AFRL-SA-WP-SR-2014-0007

Endotracheal Tube Cuff Management at Altitude

SSgt Tyler J. Britton, RRT[1]; Richard D. Branson, RRT[2]; Thomas C. Blakeman, RRT[2]; Dario Rodriquez Jr., RRT[1]; Capt Heather Ortiz, RN, FNP-C[3]; Maj John Eggert, RN[1]

[1]U.S. Air Force School of Aerospace Medicine, Air Force Expeditionary Medical Skills Institute, C-STARS Cincinnati; [2]University of Cincinnati, Department of Surgery; [3]U.S. Air Force School of Aerospace Medicine, Aeromedical Research Department

February 2014

Air Force Research Laboratory
711th Human Performance Wing
School of Aerospace Medicine
Air Force Expeditionary Med Skills Inst
C-STARS Cincinnati
2510 Fifth St.
Wright-Patterson AFB, OH 45433-7913

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
5 Feb 2014	Special Report	June 2012 – December 2013

4. TITLE AND SUBTITLE
Endotracheal Tube Cuff Management at Altitude

5a. CONTRACT NUMBER
FA8650-12-2-6B12

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
SSgt Tyler J. Britton, Richard D. Branson, Thomas C. Blakeman, Dario Rodriquez Jr., Capt Heather Ortiz, Maj John Eggert

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Cincinnati
Sponsored Research Services
51 Goodman Drive, Suite 530
Cincinnati, OH 45221-0222

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
USAF School of Aerospace Medicine
Air Force Expeditionary Medical Skills Institute/C-STARS Cincinnati
2510 Fifth St.
Wright-Patterson AFB, OH 45433-7913

10. SPONSORING/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-SA-WP-SR-2014-0007

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution A: Approved for public release; distribution is unlimited. Case Number: 88ABW-2014-2163, 9 May 2014

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Care of the mechanically ventilated patient during aeromedical transport presents a number of challenges owing to the impact of alterations in barometric pressure on gas volumes and gas density. Hypobarism reduces the partial pressure of oxygen in the atmosphere, which can lead to hypoxia and causes expansion of gas trapped in closed spaces. In the latter case, gas trapped in the body (pneumothorax, bowel gas) or in devices (endotracheal tube (ETT) cuffs, pneumatic tourniquets) expands during ascent and contracts on descent. We designed a model study of endotracheal intubation including mechanical ventilation and four methods of cuff pressure management during ascent and descent aboard a Critical Care Air Transport Team training flight. The results of this study confirm previous work demonstrating a significant rise in ETT cuff pressure during ascent to 8,000 feet. Our data also demonstrate that while filling the ETT cuff with saline reduces the impact of altitude-related changes in cuff pressure, the initial cuff pressure exceeds the pressure associated with interruption of mucosal blood flow. The passive-acting PressureEasy® device reduced the altitude-related change in pressure but did not eliminate the pressure changes, nor could it prevent the low pressures seen on descent.

15. SUBJECT TERMS
Endotracheal tube cuff, mechanical ventilation, aeromedical transport

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					SSgt Tyler J. Britton
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
U	U	U	SAR	15	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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1.0 SUMMARY

Care of the mechanically ventilated patient during aeromedical transport presents a number of challenges owing to the impact of alterations in barometric pressure on gas volumes and gas density. Hypobarism reduces the partial pressure of oxygen in the atmosphere, which can lead to hypoxia and causes expansion of gas trapped in closed spaces. In the latter case, gas trapped in the body (pneumothorax, bowel gas) or in devices (endotracheal tube (ETT) cuffs, pneumatic tourniquets) expands during ascent and contracts on descent. We designed a model study of endotracheal intubation including mechanical ventilation and four methods of cuff pressure management during ascent and descent aboard a Critical Care Air Transport Team training flight. The results of this study confirm previous work demonstrating a significant rise in ETT cuff pressure during ascent to 8,000 feet. Our data also demonstrate that while filling the ETT cuff with saline reduces the impact of altitude-related changes in cuff pressure, the initial cuff pressure exceeds the pressure associated with interruption of mucosal blood flow. The passive-acting PressureEasy® device reduced the altitude-related change in pressure but did not eliminate the pressure changes, nor could it prevent the low pressures seen on descent.

