Mechanical Analysis of Endotracheal Tubes

Honors Research Thesis

Presented in Partial Fulfillment of the Requirements for the Degree of Bachelor's of Science in Biomedical Engineering with Honors Research Distinction in Biomedical Engineering in the Undergraduate School of The Ohio State University

By

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Abstract:

An endotracheal tube (ETT) is a medical device that is crucial for the intubation process in order to deliver anesthesia and/or oxygen to a patient during a medical procedure. Device malfunctions, such as kinking, can lead to procedural complications, physical injury to the patient, or even patient death. The anesthesiology department at Nationwide Children's Hospital has expressed concern regarding malfunction of a new model of ETT the hospital has recently adopted. While the anesthesiologists believe the performance of the cuff portion of the new ETT model, Halyard Microcuff Endotracheal Tube (Halyard Health), is more effective than the cuff of the previously used model, Shiley Hi-Lo Oral/Nasal Tracheal Tube Cuffed (formerly branded as Mallinckrodt; Medtronic, Inc.), they are concerned about the Halyard model's increased susceptibility to kinking during a procedure. Therefore, this project aims to develop a repeatable mechanical test that is able to determine when a devastating ETT kink is occurring. This test will then be used to compare the mechanical properties of both the Halyard and the Shiley model ETTs under common conditions experienced in the clinic. These clinical conditions include a room (25C) and body temperature (36C), as well as oxygen airflow through the ETTs during mechanical testing. This pilot study has developed a repeatable mechanical testing procedure in order to determine the compression force and distance required to kink an ETT under different conditions. Results of this study showed that the force required to induce the devastating kink failure was determined to be lower for the heated testing conditions. Additionally 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 vs. distance curves. Further testing

must be performed to determine statistically significant differences between ETT models and conditions. It is anticipated that the further results of this study will provide insight into which model of ETT anesthesiologists should choose to promote safer medical procedures, as well as potentially influence the design of future ETTs by their manufacturers.

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Introduction:

Endotracheal tubes (ETTs) are a vital component in the inducement of patients for various medical procedures. These devices are inserted into the patient's airway and once the ETT is in the correct position, a syringe is attached to the cuff inflating tube to push air into the cuff. The cuff becomes inflated and creates a seal between the outside of the tube and the patient's trachea therefore directing all airflow through the ETT. The final position is as seen in **Figure 1 - left**. The end extending out from the patient's mouth is connected to the anesthesia machine/ventilator and is used to deliver anesthesia and/or oxygen to the patient. These machines deliver amounts of gases in the form of a set tidal volume – the quantity of gas delivered with each breath - based on the patient's age and weight. The purpose ETTs serve of controlling airflow is critical to the safety of the patient throughout an entire medical procedure that can last for many hours. Kinking of the endotracheal tubes cuts off oxygen flow to the patient during the surgery. The lack of oxygen causes a drop in the tidal volume, signaled by device alarms, causing complications and can even lead to death, according to the anesthesiologists at Nationwide Children's Hospital in Columbus, Ohio.

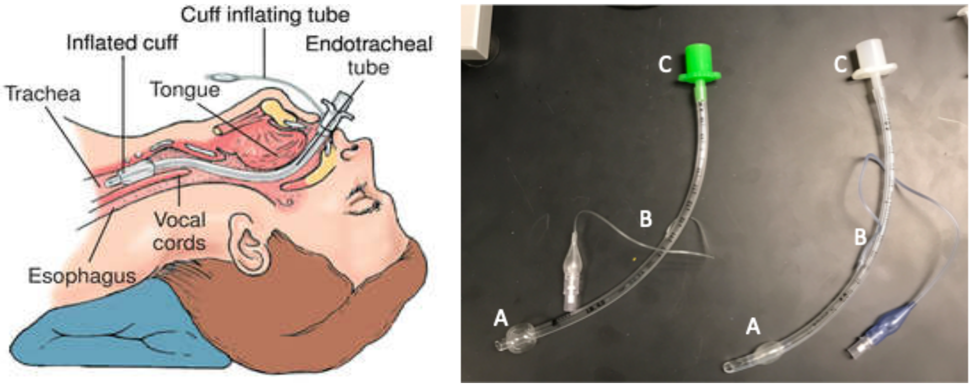

Figure 1: LEFT - Image showing how the endotracheal is placed in the trachea during medical procedures. (Farlex Partner Medical Dictionary). **RIGHT** - The Halyard (left) and the Shiley (right) ETT models. Labels A are the cuffs, B are the cuff inflation tubing and where they enter the ETT, and C are the portions that connect to the anesthesia/ventilator machine.

