation (HFJV) is a mode of ventilation that utilizes tidal volumes less than anatomical dead space, together with a constant distending pressure delivered via a conventional ventilator. Tidal ventilation is achieved using very short, high velocity jet pulses of fixed duration, at rates of at least 240 breaths per minute (BPM), which allows for inspiratory:expiratory ratios up to 1:12. Consequently, HFJV is frequently used as a rescue therapy for infants with severe lung disease associated with gas trapping, such as cystic bronchopulmonary dysplasia.[11] The lung mechanics of this patient population are complicated by inhomogeneous regional abnormalities of both airway resistance and lung compliance, resulting in relatively long expiratory time constants.[12,13] These patients are at particular risk of the seemingly contradictory consequences of alveolar collapse and gas trapping, both during and following suction.

Despite awareness of the complex impact suction has on the lungs, there are no published studies systematically examining ETT suction during HFJV and current recommendations[14] differ from suction practices commonly used during other modes of ventilation. In some part, this is due to a lack of reliable animal models for the pathologies in which HFJV is most efficacious. Enhanced understanding of the regional impact of various strategies of ETT suction during HFJV in lungs pre-disposed to gas trapping may improve the clinical management of patients who are at particular risk of complications arising from loss of lung volume.

The aim of this study was to investigate the effect of different CS techniques, catheter size, and post-suction recruitment on tracheal pressure, and global and regional end-expiratory lung volume (EELV) in a rabbit model receiving ETT suction during HFJV.

ABBREVIATIONS:

BPM	Breaths per minute
CS	Closed suction
EELV	End-expiratory lung volume
ETT	Endotracheal tube
EIT	Electrical impedance tomography
FG	French gauge
HFJV	High-frequency jet ventilation
PEEP	Peak end expiratory pressure
PIP	Peak inspiratory pressure
P_{trach}	Tracheal pressure
RIP	Respiratory inductive plethysmography
roi	Region of interest
TCPLV	Time-cycled, pressure-limited ventilation
Ti_{HFJV}	Inspiratory time for HFJV
VC	Vital capacity
Z	Impedance

MATERIALS AND METHODS

Our institution's Animal Ethics Committee approved this study. Six adult, New Zealand white rabbits without artificially induced lung injury (spontaneous inspiratory time [Ti] 0.5–0.8 sec and expiratory time 1.0–1.3 sec) were intubated via a ligated tracheostomy using a size 3.5 mm Hi-Lo Jet^{TM} ETT (Mallinckrodt Covidien-Nellcor^{TM}, Boulder, CO) after gaseous induction of anesthesia with isoflurane. 23G cannulae were inserted in the artery and vein of the ear. Ongoing anesthesia and analgesia was maintained throughout the experimental period with continuous intravenous infusions of thiopentone and morphine, after appropriate loading doses. The animals were muscle relaxed (pancuronium infusion) and ventilated with time-cycled, pressure-limited ventilation (TCPLV; VIP Bird Gold, Viasys Healthcare, Yorba Linda, CA) in the supine position using a protocol described previously.[15] Once stabilized, the animals were then transferred to HFJV using the Bunnell Life-Pulse high-frequency ventilator (Bunnell Inc, Salt Lake City, UT) with a peak inspiratory pressure (PIP_{HFJV}) 20 cm H_2O, Ti_{HFJV} 0.02 sec, $Rate_{HFJV}$ 300 BPM, and no conventional sigh inflations. The positive end-expiratory pressure (PEEP) was initially set to maintain the same mean airway pressure as during TCPLV. Animals were then ventilated for 6 hr using different HFJV settings as part of another study. By this time all animals' respiratory status had deteriorated and fraction of inspired oxygen (F_IO_2), PEEP, and PIP_{HFJV} were adjusted to maintain peripheral oxygen saturation at 88–94% and arterial partial pressure of CO_2 between 45 and 55 mmHg.

