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Three Endotracheal Cuff Pressure Management Strategies in Pigs under Simulated High-Altitude Conditions: Randomized Study

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Title: Three Endotracheal Cuff Pressure Management Strategies in Pigs under Simulated High-Altitude Conditions: Randomized Study

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Abstract

Background: Aeromedical evacuation requires advanced critical care, and precise cuff pressure management is essential for artificial airway safety. Cuff pressure is normally maintained at 25-30 cmH_2O, but during aeromedical evacuation, the dynamic hypobaric cabin environment may alter cuff volume. According to Boyle's law, gas expands as pressure decreases, and rapid cabin pressure changes during ascent and descent can cause pressure instability, ventilator leakage,

increased risk of ventilator-associated pneumonia, and acute airway mucosal injury. Although automatic pressure regulation and water-filling methods have been explored, evidence remains limited.

Methods: Twenty-four healthy adult male pigs were used to establish an artificial airway model and randomly divided into air-filled cuff group (Group A), automated cuff pressure control group (Group B), or saline-filled cuff group (Group C). Animals were exposed to a simulated high-altitude environment in a hypobaric chamber using a typical high-altitude flight profile (climb-cruise-descent). Cuff pressure was continuously monitored, and tracheal mucosal injury was assessed.

Results: Cuff pressure differed significantly among the three groups in all three phases (all $P < 0.001$). During ascent and cruise, Group A had the highest pressure and Group B the lowest (all pairwise $P < 0.05$); during descent, Group B had the highest pressure, whereas Groups A and C did not differ significantly ($P = 0.984$). The group×altitude and group×time interactions were significant in all phases (all $P < 0.001$). Group A showed significantly steeper pressure changes than Groups B and C in all three phases (all $P < 0.001$), whereas Groups B and C did not differ significantly. Mucosal injury was most frequent in Group A and least in Group B, without statistical significance ($P = 0.083$).

Conclusions: In this simulated high-altitude porcine model, automated cuff pressure control provided the most stable regulation and lowest mucosal injury, making it a favorable strategy for airway management. Conversely, air-filled cuffs performed the poorest. Saline-filled cuffs may serve as an alternative when automated devices are unavailable, though they lack active regulation. Although mucosal injury differences lacked statistical significance, larger studies with

histopathological validation are required to confirm these findings.

Keywords: Endotracheal tube cuff; cuff pressure; simulated high altitude; hypobaric chamber; pig; randomized study; automated pressure control; saline-filled cuff

Background

Aeromedical evacuation is a primary method for transporting critically ill patients during medical rescue operations worldwide and requires intensive care support throughout transport [1]. Establishing an artificial airway is a core life-support measure in severely injured patients, and accurate cuff pressure management is critical for its effectiveness and safety. In conventional settings, maintaining cuff pressure within 25–30 cmH_2O is widely accepted to balance effective airway sealing and prevent mucosal ischemic injury [2]. During aeromedical evacuation, however, cabin pressure changes with altitude. According to Boyle's law, gas expands as atmospheric pressure decreases [3]. Consequently, rapid cabin pressure changes during ascent and descent can alter the gas volume within the airway cuff (e.g., an endotracheal tube cuff), causing cuff pressure instability. This instability may lead to ventilator leakage and increase the risk of ventilator-associated pneumonia; it may also cause acute airway mucosal injury, further compromising already vulnerable patients [4]. To investigate these altitude-induced changes in a controlled setting, hypobaric chambers have been utilized to simulate dynamic flight profiles.

Previous studies have recognized the impact of high-altitude environments on artificial airway cuff pressure. While some researchers have explored continuous automated pressure stabilization [5], others have proposed or applied alternative strategies such as saline-filled cuffs [6]. However, evidence on cuff pressure management under simulated high-altitude conditions remains limited. Most available studies are descriptive or observational, and few controlled in

vivo studies have directly compared different management strategies. To address this gap, the present study simulated high-altitude conditions in a hypobaric chamber and compared three cuff management strategies—air-filled, saline-filled, and automated pressure control—in a randomized porcine model, evaluating both cuff pressure changes and tracheal mucosal injury. The results are presented below.

