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RESEARCH

Thoracoscopic versus open congenital diaphragmatic hernia repair: a systematic review and meta-analysis by the Pediatric Surgery Meta-Analysis Study Group (PESMA)

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Abstract

Purpose To compare outcomes of thoracoscopic repair (TR) versus conventional open repair (COR) for congenital diaphragmatic hernia (CDH) through a systematic review and meta-analysis.

Methods PubMed, EMBASE, SCOPUS, and Web of Science were searched up to August 2025 for comparative neonatal CDH studies. Randomized, prospective, and retrospective designs reporting at least one clinical outcome were included. Risk ratios (RR) with 95% confidence intervals (CI) were pooled using a random-effects model. The review followed PRISMA guidelines and was registered in PROSPERO (CRD420251128490).

Results Nineteen studies involving 434 TR and 631 COR cases were included. Total recurrence was higher after TR (12.9% vs. 4.1%; RR 2.40; $p=0.0003$). Primary repair recurrence showed the largest difference (12% vs. 0%; RR 4.39; $p=0.001$), and patch repair recurrence remained higher in TR (21% vs. 11.5%; RR 1.98; $p=0.04$). Bowel obstruction was lower after TR (6% vs. 14.6%; RR 0.52; $p=0.02$). No significant differences were found for chylothorax, pneumothorax, pleural effusion, or bowel injury. Mortality was lower in TR (0.9% vs. 5.9%; RR 0.31; $p<0.0001$), likely reflecting patient selection.

Conclusion TR is feasible in selected neonates and is associated with lower bowel obstruction and mortality but higher recurrence. Standardized criteria for selecting TR versus COR remain essential.

Keywords Congenital diaphragmatic hernia · Thoracoscopy · Open repair

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Introduction

Congenital diaphragmatic hernia (CDH) is a serious birth defect occurring in approximately 1 in 2000 to 4000 newborns, with the prognosis primarily determined by the severity of associated pulmonary hypertension and pulmonary hypoplasia [1–3]. Traditionally, CDH repair has been performed via laparotomy (open abdominal surgery) [4, 5]. However, with the evolution of minimally invasive surgery (MIS) over the past two decades, thoracoscopic repair (TR) has become an increasingly popular approach [5, 6]. Proponents of TR highlight several potential advantages over the conventional open repair (COR), including faster recovery, reduced postoperative ventilator days, decreased narcotic use, and a shorter hospital length of stay [6]. Despite these benefits, the efficacy of the TR, particularly when compared to COR, remains controversial [7]. The literature has consistently reported significant concerns and potential risks associated with TR. Notably, the rate of recurrence after thoracoscopic repair has been reported as substantially higher than after open repair, ranging from 0% to 39% for TR compared to 0% to 13% for open repair [7]. TR for CDH has been associated with intraoperative hypercapnia and acidosis due to CO_2 insufflation. These physiological effects have raised questions about the suitability of TR in neonates with compromised cardiopulmonary function [8, 9].

Despite these concerns, the evidence comparing TR and conventional open repair (COR) remains heterogeneous and largely retrospective. Defect size, liver position, ECMO use, and patient selection vary considerably across studies, complicating interpretation.

Given the absence of high-quality, consolidated data, a comprehensive evaluation of outcomes after TR versus COR is needed. This systematic review and meta-analysis aim to compare recurrence, postoperative complications, and mortality between both approaches, providing updated evidence to guide surgical decision-making in neonatal CDH.

Materials and methods

Search strategy

The protocol for this systematic review was prospectively registered in the PROSPERO International Database of Systematic Reviews (registration number: CRD420251128490; available at http://www.crd.york.ac.uk/PROSPERO/). A comprehensive and systematic literature search was conducted across major electronic databases, including EMBASE, PubMed, SCOPUS, and Web of Science, to identify all relevant studies published up to August 2025. Search terms included controlled vocabulary (MeSH/Emtree) and keywords related to: “diaphragmatic hernia”, “congenital diaphragmatic hernia”, “CDH”, “Bochdalek hernia”, “thoracoscopy”, and “minimally invasive surgery”, combined using Boolean operators. To improve the sensitivity and completeness of the search, reference lists of all included articles and relevant review papers were manually screened to identify any additional eligible studies. The full search strategy is presented in Appendix 1.

Study selection

Eligible for inclusion were all studies that directly compared surgical outcomes between the minimally invasive TR and the COR for the primary repair of CDH. Randomized controlled trials (RCT), prospective studies, and retrospective comparative studies were eligible.

Inclusion criteria

This meta-analysis included all clinical studies comparing TR versus COR for CDH. Eligible studies were required to report at least one relevant clinical outcome, including perioperative parameters, postoperative complications, or long-term morbidity. All open surgical approaches were considered under the COR group. Only studies in which repair was performed during the neonatal period were included.

Exclusion criteria

Comparative case series without a clearly defined control group and studies that did not provide extractable quantitative data were excluded from the analysis. In addition, single-arm case series, review articles, and isolated case reports were omitted to preserve methodological rigor and ensure the reliability of the pooled outcome estimates in this study. Non-English language publications were not automatically excluded. Because members of the review team are proficient in several languages, including Spanish, Italian, Russian, German, Arabic, and Turkish, studies published in these languages were translated, when necessary, and assessed for eligibility during the study selection process. Late-presenting CDH, Morgagni hernias, Larrey hernias and studies in which the repair was performed laparoscopically were excluded from the analysis.

PICOS strategy

Participant/population(s): Neonates with diagnosis of CDH.

Intervention(s): Neonates underwent thoracoscopic CDH repair.

Comparator(s)/control: Neonates underwent open CDH repair.

Outcome (s): The primary and secondary outcomes included recurrence rate, bowel obstruction rate, chylothorax rate, pneumothorax rate, pleural effusion rate, bowel injury rate, mortality, and conversion to open rate.

Studies: RCT, prospective, and Retrospective studies.

Risk of bias assessment

Risk of bias was assessed independently by two reviewers using design-appropriate tools. Retrospective and prospective non-randomized studies were evaluated using the Newcastle–Ottawa Scale (NOS), and the randomized trial was assessed using the Cochrane RoB 2.0 tool. Discrepancies were resolved by consensus. A summary of the quality assessment is provided in Supplementary Table 1.

Data extraction

Two independent reviewers (SK and MA) systematically evaluated all studies that meet the predefined eligibility criteria for inclusion in this study. For each study, data were extracted on study design, sample size, study period, year of publication, and journal source. Baseline patient characteristics, including gestational age, birth weight, sex distribution, side of the defect, defect size classification, liver position, and age at surgery, were recorded. The reviewers also collected comprehensive information on perioperative and postoperative outcomes relevant to CDH. All extracted data were entered into a standardized Excel database. When disagreements arose between the two primary reviewers, a third reviewer was consulted to evaluate the relevant outcome data and reach a consensus.

Management of conversion cases

In studies focusing on minimally invasive repair, conversion from thoracoscopy or laparoscopy to open surgery is not uncommon, particularly in infants, due to limited operative space or technical limitations. Some studies exclude converted cases altogether, whereas others retain them within the analysis. However, among studies that include conversion cases, there is no standardized approach regarding the analytical allocation of these patients. In certain publications, converted cases were analyzed within the minimally invasive group, while in others, they were analysed to the open surgery cohort. This variability represents an inherent methodological limitation of the available literature. In the present review, each study reported conversion management differently. Because individual patient data were not available, reclassification of conversion cases into a uniform intention-to-treat framework was not feasible. Table 1 provides a detailed summary indicating how conversion cases were classified in each included publication.

