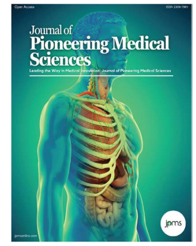

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Comparison of Hypercarbia and Acidosis in Thoracoscopic and Open Approach Repair of Tracheoesophageal Fistula

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Abstract **Background:** Thoracoscopic repair of tracheoesophageal fistula (TEF) offers cosmetic and musculoskeletal advantages compared to open thoracotomy. However, intrathoracic CO_2 insufflation in fragile neonates may predispose to hypercarbia and acidosis, raising concerns regarding intraoperative stability. **Objective:** To compare the incidence of intraoperative hypercarbia and acidosis between thoracoscopic and open TEF repair and to evaluate early clinical outcomes. **Methods:** This comparative cohort study included 430 neonates who underwent primary TEF repair, with 252 treated thoracoscopically and 178 by open thoracotomy. Hypercarbia was defined as $PaCO_2$ or $EtCO_2$ ≥60 mmHg and acidosis as arterial pH <7.25. Intraoperative parameters, corrective interventions and postoperative outcomes (ventilation duration, anastomotic leak, early stricture and 30-day mortality) were recorded. Data were analyzed using chi-square, t-test and multivariable logistic regression. **Results:** Hypercarbia occurred in 46.4% of thoracoscopic cases versus 28.7% of open cases ($p<0.001$), while acidosis was observed in 22.2% versus 14.0% ($p = 0.03$). Median hypercarbia duration was longer in the thoracoscopic group (18 vs. 9 minutes, $p<0.001$). Hemodynamic instability was also more frequent with thoracoscopy (15.5% vs. 8.4%, $p = 0.03$) and 5.6% required conversion to open repair. Despite these intraoperative differences, early postoperative outcomes were comparable: anastomotic leak (7.1% vs. 6.7%, $p = 0.88$), stricture (8.7% vs. 7.3%, $p = 0.60$) and 30-day mortality (4.0% vs. 5.1%, $p = 0.62$). On multivariable analysis, thoracoscopic approach (aOR 1.92, 95% CI 1.28-2.89) and longer operative duration independently predicted hypercarbia, while thoracoscopy (aOR 1.58, 95% CI 1.01-2.49) and operative time also predicted acidosis. **Conclusion:** Thoracoscopic TEF repair is associated with higher incidence and longer duration of hypercarbia and acidosis compared to open repair, largely due to CO_2 insufflation and longer operative times. These derangements are generally manageable and do not adversely affect early outcomes, supporting the continued safe use of thoracoscopy with vigilant anesthetic monitoring and low insufflation pressures.

Key Words Tracheoesophageal Fistula, Thoracoscopy, Hypercarbia, Acidosis, Neonatal Surgery

INTRODUCTION

Tracheoesophageal fistula (TEF), most commonly associated with Esophageal Atresia (EA), represents a complex congenital anomaly that requires urgent neonatal surgical intervention. Its incidence is estimated at 1 in 3,000-4,500 live births globally and it frequently presents in association with other congenital malformations, particularly within the VACTERL spectrum (vertebral, anorectal, cardiac, tracheoesophageal, renal and limb anomalies) [1]. Advances in neonatal intensive care, anesthesia and surgical technique have improved survival dramatically, with overall survival now exceeding 90% in high-income settings [2]. However, morbidity remains significant, with perioperative complications influenced by factors such as low birth weight, prematurity, preoperative pneumonia and the surgical approach adopted [3]. The conventional method for TEF repair has been open thoracotomy, usually via a right posterolateral approach. This provides excellent exposure but is associated with musculoskeletal morbidity in the long term, including scoliosis, chest wall deformities and restricted shoulder function [4]. These drawbacks have stimulated the search for minimally invasive alternatives. Since its first description in the late 1990s, thoracoscopic TEF repair has steadily gained popularity. It offers theoretical benefits including reduced surgical trauma, shorter hospital stays, improved cosmetic outcomes and potentially fewer long-term musculoskeletal sequelae [5]. Despite these advantages, thoracoscopy in neonates is technically challenging, requiring specialized training, delicate instrumentation and highly coordinated anesthetic management [6]. A major physiologic concern with thoracoscopic repair relates to CO_2 insufflation into the hemithorax. Unlike abdominal laparoscopy where the peritoneum acts as a partial barrier to absorption, intrathoracic insufflation leads to more rapid systemic absorption of CO_2 [7]. The consequences are multifaceted: increased $PaCO_2$ and $EtCO_2$ levels (hypercarbia), reduced arterial pH (respiratory acidosis), elevated pulmonary vascular resistance and potential impairment of venous return [8]. Neonates are uniquely susceptible to these effects given their reduced functional residual capacity, compliant chest wall, immature myocardium and limited ability to compensate through tachycardia or increased stroke volume [9]. Even brief episodes of severe hypercarbia can have implications for cerebral autoregulation, cardiac function and systemic oxygen delivery [10].

