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Samir Shah, Kevin Fung, Sandy Brim and Bruce K. Rubin

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An *In Vitro* Evaluation of the Effectiveness of Endotracheal Suction Catheters*

Samir Shah, BS; Kevin Fung, BA; Sandy Brim; and Bruce K. Rubin, MD, FCCP

Introduction: **Tracheal suction catheters (TSCs) are used to clear mucus from an endotracheal tube (ETT). The clearance rate is critical because airway mucus stasis leads to obstruction, but prolonged catheter suctioning can lead to hypoxemia. The rate of mucus clearance from an ETT is thought to be influenced by the properties of the mucus, the pressure used to suction the mucus, and the diameter of the catheter. In this study, different adult TSCs were evaluated for their ability to suction mucus simulants that had properties similar to airway mucus.**

Methods: **Six different 14F TSC designs were evaluated. All catheters had the same end hole size, but the two side holes were sized at 3 mm, 4 mm, or 5 mm. A coagulant (Polyox Water Soluble Resin Coagulant NF; Dow Chemical Company; Cary, NC) was mixed with water at concentrations of 0.5%, 1.5%, and 3.0% to simulate mucus or sputum. Suction effectiveness was evaluated by the mass percentage of the coagulant suctioned over 10 s at 100 mm Hg from an 8.0 ETT.**

Measurements and results: **The 1.5% and 3.0% simulants had properties comparable to human airway mucus and sputum. Suction effectiveness was less with the 3.0% coagulant simulant compared with the 1.5% and 0.5% simulants. Suction effectiveness was greater ($p < 0.01$) with TSCs that had nonparallel holes and a side hole diameter of 5 mm when tested with the 1.5% and 3.0% simulants. However, no best catheter could be identified among TSCs when tested with the more liquid-like 0.5% simulant.**

Conclusions: **Greater TSC side hole diameter and nonparallel positioning was important for suctioning mucus simulants that are similar to mucus or sputum. The distance between side holes, end hole size, suction force, and duration of suctioning were not tested but could also have an effect on TSC performance.** ***(CHEST 2005; 128:3699–3704)***

Key words: endotracheal tube; mucus; sputum; suction catheter

Abbreviations: ANOVA = analysis of variance; ETT = endotracheal tube; G' = storage modulus; G'' = loss modulus; TSC = tracheal suction catheter

Endotracheal tube (ETT) intubation impairs cough[1] and mucociliary transport, and mucus statis can lead to atelectasis, airway infection, and respiratory compromise. With diseases requiring an artificial airway, mucus can accumulate, making removal more difficult.[2] Tracheal suction catheters (TSCs) are used to remove mucus from an artificial airway. Catheters that clear mucus more rapidly reduce the risk of hypoxemia.

The primary factors influencing mucus clearance from an artificial airway are the viscoelastic and surface properties of the mucus, and the aerodynamic forces within the catheter. The viscoelastic properties vary with the disease, and since mucus is non-Newtonian, will vary with shear stress.[3,4] Surface properties involve the interaction between the mucus and the underlying surface.[5] The aerodynamic forces within the catheter are dependent on the pressure used for suctioning and the presence of laminar or turbulent flow.[6] In the case of laminar flow, the rate of mass transfer is related to the pressure gradient and the fourth power of the catheter radius. These effects also depend on the size, number, and location of the holes in the catheter. Several studies have attempted to evaluate how these factors affect mucus removal using a TSC. Most of these studies focused on minimizing tissue damage, and none evaluated effectiveness using a substance with viscoelastic and surface properties similar to mucus.

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*From the Departments of Biomedical Engineering (Mr. Shah) and Pediatrics (Dr. Rubin, Mr. Fung and Ms. Brim), Wake Forest University School of Medicine, Winston-Salem, NC.