Sensitivity analysis

To assess the robustness and stability of the pooled estimates, sensitivity analyses were conducted. A leave-one-out (LOO) approach was used, in which each study was sequentially removed, and the pooled effect size recalculated using the remaining dataset. This method allowed us to determine whether the overall significance or magnitude of the results was unduly influenced by any single study, thereby strengthening the reliability of the findings.

Sankey diagrams

To visualize the complex outcome distributions from this meta-analysis, we employed a Sankey diagram. This visualization technique has been previously published as an effective tool for intuitively summarizing meta-analytic data [10]. In the resulting diagram, pathways are color-coded based on statistical significance: green pathways represent outcomes with a significant difference between groups, while red pathways indicate non-significant differences.

Reporting

This systematic review's outcomes were documented following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [11].

Statistical analysis

All statistical analyses were conducted using Review Manager (RevMan) version 5.4 (Cochrane Collaboration, Oxford, UK). Continuous outcomes were synthesized as mean differences (MDs), whereas dichotomous variables were summarized as risk ratios (RRs), each reported with corresponding 95% confidence intervals (CIs). Statistical heterogeneity was evaluated using the I^2 statistic, and a two-tailed p-value < 0.05 was deemed indicative of statistical significance. Given the anticipated clinical and methodological heterogeneity among the included studies, pooled effect estimates were generated using a random-effects model. Additionally, conversion rates were visually depicted using an Excel-based graphical diagram to enhance interpretability of the findings.

Results

The literature search identified 1,604 records across PubMed, Web of Science, EMBASE, and SCOPUS. After removing duplicates and irrelevant studies, 370 records remained. Of these, 81 full titles and abstracts were screened, and 12 reports could not be retrieved. A total of 69 articles were

Table 1 Summary of included studies

Study	Study year	Study period	Published Journal	Country	Type of the study	Centers	Conversion
Bawazir et al.	2021	2011–2019	African J Ped Surg	Saudi Arabia	Retrospective	Umm Al-Qura University	Added to OR
Bishay et al.	2013	2009–2011	Annals of surgery	UK	RCT	Great Ormond Street Hospital	No conversion
Budzanowski et al.	2023	2015–2021	PSI	UK	Retrospective	Great Ormond Street Hospital	Added to TR
Cho et al.	2009	2001–2007	JPS	USA	Retrospective	Emanuel Children's hospital	Excluded
Costerus et al.	2016	2008–2012	Surgical Endoscopy	Netherlands	Retrospective	Sophia Children's Hospital	Added to TR
Criss et al.	2018	2006–2016	JPS	USA	Retrospective	Mott Children's Hospital	Excluded
Gander et al.	2011	2006–2010	JPS	USA	Retrospective	Morgan Stanley Children's Hospital	Excluded
Gourlay et al.	2009	1999–2007	JPS	USA	Retrospective	Children's Hospital of Wisconsin	Excluded
He et al.	2016	2011–2014	JLAST	China	Retrospective	Guangzhou Medical University	Added to TR
Inoue et al.	2016	2000–2014	Surgical Endoscopy	Japan	Retrospective	Mie University	No conversion
Keijzer et al.	2010	2006–2008	JPS	Netherlands	Retrospective	Sophia Children's Hospital	Added to TR
Liu et al.	2022	2013–2021	Frontiers in Ped	China	Retrospective	Zunyi Medical University	Excluded
Muensterer et al.	2024	2021–2023	Children	Germany	Retrospective	Dr. von Hauner Children's Hospital	Excluded
Nam et al.	2013	2008–2011	World J Surgery	Korea	Retrospective	Inje University Haeundae Paik Hospital	Added to TR
Okawada et al.	2021	2006–2018	Surgery Today	Japan	Retrospective	Multicenter−15 institution	Excluded
Okazaki et al.	2015	2002–2014	PSI	Japan	Retrospective	Juntendo University	Excluded
Qin et al.	2019	2015–2018	J Cardiothorac Surg	China	Retrospective	Linyi Central Hospital	Not reported
Shah et al.	2024	2017–2021	JPS	USA	Retrospective	Mott Children's Hospital	Excluded
Zani et al.	2017	2004–2014	Pediatric Anesthesia	Canada	Retrospective	Sick Children Hospital	Added to OR

assessed for eligibility, of which 50 were excluded for not meeting the predefined inclusion criteria. Ultimately, 19 studies [12–30] fulfilled all eligibility requirements and were included in the final qualitative and quantitative synthesis (Fig. 1).

Nineteen studies from 10 countries (USA, UK, Canada, Netherlands, Germany, Saudi Arabia, China, Japan, Korea, and Australia) were included. Most were retrospective, with one RCT and one study providing propensity-matched data. Study periods spanned more than two decades. Descriptive characteristics of the included studies are summarized in Table 1.

Outcomes

Total recurrence rate

Total recurrence rate (TRR) was reported in all 19 included studies, comprising 434 patients in the TR group and 631 patients in the COR group. The overall TRR was 12.9% (56/434) in the TR cohort and 4.12% (26/631) in the COR cohort. TRR was significantly higher in the TR group (RR = 2.4, 95% CI: 1.62–3.55; $p = 0.0003$), with no statistical heterogeneity ($I^2 = 0\%$) (Fig. 2). The leave-one-out sensitivity analysis revealed consistent effect estimates throughout, indicating that the overall findings were robust and not driven by any individual study.

Primary repair recurrence rate

Primary repair recurrence rate (PRR) was reported in 12 studies, comprising 166 patients in the TR group and 202 patients in the COR group. In the pooled analysis, PRR was significantly higher after TR (RR 4.39; 95% CI 2.16–8.93; $p = 0.001$), with no observed heterogeneity ($I^2 = 0\%$). A continuity correction was applied for studies with zero events in one arm. Leave-one-out sensitivity analysis demonstrated that the effect remained stable and was not driven by any individual study (Fig. 3).

Patch repair recurrence rate

Patch repair recurrence rate was reported in 9 studies, comprising 95 patients in the TR group and 113 patients in the COR group. The overall patch repair recurrence rate was 21.05% (20/95) in TR and 11.5% (13/113) in COR. Patch