Airway opening pressure was measured with the Florian respiratory monitor (Acutronic Medical Systems, Zug, Switzerland). Pressure at the distal tip of the ETT (P_{trach}) was measured using a calibrated pressure transducer (SciReq SC-24, Montreal, Quebec, Canada). Changes in global EELV ($\Delta EELV_{RIP}$) were measured at 200 Hz with a DC-coupled respiratory inductive plethysmograph (RIP; Respitrace 200, Non-invasive Monitoring Systems Inc., North Bay Village, FL) using our previously published method.[3,5,8,16] Prior to commencing HFJV, the RIP tidal amplitude was calibrated to the tidal volume signal at the airway opening over ten consecutive TCPLV inflations and $\Delta EELV_{RIP}$ expressed in ml/kg.[16] Changes in regional EELV were measured using EIT (GeoMFII, Carefusion, Hoechberg, Germany) sampling at 44 Hz.[7,17] Peripheral oxygen saturation (OxiMax-P^{TM} sensor, Nellcor Puritan Bennet Division, Pleasanton, CA), heart rate, and arterial blood pressure were continuously measured to ensure physiological stability (Hewlett Packard HP48S monitor, Hewlett Packard, Andover, MA). Arterial blood gases were performed after preparation of the model, stabilization on HFJV, and then as indicated clinically.

Mapping of the Pressure–Volume Relationship

To normalize the EIT signals, the pressure–volume relationship of the lung was mapped in each animal prior to transfer to HFJV.[7,8] This consisted of transient disconnection from the ventilator to determine the impedance signal at functional residual capacity. TCPLV was then commenced at 15 cm H_2O PIP and 0 cm H_2O PEEP. PIP and PEEP were increased in 5 cm H_2O increments every 20 sec until 20 cm H_2O PEEP, the maximum PEEP able to be delivered by the ventilator. EIT recordings were made concurrently, allowing the impedance change for vital capacity (difference in ΔZ at PEEP 0 and 20 cm H_2O; ΔZ_{VC}, in dimensionless units) to be determined in the ventral and dorsal thorax.[7]

ETT Suction Protocol

CS episodes were performed through the Neo-LINK™ universal side-port adapter (Viasys MedSystems, Wheeling, IL), which contains a self-sealing valve through which the suction catheter was inserted. Premeasured suction catheters (Mallinckrodt, Rowville, Victoria, Australia) were used to apply suction at the distal tip of the ETT at a vacuum pressure of 100 mmHg. For all suction episodes, the catheter was inserted over 10 sec and removed over 6 sec to allow for signal stabilization during each phase of suction. Three minutes prior to each suction episode, the volume state of the lung was standardized by disconnecting the rabbit from the ventilator for 10 sec. The rabbit was then reconnected at a conventional PEEP of 7 cm H_2O for 10 sec prior to returning to baseline ventilation settings.

Suction was performed using all permutations of two catheter sizes (6 French gauge, 6FG and 8 French gauge, 8FG[1]) and three suction methods, applied in random order (Fig. 1). The first method involved the application of continual negative pressure during both insertion and removal of the catheter during HFJV with the jet running (*Continual suction*). The second method involved negative pressure suction only on removal of the catheter with the HFJV in standby mode throughout the procedure, which stops the jet pulses, but allows continued delivery of PEEP (*Standby suction*). These two methods are advocated by the HFJV manufacturer.[18] The third method involved the application of negative pressure suction only during removal of the catheter with HFJV running (*Withdrawal suction*). This is the most common method of CS employed in our institution during conventional and high-frequency oscillatory ventilation. All permutations were performed with and without post-suction conventional sigh inflations, at a PIP of 22 cm H_2O and a rate of 3 BPM for 60 sec. This study did not aim to investigate oxygenation changes, thus to ensure animal stability throughout repeated CS episodes, all were performed in F_IO_2 of 1.0.

