Evaluation of a Closed Suction System With Integrated Tube-Scraping Technology

Ramandeep Kaur, J Brady Scott, Tyler T Weiss, Andrew Klein, Megan E Charlton, Kimberly A Villanueva, Robert A Balk, and David L Vines

BACKGROUND: Endotracheal tube (ETT) scraping or sweeping refers to mucus removal from an ETT that can increase airway resistance. The study objective was to evaluate the effect of ETT scraping on the duration of mechanical ventilation, time to first successful spontaneous breathing trial (SBT), duration of hospital stay, and occurrence of ventilator-associated events (VAEs). METHODS: This was a single-center, randomized clinical trial of adult subjects intubated between October 2019–October 2021. Subjects were randomly assigned to either ETT suctioning via a standard in-line suction catheter (control group) or ETT suctioning and scraping via a suction catheter with balloon-sweeping technology (experimental group). Airway suctioning was performed as clinically indicated, and the ETT was scraped every time a respiratory therapist suctioned the subject. The study outcome was duration of mechanical ventilation, time to first successful SBT, hospital length of stay, and VAE rate. Intent-to-treat statistical analysis was performed. RESULTS: Of 272 randomized subjects, the median age was 63 (interquartile range [IQR] 52–73) y; 143 (53%) were males, and 154 (57%) had a primary diagnosis of acute respiratory failure. There were no significant differences between the groups in median duration (h) of mechanical ventilation (72 [37–187] vs 70.6 [37–148], *P* = .58). There was no significant difference between the study groups in median time (h) to the first successful SBT (46.7 [IQR 30–87] vs 45.7 [IQR 27–95], *P* = .81), length of hospital stay (*P* = .76), the incidences of ventilator-associated conditions (*P* = .13), or infection-related ventilator-associated complications (*P* = .47). CONCLUSIONS: ETT suctioning plus scraping, compared to ETT suctioning alone, did not significantly improve the duration of mechanical ventilation, time to first successful SBT, length of hospital stay, and VAEs. These study findings do not support the routine use of ETT scraping for mechanically ventilated patients. *Key words: biofilm; VAP (ventilator-pneumonia); airway obstruction; mechanical ventilation; secretion clearance; endotracheal tube.* [Respir Care 2023;68(8):1023–1030. © 2023 Daedalus Enterprises]

Introduction

Artificial airway management is essential care for critically ill patients. A component of airway management is the assurance that artificial airways remain clear of secretions and biofilm that can decrease the intraluminal diameter, resulting in an increase in airway resistance (R_{aw}) or even a total airway occlusion.[1-5] Evidence suggests that standard suctioning devices cannot prevent secretions and biofilm from narrowing artificial airways, such as endotracheal tubes (ETTs); thus, devices specifically designed to clear and maintain the nominal function (by sweeping or scraping) of ETTs have been developed.[3,5,6]

Several studies have demonstrated that these ETT clearance devices are effective at reducing luminal biofilm secretions and the resultant increase in R_{aw}.[4,7-10] Randomized controlled trials by Pinciroli et al[2] and Berra et al[10] have demonstrated that compared to standard suctioning, these devices can reduce mucus accumulation and overall biofilm thickness. However, when evaluated cumulatively, the evidence has yet to confirm that ETT clearance devices improve important clinical outcomes such as prevention of ventilator-associated events (VAEs), mechanical ventilation days, and days in the ICU.[1,3]

Since the studies evaluating the impact of ETT clearance devices have been laboratory, observational, or relatively small randomized trials, we designed a large randomized trial to better understand the role of ETT scraping on patient outcomes. The primary aim of this study was to evaluate the effect of ETT scraping on the duration of mechanical ventilation. The secondary aims of this study were to assess ETT scraping on time to first successful spontaneous breathing trial (SBT), duration of hospital stay, and occurrence of VAEs.

