Open and Closed Endotracheal Suction Systems Divergently Affect Pulmonary Function in Mechanically Ventilated Subjects

Rodrigo Daminello Raimundo, Monica Akemi Sato, Talita Dias da Silva, Luiz Carlos de Abreu, Vitor Engrácia Valenti, Daniel William Riggs, and Alex Perrow Carll

BACKGROUND: In mechanically ventilated subjects, intra-tracheal secretions can be aspirated with either open suction systems (OSS) or closed suction systems (CSS). In contrast to CSS, conventional OSS require temporarily disconnecting the patient from the ventilator, which briefly diminishes PEEP and oxygen supply. On the other hand, CSS are more expensive and less effective at aspirating secretions. Thus, it was hypothesized that the 2 procedures differentially affect pulmonary and cardiovascular parameters after suction. METHODS: Subjects in the ICU ($N =$ 66) were quasi-randomized for initial treatment with OSS or CSS in a crossover design. To compare the potential for these suction systems to compromise cardiorespiratory stability, changes in cardiopulmonary physiology were assessed from before to just after use of each suction system (three 10-s aspirations). RESULTS: For most pulmonary and cardiovascular parameters (ie, peak inspiratory pressure, airway resistance, pressure plateau, heart rate, and arterial pressures), the effects of aspiration inversely correlated with baseline values for that parameter, with a similar regression slope between suction systems. However, when controlling for baseline values, OSS caused significantly greater increases in airway resistance and peak inspiratory pressure ($P <$ .001 and $<$ .01 vs CSS, respectively). CONCLUSIONS: Elevated airway resistance prior to endotracheal suction may justify use of a CSS and contraindicate a conventional OSS in mechanically ventilated subjects. Adoption of this approach into clinical guidelines may prevent suction-induced pulmonary injury in subjects, especially for those with underlying diseases involving increased airway resistance or increased alveolar pressure. (ClinicalTrials.gov registration: NCT03256214.) *Key words: endotracheal aspiration; airway resistance; pulmonary compliance; mechanical ventilation; pulmonary pressure; lung.* [Respir Care 2021;66(5):785–792. © 2021 Daedalus Enterprises]

Introduction

Mechanical ventilation is used to rescue patients from respiratory failure, maintain oxygen and carbon dioxide, reduce intracranial pressure, and prevent or reduce atelectasis and hypoxemia. However, mechanical ventilation often requires intubation or tracheostomy (or both) as well as sedation,[1,2] which promote the accumulation of secretions within airways. Consequently, endotracheal suction systems are essential for routinely aspirating airway secretions to prevent bronchial obstruction[3,4] and its attendant complications, including alveolar hypoventilation, hypertension, increasing the stretch of the alveolar wall, emphysematous bubbles, atelectasis, short-term

Drs Raimundo, Sato, and de Abreu are affiliated with the Laboratório de delineamento de estudos e escrita científica, Faculdade de Medicina do ABC, Santo André, São Paulo, Brazil. Dr Abreu is affiliated with the Departamento de Educação Integrada em Saúde, Universidade Federal do Espírito Santo (UFES), Vitória, Espírito Santo, Brazil. Drs da Silva and Carll are affiliated with the Department of Environmental Health, Harvard School of Public Health, Boston, Massachusetts. Dr da Silva is affiliated with the Departamento de Cardiologia, Universidade Federal de São Paulo, São Paulo, São Paulo, Brazil. Dr da Silva is affiliated with the Faculdade de Medicina, Universidade Cidade de São Paulo, São Paulo, Brazil. Dr Valenti is affiliated with the Departamento de estudos sobre o Sistema nervoso autonômico, Faculdade de Ciências e Tecnologia, Universidade Estadual Paulista, Presidente Prudente, São Paulo, Brazil. Drs Riggs and Carll are affiliated with the Diabetes and Obesity Center, Christina Lee Brown Envirome Institute, School of Medicine, University of Louisville, Louisville, Kentucky. Dr Carll is affiliated with the Department of Physiology, School of Medicine, University of Louisville, Louisville, Kentucky.

arterial desaturation, and alterations in cardiopulmonary measures such as blood pressure and heart rate.[5-9]

Endotracheal suction also bears several risks, including hypoxemia, arrhythmia, nosocomial pneumonia, lung hypo-inflation, bronchospasm, increased intracranial pressure, and pneumothorax.[10-13] Suction, as a short-term effect, can reduce lung compliance[3,14] and intrapulmonary pressure, leading to a decrease in oxygen saturation and retention of carbon dioxide.[15,16] Moreover, endotracheal aspiration may directly stimulate the trachea or indirectly lead to lung hyper-inflation, which can rapidly alter heart rate and blood pressure through autonomic reflexes.[16-18] Thus, numerous end points of cardiopulmonary function are used to monitor patient stability during mechanical ventilation and endotracheal aspiration. Arterial blood gas analysis provides measures of P_{aO_2} and P_{aCO_2} to guide prevention or reversal of acidosis/alkalosis, hypoxemia, central nervous system injury, and gastrointestinal and renal ischemic injury.[3,17-20] Indices of lung mechanics, oxygen saturation, and cardiovascular hemodynamics are also routinely evaluated to monitor underlying disease and cardiopulmonary stability while optimizing adjustments in mechanical ventilation to prevent barotrauma, volutrauma, and hypoxemia.[2,17,21]

