Tracheal Tube Obstruction in Mechanically Ventilated Patients Assessed by High-resolution Computed Tomography

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ABSTRACT

Background: Tracheal intubation compromises mucus clearance and secretions accumulate inside the tracheal tube (TT). The aim of this study was to evaluate with a novel methodology TT luminal obstruction in critically ill patients.

Methods: This was a three-phase study: (1) the authors collected 20 TTs at extubation. High-resolution computed tomography (CT) was performed to determine cross-sectional area (CSA) and mucus distribution within the TT; (2) five TTs partially filled with silicone were used to correlate high-resolution CT results and increased airflow resistance; and (3) 20 chest CT scans of intubated patients were reviewed for detection of secretions in ventilated patients' TT.

Results: Postextubation TTs showed a maximum CSA reduction of (mean ± SD) 24.9 ± 3.9% (range 3.3 to 71.2%) after a median intubation of 4.5 (interquartile range 2.5 to 6.5) days. CSA progressively decreased from oral to lung end of used TTs. The luminal volume of air was different between used and new TTs for all internal diameters ($P < 0.01$ for new *vs.* used TTs for all studied internal diameters). The relationship between pressure drop and increasing airflow rates was nonlinear and depended on minimum CSA available to ventilation. Weak correlation was found between TT occlusion and days of intubation ($R^2 = 0.352$, $P = 0.006$). With standard clinical chest CT scans, 6 of 20 TTs showed measurable secretions with a CSA reduction of 24.0 ± 3.9%.

Conclusions: TT luminal narrowing is a common finding and correlates with increased airflow resistance. The authors propose high-resolution CT as a novel technique to visualize and quantify secretions collected within the TT lumen. **(ANESTHESIOLOGY 2014; 121:1226-35)**

TRACHEAL intubation disrupts the physiological homeostasis of mucus clearance of the respiratory system. The presence of a tracheal tube (TT) directly interferes with the mucociliary function and depresses the cough reflex, the two primary airway defensive mechanisms.[1–3] The inability to clear secretions leads to the accumulation of mucus that adheres to the airways and, eventually, within the TT lumen.[4–7] Blind tracheal suctioning, the current standard of care for the removal of secretions in patients with artificial airways, is suboptimal and clears only those secretions that are in immediate contact with the suctioning catheter ports.[8,9] Thus, a variably thick layer of mucus often covers the inner plastic surface of the TT lumen, where bacteria find an ideal environment to grow, out of reach of both the

What We Already Know about This Topic

- Tracheal tube increases resistance to airflow
- Tracheal intubation compromises mucus clearance leading to accumulation of secretions inside the tracheal tube leading to obstruction

What This Article Tells Us That Is New

- High-resolution computed tomography scan accurately determines reduction of cross-sectional area due to mucus accumulation
- The partial occlusion is common even in the absence of clinical signs while it significantly increases airway resistance
- The partial occlusion is often overlooked by the standard computed tomography scan

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immune system and systemic antimicrobials.[10,11] The pathogenesis of ventilator-associated pneumonia has been closely related to the presence of the TT itself.[12]

The reduction of the effective cross-sectional area (CSA) of the TT available for ventilation causes an increase in the resistance to airflow that results in higher ventilatory pressures and greater work of breathing.[13–15] The resistance to airflow attributable to the TT is inversely proportional to the fifth power of the radius, as shown by the Balsius equation.[16] Accordingly, an internal diameter reduction of 50% causes a 32-fold increase in airflow resistance compared to an unused TT of the same size.[17] The increased narrowing of the TT lumen by accumulation of secretions can lead to complete occlusion, a life-threatening event that can occur abruptly requiring emergency intervention in an already critically ill patient.[18] However, there is no effective clinically implemented tool to determine a reliable estimate of the TT CSA.[15,19]

In preliminary observations, we showed that computed tomography (CT) can demonstrate secretions adhering to the TT inner lumen.[20] We hypothesized that high-resolution computed tomography (HRCT) could accurately quantify the amount of secretions collected inside the TT and depict both their distribution and the degree of luminal narrowing.

We report that partial TT occlusion is a common finding at HRCT imaging in critical care patients. The clinical relevance of our HRCT findings during intubation is supported by the correlation between different degrees of TT occlusion measured with HRCT and the increase in resistance to airflow. Large deposits of mucus may be also visualized by chest CT scans of intubated and mechanically ventilated patients.

We, therefore, propose the use of HRCT as a new technique to evaluate TT patency and deduce the adverse consequences of the TT narrowing on respiratory mechanics in intubated patients.

Materials and Methods

A three-phase study was designed in order to validate the use of HRCT in the assessment of TT occlusion:

1. In the first set of experiments, we collected at extubation and scanned 20 used TTs with HRCT to quantify the mucus attached to the internal surface of the TTs and determine the minimum CSA in a mixed population of critically ill patients. New, size-matched TTs were scanned with HRCT and used as controls. After scanning the used TTs, we retrieved and cultured secretions and biofilm to describe the prevalence of TT colonization in our critically ill patients.
2. The second set of experiments was performed in our respiratory care laboratories. We built a bench silicone model to reproduce anticipated physiologic modifications in airflow resistance to different degrees of TT luminal occlusion. This allowed us to evaluate the clinical implications of HRCT findings on work of breathing.
3. CT scans performed in 20 patients intubated for more than 48 h were reviewed to determine whether standard, clinically available chest CT scan can demonstrate TT occlusion due to secretions during mechanical ventilation.