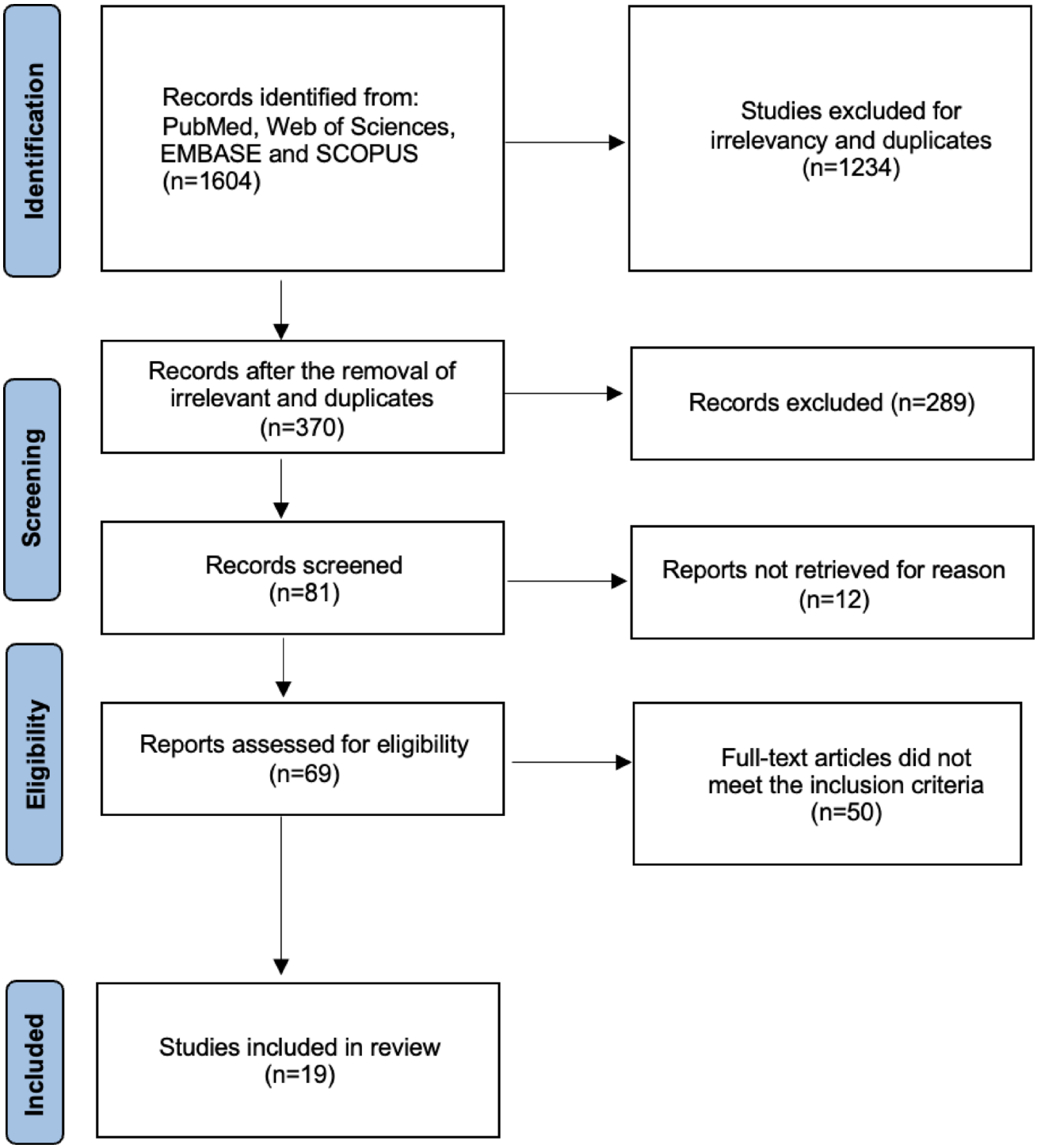


Fig. 1 PRISMA flow chart

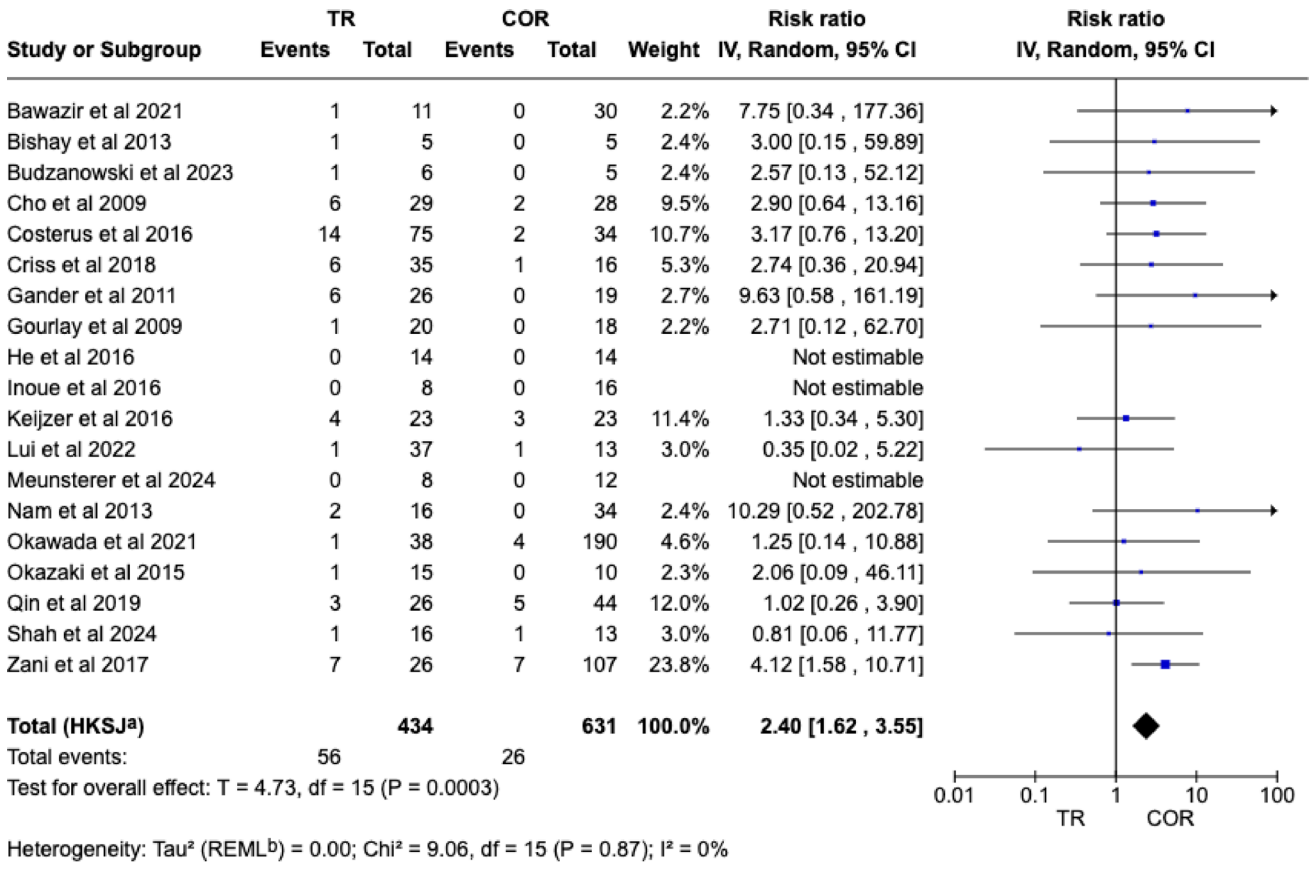


Fig. 2 Total recurrence rate

repair recurrence rate was significantly higher in the TR group (I^2=0%) (RR = 1.98, 95% CI: 1.05–3.74; p = 0.04) (Fig. 4). In the leave-one-out sensitivity analysis, the significance of this association varied when some individual studies (Costerus et al., Gander et al., Nam et al., Zani et al.) were removed.

