



Contemporary practice patterns and outcomes of isolated tricuspid valve surgery in North America: systematic review with meta-analysis

Timothy Lee[^], Sooyun Caroline Tavalacci, Percy Boateng, Ahmed El-Eshmawi

Department of Cardiovascular Surgery, Icahn School of Medicine at Mount Sinai, New York, NY, USA

Correspondence to: Ahmed El-Eshmawi, MD. Department of Cardiovascular Surgery, Icahn School of Medicine at Mount Sinai, 1190 Fifth Ave., New York, NY 10029, USA. Email: Ahmed.El-Eshmawi@MountSinai.org.

Background: Management of isolated tricuspid valve surgery has evolved over recent decades with respect to operative timing, surgical strategy, and perioperative care. However, a contemporary synthesis of North American outcomes and practice patterns is lacking.

Methods: We performed a systematic review and meta-analysis of studies published between January 1, 2020, and August 30, 2025, reporting outcomes of isolated tricuspid valve surgery in North America. Outcomes assessed included operative mortality, temporal volume trends, repair *vs.* replacement outcomes, beating-heart techniques, and results from high-volume centers. Institutional outcomes were also reviewed.

Results: Twelve studies met the inclusion criteria. Operative mortality ranged from 5% to 8% in national cohorts and was approximately 2% at reference centers, with a declining trend over time. Mortality was lower among endocarditis patients as well as patients with better functional status and normal right ventricular function. Procedure volumes peaked around 2017 and have since plateaued or modestly declined, coinciding with increased use of transcatheter therapies. At Mount Sinai Hospital, 107 patients underwent isolated tricuspid valve surgery since 2014; 46% were reoperations, 54% were performed on a beating heart, 34% underwent repair, and in-hospital mortality was 1.9%. In the pooled meta-analysis of contemporary North American studies, operative mortality following isolated tricuspid valve surgery was 6.4% [95% confidence interval (CI): 4.9–8.3%], with significantly lower mortality observed with tricuspid valve repair (TVr) compared with tricuspid valve replacement (TVR) [odds ratio (OR) =0.74; 95% CI: 0.58–0.95]. In addition, pooled meta-analysis showed that TVr was associated with a significantly reduced risk of new permanent pacemaker (PPM) implantation (OR =0.39; 95% CI: 0.32–0.47).

Conclusions: Isolated tricuspid valve surgery is increasingly safe, especially among high-volume centers and carefully selected patients. Annual case volumes seem to have plateaued, likely due to the growing application of transcatheter therapies.

Keywords: Tricuspid valve; tricuspid valve replacement (TVR); tricuspid valve repair (TVr)



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[^] ORCID: 0000-0002-3165-2816.

Introduction

Historically, the tricuspid valve was referred to as “forgotten” due to a perception of infrequent pathology and low clinical impact (1-3). However, contemporary studies show that tricuspid regurgitation affects two million individuals in the United States (4), while any degree of regurgitation is associated with increased mortality (5-7). This highlights the need for timely referral and appropriate management (8).

A modern focus on isolated tricuspid surgery intensified in the early 2010s. Multiple retrospective United States national database and single-centered studies reported increasing volume of isolated tricuspid surgery, with a mortality rate of 8–14% (9-12), far higher than that following concomitant tricuspid or isolated mitral or aortic operations (13). Accordingly, publications proposed earlier intervention before end-organ dysfunction to improve outcomes (12,14-16). The impact of these studies on recent practice patterns and survival rates is unknown.

We therefore performed a contemporary systematic review and meta-analysis of isolated tricuspid surgery in North America, evaluating contemporary practice patterns, operative outcomes, and comparative results of tricuspid repair *vs.* replacement, supplemented by a contemporary institutional perspective on perioperative management and outcomes.

Methods

This study was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and the Meta-Analysis of Observational Studies in Epidemiology (MOOSE) reporting guidelines (17,18).

Literature search strategy and eligibility criteria

A systematic literature search was performed in PubMed and EMBASE for studies published from January 1, 2020, to August 30, 2025. Although studies were limited to contemporary publications, several included cohorts contained operative periods extending beyond ten years before publication because of the limited availability of North American isolated tricuspid valve surgery data. The inclusion criteria were: (I) studies reporting outcomes of isolated tricuspid repair and replacement in North America; and (II) studies reporting outcomes of isolated tricuspid surgery as a sub-group. The exclusion criteria were: (I)

studies including only congenital cases; (II) studies involving only major concomitant heart surgery, specifically valve surgery, coronary artery bypass grafting, or implantation of a ventricular assist device; (III) studies including only tricuspid valve replacement (TVR); and (IV) studies with patients treated outside of North America.

Data extraction and critical appraisal

Two reviewers (T.L. and S.C.T.) independently searched the electronic databases. Titles and abstracts were screened to exclude non-relevant studies; subsequently, the full text of the remaining studies was reviewed. Risk of bias was assessed using the Risk of Bias in Non-Randomized Studies of Interventions (ROBINS-I) tool (19). Discrepancies were resolved through discussion with a senior reviewer (A.E.E.).

Outcome measures

The primary endpoint was early mortality, defined as death occurring during the index hospitalization or within 30 days of tricuspid valve surgery. Secondary endpoints included new permanent pacemaker (PPM) implantation and perioperative complications (including stroke, arrhythmias or cardiac complications, acute renal failure or dialysis requirement, infective endocarditis, thromboembolic events, cerebrovascular events, hemorrhagic complications, reoperation, deep sternal wound infection, respiratory complications), and length of stay. Long-term outcomes included 1-, 5-, and 10-year survival.

Statistical analysis

Operative mortality and the incidence of new PPM implantation were defined as the primary and secondary endpoints, respectively, for the meta-analysis. Pooled incidence rates were estimated using logit-transformed random-effects meta-analyses of proportions. Statistical heterogeneity was assessed using the I^2 statistic and Cochran's Q test. I^2 values of approximately 25%, 50%, and 75% were considered to represent low, moderate, and high heterogeneity, respectively. Given the anticipated clinical and methodological heterogeneity across studies, random-effects models were used for all primary analyses (20). Between-study variance (τ^2) was estimated using the maximum likelihood method, and results were back-transformed to proportions with corresponding 95% confidence intervals (CIs). Proportions were pooled using

a logit-transformed random-effects model with maximum likelihood estimation of between-study variance.