For clarity, we decided to call throughout the article "HRCT" the scan obtained in the postextubation laboratory setting (high radiation dose, and ultrathin 110-μm slice thickness), and "chest CT" the scan clinically obtained in mechanically ventilated patients (low radiation dose, 1.25-mm slice thickness).

HRCT of Used and New TTs: Patient Enrollment, HRCT Settings, TT Luminal Volume, and Minimum CSA Computation

Study Design and Setting. The first part of the study was conducted in the intensive care units (ICUs) of the Massachusetts General Hospital (Boston, MA). The Partners Healthcare Institutional Review Board approved the protocol and granted exemption of informed consent due to the collection of otherwise discarded material and absence of changes in the standard of care of the ICU patients. All adult patients requiring mechanical ventilation for more than 48 h were eligible, regardless of the etiology of the respiratory failure. Patients were enrolled if one of the study investigators was at the bedside at the moment of extubation. All patients received heated-wire humidification of the ventilatory circuit at approximately 35° to 37°C. According to institutional regular practice, the removal of airway secretions was performed through standard closed tracheal suctioning by the nurse or the respiratory therapist caring for the patient, as clinically indicated. Demographic and clinical data were recorded for all enrolled patients.

The control group (new TT group) consisted of three different unused TTs matched for internal diameter (ID) and brand to those collected in ICU patients (used TT group).

TT Collection. Immediately after extubation, the TT was sealed at both ends to prevent desiccation of secretions by exposure to ambient air. All TTs were cut at 24 cm from the lung end due to technical restrictions related to the size of the laboratory HRCT bed, primarily designed for imaging of small animals. A closed custom-made polyethylene box (Teknik, Ossona, Italy) was used to hold the tube straight and horizontal while perfectly fitting the HRCT bed. TTs were stored at 4°C until the moment of HRCT scanning. New TT group underwent exactly the same preparation and storage.

HRCT. TTs underwent HRCT scanning within 48 h after extubation. Scanning was performed by a Siemens Inveon system (Siemens Corporation, Washington, DC) with a 500 mA 80 kVp tube and 8.4 cm × 5.5 cm complementary metal–oxide–semiconductor detector. The images were

reconstructed using a modified Feldkamp cone beam algorithm (COBRA Exxim Computing Corp., Pleasanton, CA) into 110-μm isotropic voxels in a 512 × 512 × 768 matrix. Due to the length of the TT, each tube was scanned in three different segments. Three representative sections of each TT, for a total length of 13.2 cm out of the complete length of 24 cm were analyzed. The lung section started right after the Murphy's eye, at 1.6 cm from the lung tip of the TT, while the middle and the oral sections were spaced 3.3 cm from the lung section and from each other respectively. The personnel performing HRCT scanning and analysis were blind to the group to which the TTs were allocated. Distinction between the luminal space open to ventilation and secretions was based upon differences in density: air is characterized by a CT number of −1,000 Hounsfield units (HU), while secretions are essentially an aqueous compound with a density approximating 0 HU (fig. 1). HRCT images were analyzed with a combination of Amira (Berlin, Germany) and Matlab (Natick, MA) software. HRCT data were also used to reproduce a three-dimensional endoluminal "fly through" rendering of a used TT (Supplemental Digital Content 1, http://links.lww.com/ALN/B95), showing TT narrowing due to secretions. The TT air and mucus volumes were segmented by optimized region-based thresholding. The thresholding parameter was determined by maximizing mucus while minimizing the contamination from air and the tube itself through all 20 TTs after which the optimized parameter was applied to all TTs (HU −250 to 150). Visual inspection of HRCT images showed a similar pattern of mucus distribution in all used TTs. Secretions roughly formed a circular rim along the TT perimeter by adhering to the entire internal surface. Figure 1 shows the HRCT image of a used and a new TT. Subsequently, the CSA and volume of air and mucus were computed, based on knowledge of individual voxel volume and the number of voxels within each of the two HU groups (air or mucus). CSA and volume of air represent the actual area and volume available to airflow and was calculated for each CT slice of the three representative sections. The percentage of occlusion was calculated as the ratio between the effective CSA (or volume of air) measured in the used tubes and the same parameters obtained from controls of the corresponding nominal size. Due to negligible differences among TTs of different brands with the same theoretical ID, for the purpose of CSA and volumetric comparison, tubes from different manufacturers were pooled together and grouped by size only. Data from used tubes were acquired from a single HRCT scan, while paired control parameters were averaged from three separate scans of three different unused TTs for each different combination of size and brand. Volumes are reported in milliliters (ml) and correspond to the total amount of air and mucus inside the 13.2 cm of tube analyzed.

Silicone Model of TT Occlusion: In Vitro *Pressure Drop Measurement*

With the aim of establishing the physiologic significance of our HRCT findings, we evaluated *in vitro* the correlation between our imaging data and the resistance to airflow. Five ID 7.5 mm unused TTs were analyzed for resistance, measured as the pressure drop across the tube, and then imaged with HRCT. Four of them were modified in order to artificially achieve a progressive level of occlusion to airflow, while a fifth one was left intact as a negative control. The four models of occlusion were internally coated with different amounts of silicone to simulate secretions attached to the internal surface. Luminal patency was maintained through four steel bars of progressive caliber (238, 317, 476, and 635 mm; Small Parts Inc., Logansport, IN), left inside the tube overnight as a cast. The change in pressure to constant airflow across the TT was measured with a flow meter and pressure transducer connected to dedicated computed software (PTS-2000; Mallinckrodt, Inc., St. Louis, MO); the precise system description has been previously reported.[15] A customized plastic model was used to simulate the upper airway and maintain the tube in the correct position while measuring flow and pressure. Three increasing airflow rates were tested: 30, 50, and 70 l/min. Each sample TT was

