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No Room to Clamp: Endovascular vs Open Outcomes in the Porcelain Aorta Battlefield -A Systematic Review and Single Arm Meta-Analysis

Noor Abu Hantash[1], Ahmed Moawad[2], Sara Fakeh[3*], Mohammad Mahadin[4], Moaath Al-Smady[5]

[1]*School of Medicine, University of Jordan, Amman, Jordan*
[2]*Faculty of Medicine, Helwan University, Cairo, Egypt*
[3]*Faculty of Medicine, Hashemite University, Al-Zarqa, Jordan*
[4]*Faculty of Medicine, Jordan University of Science and Technology, Amman, Jordan*
[5]*General surgery and Cardiovascular Surgery Department, Jordan University Hospital, Amman, Jordan*

[*]**Correspondence to:** Sara Fakeh, Faculty of Medicine, Hashemite University, Al-Zarqa, Jordan, E-mail: sara.faqeeh33@icloud.com

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ABSTRACT

Background

Porcelain aorta (PA) presents a major technical challenge in cardiovascular surgery due to the risks associated with aortic cross-clamping. Both open and endovascular surgical approaches have been utilized to manage this condition, yet comparative outcome data remain limited and fragmented.

Objective

This systematic review and meta-analysis aimed to evaluate perioperative and mid-term outcomes of open and endovascular strategies in patients with coexisting porcelain aorta and to summarize the available evidence regarding these treatment approaches.

Methods

A comprehensive literature search identified 350 studies, of which 20 met the inclusion criteria, encompassing 1249 patients. Among them, 385 underwent open surgery and 864 received endovascular interventions. The primary outcomes analyzed included 30-day mortality, stroke, bleeding, and other complication rates. Secondary outcomes comprised ICU stay duration, technical success, 1- and 5-year survival, and re-intervention rates. Sensitivity analyses and publication bias assessments were conducted. Study quality was appraised using the ROBINS-I v2 tool and the Joanna Briggs Institute (JBI) checklists.

Results

The pooled 30-day mortality rate was 3.1% (95% CI: 0.7%–6.7%) in studies of open surgery and 5.4% (95%CI: 2.7%–8.9%) in studies of endovascular procedures. The pooled complication rate, excluding stroke and bleeding, was 26.3% (95% CI: 13.3%–41.4%) and 40.4% (95% CI: 27.0%–54.5%), respectively. Stroke and bleeding rates were similar across both groups. ICU stay was longer in studies of open surgery, while technical success rates were high in both approaches. One-year survival estimates were comparable, whereas long-term survival data remained limited. Re-intervention rates were low in both groups. A single study evaluating hybrid approaches reported favorable short-term outcomes. Sensitivity analyses identified studies contributing to heterogeneity, and publication bias was detected in selected outcomes.

Conclusion

Both open and endovascular strategies for the management of porcelain aorta demonstrated acceptable outcomes in separate single-arm meta-analyses. However, because pooled estimates were derived from non-comparative analyses and substantial clinical heterogeneity and selection bias were present across studies, no conclusions regarding the superiority of one approach over the other can be drawn. Hybrid approaches appear promising but remain supported by limited evidence. Treatment decisions should be individualized based on patient characteristics, anatomical considerations, and surgical expertise.

Keywords: Porcelain Aorta; Hostile Aorta; Endovascular; Surgical; SRMA; Single Arm Meta-Analysis; Outcomes

INTRODUCTION

Porcelain aorta (PA), characterized by severe circumferential calcification of the ascending aorta and arch, presents formidable challenges in cardiac surgery. This extensive calcification renders aortic cross-clamping hazardous during open procedures, restricts cannulation options, and significantly elevates embolic risk during surgical aortic valve replacement (SAVR) [1,2,3]. These technical limitations have established PA as a relative contraindication to conventional SAVR in patients with severe aortic stenosis (AS), highlighting the urgent need for alternative strategies [4].

While hybrid procedures such as transcatheter aortic valve implantation (TAVI) combined with off-pump coronary artery bypass grafting (OPCAB) have been described in selected high-risk patients, this analysis focuses on comparing standalone open SAVR and endovascular approaches. Current guidelines from the European Society of Cardiology and the European Association for Cardio-Thoracic Surgery recommend TAVI over SAVR in AS patients with PA, citing TAVI's ability to avoid aortic manipulation and its proven feasibility in high-risk cases [5,6,7,8,9]. Similarly, transcatheter aortic valve replacement (TAVR) has gained traction as a viable alternative [9,10]. While large-scale studies have established benchmarks for SAVR outcomes across risk strata, comparable multicenter data for endovascular approaches in porcelain aorta patients remain limited [11].

This systematic review and meta-analysis aim to address these evidence gaps by: evaluating perioperative outcomes of open and endovascular strategies including mortality, stroke, and aortic injury rates between open SAVR and endovascular TAVI/TAVR; evaluating secondary endpoints such as ICU stay duration, reintervention rates, and quality-of-life outcomes; and identifying patient-specific and procedural factors that may influence outcomes.

Through this rigorous analysis, we aim to provide evidence-based guidance for clinical decision-making in this high-risk population and to highlight key areas for future research.

MATERIALS AND METHODS

This meta-analysis was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. The protocol is registered on PROSPERO under the ID number CRD420251040976 and can be accessed at:

https://www.crd.york.ac.uk/PROSPERO/view/CRD420251040976

Research Strategy

A comprehensive electronic literature search was performed on April 20, 2025, using Embase, PubMed, and Scopus. The search terms included: ("Porcelain aorta" OR "severe calcified ascending aorta" OR "heavily calcified aorta") AND ("transcatheter" OR "endovascular" OR "open surgery" OR "sternotomy" OR "hybrid approach" OR "combined surgical and endovascular") AND ("outcomes" OR "mortality" OR "postoperative complications" OR "stroke" OR "perioperative results" OR "survival"). The PRISMA flow diagram illustrating the study selection process is presente d in Figure 1.

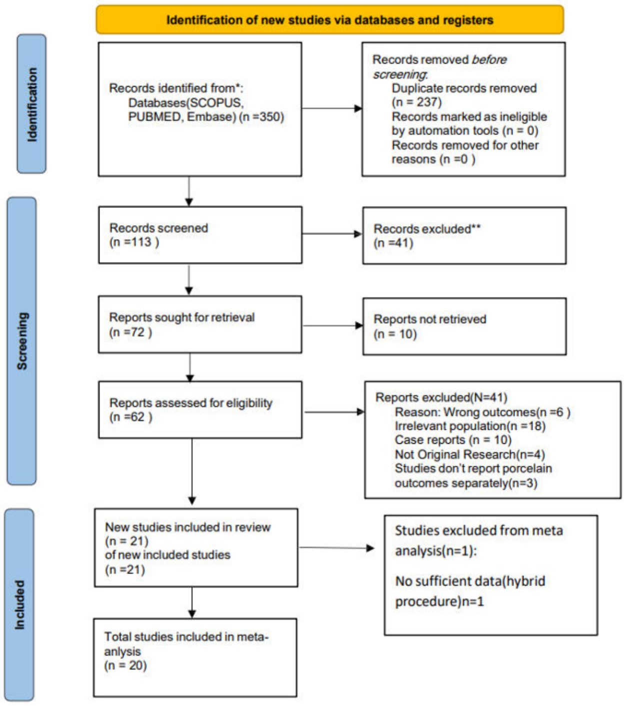

Figure 1: PRISMA Flow Diagram

Data Extraction and Quality Assessment

Studies were selected by two independent reviewers according to the inclusion and exclusion criteria. Any disagreement was resolved through group discussion and consensus. The following data were extracted from each study: first author name, year, journal, study design, country, type of operation (e.g., CABG, valve replacement), operative indications (e.g., stenosis, regurgitation, CAD), presence of concomitant procedures (%), sample sizes for hybrid, endovascular, and open groups, study duration, follow-up duration, patient age (mean), sex (% male), comorbidities (n, %), NYHA class (mean), logistic EuroSCORE (mean), porcelain aorta classification (IA, IB, II), and calcium distribution pattern. Details on diagnostic imaging, modifications to avoid aortic cannulation and clamping, access sites (transcatheter and surgical), arterial cannulation techniques, and aortic clamping approaches were also collected. Intraoperative variables such as cardiopulmonary bypass time, aortic clamp time, and cerebral perfusion time were included.

