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# Decreased Ventilation Duration and ICU Stay Associated With Early Percutaneous Dilatational Tracheostomy After Liver Transplantation

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Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
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**Background:** Liver transplantation in critically ill patients with advanced cirrhosis frequently leads to prolonged ventilation. Percutaneous dilatational tracheostomy is widely used to facilitate weaning, yet the optimal timing after liver transplantation remains uncertain.

**Material/Methods:** This retrospective single-center study analyzed 83 of 1352 liver transplant recipients (6.1%) who underwent percutaneous dilatational tracheostomy between December 2010 and June 2024. Patients were retrospectively categorized as early (≤7 days) or late (≥8 days) according to the interval from liver transplantation to tracheostomy. Clinical and laboratory parameters were assessed using group comparisons, multivariable linear regression (with and without log-transformed outcomes), Cox regression, and Kaplan-Meier survival analysis.

**Results:** Patients who underwent early percutaneous dilatational tracheostomy had lower platelet counts (57 vs $97\times10^9$/L; *P*=0.047) and higher aspartate aminotransferase (72 vs 46 U/L; *P*=0.022), alanine aminotransferase (249 vs 67 U/L; *P*<0.001), and creatinine levels (175 vs 141 µmol/L; *P*=0.033). Early percutaneous dilatational tracheostomy was independently associated with a shorter intensive care unit stay (β=-0.651; 95% CI, -1.087 to -0.214; *P*=0.004; 47.8% reduction) and shorter mechanical ventilation duration (β=-0.560; 95% CI, -1.027 to -0.093; *P*=0.020; 42.9% reduction). No significant survival difference was found between early and late percutaneous dilatational tracheostomy (Cox hazard ratio, 0.76; 95% CI, 0.41-1.40; *P*=0.37).

**Conclusions:** Early percutaneous dilatational tracheostomy was associated with reduced intensive care unit and ventilation times but did not confer a survival benefit. These findings should be interpreted cautiously, given the retrospective single-center design.

**Keywords:** **Critical Care • Liver Transplantation • Retrospective Studies • Time Factors • Tracheostomy • Transplantation**

**Abbreviations:** **ALT** – alanine aminotransferase; **AST** – aspartate aminotransferase; **$FiO_2$** – fraction of inspired oxygen; **ICU** – intensive care unit; **LT** – liver transplantation; **MELD** – Model for End Stage Liver Disease; **$PaO_2$** – arterial partial pressure of oxygen; **$PaO_2/FiO_2$** – arterial oxygen partial pressure to inspired oxygen fraction ratio (P/F ratio); **PDT** – percutaneous dilatational tracheostomy; **SAPS II** – Simplified Acute Physiology Score II

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## Introduction

Liver transplantation (LT) is a well-established surgical procedure for treating patients with acute liver failure or end-stage liver cirrhosis. Within the Eurotransplant region, Germany had the highest rate of patients either dying or becoming unfit while waitlisted (26%) [1,2].

Amid the ongoing shortage of donor organs, LT is increasingly performed in patients with more advanced stages of cirrhosis. These patients often experience a complex postoperative course, frequently marked by respiratory insufficiency and pulmonary complications. Up to 50% of patients develop pulmonary complications following LT [3,4].

LT recipients are particularly susceptible to pulmonary complications, due to their poor clinical condition resulting from liver cirrhosis and pre-existing pulmonary alterations, especially in patients with high Model for End-Stage Liver Disease (MELD) scores. Common comorbidities include hepatic hydrothorax, hepatopulmonary syndrome, α-1 antitrypsin deficiency emphysema, and portopulmonary hypertension. These pre-existing conditions significantly contribute to the development of pneumonia and other respiratory complications. Furthermore, intraoperative factors such as massive transfusions, fluid overload, hemodynamic instability, renal failure, reperfusion syndrome, and coagulopathies play a crucial role in the development of postoperative respiratory insufficiency, often leading to prolonged postoperative invasive mechanical ventilation [5].

Prolonged mechanical ventilation is the predominant context in which percutaneous dilatational tracheostomy (PDT) is considered; however, the risk of laryngotracheal injury increases with the duration of translaryngeal intubation [6,7]. On the one hand, modern ventilators with improved weaning functions, such as automatic tube compensation and endotracheal tubes with subglottic suction, allow prolonged ventilation via endotracheal tubes. On the other hand, PDT is significantly simpler, more accessible, safer, and can be performed bedside in the intensive care unit (ICU) [6,8-10]. This highlights the need to identify which patients undergoing LT are most likely to benefit from PDT and to define the optimal timing for its implementation.

Although many studies and meta-analyses have examined whether earlier tracheostomy confers advantages over later tracheostomy or continued endotracheal intubation, the evidence is mixed. Most studies in patients undergoing LT and PDT are retrospective, small, and often rely on unadjusted analyses; many emphasize predictors of prolonged ventilation and procedural complications rather than the effect of timing itself. Definitions of "early" and "late" vary widely, further limiting comparability. Consequently, the optimal timing of tracheostomy in critically ill patients—particularly after LT – remains uncertain.

Given the heterogeneity of published LT timing definitions and the absence of a universally accepted cutoff, we used a pragmatic threshold of 7 days to distinguish PDT performed within the first postoperative week from later procedures, informed by German ICU practice, in which tracheostomy is commonly performed within the first 14 days of mechanical ventilation and most often during the second week [11].

This study aims to assess the clinical impact of early (≤7 days) vs late (≥8 days) PDT after LT on ICU length of stay, mechanical ventilation duration, and short- and long-term survival.