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Correspondence to: Bruce K. Rubin, MD, FCCP, Department of Pediatrics, Wake Forest University School of Medicine, Medical Center Boulevard, Winston-Salem, NC 27157-1081; e-mail brubin@wfubmc.edu

A catheter with four small side holes and designed to avoid direct contact between the end hole and the mucosa was reported to increase suction effectiveness *in vitro*,[7] but effectiveness was measured using water, rather than with a viscoelastic gel like mucus. *In vitro*, Tri-Flo and Whistle Tip catheter designs (manufacturers since changed; see "Materials and Methods") were more effective at suctioning lower-viscosity (500 poise) mucus simulant but not higher-viscosity simulant (1,200 poise). However, the authors acknowledged that their mucus simulants did not have the non-Newtonian shear stress dependence inherent to mucus, important because suctioning is a high shear event.[3] When tested on patients, the authors[8] found no difference between the catheters. Fiberoptic bronchoscopy has been used to evaluate secretion removal and tissue trauma after ETT suctioning. However, effectiveness was evaluated by direct vision only, and the study was underpowered to detect differences in the catheters.[1] Increased suction pressure increased mucosa damage, but no difference in aspiration volume was found in a small number of anesthetized dogs when the catheter was inserted directly into the airway rather than through an ETT.[9]

Another study[10] documented that water was more effectively suctioned than egg whites, suction force was decreased when there was more than one side hole, and this decreased suctioning effectiveness. Egg whites were used because these were "ropy" (cohesive), similar to mucus. A follow-up study developed a new suction catheter design whose effectiveness was thought to be independent of the viscosity of the simulant used.[11]

Since these earlier studies were published, guidelines have been issued advising against suctioning past the ETT to decrease the risk of tissue damage.[12] However, because suctioning can decrease lung volumes, especially in newborns and in small infants, it is prudent to use the most effective catheter to decrease the amount of time spent suctioning.[6]

Numerous catheters are available, but none have been shown to have characteristics that would maximize suction effectiveness. Further, mucus can alter the function of a device, reducing its efficiency in the intended setting.[13] Thus the primary objective of this study was to identify factors affecting the effectiveness of TSCs to suction mucus simulants with similar viscoelastic and surface characteristics as human tracheal mucus from an artificial airway.

MATERIALS AND METHODS

TSCs and ETT

Suction catheters tested were the 14F Kendall Regu-Vac and Kendall Sensi-Vac (Tyco Healthcare Group; Mansfield, MA), the Medline Delee Tip and Medline Whistle Tip (Medline Industries; Mundelein, IL), the Cardinal Tri-Flo (Cardinal Health Group; McGaw Park, IL), and the Portex Suction Tray MAXI-FLO (SIMS Portex; Keene, NH). Of these catheters, only the Cardinal Tri-Flow catheter and the Medline Whistle Tip catheter were tested in an earlier study.[8] Characteristics of each suction catheter are shown in Table 1. All catheters were approximately 60-cm long and had a end hole diameter of 3 mm. An 8.0 ETT (Medline DYND43080; Medline Industries) was used as the artificial airway. Final testing used this ETT because our preliminary studies showed variation in suction efficiency between different ETT brands (data not shown).

Mucus Simulants

A mucus simulant was used for this study that was both homogenous and could be easily modified. The mucus simulant coagulant (Polyox Water Soluble Resin Coagulant NF; Dow Chemical Company; Cary, NC) is a polyethylene oxide with an approximate molecular weight of 5,000,000 and viscosity of a 1% solution at 5,500 to 7,500 cP. Simulant was prepared by raising the water temperature to 95°C, quickly adding resin, and removing the simulant from the heat while stirring for 2 h. Three concentrations of simulant were used: 0.5%, 1.5%, and 3.0%.