Postoperative outcomes were extracted, including 30-day mortality, stroke rate, incidence of aortic rupture, and other complications (n, %). Additional outcomes included ICU stay duration, procedural success rate, reintervention rate, and 5-year survival. If a study reported results for a broader patient population but presented a separate subgroup analysis for porcelain aorta patients, only the latter data were extracted and analyzed.

Statistical analysis and interpretation

Data analysis was conducted according to the guidelines of Cochrane Handbook for Systematic Reviews of Interventions

[12]. values of primary and secondary outcomes were calculated and expressed as proportions or mean difference with 95% confidence intervals in a single arm meta-analysis. Freeman-Tukey variant of the arcsine square root transformed proportion and Der Simonian-Laird weights of random effects model were used to express proportions and mean difference as pooled percentage proportions and mean difference. Chi2 and I2 tests were conducted for heterogeneity. Meta- analysis was conducted using open meta [analyst] software and metaanalisisonline.com webpage [13]. Sensitivity analyses were done to detect any high risk or biased studies. Funnel plots and Egger's tests were done to detect possible publication bias among included studies.

RESULTS

Study Characteristics

A total of 350 studies were identified through database searches. After the removal of duplicates and screening by title, abstract, and full text, 77 studies remained. Of these, 10 could not be retrieved. Following the eligibility assessment of the remaining 67 studies, 21 were deemed suitable; however, one hybrid study was excluded from the meta-analysis. Consequently, 20 studies were included in the final systematic review and meta-analysis, encompassing a total of 1249 patients. Of these, 385 patients underwent open surgery for the management of porcelain aorta, while 864 underwent endovascular procedures. Detailed patient characteristics are provided in Table S1(Supplementary).

Study	Year	Country	PA patients number	Age in years (MN ± SD) mean ± SD)	Male %	Key Comorbidities (examples)	NYHA III–IV (%)	Logistics EuroSCORE%	Porcelain-Aorta Type	Imaging
Abe et al. [23]	2010	Japan	4	73.4	25	NA	100	NA	NA	NA
Asami et al.[24]	2022	Switzerland	114	79.4 ± 7.4	52.6	DM 35.1% CAD 77% CKD 60.5%	73.7	23.5 ± 16.3	NA	
Buz et al. [25]	2011	Germany	16	77.4 ± 10.3	32.6	PVD 60.8% CAD 59% AF 39%	37	45 ± 22	Grade 4: circumferential; Grade 3: severe but non-circumferential	CT, TEE. Echo
Campanella et al. [18]	2025	Germany/ USA	161	77.2	66.5	PAD 22% CAD 18% Prior PCI 32.9% COPD 13%	NA	11.6	Non-circular vs circular	Multi-slice CT
Chang et al.[15]	2017	South Korea	32	74 ± 7	66	HTN 75% DM 53% CKD 16% AF 22%	28	21.4 ± 19.0	Extensive circumferential of ascending aortaf	CT + epiaortic US

De Paulis et al.[26]	2009	Italy	3	75	100	NA	NA	NA	severe ascending aortic calcification	Echo, Angio, CT
Del-Val et al.[18]	2018	USA	184	TAVI: 77.5 ± 10.3	TAVI: 36.5	CAD: TAVI 57.7%, SAVR 65.4%	TAVI 43 (82.7%)	NA	Diffuse circumferential calcification of the ascending aorta	CT, epiaortic
						CKD: TAVI 28.8%, SAVR 13.5%				
				SAVR: 78.8 ± 6.3	SAVR: 34.6	PVD: TAVI 30.8%, SAVR 40.4%	SAVR 36 (69.2%)			US
						DM: TAVI 36.5%, SAVR 38.5%				
Hartert et al.[27]	2018	Germany	42	AVR: 81.3 ± 6.4	AVR: 42.4	CAD 64.3%	AVR = 81.8	AVR: 29.2 ± 16.5;	Circumferential entire ascending aorta	CT, TEE
						COPD 50%				
				MVR: 80.3 ± 5.7	MVR: 55.6	DM 38.1%	MVR = 100	MVR: 28.4 ± 14.1%		
Kempfert et al.[28]	2010	Germany	29	79 ± 7.8	34.5	Renal failure 58.6%	NA	37.7 ± 18.1	Entire ascending aorta	CT, chest X-ray, cardiac cath, epiaortic echo
						COPD 62.1%				
						Carotid stenosis 34.5%				
Kramer et al.[14]	2023	USA	164	77 (7.7)*	SAVR 48	HTN 86%	NA	NA	NA	3D CT
					TAVR 41	COPD 38%				
						PAD 41%				

Lauten et al.[29]	2025	Germany	141	78.2	57.4	HTN 82.3% DM 46.8% PAD 9.9% COPD 11.3% AF 31.2% CAD 60.3%	74.1	9.4 ± 10.4	Ascending aorta to arch, Partial (78.7%), Circular (21.3%)	Non-contrast axial CT
Leyh et al. [30]	1999	Germany	23	71.6 ± 6.8	73.91	DM 57% PVD 52% prior MI 35% prior CVA 9%	NA	NA	circumferential calcification of the entire ascending aorta and proximal aortic arch	Chest X-ray, Cine-angio
Nakasu et al.[31]	2018	USA	36	81 (70-84)*	58	PAD 81% Diabetes 25%	89	NA	Extensive circumferential calcification	CT, TEE, Echo
Nishi et al.[32]	2010	Japan	11	70.2 ± 6.2	54.5	HTN 64% DM 27% CKD 45% Dialysis 36%	≈ 64	NA	NA	Non-contrast CT
Salem et al.[16]	2019	Germany	74	73 ± 7	71.6	Diabetes 41.8% PVD 41.8% HTN 79.7%	NA	9.1 (6.3–11.6)*	Entire ascending aorta	Non-contrast CT, X-ray, angio
Sasajima et al.[33]	2002	Japan	9	66.3 ± 9.2	88.89	Diabetes dialysis (DM/ GN/ PKD)	NA	NA	NA	CT
Sirin et al[17].	2013	Turkey	41	74.4 ± 6.39	88.9	HTN 66.7% DM 55.6% PAD 33.3% COPD 33.3% CAD 77.8%	NA	NA	NA	Chest x-ray, CT

Urbanski et al.[34]	2013	Germany	30	68 ± 11	NA	HTN 90% CHD 50% DM 30% COPD 13%	60	31.5 ± 25.7	NA	CT
Zahn et al. [9]	2013	Germany	147	81.4 ± 6.2	40.1	DM 46.3% COPD: 43.5% PAD: 34.7% Renal failure 68.0% CAD: 32.2%	91.8	17.4 (11.0–30.7)*	Extensive circumstantial	CT, Flouroscopy, Echo

Supplementary Table 1: Shows Patients Demographics and Characteristics in Included Studies