## Material and Methods

### Study Population

We conducted a retrospective analysis of LT recipients who underwent PDT between December 2010 and June 2024 at the University Hospital Essen, Germany. Only patients treated in the general surgical ICU were included in the study. Patients under 18 years of age were excluded from the study. Out of 1352 LT recipients treated during the study period, 83 (6.1%) underwent PDT and were included in the analysis.

The indication and timing of PDT were determined on a case-by-case basis by the attending ICU consultant, based on the patient's current clinical status, respiratory course, and anticipated need for prolonged mechanical ventilation, without a standardized institutional protocol or prespecified criteria for early vs late PDT. During the study period, all tracheostomies in the analyzed cohort were performed as bedside PDTs; no surgical tracheostomies were performed.

Clinical and laboratory data were collected retrospectively from electronic medical records and archived paper-based charts.

### Ethics Approval and Consent to Participate

The study protocol was approved by the Ethics Committee of the University of Duisburg-Essen (approval No. 23-11497-BO; October 30, 2023). The study was conducted in accordance with the Declaration of Helsinki and applicable institutional/national regulations. Due to the retrospective design and use of de-identified data, the committee waived the requirement for written informed consent. Patient confidentiality and anonymity were preserved throughout; no identifiable images or personal data are included. All organs used for the index transplants in this cohort were obtained through legally authorized donation processes; no organs from executed prisoners were used.

#### Parameters

The following clinical and laboratory parameters were recorded and analyzed for each patient (**Table 1**): demographic data: sex, age, and body mass index; primary indication for LT: alcohol-related cirrhosis, metabolic-associated steatohepatitis, viral hepatitis, cholestatic liver disease, and other etiologies; type of surgery: primary LT, primary re-transplantation, and other procedures (eg, second re-transplantation, combined liver-kidney transplantation); comorbidities: atrial fibrillation, coronary artery disease, diabetes mellitus, chronic obstructive pulmonary disease, peripheral arterial occlusive disease, stroke, nicotine use, and hepatocellular carcinoma; causes of respiratory insufficiency and indications for PDT: pneumonia, liver graft dysfunction, abdominal sepsis, and weaning failure; cause of death: septic shock, liver failure, acute hemorrhage, cardiogenic shock, and intracerebral haemorrhage; postoperative data: length of ICU stay, total hospital stay, duration of mechanical ventilation, need for renal replacement therapy, whether patients underwent initial postoperative extubation after LT before subsequent PDT, the time from LT to first postoperative extubation among those patients, and the interval from LT to PDT; and laboratory parameters: hemoglobin, international normalized ratio, activated partial thromboplastin time, fibrinogen, platelet count, aspartate aminotransferase (AST), alanine aminotransferase (ALT), bilirubin, and creatinine.

In addition, severity and organ function scores were measured using the Simplified Acute Physiology Score II (SAPS II), Horowitz index (arterial oxygen partial pressure to inspired oxygen fraction ratio [$PaO_2/FiO_2$]), and a postoperative Model for End-Stage Liver Disease (MELD) score recalculated on the day of PDT. The recalculated MELD score was used as a marker of disease severity rather than for organ allocation, consistent with previous reports that postoperative MELD-based scores may be prognostic after LT [12].

#### Statistical Analysis

Continuous variables were assessed for normality using the Shapiro-Wilk and Kolmogorov-Smirnov tests, with the Shapiro-Wilk test prioritized. Normally distributed variables were reported as mean±standard deviation, and non-normally distributed variables as median with range (minimum-maximum).

For the purposes of this analysis, patients were retrospectively categorized as having undergone early PDT (≤7 days) or late PDT (≥8 days) according to the interval from LT to PDT. The 7-day threshold was chosen as a pragmatic study-specific cutoff, reflecting heterogeneity in published LT timing definitions and common German ICU practice, whereby tracheostomy is often performed within the first 14 days of prolonged mechanical ventilation and most often during the second week [11].

Homogeneity of variances was evaluated using the Levene and Brown-Forsythe tests. For group comparisons, the Wilcoxon rank-sum test was used for continuous variables, and the Pearson chi-square or Fisher exact test were used for categorical variables, as appropriate.

Variables found to be statistically significant in univariate group comparisons, as well as clinically relevant variables, were included in multivariable linear regression models to assess associations between PDT timing and clinical outcomes. Outcome variables (ICU length of stay and mechanical ventilation duration) were log-transformed to improve model fit and facilitate interpretation in terms of relative percentage change. Because PDT timing was not randomized, the multivariable models were used to estimate adjusted associations rather than causal effects.

Survival was analyzed using Kaplan-Meier curves, with group comparisons performed by the log-rank test. Additionally, a multivariable Cox proportional hazards model was used to evaluate the association between PDT timing and survival outcomes. A $P$ value <0.05 was considered statistically significant.

All statistical analyses were performed using jamovi (version 2.5.6.0; The jamovi project, Sydney, Australia) and R (version 4.4.2; R Foundation for Statistical Computing, Vienna, Austria) within RStudio (Posit PBC, Boston, MA, USA). The following R packages were employed for data processing, modeling, and visualization: readxl, dplyr, survival, broom, ggplot2, gt, gtsummary, survminer, forcats, and tidyr.

## Results

#### Overall Cohort

During the study period, 1352 patients underwent LT, of whom 83 (6.1%) required PDT. Patient characteristics and procedural parameters are summarized in **Table 1**. Patients ranged in age from 18 to 70 years (median: 55 years). The cohort included 31 female (37.3%) and 52 male (62.7%) patients. The mean body mass index was 25.5±5.0 kg/$m^2$.