2.0 INTRODUCTION

Early aeromedical evacuation of critically injured patients has been a hallmark of the recent conflicts in the Middle East and is credited with improvements in outcomes (Ingalls N, Zonies D, Bailey JA, et al. A decade of care in the air: review of the first 10 years of critical care aeromedical transport during Operation Iraqi Freedom and Operation Enduring Freedom. Submitted for publication to JAMA Surg) [1,2]. Care of the mechanically ventilated patient during aeromedical transport presents a number of challenges owing to the impact of alterations in barometric pressure on gas volumes and gas density [3-5]. Hypobarism reduces the partial pressure of oxygen in the atmosphere, which can lead to hypoxia and causes expansion of gas trapped in closed spaces [6]. In the latter case, gas trapped in the body (pneumothorax, bowel gas) or in devices (endotracheal tube (ETT) cuffs, pneumatic tourniquets) expands during ascent and contracts on descent.

In previous investigations, the emphasis on ETT cuff management at altitude has been focused on prevention of high pressures following ascent [7-15]. A number of investigations have evaluated the change in cuff pressure and volume during actual or simulated flight at a variety of altitudes [8,9,11-16]. These investigations typically measure changes at two static points at sea level and the resulting altitude. Results of these studies focus on the avoidance of high pressures at altitude associated with reductions in mucosal blood flow [17]. However, descent is associated with cuff deflation and the passage of oropharyngeal secretions into the lower airway, a key component in the etiology of ventilator-associated pneumonia [18].

We designed a model study of endotracheal intubation including mechanical ventilation and four methods of cuff pressure management during ascent and descent aboard a Critical Care Air Transport Team (CCATT) training flight.

3.0 METHODS

The study was conducted at Lunken Airfield in Cincinnati, OH, while utilizing a C-130H airframe (U.S. Air Force, Kentucky Air National Guard) during routine CCATT training flights. We evaluated cuff management techniques at sea level, 8,000 feet, and return to sea level. An altitude of 8,000 feet (representing a barometric pressure of 562 mmHg) was chosen to represent normal cabin altitude during CCATT flights. Lunken Airfield is at 483 feet above sea level, where barometric pressure was routinely 768 mmHg.

We tested two standard ETTs in the CCATT allowance standard commonly used for men (8.0-mm inner diameter (ID); Mallinckrodt Lo-Pro Oral/Nasal Tracheal Tube, Covidien, Mansfield, MA) and women (7.5-mm ID; Portex Clear PVC, Oral/Nasal, Soft Seal® Cuff Tracheal Tubes, Smiths Medical, Dublin, OH). Each flight used new ETTs for each experimental condition.

A model was built and outfitted with four flexible tracheal models (Laerdal Medical, Wappingers Falls, NY) with an ID of 22 mm. The tracheal models were then intubated using the 8.0-mm- and 7.5-mm-ID ETT. To simulate an in vivo tracheal model, the tubes were lubricated with Surgilube (Fougera Pharmaceuticals Inc., Melville, NY). The tracheal models were then connected to test lungs (Adult 190 1 Liter, Maquet, Rastatt, Germany) with standard corrugated tubing. A saliva substitute with specific gravity matching human saliva (Oralube Saliva Substitute 125 mL, Orion Laboratories, Balcatta, Australia) was placed above the cuffs. A 15-mL volume was used to simulate oropharyngeal secretions. A graduated cylinder was used to collect and measure the volume of saliva, if any, leaking around ETT cuffs.

To simulate the clinical environment, four transport ventilators (Model 731, Impact Instrumentation, West Caldwell, NJ) were used to ventilate each tracheal model using a manufacturer-supplied ventilator circuit. Ventilator settings were respiratory rate of 12, tidal volume of 450 mL, positive end expiratory pressure of 5 cm H_2O, inspiratory time of 1 second, and an FiO_2 of 21%. The tracheal models were attached to a board that was hung in a litter stanchion of the C-130H. The tracheal models were elevated to 30° to follow ventilator-associated pneumonia prevention protocol (Figure 1). ETT pilot balloons were then attached to a three-way stopcock. Pressure transducers (Edwards TruWave Disposable Pressure Transducer, Edwards Lifesciences, Irvine, CA) were attached to the opposite end of the three-way stopcock. Pressure transducers interfaced with a data logger (Sparx Engineering LLC, Manvel, TX), which recorded cuff pressures every second. The data logger had previously been approved for flight aboard the airframe.