Recently Nationwide Children's Hospital has adopted the Halyard Microcuff Endotracheal Tube (Halyard Health) model of endotracheal tubes in place of the Shiley Hi-Lo Oral/Nasal Tracheal Tube Cuffed (formerly Mallinckrodt, Medtronic) models (**Figure 1 - right**). This change was motivated by the observed superior performance of the Halyard model's cuff in sealing off the trachea without inducing damage to the patient's tracheal mucosa (Tobias et al., 2014). While cuff performance appears to be better, according to the medical professionals who use these devices, the Halyard design appears to be inferior to Shiley in terms of ability to resist kinking during a medical procedure. The anesthesiologists believe that temperature, as well as the location of the cuff inflating tube inserting into the ETT (label B in **Figure 1 - right**), might create mechanical weakness in the tube leading to the kinking. For example, the ETT is typically inserted into the trachea at room temperature (25C). As the procedure continues, it is suspected the patient's body temperature (36C) induces an increase in temperature of the ETT, which could cause the ETT material to change mechanical properties and malform. These speculations are supported in part by literature (Shanahan et al., 2016), and will be investigated further throughout this study.

Properties of Endotracheal Tubes (ETTs)

Like many types of medical devices, endotracheal tubes tend to be made from polyvinyl chloride (PVC) softened with a plasticizer in order to make them more flexible and easier to process (Tickner et al., 2001 and The University of Massachusetts Lowell). Determined from package labeling, the plasticizer used for the Halyard and Shiley models of endotracheal tubes is Di-(2-ehtylhexyl)-phthalate (DEHP), also referred to as DOP. This is a phthalate ester that is one of the most widely used plasticizer in medical devices – though issues are being brought to light in the migration of DEHP from medical devices. This is because DEHP is not chemically bound to PVC and the effect of this on humans is being investigated (Latini et al., 2010).

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 endotracheal tubes, like the Young's modulus. From research already conducted it was determined that based on fraction of the 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 (Hernandez et al., 2000). Based on the assumption that most PVC medical devices are made from approximately 40% DEHP plasticizer (Latini et al., 2010 and Shanahan et al., 2016), the Young's modulus of the ETTs in this experiment is approximated to be 44.3MPa.

Additionally, temperature is a concern when it comes to using polymers like PVC. It is well known that polymers like PVC started to become more flexible and potentially lose some mechanical integrity in higher temperatures. Research has shown that increasing temperature softens the PVC in endotracheal tubes (Shanahan et al., 2016). Through this experiment, the effect of temperature on the PVC/DEHP material will be investigated to determine whether clinically relevant temperatures (~36C) significantly impact ETT structural integrity.

Goals for this Study

As the use of cuffed ETTs is increasing in pediatric anesthesiology, precautions must be taken to limit risk of tracheal mucosal damage as the cuff makes direct contact with the tracheal wall (Tobias et al., 2014). This is why, in previous analysis of these devices, the main focus has been the cuff at the bottom of the device (see **Figure 1**). While, by the opinions of the physicians, the Halyard Health models have a superior cuff design, it is also important to consider the overall performance and integrity of the device.

In this pilot study, we aim to develop a repeatable mechanical testing procedure to determine the force and distance of compression required to kink an ETT under clinically relevant conditions. Based on input of the anesthesiologists at Nationwide Children's Hospital, we hypothesize that the Halyard models will malform at lower applied forces compared to the Shiley model. We also hypothesize that an increase of ETT temperature to body temperature will exasperate the malformation(s). Experimental results will be used to build computational models capable of simulating ETT mechanical behavior under various conditions. To our knowledge, this the first mechanical study of ETTs. This information, in combination with the cuff performance, may help guide ETT selection for Nationwide Children's Hospital's medical procedures and could lead to proposed redesign for ETT manufacturers that will ultimately make the operating room a safer place.

Methodology:

Endotracheal Tube (ETT) Experimental Set-up and Kinking Analysis

Buckling testing of pediatric size 4.0 (inner diameter in mm, appropriate for a toddler who weights approximately 10kg) Oral/Nasal ETTs was conducted using a 100-series Modular Universal Test Frame with 1000N load cell and four inch compression platens (TestResources, Inc.). The two ETT brands included Halyard Microcuff Endotracheal Tubes (Halyard Health, Inc) and Shiley Hi-Lo Oral/Nasal Tracheal Tube Cuffed (Medtronic) models. As shown in **Figure 2**, surgical tape was used to secure the ETT to the compression plates that were initially 60 mm apart. The ETT was secured on the approximately 9 and 18 markings for the Halyard models and the corresponding positions on the Shiley model. This setup provided the visual kinking and resembled the clinical flex position of the head and neck that is used during certain medical procedures that, according to the anesthesiologists, is a position extremely prone to kinking. For each testing procedure described below, the ETT models were tested immediately after removal from sterile packaging. For each condition, three new ETT's of each brand were tested.