The most common comorbidities were nicotine use (n=22, 26.5%) and diabetes mellitus (n=21, 25.3%), followed by coronary artery disease (n=14, 16.9%), atrial fibrillation (n=13, 15.7%), hepatocellular carcinoma (n=16, 19.3%), stroke (n=4, 4.8%), chronic obstructive pulmonary disease (n=4, 4.8%), and peripheral arterial occlusive disease (n=2, 2.4%).

On the day of PDT, the median recalculated postoperative MELD score – calculated from laboratory values obtained on the day of tracheostomy and used here as a marker of disease severity – was 22.5 (range, 6-37), and the mean SAPS II was 34.1±11.8.







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**Table 1.** Baseline characteristics of liver transplant recipients undergoing percutaneous dilatational tracheostomy (N=83). Values are mean±SD or median [min-max] as appropriate. Categorical variables are n (%) of the total cohort (N=83).

| Category/variable | Value |
|---|---|
| Demographics | |
| Male/Female | 52 (62.7%)/31 (37.3%) |
| Age (years) | 55 [18-70] |
| BMI (kg/m²) | 25.5±5.0 |
| Clinical scores on tracheostomy day | |
| SAPS II (points) | 34.1±11.8 |
| Recalculated postoperative MELD on PDT day (points) | 22.5 [6-37] |
| $PaO_2/FiO_2$ (mmHg)/(kPa) | 304±85/40.5±11.3 |
| ICU and ventilation | |
| ICU length of stay (days) | 34.5 [4-161] |
| Mechanical ventilation duration (hours) | 591 [25-3,810] |
| CRRT | 62 (74.7%) |
| Time to first postoperative extubation after LT, in those extubated before PDT (n=42) (days) | 4 [1-19] |
| Time from LT to PDT (days) | 11 [4-150] |
| Initially extubated after LT before PDT | 42 (50.6%) |
| Transplant-related data | |
| Warm ischemia time (min) | 30 [16-65] |
| Primary indication for transplantation | |
| Alcoholic cirrhosis | 22 (27%) |
| Cholestatic cirrhosis | 7 (8.4%) |
| MASH | 6 (7.2%) |
| Viral hepatitis | 24 (29%) |
| Other indications | 24 (29%) |
| Indication for tracheostomy (leading cause) | |
| Weaning failure | 11 (13.3%) |
| Liver-graft dysfunction | 12 (14.5%) |
| Nosocomial pneumonia | 49 (59%) |
| Abdominal sepsis | 10 (12%) |
| Unknown | 1 (1.2%) |
| Comorbidities | |
| Atrial fibrillation | 13 (15.7%) |
| Hepatocellular carcinoma | 16 (19.3%) |
| Coronary artery disease | 14 (16.9%) |
| Diabetes mellitus | 21 (25.3%) |





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**Table 1 continued.** Baseline characteristics of liver transplant recipients undergoing percutaneous dilatational tracheostomy (N=83). Values are mean±SD or median [min-max] as appropriate. Categorical variables are n (%) of the total cohort (N=83).

| Category/variable | Value |
|---|---|
| Stroke | 4 (4.8%) |
| COPD | 4 (4.8%) |
| PAOD | 2 (2.4%) |
| Nicotine use | 22 (26.5%) |
| Mortality cause (1-year follow-up from tracheostomy day) | |
| Septic shock | 44 (53%) |
| Liver failure | 5 (6%) |
| Cardiogenic shock | 3 (3.6%) |
| Cerebral hemorrhage | 2 (2.4%) |
| Acute surgical hemorrhage | 1 (1.2%) |
| Unclear cause | 7 (8.4%) |
| Alive at 1 year | 21 (25.3%) |
| Laboratory parameters | |
| Hemoglobin (g/L) | 86.3±11.9 |
| INR | 1.07 [0.91-2.43] |
| aPTT (s) | 30 [21-79] |
| Fibrinogen (g/L) | 4.12 [1.00-10.00] |
| Bilirubin (µmol/L) | 29 [5-357] |
| Platelet count (×10⁹/L) | 90 [10-480] |
| AST (U/L) | 53 [13-586] |
| ALT (U/L) | 114 [12-1,331] |
| Creatinine (µmol/L) | 150 [42-447] |

Units: hemoglobin (g/L), fibrinogen (g/L), bilirubin (µmol/L), creatinine (µmol/L), AST/ALT (U/L), INR (ratio), aPTT (s), platelets ($\times 10^9$/L). $PaO_2/FiO_2$ (mmHg/kPa; 1 mmHg=0.133 kPa). ALT – alanine aminotransferase; AST – aspartate aminotransferase; aPTT – activated partial thromboplastin time; BMI – body mass index; COPD – chronic obstructive pulmonary disease; CRRT – continuous renal replacement therapy; ICU – intensive care unit; INR – international normalized ratio; LT – liver transplantation; MELD – Model for End-Stage Liver Disease; MASH – metabolic dysfunction-associated steatohepatitis; $PaO_2/FiO_2$ – ratio of arterial oxygen partial pressure to inspired oxygen fraction; PAOD – peripheral arterial occlusive disease; PDT – percutaneous dilatational tracheostomy; SAPS II – Simplified Acute Physiology Score II.



The median length of stay in the ICU was 34.5 days (range, 4-161), and the median total hospital stay was 63 days (range, 4-493). Upon ICU admission, the mean SAPS II was 36.6±12.0. The median duration of mechanical ventilation was 591 hours (range, 25-3810). During the ICU stay, 62 patients (74.7%) required continuous renal replacement therapy.

