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Serial Changes in Arterial Blood Gas Parameters Following Tracheostomy in Mechanically Ventilated ICU Patients

Yuni Susantri[1], Sutji Pratiwi Rahardjo[1], Yarni Alimah[1], Cita Nur Insani Akhmad[1], Muh. Fadjar Perkasa[1], Abdul Qadar Punagi[1], Ilham Murtala[2]

[1]Department of Otorhinolaryngology – Head and Neck Surgery, Faculty of Medicine, Hasanuddin University, Makassar, Indonesia
[2]Faculty of Medicine and Health Sciences, Muhammadiyah University of Kendari, Southeast Sulawesi, Indonesia, Corresponding author: Yuni Susantri; email: Yussannuril@gmail.com.

ABSTRACT:

Background: Tracheostomy is commonly performed in critically ill patients requiring prolonged mechanical ventilation. However, the temporal pattern of arterial blood gas changes following tracheostomy remains incompletely characterized. This study aimed to evaluate serial changes in arterial blood gas parameters following tracheostomy in mechanically ventilated intensive care unit patients.

Methods: This prospective longitudinal observational study included 21 mechanically ventilated patients undergoing tracheostomy. Arterial blood gas parameters were assessed before tracheostomy and on days 1, 3, 5, 7, and 9 after the procedure. The evaluated parameters included pH, PaO_2, $PaCO_2$, SaO_2, HCO_3^-, base excess (BE), total oxygen content (ctO_2), and total carbon dioxide content ($ctCO_2$). Temporal changes were analyzed using repeated-measures analysis of variance, with Greenhouse–Geisser correction applied when the sphericity assumption was violated and Bonferroni-adjusted pairwise comparisons performed for significant overall effects.

Results: Significant overall temporal changes were observed in all arterial blood gas parameters (all $p<0.05$). Mean pH increased from 7.33±0.07 at baseline to 7.39±0.03 on day 9, PaO_2 from 79.88±10.95 to 91.89±3.55 mmHg, and SaO_2 from 91.56±1.74% to 97.51±0.82%. $PaCO_2$ demonstrated significant overall temporal variation ($p=0.002$), with significant differences from baseline observed on days 5 and 7. Bonferroni-adjusted comparisons showed that SaO_2 and ctO_2 were the earliest parameters to differ significantly from baseline, beginning on day 3, whereas other ventilation and acid–base parameters exhibited later or more variable temporal patterns.

Conclusion: Significant serial changes in arterial blood gas parameters were observed during the nine-day post-tracheostomy period, with the earliest and most consistent changes occurring in oxygen saturation and arterial oxygen content. Serial arterial blood gas monitoring may provide valuable physiological information for characterizing post-tracheostomy respiratory changes in mechanically ventilated ICU patients.

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1. INTRODUCTION

Mechanical ventilation is a cornerstone of supportive care for critically ill patients with respiratory failure. However, prolonged endotracheal intubation may be associated with increased airway resistance, impaired secretion clearance, patient discomfort, and difficulties in ventilator weaning. Tracheostomy is therefore frequently considered in patients requiring prolonged ventilatory support as an alternative airway strategy that may facilitate airway management and respiratory care.(1–3)

Compared with prolonged endotracheal intubation, tracheostomy provides direct access to the trachea and may reduce airway resistance and anatomical dead space, facilitate tracheobronchial secretion clearance, improve patient comfort, and support ventilator weaning. These physiological advantages may influence alveolar ventilation and pulmonary gas exchange, potentially affecting arterial oxygenation and carbon dioxide elimination (3). Nevertheless, respiratory responses following tracheostomy may vary according to underlying disease, severity of critical illness, duration of mechanical ventilation, and ventilatory management strategies(1,4).

Arterial blood gas analysis provides objective information on oxygenation, ventilation, and acid–base homeostasis in critically ill patients. Arterial oxygen partial pressure (PaO_2) and arterial oxygen saturation (SaO_2) reflect arterial oxygenation, whereas arterial carbon dioxide partial pressure ($PaCO_2$) provides information regarding alveolar ventilation. Blood pH, bicarbonate (HCO_3^-), and base excess (BE) further characterize respiratory and metabolic components of acid–base balance. In addition, total oxygen content (ctO_2) and total carbon dioxide content ($ctCO_2$) may provide complementary physiological information regarding systemic oxygen transport and carbon dioxide balance.

Although tracheostomy has been extensively investigated in relation to timing, ventilator weaning, intensive care unit length of stay, and clinical outcomes, its association with longitudinal changes in arterial blood gas parameters remains less clearly characterized. Stripoli et al. (5) demonstrated that high-flow oxygen delivered through a tracheostomy could improve oxygenation indices and respiratory parameters. Other studies have suggested that respiratory and physiological responses following tracheostomy may be limited or heterogeneous in mechanically ventilated patients (3,5,6). In contrast, Manhas et al. (7) reported significant post-tracheostomy changes in pH, PaO_2, $PaCO_2$, and HCO_3^-, suggesting that physiological responses may differ across patient populations and clinical contexts.

To our knowledge, few prospective studies have simultaneously characterized the serial trajectories of oxygenation, ventilation, and acid–base parameters across multiple predefined time points following tracheostomy in mechanically ventilated ICU patients. Physiological changes in oxygenation, ventilation, and acid–base homeostasis may not occur immediately after the procedure but may evolve progressively during subsequent intensive care management. Serial assessment may therefore provide a more comprehensive understanding of post-tracheostomy respiratory physiology than a single pre–post comparison.

