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ORIGINAL ARTICLE

Comparison of Right Ventricular Function Between Full Sternotomy Aortic Valve Replacement, Mini-Sternotomy Aortic Valve Replacement, and Transcatheter Aortic Valve Replacement: A Prospective, Observational Study

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Received: 19 September 2025 | **Revised:** 29 October 2025 | **Accepted:** 11 November 2025

Keywords: aortic valve replacement | echocardiography | right ventricular function

ABSTRACT

Background: The importance of right ventricular (RV) function assessment has been a hot topic in cardiac surgery, and perioperative RV function is known to determine the outcome of cardiac surgery. However, RV echocardiographic assessment is challenging due to RV geometric changes. Currently, a 3D-derived RV assessment is recommended.

Previous studies have shown that RV function is reduced more in surgical aortic valve replacement (SAVR) than in transcatheter aortic valve replacement (TAVR); however, RV assessment in these studies was mostly performed using 2-dimensional echocardiography. Moreover, very few studies have assessed the difference in RV function between full sternotomy (full-SAVR) and mini-sternotomy AVR (mini-SAVR). This study assessed RV function in three types of AVR using 3D RV ejection fraction (RVEF), tricuspid annular plane systolic excursion (TAPSE), and RV fractional area change (RVFAC).

Methods: This is a prospective, observational study at a university hospital setting. Participants are adult patients who underwent TAVR, mini-SAVR, and full-SAVR.

Measurements and Main Results: Sixty-seven patients were enrolled in this study (22, 22, and 23 patients in the TAVR, mini-SAVR, and full-SAVR groups, respectively). The % change (pre- and post-procedure) in 3D RVEF, RVFAC, and TPASE in TAVR, mini-SAVR, and full-SAVR were as follows: 3D RVEF: 4.51 ± 10.89 (TAVR), −13.67 ± 19.81 (mini-SAVR), and −8.36 ± 18.24 (full-SAVR) ($p = 0.003$). RVFAC: 4.35 ± 12.33 (TAVR), −8.28 ± 23.88 (mini-SAVR), and −9.49 ± 20.92 (full-SAVR) ($p < 0.001$). TAPSE: 10.46 ± 24.17 (TAVR), −22.14 ± 32.48 (mini-SAVR), and −32.48 ± 31.81 (full-SAVR) ($p < 0.001$). Comparisons were adjusted for age, gender, central venous pressure, catecholamine amount, and each preoperative RV index.

Conclusion: There was significantly more worsening of 3D RVEF, RVFAC and TAPSE after full-SAVR and mini-SAVR than after TAVR.

Abbreviations: CPB, cardiopulmonary bypass; EF, ejection fraction; RV, right ventricular; RVEF, RV ejection fraction; RVFAC, RV fractional area change; SAVR, surgical aortic valve replacement; TAPSE, tricuspid annular plane systolic excursion; TAVR, transcatheter aortic valve replacement; TEE, transesophageal echocardiography.

This study was approved by the Institutional Review Board of Thomas Jefferson University (iRISID-2022-0802), and verbal informed consent was obtained from all participants prior to enrolment. The trial was registered on ClinicalTrials.gov (NCT05804240) on March 7, 2023.

The study was carried out at Thomas Jefferson University Hospital (Philadelphia, PA, United States).

1 | Introduction

The importance of postoperative right ventricular (RV) function after cardiac surgery has been recognized for more than 30 years; however, its assessment has been challenging due to the unique anatomy, physiology, and position [1–4]. The right ventricle (RV) has a pyramidal shape, and its contraction consists mostly of longitudinal movement; moreover, its accessibility is limited by its retrosternal position. Furthermore, the RV undergoes geometric changes in perioperative cardiac surgery settings, which makes the traditional 2-dimensional (2D) approach challenging [4, 5]. For these reasons, RV function assessment has been performed using comprehensive echocardiographic indices and "eyeballing" by the surgeon [1–3]. With the emergence of 3-dimensional (3D) echocardiography, the 3D-derived RV ejection fraction (EF) is currently considered the most accurate echocardiographic measure of global RV function, and its importance is emphasized in updated guidelines [2]. Moreover, RV geometry changes in cardiac surgery are better assessed with this imaging modality [4, 5].