In mechanical ventilation, endotracheal aspiration can be performed with open suction systems (OSS) or closed suction systems (CSS). Conventional OSS require disconnection of patients from the ventilator to allow catheter insertion. This diminishes PEEP and oxygen supply and may lead to changes in cardiopulmonary function.[3,5,16,22] In contrast, CSS do not require disconnection and hence allow maintenance of PEEP and oxygen supply during suction and improving blood oxygenation.[3,5,8,14,22,23] Because CSS use a catheter connected between the endotracheal tube and ventilator circuit in a constantly sterile route of entry, some have speculated that such systems protect the patient from contamination relative to OSS.[19,22,24] In contrast with prior negative findings,[8,25,26] a recent meta-analysis associated CSS with a lower risk for ventilator-associated pneumonia.[27] Others have noted that CSS are easier and faster to use and cause fewer physiologic disturbances.[27,28] Indeed, CSS can modestly attenuate aspiration-induced increases in heart rate and arterial pressure and declines in oxygen saturation relative to OSS.[8,16,26,28] Further, a systematic review reported that CSS maintain a higher end-

QUICK LOOK

Current knowledge

Open suction uniquely impairs pulmonary compliance. Closed suction systems may maintain and restore pulmonary function more effectively compared to open suction systems.

What this paper contributes to our knowledge

During endotracheal aspiration with a closed circuit system post-aspiration decreases in airway pressures were greater than use of the open circuit system. Both techniques had similar impact on hemodynamic variables.

expiratory lung volume than OSS,[29] but this assessment included only 2 studies and 19 total subjects.[5,30] However, most comparisons have neglected fundamental parameters of pulmonary physiology (eg, resistance and peak inspiratory pressure [PIP]), used small sample sizes, and, did not address the effectiveness of suctioning on sputum volume or sputum wet weight. With its reduced hemodynamic effects, CSS might also acutely burden pulmonary physiology less than OSS. However, the relative impacts of CSS and OSS on respiratory physiology remain unclear. CSS have been shown to increase airway resistance (R) in cases of incomplete catheter withdrawal, a complication specific to CSS that often evades detection.[31] Therefore, to resolve whether OSS and CSS differentially affect cardiopulmonary physiology differentially affect, this study used a crossover design with 66 subjects to test the hypothesis that CSS presents better pulmonary and cardiovascular parameters after suction than OSS. To compare how these techniques affect pulmonary mechanics and hemodynamics, we assessed cardiopulmonary physiology before and after endotracheal suction in mechanically ventilated subjects in an ICU.

Methods

Subjects

This study was approved by the Research Ethics Committee of Heliopolis Hospital, São Paulo, Brazil (Approval #467). Prior to enrollment, the primary investigator (RD Raimundo) screened the medical records of all mechanically ventilated patients in the ICU (> 18 y old and intubated with a 7.5-mm endotracheal tube) for past or current lung disease, upper gastrointestinal bleeding, hemodynamic instability, or airway bleeding. Subjects were not using vasoactive drugs but were under deep sedation (scores of 5 or 6 on the Ramsay scale) and analgesic effects. Subjects were quasi-randomized, and those with
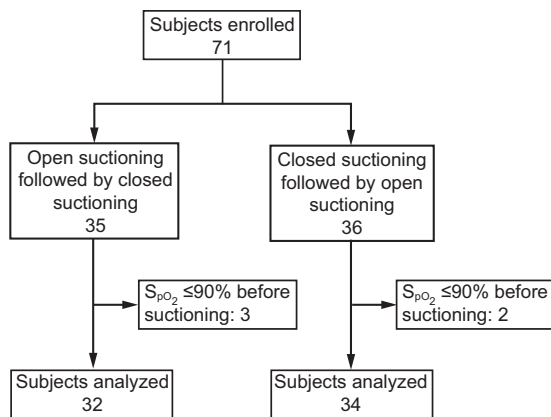
Fig. 1. Flow chart.

Table 1. Subject Characteristics

Age, y	55.8 ± 2
Gender (male/female)	59/41
Body mass index, kg/m²	23.5 ± 2.9
Procedures, %	
Abdominal surgery	36.6
Neurological surgery	26.8
Vascular surgery	11.3
Renal insufficiency	7.0
Hemotologic disease	7.0
Acid/base disorders	5.6
Cardiovascular events	5.6
APACHE II	16 ± 2
Length of stay, d	5 ± 3

Data are presented as percentages or as mean $\pm$ SD.
APACHE II = Acute Physiology and Chronic Health Evaluation II

$S_{pO_2} \leq 90\%$ immediately before aspiration were excluded from analyses ex post facto (Fig. 1).

Subject Involvement

Because sedation had rendered these subjects unresponsive, the primary investigator identified for all eligible subjects a surrogate legally able to represent that subject and provide consent for procedures and research in Brazilian hospitals (eg, a spouse, relative, or guardian $\geq$ 18 y old) per the approved protocol. Subjects were involved in the design and conduct of this research. During the subject selection stage, priority of the research question, outcome measures, and methods of recruitment were informed by discussions with subjects' surrogates.