Accordingly, this study aimed to evaluate serial changes in arterial blood gas parameters before tracheostomy and on days 1, 3, 5, 7, and 9 following the procedure in mechanically ventilated ICU patients. The evaluated parameters included pH, PaO_2, $PaCO_2$, SaO_2, HCO_3^-, BE, ctO_2, and $ctCO_2$. By characterizing their temporal patterns, this study sought to provide physiological evidence regarding changes in oxygenation, ventilation, and acid–base status following tracheostomy.

2. MATERIALS AND METHODS

Study Design

This prospective longitudinal observational study was conducted in the intensive care unit (ICU) of Wahidin Sudirohusodo Hospital, Makassar, Indonesia, from July 2025 to June 2026. The study evaluated serial changes in arterial blood gas parameters before and after tracheostomy in critically ill patients requiring mechanical ventilation.

Study Population and Sampling

The study population comprised ICU patients requiring airway support and undergoing tracheostomy during the study period. All eligible patients who met the predefined inclusion and exclusion criteria during the study period were included because of the specific and limited target population.

Eligible patients were mechanically ventilated ICU patients undergoing tracheostomy for prolonged ventilatory support, anticipated difficulty in ventilator weaning, impaired airway protection, or the need for prolonged airway management,

according to the assessment of the treating multidisciplinary team. Patients were excluded if they underwent interventions that could substantially affect oxygenation, including extracorporeal membrane oxygenation or high-frequency oscillatory ventilation; experienced major acute events between arterial blood gas measurements, including pneumothorax, cardiac arrest, or massive pulmonary embolism; or had major changes in respiratory or hemodynamic management, defined as a change in fraction of inspired oxygen (FiO_2) of ≥20%, a change in mechanical ventilation mode, transfusion of more than two units of blood, or major surgery. Patients with do-not-resuscitate or do-not-intubate limitations that restricted serial measurements and pregnant patients were also excluded.

Variables

The primary outcome was the serial change in arterial blood gas (ABG) parameters following tracheostomy in mechanically ventilated intensive care unit (ICU) patients. The evaluated parameters included arterial pH, partial pressure of oxygen (PaO_2), partial pressure of carbon dioxide ($PaCO_2$), arterial oxygen saturation (SaO_2), bicarbonate (HCO_3^-), base excess (BE), total oxygen content (ctO_2), and total carbon dioxide content ($ctCO_2$). Measurements were obtained before tracheostomy and subsequently on postoperative days 1, 3, 5, 7, and 9. The secondary outcome was the identification of the earliest postoperative time point at which each ABG parameter differed significantly from baseline.

Bias

Several measures were undertaken to minimize potential sources of bias. Selection bias was reduced by applying consecutive sampling, whereby all eligible patients admitted during the study period who fulfilled the inclusion criteria were enrolled. Measurement bias was minimized through standardized arterial blood gas analysis using the same blood gas analyzer and institutional laboratory procedures throughout the study. To reduce observer bias, blood sampling, laboratory analysis, and data recording were performed according to standardized ICU protocols. Statistical analyses were conducted using predefined analytical procedures before data interpretation.

Study Size

This prospective longitudinal study included all eligible mechanically ventilated ICU patients who underwent tracheostomy between July 2025–June 2026 at Dr. Wahidin Sudirohusodo Hospital, Makassar, Indonesia. Twenty-one patients fulfilled the inclusion and exclusion criteria and completed all scheduled arterial blood gas assessments during the nine-day follow-up period; therefore, all were included in the final analysis.

Quantitative Variables

All arterial blood gas parameters were analyzed as continuous variables. Results were summarized as mean ± standard deviation (SD). Serial measurements obtained before tracheostomy and on postoperative days 1, 3, 5, 7, and 9 were compared to evaluate temporal physiological changes following tracheostomy.

Arterial Blood Gas Assessment

Arterial blood gas analysis was performed immediately before tracheostomy and repeated on postoperative days 1, 3, 5, 7, and 9. Arterial blood samples were obtained from indwelling arterial catheters under aseptic conditions and analyzed immediately using the hospital's standard blood gas analyzer. The evaluated parameters included arterial pH, PaO_2, $PaCO_2$, SaO_2, HCO_3^-, BE, ctO_2, and $ctCO_2$. All analyses were performed according to standardized laboratory procedures to ensure consistency throughout the study period.

Tracheostomy Procedure

All tracheostomies were performed surgically by experienced otorhinolaryngology–head and neck surgeons following institutional protocols. The timing of tracheostomy was determined jointly by the multidisciplinary ICU team based on the patient's clinical condition and anticipated prolonged requirement for mechanical ventilation. Postoperative airway care, suctioning, humidification, cuff pressure monitoring, and ventilator management were performed according to standardized ICU protocols throughout the observation period.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics version 25.0 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean ± standard deviation (SD), whereas categorical variables were presented as frequencies and percentages. Normality of the data was assessed using the Shapiro–Wilk test.

Serial changes in arterial blood gas parameters were analyzed using one-way repeated-measures analysis of variance (Repeated Measures ANOVA). The assumption of sphericity was evaluated using Mauchly's test. When the sphericity assumption was violated, Greenhouse–Geisser corrected results were reported. Bonferroni-adjusted pairwise comparisons were subsequently performed to identify the earliest postoperative time point that differed significantly from baseline and to compare changes between consecutive observation periods. A two-sided p-value <0.05 was considered statistically significant.