Previous studies have shown that RV function is reduced more in surgical aortic valve replacement (SAVR) than in transcatheter aortic valve replacement (TAVR); however, in these studies, RV assessment was mostly performed by comparing preoperative and postoperative assessment parameters [6–8]. In addition, the few studies that have assessed RV function between full sternotomy (full-SAVR) and mini-sternotomy SAVR (mini-SAVR) have yielded inconsistent results, probably because of the limitations of 2D echocardiographic approaches [9, 10].

In this study, we utilized 3D echocardiography to assess RV function for TAVR, mini-SAVR, and full-SAVR. Our main hypothesis is that RV function is more depressed in SAVR than in TAVR. Our second hypothesis is that RV function is more depressed in full-SAVR than in mini-SAVR.

2 | Methods

2.1 | Study Design and Ethical Approval

This was a prospective, observational study of a cohort of adult patients who underwent TAVR, mini-SAVR, full-SAVR, and TAVR at Thomas Jefferson University Hospital.

This study was approved by the Institutional Review Board of Thomas Jefferson University (iRISID-2022-0802). Verbal informed consent was obtained from all participants prior to their enrolment. The trial was registered at ClinicalTrials.gov (NCT05804240) on March 7, 2023. Demographic data, perioperative clinical details, and postoperative outcomes were retrieved from the EPIC electronic medical record system.

2.2 | Study Participants

The included patients were aged > 18 years and underwent TAVR, mini-SAVR, and full-SAVR, or TAVR requiring intraoperative transesophageal echocardiography (TEE) between April 2023 and April 2025 at Thomas Jefferson University Hospital. The exclusion criteria were refusal to participate in the study, absolute contraindication to TEE, and suboptimal echocardiography images. All patients received general anesthesia with endotracheal intubation, standard American Society of Anesthesiologists monitoring, arterial blood pressure monitoring, central venous pressure (CVP) monitoring (except for TAVR), and a comprehensive TEE examination using a designated protocol.

2.3 | Surgical Techniques

TAVR: transfemoral approach with rapid pacing when deploying the valve.

Mini-SAVR: Upper partial mini-sternotomy approach with a small vertical pericardial incision, which was closed at the end of the procedure. A mechanical or bioprosthetic valve was placed. CPB was established using central arterial cannulation and peripheral venous cannulation. An antegrade crystalloid cardioplegia approach was used.

Full-SAVR: Full median sternotomy approach with a complete pericardial incision, which was not closed at the end of the procedure. A mechanical or bioprosthetic valve was placed. CPB was established using central arterial and venous cannulation. Antegrade and retrograde cardioplegia approaches were used.

2.4 | Echocardiographic Measurements

All images were captured and saved in the operating room and transmitted to a server for permanent cataloguing. A single investigator reviewed all images and performed the measurements described below. 3D RVEF (primary endpoint) was acquired using the software package of a 4-dimensional automatic right ventricular quantification technology (4D RVQ) on a GE Vivid E95 TEE machine (GE HealthCare, Chicago, IL, USA) [11, 12]. Tricuspid annular plane systolic excursion (TAPSE) and right ventricular fractional area change (RVFAC) were also automatically calculated with this measurement (secondary endpoints).

Measurements were made at the following times when stable hemodynamics were achieved.

TAVR:
1st: After the induction of general anesthesia (timing #1)
2nd: After the new valve was deployed (timing #3)
Mini-SAVR and full-SAVR:
1st: After the induction of general anesthesia (timing #1)
2nd: After separation from cardiopulmonary bypass (timing #2)
3rd: After the chest was closed (timing #3)

2.5 | Primary Outcome

The primary outcome was the % change in echocardiographic 3D RVEF after valve deployment compared to the baseline. More precisely, the change between timings #1 and #3 was assessed for all patients, and the change between timings #1, #2, and #3 was assessed for those who underwent full-SAVR and mini-SAVR.

2.6 | Secondary Outcomes

1. The % change in echocardiographic TAPSE and RV FAC after valve deployment compared to the baseline.
2. The correlation between post-deployment echocardiographic RV function indices and in-hospital major adverse cardiac and cerebrovascular events (in-hospital MACCE: defined as a composite of in-hospital death, myocardial infarction, angina, arrhythmia, heart failure, stroke, or cardiac arrest).