Characterization of Mucus Simulant Properties (see Table 2)

Rheology and Viscoelasticity: Mucus is a viscoelastic material, meaning that the response to stress changes with time. Hence, the response to a load depends on the rate of application and rebound may be < 100%. These responses would affect flow behavior in a suction catheter. Viscosity (loss modulus) is the loss of energy from a rheologic probe (stress) moving through a

Table 1—*The Bulk and Surface Properties of Mucus Simulants Compared with Human Mucus and Sputum*

Variables	0.50%	1.50%	3.00%	ETT Mucus	Cystic Fibrosis Sputum
Bulk properties					
G′ at 1 rad/s	0.02	155	602	201	916
G″ at 1 rad/s	0.8	49	509	81	551
G′ at 100 rad/s	13	191	1,579	275	1,643
G″ at 100 rad/s	78	1,437	3,555	1,674	3,148
Surface properties					
Cohesivity (cm dyne/cm)		12.7	24.9		14.76
Surface tension (dyne/cm/surface)		63.8	127.2		80.6
Contact angle, degrees		36	64		43

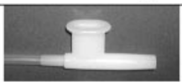
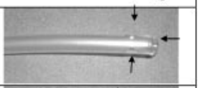
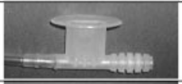
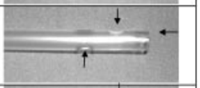
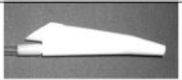
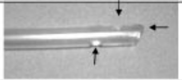
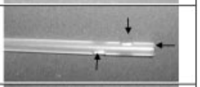
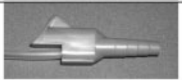
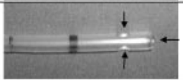
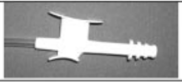
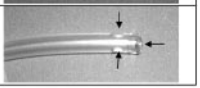
Catheter	Side hole diameter	Size	Whistle Design	Side Hole Design
Cardinal Tri-Flo	3 mm	14 Fr		
Kendall Regu-vac	4 mm, 6.35 mm apart	14 Fr		
Kendall Sensi-vac	5 mm, 9.52 mm apart	14 Fr		
Medline Delee	4 mm, 9.52 mm apart	14 Fr		
Medline Whistle Tip	4 mm	14 Fr		
Portex suction tray	4 mm	14 Fr		

TABLE 2. Viscoelastic, surface, and transport properties of mucus simulant compared to normal mucus collected from an ETT, and cystic fibrosis sputum. Surface properties for mucus simulant at 0.5% were too low to be accurately measured. Fr = French.

substance and thus the resistance to flow. Elasticity (storage modulus) is the recoil energy transmitted back to the probe. During cyclical loading, a phase lag occurs, leading to a dissipation of energy. These changes can be measured to determine the viscous and elastic moduli as a function of frequency. An controlled-stress rheometer (AR1000; TA Instruments; New Castle, DE) with parallel plate geometry was used to assess the dynamic frequency range of stress strain of a 20-μL simulant or mucus sample over driving frequencies of 1 to 100 rad/s. The loss modulus (G") and the storage modulus (G') of the specimen were determined from retardation and relaxation spectra transformation from a nondestructive creep experiment carried out at 5 dyne/cm^2 for 2 min at 37.8 C.[4]

Mucus is also non-Newtonian because its viscosity changes with shear stress. We used our rheometer to measure the viscosity as a function of shear stress, starting from 1 dyne/cm^2 with 8 points per decade of shear stress until the rotation velocity, and therefore reduction in viscosity, exceeded the limits of the instrument. These tests were run immediately after the initial creep experiment.