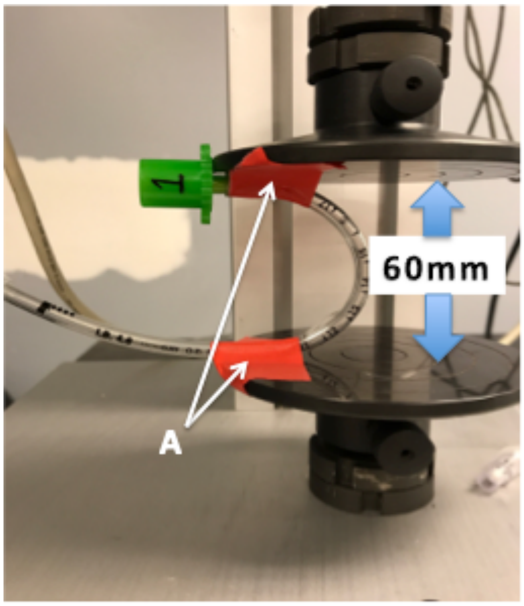

Figure 2: Experimental set-up of the ETT testing using the test frame with an initial compression platen distance of 60mm. Label A is the red surgical tape used to secure the ETT to the compression platens.

All compression testing of the endotracheal tubes was performed at a constant compression rate of 60mm/min, and force, time, and displacement data were recorded (WinCom Plus Version 2.2.11, ADMET). Force and the first derivative of force vs. 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) and that changes causes a maximum in the force that would be represented by a zero value for its first derivative. An example of the MATLAB code for these analyses can be found in Appendix A.

Fatigue Testing

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

Temperature Testing

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

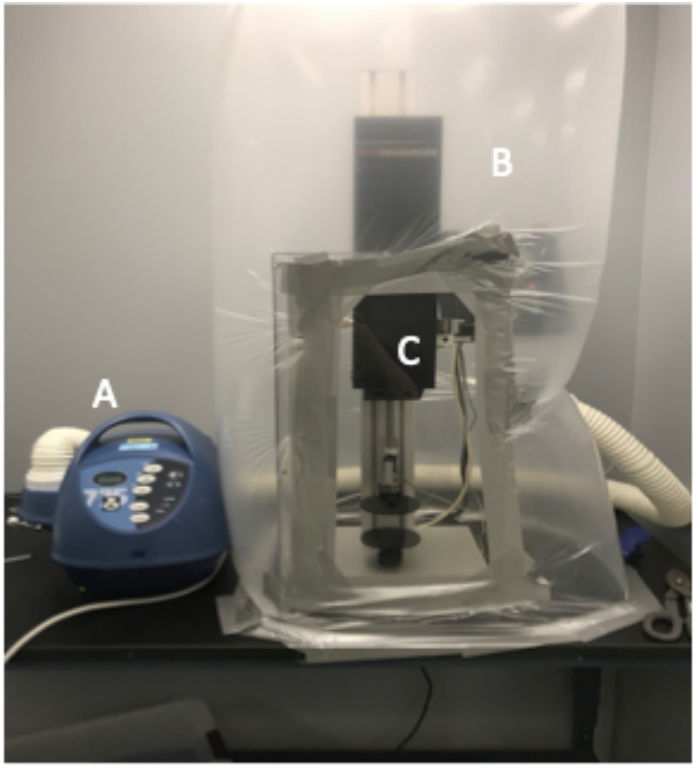

Figure 3: Tenting system used to obtain the heated clinical condition of 36C. A is the Bair Hugger that is being used to heat the system, B is the plastic used to create the boundary of the testing system, and C is the test frame located in the heated environment of the tenting system.

Airflow Testing

Airflow testing was coupled with compression testing to determine whether the kinking force identified in the force-distance analyses was indeed 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 (**Figure 4**). Oxygen (O_2) was flowed through the ETT into the mechanical lung via the ventilator setting of the anesthesia device, and the experimental time point after the start of the compression test and at which the anesthesia machine signals for airflow failure – tidal volume drops below the tolerated level of 10-15% - 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 occurs. Shortly after this tidal volume dropped, the anesthesia machine administered warning signals. These warnings indicate to an anesthesiologist when a detrimental kink is preventing proper airflow to the patient. The ventilator settings appropriate for a 4.0 ETT were provided from Nationwide Children's Hospital's anesthesiologists (**Table 1**).

Table 1: Ventilator settings for compression with airflow testing.

Condition	Tidal Volume (VT)	Rate (breaths per minute)	IE ratio	PEEP	Oxygen
Setting	100mL	20	1:2	5	100% flow at 2L/min

Because a tidal volume of 100mL was being used, the actual point of kinking was assumed and recorded to be when the tidal volume hit 80mL. This was the first displayed value outside of the 10-15% tolerance of the machine. Additionally, in order to account for the time it took the anesthesia machine to flow air to and from the lung and register a drop in airflow, the compression-testing rate was reduced from 60mm/min to 10mm/min. This testing was conducted on three of each type of ETT (Halyard and Shiley) at both room temperature (25C) and the heated condition (36C).

