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Correlation Between Endotracheal Tube Cuff Pressure and Tracheal Wall Pressure Using Air- and Saline-Filled Cuffs

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14. ABSTRACT Endotracheal tubes (ETTs) utilizing high-volume, low-pressure cuffs lower the risk of tracheal wall injury, requiring less pressure to provide a seal. Recently introduced tapered ETT cuffs, which show a lower propensity for fluid leakage, provide another ETT option. Aeromedical transport presents a challenging environment for ETT cuff management and requires diligent monitoring to maintain pressure within the recommended range. The pressure measured in the cuff is assumed to be equal to the pressure exerted on the tracheal wall (TW). We performed a bench study to evaluate this correlation at sea level and simulated altitude. Mean TW pressure and cuff pressure were compared using Student's t-test. Statistical significance was defined as $p < 0.05$. When using air in the ETT cuff, TW pressure differences were statistically significant between baseline and at altitude with all ETTs but not between baseline and at sea level after descending from altitude. When using saline in the ETT cuff, TW pressure differences with the 7.5 high-volume, low-pressure cuff and 8.0 TaperGuard™ cuff were statistically significant at altitude and back at sea level, as compared to baseline. Cuff pressure differences with saline in all ETTs were not statistically significant. Comparing TW pressure and cuff pressure, differences were statistically significant at all conditions with all ETTs. The use of saline provided the highest baseline pressure but had the lowest pressure variation, while using air provided the highest pressure at altitude and the largest pressure variation from baseline. Due to lack of ability to measure pressure, use of saline in the ETT cuff is discouraged. Maintaining cuff pressure < 30 cm H ₂ O is imperative to minimize TW pressure.					
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1.0 SUMMARY

Endotracheal tubes (ETTs) utilizing high-volume, low-pressure cuffs lower the risk of tracheal wall injury, requiring less pressure to provide a seal. Recently introduced tapered ETT cuffs, which show a lower propensity for fluid leakage, provide another ETT option. Aeromedical transport presents a challenging environment for ETT cuff management and requires diligent monitoring to maintain pressure within the recommended range. The pressure measured in the cuff is assumed to be equal to the pressure exerted on the tracheal wall (TW). We performed a bench study to evaluate this correlation at sea level and simulated altitude. Mean TW pressure and cuff pressure were compared using Student's t-test. Statistical significance was defined as $p < 0.05$. When using air in the ETT cuff, TW pressure differences were statistically significant between baseline and at altitude with all ETTs but not between baseline and at sea level after descending from altitude. When using saline in the ETT cuff, TW pressure differences with the 7.5 high-volume, low-pressure cuff and 8.0 TaperGuard™ cuff were statistically significant at altitude and back at sea level, as compared to baseline. Cuff pressure differences with saline in all ETTs were not statistically significant. Comparing TW pressure and cuff pressure, differences were statistically significant at all conditions with all ETTs. The use of saline provided the highest baseline pressure but had the lowest pressure variation, while using air provided the highest pressure at altitude and the largest pressure variation from baseline. Due to lack of ability to measure pressure, use of saline in the ETT cuff is discouraged. Maintaining cuff pressure < 30 cm H₂O is imperative to minimize TW pressure.

2.0 BACKGROUND

Aeromedical transport with intubated patients is a challenging environment in which to manage endotracheal tube (ETT) cuffs, requiring diligent monitoring to keep cuff pressures within the recommended range. A lower ETT cuff pressure is desired to minimize the pressure exerted on the tracheal wall (TW), but pressures that are too low (< 20 cm H₂O) allow oropharyngeal secretions to leak past the ETT cuff and contaminate the respiratory tract, which could lead to pneumonia [1,2]. Although cuff pressures higher than 20 cm H₂O are often required to obtain a complete seal between the ETT cuff and TW, pressure above 30 cm H₂O exceeds tracheal mucosal perfusion pressure, which may lead to tracheomalacia and tracheal stenosis with long-term exposure to pressures above this threshold. If the cuff pressure reaches 50 cm H₂O, mucosal damage can occur in as little as 15 minutes [3]. If left unadjusted, altitude-induced cuff pressure increases can easily surpass this critical threshold [4-7]. It has always been the assumption that the pressure measured at the pilot balloon is equal to the pressure exerted on the TW. We evaluated ETTs at sea level and at altitude to determine if this assumption is correct.