Cohesivity: Cohesivity is defined as interfacial tension multiplied by the new area created after a test substance is pulled apart. For Newtonian fluids, this is two times the interfacial tension, γ. For a gel such as mucus, a distraction device (Filancemeter) is used to stretch the mucus until breaking. The measurement was performed with a 25-μL sample at a distraction velocity of 10 mm/s. An electric signal conducted through the sample was interrupted when the thread was broken. Assuming a cone with a mean diameter of 1 mm to the point of breaking would mean that cohesivity = $\gamma \times \pi \times$ length (in millimeters)/100.[14,15]

Interfacial (Surface) Tension: Interfacial tension was measured at the sputum/air interface using a specially instrumented platinum-iridium ring, a metal that is completely wettable. The ring was pulled from the mucus sample at a distraction velocity of 10 mm/s until separation was achieved. The force of separation was measured by a strain gauge connected to the ring. We used a semiautomated tensiometer for these measurements (Fischer Tensiomat Model 21; Fischer Scientific; Pittsburgh, PA). We calibrated a platinum-iridium ring with a circumference of 1.7145 ± 0.0381 cm (± SD), so that with a 0.5-cm depth chamber we needed only a volume of 0.12 mL to accurately measure the adhesion tension.[5]

Suction Catheter Technique

Suction catheter effectiveness was evaluated using the apparatus diagrammed in Figure 1. The ETT was mounted in a tilted horizontal position on the frame and filled with 4 mL of mucus simulant that was allowed to spread across the ETT. Suctioning was accomplished by pulling the catheter through the ETT over 10 s at a pressure of 100 mm Hg, generated by using a portable suction vacuum (Easy-Vac PM 60; Precision Medical Devices; Northampton, PA). The suction time and pressure were based on published guidelines for endotracheal suctioning on adults with

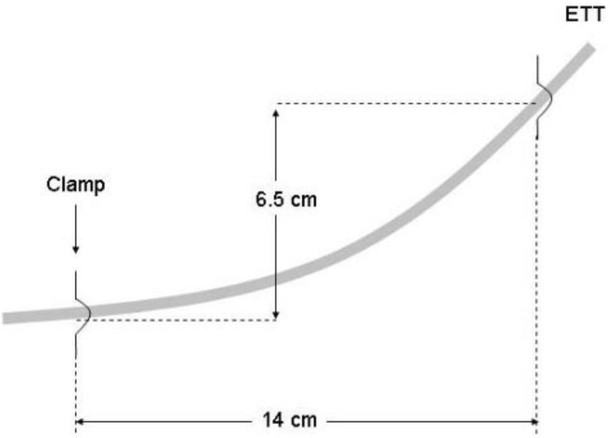


FIGURE 1. Frame used to position the ETT for suction testing. The ETT was held in between two clamps, with the distal end toward the bottom. The catheter was inserted through the ETT from the end that was higher on the frame.

artificial airways.[12,16,17] Effectiveness was measured by dividing the mass of simulant collected during the elapsed time into the original mass of simulant injected into the ETT.

Data Analysis

Analysis of variance (ANOVA) was used to test if differences between catheters or side hole size had an effect on the amount of mucus simulant suctioned. ANOVA was also used to evaluate the influence of mucus rheology on suction catheter effectiveness. The Tukey *post hoc* multiple comparison test was used to compare the effectiveness of catheters. Results are presented as means ± SEM. By convention, $p < 0.05$ was considered significant.

RESULTS

Viscoelastic and Surface Properties of Mucus Simulants

As shown in Figure 2 for the viscoelastic and surface data, and in Figure 3 for the non-Newtonian viscosity response to stress, the mucus simulants showed increasing viscosity and viscoelasticity with increasing concentration. The 1.5% simulant showed low shear G' and G" values at both low and high frequencies, shear rates that were similar to normal human airway mucus; and the viscosity vs shear stress curve appeared similar. The 3.0% mucus simulant showed low shear G' and G" that were similar to cystic fibrosis sputum. The viscosity dependence on shear stress of three cystic fibrosis sputum samples fell between the curves of the 1.5% and 3.0% simulants. The 0.5% mucus simulant showed a Newtonian-like response characterized by low viscosity with minimal changes with shear stress.

