THE ANATOLIAN JOURNAL OF CARDIOLOGY

Official journal of the TURKISH SOCIETY OF CARDIOLOGY

Transcatheter Versus Surgical Closure of Atrial Septal Defect in Children and Adults: A Systematic Review and Meta-Analysis of Observational Studies

META-ANALYSIS

ABSTRACT

Background: Atrial septal defect closure can be performed surgically or via transcatheter intervention, yet comparative outcomes remain inconsistent between children and adults. This review synthesizes observational evidence to evaluate procedural success, complications, and peri-procedural characteristics across both populations.

Methods: A systematic review and meta-analysis following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines was conducted, including 36 observational studies published through 2024. Study quality was assessed using the Newcastle–Ottawa Scale. Random effects models were applied, with subgroup analyses by age and procedure type. Publication bias was examined using funnel plots and Egger's test.

Results: The pooled procedural success rate was 95% (95% CI: 92%-97%; I^2 = 90.2%). Among children, raw procedural success was 87% (1445/1656) for transcatheter closure and 99% (505/510) with surgery. In adults, transcatheter closure achieved 97% (95% CI: 90%-99%), whereas surgery reached 98% (95% CI: 70%-100%). Transcatheter closure resulted in shorter hospitalization (mean difference: −3.86 days, 95% CI: −6.03 to −1.69; *P* = .0004) and fewer major complications (risk ratio: 0.58, 95% CI: 0.39-0.86; *P* = .006). Sensitivity analysis restricted to high-quality studies (n = 12) remained consistent. Egger's regression did not indicate significant publication bias (*P* = .069).

Conclusion: Both approaches provide high closure success, yet transcatheter intervention offers lower complication rates and faster recovery, particularly in anatomically suitable patients. These findings support individualized treatment selection based on age, anatomy, and institutional experience.

Keywords: Atrial septal defect, complications, meta-analysis, procedural outcomes, surgical repair, transcatheter closure

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Received: September 11, 2025
Accepted: December 9, 2025
Available Online Date: January 7, 2026

Cite this article as: Kannady J, Amelia P, Dwi Rifa'i A, Hany Hot Asi Sianturi G. Transcatheter versus surgical closure of atrial septal defect in children and adults: A systematic review and meta-analysis of observational studies. *Anatol J Cardiol.* 2026;XX(XX):1-12.

DOI:10.14744/AnatolJCardiol.2025.5766

INTRODUCTION

Atrial septal defect (ASD) is one of the most common congenital heart diseases, accounting for 10%-15% of cases in both children and adults. The secundum subtype predominates and, when left untreated, may lead to progressive right-sided volume overload, arrhythmia, pulmonary hypertension, and early mortality.[1-3] Closure is therefore recommended in symptomatic patients and in those with evidence of right ventricular dilation regardless of age.[3]

Surgical repair has long been the definitive treatment for ASD, achieving excellent long-term outcomes and near-complete defect closure. However, since the 1990s, transcatheter closure has emerged as a less invasive alternative for anatomically suitable patients, offering shorter recovery, reduced postoperative morbidity, and superior cosmetic results.[4,5] Current guidelines increasingly support transcatheter closure as first-line therapy when feasible.[4-6]

Despite these advantages, comparative evidence remains inconsistent. Most available data originate from observational studies rather than randomized trials, and reported outcomes vary considerably across age groups and clinical settings.

Some studies suggest that transcatheter closure provides comparable or even superior safety profiles with fewer complications, while others emphasize the procedural durability of surgery, particularly in cases with complex or unfavorable anatomy.[6-9] Additionally, children and adults exhibit distinct technical challenges and comorbidity profiles that influence procedural success and complication risk, complicating comparative interpretation.[9]

Given these uncertainties, an updated synthesis is needed to clarify outcome differences between transcatheter and surgical closure across age groups. A systematic review and meta-analysis of observational studies comparing both approaches was conducted, focusing on procedural success, complication patterns, and peri-procedural characteristics in children and adults.

METHODS

Study Design

We conducted a systematic review and meta-analysis of observational studies comparing transcatheter and surgical ASD closure. This review adhered to PRISMA 2020 guidelines.[10] The protocol was registered prospectively in the International Prospective Register of Systematic Reviews(P ROSPERO;CRD420251052612). Because the published data was analyzed and did not include new patient contact, no ethical approval or consent was required.

Eligibility Criteria

We included observational studies such as prospective cohort studies, retrospective cohort studies, case-control studies, and national registries that reported outcomes of transcatheter or surgical ASD closure in children or adults. A study was eligible if it reported at least one of the following outcomes: procedural success, procedural characteristics including procedure duration, fluoroscopy duration, radiation exposure, length of stay, or complications during the procedure or follow-up period. Case reports, review articles, conference abstracts, and studies without extractable quantifiable outcome data were excluded.

Search Strategy

We conducted a comprehensive search of PubMed, Embase, Scopus, and Web of Science up to December 2024. Search terms included "atrial septal defect," "ASD," "transcatheter closure," "device closure," "surgical repair," and "outcomes" combined with Boolean operators. Reference lists from eligible studies were manually screened to identify additional publications.

Study Selection

Three reviewers independently screened titles and abstracts. Full text review followed for studies that met preliminary criteria. Disagreements were resolved through discussion with a fourth reviewer. The selection process is summarized in the PRISMA flow diagram.[10]

Data Extraction

Three reviewers extracted data independently using a structured data form. Extracted variables included study design, publication year, country, sample size, patient demographics including age, sex, and weight, anatomical characteristics of the defect, type of intervention, success rates, intra-procedural and follow-up complications, procedure duration, fluoroscopy duration, and length of hospital stay. Device type and device diameter for transcatheter closure were recorded when available and are presented in Supplementary Tables 1 and 2.

Procedural success was defined in this review as successful closure confirmed by imaging without major complications during the same admission. The included studies did not use a uniform definition because some investigators defined success based on device deployment alone, while others required the absence of complications or complete closure on follow-up imaging. To address these differences, a single operational definition was applied and the data elements that matched this definition as closely as possible were extracted. Only a limited number of studies used identical criteria; therefore, a sensitivity analysis restricted to studies with fully consistent definitions could not be performed.

Risk of Bias Assessment

We assessed methodological quality using the Newcastle–Ottawa Scale (NOS).[11] This tool evaluates 3 domains: patient selection, comparability of groups, and outcome assessment. Studies with a score of 7 or higher were classified as high quality.

The Grading of Recommendations Assessment, Development and Evaluation (GRADE) Assessment

We assessed certainty of evidence using the GRADE framework. A summary of grading for each outcome is provided in Supplementary Table 3.

Outcomes of Interest

The primary outcome was procedural success, defined according to the standardized operational definition applied in this review. Secondary outcomes included procedure duration, fluoroscopy duration, radiation exposure, length of stay, and peri-procedural or follow-up complications. Variation in follow-up duration across studies limited time-specific outcome comparison.

Statistical Analysis

Meta analyses were performed using random effects models (DerSimonian–Laird). All analyses were conducted in

HIGHLIGHTS

- Transcatheter closure of atrial septal defect significantly reduces hospital stay and procedural complications compared to surgery.
- Both transcatheter and surgical approaches achieve high procedural success (>95%) across children and adult patients.
- Surgery remains indispensable for complex anatomy and large defects not amenable to device closure.
- Age-specific differences suggest that transcatheter closure is especially advantageous in pediatric patients.

RStudio (RStudio version 2024.12.0).[12] Risk ratios for dichotomous outcomes and mean differences for continuous outcomes were reported, each with 95% CIs. Data distribution for continuous outcomes including procedure duration and fluoroscopy duration was visually inspected and demonstrated right skew patterns in several studies. However, because most publications reported only mean and standard deviation without providing median or interquartile range values, transformation into nonparametric effect measures was not possible. Mean difference was therefore retained for consistency in pooled synthesis.

