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Timing of Tracheostomy in Critically Ill Geriatric Trauma Patients: A Nationwide Analysis

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ABSTRACT

Introduction: Tracheostomy is frequently performed in trauma patients requiring prolonged mechanical ventilation. The optimal timing in older people, with limited physiologic reserve, remains unclear. Our study aims to evaluate whether early tracheostomy (ET) *versus* late tracheostomy (LT) is associated with differences in in-hospital complications and length of stay.

Methods: We conducted a retrospective cohort study using American College of Surgeons Trauma Quality Improvement Program (2017-2023) on geriatric trauma patients (≥65 years) who underwent ET with an injury severity score (≥9). Exclusions included in-hospital mortality, transfers, tracheostomy ≤48 h, or extubation ≤7 days. Patients were dichotomized into ET (≤7 d) and LT (>7 d) groups. Propensity score matching was performed in a 1:1 ratio to adjust for demographics, vitals, injury characteristics, operative interventions, flail chest, exploratory laparotomy, and mFI. Outcomes were complications, length of stay, ventilator days, and discharge disposition. A subanalysis on head trauma and thoracic trauma was performed.

Results: A total of 3501 patients were included: 674 (19.3%) had ET and 2827 (80.7%) had LT. Median time to ET was 11 days. After propensity score matching, 442 remained in each group. There were significantly higher rates of unplanned intubation, intensive care unit (ICU) admission, and pressure ulcers ($P < 0.001$). LT had a more extended stay in the hospital and ICU and increased ventilator days ($P < 0.001$).

Conclusions: In critically ill geriatric patients, LT is associated with increased airway complications and extended hospital and ICU stays. This study supports planning ET in high-risk populations. To our knowledge, this is one of the largest national study evaluating ET timing in geriatric critically ill patients.

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Introduction

Tracheostomy is an essential mode of ventilation in critically ill patients, especially for prolonged periods. It provides a more secure airway, decreased sedation requirements, early communication, mobilization, and weaning off the ventilator.[1] Elderly trauma patients have a diminished physiologic reserve, and tracheostomy is beneficial compared to translaryngeal intubation, which is associated with more complications.[2] Observational studies in the critically ill elderly population demonstrate that even though tracheostomy may provide liberation from the ventilator and improve intensive care unit (ICU) survival, many older patients have experienced long-term mortality and dependence after discharge.[3]

Although tracheostomy offers many advantages, the optimal timing of tracheostomy remains controversial. Studies have reported that late tracheostomy (LT) patients have longer endotracheal tube time, laryngeal edema, impaired cough, delirium, and increased respiratory burden. Early tracheostomy (ET) provides a more stable airway early in the clinical course and could reduce the need for emergency airway procedures. This could reduce the frequency of unplanned intubation, which is more commonly seen in LTs due to their prolonged exposure to physiologic and airway problems associated with protracted endotracheal intubation.[4,5]

Despite the widespread use of tracheostomy, the optimal timing in the geriatric population remains poorly defined. Most studies focus on mixed ICU populations rather than older injured adults.[6] We hypothesized that ET would be associated with fewer complications and shorter hospital and ICU lengths of stay.

Methods

Study design and population

We conducted a retrospective cohort study using the American College of Surgeons Trauma Quality Improvement Program (TQIP) database from 2017 to 2023. TQIP is an American College of Surgeons managed national registry that includes data from more than 900 participating centers across the country. The data were collected by trained registrars at participant centers, in accordance with the National Trauma Data Standard. This registry is as an essential resource to enhance the quality of trauma care and to promote research to improve patient outcomes. The data in TQIP is deidentified, so this retrospective study was considered exempt from obtaining patient consent after review and approval by the institutional review board.[7] The Strengthening The Reporting of Observational Studies in Epidemiology guidelines was used to ensure proper development and documentation of this study.

Inclusion and exclusion criteria

All geriatric patients ($\geq$65 yr) with an injury severity score (ISS) of more than 9 who required mechanical ventilation more than 7 d and received a tracheostomy were included (Appendix A: Table 1, supplemental file). We excluded all in-hospital mortality, had care limited to comfort measures, were transferred to another facility, or underwent tracheostomy within 48 h of admission. Patients were categorized into two groups: ET: $\leq$7 d and LT: $>$7 d.

