An *in vitro* technique to measure resistance to compression and kinking of endotracheal tubes

ABSTRACT

Background: During intraoperative care, ventilatory parameters including peak inflating pressure (PIP) and exhaled tidal volumes are continuously monitored to assess changes in respiratory resistance and compliance. Changes in these parameters, such as an increase in PIP or a decrease in the exhaled tidal volume, may indicate various pathologic processes that may require immediate attention to prevent inadequate ventilation resulting in hypoxemia or hypercarbia. A kinked endotracheal tube (ETT) may mimic other pathologic processes including bronchospasm, mainstem intubation, or ventilator malfunction. As newer ETTs are developed, a key factor in their design should be resistance to kinking or occlusion due to patient positioning.

Methods: The current project developed and describes the process for using a repeatable *in vitro* mechanical test to determine resistance to kinking by an ETT.

Results: The mechanical testing procedure can be used to determine the compression force and distance required to kink an ETT under different conditions including temperature. The force required to induce devastating kink failure was lower during heated testing conditions. The addition of airflow through the ETTs during compression testing confirms the occurrence of airway obstruction at approximately the same time a mechanical kink is observed on the force-versus-distance curves.

Conclusions: These procedures may be used to characterize and evaluate ETT designs under *in vitro* conditions mimicking those in the clinical practice.

Key words: Airway obstruction, compression force, endotracheal tube, kinking, peak inflating pressure

Introduction

Airway management and control during intraoperative anesthetic care may include an anesthesia mask, supraglottic airway or an endotracheal tube (ETT).[1] Difficulties with bag-valve-mask ventilation, direct laryngoscopy, and placement of an ETT have received significant attention in the literature, resulting in the development and publication of guidelines for dealing with clinical scenarios during which bag-valve-mask ventilation or endotracheal intubation is problematic or impossible.[2,3] However, less attention has been directed to problems arising following

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DOI: 10.4103/sja.sja_15_24	

How to cite this article: Young E, Nocera TM, Reilly M, Tobias JD, D'Mello A. An *in vitro* technique to measure resistance to compression and kinking of endotracheal tubes. Saudi J Anaesth 2024;18:331-7.

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Submitted: 10-Jan-2024, **Accepted:** 13-Jan-2024, **Published:** 04-Jun-2024

placement of the ETT during intraoperative anesthetic care.

During intraoperative care, peak inflating pressure (PIP) and exhaled tidal volumes are continuously monitored to assess changes in respiratory resistance and compliance.[4] Changes in these parameters, such as an increase in PIP or a decrease in the exhaled tidal volume, may indicate various pathologic processes including malfunction of the anesthesia machine/ventilator, upper airway obstruction, mucus plugging, bronchospasm, obstruction of the ETT, bronchial intubation, pulmonary edema, pneumothorax, aspiration, or pneumonia. Given the impact of these changes on oxygenation and ventilation and the potential for rapid patient deterioration, it is necessary to have a clinical algorithm to identify the etiology of such problems and guide therapeutic interventions.[5]

A kinked ETT may mimic other pathologic processes including bronchospasm, mainstem intubation, or ventilator malfunction. Data collected by the Australian Incident Monitoring System revealed that the majority of kinking in an ETT occurred outside the mouth and therefore was generally easy to identify.[6] Whereas intraoperative vigilance is needed for early recognition of such problems, it may also be helpful to identify the potential for such problems to occur. As there are numerous different manufacturers of ETTs in use, it may be that there are design and manufacturing variations which may impact the potential for kinking.

In this pilot study, we aimed to develop a repeatable mechanical testing procedure to determine the force and distance of compression required to kink an ETT under clinically relevant conditions. Given the potential impact of temperature on ETT's mechanical properties, we also sought to develop a model whereby the ambient temperature could be adjusted from room temperature (25°C) to simulated body temperature (36°C). Experimental results were then used to build computational models capable of simulating ETT's mechanical behavior under conditions which are difficult to experimentally replicate.