Cardiopulmonary Measures and Suction

After confirming absence of respiratory drive, systolic blood pressure, diastolic blood pressure, mean blood pressure, heart rate, breathing frequency, S_{pO_2}, tidal volume (V_T), PIP, plateau pressure (P_{plat}), PEEP, and inspiratory flow were measured; in addition, PIP, P_{plat}, PEEP, inspiratory flow, and V_T were used to calculate compliance and airway resistance (R). Subjects receiving volume-control continuous mandatory ventilation were screened in the morning ($\sim$7:00 AM) while supine after $\geq$ 1 h free of procedures or postural changes. Immediately thereafter (ie, just before suction), physiologic data were collected. Suction involved either an OSS or a CSS according to a quasi-random crossover sequence and with data recorded 3 min later. Subjects were returned to nursing care until the alternate suction was performed approximately 6 h later ($\sim$1:00 PM), with the same timing for data collection. The procedures required 10 s to insert and remove the aspiration catheter, with each aspiration performed 3 times (see the supplementary materials at http://www.rcjournal.com).

Results

After exclusion, 66 subjects (Fig. 1) were included in the study. Baseline characteristics are summarized in Table 1, and physiology parameters prior to suction are detailed in the supplementary materials (available at http://www.rcjournal.com).

Pulmonary Physiology

The sequence in which suction types were administered did not alter the cardiopulmonary effects of either suction type. In this study, OSS increased R by 1.3 ± 0.5 cm H_2O/L/s and PIP by 1.4 ± 0.5 cm H_2O, whereas CSS decreased R by 0.9 ± 0.3 cm H_2O/L/s and PIP by 1.0 ± 0.5 cm H_2O relative to baseline (all $P < .05$). Moreover, the 2 suction types had significantly opposing mean effects ($P < .05$); however, because baseline values of R, PIP, and P_{plat} correlated inversely with suction-induced changes (Fig. 2, Table 2), models that control for baseline were used. This approach yielded results analogous to our initial observations (Fig. 2, Table 2) and revealed that CSS attenuated preexisting elevations in R and PIP more robustly and consistently than OSS ($P < .05$). Based on the x intercepts in the linear models (Fig. 2), which account for physiologic values prior to suction, CSS decreased R for individuals with baseline > 8.8 cm H_2O/L/s (76% of cases), whereas OSS increased R for subjects with baseline < 15.6 cm H_2O/L/s (87% of cases). Moreover, CSS diminished PIP in subjects with baseline PIP > 22.4 cm H_2O (83% of cases), whereas OSS increased PIP for those with baselines < 31.5 cm H_2O (83% of cases). Both suction treatments similarly increased P_{plat} if a subject's baseline undershot 14.3 cm H_2O but decreased this parameter if a subject's baseline exceeded this threshold. Interestingly, CSS did not
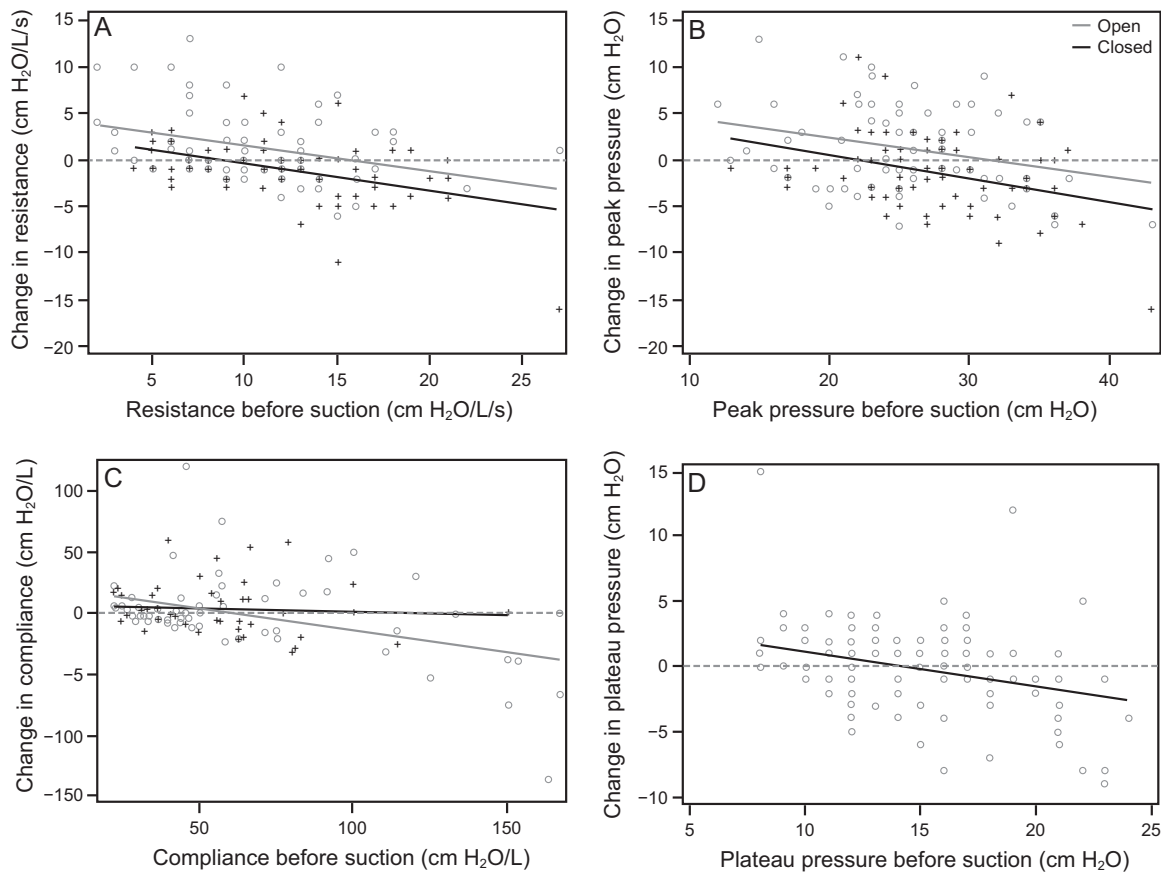
Fig. 2. Open and closed suction divergently affect pulmonary physiology dependent on baseline physiology. If open suction systems and closed suction systems differed in effects on a particular parameter, regressions are reported for each suction type, accounting for baseline value. Where open suction systems and closed suction systems did not differ in effects (eg, plateau pressure), an overall regression is displayed.