### Timing and Clinical Sequence Before PDT

The median time from LT to PDT was 11 days (range, 4-150) for the entire cohort, and the earliest PDT was performed on postoperative day 4. Of the 83 patients, 41 (49.4%) were never successfully extubated after LT and proceeded directly from endotracheal intubation to PDT. The remaining 42 patients (50.6%) were initially extubated after a median of 4 days



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**Table 2.** Comparative analysis of early (≤7 days) vs late (≥8 days) percutaneous dilatational tracheostomy after liver transplantation. Values are mean±SD or median [min-max] as appropriate. Categorical variables are n (%).

| Variable | Early (≤7 days) (N=22) | Late (≥8 days) (N=61) | *P* value |
|---|---|---|---|
| Demographics and scores on tracheostomy day | | | |
| Male/Female | 16 (73%)/6 (27%) | 36 (59%)/25 (41%) | 0.30 |
| Age (years) | 54 [29-69] | 55 [18-70] | 0.50 |
| BMI (kg/m²) | 25.9±4.2 | 25.3±5.3 | 0.50 |
| SAPS II (points) | 38±10 | 33±12 | 0.20 |
| Recalculated postoperative MELD on PDT day (points) | 23 [8-30] | 22 [6-37] | 0.80 |
| $PaO_2/FiO_2$ (mmHg)/(kPa) | 285±75/38.0±10.0 | 312±88/41.6±11.7 | 0.40 |
| ICU and ventilation | | | |
| ICU length of stay (days) | 22 [4-72] | 39 [8-161] | 0.005* |
| Mechanical ventilation duration (hours) | 439 [25-3810] | 656 [184-3721] | 0.046* |
| CRRT, n (%) | 15 (68%) | 47 (78%) | 0.30 |
| Indication for tracheostomy (leading cause) | | | |
| Weaning failure | 3 (13.6%) | 8 (13.1%) | 1.000 |
| Liver graft dysfunction | 5 (22.7%) | 7 (11.5%) | 0.287 |
| Nosocomial pneumonia | 7 (31.8%) | 42 (68.9%) | 0.005* |
| Abdominal sepsis | 7 (31.8%) | 3 (4.9%) | 0.003* |
| Global test (for indication block) | | | 0.002* |
| Laboratory parameters | | | |
| Hemoglobin (g/L) | 89.2±10.7 | 85.2±12.3 | 0.20 |
| INR | 1.03 [0.92-1.31] | 1.08 [0.91-2.43] | 0.14 |
| aPTT (s) | 30 [22-53] | 30 [21-79] | >0.9 |
| Fibrinogen (g/L) | 3.46 [1.39-7.20] | 4.26 [1.00-10.00] | 0.30 |
| Bilirubin (µmol/L) | 36 [10-238] | 26 [5-357] | 0.30 |
| Platelets (×10⁹/L) | 57 [10-423] | 97 [18-480] | 0.047* |
| AST (U/L) | 72 [28-581] | 46 [13-586] | 0.022* |
| ALT (U/L) | 249 [30-734] | 67 [12-1,331] | <0.001* |
| Creatinine (µmol/L) | 175 [89-350] | 141 [42-447] | 0.033* |

* $P<0.05$. Units: $PaO_2/FiO_2$ (mmHg)/(kPa) (1 mmHg 0.133 kPa); ALT/AST (U/L); hemoglobin (g/L); fibrinogen (g/L); bilirubin (µmol/L); creatinine (µmol/L); platelets (×10⁹/L). Statistical tests used: Pearson chi-square or Fisher exact test (categorical); Wilcoxon rank-sum/Mann-Whitney (continuous). Global test compares the distribution of leading indications (4-category chi-square test). aPTT – activated partial thromboplastin time; ALT – alanine aminotransferase; AST – aspartate aminotransferase; BMI – body mass index; CRRT – continuous renal replacement therapy; ICU – intensive care unit; INR – international normalized ratio; MELD – Model for End-Stage Liver Disease; $PaO_2/FiO_2$ – ratio of arterial oxygen partial pressure to inspired oxygen fraction; PDT – percutaneous dilatational tracheostomy; SAPS II – Simplified Acute Physiology Score II.