Ethical Considerations

The study protocol was approved by the Health Research Ethics Committee of the Faculty of Medicine, Hasanuddin University, Makassar, Indonesia (Approval No. UH25090778). Written informed consent was obtained from each participant's legal representative prior to enrolment because all patients were mechanically ventilated and unable to provide informed consent directly. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki, and patient confidentiality was strictly maintained throughout all stages of the research.

3. RESULTS

Participants

A total of 38 mechanically ventilated patients who underwent tracheostomy during the study period were initially screened for eligibility. Seventeen patients were excluded because they did not meet the inclusion criteria, had incomplete arterial blood gas measurements, died before completion of the scheduled follow-up, or had missing clinical data. Consequently, 21 eligible patients were enrolled in the study. All participants completed the scheduled arterial blood gas assessments before tracheostomy and on postoperative days 1, 3, 5, 7, and 9. No patients were lost to follow-up during the observation period, and all enrolled participants were included in the final analysis.

Demographic and Clinical Characteristics

A total of 21 mechanically ventilated intensive care unit (ICU) patients who underwent surgical tracheostomy were included in the final analysis. All participants completed the serial arterial blood gas evaluations at the predefined time points and were therefore included in the longitudinal analysis.

The demographic and clinical characteristics of the study population are summarized in Table 1. The study population was predominantly male (66.7%), with female patients accounting for 33.3% of the cohort. More than half of the patients were aged ≥60 years (52.4%), followed by those aged 40–59 years (33.3%) and 18–39 years (14.3%). Most patients underwent tracheostomy because of prolonged mechanical ventilation secondary to critical illness. Baseline clinical characteristics, including indications for tracheostomy, primary diagnoses, ventilatory support, and comorbidities, are presented in Table 1.

Table 1. Baseline characteristics of the study participants

Characteristics	n (%) / Mean ± SD
Sex	
Male	14 (66.7)
Female	7 (33.3)
Age (years)	57.8 ± 16.3
Age group (years)	
18–39	3 (14.3)

40–59	7 (33.3)
≥60	11 (52.4)
Primary diagnosis	
Stroke	8 (38.1)
Traumatic brain injury	4 (19.0)
Sepsis	3 (14.3)
Postoperative neurosurgery	3 (14.3)
Pneumonia	2 (9.5)
Others	1 (4.8)
Indication for tracheostomy	
Prolonged mechanical ventilation	15 (71.4)
Airway protection	3 (14.3)
Airway secretion management	2 (9.5)
Upper airway obstruction	1 (4.8)
Duration of endotracheal intubation before tracheostomy (days)	8.6 ± 2.3
Duration of mechanical ventilation before tracheostomy (days)	9.1 ± 2.5
Comorbidities	
Hypertension	10 (47.6)
Diabetes mellitus	6 (28.6)
Coronary artery disease	3 (14.3)
Chronic kidney disease	2 (9.5)
Chronic obstructive pulmonary disease	1 (4.8)

Abbreviation: n, number of patients.

Serial Changes in Arterial Blood Gas Parameters

Significant temporal changes were observed in all arterial blood gas parameters across the six measurement time points (all $p<0.05$). Mean pH initially decreased from 7.33±0.07 before tracheostomy to 7.31±0.05 on day 1 and subsequently increased to 7.39±0.03 on day 9 ($F=17.547$; $p<0.001$). PaO_2 remained relatively stable during the early observation period and subsequently increased from 79.88±10.95 mmHg at baseline to 91.89±3.55 mmHg on day 9 ($F=12.374$; $p<0.001$).

$PaCO_2$ demonstrated significant overall temporal variation ($F=5.881$; $p=0.002$), with mean values changing from 49.82±8.46 mmHg at baseline to 45.11±5.93 mmHg on day 9 and fluctuations across intermediate measurement points. SaO_2 progressively increased from 91.56±1.74% to 97.51±0.82% ($F=126.987$; $p<0.001$). HCO_3^- increased from 21.50±2.97 to 24.40±0.92 mmol/L ($F=7.054$; $p=0.002$). BE changed from −3.46±3.28 to −1.20±2.37 mmol/L ($F=4.601$; $p=0.008$). ctO_2 demonstrated a progressive increase from 13.50±0.92 to 18.19±1.01 mL/dL ($F=101.285$; $p<0.001$), whereas $ctCO_2$ exhibited a more variable temporal pattern, changing from 21.73±2.73 to 23.81±2.18 mmol/L ($F=7.108$; $p=0.001$) (Table 2).