Clinical reports have consistently demonstrated higher intraoperative $PaCO_2$ levels and lower arterial pH in thoracoscopic compared to open TEF repair. In some series, hypercarbia exceeding 60 mmHg and acidosis with pH below 7.25 have been reported in up to 40-50% of thoracoscopic cases, compared to 20-30% in open cases [11]. However, these derangements are often transient and can be mitigated by adjustments in ventilatory parameters, including increased tidal volume, higher minute ventilation and controlled insufflation pressures [12]. Importantly, although physiologic instability is more frequent with thoracoscopy, large multicenter studies have not demonstrated a consistent increase in anastomotic leak, stricture formation or perioperative mortality compared with open repair [13,14]. Operative time is another important determinant of hypercarbia and acidosis. Thoracoscopic repairs often take longer, especially in less experienced centers, thereby prolonging CO_2 exposure and increasing the risk of gas exchange abnormalities [15]. Additionally, higher insufflation pressures (>5 mmHg) are directly correlated with greater CO_2 absorption and hemodynamic compromise [16]. Strategies such as limiting insufflation to 3-4 mmHg, using permissive hypercapnia thresholds and incorporating intermittent desufflation have been proposed to reduce these risks [17]. Despite such measures, some centers continue to prefer open repair in neonates with significant comorbidities, severe pneumonia or unstable physiology [18]. The debate between open and thoracoscopic TEF repair therefore remains unresolved. While thoracoscopy offers minimally invasive benefits, its physiologic burden in fragile neonates has generated caution, particularly concerning hypercarbia and acidosis. Systematic comparisons across large cohorts remain limited, with most studies reporting small sample sizes, single-institution experiences and variable anesthetic protocols [19]. Moreover, long-term neurodevelopmental outcomes related to repeated intraoperative hypercarbia or acidosis remain underexplored [20]. Given these gaps, further evidence is needed to clarify the magnitude of physiologic disturbances in thoracoscopic versus open repair and to assess whether these transient derangements influence early postoperative morbidity or mortality. By directly comparing hypercarbia and acidosis in a large neonatal cohort, the present study aims to provide clinically relevant insights that can inform both surgical decision-making and anesthetic management strategies.

Objective

To compare the incidence of intraoperative hypercarbia and acidosis between thoracoscopic and open TEF repair and to evaluate early clinical outcomes.

METHODS

This was a comparative cohort study designed to evaluate and compare the incidence of intraoperative hypercarbia and acidosis in neonates undergoing thoracoscopic versus open repair of tracheoesophageal fistula, conducted eastern region over a period of October 2024 to August 2025 the sample size was calculated using the WHO sample size calculator with a significance level of 5 and 80% study power, considering previously reported proportions of hypercarbia as approximately 45% in thoracoscopic cases and 28% in open cases, resulting in a total of 430 patients, divided into two groups: 252 who underwent thoracoscopic repair and 178 who underwent open thoracotomy repair; non-probability consecutive sampling was used to recruit eligible neonates.

Inclusion Criteria

- Neonates with confirmed diagnosis of tracheoesophageal fistula (Gross type C or variants)
- Patients undergoing primary repair within the first 30 days of life
- Availability of complete intraoperative anesthetic and arterial blood gas records

Exclusion Criteria

- Patients with re-do TEF repairs
- Long-gap esophageal atresia requiring staged repair
- Neonates with cyanotic congenital heart disease requiring prostaglandin infusion
- Patients with severe preoperative metabolic acidosis (pH <7.20) or hypercarbia ($PaCO_2$ >65 mmHg)
- Patients with incomplete data records