ETT cuffs were managed using four methods:

1. Control – The ETT cuff was inflated with air to a pressure of 20-22 mmHg using a cuff pressure manometer (Rusch Endotest, Teleflex Inc., Limerick, PA) and not manipulated again.

2. Manual – The ETT cuff was inflated with air to a pressure of 20-22 mmHg using a cuff pressure manometer (Rusch Endotest, Teleflex Inc., Limerick, PA). At a cruising altitude of 8,000 feet, a respiratory therapist measured pressure and readjusted pressure to 20-22 mmHg. Upon descent, the cuffs were again adjusted to the standard pressure.

3. PressureEasy® Cuff Pressure Controller (Smiths Medical, Dublin, OH) – The PressureEasy® system was connected to the ETT pilot balloon and inflated through the device to a pressure of 20-22 mmHg and not manipulated again.

4. Saline – According to standard CCATT procedure, air was removed from the cuff and 10 mL saline inserted. The pressure was measured and the cuff was not manipulated again.

Figure 1. Model system including model trachea, ETT, test lungs, and ventilators.

During each flight, attendants were required to remain seated during ascent and descent; thus, manual cuff pressure management was restricted to cruising altitude and while on the tarmac. Measurements were obtained during three flights with each size ETT.

All pressures were continuously measured. The mean pressure over a period of 5 minutes was recorded prior to ascent, at cruising altitude, and after landing. Data are expressed as mean ± standard deviation and compared using a t-test (Microsoft Excel, Redmond, WA).

4.0 RESULTS

The mean pressure at baseline using the three techniques was 21 ± 1.3 mmHg. Saline inflation of the 8.0-mm-ID ETT resulted in a pressure of 48 ± 6 mmHg and 40 ± 2 mmHg in the 7.5 ETT. During flight, the highest cuff pressures were obtained with the control and manual management methods (Table 1). The smallest change in cuff pressure was seen during saline inflation (mean increase of 7.0 ± 0.8 mmHg in the 7.5 ETT and 7.6 ± 0.5 mmHg in the 8.0 ETT). The PressureEasy® device maintained a lower pressure than either the control or manual methods, with a mean increase of 19.3 ± 7.7 mmHg with the size 7.5 ETT and 11.3 ± 2.5 mmHg with the size 8.0 ETT.

After descent, cuff pressure using all three air-inflation techniques was lower than the first baseline measurement and below the pressure recommended to prevent aspiration of secretions around the cuff (Table 1). Pressure in the saline-filled tubes after descent was within 2 mmHg of the baseline pressure. Leakage of artificial saliva around the ETT cuff was not seen with any of the four techniques. The change in pressure per 1,000 feet of altitude with the air-filled cuffs was 8.1 ± 0.7 mmHg. The change in pressure per 1,000 feet of altitude with the

PressureEasy® device was 2.3 ± 0.9 mmHg. Using saline inflation, the mean change in pressure per 1,000 feet of altitude was 0.87 ± 0.02 mmHg. Figures 2 and 3 demonstrate continuous measurements of cuff pressures using all four methods with a 7.5-mm-ID and 8.0-mm-ID ETT.

Table 1. Changes in ETT Cuff Pressure during the Study

Method	Sea Level (Baseline)[a]		8,000 ft[a]		Sea Level (Post-Flight)[a]	
	7.5 mm	8.0 mm	7.5 mm	8.0 mm	7.5 mm	8.0 mm
Control (mmHg)	21±0.8	20±1.1	85±0.8[b]	85±0.6[b]	9±0.3[b]	8±0.6[b]
Manual (mmHg)	21±0.7	20±1.5	82±1.1[b]	84±0.4[b]	5±0.8[b]	4±0.4[b]
PressureEasy® (mmHg)	21±0.8	21±1.4	39±8.9[b]	36±1.6[b]	14±2.4[b]	14±3.2[b]
Saline (mmHg)	40±2.1	63±6.0	47±1.1[c]	68±2.9[c]	37.5±1.4	60±3.3

[a]Data are mean ± standard deviation.
[b]p<0.001 compared to baseline.
[c]p<0.01 compared to baseline.