Table 2. Serial changes in arterial blood gas parameters before and following tracheostomy

Parameter	Pre-tracheostomy	Day 1	Day 3	Day 5	Day 7	Day 9	ANOVA F	p-value
pH	7.33±0.07	7.31±0.05	7.32±0.03	7.35±0.03	7.38±0.02	7.39±0.03	17.547	<0.001
PaO_2, mmHg	79.88±10.95	79.31±10.52	80.22±4.19	84.61±5.24	87.54±3.17	91.89±3.55	12.374	<0.001
$PaCO_2$, mmHg	49.82±8.46	47.81±6.78	49.11±3.65	44.79±4.16	43.45±2.04	45.11±5.93	5.881	0.002
SaO_2, %	91.56±1.74	92.34±1.46	93.56±1.13	94.94±0.80	96.20±0.72	97.51±0.82	126.987	<0.001
HCO_3^-, mmol/L	21.50±2.97	23.01±1.50	23.23±1.08	22.51±1.15	23.42±1.03	24.40±0.92	7.054	0.002
BE, mmol/L	−3.46±3.28	−2.39±2.93	−3.12±1.09	−2.84±0.73	−1.10±0.81	−1.20±2.37	4.601	0.008
ctO_2, mL/dL	13.50±0.92	14.61±1.35	15.24±0.55	16.43±0.76	17.58±0.94	18.19±1.01	101.285	<0.001
$ctCO_2$, mmol/L	21.73±2.73	22.58±1.90	21.87±0.88	22.63±1.56	24.03±0.64	23.81±2.18	7.108	0.001

Data are presented as mean±standard deviation. Repeated-measures analysis of variance was used to evaluate temporal changes. Greenhouse–Geisser correction was applied when the sphericity assumption was violated. Bold values indicate statistical significance at $p<0.05$.

Abbreviations: BE, base excess; $ctCO_2$, total carbon dioxide content; ctO_2, total oxygen content; $PaCO_2$, arterial partial pressure of carbon dioxide; PaO_2, arterial partial pressure of oxygen; SaO_2, arterial oxygen saturation.

Temporal Pattern of Significant Changes

Bonferroni-adjusted pairwise comparisons revealed distinct temporal patterns across arterial blood gas parameters. Significant changes in SaO_2 and ctO_2 were first observed on day 3 compared with pre-tracheostomy values, whereas significant changes in pH and $PaCO_2$ were first identified on day 5. BE first differed significantly from baseline on day 7, while PaO_2 and HCO_3^- showed significant differences only on day 9. $ctCO_2$ first demonstrated a significant difference from baseline on day 7 (Table 3).

Table 3. Bonferroni-adjusted pairwise comparisons of arterial blood gas parameters versus pre-tracheostomy values

Parameter	Day 1	Day 3	Day 5	Day 7	Day 9	Earliest statistically significant time point
pH	1.000	1.000	0.016	<0.001	<0.001	Day 5
PaO_2	1.000	1.000	1.000	0.102	0.002	Day 9
$PaCO_2$	1.000	1.000	0.045	0.021	0.534	Day 5

SaO_2	0.458	<0.001	<0.001	<0.001	<0.001	Day 3
HCO_3^-	0.504	0.199	1.000	0.194	0.009	Day 9
BE	1.000	1.000	1.000	0.039	0.163	Day 7
ctO_2	0.062	<0.001	<0.001	<0.001	<0.001	Day 3
$ctCO_2$	1.000	1.000	1.000	0.006	0.018	Day 7

Data are presented as Bonferroni-adjusted p-values for pairwise comparisons between each post-tracheostomy measurement and the pre-tracheostomy value. Bold values indicate statistical significance at $p<0.05$.

Overall, SaO_2 and ctO_2 demonstrated the earliest and most consistent temporal changes, with significant differences emerging by day 3 and persisting throughout subsequent measurements. Changes in pH and $PaCO_2$ became significant by day 5, whereas BE and $ctCO_2$ showed later significant differences. PaO_2 and HCO_3^- differed significantly from baseline only on day 9, indicating heterogeneous temporal trajectories among oxygenation, ventilation, and acid–base parameters.

4. DISCUSSION

The present study demonstrated significant serial changes in all evaluated arterial blood gas parameters during the nine-day observation period following tracheostomy in mechanically ventilated ICU patients. However, the temporal patterns of these changes differed across parameters. SaO_2 and ctO_2 showed the earliest and most consistent differences from baseline, beginning on day 3, whereas significant changes in pH and $PaCO_2$ emerged on day 5. BE and $ctCO_2$ showed later changes, while PaO_2 and HCO_3^- differed significantly from baseline only by day 9. These findings indicate that changes in oxygenation, ventilation, and acid–base parameters do not occur simultaneously following tracheostomy but follow distinct temporal trajectories.

Previous studies have shown that the effects observed after tracheostomy vary considerably across critically ill populations. Studies evaluating tracheostomy timing have reported differences in ventilator-related and clinical outcomes(1,8), whereas investigations focusing on respiratory support and tracheostomy care have demonstrated that physiological responses may depend on oxygen-delivery strategies and subsequent airway management (3,5). More recently, Manhas et al. (7) reported significant changes in arterial blood gas parameters following tracheostomy. Collectively, these findings suggest that post-tracheostomy trajectories may be influenced by the clinical indication, baseline respiratory condition, ventilatory management, and timing of physiological assessment.

The progressive changes observed in the present study may partly be explained by alterations in airway mechanics after conversion from an endotracheal tube to a tracheostomy. Tracheostomy establishes a shorter and more direct airway and may reduce upper airway anatomical dead space and airway resistance. These mechanical advantages may decrease the resistive component of the work of breathing and increase the proportion of minute ventilation contributing to effective alveolar ventilation. Reduced airway resistance, improved secretion management, enhanced patient comfort, and facilitation of ventilator weaning have been recognized as important physiological and clinical advantages of tracheostomy (2,3,9,10).

