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REVIEW

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Efficacy and safety of mechanical pulmonary valve replacement: a comprehensive systematic review and meta-analysis

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Abstract

Background Pulmonary valve replacement (PVR) is the most common valve replacement procedure for pulmonary valve dysfunction in congenital heart diseases (CHD). Despite the long-term need for anticoagulation and potential bleeding complications in mechanical PVR (MPVR), prosthetic dysfunction and reoperation might occur less frequently. The major guidelines on the CHD management have no recommendation on the valve type for the PVR. So, we systematically reviewed the latest literature on the efficacy and safety of MPVR with different etiologies.

Methods This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines. The protocol was registered with PROSPERO (CRD42023425339). A systematic search was conducted in PubMed, Scopus, Web of Science, and Embase. The primary outcomes evaluated include all-cause mortality, reintervention for mechanical prostheses, valvular thrombosis, thromboembolic events, prosthetic valve dysfunction, major bleeding events, right ventricular failure, and infective endocarditis. A random-effects model was employed for the meta-analysis. The quality of the studies was assessed using the Newcastle-Ottawa Scale.

Results The literature search was conducted up to June 12, 2023, and included 16 records in the qualitative synthesis, with 13 studies also included in the quantitative synthesis. Our systematic review indicates that the previously published patient-level analysis remains the most reliable evidence to date on MPVR, with 91%, 97%, and 95% 5-year freedom from valvular thrombosis, reintervention, and all-cause mortality, respectively. Our meta-analysis indicated low pooled incidence proportions of other outcomes as follows: Major bleeding (mean follow-up = 68.79 months, 16/336, 5% [95% CI 3–8]); Valvular dysfunction (mean follow-up = 68.89 months, 70/708, 10% [95% CI 8–12]); Thromboembolic events (mean follow-up = 78.28 months, 9/293, 3% [95% CI 2–6]); and Infectious endocarditis (mean follow-up = 42.03 months, 7/518, 1% [95% CI 1–3]).

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Conclusions Despite showing acceptable efficacy and safety in MPVR, there is still a significant knowledge gap in choosing the most appropriate prosthetic valve in patients undergoing PVR. High-quality research is warranted to resolve the existing gap in evidence.

Keywords Pulmonary valve, Heart valve prosthesis, Heart valve prosthesis implantation, Reoperation, Congenital heart defect

Introduction

In patients with congenital heart diseases (CHD), pulmonary valve replacement (PVR) is the most prevalent valve replacement procedure, given that the majority of patients with right-sided CHD, mainly tetralogy of Fallot (ToF) and valvular pulmonary stenosis/regurgitation, require at least a single PVR during the course of their diseases [1–3]. Pulmonary valve dysfunction observed in CHD results in right ventricular (RV) impairment, which can lead to progressive RV failure, life-threatening arrhythmias, and sudden cardiac death [4, 5]. Alleviation of pulmonary valve function by a new valve can preserve or restore the RV size and function and mitigate the associated symptoms [6, 7].

Traditionally, patients undergoing PVR predominantly receive biological prostheses, either pulmonary homografts or bioprostheses, due to lower thrombogenicity, obviating long-term anticoagulation [8, 9]. Moreover, bioprosthetic valves could presently be replaced percutaneously by valve-in-valve transcatheter procedures, avoiding repeated surgeries [10]. Although the rate of biological prosthetic failure in the pulmonary position is reported to be lower compared to left-sided valves [1], bioprosthetic PVR failure requiring redo PVR occurs in 10–20% of patients after ten years, based on the primary etiology [11]. Meanwhile, since conducting PVR at younger ages to prevent the occurrence of RV dysfunction is now strongly advocated [4, 12], and the life expectancy of patients with CHD has improved, the need for more durable valves is growing [9]. Of note, pulmonary homografts, which bear a lower risk of structural valve degeneration and need for reintervention compared to the available xenograft bioprosthetic valves [13], are in short supply [8]. Therefore, mechanical prosthetic valves, with their longer durability and lower risk of reintervention, have received increasing attention as alternatives for biological prostheses, particularly in patients requiring anticoagulation therapy for other reasons [14, 15].

Although mechanical prostheses and the necessity of anticoagulation administration can potentially elevate the risk of thrombotic and bleeding complications, numerous evaluations revealed an acceptable rate of these adverse events following PVR with mechanical valves in the condition of appropriate anticoagulation regimens [15, 16]. In 2015, Dunne et al. conducted a systematic review and meta-analysis on 299 patients with mechanical PVR (MPVR) and determined low incidence rates of 2.2% and 1.5% for valvular thrombosis and non-structural valve dysfunction, respectively [17]. Additionally, the rates of surgical reintervention and thrombolysis were as low as 0.9% and 0.5%, respectively [17]. Nonetheless, this meta-analysis had the major limitations of a relatively small overall sample size and lack of long-term follow-up of the included studies [17]. Consequently, neither the latest guideline of the American Heart Association (AHA)/American College of Cardiology (ACC) nor the most recent guideline of the European Society of Cardiology (ESC) on the management of patients with CHD has provided any recommendation regarding the type of valve for patients undergoing PVR (Supplementary Table S1) [2, 3]. In the present study, we have systematically reviewed the latest literature concerning the role of MPVR.

Materials and methods

This systematic review was performed and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines [18] and a prespecified protocol registered with PROSPERO (CRD42023425339-no further amendment or update was made to the protocol). Since the ethical and institutional review board approvals were attained for all the included studies, no additional approvals were required for this review.

Data sources and search strategy

A systematic search was conducted through PubMed, Scopus, Web of Science, and Embase to identify the studies that addressed surgical PVR using mechanical prostheses. The search was performed until June 12, 2023, using the following search terms ("pulmonary valve" OR "right ventricular outflow tract" OR "pulmonary valve replacement" OR "pulmonary valve implantation") AND ("Mechanical" OR "tilting-disc" OR "bileaflet"). The complete systematic search syntax for all databases is provided in Supplementary Table S2. Furthermore, the bibliography of included studies and relevant review articles was manually searched to find additional studies.

Eligibility criteria and study selection

Studies that met the following eligibility criteria were included in the review: (1) contained original data from a minimum of 10 patients undergoing surgical PVR using a mechanical prosthesis, and (2) reported findings

for at least one of the outcomes of interest, measured after at least 6 months of follow-up, i.e., all-cause mortality [19], reintervention for the mechanical prostheses (characterized as redo-PVR or any surgical manipulation of the previously implanted prostheses) [19], valvular thrombosis (defined as thrombosis at or near the operated valve, interfering valve function and not caused by infection) [19], thromboembolic events (defined as any post-operative embolic event in the absence of infection) [19], prosthetic valve dysfunction (defined as structural or nonstructural valve-related abnormality, not caused by thrombosis or infection) [19], major bleeding events (defined as post-surgical bleeding that is either fatal, occurring in a critical organ or area, significantly reducing hemoglobin level, or prolonged or unexpected bleeding) [20], RV failure, and infective endocarditis (IE) (defined as any infection of the operated valve) [19]. All outcomes, except for major bleeding, were defined according to the guidelines for reporting all-cause mortality and morbidity after cardiac valve interventions [19]. Major bleeding was defined according to the International Society on Thrombosis and Haemostasis (ISTH) criteria [20]. For studies with different classifications, bleeding events were recategorized according to ISTH [20].

This decision to limit the minimum sample size per study to 10 was made to ensure a baseline level of data contribution while avoiding the exclusion of potentially relevant studies, particularly for MPVT for which evidence is limited it is only implemented in a small number of countries and centers, resulting in small sample sizes across most published studies. On the other hand, those studies with fewer than 10 participants were excluded to reduce the influence of extremely small and potentially unstable estimates on the pooled analysis [21]. The reviews, editorials, commentaries, conference abstracts, studies encompassing less than 10 patients with MPVR, and investigations related to PVR using other valve types than a mechanical prosthesis were all excluded. First, the titles and abstracts of the identified records were screened to find relevant articles. At this point, the full texts of the remaining articles were assessed against the mentioned eligibility criteria to include the studies investigating surgical PVR utilizing mechanical valves. Two investigators (SR and AR) independently selected the included studies, and discrepancies were resolved by meeting discussions. For studies with overlapping patient populations published from the same institution, the one with the most comprehensive data was included. Of note, studies comparing MPVR with bioprosthetic PVR (BPVR), consistent with the previously mentioned eligibility criteria, were also included.