SEE THE RELATED EDITORIAL ON PAGE 1186

Methods

This was a single-center, prospective, randomized clinical trial conducted at an academic medical center between October 2019–October 2021. Adult subjects (18 y or older) who were admitted to the medical ICU and received mechanical ventilation via an ETT for at least 24 h were included in the study. Any subject who was pregnant, received mechanical ventilation via tracheostomy, required extracorporeal membrane oxygenation, or transferred from an outside facility receiving > 24 h of mechanical ventilation was excluded. The study protocol was approved by our institutional review board (ORA number 20051302-IRB01), and the study was registered on ClinicalTrials.gov (NCT03868735).

Randomization

Study eligible subjects were randomly assigned in a 1:1 ratio to either the standard ETT suction catheter or the experimental ETT suction catheter with balloon-sweeping technology (CleanSweep Closed Suction System, Teleflex, Wayne, Pennsylvania). Randomization was computer generated, and the generated numbers were placed in a sealed opaque envelope. Each study envelope was opened in sequential order by the study team. Subjects and clinicians involved in the care were not blinded to the study assignment after enrollment.

Experimental Group

In the experimental group, an ETT suction catheter equipped with balloon-sweeping technology (Figure 1A and 1B) was placed on eligible subjects within 24 h of intubation. The suction catheter size was estimated by multiplying the ETT's inner diameter by 2 and using the next smallest size catheter. For example, a subject with an 8.0 ETT was given a 14Fr suction catheter. The ETT was cleaned with the balloon-sweeping technology every time a respiratory therapist suctioned the subject's airway. Airway suctioning was performed per department policy (catheter advanced until resistance is met and withdrawn slowly for a duration no longer than 15 s while applying negative pressure). The frequency of airway suctioning was determined based on the subject's clinical need. Suction catheters were changed if visibly soiled or every 7 d per departmental policy. The clinical team assessed each subject daily for a spontaneous awakening trial and an SBT using an institutional protocol. A subject was considered to have a successful SBT if they

QUICK LOOK

Current knowledge

Endotracheal tube (ETT) narrowing due to secretion accumulation or biofilm formation can increase airway resistance (R_{aw}) or cause total airway occlusion. ETT clearance devices have shown to be effective at reducing luminal biofilm secretions and R_{aw}.

What this paper contributes to our knowledge

This randomized controlled trial compared the use of ETT suctioning plus scraping to ETT suctioning alone among adult subjects receiving mechanical ventilation. ETT suctioning plus scraping did not reduce the duration of mechanical ventilation, time to first successful spontaneous breathing trial, hospital length of stay, or occurrence of ventilator-associated events when compared to ETT suctioning alone. This study does not support the routine use of ETT scraping devices in mechanically ventilated patients.

Drs Kaur, Scott, and Vines; Messrs Weiss and Klein; and Mss Charlton and Villanueva are affiliated with Department of Cardiopulmonary Sciences, Division of Respiratory Care, College of Health Sciences, Rush University, Chicago, Illinois. Dr Balk is affiliated with Internal Medicine, Division of Pulmonary, Critical Care, and Sleep Medicine, Rush University, Chicago, Illinois.

Dr Scott discloses relationships with Teleflex, Aerogen, and Medline Industries, LP. Dr. Kaur discloses a relationship with the American Association for Respiratory Care. Dr Vines discloses relationships with Teleflex Medical, Inc, and the Rice Foundation. The other authors have disclosed no conflicts of interest.

This study was funded by an investigator-initiated research grant from Teleflex, Inc, and the sponsor was not involved in study design, data collection/analysis, and manuscript preparation.

Dr Kaur presented a version of this paper as an Editors' Choice abstract at AARC Congress 2022, held November 9–12, 2022, in New Orleans, Louisiana.

Supplementary material related to this paper is available at http://www.rcjournal.com.

Drs Kaur and Scott are co-first authors.

Correspondence: J Brady Scott PhD RRT RRT-ACCS AE-C FAARC, Department of Cardiopulmonary Sciences, Division of Respiratory Care, Rush University, 600 S. Paulina Street, Suite 751, Chicago, IL 60612. E-mail: Jonathan_B_Scott@rush.edu.