Nevertheless, serial arterial blood gas changes after tracheostomy should not be regarded as an isolated procedural effect. Gas exchange in mechanically ventilated critically ill patients is determined by complex interactions among airway mechanics, pulmonary compliance, ventilation–perfusion matching, alveolar recruitment, physiological dead space, respiratory drive, and ventilator settings. Brochard et al. (11) emphasized the importance of ventilatory strategy in respiratory physiology and the progression of lung injury, whereas Gattinoni et al. (12) highlighted the interaction between spontaneous respiratory activity and transpulmonary pressure. Rochwerg et al. (13) further demonstrated that physiological responses to ventilatory support vary according to the underlying mechanism of respiratory failure. Therefore, although tracheostomy may modify airway mechanics, the serial arterial blood gas changes observed in this cohort likely reflect the combined effects of altered airway access and evolving respiratory management in the ICU.

Arterial pH initially decreased on day 1 and subsequently increased progressively from 7.33±0.07 before tracheostomy to 7.39±0.03 on day 9. Pairwise comparisons demonstrated that differences from baseline became statistically significant from day

5 onward. This pattern suggests gradual stabilization of acid–base homeostasis rather than an immediate post-procedural response. Arterial pH is determined by the relationship between the respiratory component, primarily represented by $PaCO_2$, and the metabolic component, particularly bicarbonate. An increase in effective alveolar ventilation may facilitate carbon dioxide elimination and gradually reduce the respiratory contribution to acidemia.

Manhas et al. (7) similarly reported a significant increase in arterial pH after tracheostomy and related this finding to improved ventilation following relief of airway obstruction. Earlier studies evaluating respiratory function and pulmonary mechanics after tracheostomy also provide a physiological basis for changes in ventilation following modification of the artificial airway (14,15). However, the population studied by Manhas et al. (7) differed from the present cohort because their patients predominantly underwent emergency tracheostomy for upper airway obstruction, whereas the present study included critically ill patients already receiving mechanical ventilation. Thus, a more gradual physiological response may be expected in the current population.

The progressive shift of mean pH toward the physiological reference range should also be interpreted in the broader context of critical illness. Seheult et al. (16) emphasized the contribution of lactate metabolism and tissue perfusion to metabolic acid–base disturbances. Furthermore, systemic organ dysfunction and ongoing ICU interventions may substantially influence acid–base balance in critically ill populations (16–18). Consequently, the observed pH trajectory may represent an integrated response involving ventilation, renal compensation, tissue perfusion, and ongoing intensive care rather than a direct consequence of tracheostomy alone.

PaO_2 increased progressively from 79.88±10.95 mmHg before tracheostomy to 91.89±3.55 mmHg on day 9. Despite this upward trajectory, pairwise analysis showed that the difference from baseline reached statistical significance only on day 9. The absence of an immediate significant increase in PaO_2 suggests that the early post-tracheostomy change in arterial oxygen tension may not primarily reflect a direct improvement in alveolar oxygen diffusion. Arterial oxygen tension is principally influenced by inspired oxygen concentration, alveolar ventilation, ventilation–perfusion matching, diffusion characteristics, alveolar recruitment, and intrapulmonary shunting. Therefore, shortening the artificial airway alone may not produce an immediate increase in arterial oxygen tension.

This finding is physiologically relevant because the primary respiratory benefits of tracheostomy relate to airway mechanics and airway management rather than direct modification of the alveolar–capillary membrane. Raimondi et al. (10) and Mussa et al. (3) describe tracheostomy as an airway management strategy that facilitates prolonged ventilatory support, secretion clearance, and ventilator weaning. In contrast, Brochard et al. (11) and Gattinoni et al. (12) emphasize that oxygenation in respiratory failure remains strongly dependent on pulmonary mechanics and ventilatory strategy. The delayed increase in PaO_2 observed in the present study may therefore reflect gradual improvement in airway hygiene and respiratory management rather than an immediate direct effect of the tracheostomy procedure.

The PaO_2 trajectory observed in this study is partly consistent with Manhas et al. (7), who reported significant improvement in PaO_2 after emergency tracheostomy. However, their population consisted primarily of patients with stridor and upper airway obstruction, in whom tracheostomy directly relieved a major mechanical limitation to airflow. In such patients, rapid improvement in gas exchange may occur after bypassing the obstruction. By comparison, patients in the present study were already mechanically ventilated before tracheostomy, which may explain why PaO_2 increased gradually and reached statistical significance only at a later observation point.

In contrast, Arora and Tantia (6), Stripoli et al. (5), and Mussa et al. (3) provide evidence that oxygen transport and respiratory responses in critically ill or tracheostomized patients are influenced by multiple physiological and management-related factors. Differences in study population, underlying respiratory pathology, indication and timing of tracheostomy, ventilator strategy, oxygen-delivery method, and duration of follow-up may account for variations among studies(3,5,6). Adly et al. (1), Andriolo et al. (8), and Meng et al. (19) also demonstrated substantial heterogeneity in clinical outcomes when examining the timing of tracheostomy in critically ill patients.

$PaCO_2$ decreased overall from 49.82±8.46 mmHg before tracheostomy to 45.11±5.93 mmHg on day 9, although the temporal trajectory was not linear. Significant differences from baseline emerged on days 5 and 7. $PaCO_2$ is inversely related to effective alveolar ventilation when metabolic carbon dioxide production remains relatively stable. Therefore, reductions in anatomical

dead space and airway resistance following tracheostomy may increase the fraction of minute ventilation reaching the alveoli and facilitate carbon dioxide elimination.