Data Collection and Analysis

Data were recorded continuously from 20 sec prior to 60 sec after each suction episode. The P_{trach} and $EELV_{RIP}$ signals were recorded at 200 Hz, digitalized and displayed in LabChart 7® (AD Instruments, Sydney, Australia). The unfiltered EIT time course signal for each suction recording was analyzed offline using the manufacturer's software (AUSPEX V1.5, Carefusion). EIT data were analyzed in two regions of interest: the dependent (ventral) and the non-dependent (dorsal) hemithorax.[7,18] Relative change in EELV (ΔZ_{EELV}) was defined by the trough impedance value within each region of interest (roi) and expressed as a proportion of the Z_{VC} within that region ($\%Z_{VCroi}$). For example, a ΔZ_{EELV} value of 40% Z_{VCroi} within the ventral region represents a change in EELV of 40% of vital capacity for the ventral thorax.[7]

From each recording, data were extracted at three key phases (Fig. 2), (1) at the end of catheter insertion; (2) completion of the application of negative pressure suction in the distal ETT; and (3) 60 sec after removal of the suction catheter from the ventilator circuit. Data extracted at each phase were referenced to the respective pre-suction value to enable comparison.[3,7,8,16]

Statistical analysis was performed using Stata 10.1 (StataCorp, College Station, TX) with $P < 0.05$ considered statistically significant. Data were tested for normality. The effect of suction method, catheter size, and post-suction recruitment on P_{trach}, $\Delta EELV_{RIP}$, and ΔZ_{EELV} was compared using parametric or non-parametric tests as appropriate. Combined effects and interactions were analyzed using repeated measures ANOVA, with Bonferroni post-test, or multivariate analysis as appropriate.

RESULTS

The animals had a mean (SD) weight of 3.8 (±0.2) kg. Median (range) PEEP and PIP_{HFJV} were 5 (3–6) and 20 (19–20) cm H_2O, with a resultant high-frequency tidal volume at the airway opening of 1.6 (1.5–2.2) ml/kg. All animals were haemodynamically stable at commencement of the study with oxygen saturation, heart rate and mean arterial blood pressure of

[1]The 6FG and 8FG catheters have an external diameter of 2 and 2.7 mm, and obstruct 33% and 58% of the luminal cross-sectional area of the size 3.5 ETT, respectively.

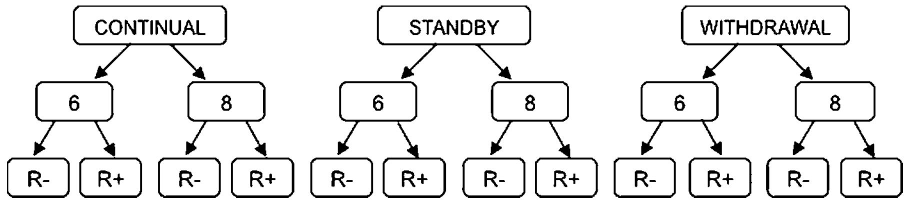

Fig. 1. Summary of the 12 suction permutations performed randomly in each subject (four different permutations for each method of suction, *Continual*, *Standby*, and *Withdrawal*). *6*: 6FG catheter, *8*: 8FG catheter, *R*−; represents episodes performed with no recruitment, *R*+; represents episodes performed with post-suction sigh inflations (3 BPM).

97.7 (95.9–100)%, 225 (205–230) bpm, and 44.9 (30.9–65.6) mmHg, respectively. These did not significantly change during the study and all animals completed the protocol without complication.

Tracheal Pressure

There was no change in P_{trach} during the entire CS period using a 6FG catheter (Fig. 3). The loss of P_{trach} was greater using an 8FG catheter, irrespective of method. Using data pooled for each catheter size, mean (SD) ΔP_{trach} was −22.5 (±5.9) cm H_2O using an 8FG catheter compared to −2.4 (±1.1) cm H_2O using the 6FG catheter (mean [95% CI] difference 20.0 [17.9, 22.2] cm H_2O; Bonferroni post-test). In all permutations, P_{trach} was restored to pre-suction values within 60 sec, even without the use of sigh inflations.