DOI: 10.4187/respcare.10830

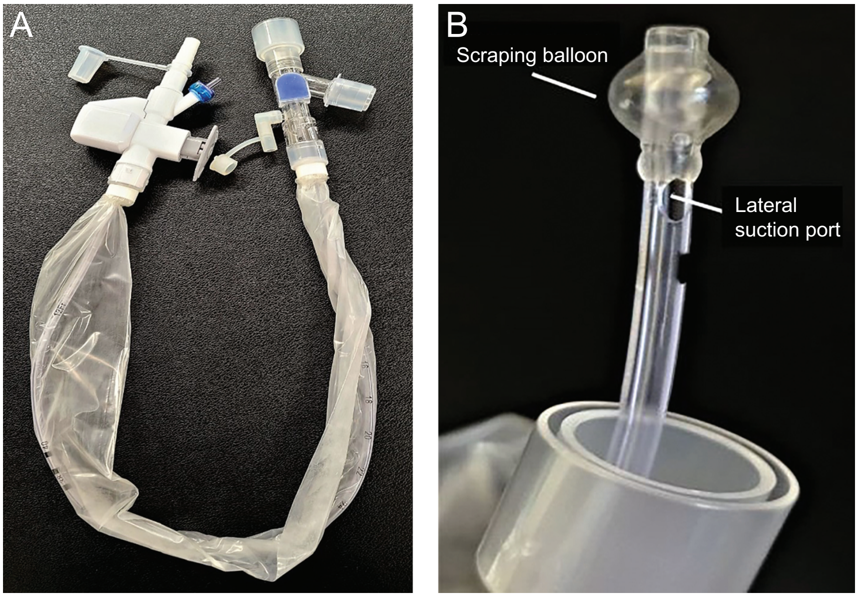

Fig. 1. A: CleanSweep closed suctioning system; B: Inflated scraping balloon.

tolerated a 30-min SBT with a rapid shallow breathing index < 105. The extubation was performed based on the medical team's decision.

Control Group

In the control group, a standard suction ETT catheter was placed on eligible subjects within 24 h of intubation. Airway suctioning was performed using a regular suction catheter per department policy, and the frequency of suctioning was determined based on the subject's clinical need. Suction catheters were changed if visibly soiled or every 7 d per departmental policy. Each subject was assessed daily by the clinical team for a spontaneous awakening trial and an SBT using an institutional protocol. A subject was considered to have a successful SBT if they tolerated a 30-min SBT with a rapid shallow breathing index < 105. Extubation was performed based on the medical team's decision.

VAE Prevention Bundle

Both the study groups received a ventilator bundle that consisted of maintaining the head-of-bed (HOB) elevation ≥ 30 degrees, ETT cuff pressure > 20 cm H_2O, deep vein thrombosis prevention, daily sedation interruption and SBT, as well as oral care every 4 h with chlorhexidine at 12 PM (noon) and 12 AM (midnight).

Data Collection

Subject's demographic characteristics, body mass index (BMI), primary diagnosis, Sequential Organ Failure Assessment (SOFA) score, reason for intubation, and ETT size were recorded at the enrollment. Data related to lung-protective strategy, airway suctioning, VAE prevention bundle, spontaneous awakening trial, and SBT were collected for the duration of mechanical ventilation. Ventilator-associated condition (VAC) and infection-related ventilator-associated condition (IVAC) data were obtained from the infection control department. Ventilator duration, need for re-intubation, use of noninvasive ventilation (NIV) postextubation, length of ICU stay, and hospital length of stay were recorded. No follow-up data were recorded. Data were collected from subjects' electronic medical record and captured using REDCap, a secure data collection platform.

Outcomes

The primary outcome was duration of mechanical ventilation. The secondary outcomes were time to first successful SBT, extubation outcome (defined as need for NIV or re-intubation within 48 h of planned extubation), length of ICU stay, total length of hospital stay, and occurrence of VAEs (VAC and IVAC). VAC and IVAC were defined based on the Centers for Disease Control and Prevention's National Healthcare Safety Network guidelines (https://www.cdc.gov/nhsn/pdfs/pscmanual/10-vae_final.pdf. *Accessed December 1, 2022*).