3.0 METHODS

We evaluated size 7.5 mm and 8.0 mm ETTs with high-volume, low-pressure (HVLV) cuffs and tapered cuffs at sea level and during simulated flights at a cabin altitude of 8,000 feet in the altitude chamber at the University of Cincinnati. The flight pattern simulated a normal take-off, cruising altitude, and landing, and pressures were continuously measured throughout the simulated flight. Each ETT was placed inside an anatomically correct, three-dimensional printed model of a human trachea (Quickparts, Atlanta, GA) that was fitted with an array of

pressure sensors (Pressure Profile Systems, Los Angeles, CA) to allow circumferential pressure measurement where the ETT cuff contacts the TW and shows pressure differences at different points on the TW (Figure 1). In total there were 96 separate pressure sensors lining the inside of the model trachea. Each ETT size and cuff type was tested in triplicate using 8 mL saline or air to inflate the cuff at sea level. Air-filled cuffs were inflated to a pressure of 25 cm H₂O. Continuous measurements were taken from the pressure sensors inside the tracheal model (Chameleon TVR, Pressure Profile Systems, Los Angeles, CA) and the ETT pilot balloon via a data logger (Sparx Engineering, Manvel, TX).

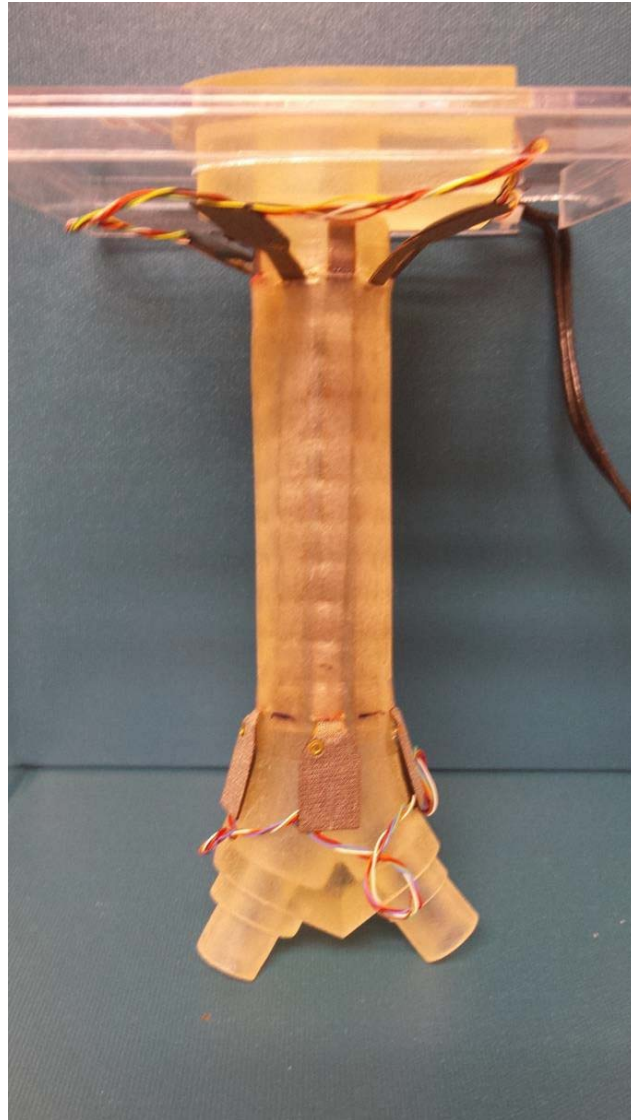


Figure 1. Tracheal model with pressure sensors used to measure TW pressure in the evaluation.

Mean TW pressure and cuff pressure were compared using Student’s t-test. Statistical significance was defined as $p < 0.05$. Any TW pressure measurements >1 mmHg (1.36 cm H₂O) were included in the analysis. With each ETT type and size and each cuff filling method, the following measurements were compared.