Suction Catheter Effectiveness

The suction catheter design had a significant effect on the amount of mucus simulant removed at each simulant concentration ($p < 0.05$, ANOVA). Figures 3–5 show that with the 0.5% mucus simulant, the five best performing catheters were roughly comparable ($p > 0.05$, Tukey). For the 1.5% mucus simulant, the Kendall Sensi-Vac was most efficient ($p < 0.05$, Tukey), followed by the Kendall Regu-Vac and Medline Delee. For the 3.0% mucus simulant concentration, the Kendall Sensi-Vac was comparable to the Medline Delee and Kendall Regu-Vac, and were significantly more effective than the other catheters tested ($p < 0.05$, Tukey comparison). Overall, less mucus was collected within a given time for the more viscous mucus simulants ($p < 0.05$, ANOVA). Figure 6 shows that the largest hole size led to improved suctioning ability for the 1.5% ($p < 0.05$) and 3.0% mucus simulants ($p < 0.05$), but that was not the case with the 0.5% mucus simulant. We also note that with the three catheters that performed best in suctioning simulants that most closely resembled

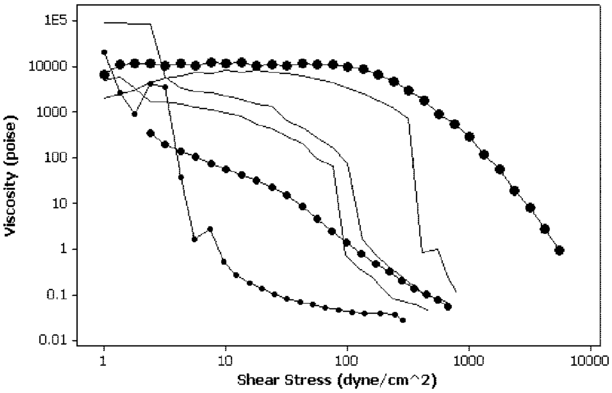


FIGURE 2. Viscosity vs shear stress for the 0.5% (small circles), 1.5% (medium circles), and 3.0% (large circles) mucus simulants, as well as three cystic fibrosis sputum samples (unmarked solid lines). These graphs show that the 1.5% and 3.0% simulants demonstrated non-Newtonian behavior similar to human secretions.

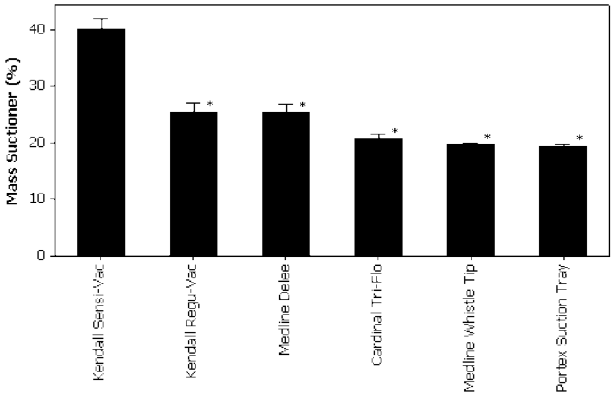


FIGURE 3. Percentage of mass suctioned for the 0.5% mucus simulant. The Cardinal suction catheter was most effective at removing mucus simulant (*$p < 0.1$, compared to the Medline Delee). Error bars indicate SEM.

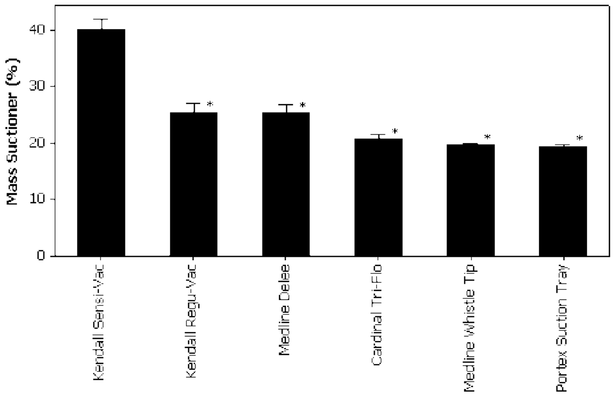


FIGURE 4. Percentage of mass suctioned for the 1.5% mucus simulant. The Kendall Sensi-Vac suction catheter was most effective at removing mucus simulant (*$p < 0.1$, compared to the Kendall Sensi-Vac). Error bars indicate SEM.