Figure 4: Setup of test frame, anesthesia machine, and mechanical lung for compression testing with airflow. Room temperature setup is shown on left and heated setup with tenting system is shown on the right. A is the test frame, B is the anesthesia machine/ventilator, C is the test lung, D is the tubing that delivers the O_2 through the ETT and into the test lung, E is the Bair Hugger, and F is the tenting system.

Modeling of ETT Mechanical Behavior

COMSOL (Multiphysics 5.3a) was used to develop a computational model of the endotracheal tube that shows the stresses occurring from the compression of ETTs under the experimental compression conditions of this study. Dimensions of the ETT – specifically the Halyard model – were determined from packaging labeling and additional caliper measurements. This included an inner ETT diameter of 4.0mm and an outer diameter of 5.6mm. As described in the introduction the material property of Young's modulus for the PVC/DEHP combination was estimated to be 47.7MPa. The model started with the ETT in is 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 above. 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.

Results and Discussion

The following summarizes the results gathered with respect to the different compression testing conditions, including fatigue, temperature, and added airflow, for two different endotracheal tube (ETT) models.

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 5** shows the load (solid curves) and derivative of load (dashed curves) of a single Shiley ETT being subject to three compression trials (Test 1, 2 and 3).

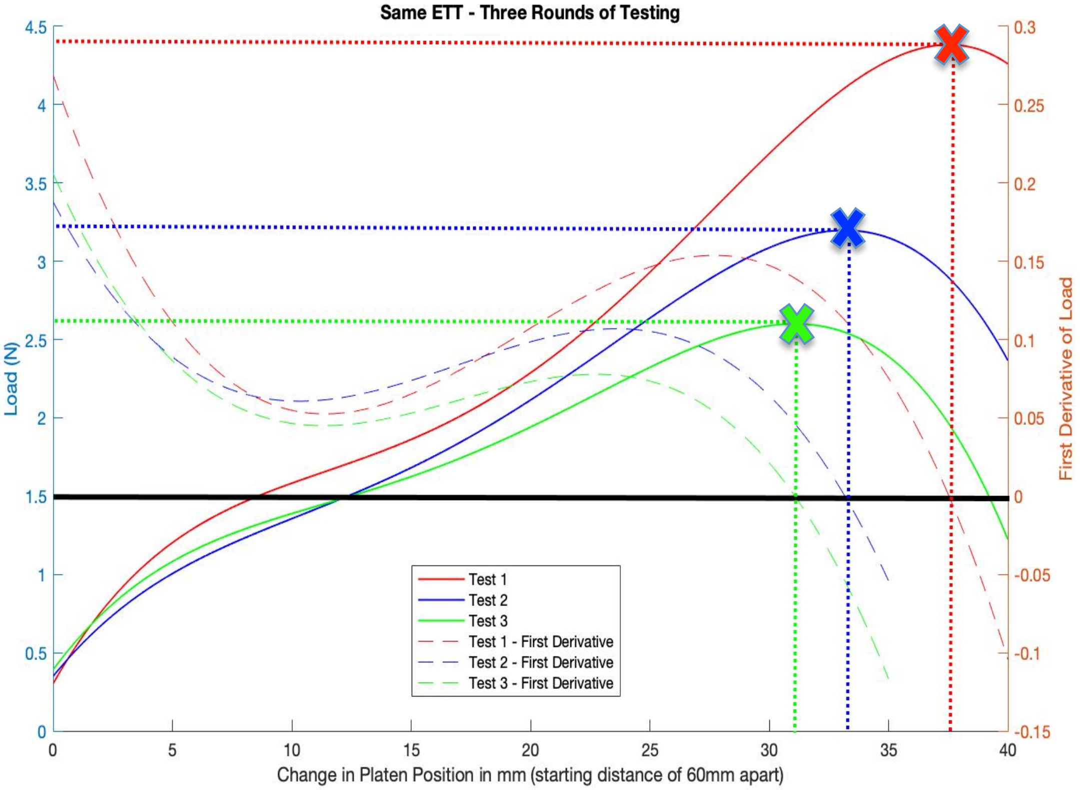

Figure 5: Plot of load and first derivative of load vs. position of the same endotracheal tube during three consecutive compression tests. The X's represent the locations of kinking: Red X = Test 1 kink at approximately 4.5N of load; Blue X = Test 2 kink at 3.25N of load; Green X = test 3 kink at approximately 2.6N of load.

Figure 5 displays a trend that was common among almost all of the endotracheal tubes tested. This trend was that 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. For this specific endotracheal tube's data shown, the load to kink started at approximately 4.5N for the first test and decreased to approximately 2.6N 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 38mm of compression and decreased to approximately 31mm of compression on the third trial. This consistent trend indicates a loss in mechanical integrity, and therefore a new ETT should be used for each compression test. This aligns with clinical practice in that a single ETT is never reused.