- Peak TW pressure at sea level vs. altitude vs. return to sea level
- Mean TW pressure at sea level vs. altitude vs. return to sea level
- Peak TW pressure vs. cuff pressure at sea level, altitude, and return to sea level
- Mean TW pressure vs. cuff pressure at sea level, altitude, and return to sea level
- Cuff pressure at sea level vs. altitude vs. return to sea level.

4.0 RESULTS

When using air in the ETT cuff, TW pressure differences were statistically significant between baseline and altitude measurements with all ETTs but not between baseline and sea level after descending from altitude. When using saline in the ETT cuff, TW pressure differences with the 7.5 HVL P cuff and 8.0 TaperGuard™ cuff (Medtronic, Minneapolis, MN) were statistically significant at altitude and back at sea level, as compared to baseline. Cuff pressure differences with saline in all ETTs were not statistically significant. Comparing peak TW pressure and cuff pressure, the differences were significant at all conditions ($p < 0.05$). Comparing TW pressure and cuff pressure, differences were statistically significant at all conditions with all ETTs with the exception of when returning to sea level after being at altitude when using air in the cuff. Cuff pressure was less than or equal to mean TW pressure at this condition. At the remaining conditions, mean TW pressure was always less than cuff pressure, although peak pressure measured on the TW was always much greater than cuff pressure. Figures 2-4 show the distribution of TW pressures and mean ETT cuff pressures at all conditions. Figure 5 shows the Chameleon software output displaying the mean and peak pressure waveforms (bottom) and the pressure on the sensors inside the model trachea at altitude using an 8.0 ETT with HVL P cuff using air to inflate the cuff (top). The display is in two-dimensional format to show the pressure exerted on each pressure sensor surrounding the inner TW.

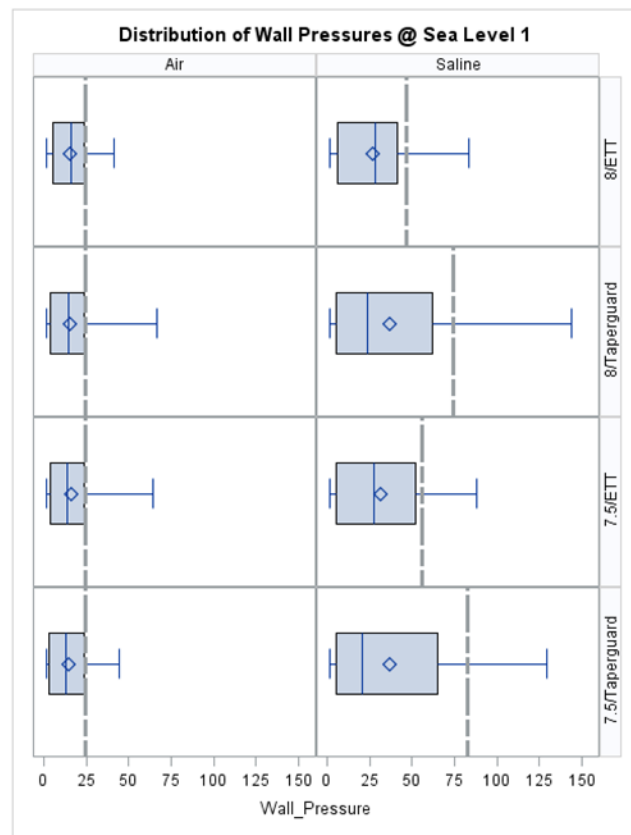


Figure 2. TW and ETT cuff pressures at baseline ambient pressure. Diamond is the mean, vertical line inside the box is the median, box is interquartile range, whiskers are overall range, and vertical dashed line is mean ETT cuff pressure.