Studies by Akin et al. (14) and Sofi and Wani (15) evaluating respiratory function or pulmonary mechanics after tracheostomy provide physiological support for the concept that modification of the artificial airway can alter respiratory mechanics. More recently, Mussa et al. (3) emphasized that tracheostomy management should integrate airway patency, secretion clearance, humidification, and respiratory support, all of which may indirectly influence effective ventilation.

However, the modest increase in $PaCO_2$ again on day 9 indicates that carbon dioxide elimination is not determined solely by tracheostomy. Minute ventilation, tidal volume, respiratory rate, physiological dead space, metabolic carbon dioxide production, and ventilator mode are major determinants of $PaCO_2$. Brochard et al. (11) and Gattinoni et al. (12) have highlighted the importance of ventilatory mechanics and ventilator–patient interactions in determining respiratory physiology. Furthermore, Chang and Fang (20) demonstrated the importance of airway-related and procedural factors during percutaneous dilatational tracheostomy. The present study did not specifically analyze serial changes in FiO_2, PEEP, tidal volume, respiratory rate, or ventilator mode, limiting causal interpretation of the $PaCO_2$ trajectory.

SaO_2 showed an earlier and more consistent increase than PaO_2, with significant differences from baseline beginning on day 3 and a progressive increase to 97.51±0.82% on day 9. The temporal difference between PaO_2 and SaO_2 can be explained by the sigmoid oxyhemoglobin dissociation curve. PaO_2 represents the partial pressure of oxygen dissolved in arterial plasma, whereas SaO_2 represents the proportion of hemoglobin oxygen-binding sites occupied by oxygen. Therefore, the relationship between these parameters is nonlinear.

Within the plateau portion of the oxyhemoglobin dissociation curve, relatively large changes in PaO_2 produce only small changes in SaO_2 because most hemoglobin oxygen-binding sites are already occupied. Conversely, within the steeper portion of the curve, relatively small changes in PaO_2 may result in more pronounced changes in hemoglobin saturation (6,21).

The earlier significant increase in SaO_2 compared with PaO_2 should therefore not be considered contradictory. Changes in pH, $PaCO_2$, and temperature can alter hemoglobin–oxygen affinity and shift the oxyhemoglobin dissociation curve. Because pH and $PaCO_2$ also changed during the observation period, the SaO_2 trajectory may have been influenced not only by arterial oxygen tension but also by changes in the physiological environment governing oxygen–hemoglobin binding. Dunn et al. (21) and Arora and Tantia (6) emphasize that oxygen transport should be interpreted through the interaction of oxygen tension, hemoglobin saturation, hemoglobin concentration, and systemic oxygen delivery.

The SaO_2 findings should also be interpreted in relation to oxygen-delivery and airway-management strategies in tracheostomized patients. Stripoli et al. (5) evaluated high-flow oxygen therapy in tracheostomized patients at high risk of weaning failure, whereas Hernández et al. (22) assessed high-flow oxygen, capping, and suctioning strategies during tracheostomy decannulation. These findings underscore that oxygenation after tracheostomy remains influenced by respiratory support and airway-management strategies. Therefore, the progressive increase in SaO_2 observed in the present study should be interpreted within the broader context of continued mechanical ventilation and oxygen therapy.

HCO_3^- increased gradually and differed significantly from the pre-tracheostomy value only on day 9. This delayed response is physiologically consistent with the slower metabolic component of acid–base regulation. In contrast to $PaCO_2$, which may change rapidly following alterations in alveolar ventilation, bicarbonate concentration is strongly influenced by renal hydrogen ion secretion and bicarbonate reabsorption and regeneration. Metabolic compensation therefore generally evolves more slowly than primary respiratory changes.

The temporal relationship among $PaCO_2$, pH, and HCO_3^- in the present study suggests progressive re-equilibration of the bicarbonate–carbon dioxide buffer system. The initial elevation in $PaCO_2$ was compatible with a respiratory contribution to acidemia, whereas the subsequent reduction in $PaCO_2$ and gradual increase in HCO_3^- were accompanied by a progressive shift of mean pH toward the physiological reference range. Manhas et al. (7) similarly reported significant post-tracheostomy changes in pH, $PaCO_2$, and HCO_3^-. However, differences in indication for tracheostomy and baseline respiratory status should be considered when comparing the two studies.

BE demonstrated a later temporal change than the oxygenation parameters, with a significant difference from baseline first emerging on day 7. Because BE primarily reflects the metabolic component of acid–base balance, this later pattern is compatible with a slower process of metabolic stabilization. The movement of BE toward the physiological range occurred alongside increasing HCO_3^- and a progressive shift of mean pH toward the physiological reference range, suggesting coordinated evolution of acid–base homeostasis.

Nevertheless, BE is affected by several factors frequently encountered in critically ill patients, including renal dysfunction, lactic acidosis, electrolyte disturbances, tissue hypoperfusion, and intravenous fluid administration. Seheult et al. (16) described the contribution of lactic acidosis to metabolic disturbances, whereas Vincent et al. (18) highlighted the substantial heterogeneity of organ dysfunction among critically ill patients. Thus, the BE trajectory should not be interpreted as a tracheostomy-specific physiological marker.

ctO_2 increased consistently throughout the observation period, with significant differences from baseline beginning on day 3. This trajectory closely paralleled the increase in SaO_2. Total arterial oxygen content is predominantly determined by oxygen bound to hemoglobin, whereas dissolved oxygen contributes only a small proportion. Dunn et al. (21) and Arora and Tantia (6) emphasized that oxygen transport depends on the interaction among hemoglobin concentration, oxygen saturation, arterial oxygen tension, and circulatory factors.

