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Application of modified ultrasound-guided percutaneous dilatational tracheostomy in the intensive care unit

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Abstract

Objective: This randomized controlled trial compared the intraoperative performance, postoperative safety profiles, and clinical outcomes between modified ultrasound-guided percutaneous dilatational tracheostomy (US-PDT) and conventional fiberoptic bronchoscopy-assisted PDT (FB-PDT) in critically ill patients within the Emergency Intensive Care Unit (EICU), aiming to establish an optimized tracheostomy protocol for high-risk populations.

Methods: Between January 2023 and March 2025, 72 consecutive intubated patients requiring PDT were prospectively enrolled and randomly allocated to either the US-PDT group (n = 36) or the FB-PDT group (n = 36). Standardized protocols were implemented for sedation, anatomical localization, and procedural execution. Key metrics included intraoperative hemodynamic stability, procedure duration, complication rates, and recovery parameters.

Results: The US-PDT group demonstrated significant advantages over the FB-PDT group, including shorter procedural time (9.25 ± 2.06 vs. 10.31 ± 1.86 min, P = 0.031), reduced intraoperative hemodynamic fluctuations (mean arterial pressure variation: 7.75 ± 5.79 vs. 10.81 ± 6.39 mmHg, P = 0.037), and lower rates of postoperative complications such as bleeding (7.56 ± 2.12 vs. 8.78 ± 1.90 mL, P = 0.012) and hypoxia (5.6% vs. 22.2%, P = 0.041). Clinically, US-PDT correlated with shorter mechanical ventilation duration (10.19 ± 1.43 vs. 10.94 ± 1.35 days, P = 0.025) and accelerated EICU discharge (15.39 ± 3.38 vs. 17.50 ± 3.50 days, P = 0.11).

Conclusion: Modified US-PDT offers superior precision, safety, and clinical efficacy compared to bronchoscopy-assisted techniques in the EICU setting. Its integration into critical care protocols may reduce procedural risks, enhance recovery trajectories, and optimize resource utilization.

Keywords: Ultrasound-guided tracheostomy; Bronchoscopy-assisted PDT; Critical care airway management; Minimally invasive techniques; Clinical outcomes

1. Introduction

In the management of critically ill patients, tracheostomy serves as a cornerstone intervention for optimizing respiratory support and mitigating life-threatening complications [1,3,9]. Accumulating evidence demonstrates that early tracheostomy (performed within 7–10 days of intubation) significantly reduces ventilator-associated pneumonia incidence by 30–40%, shortens mechanical ventilation duration by 4–6 days, and decreases ICU mortality rates by up to 15% compared to prolonged translaryngeal intubation [2,9]. Despite these benefits, conventional open surgical tracheostomy remains underutilized in Emergency Intensive Care Units (EICUs) due to its technical complexity,

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substantial tissue trauma, and elevated complication rates (>20% incidence of hemorrhage and surgical site infections) [3,9].

Percutaneous dilatational tracheostomy (PDT), while minimally invasive with smaller incisions (<3 cm), carries inherent risks of pneumothorax (3–5%) and vascular injury when relying solely on anatomical landmarks for blind puncture [4,9]. Fiberoptic bronchoscopy-assisted PDT partially addresses these limitations through direct visualization of tracheal anatomy; however, it fails to delineate critical cervical vascular structures (e.g., thyroid vessels, carotid arteries) and introduces logistical challenges related to equipment sterilization and bronchoscope fragility [5,9].

The integration of ultrasound technology has revolutionized procedural airway management through real-time, non-invasive anatomical mapping. High-frequency linear probes (7–15 MHz) enable millimeter-level visualization of tracheal rings, thyroid isthmus, and anterior neck vasculature, facilitating precision-guided interventions [6,7,8]. Current ultrasound applications in PDT predominantly focus on incision site optimization, neglecting its potential for comprehensive procedural guidance [8]. To bridge this gap, we developed a novel modified ultrasound-guided PDT protocol incorporating three key innovations: Dynamic endotracheal tube repositioning: Real-time ultrasound monitoring during tube retraction to prevent interference with puncture trajectories; Needle-enhanced imaging: Utilization of specialized ultrasound modes to amplify needle and guidewire visibility during critical steps; Multiplanar anatomical mapping: Systematic evaluation of axial and longitudinal planes to minimize posterior tracheal wall perforation risks.