Data points and grouping

We collected detailed information, including demographics (age, sex, and race), emergency department (ED)-shock index (SI), ED-Glasgow Coma Scale (GCS), mechanism of injury, ISS, head and thoracic abbreviated injury scale (AIS), flail chest, exploratory laparotomy status (Appendix A: Table 1, supplemental file), and frailty status. We calculated the 11-item modified frailty index (mFI-11), calculated from hypertension, diabetes mellitus, peripheral arterial disease, cerebrovascular accident, myocardial infarction, angina, congestive heart failure, dementia, chronic obstructive pulmonary disorder, functional dependence, and altered sensorium. Each variable was assigned 1 point if present, and the total was divided by 11 to yield a final mFI score ranging from 0.0 to 1.0. Frailty was defined as an mFI $\geq$0.25.[1,8-10]

Outcomes

The outcomes reported were in-hospital complications like ventilator-associated pneumonia, acute respiratory distress syndrome (ARDS), acute kidney injury (AKI), deep vein thrombosis, pulmonary embolism, myocardial infarction, sepsis, unplanned intubation, unplanned return to operating room (OR), and unplanned ICU admission. Hospital and ICU length of stay (LOS) and discharge disposition were also assessed. Discharge dispositions were categorized into routine discharge, inpatient rehabilitation, long-term acute care hospital, and skilled nursing facility. Since TQIP does not provide time to event relative to the tracheostomy for ventilator-associated pneumonia and ARDS, these are assessed as in-hospital complication rates without assuming the temporal order.

Data reporting and statistical analysis

We compared the characteristics and outcomes of patients who underwent ET *versus* LT. A propensity score matching (PSM) was performed in a 1:1 ratio, adjusting for age, sex, race, mechanism of injury, ISS, flail chest, GCS, and SI. Race was used as a nonbiological covariate to address potential differences in health care access. A check for multicollinearity revealed none, with all variance inflation factor values below five and tolerance values above 0.1. Nearest neighbor matching without replacement was conducted with a caliper width of 0.1 times the standard deviation of the logit of the propensity score to ensure balanced distribution between the matched groups. This was confirmed by an absolute standardized mean difference below 0.1 for all covariates post matching (Appendix B: Table 2, supplemental file).

Categorical variables were presented as frequencies and percentages. The chi-square ($\chi2$) test was used for analysis. Data were assessed for normality using the Kolmogorov–Smirnov test. Non-normally distributed data were compared using the Mann–Whitney U test and expressed using median and interquartile range.

We performed subanalyses on patients with isolated traumatic brain injury (TBI) and isolated thoracic trauma. A 1:1 PSM was done for isolated TBI while adjusting for age, sex, race, mechanism of injury, ED-GCS, head AIS, and mFI. While for isolated thoracic trauma, logistic and linear regression were done due to the small sample size. The regression model included age, sex, race, mechanism, ED-GCS, thoracic AIS, flail chest, and mFI.

Statistical analysis was performed using Statistical Package for Social Sciences (IBM SPSS Statistics for Windows, version 29.0,IBM Corp., Armonk,NY,USA). PSM was conducted using R statistical software (R Foundation for Statistical Computing, version 4.4.2). A P value of less than 0.05 was considered statistically significant.

Results

We identified 3501 tracheostomies in the critically ill geriatric population. Figure 1 demonstrates the flowchart for isolating the study population. Median age was 72, and 68% were male. The most common mechanism of injury was falls, with a median ISS of 22.

Prematch demographics and outcomes

Out of the total population, 674 (19.3%) underwent ET, while 2827 (80.7%) underwent LT. The rates of age, sex, frailty, flail chest, SI, mechanism of injury, and exploratory laparotomy were comparable between the two groups. There was a significantly higher proportion of White patients in the ET cohort (78.6% *versus* 73.6%, $P = 0.009$) (Table 1). The GCS scores were significantly lower in the LT group (12 *versus* 14, $P < 0.001$), suggesting greater initial neurologic impairment. Several in-hospital complications (AKI, ARDS, sepsis, unplanned intubation, unplanned return to the OR, unplanned ICU admission, and pressure ulcers) were more common in the LT group. ($P < 0.001$). The ICU, hospital LOS, and ventilator days were significantly more prolonged in the LT group ($P < 0.001$). The discharge disposition was similar in both groups (Table 2).