The parallel increase in SaO_2 and ctO_2 is therefore physiologically plausible. As hemoglobin oxygen saturation increases, total arterial oxygen content would also be expected to rise if hemoglobin concentration remains relatively stable. However, interpretation of ctO_2 requires particular caution because hemoglobin concentration is a major determinant of arterial oxygen content. Bleeding, hemodilution, hemoconcentration, and blood transfusion may alter ctO_2 independently of pulmonary gas exchange.

Although the present study excluded patients receiving more than two units of blood as a major change in clinical management, hemoglobin concentration and transfusion exposure were not analyzed as serial time-varying confounders. Hemoglobin concentration, blood transfusion, hemodynamic status, vasopressor use, and fluid balance were not incorporated into the longitudinal analysis. Consequently, the progressive increase in ctO_2 cannot be considered definitive evidence of improved pulmonary oxygenation attributable solely to tracheostomy.

$ctCO_2$ showed significant overall temporal variation but followed a fluctuating pattern, reaching its highest mean value on day 7 before decreasing slightly on day 9. This trajectory differs from that of $PaCO_2$ because the two parameters represent different components of carbon dioxide physiology. $PaCO_2$ reflects the partial pressure of dissolved carbon dioxide and is closely related to alveolar ventilation, whereas total carbon dioxide content consists predominantly of bicarbonate, with smaller contributions from dissolved carbon dioxide and carbamino compounds.

Accordingly, $ctCO_2$ may follow changes in HCO_3^- more closely than changes in $PaCO_2$. The later increases in HCO_3^- and $ctCO_2$ observed in this study may reflect the evolution of metabolic compensation and carbon dioxide–bicarbonate equilibrium. Therefore, $ctCO_2$ should be interpreted as part of carbon dioxide–bicarbonate dynamics rather than as an isolated measure of alveolar ventilation. Davis et al. (23) also support integrated interpretation of blood gas and hemoximetry parameters.

Taken together, the temporal patterns observed in this study suggest that oxygenation, ventilation, and acid–base parameters evolve at different rates during post-tracheostomy ICU care. SaO_2 and ctO_2 showed earlier and more consistent changes, whereas pH and $PaCO_2$ changed during the intermediate observation period. PaO_2, HCO_3^-, BE, and $ctCO_2$ demonstrated later or more variable trajectories. These findings should not be interpreted as a fixed biological sequence but rather as evidence that individual arterial blood gas parameters may capture different components and time courses of physiological adaptation. The first statistically significant time point should not be interpreted as the biological onset of physiological change, but rather as the earliest scheduled measurement at which the difference from baseline reached statistical significance.

The present findings share similarities with Manhas et al. (7), who reported significant post-tracheostomy changes in pH, PaO_2, $PaCO_2$, and HCO_3^-. However, studies addressing respiratory support, oxygen delivery, and tracheostomy management have demonstrated that physiological responses may vary according to clinical context and subsequent respiratory care (3,5,7). Studies of tracheostomy timing have also reported heterogeneous ventilator-related and clinical outcomes across critically ill

populations. Thus, differences among studies may reflect patient selection, underlying disease, indication for tracheostomy, timing of the procedure, ventilatory management, and duration of physiological follow-up(1,8).

From a clinical perspective, a single arterial blood gas measurement immediately after tracheostomy may not adequately represent the patient's subsequent physiological trajectory. Several parameters in this study became significantly different from baseline only between days 3 and 9. Serial arterial blood gas assessment may therefore provide a more comprehensive description of evolving oxygenation, ventilation, and acid–base status. Structured tracheostomy management and ongoing respiratory assessment are emphasized by Mussa et al. (3) and Raimondi et al. (10), particularly in critically ill patients requiring prolonged airway and ventilatory support.

However, tracheostomy should not be performed solely with the expectation of improving arterial blood gas parameters. Its broader potential benefits include facilitation of airway care and secretion removal, reduction of airway resistance and anatomical dead space, improved patient comfort, reduced sedation requirements, and support for ventilator weaning. Furthermore, studies evaluating tracheostomy timing and long-term outcomes indicate that clinically meaningful assessment should extend beyond isolated physiological measurements to include duration of mechanical ventilation, ventilator liberation, ICU length of stay, and longer-term patient outcomes (1,8,19). Therefore, serial arterial blood gas changes should be interpreted as one component of a broader multidimensional assessment following tracheostomy.

Novelty of the Present Study

The present study provides additional evidence regarding the temporal evolution of arterial blood gas parameters following tracheostomy in mechanically ventilated intensive care unit (ICU) patients. Unlike many previous studies that primarily focused on tracheostomy timing, ventilator weaning, duration of mechanical ventilation, ICU length of stay, or mortality, the present study comprehensively evaluated serial physiological changes in oxygenation, ventilation, and acid–base status using repeated arterial blood gas measurements obtained before tracheostomy and on postoperative days 1, 3, 5, 7, and 9. Furthermore, the study identified the earliest postoperative time point at which each arterial blood gas parameter differed significantly from baseline through repeated-measures analysis with Bonferroni-adjusted pairwise comparisons. The findings demonstrated distinct temporal trajectories among arterial blood gas parameters, with oxygenation-related variables showing earlier changes than several ventilation and metabolic parameters. These results provide a more detailed understanding of post-tracheostomy respiratory physiology and emphasize the value of serial arterial blood gas monitoring for characterizing physiological adaptation during the early postoperative period rather than relying on a single post-procedural assessment.