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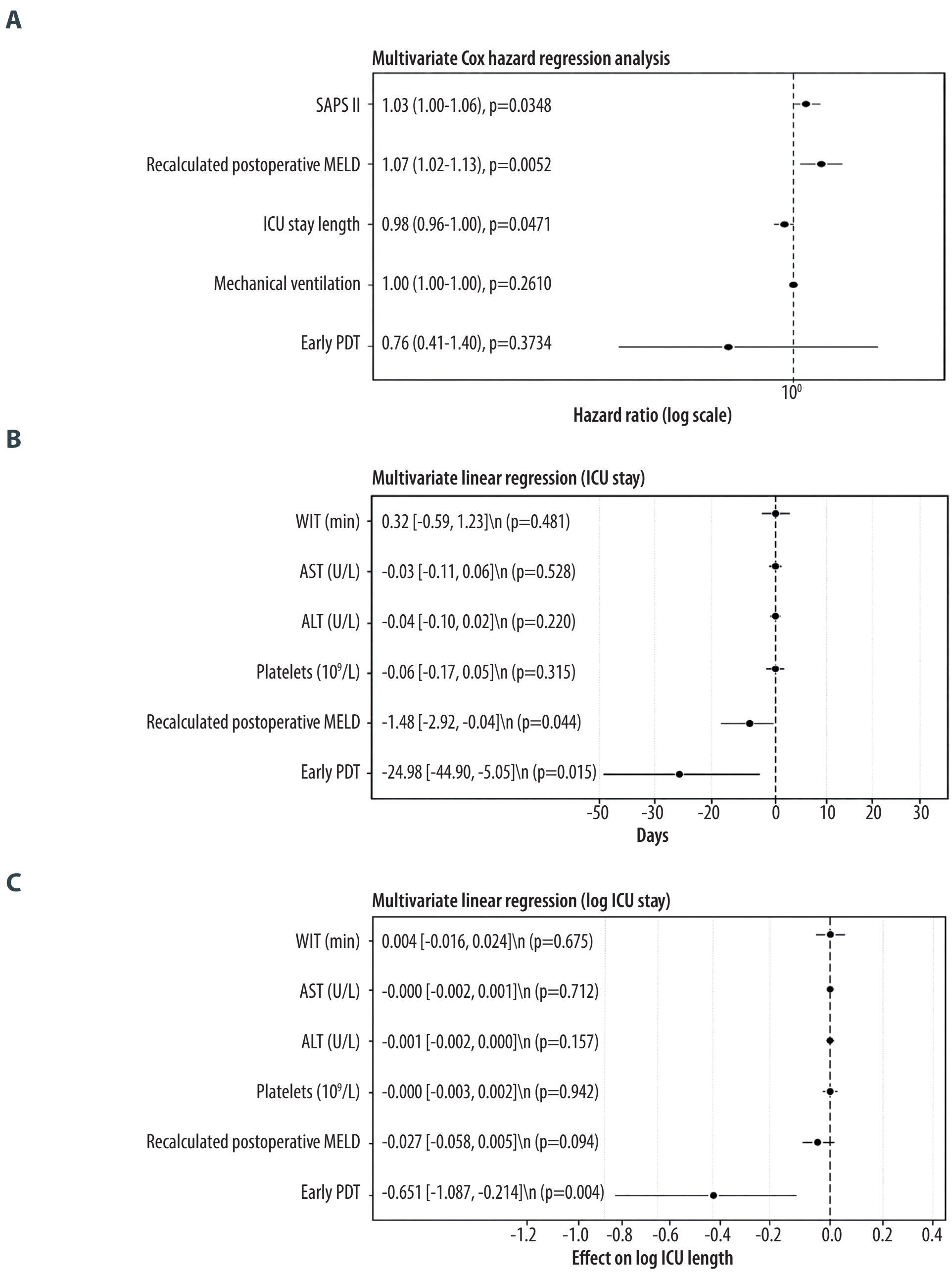
(range, 1-19) following LT; however, all 42 were subsequently re-intubated due to respiratory deterioration (eg, pneumonia, sepsis, or weaning failure) and ultimately required PDT.

The most frequent indication for PDT was prolonged respiratory insufficiency due to nosocomial pneumonia, observed in 49 patients (59%). Other indications included liver graft dysfunction in 12 patients (14.5%), abdominal sepsis in 10 patients (12%), and weaning failure in 11 patients (13.3%). In one additional patient (1.2%), the leading indication for PDT could not be clearly determined because of incomplete documentation.

**Comparative Analysis: Early vs Late PDT**

Of the 83 patients, 22 underwent early PDT (≤7 days) and 61 underwent late PDT (≥8 days). The comparative findings between the early and late PDT groups are summarized in **Table 2**.

Nosocomial pneumonia was more frequently documented as the leading indication for PDT in the late-PDT group than in the early-PDT group (68.9% vs 31.8%; *P*=0.005). In contrast, abdominal sepsis was a significantly more frequent indication in the early PDT group (31.8% vs 4.9% in the late PDT group, *P*=0.003).







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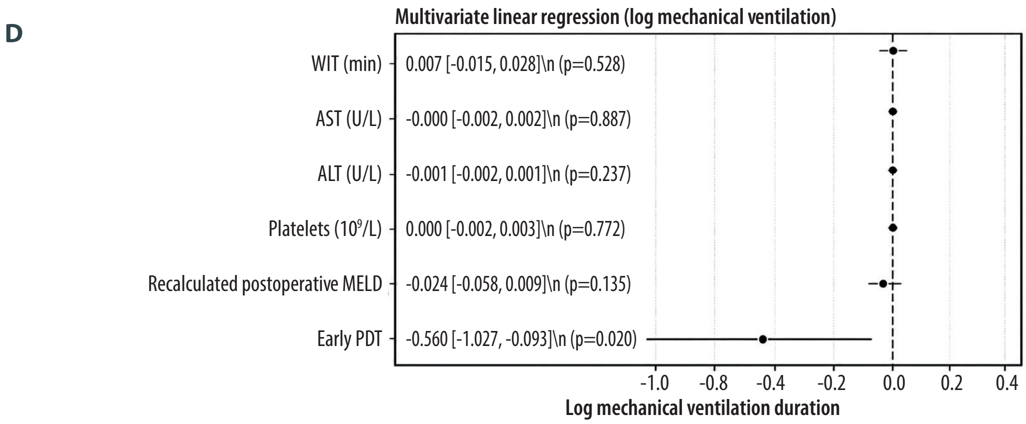


**Figure 1.** Early percutaneous dilatational tracheostomy (PDT) after liver transplantation (LT): multivariable associations with survival, ICU stay, and ventilation. Forest plots of multivariate regression analyses for clinical outcomes in liver transplant recipients with percutaneous dilatational tracheostomy. (**A**) Multivariate Cox proportional hazards regression for 1-year survival. (**B**) Multivariate linear regression for ICU length of stay (days). (**C**) Multivariate linear regression for log-transformed ICU length of stay. (**D**) Multivariate linear regression for log-transformed mechanical ventilation duration (hours). Postoperative MELD was recalculated on the day of PDT. ALT – alanine aminotransferase (U/L); AST – aspartate aminotransferase (U/L); CI – confidence interval; HR – hazard ratio; ICU – intensive care unit; LT – liver transplantation; MELD – Model for End-Stage Liver Disease; PDT – percutaneous dilatational tracheostomy; SAPS II – Simplified Acute Physiology Score II; WIT – warm ischemia time (min); platelets, $\times 10^9$/L.