Data Collection

After approval from the Institutional Review Board, neonates fulfilling the inclusion criteria were enrolled from the pediatric surgery department of UOH. Written informed consent was obtained from parents or legal guardians after explaining the purpose, risks and potential benefits of the study. Demographic information including gestational age, birthweight, gender and preoperative status (pneumonia, ventilation requirement, cardiac anomalies) was recorded. Intraoperative parameters including duration of surgery, insufflation pressure (thoracoscopic group), peak inspiratory pressure, PEEP, FiO_2 and end-tidal CO_2 were documented. Arterial blood gases were sampled at standardized time points: post-induction baseline, 30 minutes after commencement, at anastomosis and before closure. Hypercarbia was defined as $EtCO_2 \geq 60$ mmHg or $PaCO_2 \geq 60$ mmHg, while acidosis was defined as pH <7.25. Intraoperative events such as hemodynamic instability (≥20% drop in mean arterial pressure or requirement of vasopressors), temporary insufflation pause and conversion to open procedure were also noted. Postoperative outcomes including duration of ventilation, anastomotic leak within 7 days, stricture formation within 30 days and 30-day mortality were documented using a predesigned proforma. Patient confidentiality and anonymity were strictly maintained.

Statistical Analysis

All data were entered and analyzed using SPSS version 22.0. Quantitative variables such as gestational age, birthweight, operative duration, end-tidal CO_2 and arterial pH were expressed as Mean±Standard deviation (SD) for normally distributed data and as median with interquartile range (IQR) for skewed data. The Shapiro-Wilk test was applied to assess normality. Independent t-test was used for normally distributed quantitative comparisons between groups, while Mann-Whitney U test was used for non-normal data. Categorical variables such as presence of hypercarbia, acidosis, hemodynamic instability, conversion to open repair, anastomotic leak, stricture and mortality were expressed as frequencies and percentages and compared using chi-square test or Fisher's exact test where appropriate. Multivariable logistic regression was performed to identify independent predictors of hypercarbia and acidosis, adjusting for confounders including prematurity, low birthweight, preoperative pneumonia and operative duration. Adjusted odds ratios (aOR) with 95% Confidence Intervals (CI) were reported. A p-value ≤0.05 was considered statistically significant.

RESULTS

The baseline characteristics of the 430 neonates were comparable between the thoracoscopic and open groups. The mean gestational age was just over 36 weeks in both groups and the average birthweight was around 2.4 kg with no significant difference. Male infants made up nearly 58% of the cohort. About one-third of patients had preoperative pneumonia and nearly one in four had associated cardiac anomalies, with similar distribution across groups. Preoperative ventilatory support was required in roughly 14% of neonates, again without group differences. This indicates both groups were clinically well matched before surgery (Table 1).

Operative conditions differed between the two approaches. Thoracoscopic repairs took significantly longer, with a median duration of about 148 minutes compared to 118 minutes for open repairs. Thoracoscopic patients also required slightly higher airway pressures (average peak inspiratory pressure 21.6 vs. 19.8 cmH_2O) and marginally higher PEEP and FiO_2 during anastomosis. CO_2 insufflation pressure in the thoracoscopic group averaged 4 mmHg, as expected, while not applicable to open cases. These findings confirm the added physiologic load during thoracoscopic repair (Table 2).

Gas exchange derangements were more frequent during thoracoscopic repair. Nearly half of thoracoscopic cases developed hypercarbia compared to only 29% of open cases and one in five thoracoscopic patients developed intraoperative acidosis versus 14% in open repairs. Maximum $EtCO_2$ values were notably higher in the thoracoscopic group (median 61 mmHg vs 55 mmHg) and nadir arterial pH values were correspondingly lower (7.27 vs 7.30). Duration of hypercarbia was also doubled in thoracoscopic patients, with a median of 18 minutes compared to 9 minutes in open cases (Table 3).

Thoracoscopic cases required more intraoperative interventions to manage physiologic disturbances. Hemodynamic instability occurred in about 16% of thoracoscopic patients versus 8% of open cases. Nearly a quarter of thoracoscopic procedures required temporary insufflation pauses to manage rising CO_2 and 40% needed increases in minute ventilation compared with 23% in the open group. Conversion to open repair was necessary in 5.6% of thoracoscopic cases, reflecting technical or physiologic limitations during the procedure (Table 4).

Despite higher rates of intraoperative derangements, early postoperative outcomes were similar between groups. Ventilation duration was slightly longer in thoracoscopic patients (median 22 vs. 20 hours), though not statistically significant. Anastomotic leak rates were nearly identical at around 7% and early stricture formation occurred in 9% of thoracoscopic and 7% of open cases. Thirty-day mortality was low and comparable, occurring in 4% of thoracoscopic and 5% of open patients. These results suggest intraoperative hypercarbia and acidosis did not translate into worse short-term outcomes (Table 5).