Table 2.   Effect of Aspiration on Pulmonary Physiology

	Suction		Suction Type (Closed vs Open)		Baseline		Type × Baseline	
	Intercept ± SE	P	β ± SE	P	β ± SE	P	β ± SE	P
ΔR, cm H_2O/L/s	4.50 ± 0.81	< .001	−1.91 ± 0.59	< .001	−0.29 ± 0.06	< .001	NA*	.80
ΔPIP, cm H_2O	7.24 ± 1.73	< .001	−2.14 ± 0.69	.003	−0.23 ± 0.06	< .001	NA*	.73
ΔC, cm H_2O/L	22.7 ± 5.7	< .001	−12.5 ± 8.0	.12	−0.37 ± 0.08	< .001	0.26 ± 0.11	.030
ΔP$_{plat}$, cm H_2O	3.91 ± 1.04	< .001	NA*	.78	−0.27 ± 0.07	< .001	NA*	.52

Linear regressions were performed to determine effects of suction by type while accounting for baseline values of the parameter and any interaction between baseline values and suction type. Values are presented as intercept, regression coefficient (β), and standard error (SE). Aspiration differentially altered R and PIP depending on suction type. Baseline compliance influenced the effects of aspiration on C differentially by suction type. Effects of aspiration were compared between suction types (closed vs open); the interaction term (Type × Baseline) was excluded from the analysis only when this interaction was not significant. Suction type was excluded from the model only when suction system and the interaction term were both insignificant.
* NA = exclusion from the model due to nonsignificance.
R = airway resistance
PIP = peak inspiratory pressure
C = pulmonary compliance
P$_{plat}$ = plateau pressure

alter compliance, regardless of baseline value (Fig. 2, Table 2), whereas OSS progressively decreased compliance the more a subject's baseline compliance exceeded 61.6 cm H_2O/L (33% of cases); this effect differed significantly from CSS ($P = .030$) (Fig. 2, Table 2).

Cardiovascular Physiology

With the exception of S_{pO_2}, aspiration significantly altered all cardiovascular parameters both in paired t tests (data not shown) and in regressions accounting for baseline
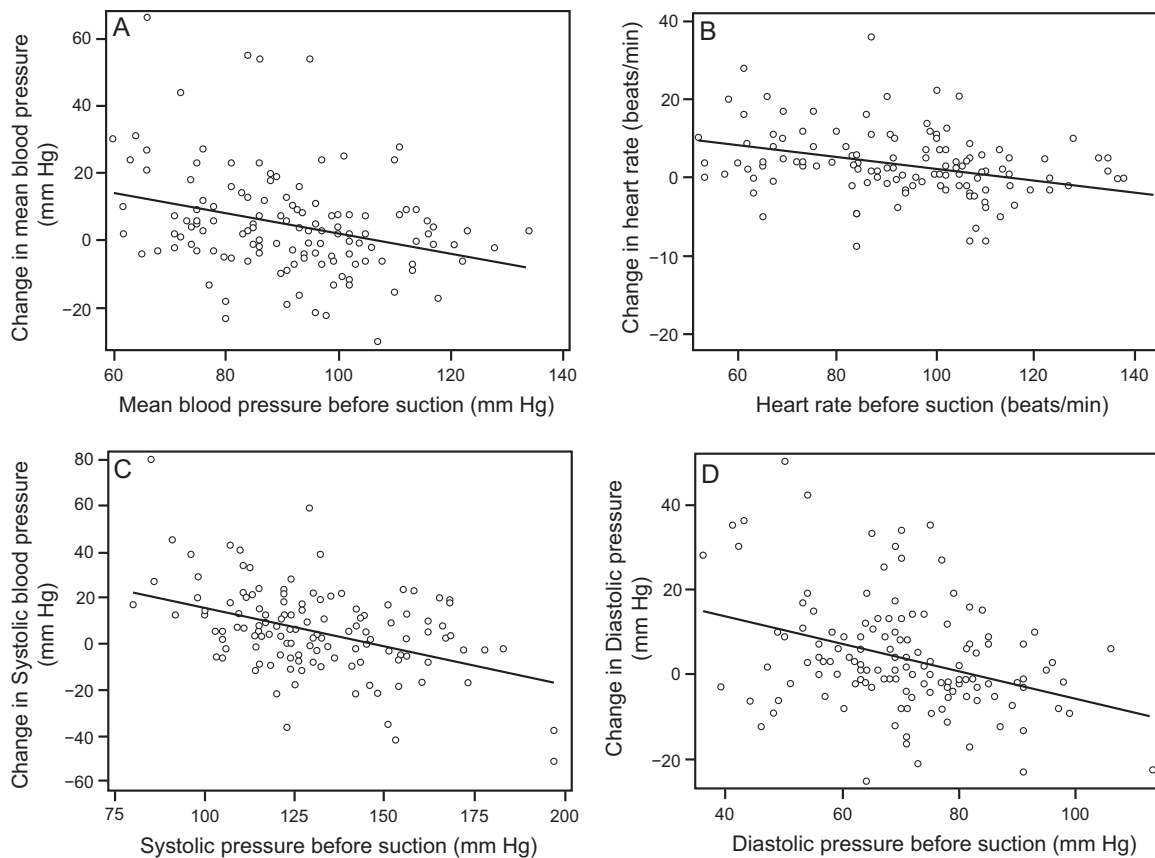
Fig. 3. The effect of suction on heart rate and blood pressure according to baseline values. Open and closed aspiration systems similarly altered heart rate and blood pressure. Because effects of suction did not significantly differ by aspiration type in linear mixed-effects models, suction effects are shown as a single regression line.