Methods

Endotracheal tube experimental set-up and kinking analysis: Buckling testing of a 4.0 mm ID ETT was conducted using a 100-series Modular Universal Test Frame with 1000 N load cell and 4-inch compression plates (TestResources, Inc.). The two cuffed ETT brands included Halyard Microcuff® Endotracheal Tubes (Halyard Health, Inc.) and Shiley™ Hi-Lo Oral/Nasal ETTs (Medtronic, Minneapolis, MN). Surgical tape was used to secure the ETT to the compression plates that were initially 60 mm apart [Figure 1]. The ETT was secured at approximately the 9 and 18 cm markings of both ETTs. This set-up was chosen as it provides optimal visualization of kinking and also resembled the clinical flex position of the ETT during specific neurosurgical and neck surgical procedures, in which we have observed clinically significant problems with intraoperative ETT kinking.[5] The ETTs were tested immediately after removal from sterile packaging. For each condition, three new ETTs of each brand were tested.

All compression testing of the ETTs was performed at a constant compression rate of 60 mm/min, and force, time, and displacement data were recorded (WinCom Plus Version 2.2.11, ADMET). Force and the first derivative of force-versus-displacement were plotted and a line of best fit was obtained using MATLAB (The MathWorks, Inc.). The point at which the first derivative of force was equal to zero was the experimentally determined point of ETT kinking. This was based on the logic that a decrease in force being applied to the ETT will be present when the ETT fails mechanically (i.e., kinks).

Fatigue testing: Compression testing was performed at room temperature (25°C) to determine whether a single ETT could be re-used for multiple experimental trials without experiencing signs of mechanical fatigue. Three ETTs of the two manufacturers were compressed three consecutive times, with a period of at least 30 minutes of rest between trials to allow regain of the original ETT shape. Force and the first derivative of force-versus-displacement data were plotted and analyzed for trial-dependent changes in the force needed to induce ETT kinking.

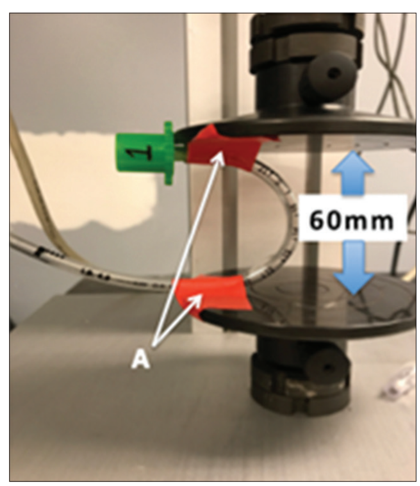

Figure 1: Experimental set-up of endotracheal tube testing using the test frame with an initial compression plate distance of 60 mm. A is the red surgical tape used to secure the ETT to the compression plates at approximately the 9 and 18 cm markings

Temperature testing: Three ETTs of each model were subjected to compression testing at simulated body temperature (36°C). This clinically relevant condition was created using a custom tenting set-up that encompassed the test frame in plastic sealed off with duct tape with a forced air warmer system (Bair Hugger Model 775, 3M Healthcare) as the heat supply [Figure 2]. Temperature was monitored using a manual glass thermometer. Force and the first derivative of force-versus-displacement data were plotted and compared to the first fatigue test trial of each ETT performed at room temperature (25°C), to determine whether temperature impacts the mechanical kinking of the ETTs.

Airflow testing: Airflow testing was coupled with compression testing to determine whether the kinking force identified in the force–distance analyses was indicative of airway obstruction. To achieve this, an anesthesia/ventilator device (DRE, Prima 460/AV-S) and mechanical lung (Respironics, 1.0L Test Lung) were connected to the ETTs during compression testing. Oxygen (O_2) was flowed through the ETT into the mechanical lung via the ventilator of the anesthesia machine. The experimental time point after the start of the compression test at which the tidal volume decreased by more than 15% of baseline was recorded via video. The recording was used to determine the time the ETT was spent being compressed. This in combination with a known compression rate was used to calculate the compression distance at which the obstructed airflow occurred.

The ventilator settings appropriate for a 10 kg patient using a 4.0 mm ID ETT were approximated as a tidal volume of 100 mL, rate of 20 breaths/minute, inspired to expired ratio of 1:2, positive-end expiratory pressure of 5 cm H_2O, and fresh gas flow rate (100% oxygen) at 2 L/min. The PIP was adjusted to achieve the desired tidal volume of 100 mL. Because a tidal volume of 100 mL was being used, the actual point of kinking was assumed to be and recorded when the tidal volume hit 80 mL (a 20% decrease from baseline). This was the first displayed value outside of the 10–15% tolerance of the machine. Additionally, to account for the time it took the anesthesia machine to flow air to and from the lung and register a decrease in airflow, the compression testing rate was reduced from 60 mm/min to 10 mm/min. This testing was conducted on three of each type of the ETTs at both room temperature (25°C) and the heated condition (36°C).