Bowel obstruction rate

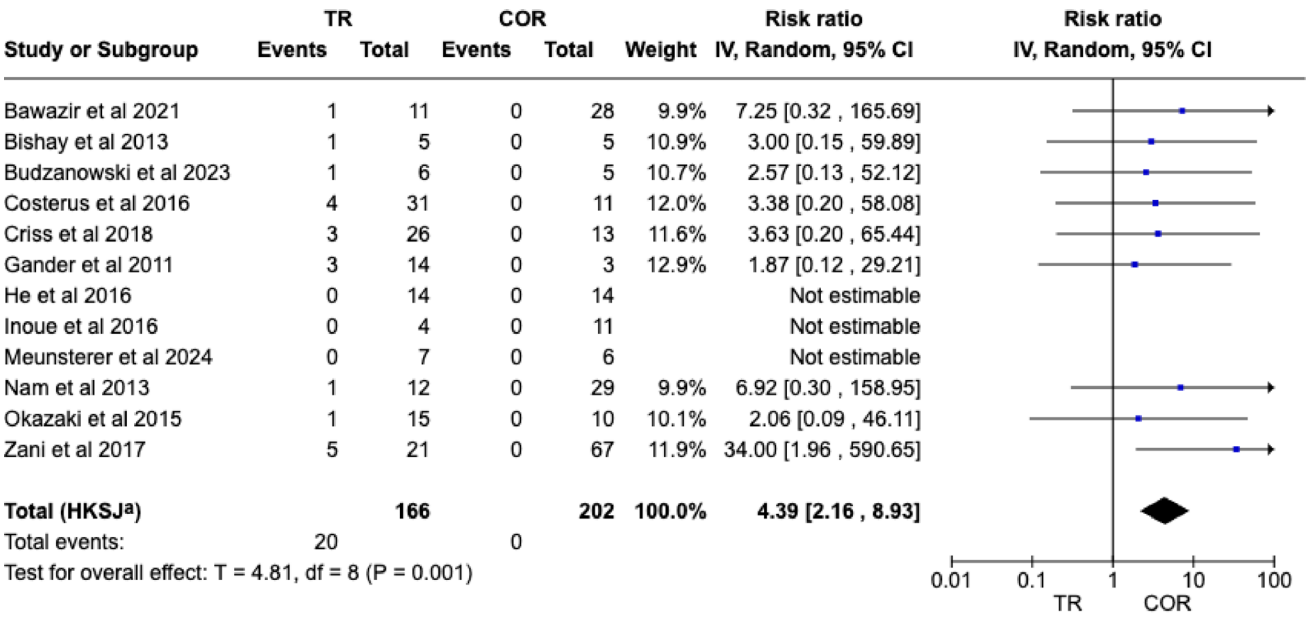
Bowel obstruction rate (BOR) was reported in 8 studies, comprising 133 patients in the TR group and 232 patients in the COR group. The overall BOR was 6% (8/133) in the TR cohort and 14.65% (34/232) in the COR cohort. The BOR was significantly lower in the TR group (I^2=0%) (RR = 0.52, 95% CI: 0.31–0.89; p = 0.02) (Fig. 5). In the leave-one-out sensitivity analysis, exclusion of certain studies (Gourlay et al., Okazaki et al.) resulted in loss of statistical significance, indicating that this finding is sensitive to individual study effects.

Chylothorax rate

Chylothorax rate (CR) was reported in 3 studies, comprising 47 patients in the TR group and 52 patients in the COR group. The overall CR was 6.38% (3/47) in the TR cohort and 13.46% (7/52) in the COR cohort. No difference was found between groups in terms of CR (I^2=64%) (RR = 0.62, 95% CI: 0.00–197.81; p = 0.76), and the pooled effect estimate showed a very wide confidence interval due to low event numbers, indicating substantial imprecision (Fig. 6). The leave-one-out sensitivity analysis did not materially change the direction of the effect, although the low number of events limits the robustness of the findings.

Pneumothorax rate

Pneumothorax rate (PR) was reported in 4 studies, comprising 70 patients in the TR group and 85 patients in the COR group. The overall PR was 4.28% (3/70) in the TR cohort and 7.05% (6/85) in the COR cohort. No difference was

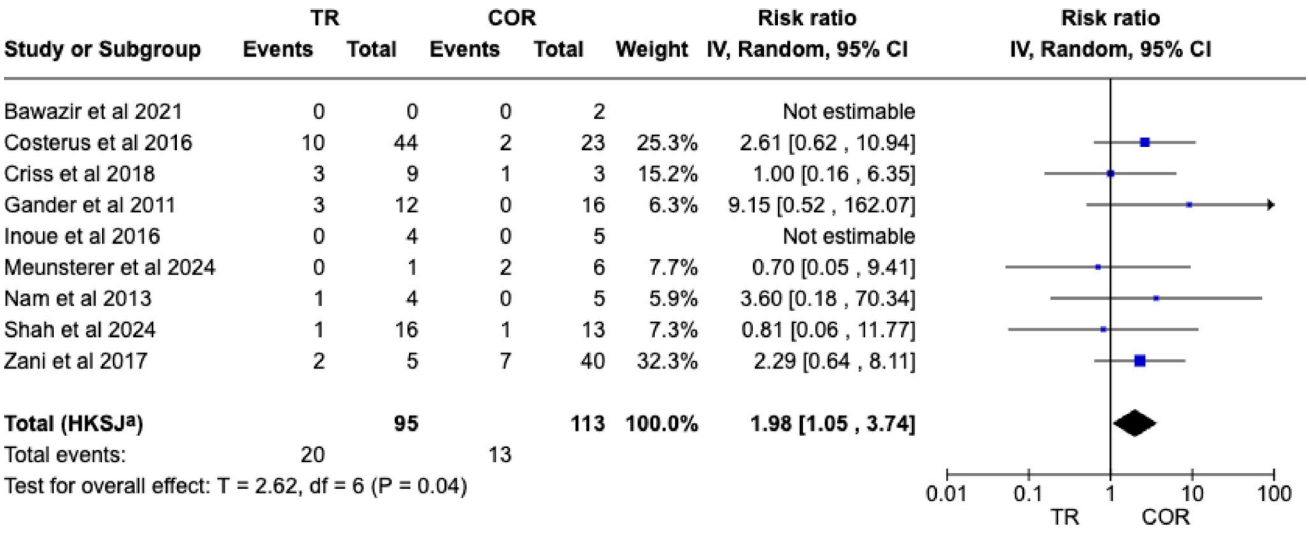


Footnotes

[a]CI calculated by Hartung-Knapp-Sidik-Jonkman method.

[b]Tau² calculated by Restricted Maximum-Likelihood method.

Fig. 3 Recurrence rate in primary repairs



Footnotes

[a]CI calculated by Hartung-Knapp-Sidik-Jonkman method.

[b]Tau² calculated by Restricted Maximum-Likelihood method.