Statistical Analysis

Based on previous institutional data, the mean duration of mechanical ventilation was noted to be approximately 6.3 ± 3.64 d. To achieve a clinically important 20% reduction in duration of mechanical ventilation ($6.3 \times 0.20 =$

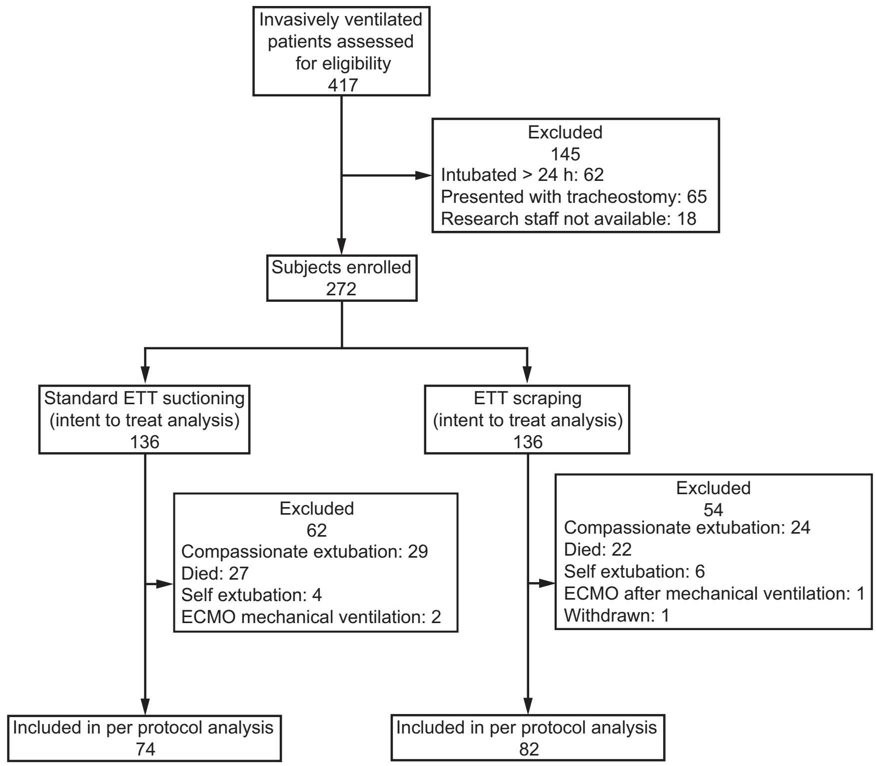

Fig. 2. Flow chart. ETT = endotracheal tube; ECMO = extracorporeal membrane oxygenation.

1.26 d), 136 subjects were needed in each group with alpha at 0.05 and power of 0.80. The categorical variables are presented as frequency and were analyzed using chi-square or Fisher exact test. Continuous variables are presented as mean ± SD or median (interquartile range [IQR]) based on the normal distribution and analyzed using *t* test or Mann-Whitney test. Intent-to-treat and per-protocol analyses were performed. Intent-to-treat analysis included all randomized subjects, whereas per-protocol analysis included all randomized subjects who received planned nonterminal extubation. A *P* value of < .05 was considered significant, and data analysis was conducted using SPSS 26.0 for Windows (IBM, Armonk, New York).

Results

A total of 417 subjects were assessed for study eligibility; 145 subjects were excluded, and 272 subjects underwent randomization; 136 were assigned to the standard group and 136 to the ETT scraping group (Fig. 2). The baseline characteristics of the subjects are presented in Table 1. Study participants' median age was 63 y; 143 (52.6%) were males; median BMI was 29; median SOFA score was 6, and 108 (39.7%) were Black. The primary diagnosis was hypoxemic respiratory failure among 131 (48.2%), and the main indication for initiating mechanical ventilation was acute respiratory failure in 178 (65.4%) subjects. The median ETT size was 7.5, and a lung-protective ventilation strategy was used for 207 (76%) subjects. The subject baseline characteristics did not differ significantly between the study groups.