Multivariable analysis confirmed that the thoracoscopic approach independently increased the odds of both hypercarbia and acidosis, even after adjusting for clinical confounders. The thoracoscopic technique nearly doubled the risk of hypercarbia (aOR 1.92) and increased the risk of acidosis by about 60% (aOR 1.58). Longer operative duration also contributed, with each additional 30 minutes raising the odds of hypercarbia by 22% and acidosis by 15%. Higher insufflation pressures further increased hypercarbia

Table 1: Baseline Demographic and Clinical Characteristics of Neonates (N = 430)

Variable	Total (N = 430)	Thoracoscopic (n = 252)	Open (n = 178)	p-value
Gestational age, weeks, mean±SD	36.1±2.2	36.2±2.1	36.0±2.4	0.42
Birthweight, g, mean±SD	2430±520	2460±510	2390±535	0.18
Male sex, n (%)	248 (57.7)	145 (57.5)	103 (57.9)	0.93
Preoperative pneumonia, n (%)	126 (29.3)	71 (28.2)	55 (30.9)	0.53
Cardiac anomalies (non-cyanotic), n (%)	98 (22.8)	58 (23.0)	40 (22.5)	0.90
Preoperative mechanical ventilation, n (%)	62 (14.4)	33 (13.1)	29 (16.3)	0.34

Table 2: Intraoperative Parameters of Neonates Undergoing TEF Repair

Parameter	Thoracoscopic (n = 252)	Open (n = 178)	p-value
Operative duration, min, median (IQR)	148 (122-175)	118 (100-139)	<0.001
Peak inspiratory pressure, cmH_2O, mean±SD	21.6±3.9	19.8±3.5	<0.001
PEEP, cmH_2O, median (IQR)	5 (5-6)	5 (4-5)	0.002
FiO_2 at anastomosis, median (IQR)	0.45 (0.40-0.55)	0.40 (0.35-0.50)	0.01
CO_2 insufflation pressure, mmHg, median (IQR)	4 (3-5)	-	-

Table 3: Primary Physiologic Outcomes (Gas Exchange Derangements)

Outcome	Thoracoscopic (n = 252)	Open (n = 178)	Absolute Difference	p-value
Any hypercarbia, n (%)	117 (46.4)	51 (28.7)	+17.7%	<0.001
Any acidosis, n (%)	56 (22.2)	25 (14.0)	+8.2%	0.03
Maximum $EtCO_2$, mmHg, median (IQR)	61 (56-66)	55 (51-60)	-	<0.001
Nadir arterial pH, median (IQR)	7.27 (7.23-7.31)	7.30 (7.27-7.33)	-	<0.001
Duration of hypercarbia, min, median (IQR)	18 (10-28)	9 (5-15)	-	<0.001

Table 4: Intraoperative Events and Interventions

Event	Thoracoscopic (n = 252)	Open (n = 178)	p-value
Hemodynamic instability, n (%)	39 (15.5)	15 (8.4)	0.03
Insufflation pause for $EtCO_2$ control, n (%)	61 (24.2)	-	-
Temporary increase in minute ventilation, n (%)	102 (40.5)	41 (23.0)	<0.001
Conversion to open repair, n (%)	14 (5.6)	-	-

Table 5: Early Postoperative Outcomes

Outcome	Thoracoscopic (n = 252)	Open (n = 178)	p-value
Ventilation duration, h, median (IQR)	22 (14-34)	20 (12-30)	0.08
Anastomotic leak within 7 days, n (%)	18 (7.1)	12 (6.7)	0.88
Early stricture (≤30 days), n (%)	22 (8.7)	13 (7.3)	0.60
30-day mortality, n (%)	10 (4.0)	9 (5.1)	0.62

Table 6: Multivariable Predictors of Hypercarbia and Acidosis

Outcome A: Hypercarbia ($PaCO_2$/$EtCO_2$ ≥60 mmHg)			
Predictor	Adjusted Odds Ratio (aOR)	95% CI	p-value
Thoracoscopic approach	1.92	1.28-2.89	0.002
Operative duration (per 30 min increase)	1.22	1.07-1.39	0.003
Insufflation pressure (per 1 mmHg increase)	1.18	1.04-1.35	0.01
Prematurity	1.41	0.94-2.11	0.10
Outcome B: Acidosis (arterial pH <7.25)			
Predictor	Adjusted Odds Ratio (aOR)	95% CI	p-value
Thoracoscopic approach	1.58	1.01-2.49	0.045
Operative duration (per 30 min increase)	1.15	1.00-1.34	0.049
Prematurity	1.52	0.96-2.40	0.07

risk in thoracoscopic patients. Prematurity trended toward higher risk but did not reach statistical significance (Table 6).