Fig. 4 Recurrence rate in patch repairs

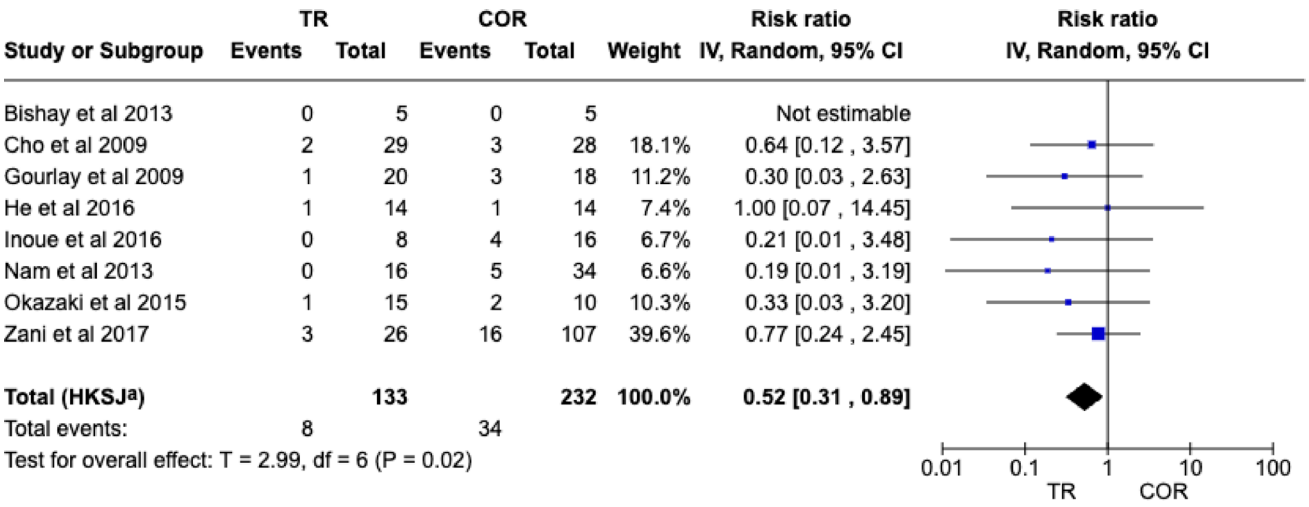


Fig. 5 Bowel obstruction rate

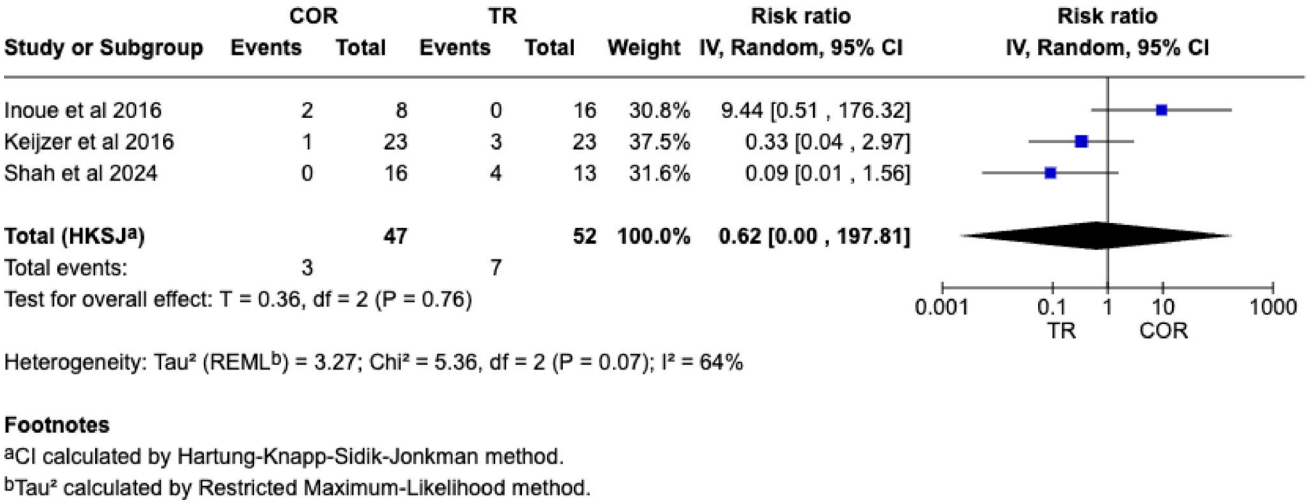


Fig. 6 Chylothorax rate

found between groups in terms of PR (I^2=0%) (RR = 0.69, 95% CI: 0.20–2.41; p = 0.42) (Fig. 7). The leave-one-out sensitivity analysis did not change the significance or direction of the effect.

Pleural effusion rate

Pleural effusion rate (PER) was reported in 6 studies, comprising 94 patients in the TR group and 135 patients in the COR group. The overall PER was 5.31% (5/94) in the TR cohort and 6.66% (9/135) in the COR cohort. No difference was found between groups in terms of PER (I^2=0%) (RR = 0.89, 95% CI: 0.16–4.82; p = 0.86) (Fig. 8). The leave-one-out sensitivity analysis confirmed that the pooled estimate remained stable when each study was sequentially excluded.

Bowel injury rate

Bowel injury rate (BIR) was reported in 5 studies. A total of 76 patients were included in the TR group and 81 in the COR group for this outcome. The overall BIR was 5.26% (4/76) in the TR cohort and 6.17% (5/81) in the COR cohort. No significant difference was found between groups in terms of BIR (I^2=0%) (RR = 0.79, 95% CI: 0.06–9.65; p = 0.72) (Fig. 9). The leave-one-out sensitivity analysis showed

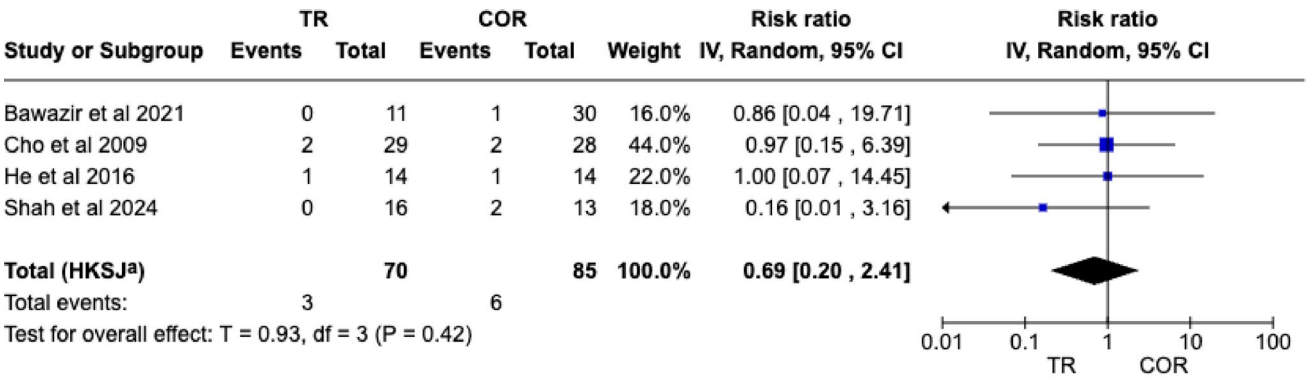


Fig. 7 Pneumothorax rate

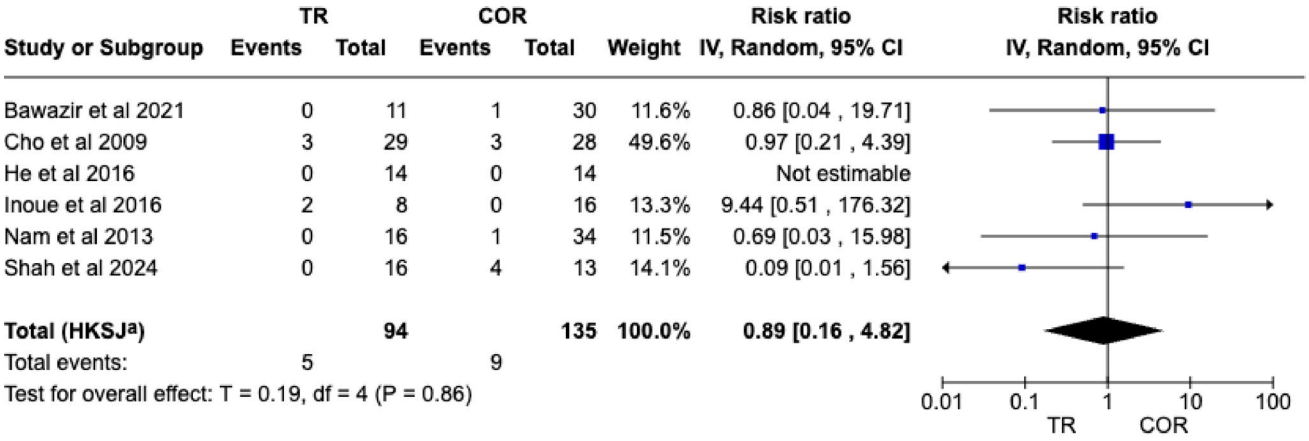


Fig. 8 Pleural effusion rate

stable effect estimates, indicating that no single study disproportionately influenced the pooled result.