Before extubation or tracheostomy, the median number of ETT suctioning performed in the standard group was 13 (IQR 4–39) and 14 (IQR 5–34) in the ETT scraping group. The overall ETT suctioning frequency did not differ significantly between the 2 groups. However, the ETT suctioning frequency per ventilator day was significantly higher for the ETT scraping group (5 [IQR 3–8] vs 4 [IQR 3–5], *P* = .031). The median number of endotracheal scrapings was 4 (2–9) in the ETT scraping group, with an average of 1 (IQR 1–2) scrapings per ventilator day. The application of the VAE prevention bundle, including cuff pressure management, and HOB elevation, was similar between the groups.

Primary Outcomes

In the intent-to-treat analysis that included 136 subjects in each group, no significant difference in the duration of mechanical ventilation (h) was observed between the study groups; 72.2 (IQR 37.0–187.0) in the standard group and 70.6 (37.0–148.0) in the ETT scraping group (*P* = .58) (Table 2).

Secondary Outcomes

In the intent-to-treat analysis, there was no significant difference in the predefined secondary outcomes between the

Table 1. Subject Baseline Characteristics

Variables	Standard ETT Suctioning Group ($n = 136$)	ETT Scraping Group ($n = 136$)	*P*
Age, y	63 (52–74)	63 (52–72)	.67
Male	65 (47.8)	78 (57.4)	.11
BMI, kg/m^2	29 (25–35)	28.8 (24–34)	.37
SOFA score	6 (4–8)	6 (4–9)	.80
Race/ethnicity			.47
Black	51 (37.5)	57 (41.9)	
White	30 (22.1)	36 (26.5)	
Hispanic	44 (32.4)	31 (22.8)	
Asian	5 (3.7)	4 (2.9)	
Other	6 (4.4)	8 (5.9)	
Primary diagnosis			.25
Hypoxemic respiratory failure	71 (52.2)	60 (44.1)	
Hypercarbic respiratory failure	8 (5.9)	15 (11)	
Sepsis	10 (7.4)	13 (9.6)	
Cardiac	8 (5.9)	14 (10.3)	
Others (eg, cancer, hepatic, renal)	39 (28.7)	34 (25)	
Reason for intubation			.08
Acute respiratory failure	89 (65.4)	89 (65.4)	
Airway protection	29 (21.3)	26 (19.1)	
Elective	14 (10.3)	8 (5.9)	
Cardiac arrest	4 (2.9)	13 (9.6)	
ETT size	7.5 (7.5–8.0)	7.5 (7.5–8.0)	.99
Lung-protective ventilation	109 (80.1)	98 (72.1)	.12
SBTs performed before extubation/receiving tracheostomy	1 (0–2)	1 (0–2)	.77
ETT suctioning/scraping prior to first successful SBT	7 (2–18)	10 (3–19)	.27
ETT suctioning/scraping prior to extubation/receiving tracheostomy	13 (4–39)	14 (5–34)	.77
ETT scraping before extubation/receiving tracheostomy	0	4 (2–9)	
ETT cuff pressure documented > 20 cm H_2O	7 (4–18)	7 (4–15)	.46
HOB documented ≥ 30 degrees	29 (14–77)	27 (13–66)	.74
Oral care documented	14 (5–34)	13 (6–30)	.73
Oral brushing (chlorhexidine) documented during mechanical ventilation	4 (1–11)	4 (1–9)	.75
Number of d DVT prophylaxis used during mechanical ventilation	4 (2–8)	4 (2–7)	.83
Number of d with stress ulcer prevention during mechanical ventilation	3 (2–8)	3 (1–6)	.39