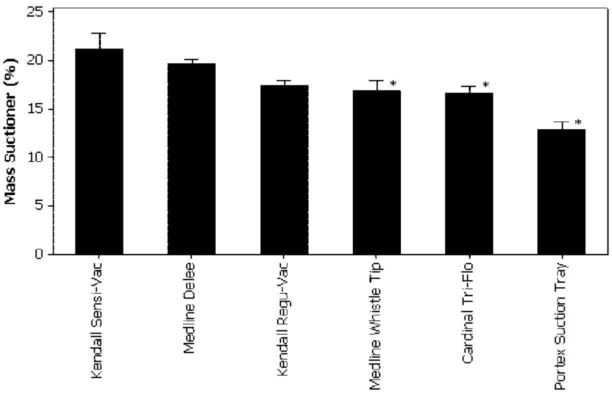


FIGURE 5. Percentage of mass suctioned for the 3.0% mucus simulant. The Kendall Sensi-Vac suction catheter was most effective at removing mucus simulant (*$p < 0.05$, compared to the Kendall Sensi-Vac). Error bars indicate SEM.

human secretions (1.5% and 3.0%), all had side holes that were not parallel to each other (Table 1). The Kendall Sensi-Vac, which performed the best, had the largest side hole.

DISCUSSION

The primary objective of this investigation was to evaluate the suction effectiveness of different catheters and the factors responsible for differences. The accurate evaluation of suction catheters requires mucus simulants with surface and viscoelastic properties similar to human tracheal mucus. A major difference in our study compared to previous studies was that we used a mucus simulant with properties that resembled real human airway secretions. We showed that increased mucus viscosity and viscoelasticity reduced suctioning effectiveness, consistent with viscosity being defined as resistance to flow.

Comparing the different suction catheters, nonparallel positioning of the side holes and increased size improved suction efficiency for the mucus simulants that more closely resembled airway secretions. This can be explained by considering that suctioning involves creating a lower than atmospheric pressure region, which then causes atmospheric pressure to "push" a substance toward the area of low pressure. For ETT suctioning, a vacuum pump created a lower pressure region. Atmospheric pressure then pushes the mucus simulant through the end hole and air through the side hole, toward the pump. For the catheters and vacuum pressure tested, the larger the side hole, the greater the airflow, resulting in greater force to move the simulant. However flow will be dependent on suction (vacuum) force because flow will decrease once the side hole reaches a critical size unless suction flow is also increased. The flow of air from the side hole back toward the pump created a pressure drop at the side hole from the Bernoulli effect, drawing mucus simulant from the end hole into the air stream. This Bernoulli effect may not be possible when the holes are opposite from each other. The greater the air flow, the greater the Bernoulli pressure drop, the more mucus will be suctioned over a short time.

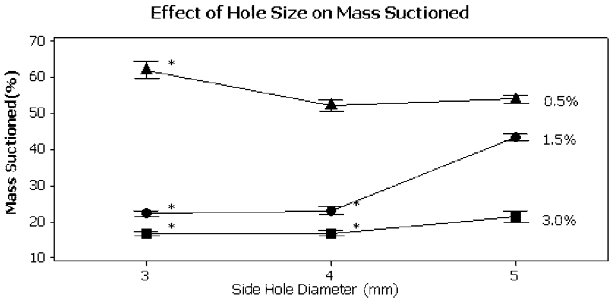


FIGURE 6. Percentage of mass suctioned showing that increasing hole size led to increasing removal for the two more viscous mucus simulants: 0.5% mucus simulant (triangles), 1.5% mucus simulant (circles), and 3.0% mucus simulant (squares) [*$p < 0.1$ compared to 5-mm side hole diameter for that simulant concentration]. Error bars indicate SEM.