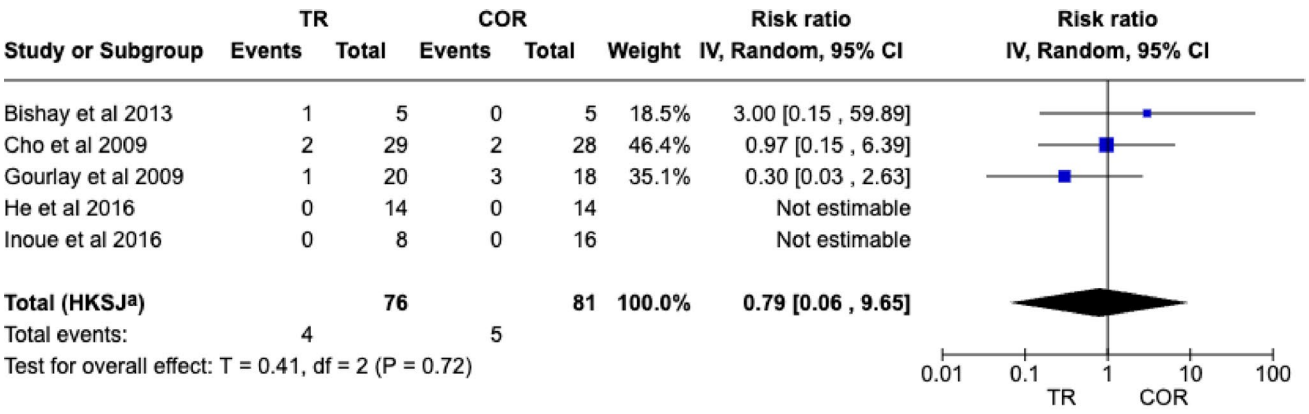
Mortality rate

Mortality rate (MR) was reported in 17 studies, comprising 403 patients in the TR group and 519 patients in the COR group. The overall MR was 0.9% (4/403) in the TR cohort and 5.97% (31/519) in the COR cohort. MR was significantly lower in the TR group (I^2=0%) (RR = 0.31, 95% CI: 0.21–0.47; $p < 0.0001$) (Fig. 10). The leave-one-out sensitivity analysis revealed consistent effect estimates throughout, indicating that the overall findings were robust and not driven by any individual study.

Conversion rate

Conversion from TR to COR was reported heterogeneously across studies. Overall, 14.5% of thoracoscopic procedures resulted in conversion, according to the classification used by each original publication. Considerable variability was observed among institutions in both thoracoscopic case volume and conversion frequency.

A correlation analysis between the number of thoracoscopic cases per center and the corresponding conversion rate demonstrated no significant association ($p = 0.695$) (Fig. 11).

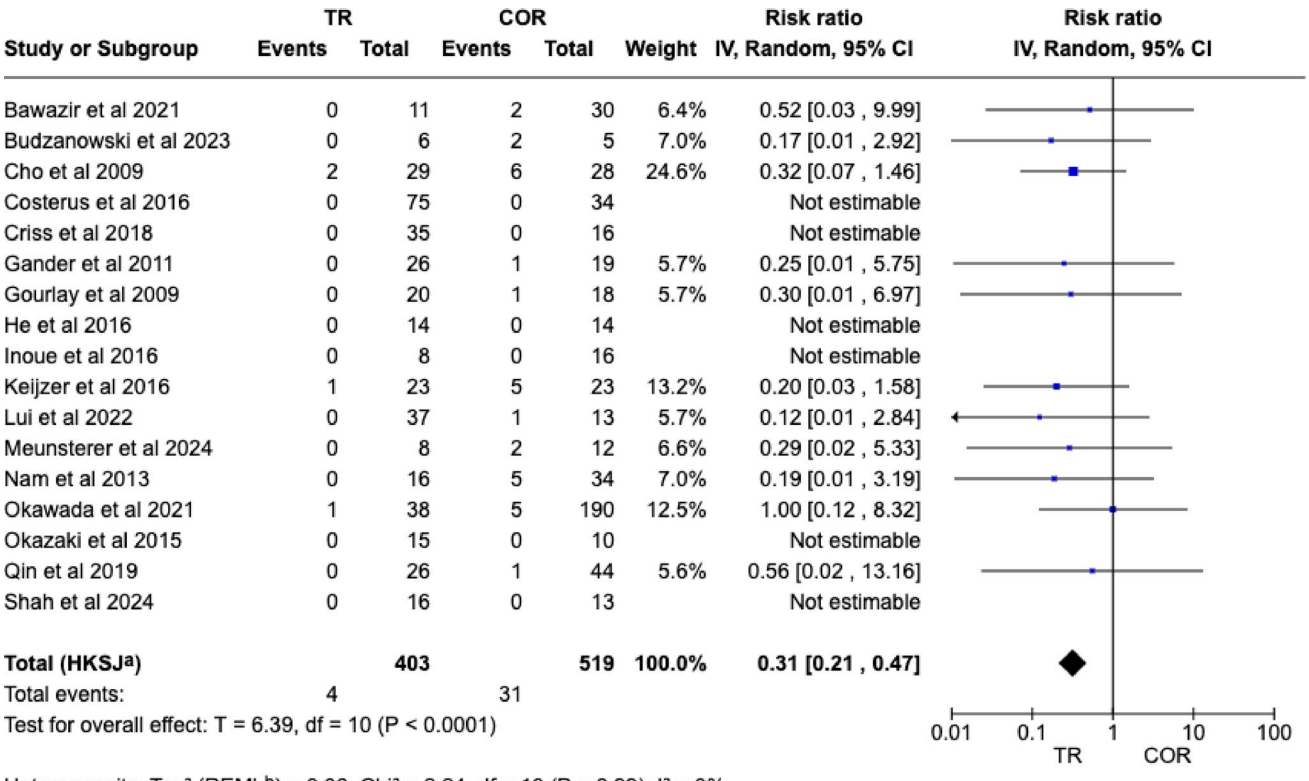


Footnotes

[a]CI calculated by Hartung-Knapp-Sidik-Jonkman method.

[b]Tau² calculated by Restricted Maximum-Likelihood method.

Fig. 9 Bowel injury rate



Footnotes

[a]CI calculated by Hartung-Knapp-Sidik-Jonkman method.

[b]Tau² calculated by Restricted Maximum-Likelihood method.

Fig. 10 Mortality rate

Given the inconsistent reporting and variable denominators across studies, conversion data were summarized descriptively and were not pooled in a meta-analysis.

A Sankey diagram was constructed to visually summarize the direction and statistical significance of all primary and secondary outcomes included in the meta-analysis. Each pathway represents one outcome, with green indicating a statistically significant difference between TR and COR, and red indicating no significant difference. This diagram serves as a complementary visualization tool to enhance interpretation of the pooled results (Fig. 12).