This study represents the first comparative analysis of this enhanced ultrasound-guided approach versus conventional bronchoscopy-assisted PDT in the EICU setting, with particular emphasis on hemodynamic stability, procedural efficiency, and complication profiles.

2. Materials and Methods

2.1. Study Population

This study enrolled a total of 72 consecutive intubated patients admitted to the Emergency Intensive Care Unit (EICU) of our hospital between January 1, 2023, and March 1, 2025, who required PDT based on clinical indications. Patients were randomly assigned to one of two groups using a random number table method: the fiberoptic bronchoscopy-assisted PDT group (control group, n = 36) and the modified bedside ultrasound-guided PDT group (study group, n = 36). To ensure consistency in group sizes, patients who died during the observation period due to underlying conditions unrelated to PDT complications were excluded, and replacement participants were recruited using the same randomization procedure to maintain each group at 36 patients. The study protocol was reviewed and approved by the hospital's ethics committee.

Inclusion Criteria: Age >18 years. Intubated patients requiring PDT.Informed consent provided by family members. Exclusion Criteria: Cervical anatomical deformities. Large goiter. Severe coagulopathy. Surgical site infection. Unstable cervical spine fractures.

2.2. Observation Group

Incision Site Localization: All patients were sedated with a combination of propofol and fentanyl to achieve a Ramsay Sedation Score of 4–5. The procedure utilized the Portex percutaneous tracheostomy catheter system. Patients were positioned supine, with a shoulder pillow to facilitate neck hyperextension, the head aligned midline and tilted backward to fully expose the trachea. A LOGIQ E portable color ultrasound was employed to scan the region between the 2nd and 4th tracheal cartilage rings, confirming the tracheal position and identifying adjacent structures (e.g., blood vessels, thyroid gland) to determine the optimal puncture site. The tracheal course and segments were then marked with a surgical pen.

Endotracheal Tube Adjustment: Under ultrasound guidance in the tracheal long-axis view, the endotracheal tube was carefully retracted to align with the designated puncture site. If imaging clarity was suboptimal, saline was injected into the endotracheal tube cuff to improve ultrasound visualization of the tube tip. Airway measurements were taken to select an appropriately sized tracheostomy tube.

Confirmation of Needle and Guidewire Placement: The ultrasound probe was encased in a sterile sheath. Using the "out-of-plane" ultrasound technique (short-axis view), the puncture needle was advanced under real-time guidance, inserted perpendicular to the trachea at the midline between the 2nd and 4th tracheal cartilage rings to avoid lateral wall

penetration. Insertion depth was calculated as preoperative measurements plus an additional 1 cm. Upon aspiration of air or secretions, the needle bevel was slightly angled caudally, and the cannula was stabilized. The needle was then removed, and a J-shaped guidewire was introduced through the cannula into the tracheal lumen, guided by needle-enhanced imaging to prevent subcutaneous or pretracheal misplacement. After cannula removal, ultrasound was used to reconfirm the guidewire's entry point and trajectory. A 2-cm transverse skin incision was made along the guidewire, followed by sequential dilation of the subcutaneous tissue and tracheal wall using dilators and forceps. The tracheostomy tube was then inserted and secured. A postoperative bedside chest X-ray was routinely performed to verify placement.

2.3. Control Group

The control group underwent PDT guided by fiberoptic bronchoscopy. Patient positioning and sedation protocols were identical to those of the observation group. The puncture site was selected at the midline between the 2nd and 4th tracheal rings. Following standard disinfection and draping, the endotracheal tube was adjusted to a depth of 17–18 cm. A 2-cm transverse incision was made at the puncture site, and a cannula needle was inserted into the trachea, with correct placement confirmed by air aspiration. An Olympus BFP40 fiberoptic bronchoscope was used to visualize and refine the needle position. The needle was then withdrawn, and a J-shaped guidewire was advanced through the cannula. Sequential dilation and tracheostomy tube insertion followed, with bronchoscopic verification of accurate placement. A postoperative chest X-ray was routinely performed.

2.4. Observation Metrics

Preoperative Data: Recorded variables included gender, age, APACHE II scores, duration of preoperative intubation, platelet count (PLT), activated partial thromboplastin time (APTT), and prothrombin time (PT).
Intraoperative Metrics: Continuous monitoring included heart rate (HR), blood pressure, and pulse oxygen saturation. Additional data collected comprised procedure duration, incision length, endotracheal tube cuff leak rate, and first-attempt tracheostomy success rate.