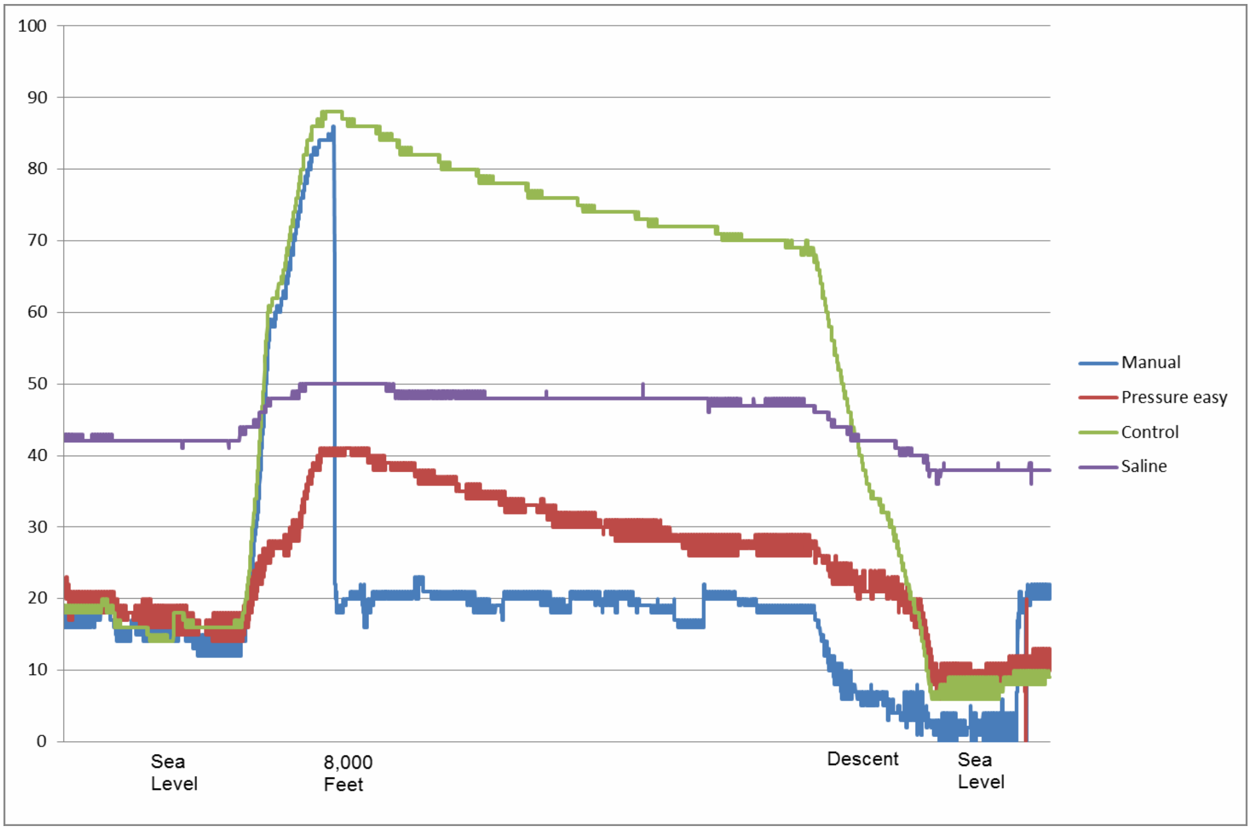

Figure 2. Continuous pressure monitoring of all four cuff management techniques using the 7.5 ETT.