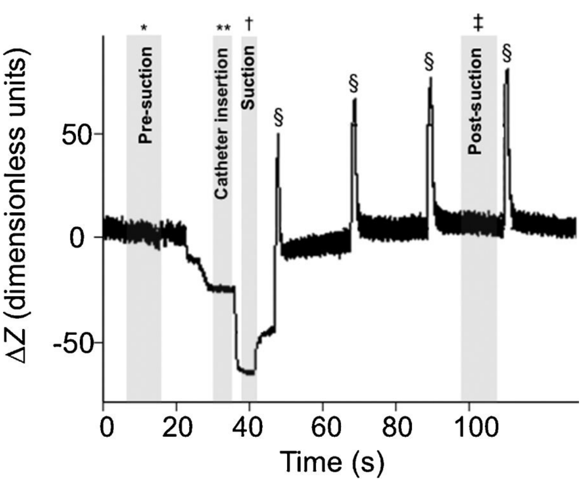

Fig. 2. Representative global EIT recording of the change in raw impedance from pre-suction baseline (ΔZ; countless units) during a single suction episode (*standby* method, using an 8FG catheter with post-suction recruitment using conventional tidal inflations at 3 BPM). Date represented from 20 sec before suction (pre-suction baseline) to 60 sec after the suction procedure. The key phases for analysis are: (A) at the end of the catheter insertion phase (**), (B) suction (†), and (C) 60 sec post-suction (‡). Data from these phases were referenced to the pre-suction value (*). § Denotes sigh inflations at 22 cm H_2O.

Global End-Expiratory Lung Volume

By the end of the suction phase, there was no difference in $\Delta EELV_{RIP}$ between the three suction methods, with overall $\Delta EELV_{RIP}$ being influenced more by catheter size. Combined, the mean (SD) $\Delta EELV_{RIP}$ was 6 (±3) ml/kg below the pre-suction value using the 8FG catheter and 2 (±1) ml/kg with the 6FG catheter ($P < 0.0001$, Bonferroni post-test). $EELV_{RIP}$ rapidly returned to baseline values by 60 sec post-suction irrespective of suction method, catheter size, or the use of sigh inflations.

Regional Lung Volume

Multivariate analysis revealed that catheter size, but not suction method, exerted a significant influence on ΔZ_{EELV} ($P < 0.05$). To simplify the results, suction method data have been combined for each catheter size. For each catheter size, ΔZ_{EELV} within the lung was uniform during suction (Fig. 4). The use of the 8FG catheter resulted in significantly greater ΔZ_{EELV} throughout the thorax compared to 6FG; mean [95% CI] difference in ventral and dorsal ΔZ_{EELV} 31.7 [21.1, 42.4] $\%Z_{VCroi}$ and 24.8 [10.9, 38.7] $\%Z_{VCroi}$, respectively (Bonferroni post-test).

The ΔZ_{EELV} had been restored to pre-suction values in both lung regions by 60 sec post-suction using a 6FG catheter, irrespective of the use of sigh inflations (Fig. 5). Without sigh inflations, the residual mean (SD) lung volume 60 sec after suction with the 8FG catheter was −19.1 (±25.6) $\%Z_{VCroi}$ and −22.3 (±39.2) $\%Z_{VCroi}$ in the ventral and dorsal hemithoraces, respectively. The use of a sigh breath after suction with an 8FG catheter restored EELV within both hemithoraces, resulting in a final ΔZ_{EELV} of 3.1 (±11.5) $\%Z_{VCroi}$ in the ventral and 5.1 (±18.3) $\%Z_{VCroi}$ in the dorsal hemithorax.

DISCUSSION

This is the first study to our knowledge that systematically examined closed ETT suction methods during HFJV. In our animal model, the greatest loss of EELV