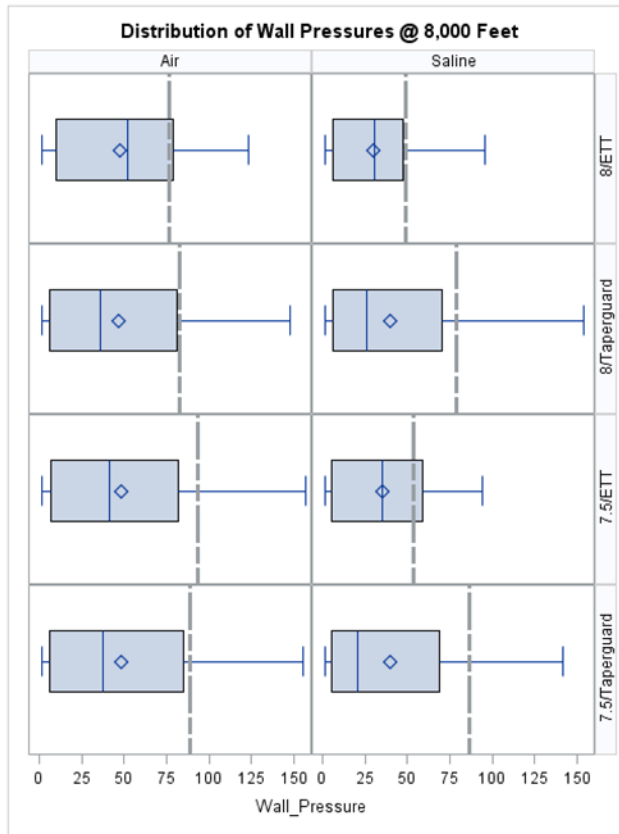


Figure 3. TW and ETT cuff pressures at simulated altitude of 8,000 ft. *Diamond is the mean, vertical line inside the box is the median, box is interquartile range, whiskers are overall range, and vertical dashed line is mean ETT cuff pressure.*

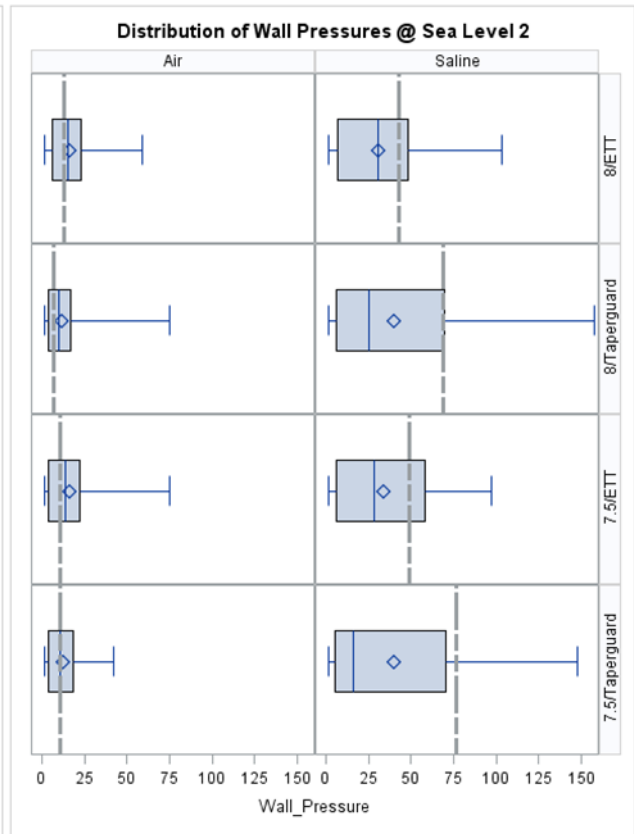


Figure 4. TW and ETT cuff pressures after return to sea level. *Diamond is the mean, vertical line inside the box is the median, box is interquartile range, whiskers are overall range, and vertical dashed line is mean ETT cuff pressure.*