For outcomes that included 1 or more 0 event cells, a continuity correction of 0.5 was applied to enable computation of risk ratios. Peto or modified Mantel–Haenszel estimators were not applied because several outcomes contained studies with unbalanced sample distribution, and risk ratios provided a more clinically interpretable measure for comparison.

Statistical heterogeneity was quantified using the I^2 statistic.[13] Follow-up duration varied substantially across the included studies and ranged from early in-hospital assessments to long-term evaluations. Because the studies did not provide a consistent prespecified follow-up window, the outcome that most closely reflected the first systematic evaluation after the intervention was extracted. The analysis was not restricted to a single follow-up length because too few studies reported outcomes at identical time points. Stratified pooling based on short-term or long-term follow-up could not be performed for the same reason. The pooled estimates for late complications should therefore be interpreted as summaries of heterogeneous follow-up intervals rather than strictly comparable time-matched outcomes. Prespecified subgroup analyses were performed according to procedure type (transcatheter versus surgical) and age group (children versus adults). Sensitivity analyses restricted to high-quality studies with Newcastle Ottawa Scale score 7 or greater were conducted to assess the robustness of the pooled estimates. Publication bias was evaluated by funnel plot assessment and Egger regression.[14]

RESULTS

Study Selection

The initial search retrieved 1683 records. After duplicate removal and screening of titles and abstracts, 36 observational studies met the eligibility criteria and were included in the quantitative synthesis. The study selection process is presented in the PRISMA 2020 flow diagram (Figure 1).

Study Characteristics

The 36 included studies comprised a total of 12 739 patients undergoing transcatheter or surgical ASD closure (7014 transcatheter; 5725 surgical). Study designs consisted of prospective and retrospective cohorts, case-control studies, and 1 nationwide registry. Mean age in adult cohorts ranged from 28 to 42 years, while pediatric cohorts ranged from 1.5 to 7 years. Baseline characteristics including age, sex, weight, and defect size on echocardiography or angiography are summarized in Table 1.

Detailed baseline patient demographics and peri-procedural characteristics stratified by closure approach are presented in Table 2.

Most studies reported the type of device used for transcatheter closure.

Amplatzer devices predominated (78.9% of all transcatheter implants), with much smaller contributions from Starflex (4.7%), Occlutech (3.7%), CardioSEAL (2.6%), Helex (2.9%), and Angelwing (2.3%). Use of other devices was uncommon or not reported.

Risk of Bias Assessment

Newcastle–Ottawa Scale scores ranged from 6 to 9. Twelve studies (33%) achieved high quality (≥7 points), while the remainder were of moderate quality. The most common limitation was lack of a concurrent control group, which affected comparability. A detailed summary of NOS assessment is provided in Supplementary Table 4.

Procedural Success

The pooled procedural success rate for ASD closure without major complications was 95% (95% CI: 92%-97%; I^2 = 90.2%). To better quantify expected effect variability across future studies, a prediction interval (0.55-1.00) was calculated, indicating a wide range of possible true effects and reflecting substantial clinical heterogeneity among included cohorts. Leave-one-out sensitivity analysis (sequential exclusion of each study) demonstrated stability of the pooled procedural success estimate. Sequential removal of individual studies produced changes of ≤0.85% in the pooled estimate, with no single study altering the direction or magnitude meaningfully. These results are reported in Supplementary Table 5.

Baujat analysis identified 2 studies, Meyer et al[9] and Marini et al[34], as the largest contributors to statistical heterogeneity while also exerting notable influence on the pooled success estimate. Several other studies, including Esraa, Formigari, and Martins, contributed moderate variability, whereas most remaining cohorts showed minimal impact on heterogeneity or the overall pooled effect. These findings are shown in Supplementary Figure 1.

In children, the raw procedural success rates were 87.3% (1445/1656) for transcatheter closure and 99.0% (505/510) for surgical closure (Table 3). The pooled meta-analytic model estimated success at 93% and 97%, respectively; differences reflect study weighting and between-study variance.

Device generation likely contributed to outcome variability. Early cohorts predominantly used first-generation Amplatzer/AGA devices, while more recent studies increasingly employed Occlutech and CERA systems, which may offer improved deployment control and stability. In the surgical group, outcomes represented a combination of sternotomy and minimally invasive approaches, although most studies did not report these separately, limiting direct comparison of technique-specific morbidity.

Cumulative meta-analysis of transcatheter procedures (studies added chronologically by publication year) showed

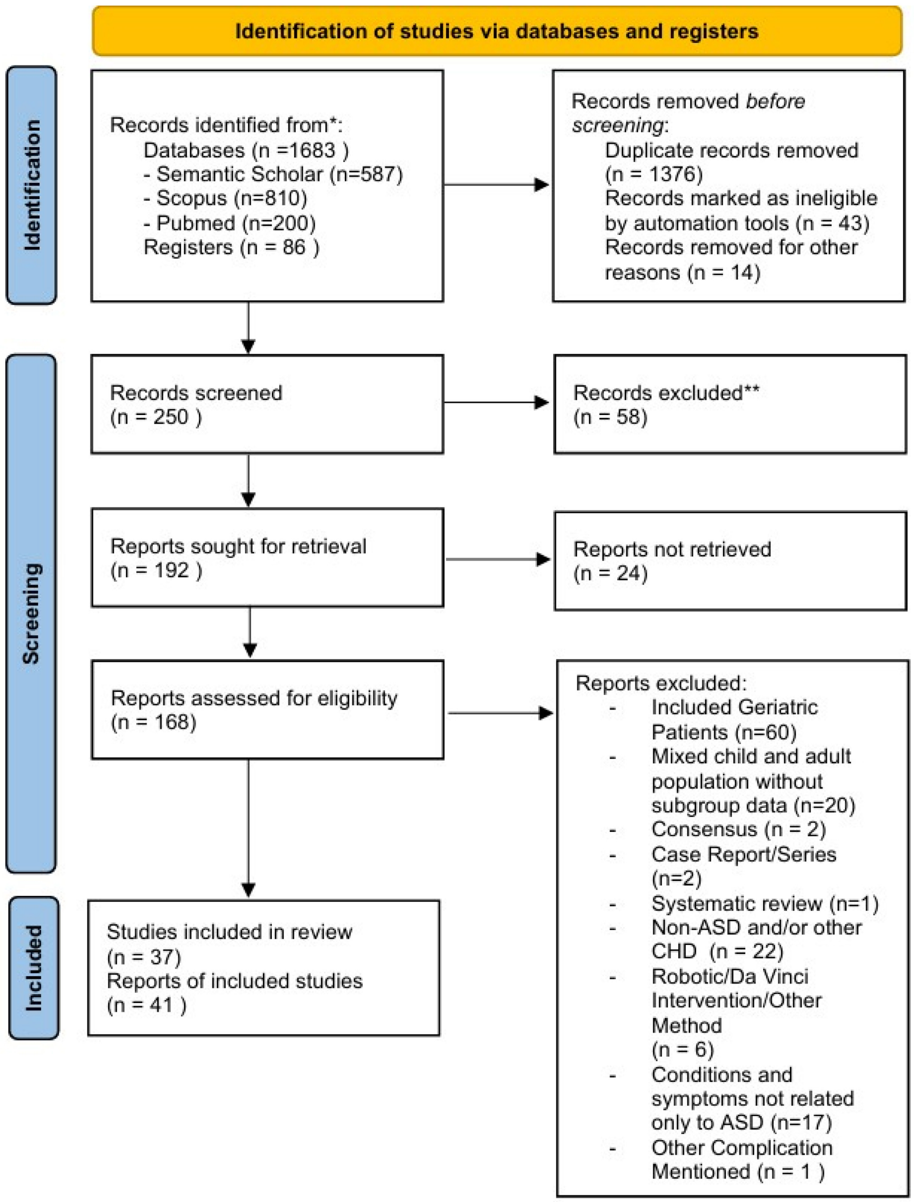

Figure 1. PRISMA 2020 flow diagram of study selection.

early variability in pooled success rates with progressive stabilization after 2008. At the most recent cumulative step (including studies up to 2022), the pooled transcatheter success proportion was 0.788 (95% CI: 0.771-0.805). Supplementary Figure 2 provide the full cumulative plot.