Temperature Testing

As discussed in the introduction, endotracheal tubes are constructed of a polymer called PVC and softened with a plasticizer – in this case DEHP - in order to become more flexible and more easily processed. While some structural compliance is necessary for placement of the tube into the patient, increased temperature of the tube once inside a ~36C patient could further impact the mechanical integrity of the PVC, leading to an obstruction of airflow. According to previous literature it was found that as the temperature of the PVC increases, its mechanical properties, such as stiffness, decrease (Al-Hashem & Al-Naeem, 2007). For the purpose of this study, a change in mechanical performance of the ETT's was investigated to determine the impact of temperature on the ETT devices' ability to resist kinking. **Figure 6** shows the results of testing two Halyard

Health ETTs at room temperature (RT) and two at the heated temperature condition of approximately 36C.

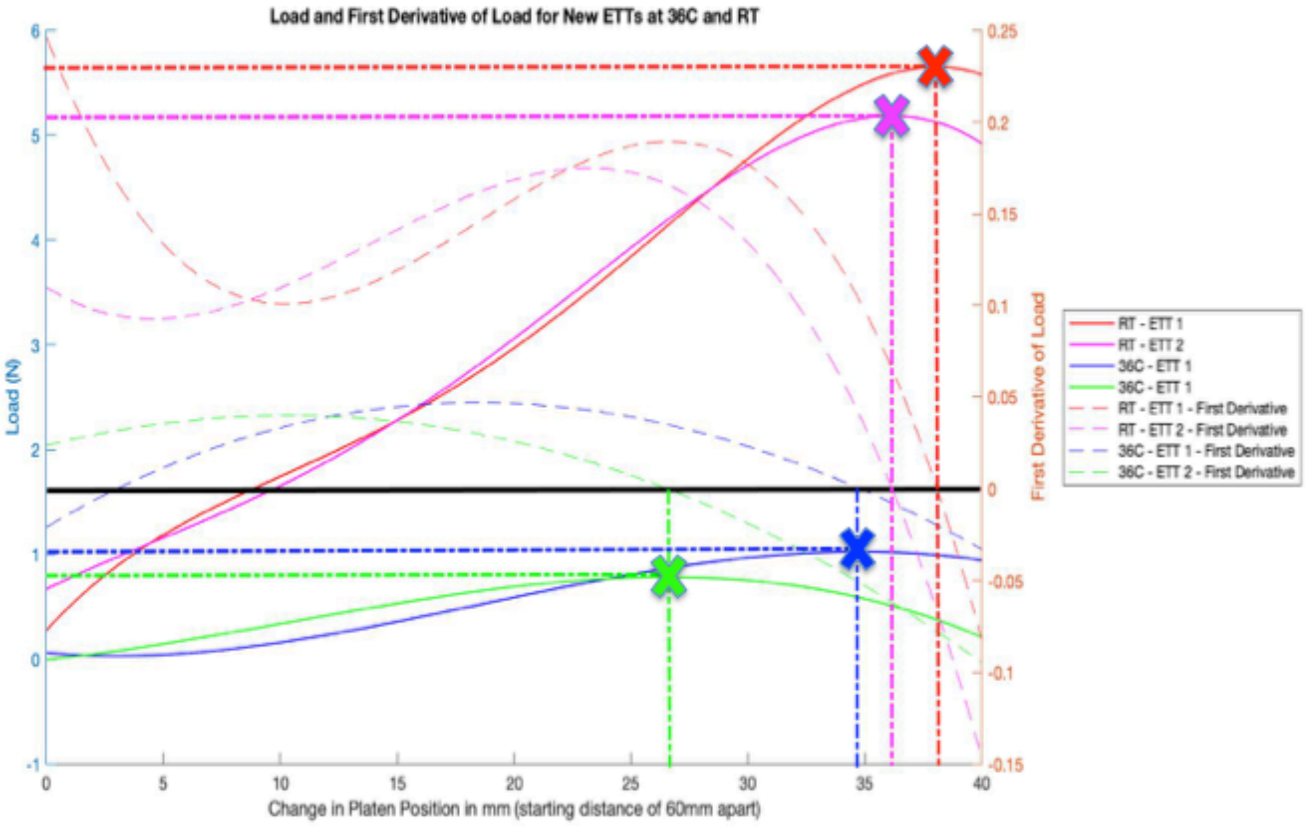

Figure 6: Load and the first derivative of load vs. distance for two models of Halyard ETTs, tested at room temperature (RT) and at 36C. The X's represent the locations of kinking: Red X = RT ETT 1 kink at 5.6N; Pink = RT ETT 2 kink at 5.2N; Blue X = 36C ETT 1 kink at 1N; Green X = 36C ETT 2 kink at 0.8N.

Figure 6 shows that under room temperature conditions, the Halyard models of ETT required between 5N and 6N of force before kinking was observed. Also, it shows that once the temperature condition was applied, the force required for kinking was reduced to approximately 0.8N and 1N of force. A decrease in the amount of load required until ETT kinking was consistently observed at the higher temperature (36C), regardless of endotracheal tube brands. These results confirm that the mechanical integrity of the ETTs is compromised at body temperature, increasing their ability to be more easily kinked.