Methods

Experimental Animals

This study has passed the ethical review of the Experimental Animal Science and Technology Ethics Committee of the Air Force Medical University, approval number: 20250165, and complies with the National Animal Experiment Ethics Operation Regulations, research ethics guidelines, and relevant clinical trial regulations in China. Twenty-four healthy adult male pigs, weighing 37.4–58.6kg, were used in this study, which were obtained from Western Mars (Shaanxi) Biotechnology Co., Ltd. (Xi'an, China). They were housed individually in clean, temperature-controlled rooms, fed a standard diet, given free access to water, and maintained under a normal circadian rhythm. The housing environment complied with Chinese standards for laboratory animals. Animals with concurrent diseases were excluded to assess the independent effect of high-altitude environmental pressure changes on cuff pressure and to clarify the relationship between pressure fluctuations and environmental changes.Before model establishment, all 24 pigs were fasted for 12–24 h, and water was withheld for 4–6 h.

Experimental materials

The following drugs, equipment, and consumables were used: Shutai 50 injection(Zoletil 50), propofol injection, isoflurane, lidocaine injection, an anesthesia ventilator, ventilator tubing, a

humidification chamber, an electrocardiogram monitor, a cylindrical endotracheal tube (7.0–8.0mm ID), an endotracheal tube fixator, a stethoscope, an anesthesia laryngoscope, an electric suction device, an oxygen mask, a mouth gag, an intravenous catheter, a restraint band, syringes, a commercial cuff pressure monitoring device (model HPC-1; Wuxi Huayao Biotechnology Co., Ltd., China), 0.9% sodium chloride injection, a thermometer, and a micro pump (or infusion pump).

Animal Model Establishment

Anesthesia was induced by intramuscular injection of Shutai 50. After an adequate level of sedation was achieved, the animal was placed in the supine position on the operating table, and the limbs were fixed with bandages in gentle abduction. A thicker, straighter vein at the ear margin was selected, disinfected with alcohol, and punctured with a 22G indwelling needle, which was then properly secured. The same procedure was performed on the other side to establish another intravenous access. Oxygen was administered via a mask for 5-10 min (pure oxygen at 4 L/min), and propofol (1.5 mg/kg) was injected intravenously within 15s. Before endotracheal intubation, lidocaine was sprayed onto the larynx to prevent laryngospasm. A laryngoscope was inserted through the right corner of the mouth, and a dedicated assistant continuously maintained the pig's mouth position and observed the laryngeal condition. After the tip of the endotracheal tube was inserted into the glottis, the stylet was removed, and the tube was ensured not to be displaced or dislodged. The tube was then carefully advanced further. Chest rise, airflow through the tube, bilateral breath sounds, and oxygen saturation were assessed. Fiberoptic bronchoscopy was used to confirm successful intubation and to observe the mucosal condition before the experiment. The cuff was inflated with a syringe. Cuff pressure was

monitored using a central venous pressure sensor and adjusted to 25-30 cmH_2O with a cuff pressure controller. Isoflurane (2%) was inhaled to maintain anesthesia. After successful intubation, the animal was connected to an anesthesia machine in controlled mechanical ventilation mode. Tidal volume was set at 6-8 mL/kg, respiratory rate at 12±2 breaths/min, oxygen flow at 1.5±0.5 L/min, and inspiratory-to-expiratory ratio at 1:2. ECG monitoring devices and thermometers were connected to monitor peripheral pulse, blood pressure, and body temperature. All animals received an intravenous infusion of 0.9% saline at 3 mL/kg/h to maintain fluid balance and compensate for anesthesia-induced fluid loss.

Intervention/ measurements

After model establishment, 24 pigs were randomly assigned to one control group (Group A) and two experimental groups (Groups B and C) using a random number table. Based on previous studies and ethical considerations to minimize animal use, 8 pigs per group were used.

Group A (air-filled cuff group; control group): The endotracheal tube cuff was inflated with air. Cuff pressure was continuously monitored using a central venous pressure sensor, and no additional adjustment was made during the experiment.

Group B (automated cuff pressure control group): The cuff was inflated with air. A commercial cuff pressure controller was used to automatically inflate and deflate the cuff, enabling real-time monitoring and dynamic adjustment of cuff pressure.

Group C (saline-filled cuff group): The cuff was filled with 0.9% sodium chloride injection. Cuff pressure was continuously monitored using a central venous pressure sensor, and no additional adjustment was made during the experiment.