Comparative analyses between tricuspid valve repair (TVr) and TVR were performed using random-effects models to calculate odds ratios (ORs) with 95% CIs based on the inverse-variance method.

Given potential overlap between institutional cohorts and patients included in large administrative database studies, complete de-duplication of study populations could not be guaranteed. To address this limitation, sensitivity analyses stratified by study design (large administrative database *vs.* institutional/single-center studies) were performed, and subgroup interaction testing was used to assess consistency of effect estimates across study types.

Forest plots were used to display individual study estimates and pooled effects. A two-sided P value <0.05 was considered statistically significant. All analyses were performed using RStudio (version 2026.01.1) with the meta package.

Mount Sinai retrospective review

We also conducted a retrospective analysis of adult patients who underwent isolated tricuspid repair or replacement at Mount Sinai Hospital between 2014 and 2025 to reflect our contemporary institutional experience. Patients with congenital etiology, concomitant major cardiac surgery including valve, aortic, or coronary artery bypass procedures, and prior cardiac transplantation were excluded. The study was approved by the Icahn School of Medicine Institutional Review Board (No. STUDY-25-01090).

Results

The study selection process is illustrated in the PRISMA flow diagram (Figure S1). A total of seven large database studies (Table 1) and five center-level studies (Table 2) met the inclusion criteria. No randomized controlled trials evaluating isolated tricuspid valve surgery were identified. Risk of bias assessment is available in Figure S2.

Society of Thoracic Surgeons (STS) database

Two recent reports utilizing the STS Adult Cardiac Surgery Database (ACSD) provide an overview of contemporary isolated tricuspid surgery in North America.

In 2023, Chen *et al.* published a study of 14,704 patients who underwent isolated tricuspid surgery between 2011

and 2020 (26). Annual case volume more than doubled during the study period, from 983 in 2012 to 2,155 in 2019. Procedures were performed at 967 hospitals, for a median annual volume of two, with 93% of hospitals performing five or fewer cases per year. A final cohort of 6,507 patients was selected after applying exclusion criteria of tricuspid stenosis, emergency status and endocarditis. The mean age was 65 years, 40% were New York Heart Association (NYHA) functional class III/IV, and 24% of operations were non-elective. Operative mortality was 7.3%, with risk factors for mortality being patient age, non-elective operations, NYHA functional class III/IV, chronic lung disease, atrial fibrillation, tricuspid replacement, Model for End-Stage Liver Disease (MELD) score >10, and annual center volume ≤5 cases. Among a subcohort of 869 patients who were NYHA functional class I/II with a MELD score <10 undergoing elective surgery, operative mortality was 1.7%. The pacemaker rate was 10.8%. TVR was performed in 49% of cases (94% receiving a bioprosthesis) and replacement was associated with higher risk-adjusted mortality and major comorbidities. Beating-heart surgery was utilized in 37% of patients and, when compared to cardioplegic arrest, was associated with similar mortality but lower risk-adjusted complications including PPM, renal failure, and blood transfusions.

Published 1 year later in 2024, Thourani *et al.* identified patients undergoing isolated tricuspid repair or replacement from 2017 to 2023, as part of an effort to develop an STS tricuspid surgery risk model (23). Exclusion criteria included unknown 30-day mortality status, prior tricuspid valve prosthesis, or prior transcatheter tricuspid interventions. Patients undergoing concomitant left atrial appendage closure, ablation, closure of atrial septal defect, or patent foramen ovale closure were included. Annual case volume decreased throughout the study period, from 2,492 cases in 2018 to 2,035 cases in 2022, for a reduction of 18%. The final cohort was 13,587 patients with a mean age of 43 years, endocarditis etiology in 36% of patients and 41% undergoing tricuspid repair. The operative mortality was 5.6%, with no difference following repair (5.4%) or replacement (5.7%). The stroke rate was 1.4%, reoperation rate was 8.0%, and the rate of mortality or morbidity was 28%. All outcomes improved during the study period, including operative mortality, stroke, renal failure, reoperation, prolonged ventilation, and length of stay. Compared to patients without endocarditis, patients with endocarditis were younger and had lower mortality after both tricuspid repair (2.7% with endocarditis *vs.* 6.2%