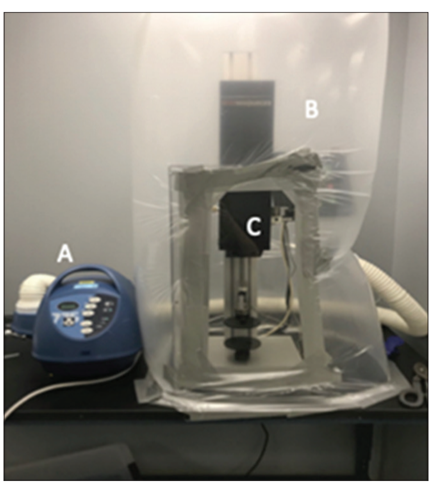

Figure 2: Tenting system used to obtain the heated clinical condition of 36°C to stimulate performance of the endotracheal tube at body temperature. A is the forced air warmer that is being used to heat the system, B is the plastic used to create the boundary of the testing system, and C is the test frame located in the heated environment of the tenting system

Modeling of ETT's mechanical behavior: COMSOL (Multiphysics 5.3a) was used to develop a computational model of the ETT that shows the stresses occurring from the compression of ETTs under the experimental compression conditions of this study. Dimensions of the ETT were determined from packaging labeling and additional caliper measurements. This included an inner ETT diameter of 4.0 mm and an outer diameter of 5.6 mm. The model started with the ETT in its natural, unstressed position. The program then moved the ETT into the slightly stressed C-curve position similar to the ETT placement at the beginning of the mechanical testing experiments described earlier. Platens modeled as rigid bodies were then used to compress the ETT model. The program generated stress images with color scales to display the stresses on the different parts of the ETT throughout the compression test.

Statistical Analysis: As this is a pilot study, the data were interpreted on both a qualitative nature and generally quantitative nature. In the future, after collecting additional trials, an analysis of variance (ANOVA) followed by Tukey's test should be conducted to determine any significant differences in loads or compression distances between the results of the different testing conditions and the different brands of ETTs.

Results

Using the above-mentioned design and set-up, compression testing conditions including fatigue were performed at two different temperatures for ETTs from two different manufacturers.

Fatigue testing: Fatigue testing was conducted on each ETT model to determine whether it would be viable to use one ETT device for multiple compression tests. Figure 3 shows the load (solid curves) and derivative of load (dashed curves) of a single Shiley ETT being subject to three compression trials (tests 1, 2, and 3). These data display a trend of decreasing kinking compression that was common among the majority of the ETTs tested. The first testing required the highest amount of load to cause kinking whereas the more it was tested, the lower the amount of force that was required to kink the ETT. For the specific ETT data shown in Figure 3, the load to kink started at approximately 4.5 N for the first test and decreased to approximately 2.6 N for the third test. In addition to the decrease in load required to kink, it was also observed that the compression distance necessary to kink the device also decreased. For this specific ETT, kinking started at a change in 38 mm of compression and decreased to approximately 31 mm of compression on the third trial. This consistent trend indicates a loss in mechanical integrity with repeated testing. Therefore, a new ETT should be used for each compression test.

Temperature Testing: As discussed previously, ETTs are constructed of the polymer, polyvinylchloride (PVC), and softened with a plasticizer, DEHP, to increase flexibility. Whereas some structural compliance is necessary for placement of the ETT into the patient's trachea, increased temperature as the ETT warms to body temperature (36–37°C) could further impact the mechanical integrity and increase the pliability of the PVC, leading to a further increased risk of kinking if there is a mechanical stress placed on the ETT. Therefore, additional testing was performed to determine a change in the mechanical performance of the ETT during an increase in temperature. Figure 4 shows the results of testing two Halyard Health ETTs at room temperature and two at the heated temperature condition of approximately 36°C. During room temperature conditions, these ETTs required between 5 N and 6 N of force before kinking was observed. At the higher temperature condition (36°C), the force required for kinking decreased to between 0.8 N and 1 N of force. A decrease in the amount of load required for ETT kinking to occur was noted at the higher temperature, regardless of the type of ETT tested. These results confirm that the mechanical integrity of the ETTs is more easily compromised at body temperature, increasing their ability to be more easily kinked. This agrees with the previous literature noting that as the temperature of the PVC increases, its mechanical properties are changed making it less rigid.[7]