5.0 DISCUSSION

It is recommended that the pressure exerted on the TW be between 20 and 30 cm H₂O [3,8], which represents a balance between having the pressure too low that aspiration of oral secretions occurs or having the pressure high enough to impede or occlude mucosal blood flow. Even in a controlled intensive care unit setting, many patients experience cuff pressure outside of the accepted range [9]. Realizing that in the prehospital setting ETT cuff pressures are not often checked after intubation resulting in dangerously high cuff pressures, Carhart et al. [10] attempted to determine the correct amount of air to put into the cuff to both seal the trachea and minimize the effects of high cuff pressures. The authors recommend 6-7 mL for adult ETTs size 6.0-8.0 mm. Although, depending on the ETT size, 7 mL of air resulted in cuff pressures >30 cm H₂O and 6 mL of air resulted in cuff pressures <20 cm H₂O, they realized that, while not perfect, this method may be better than the current practice of injecting 5-10 mL of air in the cuff with no pressure measurement. While this may represent a viable solution in this bench study, in practice, different types and sizes of ETTs may require either more or less air than the author recommended. This potential solution will be complicated by transport of patients via aeromedical evacuation when barometric pressure changes will have an effect on ETT cuff

volume. It is known that ETT cuff pressures are elevated when exposed to aircraft cabin pressure equivalent to 8,000 feet altitude, which is the typical cabin pressure at which casualties are flown during fixed wing aeromedical evacuation [6]. ETT cuff pressures are also elevated above safe levels even at lower cabin pressures [7,11].

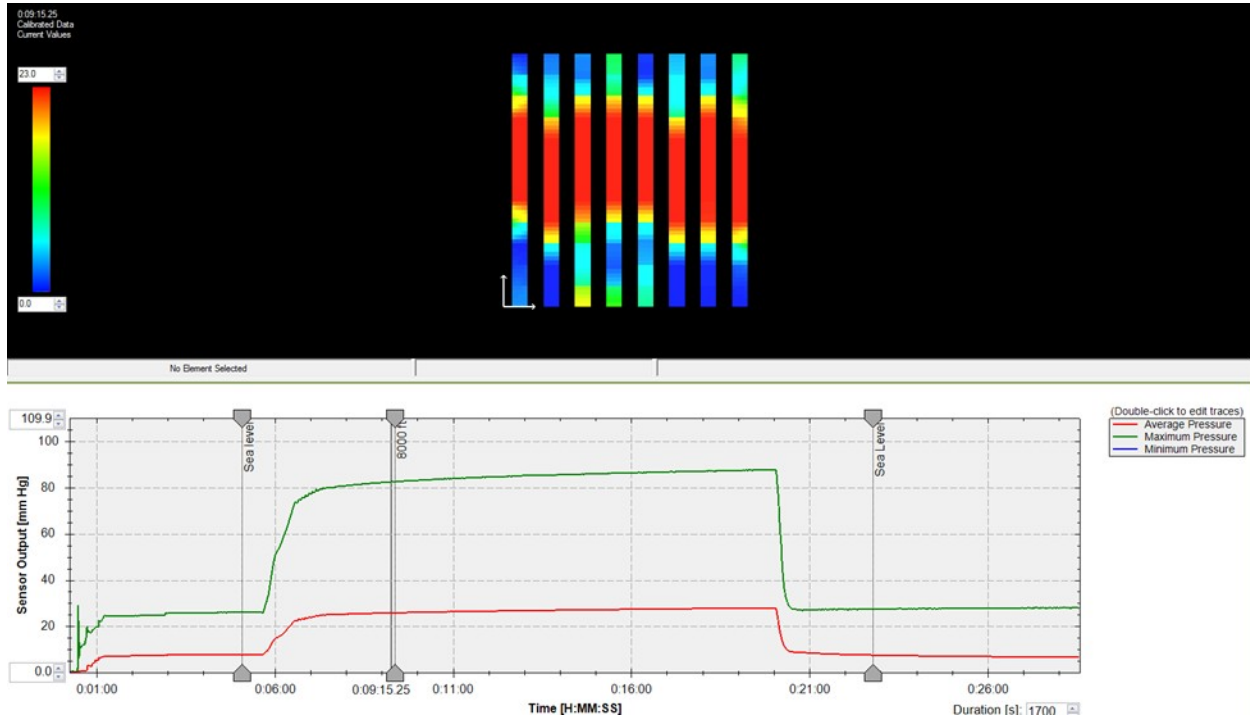


Figure 5. Chameleon software output displaying the mean and peak pressure waveforms (bottom) and the pressure on the sensors inside the model trachea at altitude using an 8.0 ETT with HVLP cuff using air to inflate the cuff (top). Areas in red represent TW pressure >30 cm H₂O.