Data are presented as *n* (%) or median (interquartile range).
ETT = endotracheal tube
BMI = body mass index
SOFA = Sequential Organ Failure Assessment
SBT = spontaneous breathing trial
HOB = head of bed
DVT = deep vein thrombosis

study groups. For subjects who received standard ETT suctioning, the time to first successful SBT (h) was 46.7 (IQR 30.0–87.0) as compared to 45.7 (IQR 27.0–95.0) in the ETT scraping group ($P = .81$). A total of 14 (10.3%) subjects required NIV or re-intubation in the standard group and 20 (14.7%) in the ETT scraping group ($P = .38$). The median d in ICU (standard group 9 [IQR 4–20] vs ETT scraping group 7.8 [IQR 4.0–18.0], $P = .62$) and hospital (standard group 14.7 [IQR 8.0–26.0] vs ETT scraping group 13.9 [IQR 8.0–25.0], $P = .76$) were not significant between the two groups. A higher number of subjects in the ETT scraping group developed VAC (11.8% vs 6.6%) and IVAC (8.8% vs 6.6%) as compared to the standard group, but no significant difference was observed.

Per-Protocol Analysis

Per-protocol analysis of the primary outcome was consistent with the main analysis, with no significant difference noted in the median duration of mechanical

Table 2. Intent-to-Treat Analysis

	Standard ETT Suctioning Group ($n = 136$)	ETT Scraping Group ($n = 136$)	P
Primary Outcomes			
Duration of mechanical ventilation, h	72.2 (37–187)	70.6 (37–148)	.58
Secondary Outcomes			
Time to first successful SBT, h	46.7 (30–87)	45.7 (27–95)	.81
Required NIV or re-intubation within 48 h	14 (10.3)	20 (14.7)	.38
ICU length of stay, d	9 (4–20)	7.8 (4–18)	.62
Hospital length of stay, d	14.7 (8–26)	13.9 (8.0–25)	.76
VAC	9 (6.6)	16 (11.8)	.13
IVAC	9 (6.6)	12 (8.8)	.47

Data are presented as n (%) or median (interquartile range).
ETT = endotracheal tube
SBT = spontaneous breathing trial
NIV = noninvasive ventilation
VAC = ventilator-associated condition
IVAC = infection-related ventilator-associated condition

Table 3. Per-Protocol Analysis

	Standard ETT Suctioning Group ($n = 74$)	ETT Scraping Group ($n = 82$)	P
Primary Outcomes			
Duration of mechanical ventilation, h	63 (41–164)	62 (36–138)	.61
Secondary Outcomes			
Time to first successful SBT, h	46.6 (28–93)	45.7 (26.0–91)	.73
Required NIV or re-intubation within 48 h	12 (16.2)	17 (20.7)	.43
ICU length of stay, d	10.4 (5.0–21.0)	8.5 (4.0–21)	.59
Hospital length of stay, d	17.9 (10.0–26)	18.6 (10–29)	.80
VAC	5 (6.8)	7 (8.5)	.68
IVAC	5 (6.8)	4 (4.9)	.74

Data are presented as n (%) or median (interquartile range).
ETT = endotracheal tube
SBT = spontaneous breathing trial
NIV = noninvasive ventilation
VAC = ventilator-associated condition
IVAC = infection-related ventilator-associated condition

ventilation (h) between the two study groups (standard group 63 [IQR 41–164] vs ETT scraping group 62 [IQR 36–138], $P = .61$) (Table 3). There were also no significant differences in the time to the first successful SBT, need for NIV or re-intubation, ICU and hospital length of stay, and occurrence of VAC or IVAC between the study groups (Table 3).

Additional Analysis

Intent-to-treat analysis among subjects intubated for > 48 h did not show any significant differences in the primary or secondary study outcomes (Supplementary Table 4, see related supplementary materials at http://www.rcjournal.com).