Table 1 Outcomes of isolated tricuspid valve surgery in large database studies

Study [year]	Database	Number of patients	Year of surgery	Etiology of TR, n (%)	Age (years), mean \pm SD or median [IQR]	Female	Previous cardiac surgery	NYHA class III/IV	Liver disease	TVr/TVR, n (%)	Operative mortality	New pacemaker	Perioperative outcome, n (%) or median [IQR]
Nammalwar <i>et al.</i> (21) [2025]	California State Admissions Database	2,597	1991–2020	IE 611 (23.5%), congenital 299 (11.5%)	TVr 53.5 \pm 18.5, TVR 54.5 \pm 17.7	57.7%	26.4%	CHF 65.9%	38.0%	TVr 1,599 (61.6%), TVR 998 (38.4%)	9.1% {10.4% [1991–2000], 8.7% [2001–2010], 6.9% [2011–2020]}	22.3%	Stroke 32 (1.2%), Afib 456 (17.6%), ARF 610 (23.5%), dialysis 179 (6.9%), IE 114 (4.4%)
Ng <i>et al.</i> (22) [2025]	NIS	9,990	2016–2021	Non-rheumatic (33.1%)	57 [38–70]	59.0%	6.3%	CHF 59.9%	13.7%	TVr (50.9%), TVR (49.1%)	4.7%	10.4%	Complication of cardiac 19.3%, renal 26.3%, respiratory 16.6%, infectious 9.3%, thromboembolic 5.6%, cerebrovascular 0.5%, hemorrhagic 4.1%, LOS 9 [6–16] days
Thourani <i>et al.</i> (23) [2024]	STS ACSD database	13,587	2017–2023	IE 4,831 (35.6%), tricuspid stenosis 716 (5.3%)	48.3 \pm 18.4	56.4%	27.3%	HF 19.8%	34.1%	TVr 5,583 (41.1%), TVR 8,004 (58.9%)	5.6%	–	Stroke 197 (1.4%), renal failure 928 (6.8%), prolonged ventilation 2,884 (21.2%), reoperation 1,083 (8%), DSWI 79 (0.6%), prolonged LOS >14 days 4,908 (36.1%), short LOS <6 days 2,368 (17.4%)
Shimoda <i>et al.</i> (24) [2024]	Centers for Medicare & Medicaid Services	1,501	2016–2020	Rheumatic disease 522 (34.8%), IE 52 (3.5%), TVr 74 [69.5–78], pacemaker/ICD leads 260 (17.3%)	TVR 75 [70–79]	59.0%	26.7%	CHF 88.7%	22.1%	TVr 891 (59.4%), TVR 610 (40.6%)	12.1%	19.3%	AKI 487 (32.4%), cardiogenic shock 233 (15.5%), respiratory 164 (10.9%), hemorrhage 71 (4.7%)
Chavez-Ponce <i>et al.</i> (25) [2024]	Vizient Clinical Data Base	4,753	2016–2021	IE and/or congenital were excluded	55.1 \pm 16.4	50.3%	–	–	–	TVr (49.4%), TVR (39.2%)	7.3%	–	–
Chen <i>et al.</i> (26) [2023]	STS ACSD database	6,507	2011–2020	Functional 52.1%, degenerative 12.8%, pacing wire/catheter 9.8%, congenital 7.1%, failed previous tricuspid intervention 5.4%. IE were excluded	65 [52–74]	61.5%	41.3%	40%	14.5%	TVr 3,308 (50.8%), TVR 3,199 (49.2%)	7.3%	10.8%	Composite major complications 2,082 (32%), permanent stroke 100 (1.5%), prolonged ventilation 1,315 (20.2%), reoperation 281 (4.3%), new dialysis requirement 359 (5.5%), DSWI 28 (0.4%), LOS 8 [6–12] days
Alqahtani <i>et al.</i> (27) [2022]	National Readmission Database	1,153	2016–2017	–	55.7 \pm 16.6	49.6%	–	Chronic HF 70.5%	16.8%	TVr (63.5%), TVR (36.5%)	8.7%	9.5%	Stroke 2.1%, AKI 41.3%, new dialysis 4.2%, blood transfusion 24.3%, vascular complication 6.7%, tamponade 4.3%, MI 1.8%, GI bleed 4.5%, prolonged mechanical ventilation 20.2%, tracheostomy 7.1%, LOS 14 [7–35], LOS >5 days 84.7%

ACSD, Adult Cardiac Surgery Database; Afib, atrial fibrillation; AKI, acute kidney injury; ARF, acute renal failure; CHF, congestive heart failure; DSWI, deep sternal wound infection; GI, gastrointestinal; HF, heart failure; ICD, implantable cardioverter-defibrillator; IE, infective endocarditis; IQR, interquartile range; LOS, length of stay; MI, myocardial infarction; NIS, National Inpatient Sample; NYHA, New York Heart Association; SD, standard deviation; STS, Society of Thoracic Surgeons; TR, tricuspid regurgitation; TVr, tricuspid valve repair; TVR, tricuspid valve replacement.

Table 2 Outcomes of isolated tricuspid valve surgery in center-level studies

Study	Center	Number of patients	Year of surgery	History/etiology of TR, n (%)	Functional, n (%)	Age (years), mean ± SD or median [IQR]	Female	Previous cardiac surgery	NYHA class III/IV, % or mean ± SD	Liver disease, % or mean ± SD	TVr/TVR, n (%)	Median follow-up (years), mean ± SD or median [IQR]	Operative mortality	New pacemaker	Perioperative outcome, n (%), mean ± SD, or median [IQR]	1-year survival, n (%)	5-year survival, n (%)	10-year survival, n (%)
Bhasin <i>et al.</i> (28) [2025]	University of Chicago Medicine	14	2014–2024	–	–	–	–	–	–	–	–	–	7.1%	14%	AKI 1 (7%), ECMO 2 (14%), reoperation for bleeding 2 (14%), pleural effusion 1 (7%), tracheostomy 1 (7%), CVA/TIA 0 (0%), Afib 0 (0%), ICU LOS 1.8±1.5 days, hospital LOS 3.5±2.7 days	–	–	–
Shih <i>et al.</i> (29) [2023]	Baylor College of Medicine	173	2007–2021	IE 24 (13.9%), rheumatic (7.5%), traumatic 9 (5.2%), pacing wire-induced 28 (16.2%), failure of previous TVS 7 (4.1%)	80 (46.2%)	60.3±18.9	68.2%	52.6%	29.5%	Tbil 0.9±0.6 mg/dL	TVr 103 (60%); TVR 70 (40%)	2.0 [0.6–4.4]	6.5% (TVr 5.9% vs. TVR 7.4%, P=0.72)	21.6% (TVr 12.4% vs. TVR 35.6%, P<0.01)	Stroke 2 (1.2%), new dialysis 9 (5.2%)	78%	65% (TVr 70% vs. TVR 55%, P=0.02)	58%
Wang <i>et al.</i> (30) [2023]	Cleveland Clinic	159	2004–2018	Past IE 13 (8.2%), rheumatic heart disease 2 (1.3%)	92 (57.9%)	59.7±15.6	57.2%	40.9%	2.0±1.1	Cirrhosis 8.2%	TVr 119 (74.8%); TVR 40 (25.2%)	5.1±4.0	5.1% (class I 7% vs. early surgery 0%)	–	Composite morbidity 49 (30.8%), stroke 1 (0.6%), AKI 35 (22%), ventilation >24 h 33 (20.8%), DSWI 1 (0.6%), return to operating room 13 (8.2%)	88.6% (class I vs. early surgery 100%)	80.3% (class I vs. early surgery 91.4%)	73.7% (class I vs. early surgery 84.7%)
Lawlor <i>et al.</i> (31) [2022]	Columbia University	58	2008–2021	–	41 (75.9%)	67.5 [58–74]	63.8%	62.1%	68.4%	Cirrhosis 10.3%	TVr 14 (24.1%); TVR 44 (75.9%)	–	19%	10.3%	SCAI shock D/E 26 (44.8%), RRT 10 (17.2%), major bleeding 7 (12.1%), stroke 0 (0%), MI 0 (0%), mechanical ventilation 1.5 [1–4] days, ICU LOS 5 [3–14] days	–	–	–
Patlolla <i>et al.</i> (32) [2021]	Mayo Clinic	223	2001–2017	Primary 39 (17.5%), pacemaker/ICD wire 49 (17.9%), carcinoid 8 (3.6%), IE 4 (1.8%)	144 (64.6%)	67.3±13.7	56.5%	61.4%	77.9%	7.6%	TVr 60 (26.9%); TVR 163 (73.1%)	9.5 [3.6–12.9]	2.7% (TVr 1.7% vs. TVR 3.1%)	4.5%	RVAD 1 (0.4%), reoperation for bleeding 13 (5.9%), new Afib 7 (6.8%), LOS 7 [5–10] days	82% (TVr 87% vs. TVR 81%)	61% (TVr 75% vs. TVR 57%)	32% (TVr 47% vs. TVR 26%)