2.7 | Anesthesia and Ventilation Protocols

General anesthesia was induced via endotracheal intubation. The arterial, central venous, and pulmonary arterial catheters (except for TAVR) were placed along with TEE to retrieve arterial pressure, CVP, and pulmonary arterial pressure (PAP), respectively. The selection of anesthetic agents, inotropes, vasopressors, transfusion strategies, and fluid management was at the discretion of the attending anesthesiologist. We used conversion equations to calculate the equivalent norepinephrine dose from the vasopressor dose at the time of the echocardiographic measurements [13]. Dexmedetomidine 0.7–1.0 mcg/kg/h was used for sedation during transport to the intensive care unit.

The operating room ventilator was set as volume control (tidal volume: 6–8 mL/ideal body weight [kg], respiratory rate: 14–16 breaths/min, PEEP: 5–10 cm H_2O, and FiO_2: 100%).

2.8 | Statistical Analysis

Summary statistics were reported for demographic and clinical data for each group. Similarly, variables are presented as mean ± SD and median (IQR), when indicated. Categorical data are presented as frequencies and percentages according to the group. Demographic data were analyzed using the independent *t*-test, and the Mann–Whitney *U* test was used for nominal variables.

RV echocardiographic indices were analyzed using the Mann–Whitney *U* test (two groups) or the analysis of covariance (ANCOVA) and pos-hoc pairwise comparisons with Bonferroni correction. For ANCOVA of % change (Timing #3 from #1) in RV indices, covariates included age, gender, norepinephrine equivalent (NE equiv) at Timing #3, CVP at Timing #1, and each RV index at the baseline (Timing #1).

Univariate or multivariable logistic regression models were used to assess the association between each echocardiographic index and in-hospital MACCEs.

Correlations between continuous variables were assessed using Pearson's or Spearman's rank correlation tests. Statistical significance was set at $p < 0.05$. All statistical analyses were performed using R version 4.5.1 (The R Foundation for Statistical Computing). The figures (box plots) were created using GraphPad Prism 10.4.2 (GraphPad Software).

2.9 | Power Analysis

Changes in RV echocardiographic measurements were used to calculate the required sample size, based on a study by Kempny et al. [14]. Kempny et al. reported % change of RV strain of -25.2 (SAVR) and - 20.0 (TAVR) before and after the procedure, respectively. With the criterion for significance (alpha) set at 0.05 and 80% power for a Mann–Whitney *U* test, we obtained a sample size of 22 patients per group. The rationale for using RV strain for power analysis is as follows: Sample size calculations for RV strain, RVFAC, and TAPSE provided 22, 7, and 15, respectively. Thus, we decided to use the strictest sample size calculation.

2.10 | Reproducibility of 3D RVEF

Cardiac anesthesiologists were trained by an instructor from the instrument manufacturer (GE HealthCare, Chicago, IL, USA) on how to use the 4D RVQ software. The reproducibility of the echocardiographic RV indices was assessed using intraclass correlation as follows:

1. Inter-rater variance: Two blinded echocardiographers obtained measurements (RVEF, RVFAC, and TAPSE) using the same images for 10 randomly chosen patients [15].
2. Intra-rater variance: One blinded echocardiographer obtained measurements (RVEF, RVFAC, and TAPSE) using the same images for 10 randomly chosen patients 6–8 months apart [15].

3 | Results

Twenty-three (full-SAVR), 22 (mini-SAVR) and 24 (TAVR) patients were enrolled in the study. Two patients were excluded from the TAVR group owing to poor TEE image quality. Thus, there were 22 patients each in the TAVR and mini-SAVR groups and 23 patients in the full-SAVR group (a total of 67 patients) (Figure 1). The baseline demographic characteristics of the three groups are summarized in Table 1. No patient had more than moderate tricuspid regurgitation. There was no significant difference among the three groups in terms of implanted valve size, STS score, EuroSCORE II, baseline RV EF, TAPSE, and RV FAC.