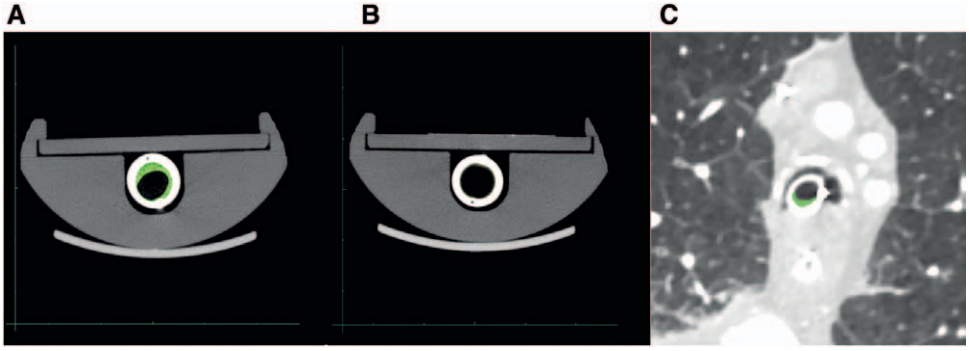

Fig. 1. High-resolution computed tomography (HRCT) and clinical chest computer tomography scan images: (*A*) HRCT of a tracheal tube (TT) recently removed from a patient showing a reduction of TT internal cross sectional area due to mucus collection (in *green*); (*B*) HRCT of a new TT; (*C*) clinical chest computer tomography image performed on an intubated and mechanically ventilated patient: secretions (in *green*) layer dependently within the TT lumen.

tested for resistance recording the average value of a 1-min pressure tracing. The test was repeated 3 times at each airflow rate. Average pressure changes resulting from the three repeated 1-min measurements are reported for each TT at every airflow rate.

Clinical Chest CT Scans: Retrospective Analysis and CSA Computation

In the last part of the study, we retrospectively reviewed 20 chest CT scans performed for clinical purposes to determine whether standard, clinically available chest CT can detect TT occlusion due to secretions during mechanical ventilation. The Partners Healthcare Institutional Review Board approved review of these chest CT examinations and granted exemption of informed consent due to the retrospective observational nature of the study. The last 20 CT scans performed over a period of 12 months in patients intubated for more than 48 h and recorded with a resolution of 1.25 mm were visually reviewed by a thoracic radiologist (J.A.) and two anesthesiologists (C.M. and L.B.). Radiological imaging was performed using standard parameters at our institution: a narrow collimation of 1.25 mm, rotation time 0.5 to 0.7 s, table speed 40 to 55 s, tube voltage 100 to 140 kV, and tube current dose 137 to 343 mA. If secretions were visualized inside the TT using the lung *versus* soft tissue window, the most occluded slice was selected for CSA computations. Total CSA was calculated by manually outlining the internal border of the TT with the "region of interest polygonal" tool (AGFA PACS; Afga-Gevaert, Mortsel, Belgium). The same procedure was repeated excluding the adherent mucus from the manual outline of the lumen in order to measure the CSA available for ventilation. CSA reduction was calculated as the difference between total endoluminal CSA and the CSA available for ventilation (upon exclusion of secretions). Anteroposterior and transverse diameters were measured and the difference between the total ID and the distance free of secretions was calculated.

Microbiology: TT Colonization

At the end of HRCT scanning, used TTs were cultured microbiologically to quantify the presence of potential airway pathogens. The detachment of the secretions from the inner surface was achieved by sonication for 90 s in an ultrasonic bath at about 36°C and vortexing for 30 s. The samples were flash frozen in liquid nitrogen, transported to the microbiology laboratory (Center for Clinical and Translational Metagenomics, Brigham and Women's Hospital, Boston, MA) and processed. Upon arrival at the microbiology laboratory the frozen samples were allowed to thaw at room temperature and each sample was vortexed for several minutes. Serial 10-fold dilutions of the sample were made in phosphate buffered saline to achieve dilutions ranging from 10^{-1} to 10^{-5}. A 0.1 ml aliquot of each dilution was plated onto enrichment or selective agar media and the aliquot spread over the surface of the medium. The media used included Tryptic Soy base with 5% sheep blood agar, Chocolate agar, MacConkey's agar, and Sabouraud Dextose agar (BBL; Becton Dickinson and Company, Sparks, MD). The agar plates were incubated in a 5% CO_2 atmosphere at 37°C for 48 h before enumeration. All quantitative counts were recorded as colony-forming unit per milliliter of sample. Following incubation colonies were enumerated on the various media and individual colony types selected for identification based on Gram stain and colony morphology. Identification of isolates was performed using standard microbiological methods and biochemical panels including the API 20E system for Gram-negative enteric species (BioMerieux, Inc., Durham, NC), the RapID NF Plus System (Remel Inc., Norcross, GA) for nonfermentative Gram-negative species, routine microbiological methods for *Staphylococci*, *Streptococci*, and other Gram-positive species, with identifications using long-chain fatty acid analysis on the Microbial Identification System (MIDI Inc., Newark, DE), and the API 20 C AUX system (BioMerieux, Inc., Durham, NC) for yeasts.

Statistical Analysis

Based on previous observational studies in literature evaluating TT occlusion with different techniques, we decided to enroll 20 patients.[17,21] Continuous variables were analyzed using the unpaired Student *t* test. ANOVA was used to test differences between different ID sizes. *Post hoc* Bonferroni correction was used for multiple comparisons. The least-squares regression method was used to determine correlation between variables. A *P* value less than 0.05 (two-tailed test) was considered statistically significant. Data are reported as mean and SD or median and interquartile range. Statistical analysis was performed with STATA software version 12 (StataCorp LP, College Station, TX).