Airflow Testing

The prior experiments were conducted as a way to develop a repeatable test in order 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 devastating kink, airflow of O_2 was put through the ETTs while the compression test was occurring. **Figure 7** summarizes the results gathered from the experimental testing of both models of endotracheal tubes at both room temperature and body temperature conditions with airflow present.

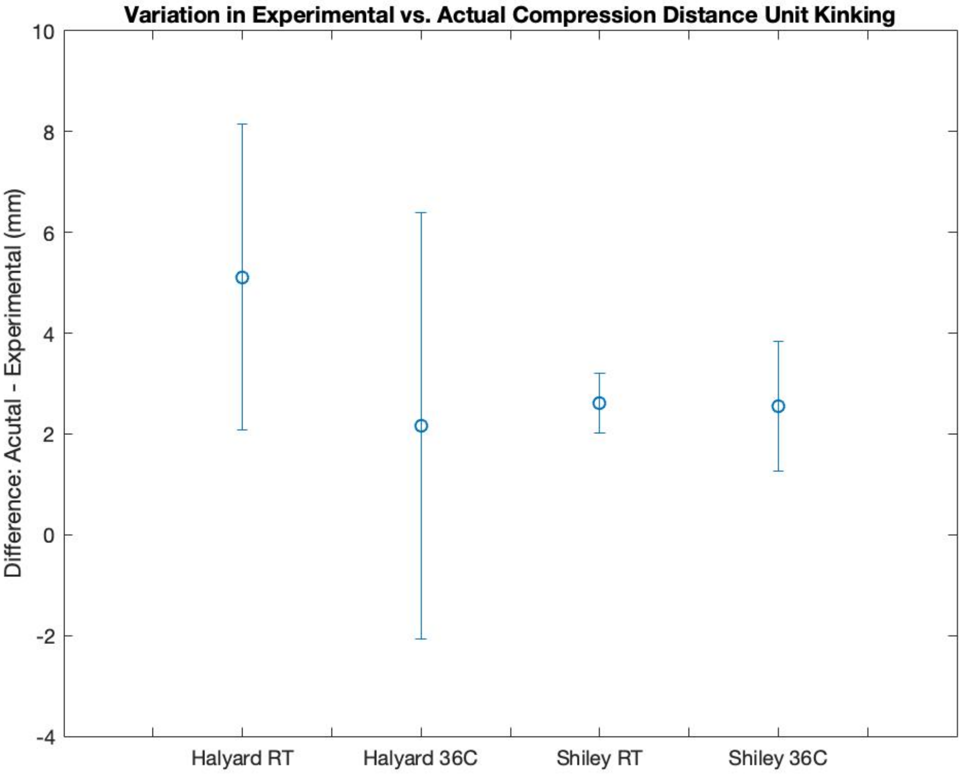

Figure 7: Plot of mean and standard deviation of differences between experimental and actual compression distances until kink obstructed airflow- when platens start 60mm apart.

By observation of plot above, it is noted that for all but one condition, the experimentally determined distance compressed when kinking occurred is slightly less than that of the calculated compression distance when the ventilator system actually registered obstructed airflow. While the values are not the same, the delay of the ventilator system in registering changes, which are based on number of breaths per minute, can help account for the delay. Additionally, the test frame has some tolerance in the compression rate from the established 10mm/min. It was also observed that the pressure the anesthesia machine was registering tended to increase noticeably before the tidal volume dropped below the tolerance threshold, indicating that deformation of the tube was impacting the pressure of the system even before a change in tidal volume could be registered. Overall this comparison shows that this developed experimental method is a reasonable test to predict kinking of the endotracheal tube.

COMSOL Modeling

COMSOL was used to recreate the basic compression test conducted in the experiments above on an ETT with no cuff inflator tube present. The images show the stresses on the device under the basic testing conditions of compressing the tube via platens when they initially start 60 mm apart.