Postmatch demographics and outcomes

After propensity score matching (PSM), there were 442 cases in each group. The baseline demographics were matched (Table 3).

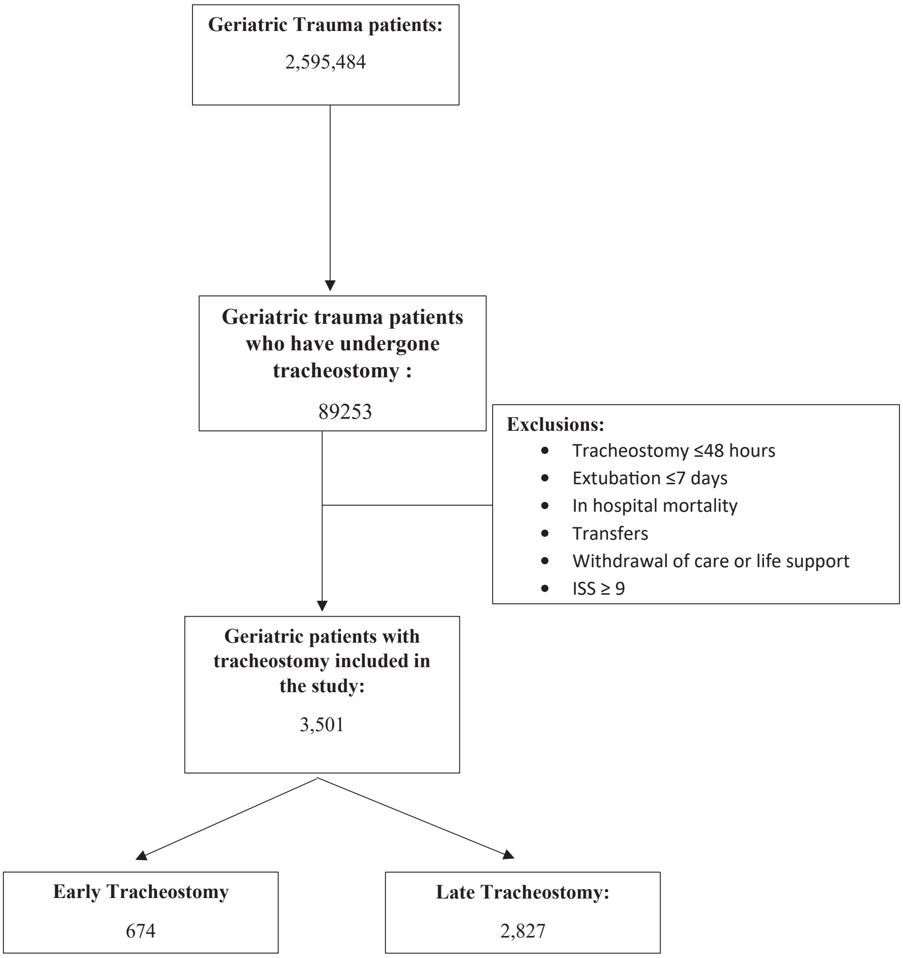

Fig. – Flow chart diagram of the study population.

Table 1 – Prematch demographics and clinical characteristics.

Variables	Early tracheostomy (≤7 d) (*n* = 674)	Late tracheostomy (>7 d) (*n* = 2827)	*P* value
Age (years)	72 [68-77]	72 [68-78]	0.224
Sex (female)	208 (30.9%)	913 (32.3%)	0.470
Race			0.009
White	526 (78.6%)	2066 (73.9%)	
Black	85 (12.7%)	373 (13.3%)	
Other	58 (8.7%)	358 (12.8%)	
Mechanism			0.399
MVT	262 (38.9%)	1139 (40.3%)	
Falls	300 (44.5%)	1276 (45.1%)	
Other	112 (16.6%)	412 (14.6%)	
ED-SI	0.67 [0.52-0.85]	0.65 [0.50-0.82]	0.051
GCS	12 [6-15]	14 [9-15]	<0.001
ISS	25 [17-29]	22 [17-29]	<0.001
mFI	0.18 [0.09-0.27]	0.18 [0.09-0.27]	0.404
Head AIS	4 [3-5]	4 [3-5]	0.750
Flail chest	72 (10.7%)	311 (11.0%)	0.812
Exploratory laparotomy	54 (8.0%)	246 (8.7%)	0.565

Using the Mann–Whitney U test and the chi-square test.
ED = emergency department, SI = shock index, GCS = glasgow coma scale, mFI = modified frailty index, ISS = injury severity scale.