Results

HRCT Can Precisely Quantify Luminal Air Volume and CSA Reduction in Used TTs

In 2 months, from November to December 2012, we collected 20 consecutive TTs (used TT group). Tubes collected were size 7.0, 7.5, or 8.0 mm ID (n = 3, 12, and 5, respectively); 15 TTs were standard polyvinyl chloride tubes, three were equipped with subglottic secretion suctioning, while two were coated with bactericidal coatings (silver-based coating). All patients were orotracheally intubated. Twenty-four new TTs were used as controls (new TT group). Table 1 shows the characteristics of patients enrolled in the study. Median length of mechanical ventilation was 4.5 days (interquartile range 2.5 to 6.5), ranging from 2 to 19 days.

High-resolution computed tomography scan analysis showed an average reduction of 8.2 ± 7.1% of total luminal air volume across all used TTs (P = 0.01 *vs.* new TTs group), ranging from 0.0 to 23.7%. The mean percentage of occlusion was 5.8 ± 4.4% (range 2.3 to 10.6%) for

ID 7.0 mm TTs, 8.3 ± 7.3% (range 0.0 to 23.3%) for ID 7.5 mm ones, and 9.2 ± 9.0% (range 1.6 to 23.7%) for TTs with ID 8.0 mm, differences not statistically significant. The grade of occlusion was weakly correlated with the length of intubation (R^2 = 0.352, P = 0.006; fig. 2). Table 2 shows the volume of air in used and new TT groups according to ID size. The total volume of air in used TTs was reduced in comparison to new TTs for all studied ID (P < 0.001 for each ID *vs.* others).

Separate analysis of the three sections showed that mucus accumulation was not uniformly distributed along the whole TT length. Figure 3 represents the distribution slice by slice of the CSA reduction in used TTs. The reduction in CSA followed an increasing pattern from the oral to the lung end with an indented border in each section. TT sections showed a progressive increase in mean obstruction going from oral to lung end (oral section 4.7 ± 5.5%, middle section 7.8 ± 8.0%, and lung section 12.6 ± 14.4%; P = 0.031 for oral *vs.* lung section) as shown in figure 4.

The minimum effective CSA was also identified for each tube and paired with data obtained from same-size controls. Overall, extubated TTs showed a minimum CSA 24.9 ± 3.9% lower than controls. CSA reduction was statistically significant compared to new TTs for all ID sizes (ID 7.0 mm, 16.4 ± 11.0%, range 6.8 to 28.4%, P = 0.022; ID 7.5 mm, 27.6 ± 18.8%, range 3.3 to 71.2%, P = 0.001; ID 8.0 mm, 23.5 ± 17.9%, range 9.1 to 52.6%, P = 0.038). Table 3 reports the minimum diameter of used TT group divided according to ID size and sections. Mean ID of used TT group was lower than the new TT group for all studied ID sizes: 6.74 ± 0.24 mm for ID 7.0 mm (P = 0.026), 7.10 ± 0.52 for ID 7.5 mm (P = 0.007), and 7.63 ± 0.43 for ID 8.0 mm (P = 0.038). In five cases the mean ID of the used TT group was more that two sizes lower than the new TT group.

Table 1. Characteristics of Patients Enrolled in the First Set of Experiments (HRCT Postextubation Study)

	n = 20
Sex (No.)	15 males (75%)
Age (yr)	68.4 ± 13.8
BMI (kg/m^2)	25.6 ± 5.6
Days intubation	4.5 (2.5–6.5)
Diagnosis (No.)	
Primary respiratory failure	8 (40%)
Septic shock	2 (10%)
Trauma	3 (15%)
CNS—stroke or TBI	5 (25%)
Cardiac failure	1 (5%)
Renal failure	1 (5%)
ICU outcome (No.)	
Alive	16 (80%)

Data are presented as count (%), mean ± SD, or median (interquartile range), as appropriate.

BMI = body mass index; CNS = central nervous system; HRCT = high-resolution computer tomography; ICU = intensive care unit; TBI = traumatic brain injury.

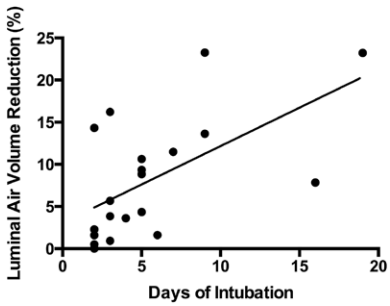

Fig. 2. Correlation between days of intubation and luminal air volume reduction. R^2 = 0.352; y = 3.1–0.91x; P = 0.006.

Silicone Model of TT Occlusion: The Increase in Resistance to Airflow Tightly Correlates with the Degree of TT Occlusion

Pressure drop was nonlinearly related to increasing airflow rates in all analyzed TTs. Moreover, at every step of set airflow (30, 50, and 70 l/min), simulated-occluded TTs showed a progressively increased resistance as expected with increasing levels of artificial obstruction (fig. 5), thereby confirming the reliability of the model (table 4). Analyzed with HRCT, silicon-filled TTs showed a reduction in air volume ranging from 8.9 to 46.5% compared with new TTs of the same ID size. The relationship between pressure drop and increasing airflow rates was nonlinear and depended on TT obstruction. Minimum CSA available to ventilation (fig. 5), the volume of air inside the TTs and the percentage of air reduction described similar nonlinear relationship between pressure drop and increasing steady airflow rates.