values and independent of suction type (Fig. 3, Table 3). Suction increased heart rate among subjects with baseline < 115 beats/min (most subjects) and increased systolic blood pressure in those with baseline < 146 mm Hg (most subjects), with more pronounced effects in subjects markedly underneath these threshold values. For instance, the regressions indicated that suction would induce an increase in heart rate of 7 beats/min for a given subject with a baseline heart rate of 70 beats/min. Likewise, suction would cause an estimated increase in systolic blood pressure of 10 mm Hg in a subject with a baseline systolic blood pressure of 120 mm Hg, and an increase of 6 mm Hg in a subject with a baseline systolic blood pressure of 130 mm Hg.

Discussion

The findings of this study indicate that open suction imposes short-term adverse effects on pulmonary physiology that are distinct from those due to closed suction, including increases in pulmonary resistance and peak pressure and decreases in compliance. Baseline pulmonary physiology also influences the effects of suction. After adjusting for baseline physiology, open suction impaired these measures in

> 80% of cases, whereas closed suction improved these parameters in > 75% of cases. These effects collectively suggest that open suction may transiently compromise pulmonary function in sedated patients in the ICU. In contrast, in individuals with high resistance or high PIP, only closed suction improved these indices, suggesting that closed systems may uniquely benefit patients with impaired pulmonary function. Although long-term health outcomes were not assessed, the findings of this study bolster prior observations that open suction, but not closed suction, is associated with potentially adverse short-term cardiopulmonary effects.

Another interesting result is that both suction types increased blood pressure and heart rate statistically equally, which may be explained by a decrease in parasympathetic activity after suctioning.[32] This should be taken into consideration by clinicians because a decrease in parasympathetic activity in the sinoatrial node decreases the ability of the heart to adapt rapidly to changing stressors, compromises arterial baroreflex sensitivity by decreasing the beat-by-beat heart rate response to changes in arterial pressure, and increases the risk of sympathetically mediated heart rate and rhythm disturbances and sudden death.[32]

Table 3. Effect of Aspiration on Cardiovascular Physiologic Parameters

	Suction		Suction Type (Closed vs Open)		Baseline		Type × Baseline	
	Intercept ± SE	P	β ± SE	P	β ± SE	P	β ± SE	P
ΔMean blood pressure	36.5 ± 7.8	< .001	NA*	.42	−0.35 ± 0.08	< .001	NA*	.52
ΔHeart rate	17.8 ± 3.6	< .001	NA*	.61	−0.15 ± 0.04	< .001	NA*	.24
ΔDiastolic blood pressure	27.6 ± 5.4	< .001	NA*	.40	−0.34 ± 0.07	< .001	NA*	.43
ΔSystolic blood pressure	55.8 ± 8.6	< .001	NA*	.40	−0.38 ± 0.06	< .001	NA*	.39
Δ S_{pO_2}	NA*	.30	NA*	.70	NA*	.29	NA*	.68

Linear regressions were performed to determine effects of suction by type while accounting for baseline values of the parameter and any interaction between baseline values and suction type. Values are presented as intercept, regression coefficient (β), and standard error (SE). Because suction type did not significantly influence the effect of suction on these parameters, regression coefficients are displayed for the effects of suction overall with P values, while accounting for baseline physiology where it was detected as a significant variable. Effects of aspiration were compared between suction types (closed vs open); the interaction term (Type × Baseline) was excluded from the analysis only when this interaction was not significant. Suction type was excluded from the model when it and the interaction term were both insignificant.

* NA = exclusion from the model due to nonsignificance.

Several studies have compared open and closed suction systems, with the majority examining incidence of ventilator-associated pneumonia, mortality, length of mechanical ventilation, and time of intensive care.[10,19,22,30,33-37] Although multiple studies have reported a higher bacterial colonization with CSS, these observations seem to bear little clinical relevance.[10,25,35-37] A recent meta-analysis by Kuriyama et al[27] associated CSS with a lower risk of ventilator-associated pneumonia; however, similar to other meta-analyses,[8,25] the authors reported no differences in mortality or length of ventilation. In our study, OSS and CSS increased heart rate and arterial pressure equally. These effects, which were relatively modest, diminished with increasing baseline values and were thus likely of little clinical concern. Furthermore, these observations agree with at least 1 prior report[32] but conflict with other observations that OSS causes greater increases in heart rate[3,16,18,37] or arterial pressure[16,23,38]; however, these earlier studies recruited fewer subjects (n = 10–19 per suction type) and typically did not control for sampling error by adjusting for baseline physiology in their statistical models. Notably, in supplementary analyses, the same statistical approach as that used in these prior studies (ie, 2-tailed paired t tests) revealed no difference between suction types in chronotropic or hemodynamic changes from baseline in our study.