Quality assessment and data extraction

The methodological quality of the included studies was assessed using the Newcastle-Ottawa Scale (NOS) [22]. This tool evaluates the observational studies in three main domains of population selection (maximum of 4 points), comparability (maximum of 2 points), and outcome assessment (maximum of 3 points). The comparability domain is not applicable to non-comparative investigations; therefore, the maximum score for comparative and non-comparative studies will be 9 and 7, respectively.

The data regarding basic study characteristics, including the first author, year, study design, number of patients with MPVR and their age and sex, implantation period, number of centers, type of mechanical prosthesis, follow-up duration, previous interventions, concomitant procedures, along with the predefined outcomes were extracted from the included studies. For studies comparing mechanical with bioprosthetic valves, the mentioned prespecified variables of the BPVR group were also extracted. Of the domains of the certainty of evidence, risk of bias and publication bias were assessed. The quality assessment and data extraction processes were independently performed by two investigators (SR and MV). A third investigator (AR) double-checked the quality appraisal findings and the extracted data to ensure accuracy.

Data synthesis

The included studies were categorized into comparative studies (i.e., studies comparing BPVR and MPVR) and non-comparative studies (i.e., reporting only MPVR outcomes). In the qualitative synthesis, the characteristics of all included studies (both comparative and non-comparative) were summarized in Tables 1 and 2. Furthermore, in the quantitative synthesis, we pooled the outcomes reported by the studies and represented them using forest plots.

Statistical analysis

The pooled rates of events and their corresponding 95% confidence intervals (CIs) for the predefined outcomes in patients undergoing MPVR were calculated by employing the Logit transformation method [23]. The statistical heterogeneity was assessed by Cochran's Q and Higgins' I-squared tests [24, 25]. In case of high heterogeneity ($I^2 > 50\%$), random-effect models were applied to pool the estimates; otherwise, fixed-effect models were implemented. Publication bias was tested using Egger's [26] test. All analyses were conducted using R package 'meta' 5.2-0 [27], R version 4.2.1 (R Foundation for Statistical Computing).

Table 1 Characteristics of studies reporting outcomes of mechanical pulmonary valve replacement

Author- Year- Source	Design	Patients, *n*	Age, year	Follow-up time	Reintervention, *n* (%)	All-cause mortality, *n* (%Total)	Valvular thrombosis, *n* (%)	Valvular dysfunction, *n* (%)	Thromboembolic events, *n* (%)	Major bleeding*, *n* (%)	IE, *n* (%)	RVF, *n* (%)
Lillehei [30] -1965-Minnesota, USA	retrospective cohort	25	4-39[a]	13m[b]	0	0	NA	NA	NA	NA	NA	NA
Reiss [31] – 2005-Bad Oeynhausen, Germany	retrospective cohort	37	21 (0.33-61)[c]	72 m (6-132)[c]	2 (2.9)	NA	3 (8)	NA	NA	NA	NA	NA
Dearani [35]- 2005-Minnesota, USA	retrospective cohort	17	NA	8.3y[b]	0	NA	0	NA	NA	NA	NA	NA
Haas [36]- 2005-Munich, Germany	retrospective cohort	14	24.8 ± 9.2[d]	35 m ± 22[d]	0	0	0	0	0	3 (21.5)	1 (7)	2 (14.3)
Waterbolk [34]- 2006-Groningen, The Netherlands	retrospective cohort	28	31.36 ± 12.43[d]	5.5y (2 m-18y)[c]	• 1 (3.6)	• Early: 1 (3.6) • Late: 1 (3.6)	NA	1 (3.6)	NA	1 (3.6)	NA	NA
Horer [15]- 2009- Munich, Germany	prospective cohort	19	25.4 ± 9.8[d]	6.1y ± 2.9[d]	0	0	1 (5.2)	1 (5.2)	0	0	NA	NA
Stulak [14]- 2010- Minnesota, USA	retrospective cohort	54	30 (5–66)[e]	2.2y (3 m-20 y)[f]	0	Late: 5 (9.3)	1 (1.8)	NA	1 (1.8)	4 (7.4)	0	NA
Dos [29]- 2011-Barcelona, Spain	retrospective cohort	22	32 ± 11[d]	7.6y ± 7.6[d]	• 3 (13.6)	• Early:1 (4.5) • Late:0	3 (1.4)	3 (1.4)	NA	0	NA	2 (0.9)
Ovcina [28]- 2011-Graz, Austria	prospective cohort	24	23.1 ± 6.6[d]	31.9 m ± 15.9[d]	NA	0	1 (4.1)	0	NA	2 (8.3)	NA	NA
Shin [32]- 2013-Seoul, Korea	retrospective cohort	37	13.5 (0.58-23)[f]	24.6 m (1.3 m-22.5y)[f]	2 (5.3)	Late: 2 (5.3)	2 (5.3)	2 (5.3)	0	1 (2.7)	NA	NA
Bigdelian [39]- 2014-Isfahan, Iran	retrospective cohort	30	6.33 ± 6.42[d]	10y[g]	• 7 (2.3)	• Late: 4 (13.3) • Early:0	0	1 (3.1)	3 (10)	2 (6.7)	2 (6.67)	1 (3.1)
Freling [8]- 2015- Groningen, The Netherlands	retrospective cohort	66	35 ± 13[d]	5.9y ± 4.8[d]	• 6 (9)	• Early: 2 (3) • Late: 10 (15.1)	7 (10)	6 (9)	NA	NA	NA	NA
Pragt [38]- 2017- patient-level multicenter[h]	retrospective cohort	364	27.16 ± 12.2[d]	4.26y (0–33)[f]	• 20 (5.4)	• Early: 7 (1.9) • Late: 31 (8.5)	35 (9.6)	NA	NA	NA	NA	NA
Gholampour Dehaki [37]- 2019-Tehran, Iran	retrospective cohort	396	24.31 ± 8.97[d]	36 m (24–49)[e]	13 (3.2)	0	41 (10.3)	7 (1.8)	NA	NA	4 (1)	NA
Kim [9]- 2021-Seoul, Korea	retrospective cohort	43	19 (14–38)[e]	7.4y[i]	6 (13.9)	Early: 1 (2.3)	4 (9.3)	7 (16.2)	4 (9.3)	1 (2.3)	NA	NA
Stammnitz [33]- 2022-nationwide, Germany	retrospective cohort	1170 (24 with mechanical PVR)	12 (5–20)[e]	10y (6–10)[e]	0	18 (1.5)[j]	0	1 (3.1)	3 (10)	NA	2 (6.7)	NA

IE, infective endocarditis; m, month; NA, not available; RVF, right ventricular failure, y, year

* Based on surgical patients' ISTH definition for major bleeding

Early mortality is defined as mortality in less than 30 days from surgery. Late mortality is defined as mortality after 30 days of the surgery

[a] Range; [b] Mean; [c] Mean (range); [d] Mean ± SD; [e] Median (IQR); [f] Median (range); [g] No measure of dispersion is reported; [h] Data from Barcelona, Spain; Graz, Austria; Groningen, The Netherlands; Munich and Lübeck, Germany; Rochester, Minnesota, USA; Seoul, Korea; and Tehran, Iran; [i] Median; [j] Time period is not mentioned

Results

Study selection

The PRISMA flow diagram in Supplementary Figure S1 shows the inclusion process. Overall, 7,936 records were yielded from the databases. Of these, 2,269 duplicates, 576 conference abstracts, and 111 non-English records were excluded. Of the remaining 4,980 records, 4,950 were excluded after the title and abstract screening. Then, 30 records were screened for full texts. Finally, of the 16 records included in the qualitative synthesis, 13 were also included in the quantitative synthesis (meta-analysis).

Study characteristics

Of the 16 included studies [8, 9, 14, 15, 28–39], the comparison between MPVR and BPVR was only presented in 4 studies [9, 14, 15, 39], 3 of which were retrospective cohorts [9, 14, 39], and 1 was a prospective cohort [15]. The other studies, 2 prospective cohorts [28, 29], and 10 retrospective cohorts [8, 30–38] presented different single-arm outcomes of MPVR. The studies' characteristics and main reported outcomes were summarized in Tables 1 and 2. The publication date ranged from 1965 to 2022. The studies were conducted in multiple cities in Austria [28], Germany [15, 31, 33, 36], Iran [37, 39], the Netherlands [8, 34], Spain [29], South Korea [9, 32], and the USA [14, 30, 35, 38].