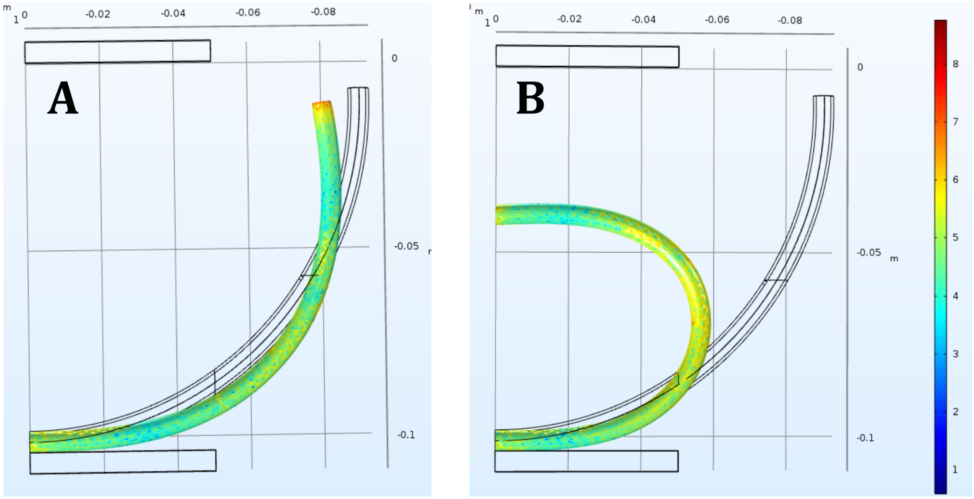

Figure 8: A - Stresses on nearly unstressed ETT. B - Stresses present on ETT from initial loading into the testing position.

As can be seen in **Figure 8A** there are initially very few stresses on the ETT when it is slightly bent from its natural position. **Figure 8B** 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.

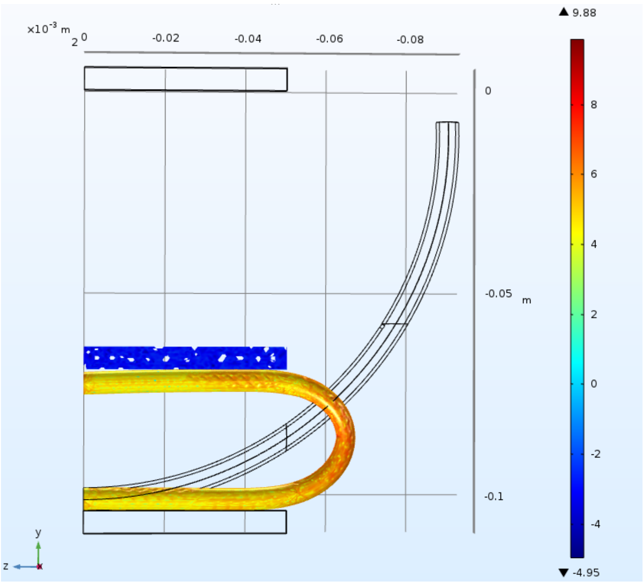

Figure 9: COMSOL modeling stress diagram of ETT at 32 mm of compression.

Figure 9 above shows the stresses present on the ETT after it has been compressed 32 mm. Based on the image, it seen that there is a concentration of stresses on the 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 to 37 mm when tested at room temperature – showing that this computational model serves as a good representation of the ETT.

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, i.e. stresses on different locations of the ETT, other physiological attributes that can put stress on the tube like the tongue, etc. Additionally, focus can be put onto the location of the cuff inflation tube that enters the ETT to see if this is a weak point in the design that leads to easier kinking – as the anesthesiologists think. Future modeling work should include insertion of the inflation tube at the region of increased stress to determine whether the ETT kinks at a lesser compression distance – or with less required force.

Statistical Analysis

As this is a pilot study, the data was interpreted on both a qualitative nature and generally quantitative nature – though not with statistical significance. In the future, after collecting additional trials, an analysis of variance (ANOVA) followed by Tukey's test should be conducted in order to determine any significant differences in loads or compression distances between the results of the different testing conditions and the different brands of ETTs.

Conclusion:

The goal of this pilot research study was to develop a repeatable mechanical testing procedure that could be used to determine conditions in which endotracheal tubes fail mechanically, resulting in an obstruction of airflow to a patient. It was hypothesized that this form of repeatable testing could be used to determine which brand of ETT is less prone to kinking. Based on the data collected, it was seen that most of the testing resulted in determining, within 3mm of compression distance, that ETT kinking occurred and correlated to drops in the tidal volume of the airflow beyond the tolerance of the ventilator system. This observation shows that the developed testing procedures are a good model for testing the mechanical performance of endotracheal tubes. As this was a pilot study, not enough trials were performed for conclusions to be drawn on the performance of the brands compared to each other. The initial data shows trends for the Halyard model kinking at higher applied loads compared to the Shiley mode. This is contradictory to the observations made by anesthesiologists in the clinic. It is speculated that the location of the cuff tube insertion may play a role in the mechanical integrity of ETTs, since this insertion point is located in different positions for the two different ETT brands.

Additional experiments were used to show the fatigue of the endotracheal tubes after the presence of a buckling. Results validate that the devices are for one time use and also shows that for the most accurate results in future testing, a new endotracheal tube should be used for each trial conducted. Beyond fatigue, temperature comparison tests showed that the mechanical properties of ETTs changed with respect to the temperature of the testing environment. The conclusion drawn from these tests were that as the temperature increased the mechanical integrity of the ETT decreased, making the ETT more susceptible to kinking.

Also, through this study it was seen that 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 endotracheal tubes, and will provide a cost effect approach for future testing.