Note: Data Reported In Median & IQR / HTN= Hypertension, DM= Diabetes Mellitus, PVD: Peripheral Vascular Disease, PAD= Peripheral Artery Disease, MI: Myocardial Infarction, CVA: Cerebrovascular Accidents, COPD= Chronic Obstructive Pulmonary Disease, CKD= Chronic Kidney Disease, CAD= Coronary Artery Disease, GN= Glomerulonephritis, PKD= Polycystic Kidney Disease, AF: Atrial Fibrillation, SAVR: Surgical Aortic Valve Replacement, TAVI: Transcatheter Aortic Valve Implantation, CABG: Coronary Artery Bypass Graft, AVR= Aortic Valve Replacement, MVR: Mitral Valve Replacement, TA: Transapical, TA: Transaortic, CT: Computed Tomography, US: Ultrasound, ECHO: Echocardiography, Angio: Angiography

Primary Outcomes

The pooled 30-day mortality rate for patients who underwent open surgery was 3.1% (95% CI: 0.7%–6.7%), compared to 5.4% (95% CI: 2.7%–8.9%) in the endovascular cohort. The pooled complication rate, excluding bleeding and stroke, was 26.3% (95% CI: 13.3%–41.4%) in the open surgery group, while it reached 40.4% (95% CI: 27%–54.5%) in the endovascular group. Stroke rates were similar between both cohorts, with the open surgery group having a rate of 3.7% (95% CI: 1.5%–6.5%) and the endovascular group 3.5% (95% CI: 2.2%–4.9%). Likewise, pooled bleeding rates were comparable, at 4.5% (95% CI: 0.5%–10.9%) in the open group and 5.7% (95% CI: 1.4%–12.4%) in the endovascular group. (Figure 2-9).

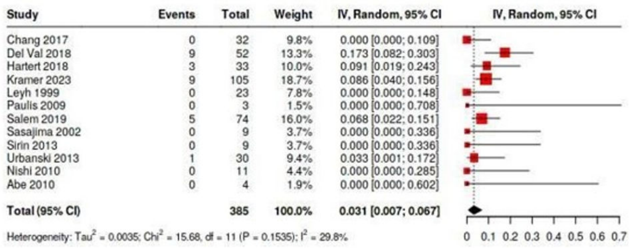

Figure 2: Forest Plot Shows Pooled 30-Day Mortality Rate for Open Surgery Cohort

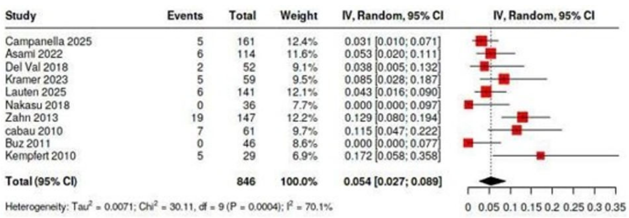

Figure 3: Forest Plot Shows Pooled 30-Day Mortality Rate for Endovascular Procedure Cohort

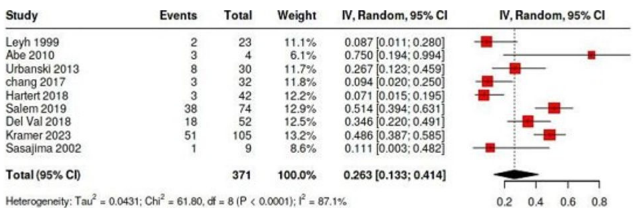

Figure 4: Forest Plot Shows the Pooled Rate of All Complications (Excluding Bleeding or Stroke) In the Open Surgery Cohort

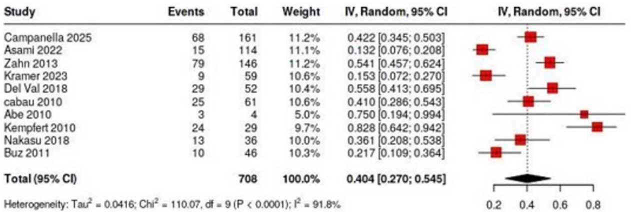

Figure 5: Forest Plot Shows the Pooled All Complications Rate (Other Than Bleeding or Stroke) In the Endovascular Procedure Cohort

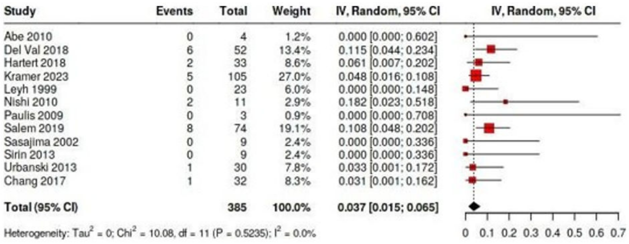

Figure 6: Forest Plot Shows Pooled Stroke Rate in Open Surgery Cohort

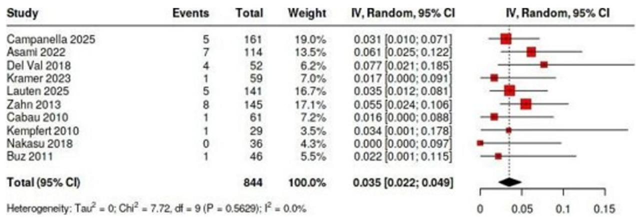

Figure 7: Forest Plot Shows Pooled Stroke Rate in Endovascular Surgery Cohort

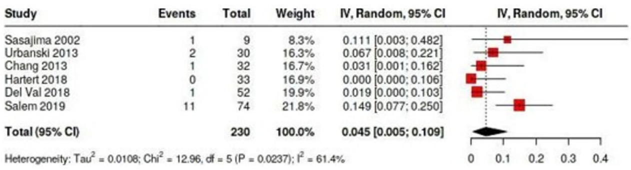

Figure 8: Forest Plot Shows Pooled Bleeding Rate in Open Surgery Cohort

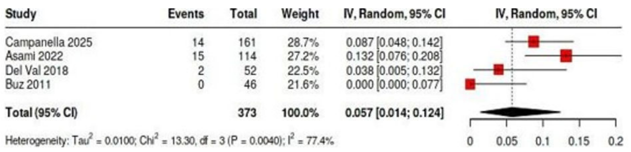

Figure 9: Forest Plot Shows Pooled Bleeding Rate in Endovascular Surgery Cohort

Secondary Outcomes

The pooled estimated mean duration of ICU stay was longer in the open surgery group at 109.0 hours (95% CI: 81.6–136.4), compared to 60.2 hours (95% CI: 44.8–75.5) in the endovascular group. The technical success rate in the open surgery group was 100% (95% CI: 99.8%–100%), whereas it was slightly lower in the endovascular group at 93.8% (95% CI: 88.2%–97.8%). Data on survival were limited and inconsistently reported across studies. However, the pooled estimated 1-year survival rate based on three studies for each group was 79.5% (95% CI: 59.1%–94.4%) for the open surgery cohort and 82.8% (95% CI: 76.4%–88.5%) for the endovascular cohort. Regarding 5-year survival, only three studies for the open cohort reported data, yielding an estimated pooled survival rate of 75.9% (95% CI: 52.6%–93.3%). While sufficient 5-year survival data for the endovascular group were lacking, one comparative study by Kramer reported a 5-year survival rate of 56% for open surgery versus 82% for endovascular procedures [14]. The pooled re-intervention rate was higher in the open group at 3.9% (95% CI: 0.4%–9.7%) compared to 1.3% (95% CI: 0%–7.3%) in the endovascular group, although data for the latter were limited (Figure 10-18).