Table 2 – Prematch outcome variables.

Variables	Early tracheostomy (≤7 d) (*n* = 674)	Late tracheostomy (>7 d) (*n* = 2827)	*P* value
In-hospital complications			
DVT	53 (7.9%)	264 (9.3%)	0.230
PE	20 (3.0%)	85 (3.0%)	0.957
ARDS	16 (2.4%)	183 (6.5%)	<0.001
VAP	101 (15.0%)	447 (15.8%)	0.596
Cardiac arrest	41 (6.1%)	225 (8.0%)	0.099
MI	9 (1.3%)	53 (1.9%)	0.340
Stroke/CVA	22 (3.3%)	133 (4.7%)	0.102
AKI	18 (2.7%)	198 (7.0%)	<0.001
CAUTI	28 (4.2%)	143 (5.1%)	0.328
Sepsis	16 (2.4%)	169 (6.0%)	<0.001
Pressure ulcer	51 (7.6%)	340 (12.0%)	<0.001
Compartment syndrome	0 (0.0%)	9 (0.5%)	0.118
Unplanned return to OR	31 (4.6%)	234 (8.3%)	0.001
Unplanned intubation	96 (14.2%)	964 (34.1%)	<0.001
Unplanned ICU admission	43 (6.4%)	450 (15.9%)	<0.001
Hospital disposition			0.100
Routine discharge	13 (1.9%)	59 (2.1%)	
Inpatient rehabilitation	154 (22.8%)	565 (20.0%)	
Skilled nursing facility	108 (16.0%)	489 (17.3%)	
Other	399 (59.2%)	1714 (60.6%)	
Hospital LOS	20 [14-29]	27 [20-38]	<0.001
ICU LOS	15 [11-21]	22 [17-29]	<0.001
Ventilator days	13 [10-19]	18 [13-25]	<0.001

Using the Mann–Whitney U test and the Chi-square test.
DVT = deep vein thrombosis; PE = pulmonary embolism; ARDS = acute respiratory distress syndrome, VAP = ventilator-associated pneumonia; MI = myocardial infarction; CVA = cerebrovascular accident; AKI = acute kidney injury; CAUTI = catheter-associated urinary tract infection; OR = operating room; ICU = intensive care unit; LOS = length of stay.

In-hospital complications were similar in both groups. However, LT patients still experienced a higher incidence of AKI (2.9% *versus* 6.6%, $P = 0.011$, needed to treat (NNT) = 27) and pressure ulcers (7.2% *versus* 12%, $P = 0.017$, NNT = 21). Unplanned intubation also showed a significantly higher number in the LT group (13.3% *versus* 29.2%, $P < 0.001$). Unplanned ICU admissions occurred more often in the LT group, aligning with the need for increased postprocedural care (6.3% *versus* 18.3%, $P < 0.001$).

LOS was similar to the prematch outcomes. LT patients had significantly more prolonged hospitalizations (27 *versus* 20 d, $P < 0.001$) and ICU LOS (21 *versus* 15 d, $P < 0.001$), and required mechanical ventilation for a longer period (17 *versus* 13 d, $P < 0.001$). Discharge disposition was similar in both groups (Table 4).

Isolated TBI analysis

The analysis of the timing of tracheostomy in patients with isolated TBI showed that most in-hospital complications were similar between the two groups. LT was associated with higher rates of unplanned intubation (32.5% *versus* 12.3%, $P < 0.001$) and unplanned ICU admissions (14.3% *versus* 5.9%, $P = 0.005$). There were also significantly prolonged hospital and ICU LOS ($P < 0.001$). Ventilator days were also prolonged in the LT group ($P < 0.001$) (Table 5).