Airflow Testing: The prior experiments were conducted as a way to develop a repeatable test to determine the point at which a kink in the ETT would occur. For the next step in validating that the developed experiment was finding the point of a kink or obstruction that might impact clinical care, we studied the flow of gases (O_2) through the ETTs while the compression test was occurring. The results gathered from the experimental testing of the two ETT models at room temperature and body temperature (36°C) conditions during the flow of gas through the ETT are summarized in Figure 5. The experimentally determined distance compressed when kinking occurred is generally slightly less than that of the calculated compression distance when obstruction was identified by the anesthesia machine ventilator by a decrease in tidal volume [Figure 5]. It was also observed that the PIP that the anesthesia machine was registering tended to increase before the tidal volume decreased below the tolerance threshold, indicating that deformation of the ETT was impacting the pressure of the system even before a change in tidal volume could be registered. Whereas the

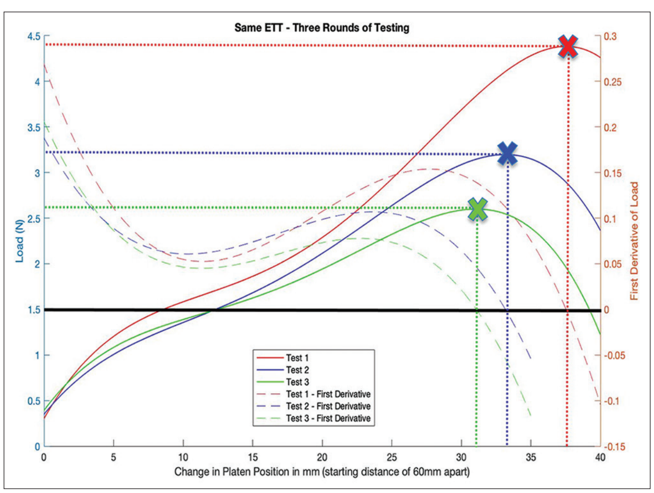

Figure 3: Plot of load and first derivative of load-versus-position of the same endotracheal tube during three consecutive compression tests. The X's represent the locations of kinking. Red X = test 1 kink at approximately 4.5 N of load; blue X = test 2 kink at 3.25 N of load; and green X = test 3 kink at approximately 2.6 N of load

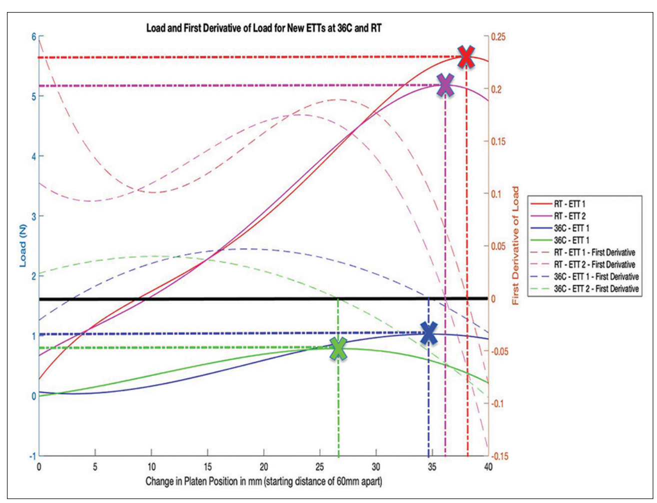

Figure 4: Load and the first derivative of load-versus-distance for two of the Halyard ETTs, tested at room temperature (RT) and at 36°C. The Xs represent the locations of kinking. Red X = RT ETT test 1 kink at 5.6 N; pink X = RT ETT test 2 kink at 5.2 N; blue X = 36°C ETT test 1 kink at 1 N; and green X = 36°C ETT test 2 kink at 0.8 N

values are not the same, the delay of the ventilator system in registering changes in tidal volume, which is based on the minute ventilation and the number of breaths per minute, may partially account for the delay. Additionally, the test frame has some tolerance in the compression rate from the established 10 mm/min. Overall, the developed experimental method is a reasonable test to predict kinking of the ETT [Figure 5].