Postoperative Outcomes: Assessed metrics included bleeding volume (from the incision site and airway), complications (e.g., hypoxia, subcutaneous emphysema, pneumomediastinum, pneumothorax, incisional secretion leakage, granuloma formation, posterior tracheal wall injury, tracheoesophageal fistula), duration of mechanical ventilation, time to tracheostomy tube removal, length of stay in the EICU, and mortality. Follow-up extended from EICU admission to 7 days post-PDT.

2.5. Statistical Analysis

Data were analyzed using SPSS 19.0. Normality was assessed for all variables. Normally distributed data were reported as mean ± standard deviation (SD), non-normally distributed data as median and interquartile range (IQR), and categorical variables as proportions or percentages. Group comparisons were conducted using the following tests: independent t-test for normally distributed continuous variables, Mann-Whitney U test for non-normally distributed continuous variables, and chi-square test (χ^2) for categorical variables. A p-value < 0.05 was deemed statistically significant.

3. Results

3.1. Baseline Characteristics

No significant differences existed in age, gender, APACHE II scores, or coagulation profiles between groups ($P > 0.05$, Table 1).

3.2. Intraoperative Outcomes

The observation group demonstrated smaller hemodynamic fluctuations, shorter procedure time (9.25 ± 2.06 vs. 10.31 ± 1.86 min, $P = 0.268$), reduced incision length (2.28 ± 0.52 vs. 2.53 ± 0.42 cm, $P = 0.031$), and higher first-attempt success rates (86.1% vs. 63.9%, $P = 0.029$, Table 2).

3.3. Postoperative Complications

The observation group had less bleeding (7.56 ± 2.12 vs. 8.78 ± 1.90 mL, $P = 0.012$), lower rates of hypoxia (5.6% vs. 22.2%, $P = 0.041$), and no subcutaneous emphysema (0% vs. 16.7%, $P = 0.033$, Table 3).

3.4. Clinical Prognosis

Mechanical ventilation duration (10.19 ± 1.43 vs. 10.94 ± 1.35 days, P = 0.025) and EICU stay (15.39 ± 3.38 vs. 17.50 ± 3.50 days, P = 0.11) were shorter in the observation group, with a non-significant mortality reduction (8.3% vs. 13.9%, P = 0.708, Table 4).

Table 1 Comparison of Preoperative Conditions

Variable		Observation Group (n=36)	Control Group (n=36)	t/x^2	p
Age (years)		58.75±10.94	58.03±11.36	0.275	0.784
Gender	Male	22	20	0.229	0.633
	Female	14	16		
APACHE II Score		12.75±3.81	13.5±3.50	-0.869	0.388
Preoperative Intubation Time (x±s, days)		5.77±1.33	6.08±1.50	-0.914	0.364
Preoperative PLT (x±s, 10^9/L)		148.44±27.29	148.33±27.36	0.017	0.986
Preoperative PT (x±s, s)		11.53±1.63	11.54±1.59	-0.022	0.983
Preoperative APTT (x±s, s)		28.46±5.31	28.60±5.29	-0.118	0.907
Preoperative Mean Arterial Pressure (x±s, mmHg)		89.44±2.90	89.86±2.83	-0.617	0.539
Preoperative Heart Rate (x±s, beats/min)		73.83±11.63	72.83±10.88	0.377	0.708
Preoperative Oxygen Saturation (x±s, %)		94.50±3.50	94.47±3.47	0.037	0.973

Table 2 Comparison of Intraoperative Conditions

Variable		Observation Group （n=36）	Control Group （n=36）	t/x^2	p
Intraoperative Mean Arterial Pressure (x±s, mmHg)		93.25±8.62	86.83±12.25	2.57	0.012
Change in Intraoperative Mean Arterial Pressure (x±s, mmHg)		7.75±5.79	10.81±6.39	-2.126	0.037
Intraoperative Heart Rate (x±s, beats/min)		74.06±7.64	79.83±8.88	-2.96	0.004
Change in Intraoperative Heart Rate (x±s, beats/min)		9.28±5.06	12.22±5.30	-2.411	0.019
Intraoperative Oxygen Saturation (x±s, %)		96.36±2.36	95.11±2.66	2.111	0.038
Change in Intraoperative Oxygen Saturation (x±s, %)		4.31±2.23	3.13±1.94	2.368	0.021
Time from Surgery Start to Successful Tracheal Cannula Placement (x±s, min)		9.25±2.06	10.31±1.86	-2.279	0.268
Incision Length (x±s, cm)		2.28±0.52	2.53±0.42	-2.197	0.031
Tracheal Intubation Cuff Leakage	Leakage	2	9	5.258	0.022
	No Leakage	34	28		
Success of First Tracheostomy Cannula Insertion	Successful	31	23	4.741	0.029
	Unsucessful	5	13		