Hypobaric chamber setup and flight profile simulation

The experiment was conducted in a hypobaric oxygen chamber, which was configured to simulate the high-altitude flight profile. The chamber was set to simulate an altitude of 3 km, with an oxygen partial pressure of 70.1 kPa, a temperature of 25 ± 3 °C, and about a humidity of 60%. After the chamber door was closed, the chamber was depressurized by personnel outside. The time required for depressurization from atmospheric pressure to the target altitude (simulating aircraft climb) and for recompression to atmospheric pressure (simulating aircraft descent) was 8–15 min, corresponding to a rate of 5 m/s. The chamber was then maintained at the simulated cruising altitude of 3 km for 90 min. According to the chamber settings, before stabilizing at the cruising altitude, the chamber first ascended to a buffer altitude of 3240m and then gradually stabilized at the target cruising altitude.

Observation indicators

Cuff pressure was measured at the following time points: before climbing (the altitude of Xi'an is 470 m, and that of the laboratory is approximately 500 m); during climbing (once for every 0.5 km increase in altitude); at the buffer altitude (3240 m); at 15, 30, 45, 60, 75, and 90 min after reaching the target cruising altitude (once every 15 min); during descent (once for every 0.5 km decrease in altitude); and 5 min after reaching atmospheric pressure. Cuff pressure was measured and recorded using a cuff pressure measuring device.

Assessment of tracheal mucosal injury: Before intubation and after extubation, the tracheal mucosa at the intubation site of each animal was examined by visual inspection and fiberoptic bronchoscopy for signs of damage, including redness, congestion, edema, and ulceration. The assessment was performed by an observer blinded to group allocation.

Euthanasia

At the end of the experiment, the animals were euthanized. Briefly, deep anesthesia was induced by intravenous injection of propofol (10 mg/kg) via the ear vein, followed by a rapid intravenous injection of 10% potassium chloride (0.5 mL/kg) to induce cardiac arrest. This two-step method ensures that the animals were completely unconscious and did not experience pain, strictly conforming to the AVMA Guidelines for the Euthanasia of Animals.

Statistical analysis

SPSS 27.0 (IBM Corp., Armonk, NY, USA) was used for statistical analysis. Non-normally distributed continuous variables were expressed as median (25th–75th percentile) and compared using the Kruskal-Wallis H test. Categorical variables were presented as n (%) and compared using Fisher' s exact test. Linear mixed-effects models were used to analyze repeated-measures data for each flight phase, with group, altitude (or time), and their interaction as fixed effects, and animal as a random effect (random intercept). Pairwise comparisons were performed with Bonferroni correction. A two-sided *P* value < 0.05 was considered statistically significant.

Results

Baseline characteristics

A total of 24 healthy adult pigs were included and randomly assigned to three groups (n = 8 per group). Baseline characteristics are summarized in Table 1. There were no significant differences among the three groups in age, weight, intubation time, or baseline cuff pressure, endotracheal tube internal diameter (all *P* > 0.05).

Table 1. Baseline characteristics of the three groups.

Variable	Group A (n=8)	Group B (n=8)	Group C (n=8)	*P* value
Age, months	13.00 (12.25–13.00)	12.50 (12.00–13.00)	12.00 (11.25–13.00)	0.242
Weight, kg	50.20 (41.2–51.33)	48.35(44.93–51.70)	39.80 (38.38–47.75)	0.204
Intubation time, min	178.00 (176.25–179.75)	180.00 (176.25–186.25)	178.00 (176.50–180.75)	0.295
Baseline cuff pressure, cmH_2O	29.9 (27.83–29.90)	28.7 (27.48–29.43)	28.5 (27.10–29.90)	0.428
Endotracheal tube ID, mm				
7.0	1 (12.5)	0 (0.0)	1 (12.5)	0.418
7.5	6 (75.0)	8 (100.0)	5 (62.5)	
8.0	1 (12.5)	0 (0.0)	2 (25.0)	

Note: Data are presented as median (25th–75th percentile) or *n* (%). Continuous variables were compared using the Kruskal-Wallis H test; categorical variables were compared using Fisher's exact test. Group A, air-filled cuff group (control); Group B, automated cuff pressure control group; Group C, saline-filled cuff group. A two-sided P value < 0.05 was considered statistically significant.