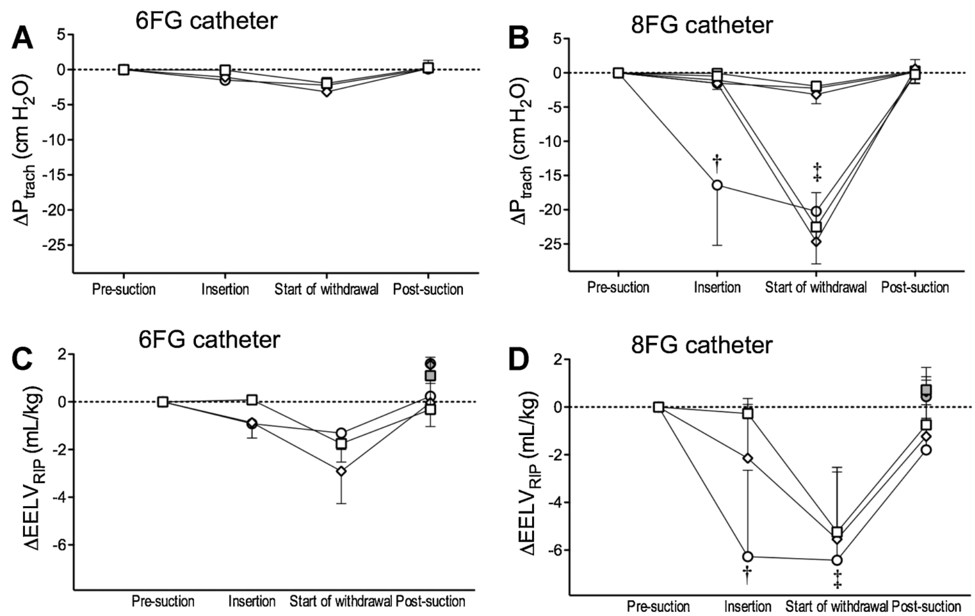

Fig. 3. Change (from pre-suction baseline value), in tracheal pressure (ΔP_{trach}), using a 6FG catheter (A) and an 8FG catheter (B), and end-expiratory lung volume ($\Delta EELV_{RIP}$), using a 6FG catheter (C) and an 8FG catheter (D), during catheter insertion, suction, and post-suction for each of the three methods of CS. *Circles*: continual suction, *Diamonds*: standby suction, *Squares*: withdrawal suction. $^{\dagger}P < 0.0001$ from baseline (Continual method) and $^{\ddagger}P < 0.0001$ (all methods); Bonferroni post-test. Post-suction sigh inflation $EELV_{RIP}$ subgroup data shown with grey symbols. All data mean ± SD.

occurred when the catheter obstructed a substantial proportion of the ETT lumen during the application of negative pressure. Active recruitment, maneuvers were only required for the suction episodes performed with an 8FG catheter. With this catheter size, a protocol of three sigh inflations within a minute was effective in quickly restoring lost lung volume.

There was little difference between the three methods of CS examined in our study. The exception was continual suction, and then only with an 8FG catheter. Using this permutation, there was significant loss of lung volume and tracheal pressure during the catheter insertion phase, as would be expected. The manufacturer suggests this method as a technique of avoiding excessively high-airway pressures during the suction process.[14] Importantly, excessive tracheal pressure was not observed during catheter insertion using any method. Indeed the opposite was observed. The continual method of CS differs from withdrawal methods usually employed during conventional and high-frequency oscillatory ventilation,[19] and may complicate clinical practices. In light of our results, the standby method, which is also recommended by the manufacturer, would currently be the most appropriate approach to CS during HFJV until the safety of the withdrawal method can be confirmed.

Similar to results from animal and human studies of CS during other modes of ventilation, catheter size accounted for much of the differences seen in tracheal pressure and lung volume, irrespective of how CS was performed.[7–9] The 8FG catheter caused a greater loss of tracheal pressure and global and regional volume than the 6FG catheter for all methods of CS. This difference was most marked during the suction phase, when combined with active negative pressure.[8,9] Although the smaller 6FG catheter was effective in preserving lung volume, it remains unknown whether this catheter size would be equally effective at removing secretions, the primary goal of suction. Secretions are difficult to standardize[15,20] and were not measured in this study. While suction could be expected to result in improved respiratory mechanics, this has been difficult to demonstrate in the clinical setting.[21] Due to the frequency with which suction was performed in this experiment, we were unable to use this as a marker of suction efficacy.