Discussion

Our findings suggest that ETT scraping with an ETT suction catheter with balloon-sweeping technology, compared to standard ETT suctioning, did not significantly improve subject outcomes. Results were similar between the intent-to-treat and the per-protocol analysis after excluding subjects who did not receive planned extubation. These findings are clinically important as they provide more insight into when and how ETT cleaning devices should be utilized. Our study suggests that these devices do not need to be used routinely as a part of an airway management regimen. Instead, these devices could be used in select patients with evidence of ETT luminal narrowing as noted by an increase in R_{aw} or the need for prompt removal of an ETT occlusion by secretions.

Similar to a study conducted in 2017 evaluating an ETT tube clearance device on R_{aw}, our findings were that ETT cleaning had no impact on SBT success.[4] In that study, the mean pre- and post-ETT scraping R_{aw} was 15.17 ± 3.83 cm H_2O/L/s and 12.05 ± 3.19 cm H_2O/L/s, respectively, ($P < .001$). The change in R_{aw} had no impact on subsequent SBT success. Interestingly, whereas a decrease in approximately 3 cm H_2O/L/s was noted as the mean change in R_{aw}, it was evident in the study data that some subjects had no change in R_{aw} pre- and post-ETT scraping, whereas others had as much as a 10 cm H_2O/L/s decrease.[4] The duration of time on the mechanical ventilator had no noticeable impact on the R_{aw} pre- and post-ETT scraping change.[4] This is in alignment with a paper published by Wilson et al[11] that demonstrated that an increase in ETT R_{aw} from secretions is unpredictable regarding the duration of intubation. Our supplementary materials among subjects intubated for > 48 h and potentially at high risk of developing mucus buildup/biofilm also did not demonstrate a significant clinical benefit from the routine ETT scraping.

Other studies have also sought to evaluate if ETT scraping devices impact bacterial colonization of ETTs and related effects. Pinciroli et al[2] performed microbiological testing on ETTs that were collected from subjects who received ETT scraping every 8 h or standard suctioning per institutional standard. They found that ETT cleaning reduced the number of ETTs that contained no bacteria when compared to the standard suctioning group. Additionally, ventilator-pneumonia–causing microorganisms were less likely to be found in cleaned ETTs but not by a statistically significant amount. Whereas promising regarding how this might impact patient outcomes, no differences were found between mean days of mechanical ventilation and days in the ICU between the control and treatment groups.[2] Bardes et al[12] evaluated ETTs treated daily with a tube cleaning device and found no significant differences in tidal volumes, peak pressures, and R_{aw} in subjects treated with the ETT cleaning devices versus those not. Interestingly, in regard to pneumonia, the device group ($n = 11$) had almost twice the number of cases of pneumonia as the control group ($n = 6$), but the difference was not statistically significant ($P = .36$). Pirrone et al[13] evaluated the impact of ETT cleaning on silver-coated ETTs. Of 36 ETTs (18 control, 18 treatment) and 29 tracheal samples, it was noted that ETT cleaning devices did not reduce bacterial colonization of ETTs (15 vs 9, $P = .18$), microbial load (1.6 ± 1.2 log CFU/mL vs 0.9 ± 1.2 logCFU/mL, $P = .15$), biofilm deposition (439.5 ± 29.0 mg vs 288.9 ± 157.7 mg, $P = .09$), positive tracheal aspirates (13 vs 10, $P = .39$), or in microbial load of tracheal secretions (4.8 ± 4.0 logCFU/mL vs 4.2 ± 3.8 logCFU/mL, $P = .70$). They concluded that when compared to standard suctioning, ETT cleaning did not decrease bacterial colonization of ETTs and did not lower respiratory tract colonization. Differences in VAE between groups in our study did not reach significance, and this study was not powered to detect a difference in VAE. Future clinical trials should be powered to determine if there is a risk associated with routine ETT scraping.