Thoracic trauma analysis

In the thoracic trauma population, multivariable logistic and linear regression analyses were used. The LT group had a significant increase in length of ICU days (B = 7.5, $P < 0.001$), hospital (B = 8.9, $P < 0.001$), and ventilator days (B = 6.9, $P < 0.001$). Frailty also contributed to more extended stays, and a higher mFI was independently associated with increased ventilator days and hospital LOS ($P < 0.005$). There was no significant difference between the two groups regarding in-hospital complications (Table 6).

Discussion

In this study, conducted on a national cohort of critically ill geriatric trauma patients, we compared ET with LT and evaluated the clinical benefits. ET was consistently associated with fewer ventilator days and a significantly shorter hospital and ICU LOS, thereby contributing to lower resource utilization. Establishing a stable airway at an early stage can reduce the cumulative exposure to endotracheal tube-related injuries and also reduce sedation, which is essential in older adults with diminished physiologic reserve.[11]

One of the most apparent differences between the two groups was unplanned intubation, which was more than twice as frequent in the LT group. This is probably due to prolonged translaryngeal intubation, which increases the risk of laryngeal edema, mucosal injury, retained secretions, or delirium, leading to failed extubation, causing higher rates of reintubation and airway instability in the LT group.[12,13] Older adults, specifically frail patients, have an increased risk of retention of secretion, causing failure of extubation due to impaired clearance of secretion and reduced cough strength.[14,15] Although several studies reported reductions in pneumonia and respiratory morbidity associated with ET, we did not observe a significant difference between the two

Table 3 – Postmatch demographic and clinical characteristics.

Variables	Early tracheostomy (≤7 d) (*n* = 442)	Late tracheostomy (>7 d) (*n* = 442)	*P* value
Age (years)	72 [68-78]	72.5 [68-78.25]	0.469
Sex (female)	148 (33.5%)	147 (33.3%)	0.943
Race			0.968
White	358 (81.0%)	355 (80.3%)	
Black	51 (11.5%)	53 (12%)	
Other	33 (7.5%)	34 (7.7%)	
Mechanism			0.736
MVT	185 (41.9%)	187 (42.3%)	
Falls	190 (43.0%)	196 (44.3%)	
Other	67 (15.2%)	59 (13.3%)	
ED-SI	0.66 [0.51-0.84]	0.64 [0.51-0.82]	0.436
GCS	13 [6-15]	14 [6-15]	0.337
mFI	0.18 [0.09-0.27]	0.18 [0.09-0.27]	0.779
ISS	24 [17-29]	22 [17-29]	0.167
Head AIS	5 [3-5]	4 [3-5]	0.427
Flail chest	52 (11.8%)	49 (11.1%)	0.751
Exploratory laparotomy	36 (8.1%)	37 (8.4%)	0.903

Using the Mann–Whitney U test and the Chi-square test.
ED = emergency department; HR = heart rate; SI = shock index; GCS = Glasgow Coma Scale; mFI = modified frailty index; TBSA = total body surface area; ISS = injury severity scale.

Table 4 – Post-match outcome variables.

Variables	Early tracheostomy (≤7 d) (*n* = 442)	Late tracheostomy (>7 d) (*n* = 442)	*P* value
In-hospital complications			
DVT	36 (8.1%)	42 (9.5%)	0.477
PE	15 (3.4%)	11 (2.5%)	0.426
ARDS	14 (3.2%)	26 (5.9%)	0.052
VAP	70 (15.8%)	88 (19.9%)	0.114
Cardiac arrest	23 (5.2%)	34 (7.7%)	0.132
MI	5 (1.1%)	9 (2.0%)	0.281
Stroke/CVA	14 (3.2%)	19 (4.3%)	0.375
AKI	13 (2.9%)	29 (6.6%)	0.011
CAUTI	20 (4.5%)	27 (6.1%)	0.294
Sepsis	12 (2.7%)	23 (5.2%)	0.058
Pressure ulcer	32 (7.2%)	53 (12.0%)	0.017
Compartment syndrome	0 (0.0%)	2 (0.5%)	0.157
Unplanned return to OR	16 (3.6%)	17 (3.8%)	0.859
Unplanned intubation	59 (13.3%)	129 (29.2%)	<0.001
Unplanned ICU admission	28 (6.3%)	81 (18.3%)	<0.001
Hospital disposition			0.228
Routine discharge	6 (1.4%)	3 (0.7%)	
Inpatient rehabilitation	114 (25.8%)	94 (21.3%)	
Skilled nursing facility	76 (17.2%)	92 (20.8%)	
Other	246 (55.7%)	253 (57.2%)	
Hospital LOS	20 [14-27]	27 [19-38]	<0.001
ICU LOS	15 [11-21]	21 [16-27]	<0.001
Ventilator days	13 [10-18]	17 [13-24]	<0.001