The hemodynamics and doses of inotropes or vasopressors at the time of echocardiographic measurements are summarized in Tables S1 and S2.

3.1 | Primary Outcomes

The main effect of surgery on % change of 3D RVEF was significant after adjusting for gender, age, RVEF (timing #1), CVP (timing #1), and norepinephrine equivalent (timing #3): $F(2, 59) = 6.50$, $p = 0.003$ (Tables 2 and 3).

There was a significant difference in adjusted % change in RVEF (timing #3 from #1) between the TAVR and mini-SAVR groups (mean difference = 16.41 ± 5.02, $t(59) = 3.27$, $p = 0.005$,

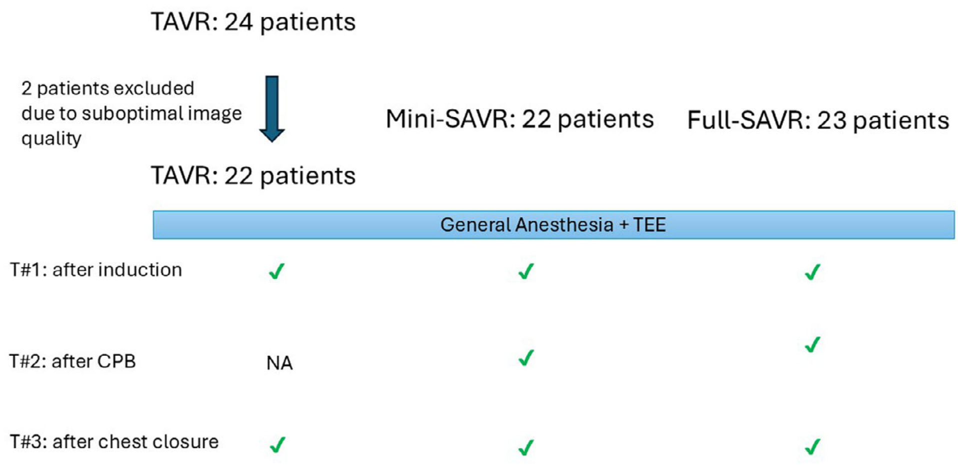

FIGURE 1 | Patient flow chart and the timing of measurement. CPB, cardiopulmonary bypass; full-SAVR, full-sternotomy surgical aortic valve replacement; mini-SAVR, mini-sternotomy surgical aortic valve replacement; TAVR, transcatheter aortic valve replacement; TEE, transesophageal echocardiography.

Bonferroni-adjusted), and between the TAVR and full-SAVR groups (mean difference = 16.57 ± 4.86, t(59) = 3.41, $p = 0.004$, Bonferroni-adjusted). Results are summarized in Table S3.

The correlation coefficient between the pre-chest closure CVP (at timing #2) and the % change in RVEF (timing #3 from #2) among patients who underwent full-SAVR was −0.281 ($p = 0.0612$) for the mini-SAVR group and −0.472 ($p = 0.0229$) for the full-SAVR group.

To address the potential impact of chest closure on RV function measurements, a sensitivity analysis was conducted comparing RVEF at full-SAVR timing #2 (post-cardiopulmonary bypass, pre-chest closure) and TAVR timing #3 (post-valve deployment).

The analysis demonstrated that RVEF remained significantly lower in full-SAVR than in TAVR even before chest closure (40.24 ± 8.02 vs. 50.48 ± 7.61, $p < 0.0001$).

3.2 | Secondary Outcome

The trends of TAPSE, and RVFAC in the TAVR, mini-SAVR, and full-SAVR groups are shown in Figure 2. The main effect of surgery on % change of RVFAC was significant after adjusting for gender, age, RVFAC (timing #1), CVP (timing #1), and norepinephrine equivalent (timing #3): F(2, 59) = 9.21, $p < 0.001$ (Tables 2 and 3). The main effect of surgery on % change of TAPSE was significant after adjusting for gender, age, TAPSE (timing #1), CVP (timing #1), and norepinephrine equivalent (timing #3): F(2, 59) = 11.86, $p < 0.001$ (Tables 2 and 3). There was a significant difference in adjusted % change both in RVFAC and TAPSE (timing #3 from #1) between the TAVR and mini-SAVR groups, and between the TAVR and full-SAVR groups, as shown in Table S3.