The early PDT group showed significantly lower platelet counts (median: 57 vs $97\times 10^9$/L; *P*=0.047), higher AST levels (median: 72 vs 46 U/L; *P*=0.022), higher ALT levels (median: 249 vs 67 U/L; *P*<0.001), and elevated serum creatinine (median: 175 vs 141 µmol/L; *P*=0.033). No significant differences were found in recalculated postoperative MELD scores on the day of PDT or bilirubin levels.

Patients receiving early PDT had a significantly shorter ICU stay (median: 22 vs 39 days; *P*=0.005) and required fewer hours of mechanical ventilation (median: 439 vs 656 hours; *P*=0.046) than those receiving late PDT.

There was no statistically significant difference in 1-year mortality between the early and late PDT groups (*P*=0.80). A similar finding was observed for 7-day mortality (*P*=0.70).

### Multivariate and Survival Analysis

Following univariate analysis, multivariable linear regression models using outcomes on their original scale identified early PDT as an independent predictor of reduced ICU length of stay (β=-24.98 days; 95% CI, -44.90 to -5.05; *P*=0.015; **Figure 1B**). Regarding the duration of mechanical ventilation, early PDT was likewise associated with a significant reduction (β=-401.43 hours; 95% CI, -801.77 to -1.09; *P*=0.049). Other covariates, including recalculated postoperative MELD at the time of PDT, aminotransferases (AST, ALT), warm ischemia time, and platelet count, did not demonstrate statistically significant associations.

Because ICU length of stay and mechanical ventilation duration showed skewed distributions and heteroscedasticity, log transformation was applied to improve model fit and assumptions, and to allow interpretation of effect sizes as relative percentage changes.

Multivariable linear regression models using log-transformed outcomes revealed that early PDT was significantly associated with a reduced ICU length of stay (β=-0.651; 95% CI, -1.087 to -0.214; *P*=0.004; **Figure 1C**), corresponding to an estimated 47.8% shorter ICU stay compared with that of late PDT. In parallel, a significant association was observed for mechanical ventilation duration (β=-0.56; 95% CI, -1.027 to -0.093; *P*=0.02; **Figure 1D**), reflecting a 42.9% reduction. None of the other clinical or biochemical covariates demonstrated statistically significant associations.

Over a follow-up period of 365 days, 62 of the 83 patients (74.7%) died, while 21 were censored (**Figure 2**). The 7-day mortality after PDT was 14.5% (12 patients). Early mortality (within 7 days) was most frequently due to septic shock (n=8, 9.6%), followed by liver failure (n=2, 2.4%) and cardiogenic shock (n=1, 1.2%). One case (1.2%) had an undetermined cause.

The most common causes of death over the whole observation period were septic shock (n=44, 53.0%), liver failure (n=5, 6.0%), cardiogenic shock (n=3, 3.6%), cerebral hemorrhage (n=2, 2.4%), and acute surgical bleeding (n=1, 1.2%). In 7 cases (8.4%), the cause of death could not be determined. No deaths were directly attributable to the PDT procedure itself.





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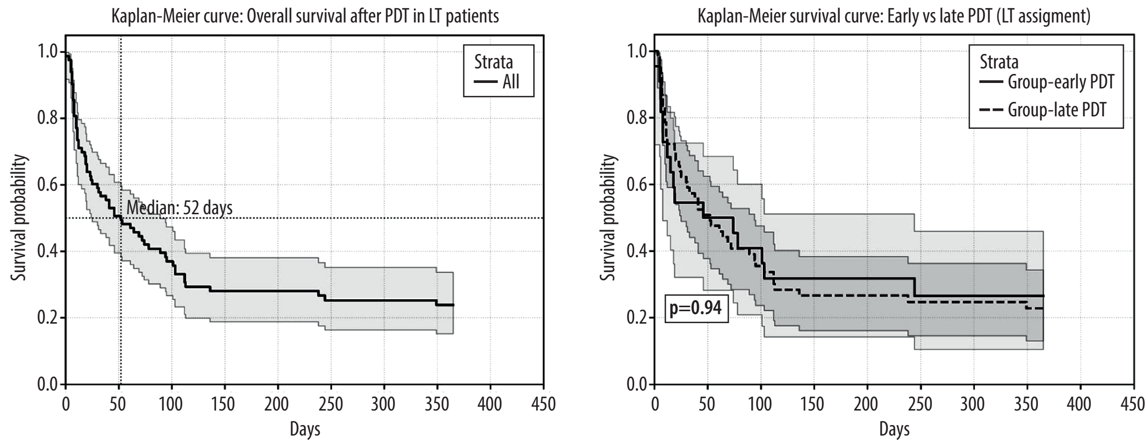


**Figure 2.** Kaplan-Meier (KM) survival from the day of percutaneous dilatational tracheostomy (PDT) in liver transplant recipients. Overall survival for the entire cohort (N=83), with time zero defined as the date of PDT. Dotted reference lines indicate the overall median survival. Survival stratified by timing of PDT after liver transplantation (LT): early (≤7 days after LT; n=22) vs late (≥8 days after LT; n=61). Follow-up time is measured from PDT. Shaded bands represent 95% CIs. The *P* value is from a 2-sided log-rank test comparing early vs late.