Using Mann–Whitney U test and Chi-square test.
DVT = deep vein thrombosis; PE = pulmonary embolism; ARDS = acute respiratory distress syndrome; VAP = ventilator-associated pneumonia; MI = myocardial infarction; CVA = cerebrovascular accident; AKI = acute kidney injury; CAUTI = catheter-associated urinary tract infection; OR = operating room; ICU = intensive care unit; LOS = length of stay.

groups postmatching. The discrepancy may be due to distinct physiology in the critically ill geriatric population, in which comorbidities, functional decline, and pulmonary disease may overshadow the effect of tracheostomy timing on pulmonary outcomes. Frailty is an independent factor that is shown to have higher complication rates and prolonged recovery in elderly ICU cohorts.[3]

We found that LT had approximately a threefold increase in unplanned ICU admissions. This could be due to physiologic decline in neurologic status, oxygenation, or airway protection, which may contribute to an unstable tracheostomy leading to unplanned ICU admissions. Recent studies report similar findings, demonstrating that LT is associated with prolonged ventilator days, dependence, and a longer ICU course.[16] At the same time, McMahon *et al.* suggest that the unplanned ICU admission is due to multifactorial deterioration, such as delirium, aspiration, secretions, and inability to protect the airway, which cumulatively accumulate over long periods and cause airway instability or clinical decline.[17]

In the overall cohort, there was also a significantly higher rate of AKI and pressure ulcers. The number NNT is 27 to prevent one AKI and 21 to prevent one pressure ulcer. These findings are possibly associated with systemic inflammation and prolonged immobilization in this critically ill and elderly cohort.[18] AKI may also be due to prolonged ventilation, which could increase the risk of renal hypoperfusion through sustained intrathoracic positive pressure, cytokine release, and neurohormonal activation.[19]

The difference in resource utilization was significant between the groups. LT was significantly associated with more extended hospital and ICU stays, along with more ventilator days. Similarly, in the thoracic trauma and head injury subgroup, LT showcased increased resource requirements. These patterns are consistent with other studies, which suggest that ET in severe TBI can decrease mechanical ventilation duration and reduce ICU and hospital LOS.[20] Another study on blunt chest trauma patients showed ET was associated with less ICU LOS and ventilator duration, which supports that early airway can facilitate weaning and pulmonary hygiene within this patient cohort.[21] Hosokawa *et al.* explain that shorter ventilation duration is associated with shorter sedation and fewer ICU stays, resulting in more ventilator-free days.[16]

We evaluated specifically the isolated TBI and thoracic trauma cohort, as these injuries can contribute to ventilation challenges. This can affect the timing of tracheostomy and lead to worse outcomes. In isolated TBI, LT showed a stronger

Table 5 – Isolated TBI analysis.

Postmatch Outcomes	Early tracheostomy (≤7 d) (*n* = 203)	Late tracheostomy (>7 d) (*n* = 203)	*P* value
AKI	5 (2.5%)	4 (2.0%)	0.736
ARDS	4 (2.0%)	9 (4.4%)	0.159
Pressure ulcer	9 (4.4%)	15 (7.4%)	0.207
Unplanned return to OR	6 (3.0%)	7 (3.4%)	0.778
Unplanned intubation	25 (12.3%)	66 (32.5%)	<0.001
Unplanned ICU admission	12 (5.9%)	29 (14.3%)	0.005
Hospital LOS	19 [13-27]	24 [18-34]	<0.001
ICU LOS	13 [10-20]	20 [15-26]	<0.001
Ventilator days	13 [10-19]	16 [12-22]	<0.001