Discussion

This systematic review and meta-analysis provide a comprehensive comparison of TR versus COR for CDH in neonates, focusing specifically on postoperative complications. Although MIS is increasingly adopted in neonatal surgery, the debate regarding its safety and long-term outcomes in CDH persists. Our findings indicate that while TR offers certain perioperative advantages, it is associated with a significantly higher recurrence rate, particularly in primary repairs.

The most striking finding of this meta-analysis was the increased recurrence rate following TR for CDH. The TRR was nearly threefold higher in the TR group compared to COR (12.9% vs. 4.1%), with consistent results across sensitivity analyses. This trend was especially pronounced in primary (non-patch) repairs, where recurrence after TR reached 12% compared to 0% after COR. These findings align with previous studies reporting recurrence rates as high as 23% in TR cohorts [16, 18, 25, 30].

One plausible explanation for this difference is that primary closure may be overindicated in TR due to the technical simplicity of suturing compared to patch placement in a confined space. Moreover, the technical challenges of suturing within the restricted intrathoracic space—particularly knot-tying—may contribute to surgeon reluctance to place a patch even when indicated. Innovations such as barbed sutures, which eliminate the need for intracorporeal knot-tying, may help overcome some of these limitations and potentially improve the durability of thoracoscopic repairs [24]. In contrast, when a patch is clearly required, the decision tends to be more consistent across approaches, and thus outcomes may converge, as supported by our subgroup analysis.

Contrary to earlier concerns, most secondary complications—including pneumothorax, pleural effusion, bowel injury, and chylothorax—were comparable between groups. Notably, TR was associated with a significantly lower incidence of postoperative bowel obstruction (6% vs. 14.6%). This likely reflects reduced visceral manipulation, less adhesiogenesis, and the avoidance of a laparotomy incision, all of which are well-described benefits of MIS [19, 27].