COMSOL Modeling: COMSOL modeling was used to re-create the basic compression test conducted in the experiments on an ETT without attachment to the anesthesia circuit and the ventilator. The images show the stresses on the device under the basic testing conditions of compressing the tube via platens when they are set at a starting distance of 60 mm apart. There are initially very few stresses on the ETT when it is slightly bent from its natural position [Figure 6a]. Figure 6b shows that securing the ETT to the platens that are initially 60 mm apart to begin the compression testing already places some stresses on the ETT. So, in this modeling system, to get the most accurate results, the stresses from the initial set up need to be taken into consideration. The stresses present on the ETT after it has been compressed to 32 mm are given in Figure 7. The stresses were concentrated on the maximally bent potion of the ETT, the location of the approaching kink. The next produced image (at 34 mm) shows a devastated ETT, meaning that the compression distance of kinking theoretically occurs between 32 and 34 mm of compression. For the most part, these values are consistent with what was seen experimentally, a range of 31–37 mm when tested at room temperature, showing that this computational model serves as a good representation of the ETT.

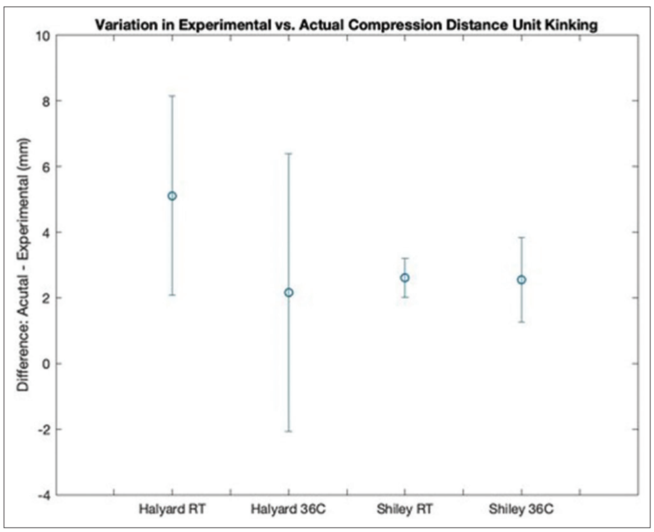

Figure 5: Plot of mean and standard deviation of differences between experimental and actual compression distances until kink obstructed airflow when plates were set up 60 mm apart

Within these models, it is possible to modify ETT properties if the composition is different than expected or if the dimensions change. Additionally, these models can be updated to include more clinically relevant factors that can contribute to kinking. Also, focus can be put onto the insertion site where the tube for cuff inflation inserts into the shaft of the ETT to see if this is a weak point in the design that leads to easier kinking.

Discussion

We have developed and report, for the first time, a novel mechanical means to study the *in vitro* performance of ETTs with the intention of identifying points of stress or weakness that may lead to ETT kinking during intraoperative care. This information, in combination with clinical performance,

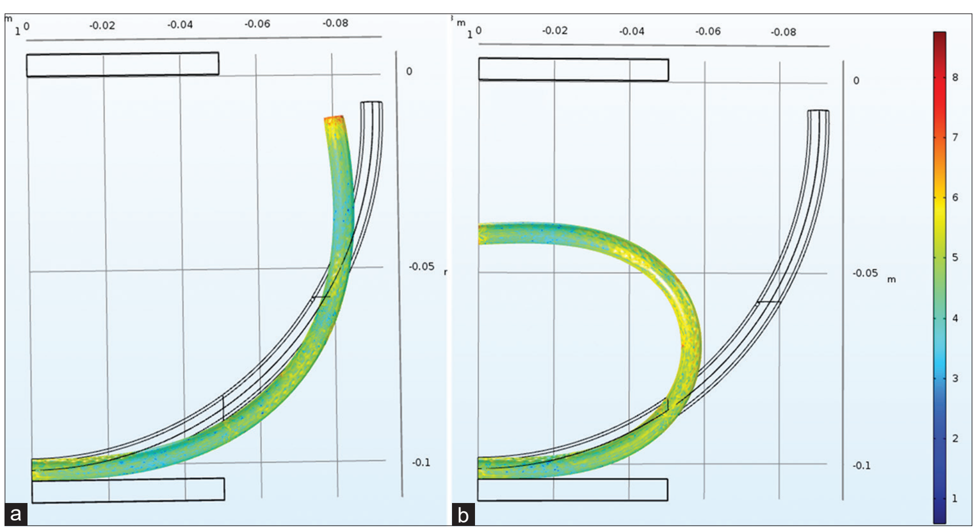

Figure 6: COMSOL modeling stress diagram on ETT without attachment to frame or anesthesia circuit and machine (a). Initial stresses present on ETT with initial loading into the testing position, positioned with plates separated by 60 mm (b)