Afib, atrial fibrillation; AKI, acute kidney injury; CVA, cerebrovascular accident; DSWI, deep sternal wound infection; ECMO, extracorporeal membrane oxygenation; ICD, implantable cardioverter-defibrillator; ICU, intensive care unit; IE, infective endocarditis; IQR, interquartile range; LOS, length of stay; MI, myocardial infarction; NYHA, New York Heart Association; RRT, renal replacement therapy; RVAD, right ventricular assist device; SCAI, Society for Cardiovascular Angiography and Interventions; SD, standard deviation; Tbil, total bilirubin; TIA, transient ischemic attack; TR, tricuspid regurgitation; TVr, tricuspid valve repair; TVR, tricuspid valve replacement; TVS, tricuspid valve surgery.

without endocarditis) and tricuspid replacement (4.1% with endocarditis *vs.* 7.1% without endocarditis).

From these two complementary studies, several key narratives arise. First, after having undergone a significant period of growth through the early 2010s, the volume of isolated tricuspid surgery appears to have plateaued in the late 2010s. Second, operative mortality nationwide has improved significantly, now in the range of 5–7%, and declines to less than 2% among patients without heart failure or liver disease. Third, operative mortality and morbidity following repair *vs.* replacement were not consistently different. It is not clear why beating heart surgery was found to have inferior unadjusted but superior risk-adjusted outcomes in the analysis by Chen *et al.*, with possible explanations including operator experience or selection bias. Fourth, endocarditis is the etiology of one-third of isolated tricuspid cases, though these patients are younger and healthier with superior outcomes to non-endocarditis cohorts. Fifth, isolated tricuspid surgeries are relatively rare, with a median annual hospital volume of two cases. The fact that patients treated at hospitals with an annual volume of at least five cases enjoyed better mortality is not surprising and supports the concept of centers of excellence in tricuspid management (1).

Additional national and state databases

Four studies of different national databases (22,25,27,33) and one statewide analysis (34) provide additional details to the STS findings.

A study of the National Inpatient Sample (NIS) published in 2025 looked at trends in tricuspid surgery in the United States between 2016 and 2021 (22). The total volume of isolated tricuspid cases was 9,990. The case volume increased from 2016 to 2017 but is stable thereafter. In-hospital mortality following isolated tricuspid surgery among a non-endocarditis cohort was 4.7%.

Alqahtani *et al.* published an analysis of the National Readmission Database from 2016 to 2017 (27). They found 1,153 isolated tricuspid surgery patients with an in-hospital mortality of 8.7%. The authors compared isolated tricuspid surgery to isolated mitral surgery in terms of preoperative risk and perioperative mortality. Isolated tricuspid patients were sicker, with a higher prevalence of acute heart failure (41% *vs.* 22%), advanced liver disease (17% *vs.* 3%), non-elective surgery (44% *vs.* 24%), pre-operative mechanical support (28% *vs.* 5%) and unplanned admissions within 90 days preoperatively (31% *vs.* 19%). The in-hospital

mortality rate following isolated tricuspid surgery was three times higher than following isolated mitral valve surgery. However, after adjustment they found no difference in mortality.

The Vizient Clinical Data Base was queried to identify 4,753 isolated tricuspid surgery patients operated between 2016 and 2021, excluding endocarditis and congenital etiologies (it is unclear whether transcatheter therapies were included) (25). As a note, this new industry-compiled database has been utilized in limited publications, and little information is available on its completeness. There was no change in the annual case volume of isolated tricuspid surgery. In-hospital mortality was 7.3% and significantly decreased during the study period, from 8.3% in 2016 to 5.7% in 2021. The risk profile of patients was quantified using the Charlson comorbidity index (33,34), which has been found to be predictive of post-cardiac surgery outcomes in other studies, and was found to be a significant predictor of mortality in this study. During the study period, the average Charlson comorbidity index of patients decreased from 3.2 in 2016 to 2.6 in 2021. The authors conclude that the temporal improvement in surgical outcomes is due to a healthier patient population, possibly due to referral of sicker patients for transcatheter therapy.

The Centers for Medicare and Medicaid Services database was utilized to conduct an analysis of isolated tricuspid repair *vs.* replacement among patients aged ≥ 65 years who underwent surgery between 2016 and 2020 (24). Among a propensity-matched cohort of 547 pairs, the median age was 75 years. There were no differences in hospital mortality (13%), 3-year overall mortality (39%), or 3-year major adverse events (46%).