No changes in peripheral arterial oxygen saturation were found with suctioning. However, because this study was limited to subjects lacking prior pulmonary disease and sedated at 5 or 6 on the Ramsay scale, such observations may not apply to patients with respiratory disease or under deeper anesthesia. Moreover, in contrast to S_{pO_2} data being collected at 1–2 min after suction,[30,39,40] we collected these data 3 min after suction. These distinctions may explain how other studies demonstrated that OSS, but not CSS, decreased S_{pO_2} after aspiration[3,30,38,41] and why several studies thus recommend preemptive hyperoxygenation or manual hyperventilation before aspiration.[3,30,37,38]

OSS and CSS divergently affected R (P < .001) and PIP (P = .003) but had comparable effects on P_{plat} (P = .78) and compliance (P = .12) when controlling for the significant influence of baseline physiology. In individuals with moderate baseline values, OSS uniquely increased R and PIP, which is directly influenced by R. Thus, the present data indicate that OSS may disproportionately increase R. Furthermore, CSS more consistently returned elevated PIP and R to normal pulmonary function. Together, these findings indicate that CSS poses fewer risks and bears greater salutary effects on pulmonary function. In contrast, Cereda et al[30] reported that both suction types negligibly affected airway pressure and PIP after suction, but OSS uniquely increased mean arterial pressure and decreased S_{pO_2}. Similarly OSS was not observed to affect R in young children.[17] However, neither study adjusted their statistical models by baseline pulmonary physiology, which, as noted in our study, significantly influenced the directionality of responses to suctioning. Elevated R can indicate airway obstruction, which may provoke bronchospasm, which is an occasional complication during endotracheal suction in the ICU. The effect of OSS on R exceeded that of CSS by 8%, which in susceptible individuals (eg, patients with asthma and elevated R) may further compromise ventilation and counteract any intended improvement in R via aspiration.[17,26,42]

Several studies[3,18,22,43] have reported specific advantages of CSS over OSS with respect to physiologic impact or potential for infection, but these have not translated to clear differences in subject outcomes. Kaur et al[20] noted that, relative to OSS, CSS decreased contamination and improved preservation of lung volumes and oxygenation, especially in severely hypoxemic subjects. Although there is no scientific evidence for the lower efficiency of secretion removal for CSS, users of CSS in ICUs report lower volumes of aspirated secretion and greater propensity for catheter obstruction by airway foreign bodies.[20,44] Dong et al[26] noted in mechanically ventilated subjects that, relative to OSS, CSS minimized the adverse effects of suction on arrhythmia, arterial pressure, and S_{pO_2}, and CSS expedited removal from mechanical ventilation. However, the 2 suction types did not

differ in ICU length of stay, risks of ventilator-associated pneumonia, microbial colonization, or adverse outcome.

Unlike OSS, CSS allows uninterrupted ventilation and maintains positive pressure, potentially contributing to the improvements in R and PIP in contrast with worsening of these parameters with OSS. In addition to demonstrating that baseline pulmonary physiology can influence the effects of suction, our results suggest that CSS may especially benefit patients with high baseline PIP and R. Conversely, OSS may uniquely impair pulmonary compliance, R, and PIP. We thus speculate that, in individuals with impaired compliance or elevations in PIP or R, CSS may provide greater therapeutic benefits than OSS. These benefits may result particularly from improved R. Conversely, increases in R with OSS may have resulted from bronchospasm, mucus obstruction, or peripheral airway edema secondary to less efficient suction or loss of positive pressure with interruption in ventilation. Although this study did not measure the aspirate collected for comparison, some studies have noted no difference in secretion volume between OSS and CSS,[10] while others report that OSS more effectively reduces secretion volume than CSS.[35] We can speculate that the increases in R and PIP and the reductions in compliance with OSS in this study may actually indicate movement of secretions into more central airways, potentially indicating that CSS is less effective, as reported by Lindgren et al.[45] Because OSS and CSS similarly affected hemodynamic end points that are particularly sensitive to airway irritation,[46] the divergent impacts of OSS and CSS on R were likely independent of airway irritant reflexes. Ultimately, the increase in R with OSS may promote pulmonary hyperinflation, increase dead space, impair ventilation, and (with increased intra-alveolar pressures) diminish alveolar perfusion, potentially explaining prior reports that OSS disproportionately decreases S_{pO_2}.[8,16,26,28] Given that patients with asthma, lung disease, or obesity are more susceptible to increases in R, our findings suggest that they may especially benefit from aspiration with CSS.

This study provides novel findings of differential pulmonary effects of OSS and CSS, but they may not be generalizable to all mechanically ventilated patients. First, the OSS used here lacked recent design improvements (eg, Bodai PEEP-SAFE) that reduce the temporary loss in pressure and risk for attendant complications. However, clinics in lower- and middle-income countries (eg, Brazil) commonly reserve these accessories for unstable patients or lack them altogether due to their added costs. Moreover, because the subjects who either declined consent (via surrogates) or did not meet initial criteria were not quantified, the generalizability of this study remains unclear. Finally, a focus on acute responses and the neglect of any long-term outcomes limit the clinical importance of our findings. Future studies involving larger subject populations, longer observation windows, and recent technological improvements may further elucidate the differential impacts of the 2 suction systems.