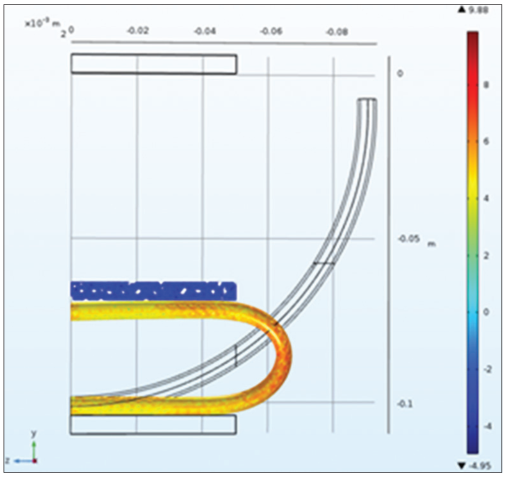

Figure 7: COMSOL modeling stress diagram of ETT at 32 mm of compression

may help guide ETT design to ensure safety during intraoperative care. In particular, these processes would allow a means of comparing the resistance to kinking and gas flow obstruction of ETTs from various manufacturers under various temperature conditions. Such evaluations may be useful as trends in clinical practice change as has occurred in the practice of pediatric anesthesia with the switch to cuffed ETTs and the transition from PVC cuffs to polyurethane cuffs.[8,9]

ETTs are manufactured from PVC softened with a plasticizer to make them more flexible for clinical use.[10] The plasticizer used for the Halyard and Shiley models of ETTs is di-(2-ethylhexyl)-phthalate (DEHP), also referred to as DOP. This is a phthalate ester that is one of the most widely used plasticizer in medical devices.[11]

Since the plasticizer plays a major role in changing the mechanical properties of the PVC, it is important to take into consideration the impact of this addition on the mechanical properties of the ETTs, like the Young's modulus. From research which was already conducted, it was determined that based on the fraction of DEHP in PVC, the modulus changed dramatically. Values of 74.8, 9.0, and 7.7 MPa for Young's modulus were found for PVC fractions of 0.63, 0.50, and 0.38, respectively.[12,13] Based on the assumption that most PVC medical devices are made from approximately 40% DEHP plasticizer, the Young's modulus of the ETTs in this experiment is approximated to be 44.3 MPa. Additionally, temperature is a concern when using clinical devices constructed of polymers such as PVC. Polymers like PVC become more flexible and potentially lose some mechanical integrity as the temperature increases. Increasing temperature softens the PVC in ETTs.[13] In our preliminary study, increasing temperature significantly altered the performance parameters of the ETTs, making them less resistant to kinking.

Difficulties with direct laryngoscopy and placement of an ETT have received significant attention in the literature with the development of guidelines for the management of clinical scenarios during which bag-valve-mask ventilation or endotracheal intubation is problematic.[2,3] However, there has been less focus on problems that may arise during intraoperative care following ETT placement such as tube kinking.[4,6] A kinked ETT may mimic other pathologic processes including bronchospasm, mainstem intubation, or ventilator malfunction. Prompt recognition is important as difficulties with ventilation can lead to cardio-respiratory complications with disastrous consequences including cardiac arrest. Given these concerns, we have outlined an algorithm to identify and manage such problems.[5] Changes in intraoperative ventilation with increased PIP and decreased tidal volume may be related to intrinsic problems of the ETT due to kinking. Such problems may be exacerbated or caused by specific scenarios related to patient positioning (prone with neck flexion and insertion of oral devices (Dingman gag during tonsillectomy, TEE probe, or gastroscope)), combined with the use of smaller ETTs in pediatric patients, and increase the pliability of PVC tubes as they warm to body temperature.