Procedural Characteristics

Transcatheter closure demonstrated shorter procedure duration compared with surgery (adults: 43.2 ± 11.9 minutes vs 89.8 ± 32.6 minutes; children: 70.7 ± 37.2 minutes vs 83.2 ± 55.0 minutes; both $P < .001$). Hospital stay was also significantly shorter (mean difference: −3.86 days; 95% CI: −6.03 to −1.69; $P = .0004$). Fluoroscopy time averaged 12.0 ± 3.6 minutes in adults and 19.3 ± 34.5 minutes in children, although pediatric comparison was limited due to fewer surgical comparators. These findings are displayed in Figure 2.

Complications During Procedure

Transcatheter closure had lower intra-procedural complication rates.

Among children, the most frequent events were residual shunt (1.8%), arrhythmia (1.2%), and device embolization (1.0%). In adults, device embolization (1.3%) and arrhythmia (1.6%) were most commonly reported. Surgical closure was associated with higher rates of pleural effusion (0.7%), pericardial effusion (2.1%), pulmonary edema (1.1%), and shock (3.9%). Full complication distribution is summarized in Table 3 and visualized in Figure 3.

Complications on Follow-Up

During follow-up, residual shunt was observed in 4.6% of children and 7.2% of adults following transcatheter closure, compared with 1.7% in surgically treated children. Arrhythmia was lower after transcatheter closure versus surgery (0.7%

Table 1. Characteristics of Included Studies

Author	Year	Country	Design	Transcatheter (n)	Surgical/Open thoracostomy (n)	Population	Age Population
Yew et al	2004	Auckland, New Zealand	Retrospective cohort	25	NA	25	Children
Rossi et al	2007	Porto Alegre-RS, Brazil	Retrospective cohort	27	NA	27	Children
Gildein et al	1997	Freiburg, Germany	Prospective cohort	3	NA	7	Children
Çeliker et al	2005	Ankara, Türkiye	Retrospective cohort	80	NA	99	Children
Fraisse et al	2008	France	Retrospective cohort	35	NA	35	Children
Russell et al	2002	Canada	Retrospective cohort	NA	43	44	Children
Han et al	2020	China	Comparative cohort	86	NA	186	Children
Ammar et al	2013	Egypt	Prospective cohort	17	NA	17	Children
Smith et al	2008	English	Retrospective cohort	33	NA	33	Children
Zhang et al	2007	China	Comparative cohort	NA	10	12	Children
Tuzcu et al	2004	Germany	Retrospective cohort	65	NA	129	Children
Esraa et al	2020	Egypt	Retrospective cohort	65	NA	67	Children
Lu et al	2022	China	Prospective cohort	11	NA	11	Children
Liao et al	2023	China	Retrospective cohort	NA	NA	24	Children
Costa et al[8]	2013	Brazil	Comparative cohort	75	105	180	Children
Sharfi et al	2018	Saudi Arabia	Case - control	44	NA	44	Children
Ali et al	2014	Egypt	Retrospective cohort	24	NA	24	Children
Formigari et al	2001	Dallas, USA	Comparative cohort	54	NA	57	Children
Marini et al	2012	Paris, France	Prospective cohort	47	NA	50	Children
Bolz et al	2005	Basel, Switzerland	Retrospective cohort	NA	135	135	Children
Fischer et al	1999	Germany	Prospective cohort	30	50	80	Children
Thomson et al	2002	UK	Prospective cohort	24	19	46	Children
Hughes et al	2002	Australia	Prospective cohort	43	19	62	Children
Vida et al	2006	Guatemala	Comparative cohort	72	28	111	Children
Cardenas et al	2007	Belgia	Retrospective cohort	49	NA	52	Children
Huang et al	2008	China	Prospective cohort	58	NA	63	Children
Sahin et al	2011	NA	Prospective cohort	40	NA	40	Children
Yuan et al	2012	China	Prospective cohort	61	NA	61	Children
Sagar et al	2022	India	Comparative cohort	25	NA	25	Adult
Doğan et al	2024	Türkiye	Retrospective cohort	319	NA	323	Children
Marini et al	2007	Paris, France	Prospective cohort	51	NA	51	Children
Zheng et al	2014	China	Comparative cohort	NA	507	508	Adult
Lee et al	2017	South Korea	Prospective cohort	52	14	66	Adult
Meyer et al[9]	2016	Switzerland	Comparative cohort	99	NA	107	Adult
Świątkiewicz et al	2022	Poland	Comparative cohort	182	NA	184	Adult
English et al[5]	2025	England	National cohort	NA	1181	1346	Adult

NA = data not available (information not reported or not retrievable from the original study).

Table 2. Baseline Demographics and Defect Characteristics of Patients Undergoing Transcatheter and Surgical Closure

Age (Years)	Transcatheter (Mean ± SD)	Surgical (Mean ± SD)	*P*
Adult	33.67 ± 6.14 (n = 5625)	31.36 ± 10.6 (n = 2632)	<.001
Child	3.69 ± 3.73 (n = 1389)	4.03 ± 1.99 (n = 603)	.035
Gender (male)			
Adult	n = 1939	n = 1865	<.001
Child	n = 1298	n = 588	.056
Weight (kg)			
Adult	45.70 ± 15.7 (n = 254)	52.4 ± 13.85 (n = 508)	<.001
Child	22.57 ± 8.74 (n = 1352)	14.6 ± 3.8 (n = 416)	<.001

vs. 5.8% in children). Late device-related complications such as embolization were rare (0.2%-0.8%). Surgical follow-up complications included heart failure (1.9%) and renal failure (0.5%). Complete outcome data are provided in Table 4 and Figure 4.

Sensitivity Analysis

Sensitivity analysis restricted to 12 high-quality studies (NOS ≥ 7) yielded similar results to the primary analysis, reinforcing robustness. Corresponding forest plots are shown in Supplementary Figure 3.

Publication Bias

Funnel plot distribution appeared largely symmetrical, and Egger's regression test showed no significant small study effects ($P = .069$), although minor asymmetry suggests publication bias cannot be fully excluded.

DISCUSSION

Principal Findings

This systematic review and meta-analysis of 36 observational studies involving more than 12 thousand patients provides updated comparative evidence for transcatheter and surgical ASD closure. Both approaches demonstrated very high procedural success, consistently above 95%. Transcatheter closure resulted in shorter hospital stays, shorter procedure duration, and lower complication rates, particularly in children. Surgical closure remained effective and continues to be the preferred option for patients with large defects, deficient rims, or anatomical variants that are not suitable for device placement.

Many factors caused the wide differences between studies. Centers used different device generations, starting from early Amplatzer and AGA devices and later moving to Occlutech and CERA models. Operators also became more skilled over time, so older studies often reflect early learning periods while newer studies show more stable practice. Each center also used different rules for choosing which patients were suitable for device closure, which changed the types of defects included. The length of follow-up and the way outcomes were defined also varied a lot. Some studies reported only events during the hospital stay, while others followed patients for months or years. Practice patterns also differed across countries, including the type of device used, the style of care, and whether surgeons preferred a small chest cut or a full chest opening. All these differences created the large variation seen in the results, and readers should keep this in mind when interpreting the pooled findings. Cumulative meta-analysis suggests that pooled transcatheter success rates became more consistent after 2008, supporting the hypothesis that improvements in device generation and growing operator experience contributed to more reliable procedural outcomes.