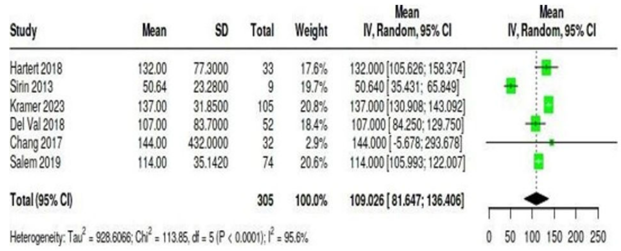

Figure 10: Forest Plot Shows Pooled Estimated Mean of ICU Stay in Hours for Open Surgery Cohort

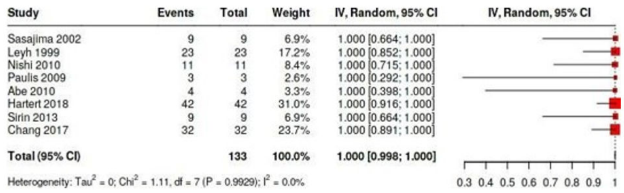

Figure 11: Forest Plot Shows Pooled Success Rate for The Open Surgery Cohort

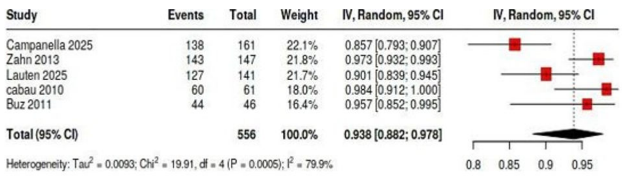

Figure 12: Forest Plot Shows Pooled Success Rate for Endovascular Surgery Cohort

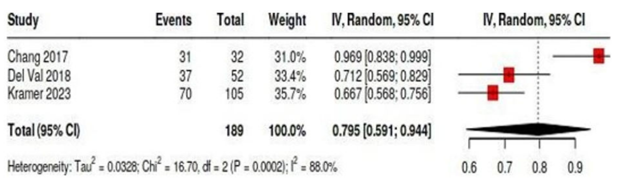

Figure 13: Forest Plot Shows the Pooled Estimated Available 1-Year Survival Rates in The Open Surgery Cohort

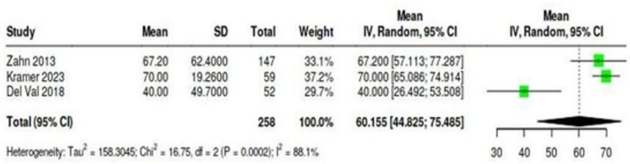

Figure 14: Forest Plot Shows Pooled Estimated Mean of ICU Stay in Hours for The Endovascular Surgery Cohort

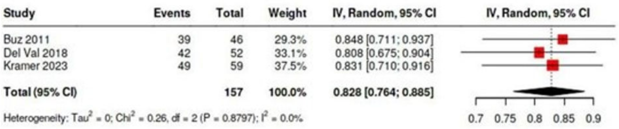

Figure 15: Forest Plot Shows the Pooled Estimated Available 1-Year Survival Rates in the Endovascular Surgery Cohort

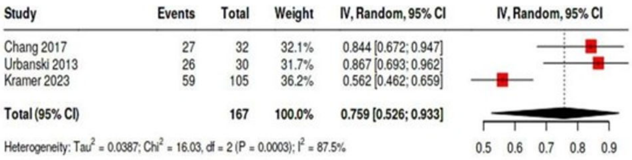

Figure 16: Forest Plot Shows the Pooled Estimated Available 5-Year Survival Rates in Open Surgery Cohort

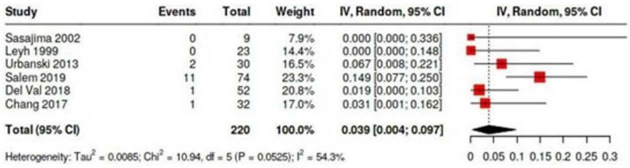

Figure 17: Forest Plot Shows Pooled Estimated Re-Intervention Rates in Open Surgery Cohort

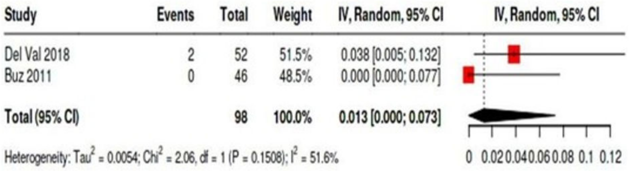

Figure 18: Forest Plot Shows the Pooled Estimated Re-Intervention Rates in the Endovascular Surgery Cohort

Hybrid Procedure Outcomes

The only identified study reporting hybrid procedures in porcelain aorta patients was conducted by Mayr, a retrospective single-center study from Germany [5]. The cohort included 20 patients undergoing hybrid interventions (12 simultaneous TAVI + OPCAB, 6 MIDCAB + TAVI, 2 staged TAVI/OPCAB), of whom 15 (75%) had a porcelain aorta. Device success was achieved in 100% of cases. There were no 30-day mortalities, strokes, myocardial infarctions, or vascular complications. Re-exploration for bleeding was required in one patient (~7%), and the median ICU stay was 4 days (IQR: 2–7 days).

Publication bias

Funnel plots and Egger's tests were done to assess publication bias (figures19-33). Success rate of open surgery cohort figure (3) and 5-years survival rates in the same cohort figure (33) shows probable publication bias.

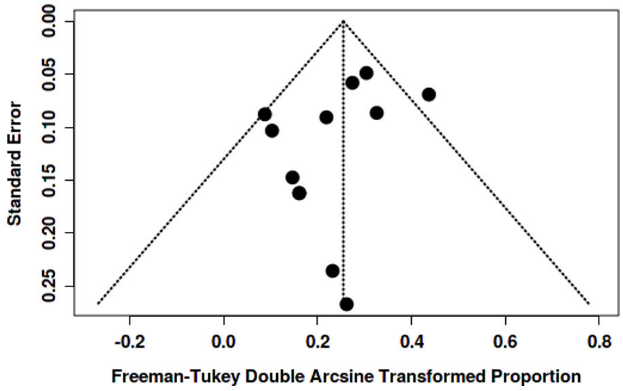

Figure 19: 30- Day Mortality Rate of Open Surgery Cohort's Funnel Plot Does Not Indicate a Potential Publication Bias. The Egger's Test Does Not Support the Presence of Funnel Plot Asymmetry (Intercept: -1.14, 95% CI: -2.59 - 0.32, T: -1.531, P-Value: 0.157)

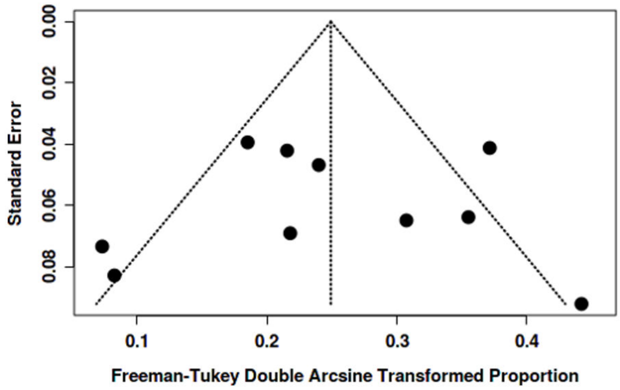

Figure 20: 30-Day Mortality Rate in Endovascular Surgery Cohort's Funnel Plot Does Not Indicate a Potential Publication Bias. The Egger's Test Does Not Support the Presence of Funnel Plot Asymmetry (Intercept: -0.26, 95% CI: -4.54 - 4.02, T: -0.121, P-Value: 0.907)

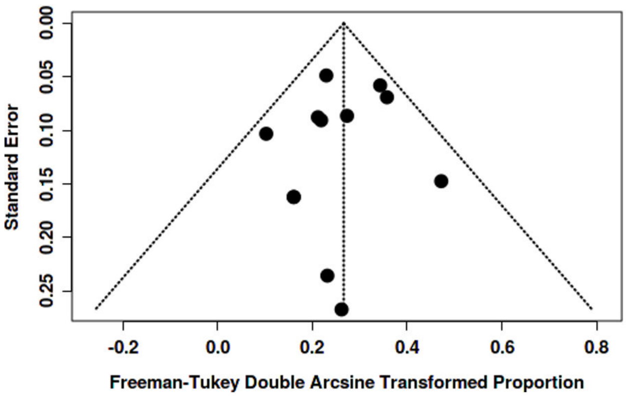

Figure 21: Stroke Rates of Open Surgery Cohort's Funnel Plot Does Not Indicate a Potential Publication Bias. The Egger's Test Does Not Support the Presence of Funnel Plot Asymmetry (Intercept: -0.36, 95% Ci: -1.63 - 0.92, T: - 0.549, P-Value: 0.595)