Conclusions

This study demonstrates that endotracheal suction with a CSS alleviated elevations in airway resistance and PIP more consistently and effectively. In mechanically ventilated patients, high airway resistance or PIP prior to suction may clinically indicate aspiration with a CSS and contraindicate suction with an OSS. Additional studies are required to resolve whether such practices prevent pulmonary injury during mechanical ventilation. In addition, the clear effects of both suction systems on pulmonary physiology immediately after suctioning suggest that, when assessing pulmonary physiology in ventilated patients, clinicians should account not only for the baseline pulmonary function (ie, prior to suctioning) but also the time relative to last suctioning; patients should be allowed some time for recovery after suctioning, even with CSS, before acquiring measures that inform a patient's general pulmonary stability.

REFERENCES

1. Carrothers KM, Barr J, Spurlock B, Ridgely MS, Damberg CL, Ely EW. Contextual issues influencing implementation and outcomes associated with an integrated approach to managing pain, agitation, and delirium in adult ICUs. Crit Care Med 2013;41(9 Suppl 1):S128-S135.
2. Vieira JE, Silva AR, Garcia DJ. Patterns of ventilation in anesthesia: a retrospective study. Rev Bras Anestesiol 2002;52(6):756-763.
3. Johnson KL, Kearney PA, Johnson SB, Niblett JB, MacMillan NL, McClain RE. Closed versus open endotracheal suctioning: costs and physiologic consequences. Crit Care Med 1994;22(4):658-666.
4. Konrad F, Schreiber T, Brecht-Kraus D, Georgieff M. Mucociliary transport in ICU patients. Chest 1994;105(1):237-241.
5. Maggiore SM, Lellouche F, Pignataro C, Girou E, Maitre B, Richard JC, et al. Decreasing the adverse effects of endotracheal suctioning during mechanical ventilation by changing practice. Respir Care 2013;58(10):1588-1597.
6. Kerr ME, Rudy EB, Brucia J, Stone KS. Head-injured adults: recommendations for endotracheal suctioning. J Neurosci Nurs 1993;25 (2):86-91.
7. Sánchez-García M, Santos P, Rodríguez-Trigo G, Martínez-Sagasti F, Fariña-González T, del Pino-Ramírez Á, et al. Preliminary experience on the safety and tolerability of mechanical "insufflation-exsufflation" in subjects with artificial airway. Intensive Care Med Exp 2018;6(1):8.
8. Jongerden IP, Rovers MM, Grypdonck MH, Bonten MJ. Open and closed endotracheal suction systems in mechanically ventilated intensive care patients: a meta-analysis. Crit Care Med 2007;35(1):260-270.
9. Nakstad ER, Opdahl H, Heyerdahl F, Borchsenius F, Skjønsberg OH. Manual ventilation and open suction procedures contribute to negative

pressures in a mechanical lung model. BMJ Open Respir Res 2017;4 (1):e000176.

10. Combes P, Fauvage B, Oleyer C. Nosocomial pneumonia in mechanically ventilated patients, a prospective randomised evaluation of the Stericath closed suctioning system. Intensive Care Med 2000;26 (7):878-882.

11. Bruschettini M, Zappettini S, Moja L, Calevo MG. Frequency of endotracheal suctioning for the prevention of respiratory morbidity in ventilated newborns. Cochrane Database Syst Rev 2016;3:CD011493.

12. Bhat Yellanthoor R, Ramdas V. Frequency and intensive care related risk factors of pneumothorax in ventilated neonates. Pulm Med 2014;2014:727323.

13. Jaw MC, Soong WJ, Chen SJ, Hwang B. Pneumothorax: a complication of deep endotracheal tube suction: report of 3 cases. Zhonghua Yi Xue Za Zhi (Taipei) 1991;48(4):313-317.

14. Corley A, Sharpe N, Caruana LR, Spooner AJ, Fraser JF. Lung volume changes during cleaning of closed endotracheal suction catheters: a randomized crossover study using electrical impedance tomography. Respir Care 2014;59(4):497-503.

15. Frengley RW, Closey DN, Sleigh JW, Torrance JM. The effect of closed system suction on airway pressures when using the Servo 300 ventilator. Crit Care Resusc 2001;3(4):230-235.

16. Jongerden IP, Kesecioglu J, Speelberg B, Buiting AG, Leverstein-van Hall MA, Bonten MJ. Changes in heart rate, mean arterial pressure, and oxygen saturation after open and closed endotracheal suctioning: a prospective observational study. J Crit Care 2012;27(6):647-654.

17. Avena MJ, Carvalho WB, Beppu OS. Assessment of respiratory mechanics and oxygenation before and after aspiration of secretion in children undergoing mechanical ventilation. Rev Assoc Med Bras 2003;49(2):156-161.

18. Perini R, Veicsteinas A. Heart rate variability and autonomic activity at rest and during exercise in various physiological conditions. Eur J Appl Physiol 2003;90(3-4):317-325.

19. Masry A, Willians PF, Chipman DW, Kratohvil JP, Kamarek RM. The impact of close endotracheal system suctions on mechanical ventilator performance. Respir Care 2005;50(3):345-353.

20. Kaur S, Singh S, Gupta R, Bindra T. Foreign body blocking closed circuit suction catheter: an unusual cause of retained tracheal secretions in a mechanically ventilated patient. Int J Appl Basic Med Res 2014;4 (1):50-52.