Cuff pressure during different flight phases

Cuff pressure differed significantly among the three groups during ascent, cruise, and descent (all $P < 0.001$, Kruskal-Wallis H test; Table 2, Figure 1). Pairwise comparisons with Bonferroni correction showed that, during ascent, Group A had significantly higher pressure than Groups B and C, and Group B had significantly lower pressure than Group C (all $P < 0.001$). During cruise, Group A again had significantly higher pressure than Groups B and C (both $P < 0.001$), and Group B had significantly lower pressure than Group C ($P = 0.021$). During descent, Group B had significantly higher pressure than Groups A and C (both $P < 0.001$), whereas no significant difference was found between Groups A and C ($P = 0.984$). The pressure trends across the three flight phases are illustrated in Figure 1.

Table 2. Median cuff pressure during ascent, cruise, and descent in the three groups.

Flight Phase	Group A (n=8)	Group B (n=8)	Group C (n=8)	*P* value	Pairwise comparison
Ascent (cmH_2O)	106.05 (59.75–130.93)	29.30 (27.13–30.95)	33.25 (28.50–36.60)	＜0.001	A vs B: <0.001; A vs C: <0.001; B vs C: <0.001
Cruise (cmH_2O)	82.95 (71.90–91.25)	29.30 (28.43–30.08)	33.90 (23.43–39.40)	＜0.001	A vs B: <0.001; A vs C: <0.001; B vs C: 0.021
Descent (cmH_2O)	8.10 (4.10–30.05)	28.45 (27.33–30.20)	19.70 (8.10–27.10)	＜0.001	A vs B: <0.001; A vs C: 0.984; B vs C: <0.001

Note: Data are presented as median (25th-75th percentile). Overall between-group comparisons were performed using the Kruskal-Wallis H test. Pairwise comparisons were performed using the Mann-Whitney U test with Bonferroni correction; adjusted *P* values are shown. Group A, air-filled cuff group (control); Group B, automated cuff pressure control group; Group C, saline-filled cuff group. cmH_2O, centimeters of water. A two-sided *P* value < 0.05 was considered statistically significant.

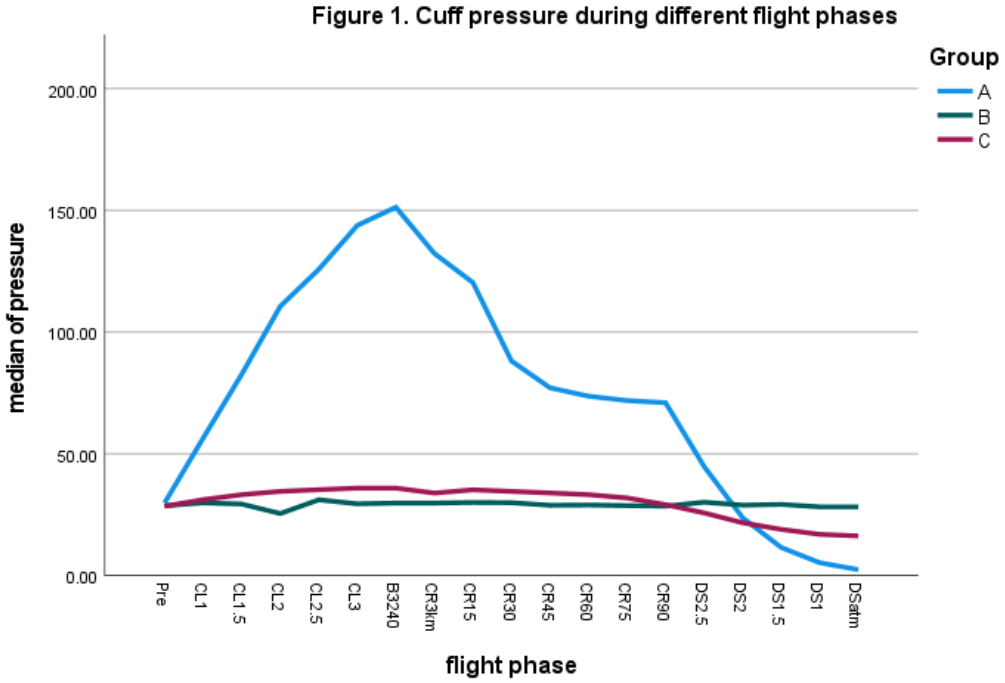


Figure 1. Cuff pressure changes during ascent, cruise, and descent in the three groups.

Group A, air-filled cuff group (control); Group B, automated cuff pressure control group; Group C,

saline-filled cuff group. Pre, pre-climb; CL1–CL3, climb at 1–3 km; B3240, buffer altitude of 3240 m; CR3km, cruise at 3000 m; CR10–CR90, cruise duration in minutes; DS1–DS2.5, descent at 1–2.5 km; DSatm, descent to atmospheric pressure. Data are presented as median. The x-axis represents simulated altitude during ascent and descent and time during cruise. cmH_2O, centimeters of water.