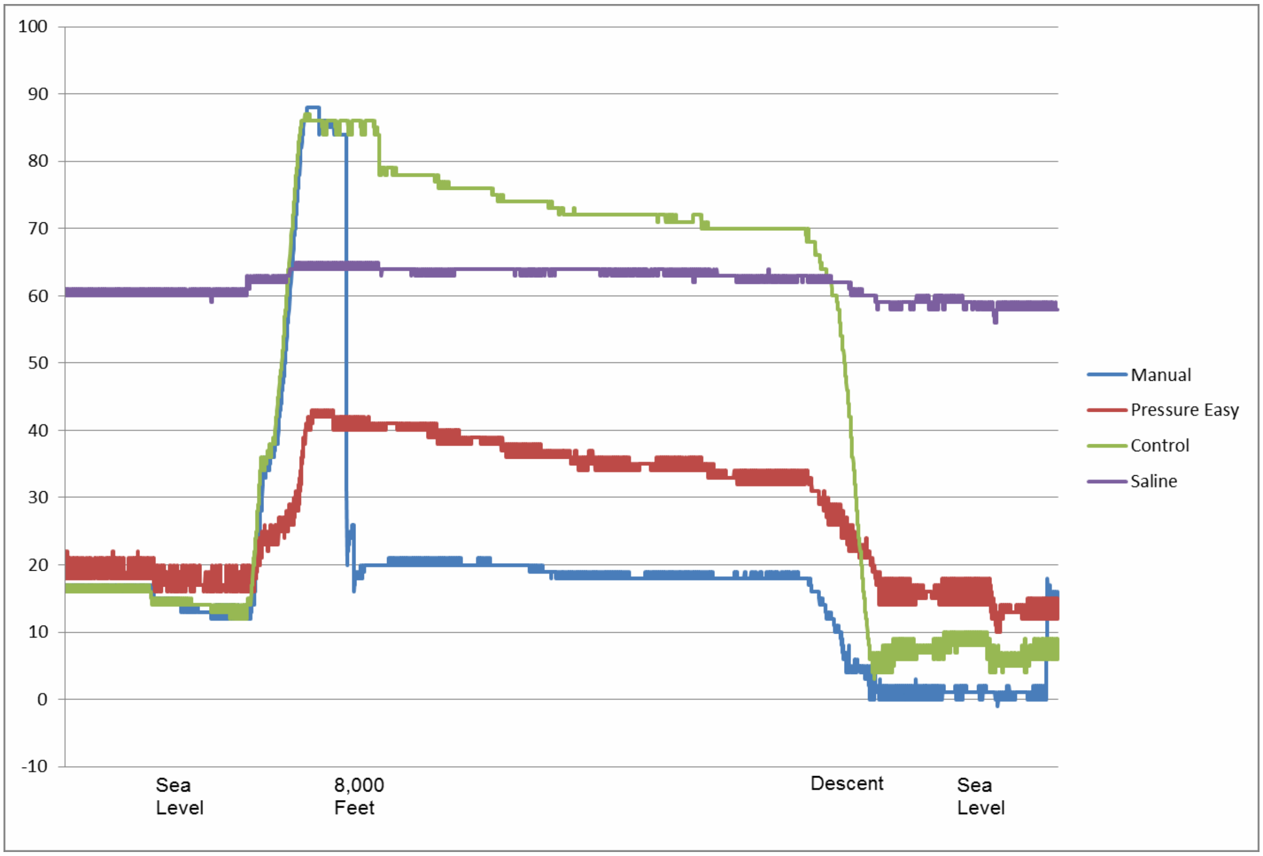

Figure 3. Continuous pressure monitoring of all four cuff management techniques using the 8.0 ETT.

5.0 DISCUSSION

The results of this study confirm previous work demonstrating a significant rise in ETT cuff pressure during ascent to 8,000 feet. Our data also demonstrate that while filling the ETT cuff with saline reduces the impact of altitude-related changes in cuff pressure, the initial cuff pressure far exceeds the pressure associated with interruption of mucosal blood flow. The passive-acting PressureEasy® device reduced the altitude-related change in pressure but did not eliminate the pressure changes, nor could it prevent the low pressures seen on descent.