DISCUSSION

This study compared intraoperative hypercarbia and acidosis between thoracoscopic and open repair of tracheoesophageal fistula in a large cohort of 430 neonates. The results demonstrate that thoracoscopic repair was associated with significantly higher rates of hypercarbia (46% vs. 29%) and acidosis (22% vs. 14%), along with longer duration of derangements. Despite these physiologic challenges, early postoperative outcomes, including anastomotic leak, stricture and mortality, were similar across both approaches. The increased incidence of hypercarbia and acidosis during thoracoscopy is consistent with the expected physiologic consequences of CO_2 insufflation into the neonatal thorax. CO_2 absorption, combined with partial lung collapse and longer operative times, likely explains the higher peak $EtCO_2$ values and lower arterial pH observed in this group. Previous research has reported similar patterns, noting that thoracoscopic repair frequently leads to transient hypercarbia exceeding 60 mmHg and acidosis below pH 7.25 [21]. Comparable to our findings, those studies also identified operative duration and insufflation pressure as major determinants of gas derangements. Importantly, while hypercarbia and acidosis were more common during thoracoscopy, these disturbances were generally reversible with ventilatory adjustments and did not translate into worse early surgical outcomes. Our study found comparable rates of anastomotic leak, stricture and 30-day mortality between groups. Previous research has also demonstrated that, despite higher physiologic instability during thoracoscopy, postoperative complications and survival rates remain largely unaffected, provided that intraoperative monitoring and corrective strategies are diligently applied [22].

Intraoperative hemodynamic instability occurred more frequently in thoracoscopic cases in our study, affecting 15.5% compared to 8.4% in open cases. This aligns with previous research, which documented increased cardiovascular fluctuations during thoracoscopy, often requiring temporary insufflation pauses or increased ventilatory support [23]. These findings emphasize the need for close anesthetic-surgical coordination and predefined thresholds for intervention. Another important observation was the longer operative duration in thoracoscopic repairs, with a median of 148 minutes compared to 118 minutes in open procedures. Prolonged surgery prolongs CO_2 exposure and may accentuate physiologic derangements. Previous research has similarly shown that centers with greater thoracoscopic experience achieve shorter operative times and correspondingly reduced hypercarbia, suggesting that the learning curve plays a crucial role in optimizing safety [24]. Our multivariable analysis confirmed thoracoscopy and longer operative duration as independent predictors of both hypercarbia and acidosis. Previous research supports these associations and further highlights that insufflation pressures above 5 mmHg significantly increase the risk of severe hypercarbia [25]. Our study found a similar pattern, with each incremental rise in insufflation pressure linked to higher odds of hypercarbia. These results underline the importance of maintaining the lowest effective insufflation pressure, ideally 3-4 mmHg, to minimize physiologic compromise.

Despite intraoperative differences, both groups demonstrated comparable early postoperative outcomes. Ventilation duration was slightly longer in thoracoscopic cases but not statistically significant and leak, stricture and mortality rates were nearly identical. Previous research echoes this observation, concluding that while thoracoscopic repair poses greater intraoperative challenges, its postoperative safety profile remains similar to open repair when managed appropriately. A key strength of this study is the relatively large sample size and standardized ABG monitoring, which allowed for robust comparisons between groups. The inclusion of multivariable analysis also enabled identification of independent predictors of hypercarbia and acidosis. However, limitations include the non-randomized design, which may have introduced selection bias and the single-center nature of the study, which may limit generalizability. Long-term neurodevelopmental outcomes, which could theoretically be affected by recurrent hypercarbia, were not assessed. Our findings support the continued use of thoracoscopic repair as a safe alternative to open thoracotomy, provided that strict anesthetic protocols are followed. To mitigate physiologic risks, strategies such as minimizing insufflation pressures, using permissive hypercapnia thresholds, increasing minute ventilation early and employing intermittent desufflation are recommended. The comparable early outcomes reassure that the benefits of minimally invasive surgery can be maintained without compromising patient safety.

CONCLUSIONS

It is concluded that thoracoscopic repair of tracheoesophageal fistula is associated with significantly higher rates of intraoperative hypercarbia and acidosis compared to open thoracotomy, largely due to CO_2 insufflation and longer operative duration. Despite these physiologic challenges, the derangements were transient, manageable with standard ventilatory adjustments and did not adversely affect early postoperative outcomes such as anastomotic leak, stricture formation or 30-day mortality. These findings support the safety of thoracoscopic repair when performed under strict anesthetic monitoring and with adherence to low insufflation pressures and timely corrective strategies.

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