Kaplan-Meier survival analysis showed median survival times of 60 days in the early PDT group and 52 days in the late PDT group; however, this difference was not statistically significant by the log-rank test (*P*=0.94; **Figure 2**).

Additionally, multivariate Cox survival analysis showed no significant association between early PDT and overall survival (hazard ratio [HR], 0.76; 95% CI, 0.41-1.40; *P*=0.374, **Figure 1A**), as the confidence interval included 1.0, and the *P* value was not statistically significant. ICU stay length (HR, 0.98; 95% CI, 0.96-1.00; *P*=0.0471) and SAPS II (HR 1.03; 95% CI, 1.00-1.06; *P*=0.0348) demonstrated borderline statistical significance, with confidence intervals extending to 1.0, suggesting cautious interpretation. In contrast, recalculated postoperative MELD at the time of PDT (HR, 1.07; 95% CI, 1.02-1.13; *P*=0.005) was independently and significantly associated with overall survival, with the confidence interval entirely above 1.0.

## Discussion

At our institution, immediate postoperative extubation is standard when clinically feasible. Nevertheless, postoperative respiratory complications remain common, occurring in 10% to 40% of cases after abdominal surgery [13-15] and up to 50% after LT [3]. When respiratory failure persists after LT because of pulmonary or surgical complications, extubation may not be feasible, and PDT is considered for selected patients. The optimal timing of PDT after LT remains debated: some studies define early as ≤14 days [16], others as ≤3 days [17]. Most LT reports distinguish between early and late based on the interval between LT and PDT [16,18].

We defined early PDT as ≤7 days after LT – a pragmatic threshold anchored in German ICU practice, whereby most tracheostomies are performed during the second week [11]. In our retrospective cohort of LT recipients requiring prolonged mechanical ventilation, early PDT was independently associated with shorter ICU stays and reduced duration of mechanical ventilation. This association remained significant in multivariable linear regression models after adjustment for relevant clinical covariates (including recalculated postoperative MELD at the time of PDT, AST, ALT, platelet count, and warm ischemia time). In our linear models with log-transformed outcomes, early PDT was independently associated with clinically and statistically significant reductions in ICU length of stay (approximately 47.8%; *P*=0.004) and mechanical ventilation duration (approximately 42.9%; *P*=0.020) compared with late PDT.

Early PDT may be associated with lower ICU costs by reducing the length of stay. Using the estimate of Martin et al of €1426 per ventilated ICU Day [19] and the adjusted 47.8% reduction in ICU stay, an illustrative calculation suggests median per-patient ICU costs could fall from approximately €49 900 to €26 100 (€23 800 difference), corresponding to roughly €1.45 million for the 61 patients in the late-PDT group. While hypothetical, this highlights the economic relevance of timely tracheostomy in ICU care.

These associations persisted despite the early-PDT group showing worse clinical parameters at the time of PDT (higher







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AST, ALT, and creatinine levels, and lower platelet counts) and a higher frequency of abdominal sepsis. In multivariable Cox models, early PDT was not independently associated with survival (**Figure 1A**), whereas higher postoperative recalculated MELD and SAPS II scores at the time of PDT were linked to increased mortality.

Indications differed by PDT timing: nosocomial pneumonia was more frequently documented as the leading indication for PDT in the late-PDT group than in the early-PDT group (68.9% vs 31.8%; *P*=0.005), whereas abdominal sepsis was more frequent in the early-PDT group (31.8% vs 4.9%; *P*=0.003). Because this analysis reflects the documented leading indication for PDT rather than all pneumonia episodes occurring throughout the ICU course, the higher pneumonia rate in the late group represents a potential confounder, as pneumonia itself prolongs mechanical ventilation and ICU stay independently of tracheostomy timing. Although our multivariable models adjusted for several clinical covariates, pneumonia acted both as an indication for PDT and as a determinant of prolonged ICU course; therefore, part of the apparent advantage associated with early PDT may reflect differences in indication patterns and pulmonary case mix in the late group rather than a pure timing effect, which cannot be fully disentangled in this retrospective analysis.

Across comparative and survival analyses, 7-day and 1-year mortality rates did not differ significantly between groups, indicating that shorter ICU stays and shorter ventilation exposure with early tracheostomy (PDT) were not associated with a significant survival benefit.

Overall, these data suggest that early PDT was associated with improved ICU efficiency (shorter ICU stays and shorter ventilation durations) in selected posttransplant patients, while survival outcomes remained unchanged.

The high 1-year mortality observed in our PDT cohort (74.7%) merits comment. For context, Graham et al [18] reported 35% 1-year mortality, whereas Reparaz et al [7] observed 52% ICU mortality in the immediate postoperative period, suggesting that our center primarily applies tracheostomy to a particularly vulnerable subgroup of transplant recipients with severe early postoperative trajectories.

According to Loosen et al [20], liver transplant-related mortality rates in Germany were 11% in 2017, with the University Hospital Essen reporting 9.3% in 2016 and 12.35% in 2017. According to the Institute for Quality Assurance and Transparency in Health Care (IQTIG, Germany) national quality report, the 1-year mortality after LT in Germany was 14.58% in 2023 (all ages; retransplantations excluded) [21], whereas at the University Hospital Essen, it was 19.05% in the same year (adults aged ≥18 years only; retransplantations included).