Clinical Chest CT Scan: Partial TT Occlusion Can Be Visualized on Images of Intubated Patients

Twenty chest CT scans, performed during a 12-month period throughout Massachusetts General Hospital ICUs, were reviewed. Only the intrathoracic part of TT was reviewed (neck and oral cavity were not included in the field-of-view of the chest CTs). Reasons for intubation were: septic shock (six patients), primary respiratory failure (five cases), neurological failure (four patients), end-stage liver disease (three patients), and other diagnoses (two cases). Secretions were visually detectable inside six TTs (30%). The 14 remaining TT lumens appeared clear. The average CSA reduction in the six TTs was 24.0 ± 3.9%, with an absolute reduction of 1.5 ± 0.4 mm in the anteroposterior diameter (fig. 1). The transverse diameter was less affected with an average reduction of 0.5 ± 0.6 mm. Mean total exam dose length product was 344 ± 102 mGy/cm and CT dose index of 10 ± 4 mGy.

Microbiology: TT Colonization

Silver-coated TTs showed no bacterial or fungal growth (2 tubes of 2, 0%), whereas 17 out 18 noncoated TTs were colonized by microorganisms (94%). The most represented species was *Candida albicans* in 61% of noncoated TTs. In decreasing order, the other pathogens identified were:

Table 2. Internal Lumen Volume of Air (ml) in Used and New TT Groups According to ID Size

	ID 7.0 mm			ID 7.5 mm			ID 8.0 mm		
	Used TTs (n = 3)	New TTs (n = 6)	*P* Value	Used TTs (n = 12)	New TTs (n = 9)	*P* Value	Used TTs (n = 5)	New TTs (n = 9)	*P* Value
Mean ± SD	4.73 ± 0.22	5.01 ± 0.10	0.025	5.27 ± 0.42	5.74 ± 0.13	0.004	6.06 ± 0.60	6.67 ± 0.40	0.040
Range (min–max)	4.48–4.90	4.86–5.16		4.41–5.75	5.55–5.95		5.12–6.57	6.32–7.57	

Data are presented as mean ± SD and range.
ID = internal diameter; TT = tracheal tube.

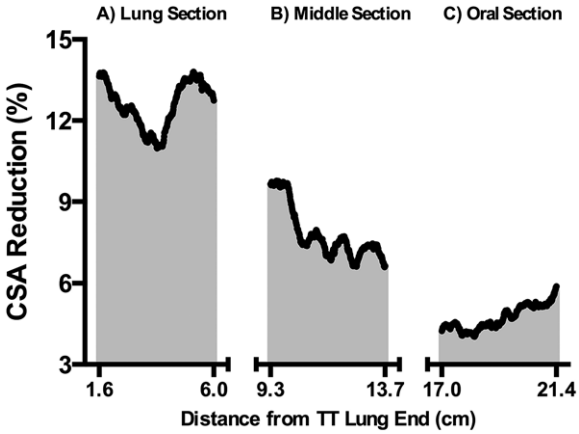

Fig. 3. Distribution of cross sectional area (CSA) reduction of used tracheal tube (TT) group along the tube length. Average CSA reduction for each slice of all used TTs is reported for each high-resolution computed tomography scan slice of the three TT sections: (*A*) lung end, (*B*) middle section, and (*C*) oral end of the TT. SD is not shown in the graph for clarity.

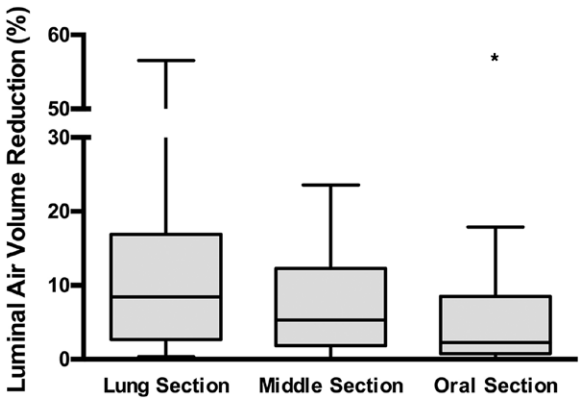

Fig. 4. Luminal air volume reduction in individual sections of used tracheal tube group. **P* = 0.03 *versus* oral *versus* lung section. *P* value refers to one-way ANOVA with *post hoc* Bonferroni adjustment for multiple comparisons.

Staphylococcus aureus (16%), *Enterobacter* sp. (11%), *Klebsiella* sp. (6%), and *Pseudomonas aeruginosa* (6%). Species indicative of oral flora or skin contamination (*i.e.*, *Viridans streptococci*, *lactobacilli*, *coagulase-negative staphylococci*, *corynebacterium* sp.) colonized 14 TTs out of 18 (78% of the samples). In eight cases (44% of TTs) multiple bacterial species colonized the same TT (table 5). In this small sample of TTs, we observed no significant correlations between microbiological and volumetric findings.