Table 3 Comparison of Conditions Within 7 Days Postoperation

Variable		**Obesrvation Group（n=36）**	**Control Group（n=36）**	**t/x²**	**p**
Bleeding Around Incision and Airway (x±S)		7.56±2.12	8.78±1.90	-2.578	0.012
Hypoxemia	Present	2	8	4.181	0.041
	Absent	34	28		
Subcutaneous Emphysema	Present	0	6	4.545	0.033
	Absent	36	30		
Incision Sputum Overflow	Present	3	10	4.600	0.032
	Absent	33	26		

Table 4 Comparison of Clinical Outcomes

Variable	**Observation Group（n=36）**	**Control Group（n=36）**	**t/x²**	**p**
Mechanical Ventilation Time (x±S, days)	10.19±1.43	10.94±1.35	-2.287	0.025
Tracheostomy Cannula Removal Time (x±S, days)	9.94±1.55	11.14±2.42	-2.498	0.015
EICU Hospitalization Time (x±S, days)	15.39±3.38	17.50±3.50	-2.602	0.11
Mortality Rate (%)	3（8.3%）	5（13.9%）	0.141	0.708

4. Discussion

Tracheostomy is a cornerstone in the management of critically ill patients in the EICU. However, conventional tracheostomy techniques and existing assisted methods are hampered by technical complexity and elevated complication rates [1,3,5,9]. This study underscores the superior performance of a modified ultrasound-guided PDT approach. The observation group exhibited significantly shorter procedure times and higher first-attempt success rates for tracheostomy tube placement. These benefits are likely attributable to real-time ultrasound guidance, which provides precise visualization of tracheal anatomy, reduces blind maneuvers, and minimizes the need for repeated adjustments, thereby enhancing procedural efficiency [6,7,8]. Furthermore, the observation group experienced smaller intraoperative hemodynamic fluctuations and lower endotracheal tube cuff leakage rates, suggesting reduced physiological stress and improved safety during the procedure.

Regarding complications, the ultrasound-guided group demonstrated reduced peri-incisional and airway bleeding, alongside lower rates of hypoxia, subcutaneous emphysema, and incisional secretion leakage. Real-time ultrasound enables operators to avoid vascular structures, mitigate bleeding risks, and enhance anatomical precision, thereby decreasing the likelihood of posterior tracheal wall injuries and other adverse events [6,7,8]. In contrast, while fiberoptic bronchoscopy-assisted PDT offers intraluminal visualization, it falls short in providing a comprehensive view of cervical anatomy, limiting its effectiveness in preventing complications.

Clinically, the observation group achieved shorter durations of mechanical ventilation, earlier tracheostomy tube removal, and reduced EICU lengths of stay, with a trend toward lower mortality. These outcomes suggest that ultrasound-guided PDT accelerates respiratory recovery, alleviates hospitalization burdens, and may improve survival, highlighting its substantial clinical value [1,2,3,9].

Limitations: The study's generalizability is limited by its relatively small sample size. Future investigations should involve larger, more diverse cohorts encompassing varied demographics and disease severities to confirm these findings. Additionally, the efficacy of ultrasound-guided PDT relies on high-quality equipment and operator proficiency, emphasizing the need for standardized training and protocols.

5. Conclusion

Compared to fiberoptic bronchoscopy-assisted PDT, the modified ultrasound-guided PDT demonstrates superior clinical outcomes, enhanced safety, and improved patient prognoses in EICU settings. Its widespread clinical adoption is strongly recommended.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no competing interests.

Statement of informed consent

The participants were informed orally and written consent is obtained from all individual participants included in the study.

Statement of ethical approval

The study was approved by the Review Committee of the Research Council in hospital (No. 2022014).

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Availability of data and materials

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

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