21. Kondili E, Prinianakis G, Georgopoulos D. Patient-ventilator interaction. Br J Anaesth 2003;91(1):106-119.

22. Pedersen CM, Rosendahl-Nielsen M, Hjermind J, Egerod I. Endotracheal suctioning of the adult intubated patient—what is the evidence? Intensive Crit Care Nurs 2009;25(1):21-30.

23. Sole ML, Bennett M, Ashworth S. Clinical indicators for endotracheal suctioning in adult patients receiving mechanical ventilation. Am J Crit Care 2015;24(4):318-324.

24. Freytag CC, Thies FL, König W, Welte T. Prolonged application of closed in-line suction catheters increases microbial colonization of the lower respiratory tract and bacterial growth on catheter surface. Infection 2003;31(1):31-37.

25. Subirana M, Solà I, Benito S. Closed tracheal suction systems versus open tracheal suction systems for mechanically ventilated adult patients. Cochrane Database Syst Rev 2007(4):CD004581.

26. Dong L, Yu T, Yang Y, Qiu HB. The effects and safety of closed versus open tracheal suction system: a meta analysis. Zhonghua Nei Ke Za Zhi 2012;51(10):763-768.

27. Kuriyama A, Umakoshi N, Fujinaga J, Takada T. Impact of closed versus open tracheal suctioning systems for mechanically ventilated adults: a systematic review and meta-analysis. Intensive Care Med 2015;41(3):402-411.

28. Afshari A, Safari M, Oshvandi K, Soltanian AR. The effect of the open and closed system suctions on cardiopulmonary parameters: time and costs in patients under mechanical ventilation. Nurs Midwifery Stud 2014;3(2):e14097.

29. Overend TJ, Anderson CM, Brooks D, Cicutto L, Keim M, McAuslan D, et al. Updating the evidence-base for suctioning adult patients: a systematic review. Can Respir J 2009;16(3):e6-e17.

30. Cereda M, Villa F, Colombo E, Greco G, Nacoti M, Pesenti A. Closed system endotracheal suctioning maintains lung volume during volume-controlled mechanical ventilation. Intensive Care Med 2001;27 (4):648-654.

31. Ruan SY, Lin FC, Huang CT, Ku SC, Wu HD. Effect of incomplete withdrawal of a closed-suction catheter on airway resistance. Intensive Care Med 2015;41(8):1496-1497.

32. Bourgault AM, Brown CA, Hains SM, Parlow JL. Effects of endotracheal tube suctioning on arterial oxygen tension and heart rate variability. Biol Res Nurs 2006;7(4):268-278.

33. Corley A, Caruana L, Barnett A, Fraser J. Open and closed suctioning result in significant lung derecruitment: a randomised controlled study using electrical impedance tomography. Australian Critical Care 2011;24(1):62-63.

34. AARC Clinical Practice Guidelines. Endotracheal suctioning of mechanically ventilated patients with artificial airways 2010. Respir Care 2010;55(6):758-764.

35. Lasocki S, Lu Q, Sartorius A, Fouillat D, Remerand F, Rouby JJ. Open and closed-circuit endotracheal suctioning in acute lung injury: efficiency and effects on gas exchange. Anesthesiology 2006;104(1):39-47.

36. Lee CK, Ng KS, Tan SG, Ang R. Effect of different endotracheal suctioning systems on cardiorespiratory parameters of ventilated patients. Ann Acad Med Singapore 2001;30(3):239-244.

37. Lee ES, Kim SH, Kim JS. Effects of a closed endotracheal suction system on oxygen saturation, ventilator-associated pneumonia, and nursing efficacy. Taehan Kanho Hakhoe Chi 2004;34(7):1315-1325.

38. Radaelli A, Ricordi L, Corbellini D, Soldà PL, Calciati A, Salvucci F, et al. The variability of the heart rate, arterial pressure and peripheral circulation as the indices of autonomic control in essential hypertension. Cardiologia 1991;36(12):961-969.

39. Gunderson LP, Stone KS, Hamlin RL. Endotracheal suctioning-induced heart rate alterations. Nurs Res 1991;40(3):139-143.

40. Pagotto IM, Oliveira LR, Araújo FC, Carvalho NA, Chiavone P. Comparison between open and closed suction systems: a systematic review. Rev Bras Ter Intensiva 2008;20(4):331-338.

41. Vonberg RP, Eckmanns T, Welte T, Gastmeier P. Impact of the suctioning system (open vs. closed) on the incidence of ventilation-associated pneumonia: Meta-analysis of randomized controlled trials. Intensive Care Med 2006;32(9):1329-1335.

42. Witmer MT, Hess D, Simmons M. An evaluation of the effectiveness of secretion removal with the Ballard closed-circuit suction catheter. Respir Care 1991;36(8):844-848.

43. Vallés J, Millán S, Díaz E, Castanyer E, Gallardo X, Martín-Loeches I, et al. Incidence of airway complications in patients using endotracheal tubes with continuous aspiration of subglottic secretions. Ann Intensive Care 2017;7(1):109.

44. Branson RD. Secretion management in the mechanically ventilated patient. Respir Care 2007;52(10):1328-1342.

45. Lindgren S, Almgren B, Högman M, Lethvall S, Houltz E, Lundin S, et al. Effectiveness and side effects of closed and open suctioning: an experimental evaluation. Intensive Care Med 2004;30(8):1630-1637.

46. Carll AP, Farraj AK, Roberts AM. In: Campen MJ, editor. The role of the autonomic nervous system in cardiovascular toxicity, 3rd ed. Oxford: Elsevier; 2018.