As shown in Table 1, there is a patient-level multicenter international retrospective single-arm study [38] on 364 patients with de novo MPVR. This patient-level study reported the outcomes of valvular thrombosis, reintervention, and all-cause mortality, encompassing the majority of the previously published data [8, 14–16, 28, 29, 32] in studies already included in the present review (7 [8, 14–16, 28, 29, 32] of 16 studies). Since the publication of the patient-level study [38], three studies [9, 33, 37] reporting the mentioned outcomes (i.e., valvular thrombosis, reintervention, and all-cause mortality) were published, one [37] had a significant overlap with the patient-level study, and two were comparative studies [9, 33]. Considering the superior quality of patient-level data owing to the fact that this study had no data overlapping and had direct access to the datasets of each included center, no new pooled analyses were performed for valvular thrombosis, reintervention, and all-cause mortality. Consequently, in our systematic review, only major bleeding, valvular dysfunction, thromboembolic events, and RV failure, which were not reported by the patient-level study [38], were pooled and analyzed. Of note, considering the retrospective nature of the majority of the comparative studies, their limited sample size, and inter-study high heterogeneity, a pooled comparison between the MPVR and BPVR was not conducted, and their results were just systematically reviewed.

Quality assessment

Among the included 16 studies, 4 studies [9, 14, 15, 39] were comparative, and the remaining 12 studies were non-comparative [8, 28–38]. The total NOS scores for comparative studies were in the range of 7 to 9 out of 9, and the total scores for non-comparative studies were 6 or 7 out of 7. All studies scored well in the assessment of risk of bias, indicating the acceptable methodological quality of the included studies. The results of the quality assessment are shown in Supplementary Table S3.

Outcomes

As mentioned earlier, considering the validity of the available patient-level study [38], valvular thrombosis, reintervention, and all-cause mortality were not re-analyzed. The results of the pooled cumulative incidence proportion of each outcome are represented subsequently. Different outcomes reported by each study are presented in Table 3.

Valvular thrombosis, reintervention, and all-cause mortality

The patient-level study [38] was a multicenter retrospective study conducted in 2017. This study collected data from studies reporting at least 15 MPVR patients between 2009 and 2015, hence including the data of 7 other included studies [8, 14–16, 28, 29, 32]. Overall, they collected the data on 364 first MPVR patients. The mean (standard deviation (SD)) age of the patients was 27.16 (12.2) years at the time of MPVR, with a median (range) of 4.26 (0–33) years.

Valvular thrombosis occurred in 35 (9.6%) patients with a median (range) time of 2.9 (0.3–23.2) years between PVR and valvular thrombosis. Five-year, 10-year, and 15-year freedoms from valvular thrombosis were 91% (95% CI, 87-94%), 86% (95% CI, 81-91%), and 79% (95% CI, 70-87%), respectively.

Reintervention occurred in 20 (5.5%) patients with a mean (SD) time of 7.6 (5.5) years between the first PVR and reintervention. Five-year, 10-year, and 15-year freedoms from reintervention were 97% (95% CI, 94-99%), 91% (95% CI, 85-95%), and 81% (95% CI, 71-90%), respectively. All-cause mortality occurred in 31 (8.5%) patients, of whom 1 (22.6%) died operatively, 15 (48.4%) died of cardiac cause (none were valve- or thrombosis-related), and in 9 (29%) patients, the cause of mortality was unknown. Five-year, 10-year, and 15-year survivals were 95% (95% CI, 92-97%), 91% (95% CI, 85-95%), and 79% (95% CI, 67-88%), respectively. Other outcomes not reported by the patient-level study [38], are presented below.

Table 2 Characteristics of the studies reporting comparison between mechanical versus bioprosthetic pulmonary valve replacement

Author- Year- Source	Design	MPVR/ BPVR, *n*	Reintervention, *n* (%)			All-cause mortality, *n* (%)			Valvular dysfunction, *n* (%)			Thromboembolic events, *n* (%)			Major bleeding, *n* (%)		
			MPVR	BPVR	*P*	MPVR	BPVR	*P*	MPVR	BPVR	*P*	MPVR	BPVR	*P*	MPVR	BPVR	*P*
Bigdelian [39]-2014 Isfahan, Iran	retrospective cohort	30/32	7 (23.3)	12 (37.5)	0.17	4 (13.3)	3 (9.3)	0.46	1 (3.1)	5 (15.6)	0.33	3 (10)	0	0.1	2 (6.7)	0	0.47
Kim [9]- 2021-Seoul, Korea	retrospective cohort	43/88	6 (13.9)	4 (4.5)	0.06	1 (2.3)	0	0.15	7 (16.2)	9 (10.2)	0.32	4 (9.3)	0	0.003	NA	NA	NA
Stulak [14]- 2010- Minnesota, USA	retrospective cohort	54/108	5-year freedom from reintervention: MPVR 100% vs. BPVR 90%		0.018	5-year survival: MPVR 81% vs. BPVR 75%		0.1	NA		NA	NA			5-year freedom from bleeding complications: MPVR 88% vs. BPVR 96%		0.08
Horer [15]- 2009- Munich, Germany	prospective cohort	19/19	10-year freedom from reintervention was not significantly different between the groups		0.32	NA		NA	NA		NA	NA			NA		NA

BPVR, bioprosthetic pulmonary valve replacement; MPVR, mechanical pulmonary valve replacement; P, *p*-value

Other outcomes

Major bleeding

Ten studies [8, 9, 14, 15, 28, 29, 32, 34, 36, 39] reported the major bleeding cumulative incidence in a total of 336 patients following MPVR (Fig. 1). Major bleeding occurred in 16 out of 336 patients in a mean (95% CI) follow-up of 68.79 months (46.61–90.98), accounting for a pooled incidence proportion of 0.05 (95% CI 0.03–0.08, $I^2 = 0\%$, Cochran's Q *p*-value = 0.52). A significant publication bias was found with Egger's test *p*-value of 0.06, as visualized in the funnel plot in Supplementary Figure S2.

Valvular dysfunction

Eleven studies [8, 9, 14, 15, 28, 29, 32, 34, 36, 37, 39] reported the cumulative incidence of valvular dysfunction in 708 patients who had undergone MPVR (Fig. 2). Valvular dysfunction occurred in 70 out of 708 patients in a mean (95% CI) follow-up of 68.89 months (47.61–90.18), accounting for a pooled incidence proportion of 0.10 (95% CI 0.08–0.12, $I^2 = 0\%$, Cochran's Q *p*-value = 0.74). A significant publication bias was found with Egger's test *p*-value of 0.02. The funnel plot is represented in Supplementary Figure S3.

Thromboembolic events

Eight studies [8, 9, 14, 29, 32, 34, 36, 39] reported cumulative incidence of thromboembolic events in 293 patients who had undergone MPVR (Fig. 3). Thromboembolic events were reported in 9 out of 293 patients in a mean (95% CI) follow-up of 78.28 months (49.83- 106.74), and the pooled incidence proportion was measured to be 0.03 (95% CI 0.02–0.06, $I^2 = 0\%$, Cochran's Q *p*-value = 0.65). There was a significant publication bias among the studies, as visualized in the funnel plot (Supplementary Figure S4), showing Egger's test *p*-value of 0.004.

IE

Five studies [14, 33, 36, 37, 39], including 518 patients who had undergone MPVR, reported the cumulative incidence of IE (Fig. 4). IE occurred in 7 out of 518 patients in a mean (95% CI) follow-up of 42.03 months (4.01–80.05), with the pooled incidence proportion of 0.01 (95% CI 0.01–0.03, $I^2 = 37\%$, Cochran's Q *p*-value = 0.17). No publication bias was found among the studies with Egger's test *p*-value of 0.60, and the funnel plot is represented in Supplementary Figure S5.