Active post-suction recruitment maneuvers have been advocated to prevent residual atelectasis.[22,23] In our study, post-suction recovery occurred relatively quickly, and uniformly, with residual lung volume loss at 60 sec post-suction estimated at less than 2 ml/kg, a pattern that has been observed in other studies.[3,7,8,16,24] Our findings suggest that active post-suction recruitment maneuvers were only beneficial following significant ETT obstruction. Respiratory mechanics monitoring is difficult during HFJV. Consequently, the need for, and response to, post-suction recruitment maneuvers are

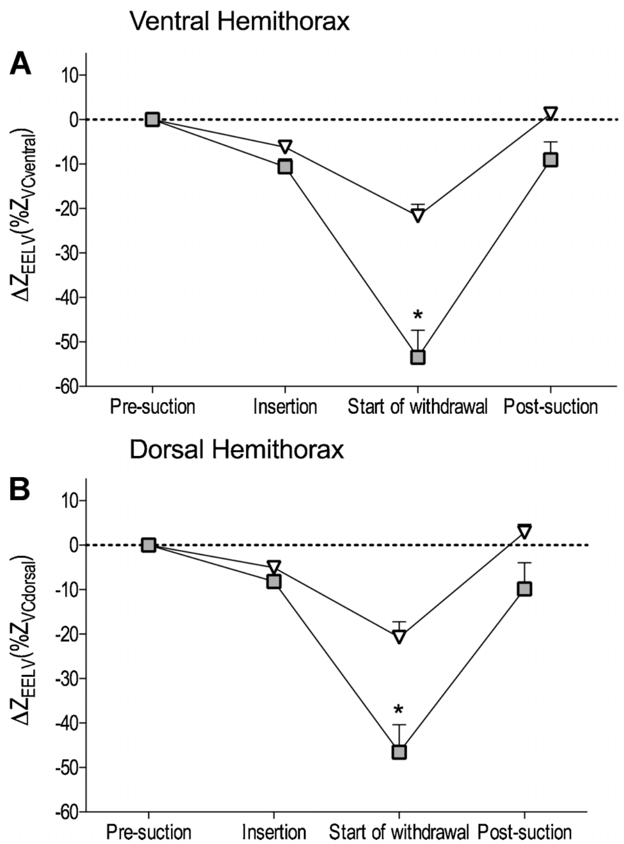

Fig. 4. Change in relative regional lung volume (ΔZ_{EELV}), expressed as a ratio of the vital capacity ΔZ ($\%Z_{VCroi}$) and referenced to pre-suction Z_{EELV}, during catheter insertion, suction, and post-suction, within the ventral (A) and dorsal (B) hemithorax using a 6FG catheter (*open triangles*) and an 8FG catheter (*filled squares*). In both hemithoraces, ΔZ_{EELV} was significantly greater using the 8FG catheter ($^*P < 0.0001$; Bonferroni post-test). Data from the three CS methods pooled for each catheter size. All data mean ± SEM.

hard to assess clinically and there is a need for reliable lung volume monitoring at the bedside.

Both RIP and EIT were able to track volume change during HFJV, however, unlike RIP, EIT cannot be reliably calibrated to a known volume and is limited to defining relative behavior of regional lung volume.[13] This study is the first to our knowledge that used both EIT and RIP simultaneously to assess lung volume changes during suction. Similar patterns of volume change were obtained using both methods. EIT may therefore be a valuable, real time method by which acute lung volume changes during suction can be monitored at the bedside. Because the clinical presentation of atelectasis and over-distension are similar, it may be particularly useful for identifying significant loss of lung volume before clinical manifestations of derecruitment including desaturation, hypoxia, or bradycardia become apparent.[5] A continuing challenge in the clinical setting is the lack of specific and sensitive measures of the accumulation of secretions and thus, the need for