Using the Mann–Whitney U test and Chi-square test.
AKI = acute kidney injury; ARDS = acute respiratory distress syndrome; OR = operating room; ICU = intensive care unit; LOS = length of stay.

association with unplanned intubation, unplanned ICU admission, and LOS. Multiple meta-analyses suggest similar findings, mainly due to airway timing interacting with sedation requirements, neurologic monitoring, and neuroprotection.[22,23]

Between the two groups, the discharge disposition was similar. This is because discharge disposition is also influenced by factors such as neurologic status, baseline function, availability of a skilled nursing facility, payer authorization, and social support. The timing of tracheostomy alone will not shift the disposition, even if the latter group has worse outcomes.[24]

This retrospective study has limitations based on registry analysis. Despite PSM, residual confounding may persist due to unmeasured variables, such as sedation type, ventilator weaning strategies, changes in sedation, neurologic trajectory, airway secretions management, and the institutional tracheostomy threshold. The lack of this data limits our ability to fit a time-to-event model. The insufficient time to event data, makes it difficult to determine whether unplanned intubation or ICU readmission occurred before or after the tracheostomy event, which could limit causal inference. TQIP also lacks information on the depth of sedation, incidence of delirium, airway secretions, ongoing transfusion status, and functional outcomes postdischarge, all of which are highly relevant to geriatric airway management. The mFI measures comorbidity-based frailty rather than cognitive or functional frailty, potentially underestimating vulnerability. Decisions about tracheostomy timing, especially in elderly patients, can also be based on the patient's or family's preferences, their care goals, and institutional practice patterns. These factors are not included in this dataset and may lead to confounding. These limitations point toward the need for more multicenter, prospective studies along with granular periprocedural variables as well as longitudinal follow-ups to clarify the optimal timing of tracheostomy in geriatric trauma patients.

Conclusions

In this study, focusing on a large national cohort of critically ill elderly patients with traumatic injuries, we found that ET was associated with fewer airway complications and lower resource utilization. Although most in-hospital pulmonary complications were similar between the groups, ET showed reductions in unplanned intubation, ICU admissions, ventilator days, and LOS, highlighting the importance of early airway stabilization in older people. These findings were similarly seen in patients with isolated TBI and thoracic

Table 6 – Isolated thoracic analysis.

Outcomes	Early tracheostomy (≤7 d) (*n* = 63)	Late tracheostomy (>7 d) (*n* = 470)	*P* value
AKI	3 (4.8%)	38 (8.1%)	0.341
ARDS	3 (4.8%)	39 (8.3%)	0.159
Pressure ulcer	5 (7.9%)	49 (10.4%)	0.703
Unplanned return to OR	3 (4.8%)	30 (6.4%)	0.997
Unplanned intubation	14 (22.2%)	221 (47.0%)	0.005
Unplanned ICU admission	8 (12.7%)	107 (22.8%)	0.476
Hospital LOS	19 [15-26]	27 [22-37]	<0.001
ICU LOS	17 [14-21]	23 [18-29]	<0.001
Ventilator days	14 [11-19]	19 [15-26]	<0.001

Using the Mann–Whitney U test and Chi-square test.
AKI = acute kidney injury; ARDS = acute respiratory distress syndrome; OR = operating room; ICU = intensive care unit; LOS = length of stay.

trauma, where LT was associated with worse LOS and more ventilator days.

Study Type

Observational cohort study.

Level of Evidence

Level III retrospective study.

Supplementary Materials

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jss.2026.03.043.

Disclosure

None declared.

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Meeting Presentation

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CRediT authorship contribution statement

Samyuktha Harikrishnan: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Riddhi Mehta:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Kartik Prabhakaran:** Writing – review & editing, Supervision, Resources, Project administration. **Vishmita Kannichamy:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Data curation. **Gabriel Froula:** Writing – review & editing, Investigation, Data curation. **Ilya Shnaydman:** Writing – review & editing, Visualization, Validation. **Jordan Kirsch:** Writing – review & editing, Validation, Resources. **Matthew Bronstein:** Writing – review & editing, Visualization, Investigation. **Amanda Carlson:** Writing – review & editing, Validation, Investigation. **Aaron Zuckerman:** Writing – review & editing, Validation, Resources. **Bardiya Zangbar:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization.

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