A likely explanation for the elevated mortality is that tracheostomy at our institution is primarily reserved for patients with severely compromised clinical conditions or already limited prognoses. This reflects a highly selective application of PDT in a particularly vulnerable subgroup of liver transplant recipients. Contributing factors may include higher MELD scores at the time of transplantation, a greater burden of pre-existing comorbidities, and a higher incidence of early postoperative complications compared with other published cohorts.

Placed alongside evidence from mixed ICU populations, our findings fit a recurring pattern: earlier tracheostomy is associated with shorter ICU length of stay and shorter mechanical ventilation duration, whereas effects on survival and ventilator-associated pneumonia are heterogeneous [22-26]. In a recent meta-analysis of randomized controlled trials, Merola et al reported a modest mortality signal with early tracheostomy, but a more precise and consistent reduction in ICU length of stay and mechanical ventilation duration; ventilator-associated pneumonia rates did not differ [22]. Griffiths et al similarly found no mortality or pneumonia benefit but confirmed shorter mechanical ventilation and ICU stays with earlier procedures [23]. Deng et al corroborated these reductions across randomized trials [24]. By contrast, Siempos et al observed no benefit in ICU mortality. Still, they noted a significantly lower ventilator-associated pneumonia incidence with early tracheostomy [25], and the multicenter randomized study by Terragni et al did not demonstrate a statistically significant reduction in ventilator-associated pneumonia despite more ventilator-free and ICU-free days in the early group [26]. Taken together, these data indicate that, in heterogeneous ICU settings, the principal advantage of earlier tracheostomy lies in efficiency gains, with survival effects inconsistent across trials and populations [22-26].

Within LT cohorts, conclusions depend on the chosen early-to-late window and differences in case mix; using ≤14 days as early, Miller et al reported associations with lower in-hospital mortality and a shorter ICU stay [16].

In contrast, Cammann et al (≤3 days) found no difference in 3-month mortality but a marked reduction in mechanical ventilation and ICU stay with early PDT [17]. Graham et al described longer LT-to-PDT intervals than in our cohort and, consistent with our data, found no evidence that earlier PDT reduced mortality [18].

Across mixed ICU and LT-specific studies, earlier PDT is associated with shorter ICU stays and reduced ventilation duration; effects on ventilator-associated pneumonia and mortality vary by study design and timing definitions. Our findings with a ≤7-day definition fit this pattern.





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Our study has several limitations. Its retrospective, single-center design precludes causal inference and limits generalizability; findings from a single transplant center with specific clinical protocols and patient selection criteria may not be directly transferable to other institutions or transplant populations with different case mixes. The absence of a protocol for PDT timing and indication introduces selection bias and confounding by indication; in particular, the decision to perform early vs late PDT was made by individual clinicians based on clinical judgment rather than standardized criteria, making it difficult to separate the effect of timing from underlying differences in clinical decision-making across the study period. Immortal-time (survivor) bias is inherent: patients in the late-PDT group necessarily survived 8 or more days after transplant. This may have influenced group characteristics and the distributions of outcomes. The observed association between early PDT and improved intermediate outcomes may not reflect a causal effect per se, but rather the result of a targeted clinical strategy: in our center, patients with signs of early septic deterioration or liver graft dysfunction – predicting prolonged mechanical ventilation – might have been selected for early tracheostomy to preempt complications such as ventilator-associated pneumonia and to facilitate early weaning. Thus, the decision for early PDT could represent a proactive response to expected clinical deterioration rather than the tracheostomy itself being the primary driver of improved outcomes. Conversely, patients undergoing late PDT may initially have been perceived as clinically more stable and were treated conservatively until unexpected complications, such as nosocomial pneumonia, necessitated delayed tracheostomy. This reactive indication pattern may partially explain their longer ICU stays and ventilation durations. This study included only patients who underwent PDT; no patients with open surgical tracheostomy were analyzed. PDT can be performed at the bedside, which avoids operating room transfers and allows more flexible scheduling. Both factors may have facilitated earlier procedural timing. Importantly, our study compared the timing of tracheostomy within a cohort treated exclusively with PDT. It therefore does not permit conclusions as to whether the observed associations are attributable to tracheostomy per se, are attributable to the percutaneous technique specifically, or would also apply to surgical tracheostomy. Accordingly, our findings should be interpreted as associations indicating possible efficiency gains with earlier PDT. Prospective, protocolized, multicenter studies – ideally incorporating time-dependent methods and predefined timing thresholds – are needed to define optimal PDT timing in LT recipients.

## Conclusions

In this retrospective cohort study, early PDT within 7 days of LT, even in more clinically compromised patients, was associated with a significantly shorter ICU length of stay and shorter mechanical ventilation duration, but no survival benefit was demonstrated. These findings are consistent with prior studies in liver transplant and general ICU populations.

Given the study's single-center retrospective design and the highly selected cohort, these findings should be interpreted as associative rather than causal and may not be directly generalizable to other centers or broader LT populations.

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**Data Availability**

Due to data protection and confidentiality regulations, individual patient data cannot be shared publicly. De-identified data supporting the findings of this study are available from the corresponding author upon reasonable request and with approval from the institutional data protection officer.

**Declaration of Figures' Authenticity**

All figures submitted have been created by the authors who confirm that the images are original with no duplication and have not been previously published in whole or in part.



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