Slopes and pairwise comparisons

The group × altitude (or time) interaction was significant in all three phases (all $P < 0.001$; Table 3). During ascent, Group A showed the steepest increase with altitude (0.0448 cmH_2O/m), followed by Group C (0.0048 cmH_2O/m), whereas Group B showed no significant change ($P = 0.059$). Pairwise comparisons showed that Group A differed significantly from Groups B and C (both $P < 0.001$), whereas Groups B and C did not differ significantly ($P = 0.059$). During cruise, Group A showed a significant decline over time (−0.6944 cmH_2O/min), whereas Groups B and C remained stable. Group A differed significantly from Groups B and C (both $P < 0.001$), whereas Groups B and C did not differ significantly ($P = 0.588$). During descent, Group A showed a significant decrease with decreasing altitude (0.0224 cmH_2O/m), whereas Groups B and C showed no significant change. Group A differed significantly from Groups B and C (both $P < 0.001$), whereas Groups B and C did not differ significantly ($P = 0.398$).

Table 3. Estimated slopes of cuff pressure change.

Flight phase	Group A slope (95% CI)	*P* value	Group B slope (95% CI)	*P* value	Group C slope (95% CI)	*P* value	*P* value (interaction)
Ascent (cmH_2O/m)	0.0448 (0.0352−0.0448)	＜0.001	0.0001 (−0.0094−0.0002)	0.059	0.0048 (0.0014−0.0082)	0.006	＜0.001
Cruise (cmH_2O/min)	−0.6944 (−0.8301 to −0.4207)	＜0.001	−0.0127 (−0.1484−0.2610)	0.588	−0.0690 (−0.2137−0.0757)	0.348	＜0.001
Descent (cmH_2O/m)	0.0224 (0.0121−0.0248)	＜0.001	0.0012 (−0.0092−0.0037)	0.396	0.0040 (−0.0006−0.0085)	0.086	＜0.001

Note: Data are slopes (95% CI) estimated from linear mixed-effects models. *P* values for each group refer to whether the slope differs from zero. The *P* (interaction) refers to the group × altitude interaction for the ascent and descent phases and the group × time interaction for the cruise phase.

Pairwise comparisons of slopes were performed using custom hypothesis tests:

Ascent: A vs B, $P < 0.001$; A vs C, $P < 0.001$; B vs C, $P = 0.059$.

Cruise: A vs B, $P < 0.001$; A vs C, $P < 0.001$; B vs C, $P = 0.588$.

Descent: A vs B, $P < 0.001$; A vs C, $P < 0.001$; B vs C, $P = 0.398$.

Group A, air-filled cuff group (control); Group B, automated cuff pressure control group; Group C, saline-filled cuff group. cmH_2O, centimeters of water; CI, confidence interval. A two-sided *P* value < 0.05 was considered statistically significant.

Tracheal mucosal injury

The incidence of tracheal mucosal injury was highest in Group A and lowest in Group B, but the difference was not statistically significant ($P = 0.083$; Table 4, Figure 2).

Table 4. Incidence of tracheal mucosal injury in the three groups.

Mucosal injury	Group A (n = 8)	Group B (n = 8)	Group C (n = 8)	*P* value
Yes	8 (100.0)	4（50.0）	7（87.5）	0.083
No	0（0.0）	4（50.0）	1（12.5）	

Note: Data are presented as n (%). Between-group comparisons were performed using Fisher’s exact test. Group A, air-filled cuff group (control); Group B, automated cuff pressure control group; Group C, saline-filled cuff group. A two-sided P value < 0.05 was considered statistically significant.