RV failure

Three studies [29, 36, 39] were pooled for the cumulative incidence of RV failure following MPVR in 66 patients (Supplementary Figure S6); however, none of these 3 studies reported a definition for RV failure. RV failure was reported in 5 out of 66 patients in a mean (95% CI) follow-up of 60.04 months (5.29-114.79), accounting for

Table 3 Different outcomes reported in the included studies

Outcomes	Lillehei 1965	Reiss 2005	Dearani 2004	Hass 2004	Waterbolk 2006	Horer 2009	Stulak 2010	Dos 2011	Ovcina 2011	Shin 2013	Bigdelian 2014	Freling 2014	Pragt 2017	Gholampour Dehaki 2019	Kim 2021	Stammnitz 2022
Reintervention	×	×	×	×	×	×	×	×		×	×	×	×	×	×	×
Mortality	×			×	×	×	×	×	×	×	×	×	×	×	×	×
Valvular thrombosis		×	×	×		×	×	×	×	×	×	×	×	×	×	×
Valvular dysfunction				×	×			×	×	×	×	×		×	×	×
Thromboembolism				×		×	×			×	×				×	×
Major bleeding				×	×	×	×	×	×	×	×				×	×
Infectious endocarditis				×			×				×			×		×
Right ventricular failure				×				×			×					

a pooled incidence of 0.08 (95% CI 0.03–0.17, $I^2 = 0\%$, Cochran's Q p-value = 0.46). Due to the small number of studies, no tests were performed for publication bias; rather, publication bias was visually investigated in a funnel plot (Supplementary Figure S7). The summary of key findings from the meta-analysis of predefined outcomes can be found in Supplementary Table S4.

Outcomes: comparative studies

Four studies [9, 14, 15, 39] compared the outcomes of BPVR and MPVR (Table 2). The first study compared 30 patients treated with MPVR versus 32 patients with BPVR [39]. No significant difference was observed between the two groups in terms of reintervention, all-cause mortality, valvular dysfunction, and thromboembolic events (reintervention: MPVR 7 (23.3%) vs. BPVR 12 (37.5%), p-value = 0.17; all-cause mortality: MPVR 4 (13.3%) vs. BPVR 3 (9.3%), p-value = 0.46; valvular dysfunction: MPVR 1 (3.1%) vs. 5 (15.6%), p-value = 0.33; thromboembolic events: MPVR 3 (10%) vs. BPVR 0 (0.0%), p-value = 0.10). Likewise, in the second study [9] comparing 43 MPVR and 88 BPVR patients, no significant differences were observed in terms of reintervention, all-cause mortality, and valvular dysfunction (reintervention: MPVR 6 (13.9%) vs. 4 (4.5%), p-value = 0.06; all-cause mortality: MPVR 1 (2.3%) vs. BPVR 0 (0.0%), p-value = 0.15; valvular dysfunction: MPVR 7 (16.2%) vs. BPVR 9 (10.2%), p-value = 0.32), but reported a significantly higher rate of thromboembolic events in the MPVR group (MPVR 4 (9.3%) vs. BPVR 0 (0.0%), p-value = 0.003). In the third study [14] on 54 MPVR and 108 BPVR patients, 5-year freedom from reintervention was 100% for MPVR vs. 90% for BPVR, and the difference between the groups was significant (p-value = 0.018). However, no significant difference was found between the groups in terms of survival (5-year survival: MPVR 81% vs. BPVR 75%, p-value = 0.1) and bleeding (5-year freedom from bleeding complications: MPVR 88% vs. BPVR 96%, p-value = 0.08). The last study [15] on 19 MPVR vs. 19 BPVR patients, reported that the 10-year freedom from reintervention was not significantly different between the groups (p-value = 0.32).

Discussion

This is a comprehensive and updated systematic review of the current literature regarding the efficacy and safety of MPVR. The procedure is still exerted by a few centers worldwide, which justifies the small number of studies and their limited sample size. Our updated review showed that the patient-level analysis published by Pragt et al. [38] in 2016, encompassing the majority of previously published evidence, is still the most reliable evidence on valvular durability and patient survival, reporting freedom rates from valvular thrombosis,

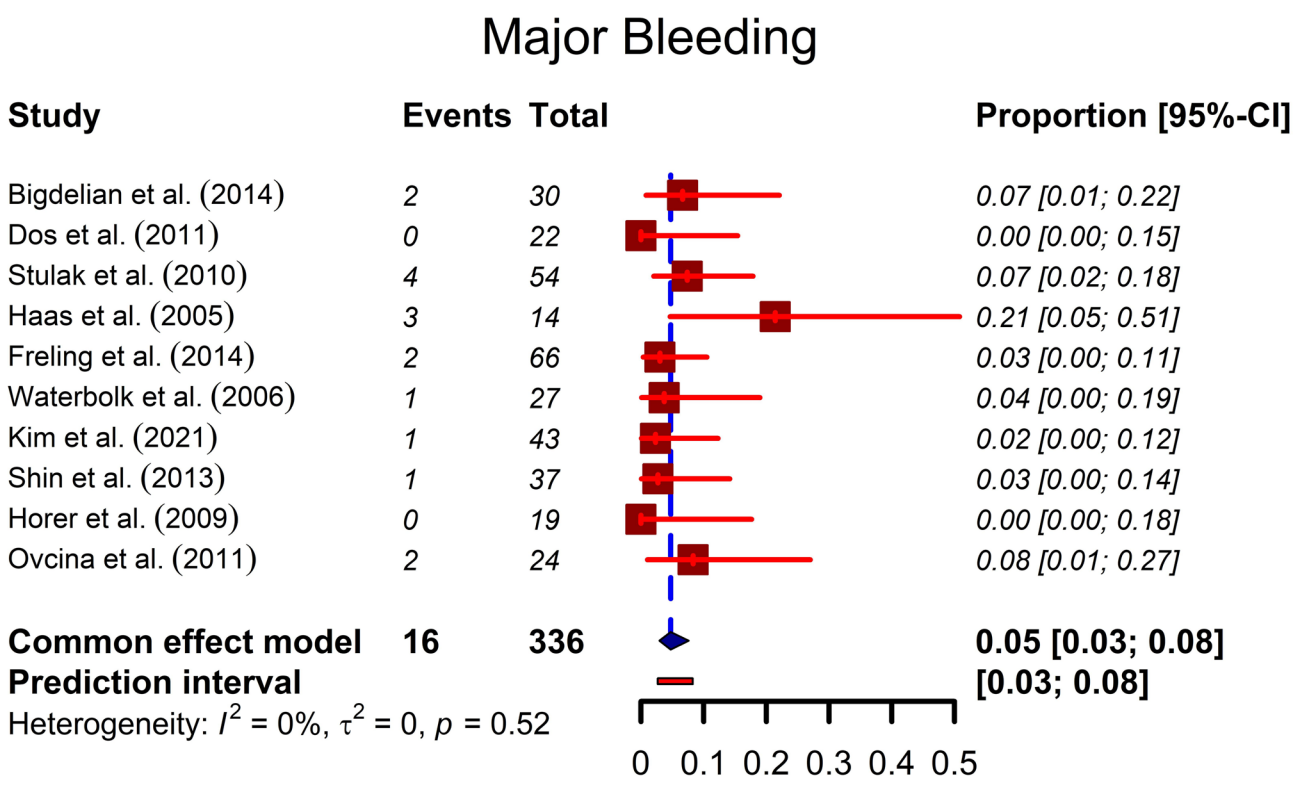

Fig. 1 Cumulative incidence of major bleeding in mechanical pulmonary valve replacement