Given our clinical practice and experience with these scenarios related to the rare clinical occurrence of ETT kinking, we have developed a device that would allow for testing of different ETTs of varying compositions to evaluate their structural integrity and resistance to kinking and also allow an evaluation of the effect of temperature on these properties. The goal of this pilot research study was to develop a repeatable mechanical testing procedure that could be used to determine conditions in which ETTs may fail mechanically, resulting in an obstruction of airflow to the patient. It was hypothesized that this form of repeatable testing could be used to determine the safety of various ETTs when stressed under clinical conditions which may predispose to intraoperative kinking and obstruction. The method we described can be used for either pressure- or volume-limited ventilation, with the clinician deciding on the threshold values (either decrease in tidal volume or increase in PIP) used to identify a clinically significant obstruction to flow. For the purpose of this initial evaluation of the technique, we chose a 20% decrease in the delivered tidal volume of 100 mL; hence the cut-off was set at a tidal volume of 80 mL. As noted in our study, as expected, changes in PIP are more sensitive to ETT obstruction as these occurred prior to significant decreases in tidal volume. During volume ventilation, compensatory increases in PIP may occur to compensate for the increased resistance during ETT kinking.

Most importantly, the device and technique we described can be used to determine the site of ETT kinking and perhaps identify design flaws which predispose to kinking at specific sites along the shaft of the ETT. It can also be used to compare various brands of ETT and determine which are least prone to kinking. It may be that these would offer clinical advantages in specific scenarios such as prone surgery with the neck flexed.

Additional experiments were used to show the fatigue of the ETTs after the presence of buckling. Results validate that testing of the ETTs can only be performed once and that a new ETT should be used. The device described also allowed easy regulation of external temperature. Temperature comparison tests showed that the mechanical properties of ETTs changed with respect to the temperature of the testing environment. As the temperature increased, the mechanical integrity of the ETT decreased, making it more susceptible to kinking. COMSOL computer modeling could be used as a method to replicate the ETT experimental conditions. This allows for the ability to easily change testing conditions and environmental factors to evaluate the performance of ETTs. The COMSOL model can also be used to experiment with different levels of plasticizers to optimize mechanical performance.

Financial support and sponsorship
Nil.

Conflicts of interest
There are no conflicts of interest.

References

1. Holm-Knudsen RJ, Rasmussen LS. Paediatric airway management: Basic aspects. Acta Anaesthesiol Scand 2009;53:1-9.
2. Hsu G, von Ungern-Sternberg BS, Engelhardt T. Pediatric airway management. Curr Opin Anaesthesiol 2021;34:276-83.
3. Engelhardt T, Fiadjoe JE, Weiss M, Baker P, Bew S, Echeverry Marín P, *et al*. A framework for the management of the pediatric airway. Paediatr Anaesth 2019;29:985-92.
4. Hans GA, Sottiaux TM, Lamy ML, Joris JL. Ventilatory management during routine general anaesthesia. Eur J Anaesthesiol 2009;26:1-8.
5. D’Mello A, Grischkan J, Tobias JD. Intraoperative endotracheal tube kinking: Clinical findings and early diagnosis. Pediatr Anesth Crit Care J 2022;10:17-21.
6. Szekely SM, Webb RK, Williamson JA, Russell WJ. The Australian Incident Monitoring Study. Problems related to the endotracheal tube: An analysis of 2000 incident reports. Anaesth Intensive Care 1993;21:611-6.
7. Al-Hashem HAS, Al-Naeem MAH. Effect of temperature on the stiffness of polyvinyl chloride and chlorinated polyvinyl chloride joints under bending. J Appl Sci 2007;7:3442-50.
8. Williams ZC, Kim SS, Naguib A, Shafy SZ, Tobias JD. Use of cuffed endotracheal tubes in infants less than 5 kilograms: A retrospective cohort study. J Pediatr Surg 2022;57:375-81.
9. Tobias JD. Pediatric airway anatomy may not be what we thought: Implications for clinical practice and the use of cuffed endotracheal tubes. Paediatr Anaesth 2015;25:9-19.
10. Tickner JA, Schettler T, Guidotti T, Rossi M. Health risks posed by use of Di-2-ethylhexyl phthalate (DEHP) in PVC medical devices: A critical review. Am J Ind Med 2001;39:100-11.
11. Latini G, Ferri M, Chiellini F. Materials degradation in PVC medical devices, DEHP leaching and neonatal outcomes. Curr Med Chem 2010;17:2979-89.
12. Hernandez R, Pena JJ, Irusta L, Santamaria A. The effect of a miscible and an immiscible polymeric modifier on the mechanical and rheological properties of PVC. Eur Polym J 2000;36:1011-25.
13. Shanahan E, Yu CV, Tang R, Sawka A, Vaghadia H. Thermal softening of polyvinyl chloride nasotracheal tubes: Effect of temperature on tube navigability. Can J Anesth 2016;64:331-2.