Finally, Nammalwar *et al.* studied a California administrative database of 3,706 patients operated on between 1991 and 2020, with the aim of comparing outcomes of isolated tricuspid repair and replacement (21). From this initial cohort they utilized 25 baseline characteristics to produce 789 propensity-matched pairs. Operative mortality declined significantly during the study period among the overall cohort, from 10.4% between 1991 and 2000, to 8.7% between 2001 and 2010, to 6.9% between 2011 and 2020. They found no difference in operative mortality following repair and replacement among the overall cohort (8.2% *vs.* 9.9%) and matched pairs (6.3% *vs.* 7.4%). Pacemaker rates were higher after replacement (14% *vs.* 32%). At 25 years, tricuspid repair was associated with significantly decreased mortality (58% *vs.* 66%) and rates of reoperation (6% *vs.* 11%).

The above studies support and build upon findings from the STS database in the following ways. The volume of isolated tricuspid surgery plateaued during the study period around 2017. Operative mortality rates were consistent with those found in the STS database, and rates have steadily decreased over the past decade. The study by Chavez-Ponce *et al.* provides evidence that the improved outcomes are attributable to a lower-risk patient population (25). Finally, isolated tricuspid repair and replacement do not appear to differ in near-term follow-up; however, a long-term difference favoring repair may be attributable to different baseline patient risk, or an actual treatment effect which was only observed with a large patient population and very long-term (25 years) follow-up.

Reference centers

Only one single-center study included a cohort of patients primarily operated on within the past 10 years (Table 2) (28). The team at the University of Chicago reported outcomes of 14 isolated tricuspid surgeries from 2014 to 2024, all of which were performed with robotic assistance using a totally endoscopic technique. There was one in-hospital mortality (7%), no conversions to sternotomy, and discharge after a mean of 3.5 hospital days.

Four reference centers—the Cleveland Clinic (30), Mayo Clinic (32), Columbia University (31), and Baylor College of Medicine (29)—have recently published their institutions' case series on isolated tricuspid surgery, though most patients underwent surgery prior to 2015. Cohorts ranged in size from 50 to 250 patients. The operative mortality following isolated tricuspid surgery in these series primarily ranged from 2.7% to 6.5%, except for the Columbia series (31) which reported a 19% in-hospital mortality attributed by the authors to an older cohort with a higher prevalence of prior cardiac surgery and severe right ventricular remodeling. The Cleveland Clinic group reported an operative mortality of 5.1%, which decreased to 0% among a sub-cohort of patients with asymptomatic severe tricuspid regurgitation without right ventricular dilatation or dysfunction (30). A study from Michigan reported results of 250 isolated and concomitant TVRs from 2000 to 2023, with an operative mortality of 6.8%, though outcomes were not stratified by isolated *vs.* concomitant tricuspid surgery (35).

Together, these studies show excellent early and near-term outcomes achievable at reference centers, where patient selection and perioperative management are likely to be optimized. Additional earlier publications from the same

groups are not cited. Briefly, few studies reported long-term outcomes, with 1-year survival ranging from 78% to 89%. Reported 5- and 10-year survival rates varied across studies, ranging from 61% to 80% at 5 years and from 32% to 74% at 10 years.

Mount Sinai

Preoperative evaluation

At the Icahn School of Medicine at Mount Sinai, patients with isolated tricuspid disease undergo comprehensive assessment and rigorous perioperative optimization (Table 3). This begins with an initial work-up including transthoracic echocardiogram, transesophageal echocardiogram if transthoracic echocardiogram is insufficient or to help rule out other valve pathology (e.g., mitral valve disease), computed tomography (CT) of the chest with or without contrast, coronary imaging with coronary CT angiogram or catheter-based coronary angiogram, and right heart catheterization for hemodynamic assessment. Further evaluation of tricuspid regurgitation and right ventricular function is rarely required but may be obtained by cardiac magnetic resonance imaging (MRI). Liver work-up includes liver ultrasound, calculation of MELD and Child-Pugh scores, and consultation with the liver medicine team; additional studies are indicated for fibrosis or cirrhosis and include MRI abdomen and/or right heart catheterization with liver biopsy and transhepatic wedge pressure measurement. Any patient with a history of gastrointestinal (GI) bleeding should obtain a gastroenterology consultation, with colonoscopy for lower GI bleeding or esophagogastroduodenoscopy for a history of upper GI bleeding or esophageal varices. Patients with thrombocytopenia or an elevated international normalized ratio require hematology consultation to exclude co-existing hematologic abnormalities. Electrophysiology consultation is obtained for patients with an existing implantable electronic device (IED), preoperative rhythm abnormalities, high risk of conduction block, or likely tricuspid replacement. An algorithm for the removal of prior IEDs and placement of new pacemaker leads is shown (Figure 1), with the majority of new pacemaker devices being intraoperative leadless pacemakers (36). Other multidisciplinary evaluations are guided by concomitant comorbidities, such as neurologic, pulmonary, or renal disease.

Patients are optimized preoperatively with guideline-directed medical therapy including inotropes and diuretics,

Table 3 Mount Sinai Hospital perioperative workup and management protocol for patients with isolated tricuspid valve disease