To explain why the largest side hole size did not increase suction effectiveness for the 0.5% mucus simulant, we consider the biophysical properties of the mucus simulant. This mucus simulant was very liquid like and had a low elasticity or recoil energy. The contact angle and surface tension were so low they could not be accurately measured, indicating that the 0.5% mucus simulant favored spreading on the ETT surface. Thus, this simulant would be least likely to resist suctioning and would travel easily through the catheter; so easily, in fact, that the force differences caused by the side hole at the pressure we used were negligible. As a result, the differences between the top performing catheters were indistinguishable. This is in agreement with an earlier study[8] that used a liquid-like "mucus" simulant. However, these findings using the low-elasticity, low-surface properties mucus simulant (0.5%) would not apply to most patients with an artificial airway. The reason is because, as shown in Figure 3, human airway secretions are like the 1.5% and 3.0% mucus simulants with higher viscosity and viscoelasticity, and are less likely to spread. This would also explain the variability in the results of earlier studies[7,10] that used simulants that were liquid like, and explain why *in vivo* studies using animals or humans did not correlate with the *in vitro* studies using simulants.[8]

There are three principal dangers associated with suctioning an ETT: iatrogenic infection,[18] degassing the lung,[6] and tissue trauma.[12] Although we have not addressed the issue of infection control in this article, it is well recognized that even with modern closed-circuit suction systems, the risk of infection is increased with the frequency of suctioning, presumably due to the unavoidable introduction of bacteria into the airway with either the catheter or the saline solution that is often instilled at the time of suctioning.[18] Thus, any improvement in suction catheter efficiency that reduces the need to violate the airway might be expected to decrease nosocomial pulmonary ETT-associated infections.

Pulmonary degassing and associated hypoxemia and atelectasis is dependent on the communicating gas volume of the lung (total lung capacity) and the volume of air removed during suctioning, which, in turn, is a function of suction flow multiplied by the duration of the suctioning event. Because of their small size, this tends to be a greater problem with infants and small children.[6] Although we did not evaluate this potential with these catheters, we note that anything that would reduce flow, especially through the end hole, or decrease the requirement for prolonged suctioning would also reduce this risk.

Tissue trauma can result either from the blunt end of the catheter being pushed into airway tissue during insertion or due to tissue being pulled into the catheter holes by the force of suction. The purpose of suctioning is to clear the artificial airway of mucus and debris and not to clear the airway itself. There is no evidence that suctioning past the end of an artificial airway is any more effective then suctioning only up to the end of the airway and the risk of tissue damage is greatly increased once the catheter passes past the tube into the patient's airway. For this reason, suctioning guidelines now caution against "deep suctioning."[12] We evaluated the effectiveness of these catheters in clearing an artificial airway only, but we hypothesize that even with pliable catheters and smooth, rounded edges to the end and side holes, those catheters that were most effective at removing mucus could pose an increased risk of tissue damage if guidelines were not followed and the catheter was inserted deeply so that it contacted the airway.

In summary, the viscoelastic and surface properties of secretions and suction catheter side hole positioning and size were the most significant factors that affected mucus removal effectiveness. TSC used to clear normal or viscous mucus could be improved by ensuring they were not opposed and, up to a point, by increasing side hole size. However flow will be dependent on suction (vacuum) force,[6] and flow could decrease once the side hole reaches a critical size unless suction flow is also increased. As well, a side hole that is very small with flow that is great will increase the Reynolds number, producing turbulent flow that may decrease suction efficiency by disrupting the Bernoulli effect. As such, other effects such as the difference in area between the suction catheter and the ETT could affect the pressure,[6] and so these results cannot be directly extrapolated to the smaller suction catheters used clear the pediatric airway.

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