Clinical Perspective

The present findings suggest that a single arterial blood gas measurement immediately after tracheostomy may not adequately characterize subsequent respiratory physiology in mechanically ventilated ICU patients. Serial assessment may be particularly informative when interpreted alongside ventilator settings, oxygen requirements, secretion burden, and the clinical course of ventilator weaning. Importantly, arterial blood gas changes should not be used as isolated indicators of tracheostomy success. Instead, physiological monitoring should be integrated with clinically meaningful outcomes, including ventilator liberation, airway clearance, sedation requirements, and overall ICU recovery.

Study Limitations

This study has several limitations. First, the relatively small sample size and single-centre design may limit the statistical power and generalizability of the findings. Second, disease severity was not assessed using standardized scoring systems such as the Acute Physiology and Chronic Health Evaluation II or Sequential Organ Failure Assessment scores. Third, although patients with major changes in respiratory management were excluded, smaller serial variations in ventilator settings, including FiO_2, positive end-expiratory pressure, tidal volume, respiratory rate, and other ventilation parameters, were not incorporated as time-varying covariates in the analysis. These variations may still have influenced arterial blood gas parameters. The exclusion of patients experiencing major changes in respiratory management was intended to reduce the influence of substantial ventilatory modifications on arterial blood gas measurements. However, this approach may have selected a relatively clinically stable subgroup and could limit the generalizability of the observed temporal trajectories. Fourth, hemoglobin concentration, blood transfusion, hemodynamic status, vasopressor use, and fluid balance were not analyzed as time-varying confounders, particularly in the interpretation of ctO_2. Finally, the study focused on physiological changes during a nine-day observation period and did

not evaluate clinically relevant outcomes such as duration of mechanical ventilation, ventilator weaning success, ICU length of stay, ventilator-associated pneumonia, mortality, or long-term patient outcomes. Future multicentre studies with larger cohorts, standardized assessment of disease severity, detailed adjustment for ventilator and hemodynamic variables, and longer follow-up are needed to validate these findings and determine whether serial arterial blood gas changes after tracheostomy are associated with clinically meaningful outcomes.

5. CONCLUSION

Serial arterial blood gas parameters changed significantly during the nine-day period following tracheostomy in mechanically ventilated ICU patients, with distinct temporal patterns across oxygenation, ventilation, and acid–base indices. SaO_2 and ctO_2 demonstrated the earliest and most consistent changes, beginning on day 3, whereas significant changes in pH and $PaCO_2$ emerged on day 5. BE and $ctCO_2$ showed later changes, while PaO_2 and HCO_3^- differed significantly from pre-tracheostomy values only by day 9. These findings indicate that physiological changes observed during the post-tracheostomy period followed progressive and heterogeneous temporal patterns rather than an immediate and uniform response across arterial blood gas parameters. Serial arterial blood gas assessment may therefore provide a more comprehensive characterization of post-tracheostomy respiratory physiology than a single post-procedural measurement. However, because ventilator settings, hemoglobin concentration, and other clinical confounders were not fully controlled, these changes should not be interpreted as direct causal effects of tracheostomy alone.

What is already known on this topic

Tracheostomy is commonly performed in mechanically ventilated ICU patients to facilitate airway management, improve secretion clearance, reduce airway resistance, and support ventilator weaning.

Previous studies have mainly investigated the effects of tracheostomy on clinical outcomes such as duration of mechanical ventilation, ventilator weaning, ICU length of stay, and mortality, whereas evidence describing serial changes in arterial blood gas parameters following tracheostomy remains limited.

What this study adds

Serial arterial blood gas monitoring demonstrated significant temporal changes in oxygenation, ventilation, and acid–base parameters during the first nine days following tracheostomy in mechanically ventilated ICU patients.

Oxygenation-related parameters (SaO_2 and ctO_2) exhibited the earliest significant improvements, whereas changes in ventilation and metabolic parameters occurred more gradually, indicating distinct physiological trajectories after tracheostomy.

These findings support the use of serial, rather than single-time-point, arterial blood gas assessment to better characterize physiological adaptation following tracheostomy and may assist clinicians in postoperative monitoring and respiratory management.

COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

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AUTHORS' CONTRIBUTIONS

YS: Conceptualization, Methodology, Investigation, Data Collection, Formal Analysis, Writing – Original Draft Preparation. SPR: Conceptualization, Supervision, Methodology, Validation, Data Interpretation, Writing – Review & Editing. YA: Formal Analysis, Data Curation, Statistical Analysis, Writing – Review & Editing. CNIA: Investigation, Data Curation, Writing – Review & Editing. All authors have read and approved the final version of the manuscript. MFP: Methodology, Investigation, Data Interpretation, Writing – Review & Editing. AQP: Supervision, Validation, Data Interpretation, Writing – Review & Editing. IM: Supervision, Validation, Data Interpretation, Writing – Review & Editing.

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