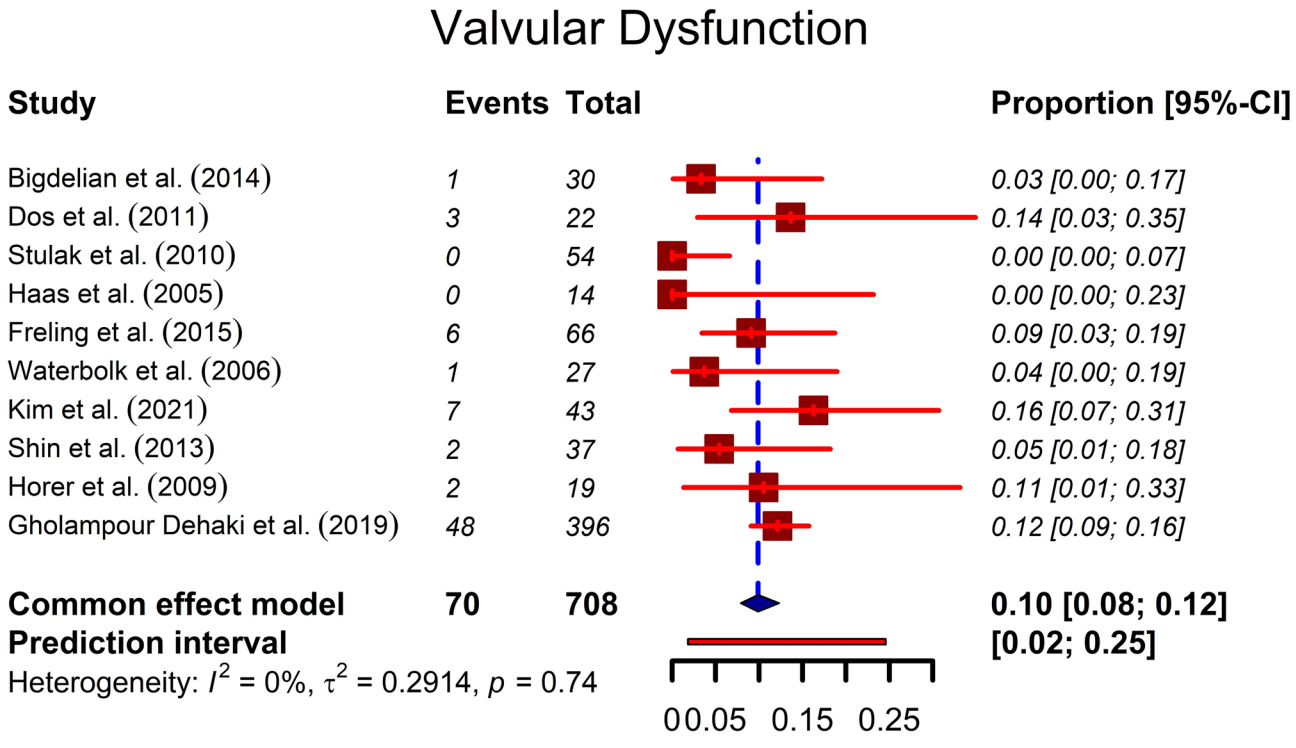

Fig. 2 Cumulative incidence of valvular dysfunction in mechanical pulmonary valve replacement

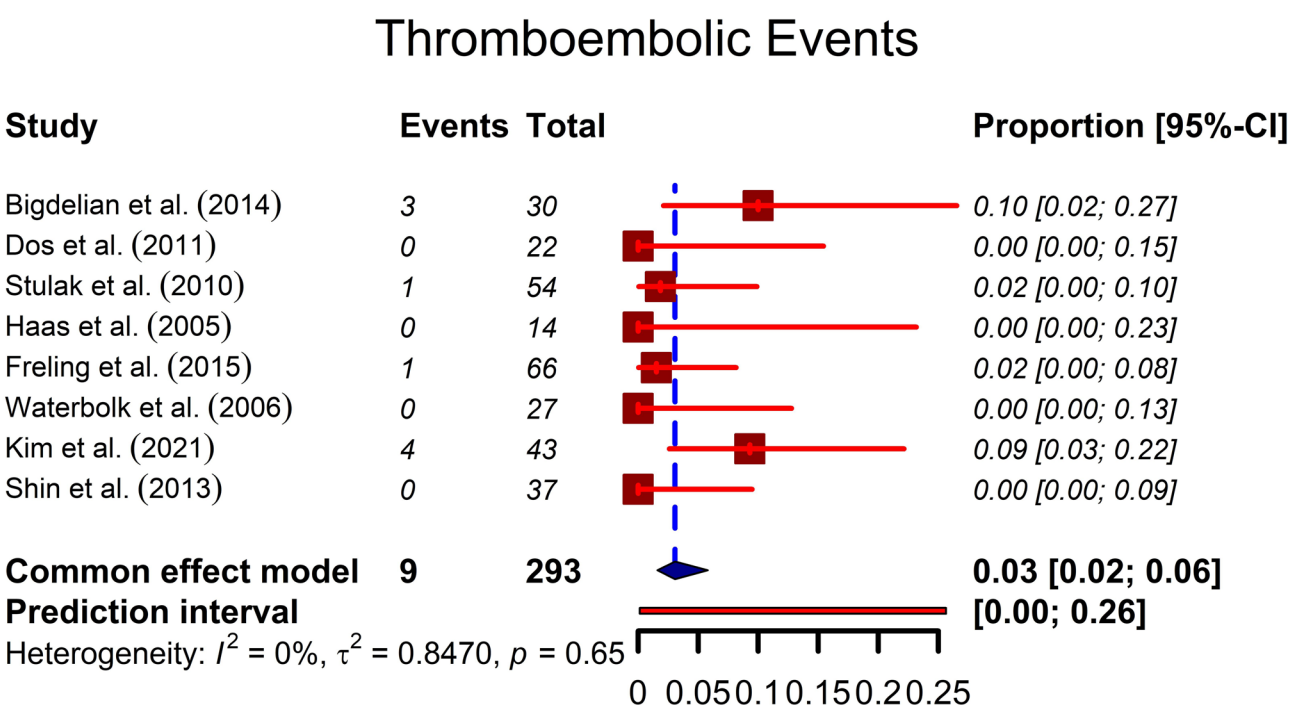

Fig. 3 Cumulative incidence of thromboembolic events in mechanical pulmonary valve replacement

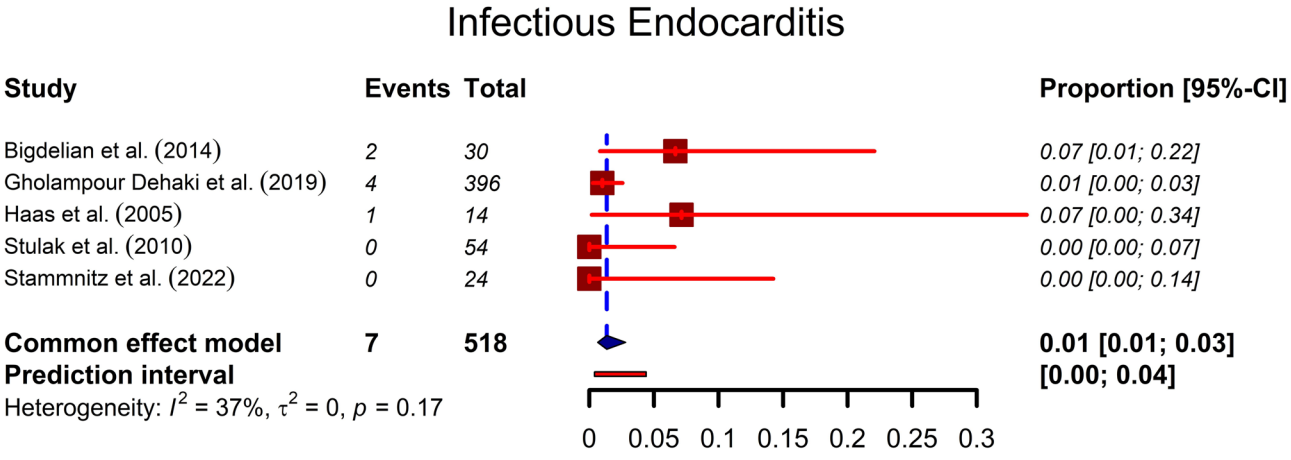

Fig. 4 Cumulative incidence of infective endocarditis in mechanical pulmonary valve replacement

reintervention, and all-cause mortality at 91%, 97%, and 95%, respectively. However, despite its large sample size and the unified approach to outcome reporting, outcome assessment in the majority of the previous studies was retrospective and some major determinants were not analyzed. Thus, new pooled analyses were performed for remaining pivotal outcomes such as major bleeding, which despite acceptable and low incidence proportions, the majority of the data are derived from retrospective cohorts. Our meta-analysis indicated low pooled incidence proportions for key outcomes, including major bleeding (5 [95% CI 3–8]), valvular dysfunction (10 [95% CI 8–12]), thromboembolic events (3 [95% CI 2–6]), and infectious endocarditis (1 [95% CI 1–3]).