Organ system	Multidisciplinary evaluation/management	Parameters
Cardiac evaluation	Transthoracic echocardiogram	Assess TR severity, RV size, or function
	Transesophageal echocardiogram [†]	Evaluate leaflet anatomy and exclude concomitant valve disease
	CT chest	Assess aortic calcification/preoperative anatomy
	Coronary imaging	Evaluate coronary artery disease
	Right heart catheterization	Assess pulmonary pressures and cardiac output
	Cardiac MRI [†]	Quantify RV function and TR severity
	Electrophysiology consultation [†]	Assess conduction disease/device strategy
	Heart failure consultation [†]	
Hemodynamic optimization	Inotropic support [†]	Optimize cardiac output and RV function
	Milrinone if normotensive/hypertensive	
	Dopamine if hypotensive or bradycardic	
	Volume optimization	Achieve euvolemia and reduce venous congestion
	Diuresis	
	Renal replacement therapy [†] (UF, CVVH, iHD)	
	Rhythm optimization	Maintain hemodynamic stability and atrioventricular synchrony
	Rate control	
Extracardiac assessment	Carotid ultrasound	Assess carotid stenosis
	Pulmonary evaluation	Assess pulmonary disease and operative pulmonary risk
	Nutritional evaluation and support [†] (enteral or parenteral)	Assess frailty/malnutrition
	Physical and occupational evaluation and therapy	Assess functional reserve
	Additional consultations and investigations as needed [†]	Evaluate patient-specific comorbidities and operative candidacy
Hepatic evaluation	MELD score	Estimate hepatic dysfunction operative risk
	Liver ultrasound	Evaluate congestion/cirrhosis
	CT abdomen [†]	Evaluate hepatic morphology, ascites, and portal hypertension
	MRI liver [†]	Further characterize hepatic fibrosis/cirrhosis
	Right heart catheterization with hepatic wedge measurement and/or liver biopsy [†]	Assess advanced fibrosis/cirrhosis

[†], obtained as-needed. CT, computed tomography; CVVH, continuous venous-venous hemofiltration; iHD, intermittent hemodialysis; MELD, Model for End-Stage Liver Disease; MRI, magnetic resonance imaging; RV, right ventricle; TR, tricuspid regurgitation; UF, ultrafiltration.

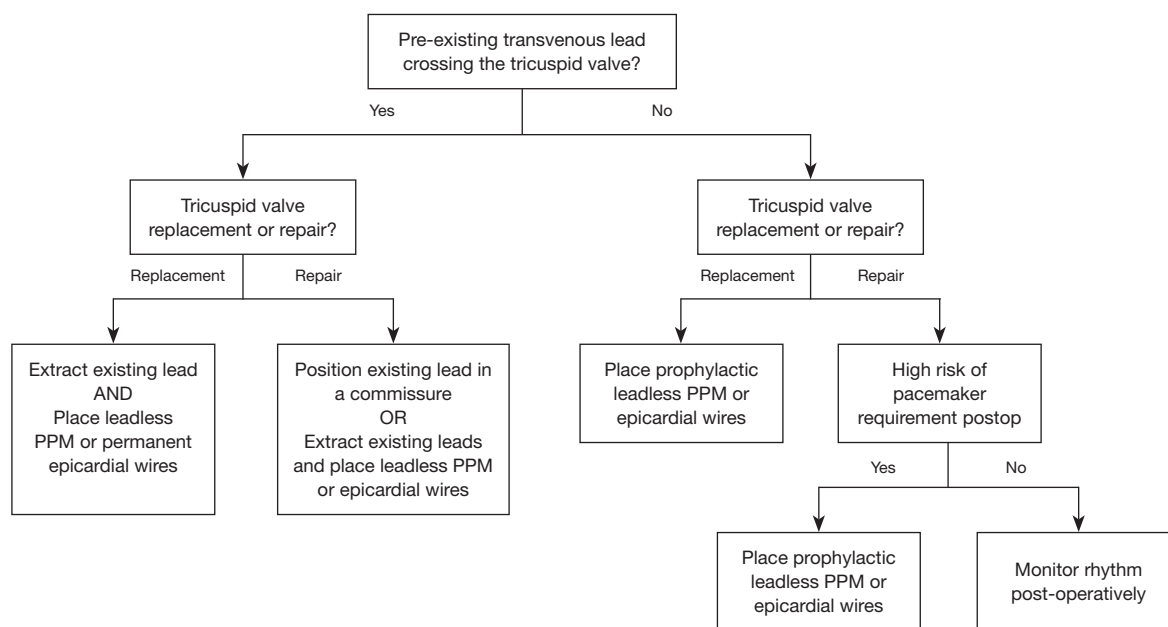


Figure 1 Mount Sinai Hospital algorithm for intraoperative pacemaker implantation. PPM, permanent pacemaker.

often in consultation with heart failure specialists. Milrinone is our preferred inotropic agent, with dopamine used in patients who are hypotensive or bradycardic. Occasionally, renal replacement therapy is initiated in patients with advanced chronic kidney disease (e.g., stage IV) who are not anuric. Once the patient is euvolemic, we may obtain a right heart catheterization several days prior to surgery to assess volume status and cardiac index; these findings may trigger an increase in medical therapy and a delay in the operative date should additional optimization be required.

Intraoperative strategy

The decision to operate is dependent on all of the above work-up. The patient and all of their organs must be able to tolerate surgery and the post-operative recovery. Our standard intraoperative approach is a median sternotomy for both primary surgeries and reoperations, with a right thoracotomy reserved for hostile aortas. A beating heart technique is used for patients with poor right ventricular function, with repairs and replacements both feasible. Valve repairs are performed preferentially over replacements (37) and typically this is completed with a semi-rigid incomplete ring. Valve replacements are generally performed with porcine bioprostheses. For patients with right ventricular dysfunction, inotropes are prophylactically started intraoperatively in all cases, with multiple inotropes and/or inhaled nitric oxide utilized in cases of severe dysfunction.

Postoperative management

Postoperatively, patients undergoing both repair and replacement are placed on aspirin 81 mg and oral anticoagulation starting on post-operative day one for a period of at least 3 months. Inotropes are weaned slowly, depending on the degree of ventricular dysfunction and the need to support diuresis. A pre-discharge transthoracic echocardiogram is obtained in all patients once the patient is close to euvolemic.

A comprehensive publication of Mount Sinai Hospital's outcomes following isolated tricuspid surgery is forthcoming, though we will briefly review them here. From July 2014 to August 2025, we identified 107 isolated tricuspid surgeries, of which 49 (46%) were reoperations. The procedure was performed on a beating heart in 58 (54%) patients, with 36 (34%) patients undergoing repair. In-hospital mortality occurred in two (1.9%) patients, with intraoperative pacemaker placement in 44 (41%) cases.