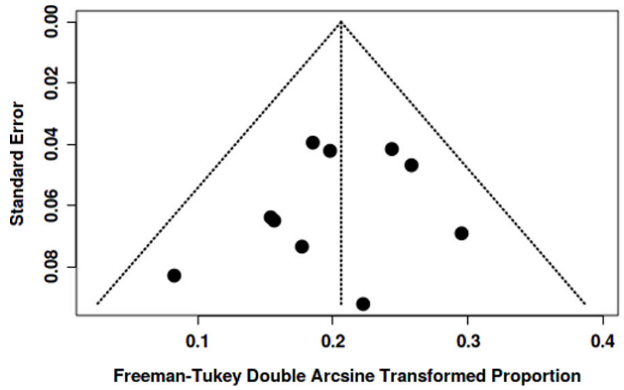

Figure 22: Stroke Rates of Endovascular Surgery Cohort's Funnel Plot Does Not Indicate a Potential Publication Bias. The Egger's Test Does Not Support the Presence of Funnel Plot Asymmetry (Intercept: -0.91, 95% CI: -2.99 - 1.17, T: - 0.859, P-Value: 0.415)

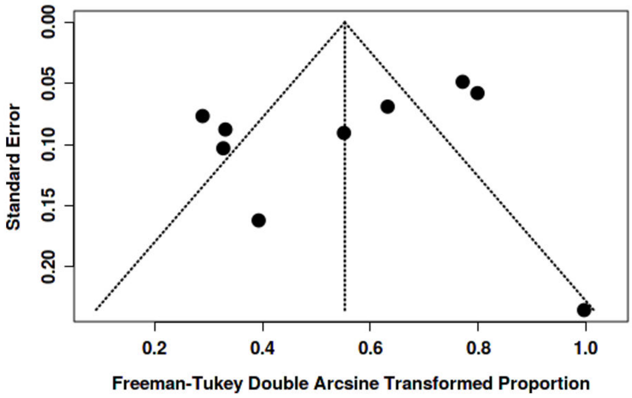

Figure 23: Complications Rates (Other Than Bleeding and Stroke) Of Open Surgery Cohort's Funnel Plot Does Not Indicate a Potential Publication Bias. The Egger's Test Does Not Support the Presence of Funnel Plot Asymmetry (Intercept: -3.03, 95% CI: -7.73 - 1.67, T: -1.262, P-Value: 0.247)

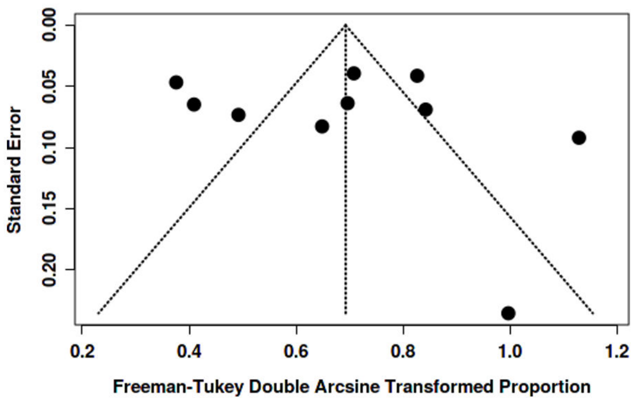

Figure 24: Complications Rates (Other Than Bleeding and Stroke) In Endovascular Surgery Cohort's Funnel Plot Does Not Indicate a Potential Publication Bias. The Egger's Test Does Not Support the Presence of Funnel Plot Asymmetry (Intercept: 1.38, 95% CI: -4.9 - 7.67, T: 0.431, P-Value: 0.678)

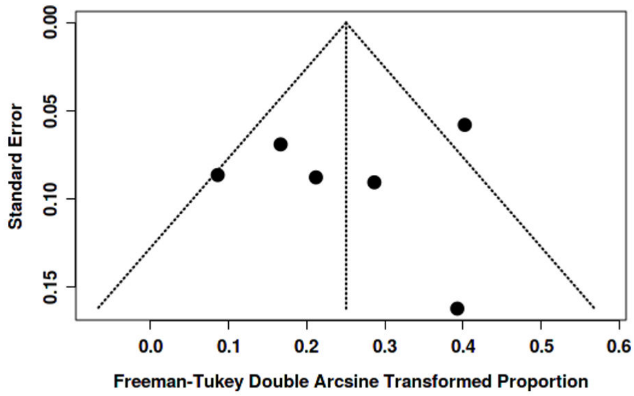

Figure 25: Bleeding Rates in Open Surgery Cohort's Funnel Plot Does Not Indicate a Potential Publication Bias. The Egger's Test Does Not Support the Presence of Funnel Plot Asymmetry (Intercept: -1.04, 95% CI: -6.22 - 4.14, T: - 0.393, P-Value: 0.714)

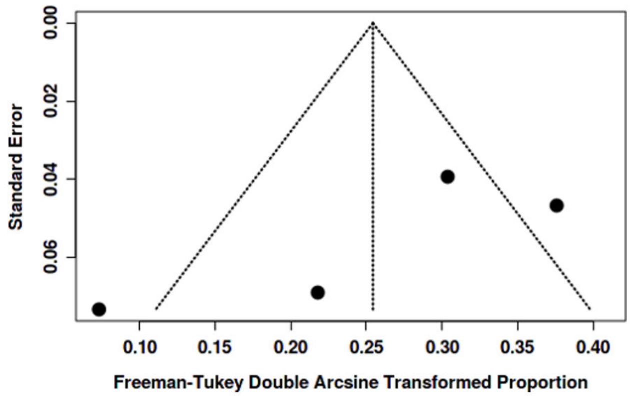

Figure 26: Bleeding Rates in Endovascular Surgery Cohort's Funnel Plot Does Not Indicate a Potential Publication Bias. The Egger's Test Does Not Support the Presence of Funnel Plot Asymmetry (Intercept: -5.69, 95% CI: -11.85 - 0.47, T: -1.811, P-Value: 0.212)

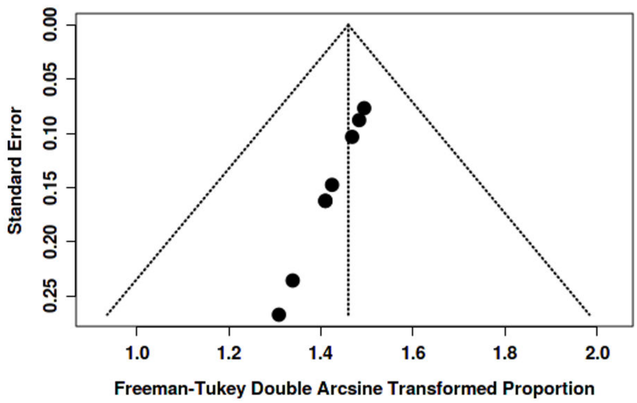

Figure 27: Success Rates in Open Surgery Cohort's Funnel Plot Indicates a Potential Publication Bias. The Egger's Test Supports the Presence of Funnel Plot Asymmetry (Intercept: -0.98, 95% CI: -0.98 - -0.97, T: -317.659, P-Value: 0)