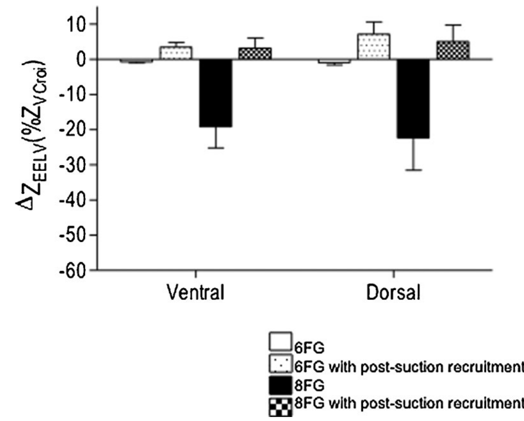

Fig. 5. Change in relative end-expiratory lung volume (ΔZ_{EELV}), expressed as a ratio of the vital capacity ΔZ ($\%Z_{VCroi}$) and referenced to pre-suction Z_{EELV}, at 60 sec post-suction in the ventral and dorsal hemithoraces using an 8FG (black) and 6FG (white) catheter with (speckled) and without (solid color) post-suction recruitment maneuver. The use of post-suction recruitment maneuver to restore EELV was only necessary during CS with the 8FG catheter. All data mean ± SEM.

suction.[21] Whether EIT, which can identify small variations in regional tidal ventilation,[18] can assist in detecting changes in ETT patency or position remains to be elucidated.

The lung mechanics of severe chronic neonatal lung disease are complex, characterized by inhomogeneity and often associated with regional gas trapping and long expiratory time constants. The lack of an established animal model of this pathology is a major hindrance for understanding the physiology of these pathologies during mechanical ventilation. We intentionally choose to study a muscle-relaxed animal with normal lungs, which had been exposed to a prolonged period of variable mechanical ventilation, rather than an acutely injured lung model, in an attempt to replicate the longer time-constants and predisposition to gas trapping. Despite this, our model was still not ideal and, most likely, expressed better lung mechanics and elastic recoil than the clinical scenario we were trying to replicate. This may explain the uniform regional changes in relative lung volume throughout the thorax during CS. A gravity-dependent pattern of volume change during suction has been reported in saline-lavage animal models[7,20] and children and infants with acute respiratory distress syndrome.[25] Similarly, this lung model precluded meaningful interpretation of the influence of CS method on oxygenation or haemodynamic state, both of which are transiently disturbed during CS in infants.[3] The relative ease of the use of RIP and EIT suggests that detailed study in infants receiving HFJV for severe chronic lung disease would be feasible.

This study has some limitations not previously mentioned. Prophylactic ETT suction is rarely advocated, but rather directed by signs of compromised ETT patency or respiratory state. In our study ETT suction was not performed due to clinical need, and was repeated numerous times during a short period. This was intentional to address the primary aims and standardize lung mechanics. Also, our study did not aim to explore the injurious influences of ETT suction. Repeated atelectasis and recruitment may predispose the more diseased lung to ventilator-induced lung injury.[26]

Volume change is dependent on the absolute pre-suction volume, with greater potential for volume loss within a lung that is well recruited compared to the one that is not. Although we attempted to standardize the pre-suction lung volume rather than the PEEP prior to each suction episode, the differences observed between animals may still have been due to ventilation with different pre-suction lung volumes. Neither RIP nor EIT have been reported during HFJV before, however both have been used during high-frequency oscillatory ventilation and it is unlikely that either will perform differently.[5,8,16,24] Like HFOV, the respiratory signal occurs over multiple frequencies. Filtering out the cardiac component to the impedance values is therefore difficult. As this study was the first to use EIT during HFJV we elected not to filter the raw signal and limited our analysis to EELV alone. It is possible that the different suction methods exerted a different influence on the regional distribution of tidal ventilation. RIP cannot distinguish between changes due to air or fluid within the thorax.[5] As the animals were haemodynamically stable during the short-study periods we contend that the majority of volume change observed likely represents variations in air content.

CONCLUSIONS

CS can result in transient, but significant loss of EELV that was uniform throughout the thorax in this animal model. Catheter size and to a lesser extent, active post-suction recruitment maneuvers influence suction-related change in tracheal pressure and lung volume during HFJV, more so than the method of CS. Further studies are required to determine effects of suction in the diseased lung and the effectiveness of various suction methods in removing secretions.

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