This study has several limitations. First, this was a single-center study with institutional-specific ventilation weaning protocols. Second, the treatment allocation could not be blinded to the clinicians, which might have led to a bias due to clinicians being aware of the experimental device. Third, ETT suctioning and scraping were done at clinicians' discretion based on their clinical patient assessment, as the study protocol did not dictate a specific ETT cleaning time or pattern. However, although noted as a potential limitation, we felt it necessary to leave the decision to suction and subsequently clean the artificial airway suctioning at the discretion of the respiratory therapist based on their assessment of the subject, departmental policy, and reflecting actual clinical practice. Finally, all subjects in the experimental group received ETT scaping when suctioned by the respiratory therapist. Future research should focus on ways to identify subjects with a clinically important R_{aw} (> 10 cm H_2O/L/s)[4,14] from secretions and biofilm and the impact of ETT scraping on their clinical outcomes.

Conclusions

Our results suggest that the use of ETT suctioning plus scraping, compared to ETT suctioning alone, does not significantly reduce the duration of mechanical ventilation, time to first successful SBT, length of hospital stay, or occurrence of VAEs. These study findings do not support the routine use of ETT scraping for mechanically ventilated patients, and future studies are needed to identify patients who may benefit from ETT cleaning.

ACKNOWLEDGMENTS

We would like to thank respiratory therapists at Rush University Medical Center for their contributions to this project.

REFERENCES

1. Dexter AM, Scott JB. Airway management and ventilator-associated events. Respir Care 2019;64(8):986-993.
2. Pinciroli R, Mietto C, Piriyapatsom A, Chenelle CT, Thomas JG, Pirrone M, et al. Endotracheal tubes cleaned with a novel mechanism for secretion removal: a randomized controlled clinical study. Respir Care 2016;61(11):1431-1439.
3. Blakeman TC, Scott JB, Yoder MA, Capellari E, Strickland SL. AARC clinical practice guidelines: artificial airway suctioning. Respir Care 2022;67(2):258-271.

4. Scott JB, Dubosky MN, Vines DL, Sulaiman AS, Jendral KR, Singh G, et al. Evaluation of endotracheal tube scraping on airway resistance. Respir Care 2017;62(11):1423-1427.
5. Mietto C, Foley K, Salerno L, Oleksak J, Pinciroli R, Goverman J, Berra L. Removal of endotracheal tube obstruction with a secretion clearance device. Respir Care 2014;59(9):e122-e126.
6. Glass C, Grap MJ, Sessler CN. Endotracheal tube narrowing after closed-system suctioning: prevalence and risk factors. Am J Crit Care 1999;8(2):93-100.
7. Conti G, Rocco M, De Blasi RA, Lappa A, Antonelli M, Bufi M, et al. A new device to remove obstruction from endotracheal tubes during mechanical ventilation in critically ill patients. Intensive Care Med 1994;20(8):573-576.
8. Adi NA, Tomer NT, Bergman GB, Kishinevsky EK, Wyncoll DW. Effects of prolonged mechanical ventilation with a closed suction system on endotracheal tube resistance and its reversibility by a closed suction cleaning system. Anaesth Intensive Care 2013;41(6):728-735.
9. Waters C, Wiener RC, Motlagh HM. Ex vivo evaluation of secretion-clearing device in reducing airway resistance within endotracheal tubes. Crit Care Res Pract 2018;2018:3258396.
10. Berra L, Coppadoro A, Bittner EA, Kolobow T, Laquerriere P, Pohlmann JR, et al. A clinical assessment of the Mucus Shaver: a device to keep the endotracheal tube free from secretions. Crit Care Med 2012;40(1):119-124.
11. Wilson A, Gray D, Thomas J. Increases in endotracheal tube resistance are unpredictable relative to duration of intubation. Chest 2009;136(4):1006-1013.
12. Bardes JM, Gray D, Wilson A. Effect of the endOclear device on biofilm in endotracheal tubes. Surg Infect (Larchmt) 2017;18(3):293-298.
13. Pirrone M, Imber DA, Marrazzo F, Pinciroli R, Zhang C, Bry L, et al. Silver-coated endotracheal tubes cleaned with a mechanism for secretion removal. Respir Care 2019;64(1):1-9.
14. Hess DR. Respiratory mechanics in mechanically ventilated patients. Respir Care 2014;59(11):1773-1794.