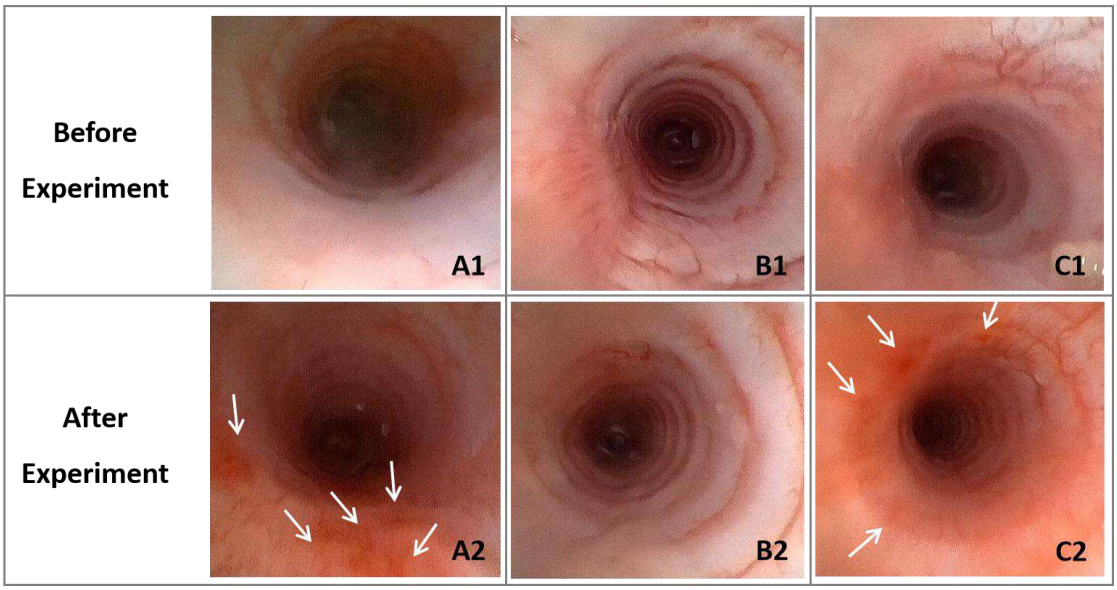


Figure 2. Gross appearance of the tracheal mucosa before and after the experiment in the three groups.

(A1-C1) Tracheal mucosa before intubation in Groups A, B, and C, respectively. (A2-C2) Tracheal mucosa after extubation in Groups A, B, and C, respectively. Group A, air-filled cuff group (control); Group B, automated cuff pressure control group; Group C, saline-filled cuff group. Scale bars: 1 mm. Images are representative of each group.

Discussion

Air-filled cuffs: high susceptibility to barometric pressure changes.

Endotracheal tube cuffs inflated with gas are theoretically highly vulnerable to barometric pressure changes. According to Boyle's law, gas volume expands as ambient pressure decreases. In this study, the air-filled cuff group (Group A) exhibited the most unstable pressure profile among the three strategies. During ascent, cuff pressure increased steeply (slope = 0.0448 cmH_2O/m, $P < 0.001$), reaching a median peak of 106.05 cmH_2O—far exceeding the target range of 25–30 cmH_2O and the pressures of the other two groups (33.25 and 29.30 cmH_2O). Notably, the maximum cuff pressure recorded in one animal reached 191.3 cmH_2O at the buffer altitude

of 3,240 m, which is substantially higher than the values reported in previous studies. We speculate that besides cabin barometric changes, biomechanical factors in this in vivo model—such as the transmission of intrathoracic pressure and dynamic deformation of the trachea—may also jointly contribute to this extreme pressure surge. Even during the cruise phase, it remained at a persistently high level (median 82.95 cmH_2O).

These findings strongly align with previous studies reporting that cuff pressures in high-altitude environments often exceed safe ranges by 23 to 120 cmH_2O [5, 7–14]. Such extreme overinflation is highly detrimental. Studies have shown that when cuff pressure exceeds 30 cmH_2O, tracheal mucosal blood flow begins to decrease, causing ischemic injury, and at pressures reaching 50 cmH_2O, mucosal blood flow is completely obstructed, leading to severe complications such as ulceration, necrosis, and tracheoesophageal fistula [15, 16]. Furthermore, basic research [17, 18] reveals that sustained high pressure induces short-term submucosal hemorrhage and epithelial disruption, progressing to long-term granulation and fibrotic remodeling. Consistent with these pathological mechanisms, our study observed a 100% (8/8) incidence of tracheal mucosal injury in the air-filled group. Although this difference did not reach statistical significance compared to the other groups ($P = 0.083$, likely due to the small sample size), it demonstrates a clear trend of clinical risk.

Furthermore, while most previous studies have focused primarily on overinflation during ascent, less attention has been paid to the pressure changes during descent. Our study specifically monitored this phase and found a dramatic pressure drop in the air-filled group, reaching a median of 8.10 cmH_2O (significantly lower than the stable levels of 19.70 and 28.45 cmH_2O in the other groups). In some animals, the pressure dropped to nearly zero upon landing.