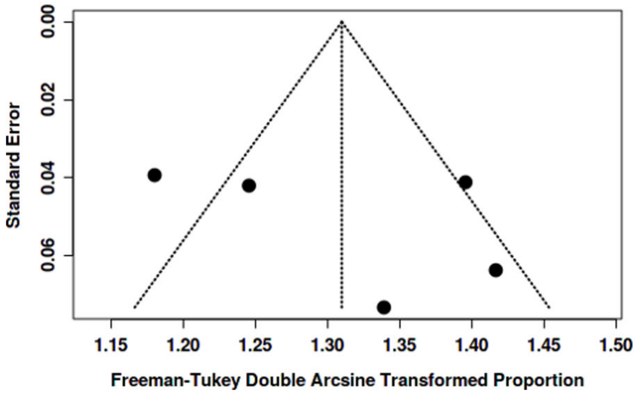

Figure 28: Success Rates in Endovascular Surgery Cohort's Funnel Plot Does Not Indicate a Potential Publication Bias. The Egger's Test Does Not Support the Presence of Funnel Plot Asymmetry (Intercept: 4.01, 95% CI: -4.62 - 12.65, T: 0.911, P-Value: 0.43)

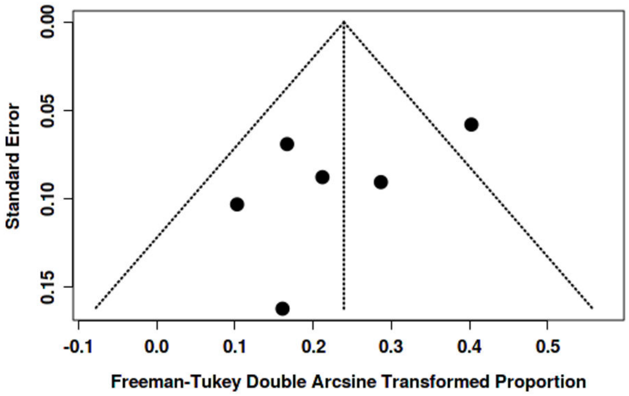

Figure 29: Re-Intervention Rates in Open Surgery Cohort's Funnel Plot Does Not Indicate a Potential Publication Bias. The Egger's Test Does Not Support the Presence of Funnel Plot Asymmetry (Intercept: -2.78, 95% CI: -6.48 - 0.92, T: - 1.475, P-Value: 0.214)

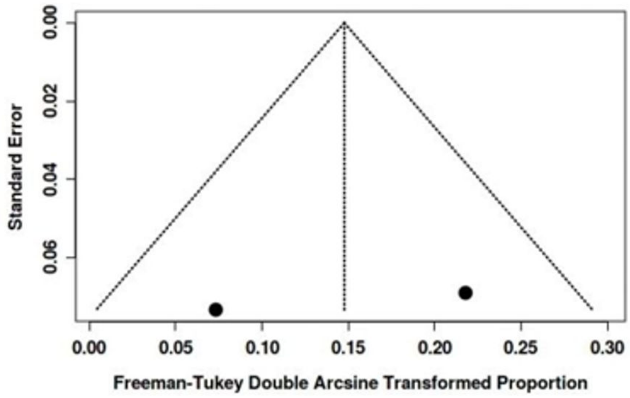

Figure 30: Funnel Plot of Re-Intervention Rates of Endovascular Surgery Cohort Shows No Publication Bias

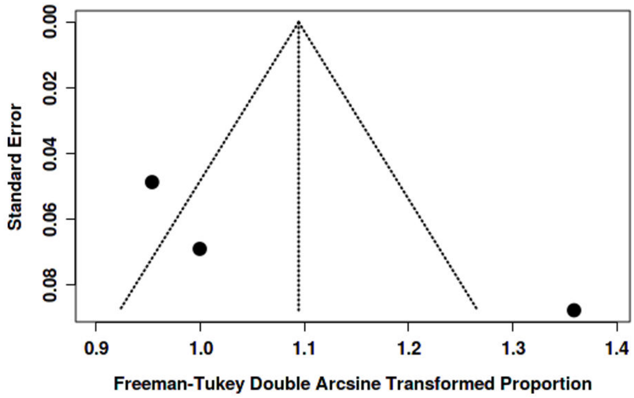

Figure 31: 1-Year Survival Rates of Open Surgery Cohort's Funnel Plot Does Not Indicate a Potential Publication Bias. The Egger's Test Does Not Support the Presence of Funnel Plot Asymmetry (Intercept: 8.74, 95% CI: -0.39 - 17.87, T: 1.876, P-Value: 0.312)

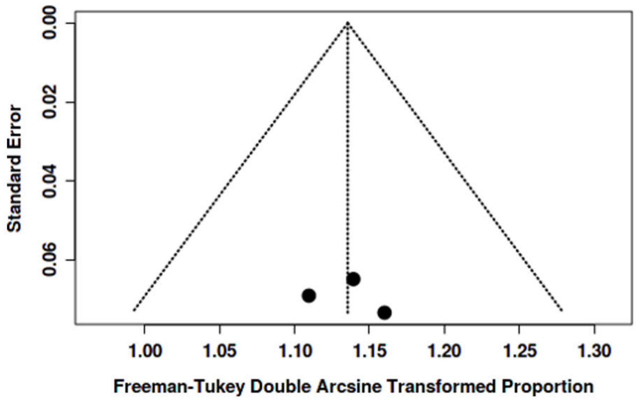

Figure 32: 1-Year Survival Rates of Endovascular Surgery Cohort's Funnel Plot Does Not Indicate A Potential Publication Bias. The Egger's Test Does Not Support the Presence of Funnel Plot Asymmetry (Intercept: 2.1, 95% CI: -8.52 - 12.73, T: 0.388, P-Value: 0.764)

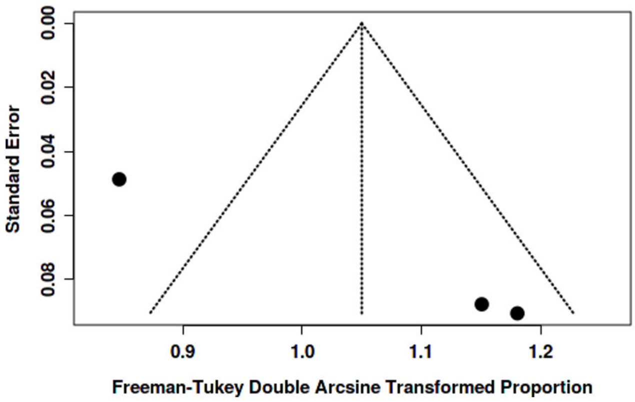

Figure 33: 5-Years Survival Rates of Open Surgery Cohort's Funnel Plot Indicates a Potential Publication Bias. The Egger's Test Supports the Presence of Funnel Plot Asymmetry (Intercept: 7.88, 95% CI:7.65 - 8.11, T: 67.124, P- Value: 0.009)

Sensitivity Analysis

Leave-one-out sensitivity analysis identified several studies that significantly influenced heterogeneity. Notably, Chang impacted the 1-year survival analysis in the open group; after its removal, heterogeneity dropped to $I^2 = 0\%$ [15]. Similarly, the exclusion of Kramer resolved heterogeneity in the 5-year survival analysis for open surgery, also bringing I^2 to 0% [14]. Salem contributed to heterogeneity in bleeding rates in the open group, which decreased to $I^2 = 7\%$ upon its removal [16]. For ICU stay duration, Sirin and Del Val were responsible for heterogeneity in the open and endovascular cohorts respectively; removal of Del Val eliminated heterogeneity ($I^2 = 0\%$) in the endovascular group, though it remained high ($I^2 = 83\%$) in the open group [8,17]. Zahn also showed influence in the 30-day mortality analysis, reducing heterogeneity to 59.5% when removed [9]. Additionally, Campanella influenced success rate heterogeneity in the endovascular cohort, which dropped to 64% after exclusion [18]. (Figure 34-50)