Prediction intervals are wider than CIs and reflect the expected range of effects in a new study; the wide prediction intervals that were observed indicate that effects may differ substantially between settings, underscoring caution when applying pooled estimates to individual centers.

Baujat influence analysis further demonstrated that heterogeneity in transcatheter success was disproportionately driven by a small subset of studies, particularly Meyer and Marini (2007), which deviated more prominently from the pooled effect relative to the larger evidence base. These cohorts likely reflect differences in operator experience, device era, anatomical case selection, or institutional technical protocol during earlier adoption phases. The concentration of heterogeneity within only a few influential studies indicates that the majority of included cohorts cluster closely around the pooled effect, supporting the robustness of the overall estimate despite substantial I^2.

These variations collectively contribute to the high heterogeneity, and they should be considered carefully when interpreting the pooled effect estimates. Leave-one-out analysis confirmed that the pooled procedural success estimate was robust; no individual study exerted a dominant influence on the overall result.

This finding increases confidence that the observed heterogeneity reflects between-study clinical and methodological variation rather than outlier-driven distortion. In addition to high I^2 values, prediction interval analysis further supported

Table 3. Procedural Success Rates Stratified by Age Group and Closure Type

General Characteristic Associated with Surgical and Transcatheter Defect Closure

	Children		Adults		
	Transcatheter, n (%)	Surgical, n (%)	Transcatheter, n (%)	Surgical, n (%)	*P*
Procedural success* rate, n/total (%)	1445/1656 (87.25)	505/510 (99.0)	351/361 (97.2)	1702/1868 (91.1)	<.001
Devices used in successful procedures, n	1445	505	351	1702	

*Success was defined as complete closure without major peri-procedural complications, based on the standardized operational definition applied in this review.

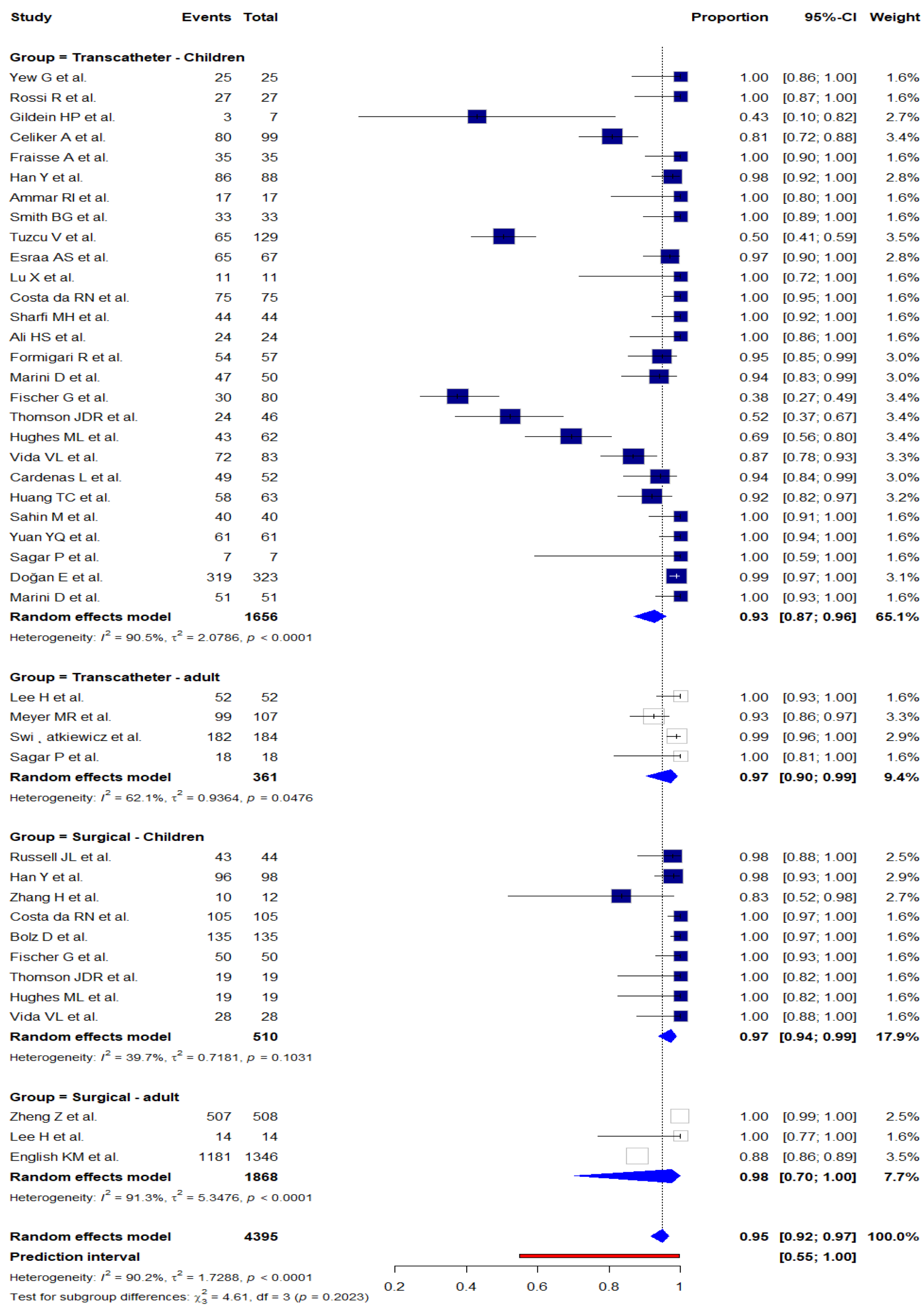

Figure 2. Forest plot of procedural success rate by subgroup (children vs. adults).

the presence of real-world variability. For procedural success, the prediction interval ranged from 0.55 to 1.00, indicating that while the pooled success rate was high, true effects in future clinical settings may lie anywhere within this broader distribution.

This implies that although most centers achieve excellent results, outcomes may differ depending on device generation, operator familiarity, anatomical complexity, and periprocedural protocol differences, consistent with the clinical heterogeneity described above. Incorporating prediction intervals therefore improves interpretability and provides a more clinically realistic expectation range beyond the conventional pooled estimate.

Variation in the definition of procedural success across studies also contributes to inconsistency in the pooled estimates. Some investigators defined success based solely on successful device placement, while others required the absence of complications or complete closure on imaging. A single operational definition was applied to harmonize reporting, but the lack of uniform criteria across studies limits the ability to perform sensitivity analyses with consistent definitions. This limitation should be considered when the results are interpreted.