In other words, none of the studies included in the meta-analysis were randomized trials, and only 2 were prospective cohorts, one of which had a matched comparison group. Finally, similar methodological limitations existed in the available comparative studies on MPVR versus other valve types which rendered any direct comparison.

Bioprosthetic valves are widely utilized during PVR due to their better-matched size, their lower risk of thromboembolic events, and lack of need for lifelong anticoagulation [8, 9]. On the other hand, mechanical valves are considered more durable but bear a high risk of thrombosis and warrant anticoagulation therapy with vitamin K antagonists (VKAs), which might translate to

excess bleeding events. Consequently, valve durability and thrombosis, patient survival, and major bleeding are the major determinants for the selection of optimal heart valves.

The rate of valve dysfunction, defined as structural or nonstructural valve-related abnormality not caused by thrombosis or infection [19], among the included studies in the current analysis was between 0% and 16.2%, with a pooled rate of 10% (95% CI 8%-12%) (Table 1). In the patient-level multicenter study by Pragt et al., 10-year freedom from reintervention was 91% (95% CI, 85-95%) [38]. A heterogenous rate of 36% [40] to 96% [41] was reported for valvular failure and reintervention in patients with BPVR, which varied based on bioprosthesis types and characteristics of patients. For instance, younger age, pulmonary atresia with ventricular septal defect, and stentless bioprosthetic were associated with an increased risk of reintervention [12, 42, 43]. The pooled rate of 5-year redo PVR was 4.9% in a meta-analysis of 48 studies including patients with PVR after operative repair of ToF [6]. In a recent updated meta-analysis of 84 studies, the rates of redo PVR in patients with repaired ToF were 3.7% and 16.8% within 5 years and 10 years, respectively [11]. Of note, all the described systematic reviews limited their population to ToF patients and occasionally, their population has a small subgroup of MPVR. The median BPVR durability in a recent nationwide study was 17 years and was inversely associated with younger patient age at PVR and a smaller true inner valve diameter [44]. In summary, available evidence showed potentially similar valve durability in patients undergoing MPVR with an acceptable rate of reintervention. It should be noted that, unlike bioprosthetic valves, percutaneous valve-in-valve redo PVR cannot be performed in patients with prior MPVR. High-quality prospective studies are required to ascertain the durability of mechanical valves compared to bioprostheses in the pulmonary position.

Contrary to the durability, valve thrombosis is a major concern in MPVR. Compared to bioprosthesis, mechanical valves carry a substantially higher risk of thrombosis, and approximately 95% of prosthetic valve thrombosis occurs in mechanical valves [45]. To date, no mechanical prosthetic valve has been designed specifically for the pulmonary position, and aortic mechanical prostheses are usually employed during the PVR [38]. However, due to the lower blood pressure in the right heart compared to the left, the rate of mechanical valve thrombosis in the pulmonary position is higher than in the aortic position. The rate of mechanical valve thrombosis in the aortic position has been estimated to be between 0 and 0.6% per patient-year [46–48], while, for the MPVR, it is reported to be 1.7% per patient-year [38]. However, the rate of valvular thrombosis after MPVR shows large variations between studies from various centers, from 0% [36] up to 10.3% [37] (Table 1). Inadequate anticoagulation is considered the most crucial factor leading to mechanical valve thrombosis [39]. Direct oral anticoagulants were inferior to VKAs in several RCTs in patients with mechanical prosthetic valve thrombosis [49–52]. Thus, VKAs remain the only anticoagulant for the life-long treatment of patients with mechanical heart valves, which have a narrow therapeutic window and require routine international normalized ratio (INR) monitoring [49]. Apart from VKA-related challenges, unlike the left prosthetic heart valves, no definite INR range was defined for MPVR by international guidelines [2, 3] and studies reported varied thrombosis and bleeding outcomes based on their tested INR range [9, 37–39]. The pooled estimates in our meta-analysis detected a rate of 3% (95% CI 2%-6%) for thromboembolic events in MPVR. On the other hand, the risk of hemorrhagic complications increases exponentially in INR above 4.5 [53]. The rate of major bleeding across the included studies is estimated to be 5% (95% CI 3%-8%). In comparison with BPVR, the rate of hemorrhagic complications is believed to be higher in MPVR due to the life-long use of VKAs. In the study by Stulak et al. [14], the rate of major bleeding was compared between 54 patients with MPVR and 104 age-, gender-, and diagnosis-matched patients with BPVR. In MPVR group 3 of 54 patients and in BPVR group 4 of 108 patients developed major bleeding events; however, it should be noted that two of the four patients with major bleeding in the BPVR group were taking warfarin for atrial fibrillation. Actuarial freedom from bleeding events was 88% for the MPVR versus 96% for the BPVR ($p = 0.08$). Similarly, Bigdelian et al. reported major bleeding in 6.7% of patients with MPVR and 0% in patients undergoing BPVR [39]. The majority of available systematic reviews on BPVR patients did not address bleeding outcomes [6, 11, 54, 55]. Although these findings were not derived from fully adjusted analyses, it is highly plausible that real-world practice follows similar patterns. In this regard, adequate availability of anticoagulation services and approaches to educating patients about anticoagulation therapy play crucial roles in achieving stable anticoagulation in the therapeutic range and prevention of thromboembolic and hemorrhagic events [38, 49].

Concerning mortality, the results of the multicenter study by Pragt et al. indicated a 10-year survival rate of 91% (95% CI, 85-95%) in patients undergoing MPVR [38]. Similar survival rates have been reported for patients undergoing BPVR. In a study using homografts in 136 patients, the rate of 10-year survival was 91%, and the mortality was associated with the male sex, older age at the time of operation, and the use of preoperative diuretics [56]. The recent meta-analysis of PVR in patients with ToF reported a pooled mortality rate of 6.2% in 10 years

Table 4 Gaps of evidence in mechanical pulmonary valve replacement

Condition	Question
Indication	Which patients are more suitable for MPVR versus BPVR? What are the potential predictors for valve selection?
Valve type selection	Are left-sided heart valves for right-sided valves pathologies? Should potentially-less-thrombogenic heart valves (e.g., On-X) be more advocated for right-sided valve pathologies?
Medical therapy	
Optimum INR range	What is the optimum INR range in patients with MPVR?
RV dilatation therapies	What is the optimal right-sided heart failure medical treatment in patients undergoing PVR?
PAH therapies	Is there a role for PAH therapies in ToF before or after PVR?
Follow-up	
Long-term outcomes	How long is the valve durability after MPVR? Are patients with right-sided valve replacement more susceptible to valvular dysfunction compared to left-sided valve replacement? What proportion of the patients undergoing MPVR will experience adverse events (e.g., endocarditis, major bleeding, RV failure, and valve thrombosis)? Do PVR and ventricular tachycardia ablation decrease the risk of sudden cardiac death?
Quality of life	What are the determinants of impaired quality of life in patients undergoing MPVR?
Serial testing	What is the optimal timing for PVR in asymptomatic patients with ToF?
Imaging	What is the best protocol of imaging for follow-up after MPVR?
Special populations	
Pregnancy	Is there room for MPVR in women at childbearing age considering the potential higher durability?

BPVR, bioprosthetic pulmonary valve replacement; INR, international normalized ratio; MPVR, mechanical pulmonary valve replacement; PAH, pulmonary arterial hypertension; PVR, pulmonary valve replacement; RV, right ventricle; ToF, tetralogy of Fallot; VKA, vitamin K antagonist

[11]. In another systematic review, the 10-year survival rate after PVR in patients with repaired ToF ranged from 76.4 to 100% [54]. It is worth mentioning that mortality after right-sided valve replacement surgeries is strongly associated with patient characteristics and underlying diseases [42, 57]; therefore, these findings should be interpreted with caution. Regarding IE, our meta-analysis indicated a rate of 1% (95% CI 1%-3%), which was in line with the previous estimates of 1–6% [58]. Similar IE rates have been reported for mechanical and bioprosthetic valves [58].