An important finding of our study is the reduction in cuff pressures during and following descent. In fact, the pressures were lower than at baseline. Our observation of the cuffs suggests that the high pressures at altitude stretch the cuff, resulting in lower pressures after descent despite no change in the volume of air. In all three techniques using air-filled cuffs, the pressure upon landing falls below the threshold typically required to prevent aspiration of secretions around the cuff. These findings have important clinical implications, as cuff pressures < 25 cm H_2O are associated with the development of ventilator-associated pneumonia [19,20]. We did not experience any leakage of fluid around the cuffs using any cuff management method during the short period of reduced pressure after landing (approximately 10 minutes). However, our model included lubrication of the cuffs and the use of 5 cm H_2O positive end expiratory pressure, both of which have been shown to reduce or prevent leakage around the cuff in analog models [21]. The increase in ETT cuff pressure at altitude is easily explained by Boyle's law. Boyle's law states that at a constant temperature, pressure is inversely proportional to volume. Commonly written as PV ∝ k, P is pressure, V is volume, and k is a constant. With respect to the ETT cuff, the law can be written as P1V1 = P2V2. The decrease in barometric pressure at altitude results in a nearly linear change in volume, increasing the cuff pressure within the trachea. Table 2 compares studies evaluating the impact of altitude on cuff pressures and volume. Both patient and model studies demonstrate predictable increases in cuff pressure and volume. In studies where the tube and cuff are tested outside of a model or patient, the pressure changes are smaller. When the tubes are placed in the patient or in a model, the restriction of the cuff volume expansion results in higher measured pressures. This explains much of the disparity in the results of these trials.

Table 2. Comparison of Studies Evaluating the Impact of Changes on Cuff Pressures of Artificial Airways

Author	Device	Method	Cuff Measurement	Subject	Altitude Method/Height (ft)	Outcome
Smith [8]	ETTs	Air filled	Pressure	Tracheal model	Chamber/10,000	Cuff pressure > 100 cm H_2O at 8,000 ft
Henning [9]	ETTs	Air filled	Pressure	10 adults	Fixed wing/3,000	Cuff pressure 45 cm H_2O at 3,000 ft
Mann [11]	ETTs LMA	Air filled	Diameter	Bench top	Rotor wing/10,000	Cuff diameter increased by 4.5 mm at 10,000 ft
Wilson [12]	LMA	Air filled	Pressure	Adult & infant mannequin	Fixed wing/6,000 Rotor wing/2,200	Cuff pressure > 120 cm H_2O at 5,000 ft
Miyashiro [13]	ETTs LMA	Air filled	Pressure	Tracheal model	Ground ascent/ 7,874	Cuff pressure > 80 cm H_2O at 8,000 ft. In vitro pressures 30% greater than bench top
Law [14]	ETTS LMA LT Combitube	Air and water filled	Volume (volume displacement)	Bench top	Chamber/15,000	Cuff volume constant with saline-filled cuffs
Brendt [15]	ETTs	Air filled	Pressure	35 adults	Fixed wing/3,594[a]	Cuff pressures exceed 40 cm H_2O at 3,000 ft
Bassi [16]	ETTs	Air filled	Pressure	114 patients	Rotor wing/2,260[a]	Cuff pressure doubled at altitude, 72% were > 50 cm H_2O

Note: LMA = laryngeal mask airway; LT = laryngeal tube.
[a]Mean value.

We noted that it is difficult to completely empty the cuff of air and then fill it with saline. During initial model development, we noted that if a small amount of air remained in the cuff along with the saline, pressures as high as 80 mmHg could be measured at altitude. We believe the presence of 2-4 mL of air within the non-compressible saline creates these high pressures and uneven inflation of the cuff. Most ETT manufacturers warn against saline inflation, as the saline is difficult to remove and can lead to cuff wear and rupture. Additionally, a single 10-mL filling volume is associated with excessive pressures at sea level.

6.0 LIMITATIONS

Our study uses a mechanical model to simulate the trachea and may not accurately represent the human anatomy. The size and shape of the trachea vary widely and the size of the tracheal diameter relative to the internal diameter of the ETT and cuff can alter the volume required to create an effective seal [22]. Ventilator settings can also alter cuff pressures. Our model only used a single set of ventilator parameters and lung model characteristics.

7.0 CONCLUSION

Management of the ETT cuff at altitude remains a challenge for civilian and military operations. The use of a single inflation with 10 mL of saline avoids pressure changes at altitude, but pressure at sea level exceeds the pressure associated with tracheal mucosal blood flow occlusion. Additionally, most ETT manufacturers warn against saline inflation. Manual adjustment is limited by access to the patient. A passive device helps ameliorate the high pressures, but cannot prevent low pressures on descent, which may lead to aspiration of secretions above the cuff. Closed loop control of cuff pressure may represent an answer to management at altitude, but should be tested in a tactical environment [23].

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LIST OF ABBREVIATIONS AND ACRONYMS

CCATT Critical Care Air Transport Team

ETT endotracheal tube

ID inner diameter