Variation in follow-up duration across studies also affects the interpretation of late outcomes such as arrhythmia and residual shunt. Some investigators reported outcomes

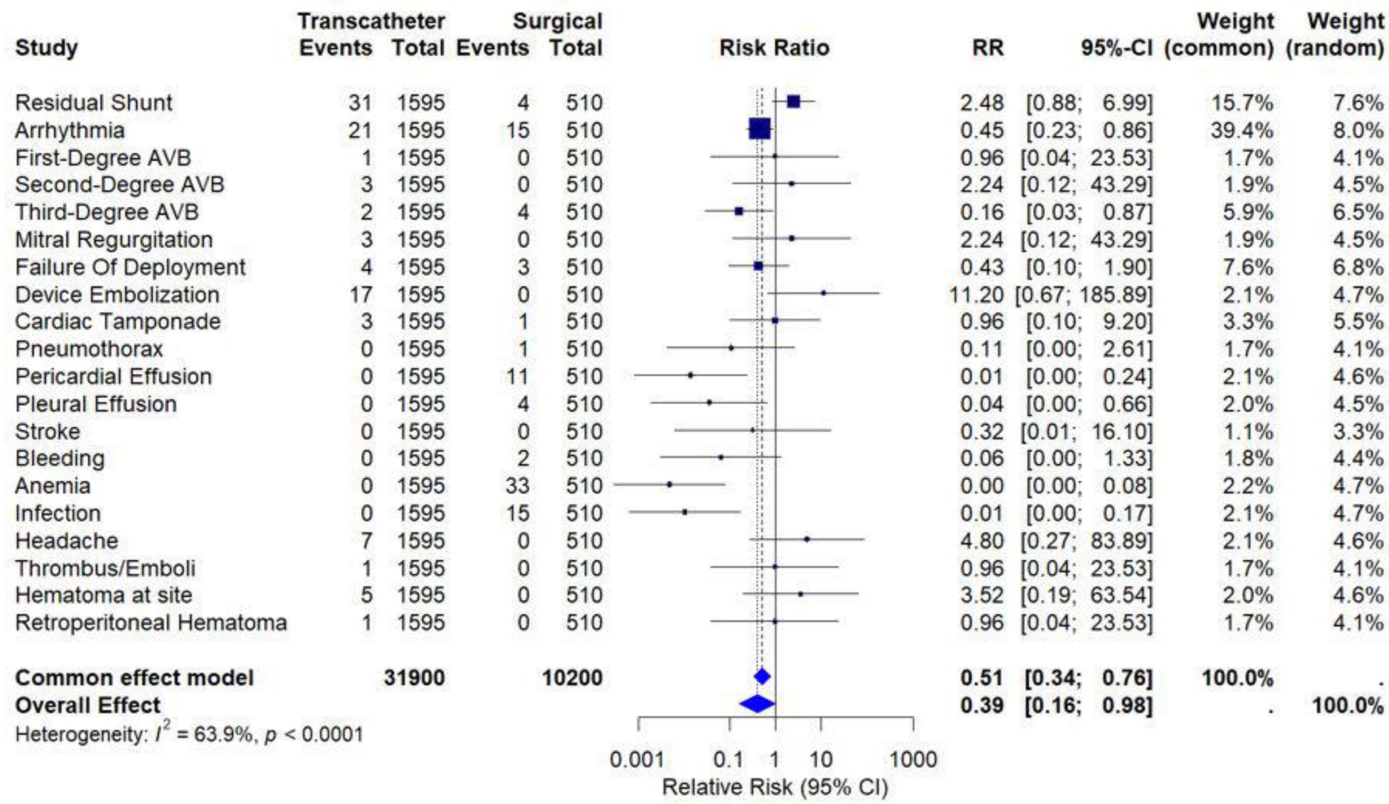

Figure 3. Forest plot of complications during procedure (transcatheter vs. surgical). Squares represent the effect size of each study; horizontal lines represent 95% CI; diamond indicates pooled effect. Complications include arrhythmia, pericardial effusion, pleural effusion, pulmonary edema, device embolization, and procedure-related shock. RR, risk ratio.

within the first year while others included longer-term evaluations, which introduces inconsistency in the time frames represented in the pooled estimates. Because only a small number of studies reported outcomes at uniform intervals, stratified analyses could not be performed based on predefined follow-up lengths. As a result, the pooled findings reflect aggregated data from heterogeneous follow-up periods, and this should be considered when comparing late outcomes between transcatheter and surgical closure.

Assessment of publication bias showed no statistical evidence of small study effects because the Egger regression test did not demonstrate significant asymmetry. However, the test had limited power because several pooled outcomes included a small number of studies. Funnel plots for the major outcomes are provided in the supplementary material to enhance transparency and allow visual inspection of plot symmetry.

Differences in device design may also contribute to variation in procedural complexity and clinical outcomes. Most transcatheter studies used the Amplatzer septal occluder while others used Occlutech, CERA, or related double disk devices. Earlier generation devices tended to be stiffer or bulkier, whereas newer systems provide improved flexibility and more controlled deployment, which may reduce complications in anatomically challenging defects. Although the present analysis was not powered to compare individual device types, variation in device characteristics and generational improvements should be considered when interpreting pooled estimates from transcatheter closure cohorts. In the surgical group, several studies combined conventional sternotomy with minimally invasive thoracotomy approaches. Because the number of studies reporting minimally invasive techniques was limited and reporting formats were inconsistent, these approaches were pooled with standard surgery for quantitative analysis. This pooling may shorten length of stay or influence complication rates in some cohorts and represents an additional source of clinical variation across studies.

Comparison with Previous Evidence

Our findings align with earlier systematic reviews that demonstrated the non-inferiority of transcatheter closure compared with surgery in terms of success rates and safety.[6] Xu et al[1] confirmed the superiority of transcatheter closure for children secundum ASDs with fewer complications and faster recovery. Similarly, national registry data demonstrated favorable long-term outcomes with transcatheter techniques, though residual shunts occurred more frequently compared with surgery.[7] In contrast, surgical closure continues to show excellent durability and remains the preferred approach in complex anatomy or large defects not amenable to transcatheter closure.[9] Furthermore, a recent *Anatolian Journal of Cardiology* case report highlighted successful transcatheter ASD closure in patients with challenging

Table 4. Complications During Procedure and Follow-Up (Transcatheter Vs. Surgical)

Complications During Procedure Associated with Surgical and Transcatheter closure

	Children		Adults	
Complication	**Transcatheter, n (%)**	**Surgical, n (%)**	**Transcatheter, n (%)**	**Surgical, n (%)**
Residual shunt	31 (1.8)	4 (0.7)	NR	NR
Arrhythmia*	21 (1.2)	15 (2.9)	6 (1.6)	NR
First-degree Atrioventricular Block	1 (0.0)	NR	NR	NR
Second-degree Atrioventricular Block	3 (0.1)	NR	NR	NR
Third-degree Atrioventricular Block	2 (0.1)	4 (0.7)	NR	NR
Mitral regurgitation	3 (0.1)	NR	NR	NR
Tricuspid regurgitation	NR	NR	NR	NR
Failure of deployment†	4 (0.2)	3 (0.5)	2 (0.5)	2 (0.1)
Device embolization	17 (1.0)	NR	5 (1.3)	NR
SVC stenosis	NR	1 (0.1)	NR	NR
Stroke	NR	NR	NR	NR
Transient ischemic attack	NR	NR	NR	NR
Pericardial effusion	NR	11 (2.1)	NR	NR
Pleural effusion	NR	4 (0.7)	NR	NR
Cardiac tamponade	3 (0.1)	1 (0.1)	NR	NR
Pneumothorax	NR	1 (0.1)	NR	2 (0.1)
Pulmonary edema	NR	6 (1.1)	NR	NR
Pneumonia	NR	NR	NR	NR
AV fistula	NR	NR	NR	NR
Thrombus/Emboli	1 (0.0)	NR	NR	NR
Hematoma at site	5 (0.3)	NR	NR	NR
Retroperitoneal Hematoma	1 (0.0)	NR	NR	NR
Bleeding	NR	2 (0.3)	3 (0.8)	NR
Anemia	NR	33 (6.4)	NR	NR
Fever	NR	NR	NR	NR
Headache	7 (0.4)	NR	NR	NR
Hypertension	NR	NR	NR	NR
Infection	NR	15 (2.9)	NR	NR
Reintubation	NR	NR	NR	2 (0.1)
Reoperation	NR	NR	NR	2 (0.1)
Shock	NR	20 (3.9)	NR	NR
Acute kidney injury	NR	NR	NR	NR
Acute decompensated heart failure	NR	NR	1 (0.2)	NR
Increase length of stay	NR	NR	NR	NR
Cosmesis	NR	NR	NR	1 (0.0)
Death	NR	NR	1 (0.2)	5 (0.2)