Limitations

This study has some limitations that merit consideration. First, all the included studies had observational designs, which may be subjected to selection or reporting bias. Second, because of the publication of a patient-level multicenter study by Pragt et al. [38] and the overlap between this study and several previously published articles, we were unable to conduct a meta-analysis for the three outcomes of valvular thrombosis, reintervention, and all-cause mortality. Third, the number of comparative studies was limited, and the direct statistical comparison between MPVR and BPVR was not plausible.

Conclusions

In the present systematic review, available evidence regarding the efficacy and safety of MPVR was reviewed. Considering the quality of the evidence, we believe a significant knowledge gap (summarized in Table 4) still exists on the selection of optimal prosthetic valves in patients undergoing PVR. As proven by studies of left heart valves and considering the complexity of the primary etiology of PVR, the one-size-fits-all approach will probably fail, and the determination of valid predictors is crucial.

Abbreviations

BPVR	Bioprosthetic pulmonary valve replacement
CHD	Congenital heart diseases
MPVR	Mechanical pulmonary valve replacement
PVR	Pulmonary valve replacement
ToF	Tetralogy of Fallot

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

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Author contributions

AR, SR, YP, MV, and HG conducted the literature search and screening. YT, MM, and SS performed data extraction and ensured data accuracy. HB, SR, and AR conducted statistical analyses. AJ, ZK, HT, and FF contributed to the result interpretation. MGD, BG, and PS critically revised the manuscript and prepared the final draft. All authors read and approved the final manuscript.

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
The authors declare no competing interests.

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References

1. Stulak JM, Mora BN, Said SM, Schaff HV, Dearani JA. Mechanical pulmonary valve replacement. Seminars in thoracic and cardiovascular surgery pediatric cardiac surgery annual. 2016;19(1):82–9.
2. Baumgartner H, De Backer J, Babu-Narayan SV, Budts W, Chessa M, Diller GP, et al. 2020 ESC guidelines for the management of adult congenital heart disease. Eur Heart J. 2021;42(6):563–645.
3. Stout KK, Daniels CJ, Aboulhosn JA, Bozkurt B, Broberg CS, Colman JM, et al. 2018 AHA/ACC guideline for the management of adults with congenital heart disease: a report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines. J Am Coll Cardiol. 2019;73(12):e81–192.
4. Frigiola A, Tsang V, Bull C, Coats L, Khambadkone S, Derrick G, et al. Biventricular response after pulmonary valve replacement for right ventricular outflow tract dysfunction: is age a predictor of outcome? Circulation. 2008;118(14 Suppl):S182–90.
5. Gatzoulis MA, Balaji S, Webber SA, Siu SC, Hokanson JS, Poile C, et al. Risk factors for arrhythmia and sudden cardiac death late after repair of tetralogy of fallot: a multicentre study. Lancet (London England). 2000;356(9234):975–81.
6. Ferraz Cavalcanti PE, Sá MP, Santos CA, Esmeraldo IM, de Escobar RR, de Menezes AM, et al. Pulmonary valve replacement after operative repair of tetralogy of fallot: meta-analysis and meta-regression of 3,118 patients from 48 studies. J Am Coll Cardiol. 2013;62(23):2227–43.
7. Gengsakul A, Harris L, Bradley TJ, Webb GD, Williams WG, Siu SC, et al. The impact of pulmonary valve replacement after tetralogy of fallot repair: a matched comparison. Eur J cardio-thoracic Surgery: Official J Eur Association Cardio-thoracic Surg. 2007;32(3):462–8.
8. Freling HG, van Slooten YJ, van Melle JP, Ebels T, Hoendermis ES, Berger RM, et al. Pulmonary valve replacement: twenty-six years of experience with mechanical valvar prostheses. Ann Thorac Surg. 2015;99(3):905–10.
9. Kim DH, Choi ES, Kwon BS, Yun TJ, Cha SG, Baek JS, et al. Pulmonary valve replacement following repair of tetralogy of fallot: comparison of outcomes between bio- and mechanical prostheses. Eur J cardio-thoracic Surgery: Official J Eur Association Cardio-thoracic Surg. 2021;60(4):947–54.
10. Asoh K, Walsh M, Hickey E, Nagiub M, Chaturvedi R, Lee KJ, Benson LN. Percutaneous pulmonary valve implantation within bioprosthetic valves. Eur Heart J. 2010;31(11):1404–9.
11. Van den Eynde J, Sá MPBO, Vervoort D, Roever L, Meyns B, Budts W, et al. Pulmonary valve replacement in tetralogy of fallot: an updated meta-analysis. Ann Thorac Surg. 2022;113(3):1036–46.
12. Lee C, Kim YM, Lee CH, Kwak JG, Park CS, Song JY, et al. Outcomes of pulmonary valve replacement in 170 patients with chronic pulmonary regurgitation after relief of right ventricular outflow tract obstruction: implications for optimal timing of pulmonary valve replacement. J Am Coll Cardiol. 2012;60(11):1005–14.
13. Cocomello L, Meloni M, Rapetto F, Baquedano M, Ordoñez MV, Biglino G, et al. Long-term comparison between pulmonary homograft versus bioprosthesis for pulmonary valve replacement in tetralogy of fallot. J Am Heart Association. 2019;8(24):e013654.
14. Stulak JM, Dearani JA, Burkhart HM, Connolly HM, Warnes CA, Suri RM, Schaff HV. The increasing use of mechanical pulmonary valve replacement over a 40-year period. Ann Thorac Surg. 2010;90(6):2009–14. discussion 14–5.
15. Hörer J, Vogt M, Stierle U, Cleuziou J, Prodan Z, Schreiber C, Lange R. A comparative study of mechanical and homograft prostheses in the pulmonary position. Ann Thorac Surg. 2009;88(5):1534–9.
16. Dehaki MG, Ghavidel AA, Omrani G, Javadikasgari H. Long-term outcome of mechanical pulmonary valve replacement in 121 patients with congenital heart disease. Thorac Cardiovasc Surg. 2015;63(5):367–72.
17. Dunne B, Xiao A, Litton E, Andrews D. Mechanical prostheses for right ventricular outflow tract reconstruction: a systematic review and meta-analysis. Ann Thorac Surg. 2015;99(5):1841–7.
18. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ (Clinical Res ed). 2009;339:b2535.
19. Akins CW, Miller DC, Turina MI, Kouchoukos NT, Blackstone EH, Grunkemeier GL, et al. Guidelines for reporting mortality and morbidity after cardiac valve interventions. Ann Thorac Surg. 2008;85(4):1490–5.
20. Schulman S, Angerås U, Bergqvist D, Eriksson B, Lassen MR, Fisher W. Definition of major bleeding in clinical investigations of antihemostatic medicinal products in surgical patients. J Thromb Haemost. 2010;8(1):202–4.
21. Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, Welch VA, editors. Cochrane handbook for systematic reviews of interventions version 6.5 (updated August 2024). Cochrane, 2024. Available from www.training.cochrane.org/handbook
22. Peterson J, Welch V, Losos M, Tugwell P. The Newcastle-Ottawa scale (NOS) for assessing the quality of nonrandomised studies in meta-analyses. Ottawa: Ottawa Hospital Research Institute. 2011;2(1):1–12.
23. Stijnen T, Hamza TH, Ozdemir P. Random effects meta-analysis of event outcome in the framework of the generalized linear mixed model with applications in sparse data. Stat Med. 2010;29(29):3046–67.
24. Cohen JF, Chalumeau M, Cohen R, Korevaar DA, Khoshnood B, Bossuyt PM. Cochran's Q test was useful to assess heterogeneity in likelihood ratios in studies of diagnostic accuracy. J Clin Epidemiol. 2015;68(3):299–306.
25. Higgins JP, Thompson SG. Quantifying heterogeneity in a meta-analysis. Stat Med. 2002;21(11):1539–58.
26. Egger M, Davey Smith G, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. BMJ (Clinical Res ed). 1997;315(7109):629–34.
27. Balduzzi S, Rücker G, Schwarzer G. How to perform a meta-analysis with R: a practical tutorial. Evid Based Ment Health. 2019;22(4):153–60.
28. Ovcin I, Knez I, Curcic P, Ozkan S, Nagel B, Sorantin E, et al. Pulmonary valve replacement with mechanical prostheses in re-do fallot patients. Interact Cardiovasc Thorac Surg. 2011;12(6):987–91.
29. Dos L, Muñoz-Guijosa C, Mendez AB, Ginel A, Montiel J, Padro JM, Subirana MT. Long term outcome of mechanical valve prosthesis in the pulmonary position. Int J Cardiol. 2011;150(2):173–6.
30. Lillehei CW, Simmons RL, Todd DB. Late hemodynamic response to correction of isolated pulmonary stenosis. Circulation. 1965;32:258–64.
31. Reiss N, Blanz U, Bairaktaris H, Koertke A, Korfer R. Mechanical valve replacement in congenital heart defects in the era of international normalized ratio self-management. ASAIO J. 2005;51(5):530–2.
32. Shin HJ, Kim YH, Ko JK, Park IS, Seo DM. Outcomes of mechanical valves in the pulmonic position in patients with congenital heart disease over a 20-year period. Ann Thorac Surg. 2013;95(4):1367–71.
33. Stammnitz C, Huscher D, Bauer UMM, Urban A, Nordmeyer J, Schubert S, et al. Nationwide registry-based analysis of infective endocarditis risk after pulmonary valve replacement. J Am Heart Association. 2022;11(5):e022231.
34. Waterbolk TW, Hoendermis ES, den Hamer IJ, Ebels T. Pulmonary valve replacement with a mechanical prosthesis. Promising results of 28 procedures in patients with congenital heart disease. Eur J cardio-thoracic Surgery: Official J Eur Association Cardio-thoracic Surg. 2006;30(1):28–32.
35. Dearani JA. Is there a role for mechanical valved conduits in the pulmonary position? Invited commentary. Ann Thorac Surg. 2005;79(5):1667–8.
36. Haas F, Schreiber C, Horer J, Kostolny M, Holper K, Lange R. Is there a role for mechanical valved conduits in the pulmonary position? Ann Thorac Surg. 2005;79(5):1662–8.