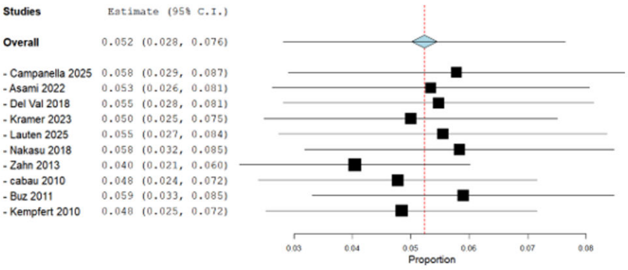

Figure 34: Leave-One-Out Sensitivity Analysis of 30-Day Mortality Rate in Endovascular Surgery Cohort

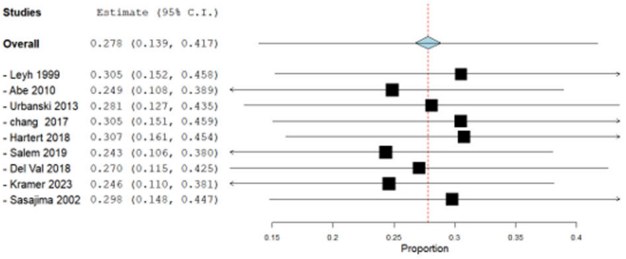

Figure 35: Leave-One-Out Sensitivity Analysis of All Complications Rates (Other Than Bleeding & Stroke Rates) in Open Surgery Cohort

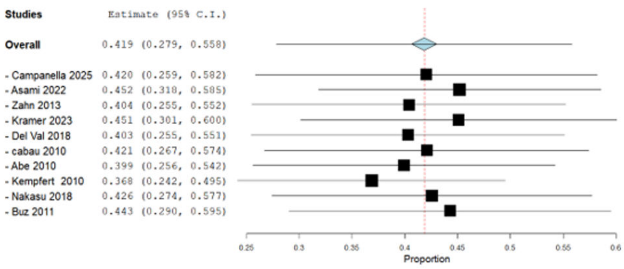

Figure 36: Leave-One-Out Sensitivity Analysis of All Complications Rates (Other Than Bleeding & Stroke Rates) in Endovascular Surgery Cohort

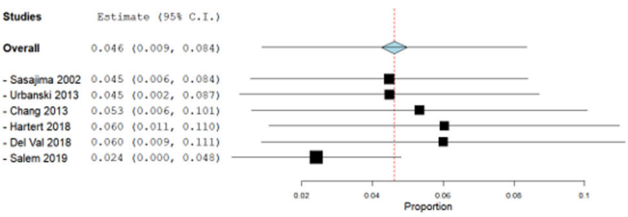

Figure 37: Leave-One-Out Sensitivity Analysis of Bleeding Rates in Open Surgery Cohort

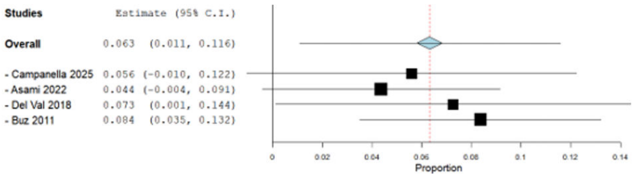

Figure 38: Leave-One-Out Sensitivity Analysis of Bleeding Rates in Endovascular Surgery Cohort

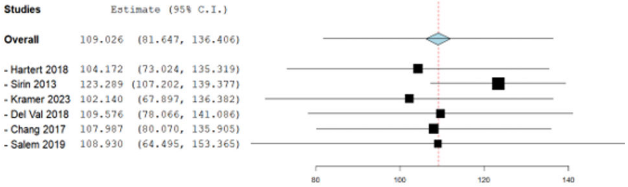

Figure 39: Leave-One-Out Sensitivity Analysis of ICU Stay Means in Open Surgery Cohort

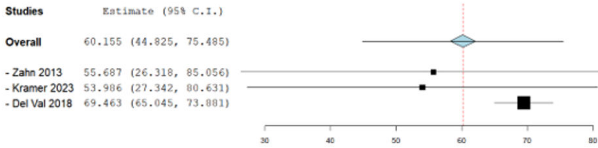

Figure 40: Leave-One-Out Sensitivity Analysis of ICU Stay Means in Endovascular Surgery Cohort

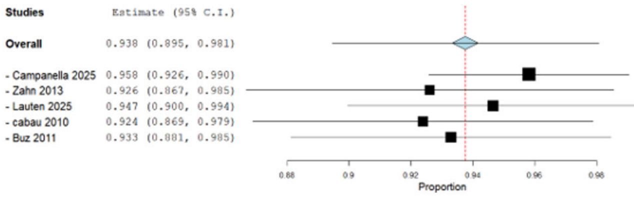

Figure 41: Leave-One-Out Sensitivity Analysis of Success Rates in Endovascular Surgery Cohort

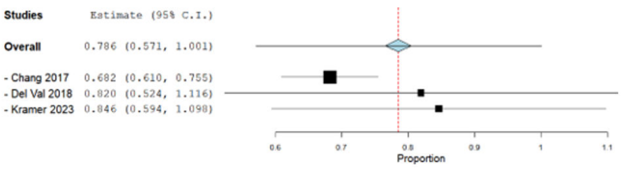

Figure 42: Leave-One-Out Sensitivity Analysis Of 1-Year Survival Rates in Open Surgery Cohort

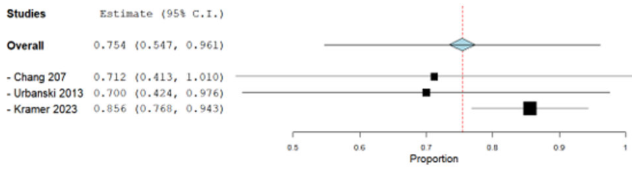

Figure 43: Leave-One-Out Sensitivity Analysis Of 5-Years Survival Rates in Open Surgery Cohort

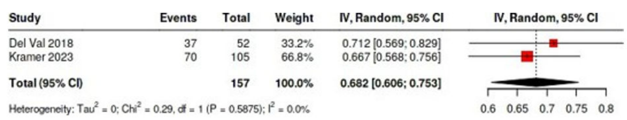

Figure 44: Forest Plot Shows the Effect of Removal of Chang from the Original Forest Plot Of 1-Year Survival Rates in Open Vascular Surgery Cohort Figure (14)

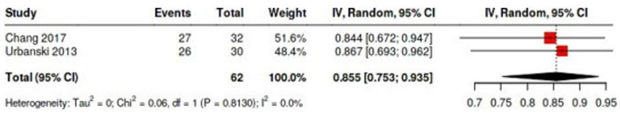

Figure 45: Forest Plot Shows the Effect of Removal of Kramer from Original Forest Plot Of 5-Years Survival Rate in Open Vascular Cohort Figure (16)

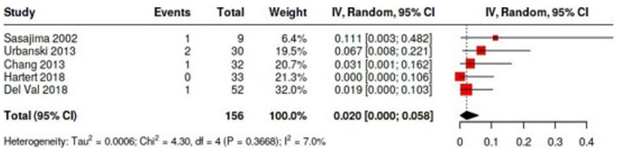

Figure 46: Forest Plot Shows the Effect of Removal of Salem from Original Forest Plot of Bleeding Rates In Open Surgery Cohort Figure 8)

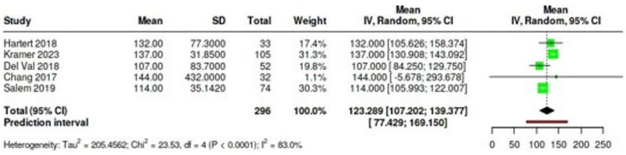

Figure 47: Forest Plot Shows the Effect of Removal of Sirin from Original Forest Plot Of ICU Stay Hours in Open Surgery Cohort Figure (10)