NR, not reported. Absence of reporting does not indicate absence of events; cells with NR reflect studies that did not provide data for that specific outcome.
*Arrhythmia includes atrial fibrillation, supraventricular tachycardia, and non-specific conduction abnormalities as reported in individual studies.
†Failure of deployment refers to unsuccessful device positioning requiring retrieval or conversion to surgery.

venous anatomy, illustrating the expanding applicability of transcatheter closure in complex clinical scenarios.[15,16]

Children Versus Adult Considerations

Age subgroup analyses revealed clinically meaningful differences. In children, transcatheter closure reduced arrhythmia, bleeding, and pleural complications compared with surgical closure, supporting its role as first-line therapy when anatomy is favorable.[1,4] In adults, both approaches achieved high success, but surgery was more often associated with pulmonary edema and longer recovery. Conversely, adults undergoing transcatheter closure faced slightly higher risks of late residual shunt, which requires long-term echocardiographic monitoring.[7,9]

Clinical Implications

These findings emphasize that treatment strategy should be individualized. Transcatheter closure offers clear

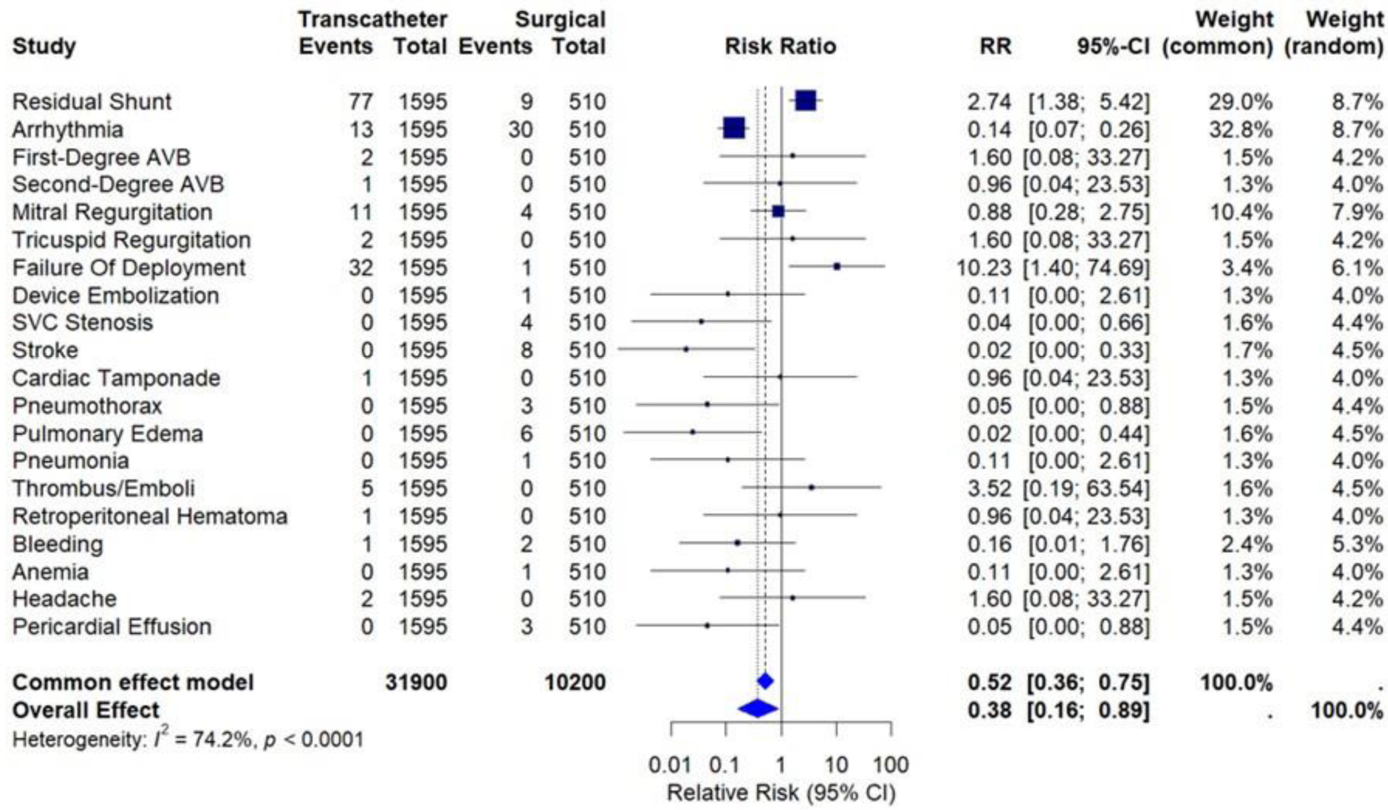

Figure 4. Forest plot of complications during follow-up (transcatheter vs surgical). Squares represent the effect size of each study; horizontal lines represent 95% CI; diamond indicates pooled effect. RR, risk ratio.

advantages in terms of safety, recovery, and patient quality of life, particularly in younger patients. However, surgical closure remains critical for patients with very large defects, deficient septal rims, or concomitant cardiac anomalies requiring repair. The procedural decision should therefore integrate patient age, anatomy, comorbidities, and institutional expertise.

Strengths and Limitations

The main strengths of this meta-analysis include a large pooled sample size, adherence to PRISMA 2020 guidelines,[10] a prospectively registered protocol in PROSPERO (CRD420251052612) that reduces the risk of selective reporting bias, and comprehensive subgroup analyses stratified by age and procedure type. Sensitivity analysis restricted to high-quality studies further confirmed the robustness of the findings. To enhance transparency, the certainty of evidence was assessed using the GRADE approach, which demonstrated moderate certainty for procedural success, peri-procedural complications, hospital stay, and procedure time, whereas outcomes with low event rates or inconsistent follow-up yielded lower certainty ratings.

However, several limitations should be acknowledged. All included studies were observational, which may introduce confounding. Heterogeneity across studies was substantial, reflecting differences in patient selection, operator experience, and device evolution. Because surgical cohorts frequently reported longer follow-up than transcatheter cohorts, the higher rate of some late complications after surgery may partly reflect longer observation time rather than a true difference in per-time risk. Long-term data beyond 10 years remain limited, particularly for device closure, which precludes definitive conclusions on durability. Outcomes between minimally invasive thoracotomy and conventional sternotomy could not be differentiated because most surgical studies did not stratify results by operative technique, which restricts interpretation of the relative morbidity of modern surgical approaches. Egger's regression did not show statistically significant small study effects (P = .069), although the borderline value and asymmetry on visual inspection suggest that publication bias cannot be entirely excluded.

Future Directions

Future research should prioritize high-quality prospective comparative studies, particularly in adults with complex anatomy. Long-term durability data for transcatheter device closure remain limited, particularly regarding late adverse events such as device erosion, arrhythmia, and right ventricular dysfunction. Future work should therefore include long-duration registries and surveillance to better characterize late risk profiles.

Both transcatheter and surgical closure of ASDs are highly effective. Transcatheter closure offers advantages of shorter recovery and fewer complications, supporting its preferential use in anatomically suitable patients, whereas surgery remains essential for complex cases. Individualized treatment planning that incorporates patient-specific and anatomical factors is paramount to optimize outcomes.

Ethics Committee Approval: This study was approved by the Health Research Ethics Committee of Universitas Sumatera Utara, Ministry of Education, Culture, Research, and Technology, Indonesia (Approval No.: 157/KEPK/USU/2024; Date: July 6, 2025).

Informed Consent: Informed consent was not required as this study was a systematic review and meta-analysis based exclusively on previously published data and did not involve direct patient contact.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept and design were performed by J.K. and P.A.; supervision by P.A.; resources by P.A., A.D.R., and G.H.H.A.S.; materials by P.A.; data collection and/or processing by J.K., A.D.R., and G.H.H.A.S.; analysis and/or interpretation by J.K. and P.A.; literature search by P.A.; writing by J.K., A.D.R., G.H.H.A.S., and P.A.; and critical review by P.A., A.D.R., and G.H.H.A.S.