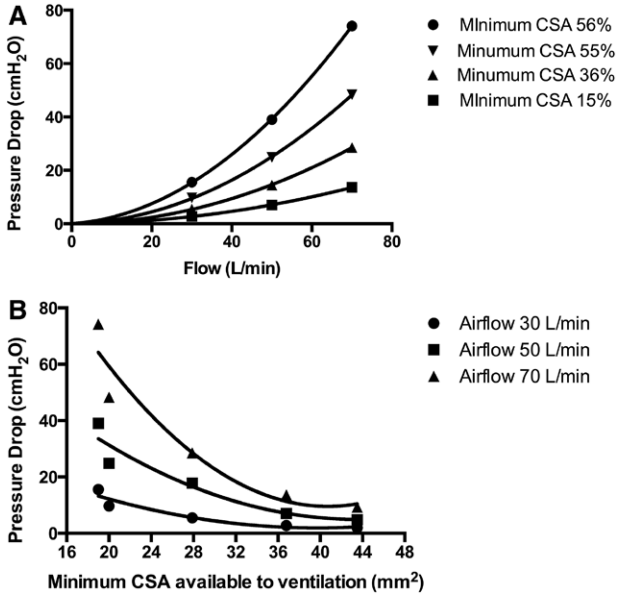

Fig. 5. (*A*) Pressure drop-flow curves in the tracheal tube *in vitro* experiments. Resistive curves of increasingly obstructed tracheal tubes were performed under condition of constant airflow. Minimum cross sectional area (CSA) is the percentage of CSA reduction compared with a never used tracheal tube of the same size; (*B*) nonlinear relationship between minimum CSA and the pressure drop to increasing airflow rates.

Discussion

In this study, we investigated the value of HRCT as a novel method to accurately determine TT occlusion of critically ill patients ventilated for more than 48 h (Supplemental Digital Content 1, http://links.lww.com/ALN/B95: three-dimensional endoluminal "fly through" rendering of a used TT).

We observed that partial TT occlusion is a common finding even in the absence of clinical signs suggesting a reduction in TT luminal patency. At extubation, we measured on average a 25% reduction of the narrowest CSA compared to the same-size control TT. We found a similar reduction of CSA in selected TT of patients on the ventilator. In an *in vitro* simulation, we described the nonlinear relationship between ID reduction and airway resistance (fig. 5).

The accumulation of secretions inside the TT is an important phenomenon for two primary reasons: (1) debris

Table 3. Minimum Diameter (mm) of Used TT Group Divided According to ID Size and Section

		Used TTs		
		7.0 (n = 3)	7.5 (n = 12)	8.0 (n = 5)
Lung section	Mean ± SD	6.37 ± 0.46	6.39 ± 0.95	6.97 ± 0.87
	Range (min–max)	5.88–6.78	3.99–7.35	5.52–7.64
Middle section	Mean ± SD	6.41 ± 0.31	6.88 ± 0.51	7.50 ± 0.56
	Range (min–max)	6.10–6.71	5.88–7.48	6.63–7.93
Oral section	Mean ± SD	6.80 ± 0.05	7.12 ± 029	7.57 ± 0.33
	Range (min–max)	6.78–6.86	6.45–7.46	7.17–7.98

Data are presented as mean ± SD and range.
ID = internal diameter; TT = tracheal tube.

Table 4. Airflow and Pressure Drop Recorded for the *In Vitro* Model for Different Grades of TT Occlusion

Occlusion, %	Airflow (l/min)	Pressure drop (cm H_2O)
0	30.17 ± 0.07	1.96 ± 0.06
	50.19 ± 0.14	4.84 ± 0.11
	70.16 ± 0.28	9.31 ± 0.20
8.9	30.12 ± 0.08	2.78 ± 0.08
	50.05 ± 0.09	7.01 ± 0.12
	70.33 ± 0.25	13.63 ± 0.53
25.2	30.15 ± 0.09	5.49 ± 0.10
	50.19 ± 0.11	17.82 ± 0.19
	70.27 ± 0.25	28.54 ± 0.59
42.4	30.15 ± 0.08	9.68 ± 0.09
	50.06 ± 0.12	24.87 ± 0.37
	70.10 ± 0.32	48.32 ± 0.54
46.5	30.12 ± 0.07	15.56 ± 0.12
	50.17 ± 0.13	39.05 ± 0.20
	70.28 ± 0.23	74.20 ± 0.67

All data are presented as mean ± SD. Occlusion is the percentage of luminal air reduction; airflow reported is the measured value at level of the flowmeter.
TT = tracheal tube.

attached to the internal surface causes a reduction of the TT effective diameter, leading to an increase in dynamic resistance to airflow;[13–15] and (2) the layer of mucus quickly becomes colonized by microorganisms that organize into a complex biofilm, serving as a reservoir for pathogens that may spread to the lung and cause pneumonia.[10,11]

TT narrowing affects gas flow dynamics leading to an increase of resistance to airflow and work of breathing. Indeed, for flow rates commonly used in adult mechanically ventilated patients, gas flows thru the TT in a turbulent manner.[22] The relationship linking the TT radius and the pressure drop across the tube is described by the Blasius equation[14,17,21]:

$$\Delta P = V^2 dfL / (\pi^2 r^5)$$

where ΔP is the change in pressure across the TT, V is flow, d is the density of the gas, f is a constant, L is the length of the tube, and r is the radius. Based on Blasius equation, a reduction in the CSA available to ventilation would considerably increase the workload imposed on patients spontaneously breathing through a TT. Bock *et al.*[17] proposed a method to estimate the influence of reductions in CSA on the pressure drop and resistance to TT airflow. In this model, TT-related resistance and pressure drop will increase by a multiplier equal to the fifth power of the ratio between the radius of a new TT (TTr) and the actual TT radius (TTa): (TTr/TTa)[5]. In our population, the mean reduction in CSA was 25%, which leads to a 4.2 times increase in airflow resistance; on the extreme, a patient with a reduction of 71.2% in TT CSA experiences a 504-fold increase in resistance and pressure drop across the TT. This computation highlights the potential effects of TT obstruction on patient's work of breathing during spontaneous or patient triggered ventilation. The only factor that may be preventing successful weaning from ventilatory support is the reduced lumen of the TT and the associated increase in the working of breathing. Indeed, in 5 of the 20 TTs we examined the collection of mucus was sufficient to reduce the functional mean ID of the TT more than two ID sizes.