Overall, this pilot study developed a repeatable mechanical test that consistently predicts when kinking of an endotracheal tube occurs. In the future, more tests can be conducted to better compare the two endotracheal tube models to determine whether one model is mechanically superior to the other. Additionally the COMSOL model can be used to experiment with different levels of plasticizers in order to optimize mechanical performance. Finally the compression tests can be conducted to focus on different areas of the ETT to experimentally determine if the cuff tubing insert location is a weak point of the device – this can also be tested with a modified COMSOL model. Overall this pilot study shows potential to make the operating room environment a safer place by learning more about optimizing the performance of endotracheal tubes.

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Appendix A – MATLAB Code

Example of the code used to determine experimental kinking point: This code is specifically from the fatigue testing of the Shiley ETTs at room temperature without airflow.

```
%% Fatigue Testing
% Old ETTs at Room Temperature with No Airflow
clear all
clc

%% Mallinckrodt/Shiley ETT 1 - Test 1
% read csv file into matrix
data11 = csvread('Old ETT 1 - Test 1 - No Airflow.csv', 2, 0);

% pull data out into individual variables
% pull out time data
time11 = data11(:,1);
% identify load
loadn11 = data11(:,2);
% identify position data
position11 = data11(:,3);

% set limits in order to avoid unnecessary data
lowerlim = 1;
upperlim = 1250;
% set new data vectors based on limits
loadl11 = loadn11(lowerlim:upperlim,:);
positionl11 = position11(lowerlim:upperlim,:);
timel11 = time11(lowerlim:upperlim,:);

% Create Vector for line of Best fit to span from 0 to 40mm of
compression
bestfitposition = [0:0.001:40];

% find line of best fit for the data using polyfit
p11 = polyfit(positionl11, loadl11, 4);
% generate equation of that line
y11 = polyval(p11,bestfitposition);

% find the first derivative using polyder
p11firstderiv = polyder(p11);
% generate the equation of that line
y11firstderiv = polyval(p11firstderiv,bestfitposition);

%% Mallinckrodt/Shiley ETT 1 - Test 2
% read csv file into matrix
data12 = csvread('Old ETT 1 - Test 2 - No Airflow.csv', 2, 0);

% pull data out into individual variables
% pull out time data
time12 = data12(:,1);
% identify load
loadn12 = data12(:,2);
% identify position data
```

```
position12 = data12(:,3);

% set limits in order to avoid unnecessary data
lowerlim = 1;
upperlim = 1000;
% set new data vectors based on limits
loadl12 = loadn12(lowerlim:upperlim,:);
positionl12 = position12(lowerlim:upperlim,:);
timel12 = time12(lowerlim:upperlim,:);

% find line of best fit for the data using polyfit
p12 = polyfit(positionl12, loadl12, 4);
% generate equation of that line
y12 = polyval(p12,bestfitposition);

% Create a vector that goes to 35mm of compression to best plot first
deriv
bestfitderiv = [0:0.001:35];

% find the first derivative using polyder
p12firstderiv = polyder(p12);
% generate the equation of that line
y12firstderiv = polyval(p12firstderiv,bestfitderiv);

%% Mallinckrodt/Shiley ETT 1 - Test 3
% read csv file into matrix
data13 = csvread('Old ETT 1 - Test 3 - No Airflow.csv', 2, 0);

% pull data out into individual variables
% pull out time data
time13 = data13(:,1);
% identify load
loadn13 = data13(:,2);
% identify position data
position13 = data13(:,3);

% set limits in order to avoid unnecessary data
lowerlim = 1;
upperlim = 1000;
% set new data vectors based on limits
loadl13 = loadn13(lowerlim:upperlim,:);
positionl13 = position13(lowerlim:upperlim,:);
timel13 = time13(lowerlim:upperlim,:);

% find line of best fit for the data using polyfit
p13 = polyfit(positionl13, loadl13, 4);
% generate equation of that line
y13 = polyval(p13,bestfitposition);

% find the first derivative using polyder
p13firstderiv = polyder(p13);
% generate the equation of that line
y13firstderiv = polyval(p13firstderiv,bestfitderiv);

%% Comparison Between Three Rounds
% Plot the best fit data on left axis and label
```

```
figure(7)
yyaxis left
hold on
plot (bestfitposition,y11, 'r')
plot (bestfitposition,y12, 'b')
plot (bestfitposition,y13, 'g')
ylabel('Load (N)')
% Plot the first derivatives on a right axis
yyaxis right
plot (bestfitposition,y11firstderiv, '--r')
plot (bestfitderiv,y12firstderiv, '--b')
plot (bestfitderiv,y13firstderiv, '--g')

% Label right axis and plot
title('Same ETT - Three Rounds of Testing')
ylabel('First Derivative of Load')
xlabel ('Change in Platen Position in mm (starting distance of 60mm
apart)')
legend('Test 1','Test 2','Test 3','Test 1 - First Derivative','Test 2 -
First Derivative','Test 3 - First Derivative','Location','northwest')
xlim ([0 40])
```