Since direct measurement of the TW pressure exerted by the ETT cuff is technically difficult to accurately measure in a laboratory setting much less in intubated patients, measurement of the cuff pressure via the pilot balloon is employed as the surrogate. For decades, investigators have used various methods to measure TW pressure in a laboratory model in an attempt to determine if cuff pressure is a suitable alternative for direct measurement of pressure exerted on the tracheal mucosa by the ETT cuff [12-20]. The results of these studies were mixed, with a few finding that cuff pressure approximated or overestimated TW pressure while the majority found TW pressure was underestimated based on cuff pressure. There were large differences in TW pressure between different types of ETTs and cuff shapes and types of material used to manufacture the cuff. The majority of these studies used a rigid cylindrical tube as the tracheal model and employed a single pressure transducer placed between the ETT cuff and wall of the tracheal model to determine TW pressure and compare to cuff pressure. While this model and technique is fairly simple and reproducible, it may not represent the true pressure exerted on the TW and certainly not on all parts of the trachea where contacted by the ETT cuff. Tonnesen et al. [20] used a tracheal model constructed of half elastic material and half rigid plastic with a hole in which a pressure transducer was inserted to determine TW pressure exerted by the ETT cuff in a simulated trachea. The authors found that there was no relationship between

cuff pressure and TW pressure when the ETT cuffs were inflated with enough pressure to seal the trachea.

The TW is not a homogenous structure, as it is rigid anteriorly, elastic posteriorly, and D-shaped, not cylindrical. To our knowledge, our study is the first to use an anatomically correct, three-dimensional printed tracheal model in an attempt to map the pressures on the TW by the ETT cuff. Li Bassi et al. [15] used an array of pressure sensors similar to those used in our study in a cylindrical model but only to show the distribution of pressure on the TW by the ETT cuff at different cuff pressures, not the actual pressures. Our study was the first to measure TW pressure circumferentially both at sea level and simulated altitude to determine the magnitude of changes induced by the hypobaric environment and to compare to the ETT cuff pressures. In our study, Figures 2 and 3 showed that at sea level and at altitude, cuff pressure was equal to or higher than the highest interquartile pressure, except with the 7.5-mm HVLP ETT using saline at altitude, peak TW pressure was always much higher than cuff pressure ($p < 0.05$). With return to sea level after exposure to altitude, pressure in the air-filled cuff was less than the highest interquartile and mean cuff pressure owing to the stretching of the cuff as a result of high volume and pressures due to hypobaric exposure at altitude. This was seen in our earlier work [6]. Cuff and TW pressures with the air-filled cuffs were statistically unchanged ($p > 0.05$) when descending from altitude to sea level (Figure 4).

6.0 CONCLUSIONS

Instillation of saline resulted in the greatest pressure at baseline, but the least amount of variability. The highest fluctuation and peak pressure at altitude resulted from the use of air. Mean TW pressure at all conditions with saline differed significantly and, with the exception of sea level post-descent, with air in the ETT cuff. The impact of hypobarism on ETT management remains a challenge for civilian and military operations. Although this work described functional characteristics in a typical flight profile, military operations provide considerably more variability, suggesting even greater potential impact on patients. To date, best practice is likely constant vigilance in an attempt to mitigate any potential untoward consequences relative to environmental conditions.

A limitation of our study is that it was conducted in a laboratory setting using a tracheal model. Although the model was anatomically correct and three-dimensionally printed based on measurements of actual human tracheas, we cannot be certain that the pressures generated on the TW would translate to the pressure applied to human tracheas. Additionally, we only tested two types of ETTs. We used ETTs with HVLP cuffs, which are the most common ETTs currently in use, and ETTs with tapered cuffs, which represent the most recent innovation in cuff technology. We cannot be certain that pressures exerted on the TW would be the same using other ETT types.

7.0 REFERENCES

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LIST OF ABBREVIATIONS AND ACRONYMS

ETT	endotracheal tube
HVLP	high-volume, low-pressure
TW	tracheal wall