We found only a weak correlation between level of TT occlusion and the time of mechanical ventilation. Data in the literature are conflicting and our study was not properly powered to identify such an association.[7,15,19] However, as a common observation for any healthcare provider working in the ICU, the TT acts as a foreign body inserted in the airways, damaging the tracheal mucosa, increasing mucus production over time, while hindering clearance. Other factors might increase production and/or worsening clearance of secretions such as, chronic obstructive pulmonary disease, cystic fibrosis, and pneumonia.

The build-up of secretions on the TT internal surface has been a well-known phenomenon for at least 40 yr, but its clinical significance has been constantly underestimated. All patients enrolled in this study (*in vivo* and postextubation settings) received current standard of care for intubated patients: closed-system blind tracheal suctioning was performed as per clinical indication and heated wire circuit humidification was used in all cases.[8] Intraluminal volume loss attributable to the accumulation of secretions on the inner wall of TTs is not prevented by standard suctioning and/or humidification.[7,19,21,23] Previous studies found similar TT intraluminal volume loss using different techniques,

Table 5. Microorganisms Isolated from Used TTs Group

TT	DOI (days)	*Candida albicans*	Other Fungi	Oral Flora*	*Staphylococcus aureus*	*Pseudomonas aeruginosa*	*Klebsiella* Spp.	*Enterobacter* Spp.
1	4	7.2×10^{3}						
2	2	1.0×10^{5}	1.0×10^{4}					5.0×10^{1}
3	19	8.9×10^{1}		8.7×10^{5}				
4	2			7.4×10^{5}		3.5×10^{4}		
5†	3							
6	3			1.0×10^{1}				
7†	3							
8	5			6.9×10^{4}				
9	3	7.9×10^{3}		5.4×10^{4}				
10	9							
11	2			3.4×10^{2}			2.0×10^{1}	
12	7	2.0×10^{1}		5.0×10	4.0×10^{1}			
13	6			4.0×10^{4}	4.0×10^{6}			
14	5	5.5×10^{2}	30×10^{2}	3.6×10^{3}				
15	2	1.4×10^{3}		1.1×10^{4}				
16	9			9.8×10^{3}				1.0×10^{1}
17	2	2.5×10^{2}						
18	16	1.0×10^{2}		3.0×10^{1}				
19	5	6.5×10^{4}		1.5×10^{5}				
20	5	1.1×10^{4}	5.0×10^{2}	4.0×10^{3}	4.0×10^{2}			

* Oral flora includes: *Streptococci*, *Lactobacilli*, *Staphylococci*, and *Corynebacterium*. † Silver-coated TTs.
DOI = days of intubation; TT = tracheal tube.

such as acoustic reflectometry.[7,19,21,23] In line with these findings, in our cohort of patients, tracheal suctioning was not able to fully remove secretions attached on the TT surface. This vicious process of secretion accumulation can potentially lead to life-threatening occlusion of the TT. Different dedicated medical devices have specifically been designed to retrieve secretions by physically removing them from the inner walls of the TT.[12] The Mucus Shaver was the first TT cleaning device to be developed and tested in animal and clinical studies.[24–26] Although not commercially available, it might be helpful in preventing TT colonization by potentially harmful microorganisms.[25,26] The Rescue Cath (Omneotech, Tavernier, FL) is a similar marketed device. So far it has only been reported as a rescue device used to relieve the adverse effects of acute TT mucus obstruction in three patients.[18,27] More recently, in a similar case-series, we reported the use of the endOclear (endOclear LLC, Petoskey, MI), with three patients in which the use of a TT cleaning device succeeded in restoring airway patency and preventing an emergent TT exchange maneuver.[28]

We propose the use of the HRCT scan as a method to visualize and quantify secretions inside TT. The CT scan measures the attenuation of radiation passing through matter. The difference in attenuation of plastic, air, and water on HRCT scan images enabled detection of the exact contour of secretions laying on the TT internal surface (fig. 1).[20] In order to validate our results and increase our understanding of their potential physiologic correlate, we tested the HRCT scan findings in an *in vitro* setting. The increase in pressure due to partial TT luminal occlusion depended on image-derived data. Thus, based on the imaging of an extubated TT, we could infer the impact of mucus accumulation on resistance and the work of breathing, and how any intervention aiming to prevent or treat this complication might benefit mechanically ventilated patients.

The findings of this study may benefit future studies testing the efficacy of preventive strategies to clear secretions from the TT. The Food and Drug Administration (Silver Spring, MD) and the International Organization for Standardization (Genève, Switzerland) recommend using "nominal inside diameter" for evaluation of TT.* HRCT allows the precise measurement of the actual TT ID and computation of even low grade of loss in patency altering airflow dynamics in ventilated patients.

Low radiation dose is mandatory to limit the risk of x-ray exposure to patients. This necessity limits the accuracy of the CT scanning in detection of TT occlusion *in vivo* (fig. 1). Only larger secretion deposits were visible on the clinical chest imaging that we analyzed. Clinical CT scan parameters entail a lower sharpness of the images compared to the laboratory setting, which may preclude the ability to detect smaller amount of secretions collected inside the TT. Moreover, only the intrathoracic part of the TT is generally imaged on chest CT (the distal third part of the TT). The oral/pharyngeal and laryngeal part of the TT are not included in the field-of-view of a standard chest CT.

* International Organization for Standardization: ISO 5361:2012. Avaliable at: http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=54561. Accessed July 20, 2014.