Meta-analysis: operative mortality

Across 13 studies including 41,177 patients and 2,558 events, the pooled operative mortality of isolated tricuspid valve surgery was 6.4% (random-effects: 6.4%; 95% CI: 4.9–8.3%), with substantial heterogeneity ($I^2=94%$, $\tau^2=0.054$) (Figure 2A). In subgroup analyses, pooled mortality was 7.1% (95% CI: 5.7–8.7%) among large

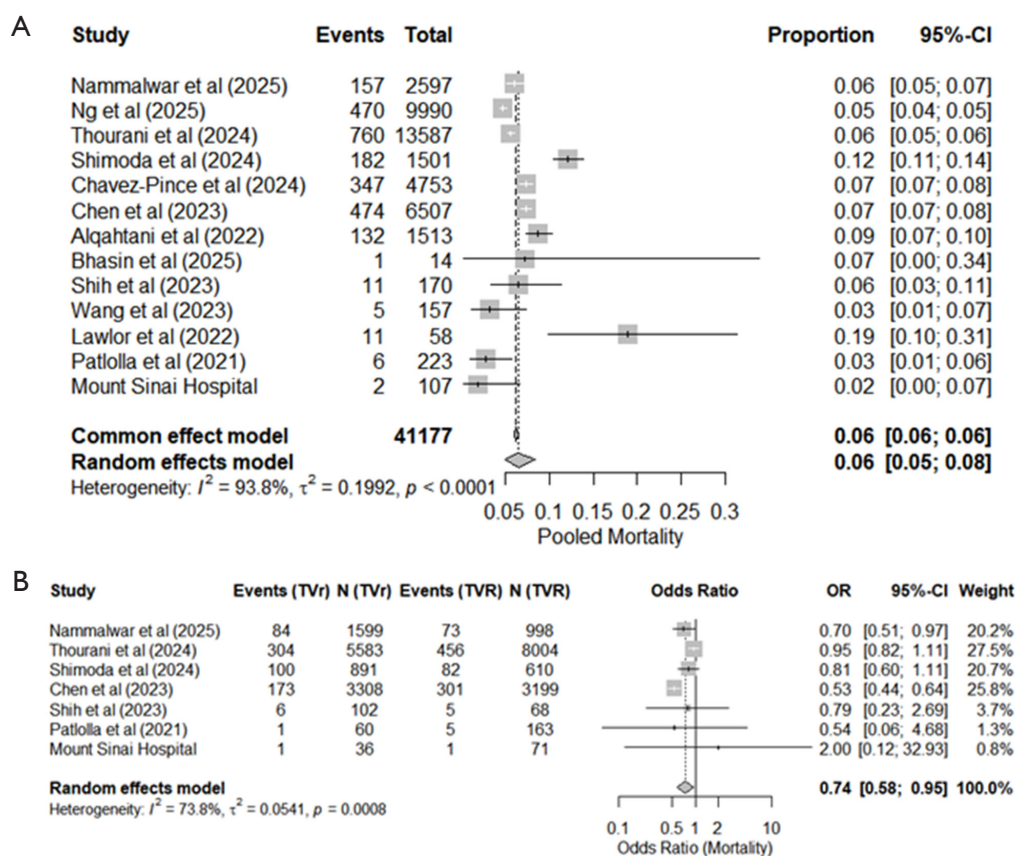


Figure 2 Meta-analysis of operative mortality following tricuspid valve surgery: (A) overall pooled incidence; (B) TVr vs. TVR. CI, confidence interval; OR, odds ratio; TVr, tricuspid valve repair; TVR, tricuspid valve replacement.

administrative database studies and 4.9% (95% CI: 2.4–9.7%) among institutional and smaller center studies (Figure S3A). Substantial heterogeneity persisted within both subgroups, and no statistically significant difference in mortality incidence was observed between study types (P for interaction =0.31).

In the comparative analysis, TVr was associated with lower operative mortality compared with TVR (OR =0.74; 95% CI: 0.58–0.95; P=0.02), with moderate-to-high heterogeneity ($I^2=74\%$, $\tau^2=0.054$) (Figure 2B). Subgroup analyses demonstrated consistent direction of effect across study designs (Figure S3B). Among large administrative database studies, TVr remained associated with reduced mortality (OR =0.73; 95% CI: 0.56–0.96), whereas center-level studies showed a similar but non-significant association (OR =0.82; 95% CI: 0.30–2.22). No statistically significant difference in treatment effect was observed between subgroups (P for interaction =0.84).

Meta-analysis: new PPM implantation

Across 10 studies including 21,753 patients and 2,623 events, the pooled incidence of new PPM implantation after isolated tricuspid valve surgery was 12.6% (random-effects: 12.6%; 95% CI: 9.4–16.8%), with high heterogeneity ($I^2=97\%$, $\tau^2=0.231$, $P<0.001$) (Figure 3A).

In subgroup analyses, PPM incidence was 13.7% (95% CI: 9.9–18.6%) among large administrative database studies and 11.0% (95% CI: 6.3–18.5%) among institutional and smaller center studies (Figure S4A). Substantial heterogeneity persisted within both subgroups, with no statistically significant difference between study types (P for interaction =0.49).