37. Dehaki MG, Al-Dairy A, Rezaei Y, Omrani G, Jalali AH, Javadikasgari H, Dehaki MG. Mid-term outcomes of mechanical pulmonary valve replacement: a single-institutional experience of 396 patients. Gen Thorac Cardiovasc Surg. 2019;67(3):289–96.
38. Pragt H, van Melle JP, Javadikasgari H, Seo DM, Stulak JM, Knez I, et al. Mechanical valves in the pulmonary position: an international retrospective analysis. J Thorac Cardiovasc Surg. 2017;154(4):1371–e81.
39. Bigdelian H, Mardani D, Sedighi M. Comparative effects of pulmonary valve replacement (PVR) surgery with bioprosthetic and mechanical valves on early and late outcome of patients after congenital heart surgeries: 10 years of experience. Ind J Thorac Cardiovasc Surg. 2014;30(4):257–63.
40. Chen XJ, Smith PB, Jaggers J, Lodge AJ. Bioprosthetic pulmonary valve replacement: contemporary analysis of a large, single-center series of 170 cases. J Thorac Cardiovasc Surg. 2013;146(6):1461–6.
41. Babu-Narayan SV, Diller GP, Gheta RR, Bastin AJ, Karonis T, Li W, et al. Clinical outcomes of surgical pulmonary valve replacement after repair of tetralogy of fallot and potential prognostic value of preoperative cardiopulmonary exercise testing. Circulation. 2014;129(1):18–27.
42. Sabate Rotes A, Eidem BW, Connolly HM, Bonnichsen CR, Rosedahl JK, Schaff HV, et al. Long-term follow-up after pulmonary valve replacement in repaired tetralogy of fallot. Am J Cardiol. 2014;114(6):901–8.
43. Kwak JG, Bang JH, Cho S, Kim ER, Shih BC, Lee CH, Kim WH. Long-term durability of bioprosthetic valves in pulmonary position: pericardial versus porcine valves. J Thorac Cardiovasc Surg. 2020;160(2):476–84.
44. Gröning M, Smerup MH, Munk K, Andersen H, Nielsen DG, Nissen H, et al. Pulmonary valve replacement in tetralogy of fallot: procedural volume and durability of bioprosthetic pulmonary valves. JACC Cardiovasc Interventions. 2024;17(2):217–27.
45. Dürrleman N, Pellerin M, Bouchard D, Hébert Y, Cartier R, Perrault LP, et al. Prosthetic valve thrombosis: twenty-year experience at the Montreal Heart Institute. J Thorac Cardiovasc Surg. 2004;127(5):1388–92.
46. Bryan AJ, Rogers CA, Bayliss K, Wild J, Angelini GD. Prospective randomized comparison of carbomedics and St. Jude medical bileaflet mechanical heart valve prostheses: ten-year follow-up. J Thorac Cardiovasc Surg. 2007;133(3):614–22.
47. Bouchard D, Mazine A, Stevens LM, Pellerin M, Cartier R, Demers P, et al. Twenty-year experience with the carbomedics mechanical valve prosthesis. Ann Thorac Surg. 2014;97(3):816–23.
48. Bouhout I, Stevens LM, Mazine A, Poirier N, Cartier R, Demers P, El-Hamamsy I. Long-term outcomes after elective isolated mechanical aortic valve replacement in young adults. J Thorac Cardiovasc Surg. 2014;148(4):1341–e61.
49. Vahanian A, Beyersdorf F, Praz F, Milojevic M, Baldus S, Bauersachs J, et al. 2021 ESC/EACTS guidelines for the management of valvular heart disease. Eur Heart J. 2022;43(7):561–632.
50. Otto CM, Nishimura RA, Bonow RO, Carabello BA, Erwin JP 3rd, Gentile F, et al. 2020 ACC/AHA guideline for the management of patients with valvular heart disease: executive summary: a report of the American College of Cardiology/American Heart Association Joint Committee on Clinical Practice Guidelines. Circulation. 2021;143(5):e35–71.
51. Eikelboom JW, Connolly SJ, Brueckmann M, Granger CB, Kappetein AP, Mack MJ, et al. Dabigatran versus warfarin in patients with mechanical heart valves. N Engl J Med. 2013;369(13):1206–14.
52. Wang TY, Svensson LG, Wen J, Vekstein A, Gerdisch M, Rao VU, et al. Apixaban or warfarin in patients with an On-X mechanical aortic valve. NEJM Evid. 2023;2(7):EVIDoa2300067.
53. Crowther MA, Ageno W, Garcia D, Wang L, Witt DM, Clark NP, et al. Oral vitamin K versus placebo to correct excessive anticoagulation in patients receiving warfarin: a randomized trial. Ann Intern Med. 2009;150(5):293–300.
54. McRae ME, Coleman B, Atz TW, Kelechi TJ. Patient outcomes after transcatheter and surgical pulmonary valve replacement for pulmonary regurgitation in patients with repaired tetralogy of fallot: a quasi-meta-analysis. Eur J Cardiovasc Nurs. 2017;16(6):539–53.
55. Mongeon FP, Ben Ali W, Khairy P, Bouhout I, Therrien J, Wald RM, et al. Pulmonary valve replacement for pulmonary regurgitation in adults with tetralogy of fallot: a meta-analysis-a report for the writing committee of the 2019 update of the Canadian cardiovascular society guidelines for the management of adults with congenital heart disease. Can J Cardiol. 2019;35(12):1772–83.
56. van de Woestijne PC, Mokhles MM, de Jong PL, Witsenburg M, Takkenberg JJ, Bogers AJ. Right ventricular outflow tract reconstruction with an allograft conduit in patients after tetralogy of fallot correction: long-term follow-up. Ann Thorac Surg. 2011;92(1):161–6.
57. Jain A, Oster M, Kilgo P, Grudziak J, Jokhadar M, Book W, Kogon BE. Risk factors associated with morbidity and mortality after pulmonary valve replacement in adult patients with previously corrected tetralogy of fallot. Pediatr Cardiol. 2012;33(4):601–6.
58. Habib G, Lancellotti P, Antunes MJ, Bongiorni MG, Casalta JP, Del Zotti F, et al. 2015 ESC guidelines for the management of infective endocarditis: the task force for the management of infective endocarditis of the European society of cardiology (ESC). Endorsed by: European association for Cardio-Thoracic surgery (EACTS), the European association of nuclear medicine (EANM). Eur Heart J. 2015;36(44):3075–128.

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