Acknowledgments: The authors would like to acknowledge the Library of Universitas Sumatera Utara for their support.

Declaration of Interests: The authors declare that none of them is a member of the Editorial Board or Advisory Board of the journal.

Funding: The authors declare that this study received no financial support.

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Supplementary Table 1. Device type distribution in transcatheter closure

Device type used in successful procedures, n (%)

	Children		Adults	
	Transcatheter, n(%)	**Surgical, n(%)**	**Transcatheter, n(%)**	**Surgical, n(%)**
AGA	1268	NR	104	NR
CARDIOSEAL / CARDIO-O-FIX	46	12	NR	NR
STARFLEX	82	NR	NR	NR
Buttoned	7	NR	NR	NR
ANGELWING	40	NR	NR	NR
HELEX	50	NR	1	NR
OCCLUTECH / FIGGULA	53	NR	12	NR
MEMOPART	NR	NR	NR	NR
CERA / CSO	NR	NR	NR	NR
CRIBIFORM	2	NR	9	NR
BIOSTAR	NR	NR	NR	NR
COCOON	NR	NR	NR	NR
CARDIASTAR	NR	NR	NR	NR
LIFETECH	NR	NR	NR	NR
LONGZHOUFEDU	NR	NR	NR	NR
SOLYSAFE	2	NR	11	NR
PERICARDIAL PATCH (DACRON & BOVINE)	NR	70	52	NR
DIRECT SURTURE	NR	18	NR	522
SHANGHAI SHAPE MEMORY	NR	98	NR	NR

NR = not reported. Absence of reporting does not indicate absence of events; cells with NR reflect studies that did not provide data for that specific outcome. Device abbreviations: AGA = Amplatzer/AGA septal occlude, CERA = CeraFlex septal occlude, HELEX = Gore HELEX septal occlude, Occlutech = Occlutech Figulla septal occlude

Supplementary Table 2. Device size/diameter used across studies

Device diameter used in successful procedures, mm					
Children			Adults		
Transcatheter, n(%)	**Surgical, n(%)**	**P-value**	**Transcatheter, n(%)**	**Surgical, n(%)**	***P*-value**
20.09 (11.4-40.0)	21.73 (12.0-35.0)	0.839	24.1 (16.3-30.0)	25.8*	>0.99

*Device diameter for adults in the surgical group corresponds to intraoperative patch sizing, not device implantation.

Supplementary Table 3. GRADE Summary of Findings: Transcatheter versus Surgical ASD Closure

Outcome	Effect (Summary)	No of Studies	Certainty of Evidence (GRADE)	Rationale
Procedural success	Both procedures showed very high success (>95%). TC 93–97%; Surgery 97–98%.	36	●●●○ **Moderate**	Observational evidence; large consistent effect; downgraded for study design.
Major procedural complications	TC reduces complications compared with surgery (RR ≈ 0.58).	28	●●○○ **Low**	Observational studies, heterogeneity, risk of confounding.
Hospital stay	TC reduces length of stay by ~3.9 days (MD −3.86 days).	16	●●●○ **Moderate**	Consistent direction of effect; downgraded due to inconsistency.
Procedure time	TC significantly shorter procedure time (adults: −46 mins; children: −12 mins).	12	●●●○ **Moderate**	Observational studies; moderate heterogeneity.
Arrhythmia (procedural)	Lower in TC group (children 1.2% vs surgery higher).	20	●●○○ **Low**	Event rates low; risk of underreporting; observational.
Residual shunt (follow-up)	More common in TC (adults: 7.2%) than surgery.	22	●●○○ **Low**	Outcome definitions vary; follow-up duration inconsistent.
Device embolization	Rare in TC (0.2–1.3%).	18	●●○○ **Low**	Very low event rate; imprecision; observational.
Mortality (short-term/ long-term)	Extremely low in both groups (<1%).	10	●●○○ **Low**	Rare events; imprecision; observational data only.

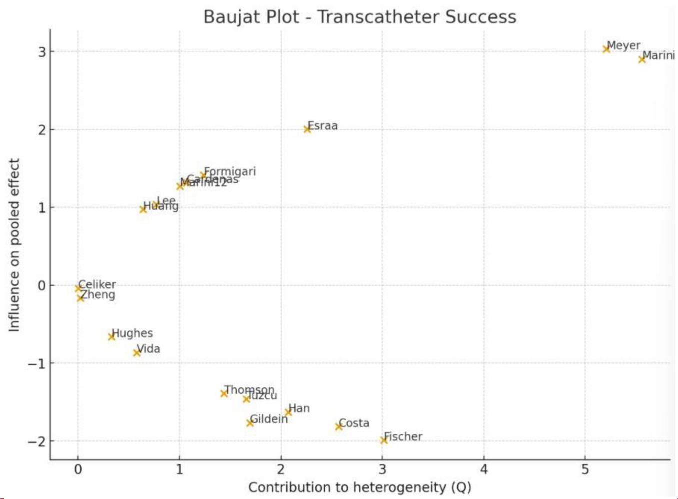
Supplementary Table 4. Newcastle–Ottawa Scale (NOS) risk of bias assessment of included studies

No	Study (Author, Year)	Study Design	Selection (4)	Comparability (2)	Outcome (3)	Total Score
1	Fraisse 2008	Retrospective cohort	3	0	3	6
2	Çeliker 2005	Retrospective cohort	3	0	3	6
3	Gildein 1997	Prospective cohort	3	0	3	6
4	Rossi 2008	Retrospective cohort	3	0	3	6
5	Yew 2005	Retrospective cohort	3	0	3	6
6	Russell 2002	Retrospective cohort	3	0	3	6
7	Han 2020	Comparative cohort	4	2	3	9
8	Ammar 2013	Prospective cohort	3	0	3	6
9	Zhang 2007	Comparative cohort	4	2	3	9
10	Smith 2008	Retrospective cohort	3	0	3	6
11	Tuzcu 2004	Retrospective cohort	3	0	3	6
12	Lu 2022	Prospective cohort	3	0	3	6
13	Liao 2023	Retrospective cohort	3	0	3	6
14	Costa 2013	Comparative cohort	4	2	3	9
15	Sharfi 2019	Case Control	4	2	3	9
16	Ali 2014	Restrospective cohort	3	0	3	6
17	Formigari 2001	Comparative cohort	4	2	3	9
18	Marini 2012 (MSCT)	Prospective cohort	3	0	3	6
19	Bolz 2005	Restrospective cohort	3	0	3	6
20	Fischer 1999	Prospective cohort	3	0	3	6
21	Thomson 2002	Comparative cohort	4	2	3	9
22	Hughes 2002	Comparative cohort	4	2	3	9
23	Vida 2006	Comparative cohort	4	2	3	9
24	Cardenas 2007	Restrospective cohort	3	0	3	6
25	Huang 2008	Prospective cohort	3	0	3	6
26	Sahin 2011	Prospective cohort	3	0	3	6
27	Yuan 2012	Prospective cohort	3	0	3	6
28	Sagar 2022	Comparative cohort	4	2	3	9
29	Doğan 2024	Restrospective cohort	3	0	3	6
30	Marini 2012 (echo)	Prospective cohort	3	0	3	6
31	Zheng 2014	Comparative cohort	4	2	3	9
32	Esraa 2020	Prospective cohort	3	0	3	6
33	Lee 2017	Prospective cohort	3	0	3	6
34	Świątkiewicz 2022	Comparative cohort	4	2	3	9
35	English 2024	National Cohort	4	2	3	9
36	Meyer 2016	Comparative cohort	4	2	3	9