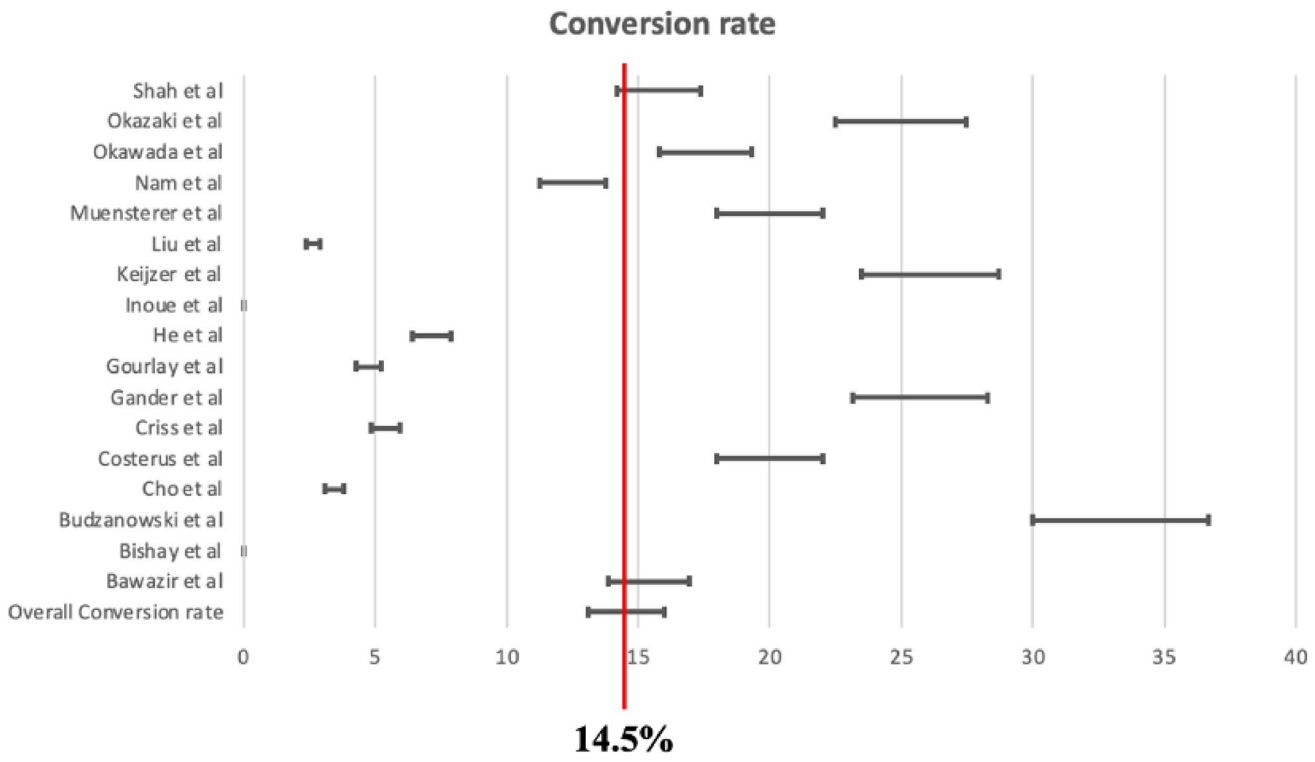


Fig. 11 Conversion rate

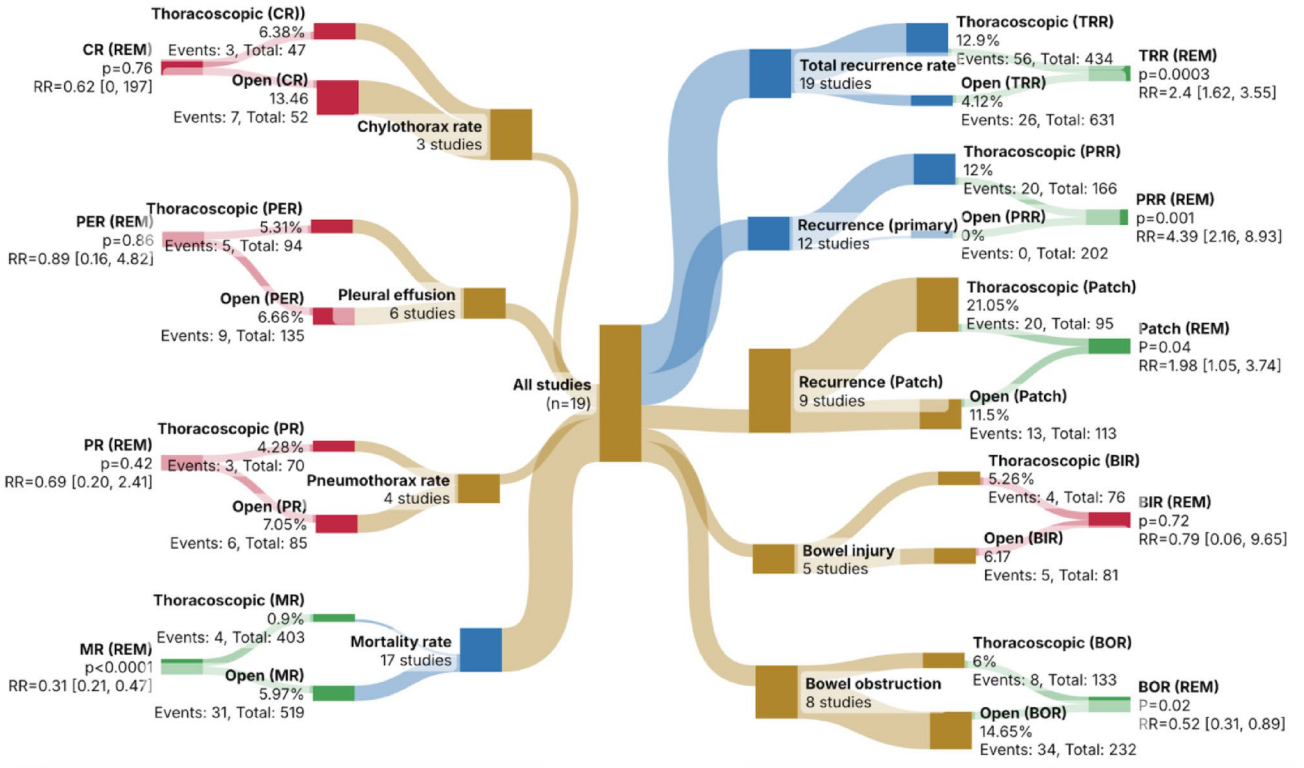


Fig. 12 Summarizing outcomes with Sankey diagram (*red color* no statistically significant, *green color* statistically significant, *blue color* relevant outcome is reported by at least > 50% of included studies, *REM* random effects model, *TRR* total recurrence rate, *PRR* primary repair recurrence rate, *BIR* bowel injury rate, *BOR* bowel obstruction rate, *CR* chylothorax rate, *PER* pleural effusion rate, *PR* pneumothorax rate, *MR* mortality rate)

The issue of intraoperative acidosis and hypercapnia in TR, due to CO_2 insufflation and systemic absorption, was highlighted by Zani et al. (2017), who reported more pronounced blood gas alterations during MIS [30]. Although these physiological disturbances — including hypercapnia, respiratory acidosis, and elevated end-tidal CO_2 — have been documented, our pooled analysis suggests that they do not translate into increased postoperative morbidity. Improvements in anesthetic management, tighter control of insufflation pressures, and growing surgeon experience may partially explain these findings, which are consistent with more recent series. However, intraoperative respiratory parameters were inconsistently reported across studies and were not prespecified meta-analytic outcomes, limiting the possibility of performing a pooled physiologic analysis. Consequently, definitive conclusions regarding the clinical significance of these intraoperative changes cannot be drawn from the available evidence.

Perhaps unexpectedly, the mortality rate was significantly lower in the TR group. This finding should be interpreted with caution, as thoracoscopy is typically reserved for hemodynamically stable neonates without severe pulmonary hypertension or the need for ECMO [22, 29]. Therefore, the lower mortality likely reflects selection bias rather than an inherent advantage of the thoracoscopic technique. These factors underscore the challenge of comparing outcomes across inherently different risk profiles.

A consistent theme across included studies is the importance of appropriate patient selection and institutional experience. TR appears most appropriate in hemodynamically stable neonates without severe pulmonary hypertension, large defects, right-sided hernias or the need for ECMO. As several authors have noted, outcomes improve significantly with increased surgeon experience and adherence to standardized protocols [20, 24]. Our findings reinforce the principle that TR should be reserved for well-selected patients and performed in centers with sufficient MIS expertise.

Conversion to open repair, reported in 14.5% of TR cases, should not be perceived as failure but rather as a prudent intraoperative decision. Our analysis showed no correlation between institutional thoracoscopic volume and conversion rates, suggesting that anatomical and clinical variability play a more prominent role than experience alone. However, as pointed out by Bishay et al. (2013), early conversion may actually contribute to better outcomes by avoiding undue tension or hypoxia during challenging MIS repairs [12].

Overall, the present meta-analysis highlights the strengths and limitations of the thoracoscopic approach. While it

offers certain perioperative advantages and may reduce bowel obstruction, recurrence rates—particularly in primary repairs—remain substantially higher than with open surgery. Continued refinement of thoracoscopic techniques, better intraoperative decision-making regarding patch use, and innovations in MIS instrumentation may help reduce recurrence in the future.

This study has several limitations. The predominance of retrospective studies, lack of standardization in outcome reporting (particularly regarding the allocation of converted cases), and variability in follow-up duration all limit the strength of our conclusions. Only one randomized controlled trial was identified, and prospective comparative studies remain scarce. Detailed information on diaphragmatic defect size, liver position, and patch use was inconsistently reported, preventing adjustment for these key prognostic variables. Long-term outcomes—including pulmonary function, musculoskeletal development, growth, and neurodevelopment—were rarely described and could not be analyzed. Furthermore, the paucity of intraoperative physiological data limits our ability to evaluate the true significance of hypercapnia and acidosis during TR.

Future research should prioritize standardized reporting of defect characteristics, surgical decision-making (including criteria for primary versus patch repair), liver position, and follow-up duration. Prospective, multicenter studies are needed to better define selection criteria for TR, to quantify the learning curve, and to understand the influence of surgeon experience and institutional volume. The laparoscopic (transabdominal) approach—identified in our search but not included due to insufficient comparable data—also warrants dedicated evaluation. Long-term outcomes such as pulmonary function, musculoskeletal development, and late recurrence should be systematically assessed.

In conclusion, TR of CDH is a safe and feasible approach in well-selected neonates and offers advantages such as reduced bowel obstruction and lower short-term mortality. However, it is consistently associated with higher recurrence rates, especially in primary repairs, possibly due to the overuse of primary closure under tension and the technical limitations of thoracoscopic suturing in a confined space. When a patch is indicated, outcomes appear more comparable to COR, particularly when performed by experienced surgeons in high-volume centers. These findings emphasize the need for careful patient selection, rigorous surgeon training, and standardized surgical criteria to optimize outcomes in TR of CDH. Future prospective, multicenter trials are necessary to define optimal indications and improve reproducibility in thoracoscopic CDH repair.

Appendix 1 — full electronic search strategies

PubMed (MEDLINE)
("Hernia, Diaphragmatic, Congenital"[MeSH]
OR "congenital diaphragmatic hernia"
OR "CDH"
OR "Bochdalek hernia")
AND
("Thoracoscopy"[MeSH]
OR thoracoscop*
OR "minimally invasive"
OR "video-assisted")
AND
(neonate OR newborn OR infant)
AND
(repair OR surgery OR surgical)

EMBASE
('congenital diaphragmatic hernia'/exp
OR 'bochdalek hernia'/exp
OR 'congenital diaphragmatic hernia'
OR 'cdh')
AND
('thoracoscopy'/exp
OR thoracoscop*
OR 'minimally invasive surgery'/exp
OR 'video assisted thoracoscopic surgery')
AND
(neonate* OR newborn* OR infant*)
AND
(repair OR surg*)

SCOPUS
TITLE-ABS-KEY("congenital diaphragmatic hernia"
OR "Bochdalek hernia"
OR CDH)
AND
TITLE-ABS-KEY(thoracoscop*
OR "minimally invasive"
OR MIS
OR "video assisted")
AND
TITLE-ABS-KEY(neonate
OR newborn
OR infant)
AND
TITLE-ABS-KEY(repair
OR surgery
OR surgical)

Web of Science
TS=("congenital diaphragmatic hernia"
OR "Bochdalek hernia"
OR CDH)
AND
TS=(thoracoscop*
OR "minimally invasive"
OR "video assisted")
AND
TS=(neonate OR newborn OR infant)
AND
TS=(repair OR surgery OR surgical)

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Author contributions S.P.B. drafted the initial manuscript. M.A. conducted the statistical analysis. M.A., S.K., F.P., M.E., B.S., B.A., C.G.H., C.E., A.M., S.S., A.C., M.L., O.M., and F.C. contributed to data interpretation, provided critical revisions, and improved the scientific content of the manuscript.All authors reviewed, revised, and approved the final version of the manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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