This is consistent with previous reports [19] indicating that a cuff pressure below 25 cmH_2O leads to airway leakage. The massive gas leak caused by this pressure collapse led to a temporary cessation of the anesthesia ventilator, severely compromising ventilation and posing a life-threatening risk to the animals.

In summary, within dynamic high-altitude environments, air-filled cuffs are highly vulnerable to ambient pressure fluctuations resulting in severe overinflation (mucosal injury risk) during ascent and extreme underinflation (ventilation failure risk) during descent.

Automated pressure control: reliable maintenance of target cuff pressure.

In recent years, continuous cuff pressure monitoring and automated dynamic control have been increasingly recommended [2]. This approach utilizes a continuous control system to dynamically reflect cuff pressure in real time and make automatic adjustments to maintain the target value [20]. Previous studies have demonstrated its clinical benefits in routine settings; it can significantly reduce nursing workload (shortening adjustment time by 575 seconds within 48 hours) and increase the qualification rate of cuff pressure from 70.7% to 96.9% [4]. Furthermore, it can alleviate the severity of postoperative sore throat and hoarseness in intubated patients [21].

Based on this stability, preliminary explorations have been conducted in high-altitude environments. For instance, Thomas Blakeman [5] compared three automatic cuff pressure devices in vitro at simulated altitudes of 8,000 and 16,000 feet. Although these devices maintained pressure to a certain extent, limitations remained, including difficulty in stabilizing pressure during early altitude changes, discrepancies between in vitro models and real human airways, and device airworthiness concerns.

The present in vivo study provides further data on the performance of automated control under dynamic barometric conditions. In our study, the automated pressure control group (Group B) maintained the most stable pressure profile. During both ascent and cruise phases, its median pressures were lower than those of the air-filled and saline-filled groups, thereby remaining closer to the target range (25–30 cmH_2O). Similarly, during descent, its median pressure was higher than the other two groups, again staying closer to the normal range. Furthermore, the slopes across all three phases were statistically non-significant, indicating that the cuff pressure remained highly stable throughout the flight profile. While pairwise comparisons showed that Group B differed significantly from the air-filled group (all $P < 0.001$), there was no statistical difference between Group B and the saline-filled group. This suggests that while automated control provides highly stable regulation, saline filling might also serve as an acceptable alternative when advanced equipment is unavailable, as both prevented severe pressure fluctuations.

The continuous maintenance of pressure within the safe range likely reduced the physical stress on the airway. Consequently, Group B exhibited the lowest incidence of tracheal mucosal injury (50.0%). Meanwhile, none of the 8 animals in this group experienced cuff air leakage or ventilator failure, demonstrating effective airway sealing. However, mucosal injury was not completely eliminated in this group. This may be attributed to the inherent time lag (feedback delay) of the automated regulation system during rapid altitude changes, allowing the pressure to occasionally exceed the target range. Additionally, as the commercial device was not specifically certified for aeromedical environments, its sensor and pump performance may be slightly affected by extreme hypobaric conditions. Although the difference in mucosal injury

among the three groups did not reach statistical significance (P = 0.083), this trend supports the potential safety advantage of automated regulation. In summary, by actively counteracting barometric pressure changes, automated pressure control may help reduce extreme pressure swings, ensuring both mucosal protection and reliable ventilation during aeromedical evacuation.

Saline-filled cuffs: intermediate stability due to liquid incompressibility.

Unlike gases, liquids are nearly incompressible. Researchers have applied saline filling in both routine clinical settings and high-altitude environments, and studies suggest that cuff pressure with saline filling is lower than that with air filling; therefore, this approach may has potential value [6, 22]. However, previous studies have also raised specific concerns. For instance, changes in external pressure-such as those caused by airway edema-may lead to a more rapid increase in cuff pressure. Additionally, completely evacuating all air from cuff is highly difficult, and the use of inappropriate measurement devices may result in inaccurate monitoring data [23]. Furthermore, some theoretical risks exist. If the cuff ruptures, the liquid could directly enter the airway, potentially causing infection or suffocation. Moreover, the incompressibility of the liquid may complicate extubation, posing additional risks to patients.