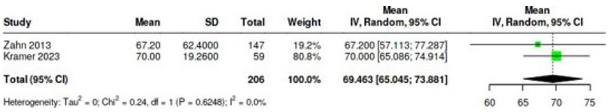

Figure 48: Forest Plot Shows the Effect of Removal Of Del Val from Original Forest Plot Of ICU Stay Hours In Endovascular Surgery Cohort Figure (11)

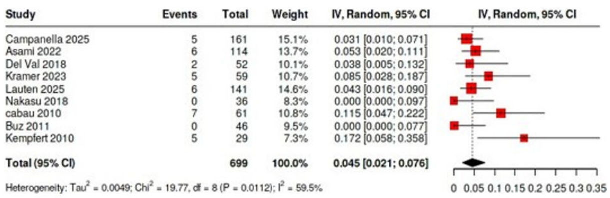

Figure 49: Forest Plot Shows the Effect of Removal of Zahn from Original Forest Plot of 30-Day Mortality Rates in Endovascular Surgery Cohort Figure (3)

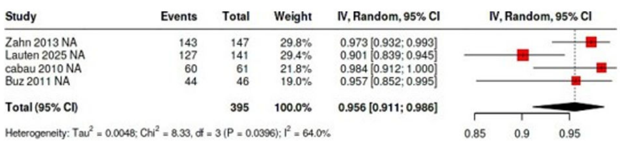

Figure 50: Forest Plot Shows the Effect of Removal of Campanella from Original Forest Plot of Success Rates in Endovascular Surgery Cohort Figure (13)

Quality Assessment

Two reviewers independently and blindly assessed the quality of the included studies, with disagreements resolved by a third reviewer. The ROBINS-I v2 tool was used to evaluate bias across seven domains: confounding, classification of interventions, selection of participants, deviations from intended interventions, missing data, outcome measurement, and selective reporting. The tool uses standardized signaling questions with responses such as "Yes," "Probably Yes," "No," "Probably No," and "No Information" to guide judgments. For studies where ROBINS-I was not applicable, the Joanna Briggs Institute (JBI) checklists for case series and cohort studies were used. Full assessments are detailed in Figures 51 and Tables 1 and 2. Overall, most included studies were judged to be at low risk of bias.

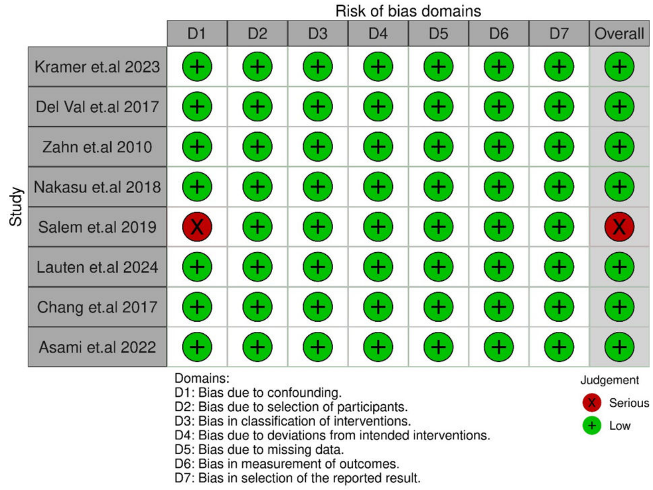

Figure 51: Shows Quality Assessment Using ROBINS-Is Tool

DISCUSSION

Overview of Key Findings

Managing patients with porcelain aorta (PA) remains a significant clinical challenge due to the risks associated with extensive aortic calcification. In this systematic review and meta-analysis of 20 studies involving 1249 patients, both open and endovascular strategies demonstrated comparable short-term outcomes, particularly regarding 30-day mortality (3.1% vs. 5.4%) and stroke rates (3.7% vs. 3.5%). However, each approach presented distinct advantages and drawbacks that merit careful consideration.

Surgical vs. Endovascular Trade-Offs

Open surgery demonstrated a higher technical success rate (100% vs. 93.8%), which may be attributed to direct visualization and precise control during the procedure despite the complexity introduced by calcification. On the other hand, endovascular approaches, while less invasive and associated with shorter ICU stays (60.2 vs. 109.0 hours), had a higher pooled bleeding rate (5.7% vs. 4.5%). This aligns with findings from broader TAVI literature, including the PARTNER trials, which reported elevated vascular complication rates in transfemoral TAVI compared to surgical aortic valve replacement (SAVR), largely due to access-site complications and earlier-generation device profiles [19,20].

Alignment with Guidelines

The 2021 ESC/EACTS guidelines recommend TAVI over SAVR in patients with PA due to the increased technical and embolic risk posed by extensive aortic calcification [6]. Our findings support this recommendation, particularly for patients at high surgical risk. Nevertheless, open surgery remains a viable option, especially in experienced centers where advanced surgical strategies and intraoperative planning can mitigate the risks associated with a porcelain aorta.

Hybrid Approaches: A Promising Option

Although limited in number, studies evaluating hybrid procedures most commonly combining TAVI with off-pump coronary artery bypass (OPCAB) show promising outcomes. One retrospective study reported 100% device success with no 30-day mortality or stroke in a 12-patient hybrid cohort [5]. Another series involving MIDCAB and TAVI in high-risk patients also reported favorable outcomes [21]. These preliminary results suggest that hybrid strategies may offer a safe and effective option for select patients with complex anatomical or comorbid profiles, though further evidence is needed.

Need for Long-Term Evidence

Limited data on long-term outcomes remains a concern. Only three studies reported one-year survival (79.5% open vs. 82.8% endovascular), and just one study Kramer provided five-year data (56% open vs. 82% endovascular) [14,22]. This lack of consistent long-term follow-up makes it difficult to draw firm conclusions about durability and survival, highlighting the need for standardized outcome reporting in future research.

Study Limitations and Sources of Heterogeneity

This meta-analysis has several limitations that warrant consideration. Publication bias was identified for open surgery success rates and five-year survival outcomes, which may have influenced pooled estimates. An important limitation of this review is that all pooled estimates were derived from separate single-arm meta-analyses. Consequently, the study was not designed to perform direct statistical comparisons between open and endovascular strategies, and differences observed between pooled estimates should be interpreted as descriptive rather than comparative. Patients undergoing endovascular procedures are frequently older and have a higher operative risk profile, introducing substantial selection bias that may influence observed outcome differences. Therefore, the apparent advantages of one strategy over another cannot be interpreted as evidence of superiority and should instead be considered hypothesis-generating.

Furthermore, the definition of overall complications was not standardized across included studies, which may have influenced pooled complication estimates. Publication bias analyses should also be interpreted cautiously because several outcomes were reported by a limited number of studies, reducing the reliability of funnel plots and Egger's tests.

Variability in outcome reporting was particularly notable for ICU stay duration and procedural success definitions (ranging from technical completion to valve performance metrics). Most included studies were retrospective, non-randomized, and subject to potential biases, including selection bias, confounding by indication, and unmeasured confounding. Additionally, small sample sizes, incomplete follow-up, and the presence of publication bias, particularly in bleeding and long-term survival outcomes, may affect the accuracy and generalizability of pooled estimates.

CONCLUSION

Both open and endovascular approaches appear to be feasible treatment options for patients with porcelain aorta. In this review, separate single-arm meta-analyses demonstrated acceptable short-term outcomes for both strategies, with differences observed in technical success, complication profiles, and recovery metrics. However, because pooled estimates were derived from separate non-comparative analyses and because substantial clinical heterogeneity and selection bias were present across studies, no conclusions regarding the superiority of one approach over the other can be drawn. Hybrid strategies remain promising but are supported by limited evidence. Further prospective studies with standardized definitions and longer follow-up are needed to determine optimal management strategies for this complex patient population.

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