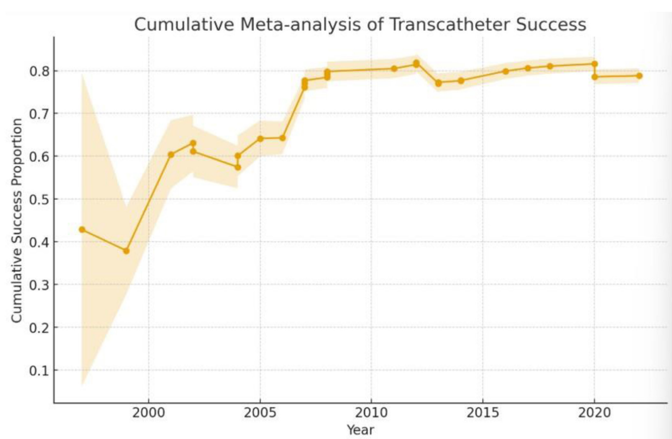
Supplementary Table 5. Leave-one-out sensitivity analysis for pooled procedural success rates comparing transcatheter versus surgical ASD closure

Study removed	Pooled proportion	95% CI	Δ change	Tau^2	Q
Yew G et al.	0.894	0.849–0.940	−0.003	2.044	805.41
Rossi R et al.	0.891	0.845–0.938	−0.006	2.036	799.72
Gildein HP et al.	0.892	0.847–0.939	−0.005	2.039	802.11
Çeliker A et al.	0.894	0.849–0.940	−0.003	2.042	803.98
Fraisse A et al.	0.896	0.851–0.941	−0.001	2.047	807.61
Russell JL (surg)	0.892	0.847–0.940	−0.005	2.039	801.35
Russell JL (TC)	0.892	0.847–0.938	−0.005	2.038	801.87
Han Y et al.	0.895	0.850–0.940	−0.002	2.041	802.99
Ammar RI et al.	0.893	0.848–0.939	−0.004	2.041	802.51
Smith BG et al.	0.894	0.849–0.940	−0.003	2.044	805.41
Zhang H et al.	0.893	0.847–0.938	−0.004	2.037	800.72
Tuzcu V et al.	0.893	0.847–0.938	−0.004	2.038	801.26
Esraa AS et al.	0.893	0.848–0.939	−0.004	2.040	803.07
Lu X et al.	0.893	0.848–0.939	−0.004	2.041	804.55
Liao LC (TC)	0.894	0.849–0.940	−0.003	2.044	806.79
Liao LC (surg)	0.894	0.849–0.940	−0.003	2.044	806.97
Costa RN (TC)	0.894	0.849–0.939	−0.003	2.042	804.50
Costa RN (surg)	0.895	0.850–0.940	−0.002	2.039	802.10
Sharfi MH et al.	0.894	0.848–0.939	−0.003	2.040	802.94
Ali HS et al.	0.894	0.849–0.940	−0.003	2.043	805.94
Formigari R et al.	0.894	0.849–0.940	−0.003	2.043	805.88
Marini D (child)	0.893	0.848–0.939	−0.004	2.041	804.39
Bolz D et al.	0.893	0.848–0.939	−0.004	2.041	804.43
Fischer (TC)	0.894	0.849–0.939	−0.003	2.042	804.91
Fischer (Surg)	0.894	0.849–0.940	−0.003	2.043	805.52
Thomson (TC)	0.893	0.848–0.939	−0.004	2.041	804.39
Thomson (Surg)	0.894	0.849–0.940	−0.003	2.042	804.83
Hughes (TC)	0.894	0.849–0.940	−0.003	2.043	806.20
Hughes (Surg)	0.894	0.849–0.940	−0.003	2.042	805.15
Vida (TC)	0.894	0.849–0.940	−0.003	2.043	806.01
Vida (Surg)	0.894	0.849–0.939	−0.003	2.042	805.15
Cardenas L et al.	0.894	0.849–0.940	−0.003	2.043	804.88
Huang TC et al.	0.894	0.849–0.940	−0.003	2.043	805.41
Sahin M et al.	0.893	0.848–0.938	−0.004	2.042	805.07
Yuan YQ et al.	0.893	0.848–0.939	−0.004	2.041	804.66
Sagar P et al.	0.896	0.851–0.941	−0.001	2.047	807.91
Doğan	0.893	0.847–0.939	−0.004	2.037	800.57
Marini D (adult surg)	0.892	0.846–0.938	−0.005	2.035	799.09
Zheng Z (TC)	0.895	0.850–0.940	−0.002	2.041	804.28
Zheng Z (surg)	0.895	0.850–0.940	−0.002	2.041	804.10
Lee H (TC)	0.895	0.850–0.940	−0.002	2.040	803.99
Lee H (surg)	0.894	0.849–0.939	−0.003	2.039	803.26
Meyer MR et al.	0.894	0.849–0.940	−0.003	2.044	806.77
Świątkiewicz	0.893	0.847–0.939	−0.004	2.037	801.69
English	0.892	0.846–0.938	−0.005	2.034	799.40

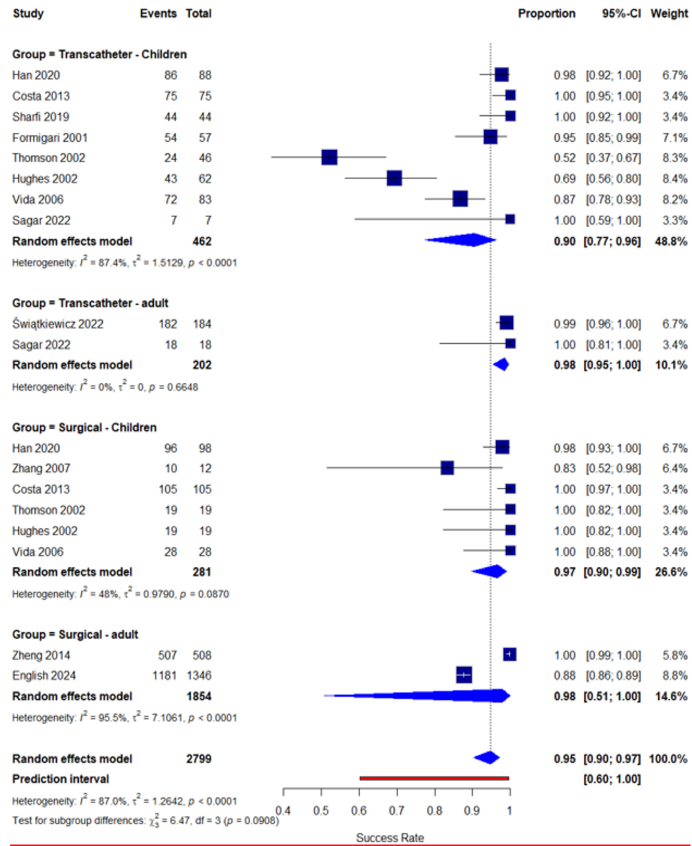
Each iteration reflects the pooled proportional success rate after removing 1 study at a time. Minimal variation was observed across all iterations (Δ ≤ 0.85%), indicating that no individual study exerted disproportionate influence on the summary effect estimate.



Supplementary Figure 1. Baujat plot showing each study's contribution to heterogeneity (x-axis, Q statistic) and influence on the pooled transcatheter success estimate (y-axis). Meyer and Marini were the most influential studies, contributing disproportionately to between-study variability, while most other cohorts showed minimal impact on heterogeneity and pooled effect size.



Supplementary Figure 2. Cumulative meta-analysis of transcatheter procedural success. Pooled proportion (points) and 95% CI (vertical bars) after sequential addition of studies by publication year. Stabilization of estimates is apparent after 2008.



Supplementary Figure 3. Sensitivity analysis restricted to high-quality studies (NOS ≥7).