Our results provide systematic in vivo data for this approach. The saline-filled group (Group C) exhibited an intermediate pressure profile. During ascent, its pressure increased mildly but significantly (slope = 0.0048 cmH_2O/m, P = 0.006), with the median (33.25 cmH_2O) significantly lower than the air-filled group (106.05 cmH_2O) but slightly higher than the automated group (29.30 cmH_2O). The ascent slope was significantly flatter than the air-filled group (P < 0.001), showing no statistical difference from the automated group. Despite its relative stability, saline filling lacks the capacity for active regulation. This is consistent with previous findings [23], which

demonstrated that saline filling cannot prevent pressure elevation when respiratory compliance decreases. In our high-altitude model, similar changes in airway compliance or dynamic tracheal deformation may likely explain the pressure fluctuations observed in Group C. During descent, its median pressure was 19.70 cmH_2O—more stable than underinflation in the air-filled group, though slightly below the target range. Although the pressure fell below 20 cmH_2O during this phase, no ventilator cessation occurred in Group C, which is likely attributable to the incompressibility of the liquid maintaining partial airway sealing. Overall, saline filling effectively attenuates barometric pressure swings, but lacks the active regulation to strictly maintain the 25–30 cmH_2O range.

Consequently, the mucosal injury rate in Group C (87.5%) was intermediate. In summary, while saline filling provides a reasonable alternative in resource-limited environments, its inability to self-regulate and its associated operational risks suggest that automated pressure control remains a more reliable strategy.

Time-dependent pressure decay during the cruise phase at constant barometric pressure.

Even when barometric pressure is constant, cuff pressure can naturally decay due to airway compression or micro-leakage. Previous research [24] monitoring obese patients under atmospheric pressure found that cuff pressure decays rapidly over time, with the majority falling below the safe range within a few hours. Our study confirms that similar decay occurs during the steady-altitude cruise phase at high altitude. As shown in Table 3, the air-filled group exhibited a significant pressure decline (slope = -0.6944 cmH_2O/min, $P < 0.001$). In contrast, the automated system effectively counteracted this decay, maintaining stable pressure (-0.0127 cmH_2O/min, $P = 0.588$). The saline-filled group showed a slower attenuation (-0.0690 cmH_2O/min, $P = 0.348$) due

to the limited volume change of the liquid.

Therefore, during the high-altitude cruise phase, the natural decay of cuff pressure cannot be ignored. Prolonged exposure requires continuous monitoring or automated dynamic management to prevent underinflation and maintain airway sealing.

Conclusions

In summary, the automated pressure control group demonstrated more favorable cuff pressure regulation and mucosal protection in the simulated high-altitude environment, whereas the saline-filled cuff group may serve as a viable backup strategy despite lacking active regulation. Conversely, the air-filled cuff group exhibited poorer stability and a higher mucosal injury rate, indicating a risk that warrants clinical attention. Furthermore, while the pressure decay in the automated and saline-filled groups did not reach statistical significance, all three strategies showed a trend of natural decay during the cruise phase, highlighting the need for continuous monitoring and timely intervention.

This study has several limitations. The sample size was small (n = 8 per group), and the classical flight profile may not fully replicate real-world scenarios. Additionally, the observed indicators were limited, leaving the complex multifactorial mechanisms of cuff pressure changes insufficiently explored. Finally, mucosal injury was assessed only by gross and bronchoscopic observation without histopathological validation. Further in-depth studies are warranted.

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Declarations

Ethics approval and consent to participate

All animal experiments were approved by the Animal Ethics Committee of Air Force Medical University (approval number: 20250165). All procedures were performed in accordance with the relevant guidelines and regulations for the care and use of laboratory animals. The animals used in this study were obtained from a licensed commercial supplier (Western Mars (Shaanxi) Biotechnology Co., Ltd., Xi'an, China). Therefore, the animals were not privately owned by an individual or institution, and the informed consent of the animal owners was not applicable.

Clinical trial number

not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

automated cuff pressure control devices have been provided unconditionally for research purposes only by the manufacturer. The authors declare that there are no further conflicts of interest.

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Authors' contributions

XC (first author) designed the study, coordinated the project, conducted the experiments,

analyzed the data, and drafted the manuscript.

JY (co-first author) designed the study, collected and analyzed the experimental data.

QC assisted in experimental data collection and analysis.

XL and YL provided experimental equipment and materials and offered theoretical guidance on artificial airways.

XH (corresponding author) designed and coordinated the study and provided overall supervision.

RZ (co-corresponding author) supervised the experimental implementation and provided theoretical guidance on critical care.

All authors read and approved the final manuscript.

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