In the comparative analysis, TVr was associated with a significantly lower risk of PPM implantation compared with TVR (OR =0.39; 95% CI: 0.32–0.47; P<0.001), with low-to-moderate heterogeneity ($I^2=31\%$) (Figure 3B). Subgroup analyses showed consistent reduction in PPM risk across

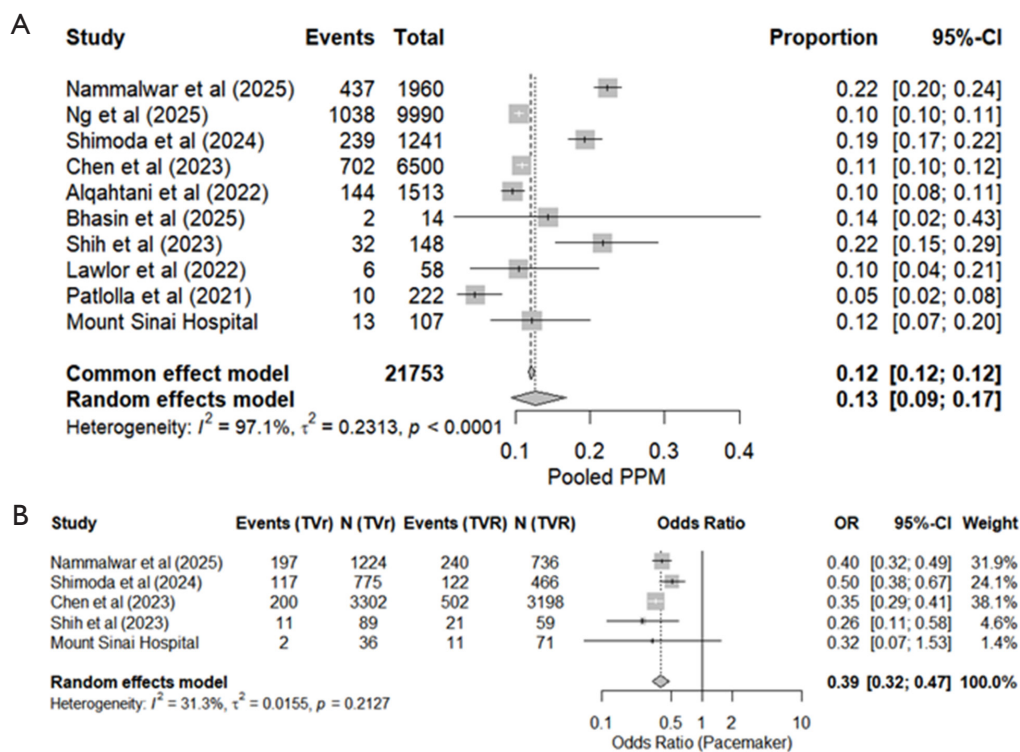


Figure 3 Meta-analysis of PPM implantation following tricuspid valve surgery: (A) overall pooled incidence; (B) TVr vs. TVR. CI, confidence interval; OR, odds ratio; PPM, permanent pacemaker; TVr, tricuspid valve repair; TVR, tricuspid valve replacement.

study designs (Figure S4B). Among large administrative database studies, TVr was associated with reduced PPM implantation (OR =0.40; 95% CI: 0.33–0.49), whereas center-level studies demonstrated a similar direction of effect (OR =0.27; 95% CI: 0.13–0.56). No statistically significant difference in treatment effect was observed between subgroups (P for interaction =0.30).

Discussion

This study provides a comprehensive contemporary understanding of North American practices and outcomes of isolated tricuspid surgery over the past two decades. Operative mortality ranged from 5% to 12.7%; however, in expert centers or among carefully selected patients, mortality rates were as low as 2–3%. Case volumes rose steadily in the early 2010s and then peaked around 2017, with volumes stable or declining since. We found that TVr was associated with lower operative mortality and lower rates of PPM implantation compared with replacement, while other near-term morbidity outcomes were generally similar between approaches. Beating heart surgery demonstrated comparable

safety as cardioplegic arrest. Minimally invasive approaches, including robotic surgery, are feasible.

The key finding of this study is the continued improvement in operative mortality, which is significantly reduced from the 10–12% historical rates reported in the preceding decade (9–11). The reasons behind this improvement are three-fold. First is increased awareness and earlier referral, which has been increasingly advocated since the 2010s and earlier (16). Second is an emphasis on surgery prior to end stage heart failure and multi-organ dysfunction. Third is the increased use of transcatheter therapies, which are now used to treat the highest-risk patients who would have been operated on previously. Transcatheter therapies have grown significantly during the study period: among the Medicare population the number of tricuspid transcatheter edge-to-edge repair (T-TEER) procedures has eclipsed the number of isolated tricuspid surgeries as of 2020 (38). This finding also explains the decrease in surgical volume between 2017 and 2023 identified by the STS analysis by Thourani *et al.* (23). Contemporary transcatheter therapies are primarily utilized in older, higher-risk patients with severe functional tricuspid regurgitation and multiple comorbidities.

This evolving treatment paradigm has likely shifted the highest-risk patients away from surgery and contributed to improved contemporary surgical outcomes (39).

Overall, pooled operative mortality after isolated tricuspid valve surgery was 6.4%, and TVr was associated with lower mortality compared with replacement (OR =0.74; 95% CI: 0.58–0.95). The pooled incidence of PPM implantation was 12.6%, with a robust reduction observed with repair *vs.* replacement (OR =0.39; 95% CI: 0.32–0.47). Subgroup analyses demonstrated consistent effect estimates across study designs for both outcomes. A potential limitation of this meta-analysis is the possibility of partial overlap between institutional cohorts and patients included in large administrative database studies, which could not be fully quantified. However, sensitivity analyses stratified by study design and formal tests for subgroup differences showed no evidence of effect modification, suggesting that any potential overlap is unlikely to have materially influenced the overall findings.

We predict that outcomes for isolated tricuspid surgery will continue to improve, as referral patterns mature and increasing evidence supports earlier operation. It is logical that surgery for the tricuspid valve will eventually follow the pathway already laid out by the mitral valve: surgery for all severely regurgitant patients, ideally before the development of symptoms and ventricular dysfunction. Similarly, we envision that transcatheter therapies will continue to increase in utilization. No randomized studies exist comparing surgery and transcatheter therapies for isolated tricuspid disease, a key area for future study. The role of tricuspid repair or replacement, and which etiologies and lesions are most amenable to one procedure or the other, is also likely to be another focus of future investigation. Finally, we envision an increase in high-risk tricuspid valve surgeries in patients after failed transcatheter interventions, similar to the growth in failed mitral TEER and transcatheter aortic valve replacement (TAVR) explantation procedures.

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Footnote

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to declare.

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