Sticky secretions attached to the TT inner surface contribute to the colonization of the TT itself. Studies have shown that a well-structured biofilm can quickly develop on the internal surface of the TT.[10,11,29] The role of TT biofilm as a potential source of respiratory pathogens has been pointed out by Gil-Perotin *et al.*[10] They found biofilm on the internal surface of 95% of the TTs they examined and in 50% of cases of ventilator-associated pneumonia the causative agent was present on the TT despite adequate antibiotic treatment.[10] The most common isolates in our samples were *Candida albicans*, *Staphylococcus aureus*, and normal oral flora consisting of predominantly Gram-positive species. Surprisingly, Gram-negative species were less represented in our comparison than expected. A possible explanation of this mismatch is that the flash freezing of the samples may have damaged the cell wall of bacteria to a varying extent depending on a given organism's susceptibility to thermal shock.

In conclusion, we found a significant TT CSA reduction of almost 25% at the time of extubation. A similar grade of TT occlusion can be visualized during mechanical ventilation (while the patient is intubated) using clinical standard CT scan. HRCT imaging data were directly related to an increase in pressure required to maintain flow, identifying the influence of partial TT luminal occlusion on the work of breathing. Even mild levels of TT obstruction may have clinical impact in terms of the work of breathing and bacterial colonization of the airways. The impact of retained secretions within the TT lumen is of greater clinical importance than often recognized. Development of safe and reliable means of more thoroughly evacuating the TT of secretions would be of substantial value to patient care.

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Competing Interests

The authors declare no competing interests.

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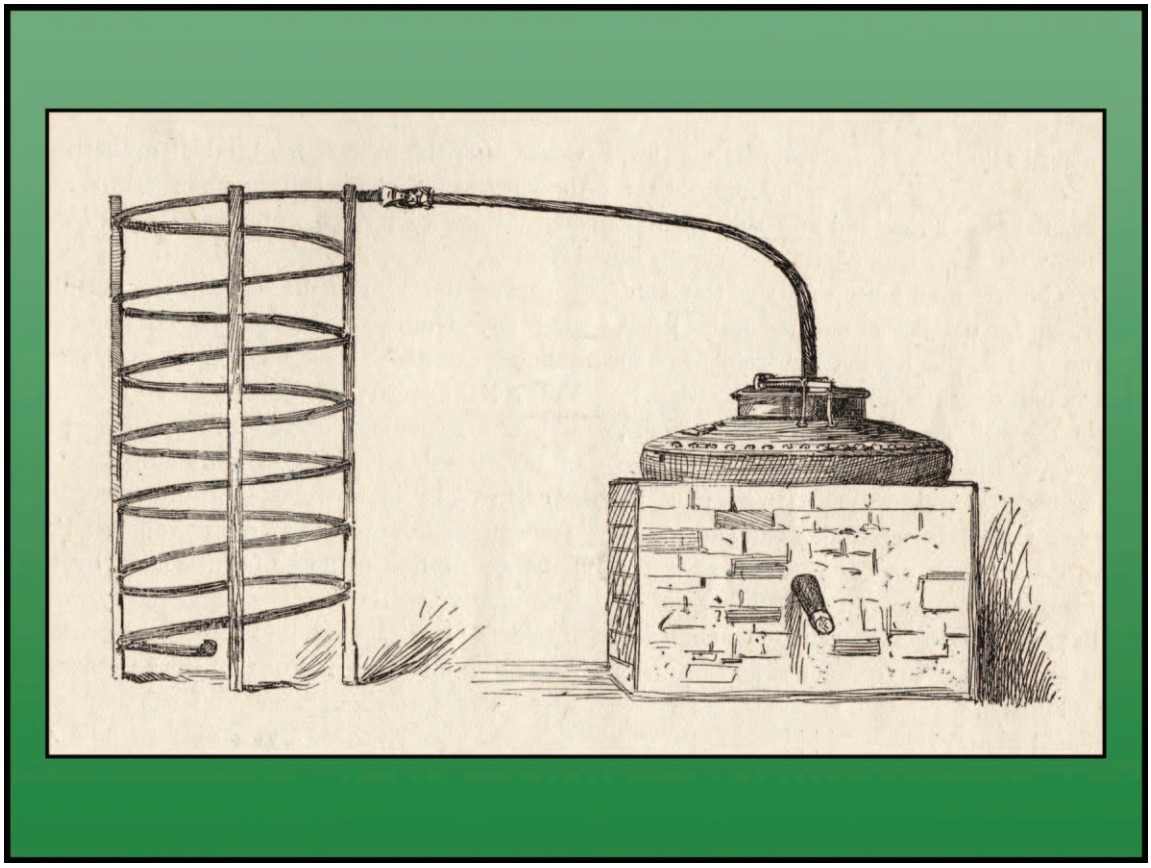
The Chloroform Still of Dr. Samuel Guthrie, Jr.



As early as July of 1831, New York physician Samuel Guthrie, Jr., had submitted for publication his method of generating "sweet whisky" or "chloric ether" (chloroform in alcohol): "Into a clean copper still [*above*] put … chloride of lime and … alcohol … and distill ... and when the product ceases to come highly sweet and aromatic remove and cork it up closely in glass vessels." Inside a retort in a water bath, redistill that product in an excess of chloride of lime to concentrate the product as "caustic and intensely sweet and aromatic." Further concentration results from distilling the "solution of chloric ether from carbonate of potash." And that is how a primitive still helped an eccentric American physician discover chloroform independently from the better-equipped laboratories of France's Soubeiran and Germany's Liebig! (Copyright © the American Society of Anesthesiologists, Inc.)

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