The odds ratios of RV echocardiographic indices (RVEF, TAPSE, and RVFAC at timing #3) for in-hospital MACCE in the three groups are shown in Table 4. Of note, MACCE consists of the following: TAVR: four left bundle branch block, four complete atrioventricular block; mini-SAVR: four atrial fibrillation, three heart failure; full-SAVR: eight atrial fibrillation, three heart failure, and one stroke.

Ventilator setting, hemodynamics, and vasopressor dosing at each timing of echocardiographic assessment (Timing #1, #2, and #3) are shown in Table 5.

The reproducibility of RVEF and RVFAC is excellent (>0.90), while good for TAPSE (>0.80), as shown in Table S4 and Figure S1.

4 | Discussion

Our study found that 3D RVEF decreased more in SAVR (full-AVR or mini-AVR) than in TAVR pre- and post-procedure, but no significant difference was observed between full-SAVR and mini-SAVR. The postoperative (Timing #3) and % change in RVEF, RVFAC, and TAPSE (Timing #3 from #1) were significantly affected by baseline RVEF, RVFAC, and TAPSE (Timing #1, respectively). Overall, negative odds ratios were noted between postoperative (timing #3) 3D RVEF and in-hospital MACCE in mini-SAVR and full-SAVR. Furthermore, good or excellent reproducibility was observed for RVEF, RVFAC, and TAPSE. Our study is novel for the following reasons: (1) we compared intraoperative RV function pre- and post-procedure in patients who underwent TAVR, mini-SAVR, and full-SAVR; (2) we assessed RV function using 3D approaches; and (3) we assessed the reproducibility of the echocardiographic indices.

It is known that perioperative RV function assessment using 2D echocardiography is limited by geometric changes in cardiac surgery [4, 5]. 3D echocardiography obviates the geometric assumptions and is superior to standard 2D echo for assessing RV volume and function in cardiac surgery [16].

4D RVQ software is a software package that helps visualize and quantify RV in TTE or TEE images using a semiautomatic surface-detecting algorithm [11, 12]. It has been validated and

TABLE 1 | Patient demographics.

	TAVR ($n = 22$)	Mini-SAVR ($n = 22$)	Full-SAVR ($n = 23$)	p value
Sex (male:n)	13	15	17	0.581
Age (year)	75.54 ± 6.24	61.31 ± 12.72	65.43 ± 12.95	0.000198
BMI	29.94 ± 5.82	30.76 ± 7.14	31.95 ± 6.17	0.574
Preop LVEF (%)	57.52 ± 11.03	58.64 ± 10.14	60.64 ± 8.52	0.617
Postop LVEF (%)	57.63 ± 11.23	57.73 ± 5.29	60.52 ± 7.14	0.203
AS	21	17	22	0.147
AR	5	6	4	0.714
MS	0	0	0	NA
MR	2	0	0	0.209
CAD	9	5	8	0.467
HTN	19	16	21	0.246
DM	7	9	11	0.608
HLD	14	13	12	0.781
CKD > stage IIIb	2	3	0	0.191
Dialysis	1	1	0	0.542
Afib	4	3	3	0.915
OSA	3	5	6	0.651
Pulmonary disease	3	4	1	0.329
CVA	1	2	2	1
CPB time (min)	NA	98 [85, 113]	140 [124.5, 173]	0.000998
AoXclamp time (min)	NA	71 [47, 82]	107 [90, 136]	0.000551
PRBC (mL)	0 [0, 0]	0 [0, 0]	0 [0, 150]	0.114
FFP (mL)	NA	0 [0, 0]	0 [0, 0]	0.568
Plateket (mL)	NA	0 [0, 0]	0 [0, 360.5]	0.241
Cryo (mL)	NA	0 [0, 0]	0 [0, 131]	0.0356
UOP (mL)	286.4 ± 72.67	674.54 ± 381.61	573.26± 399.76	0.000509
Valve size (mm)	25.32 ± 2.25	23.86 ± 2.23	23.43 ± 2.086	0.0145
Baseline RV EF (%)	48.74 ± 8.55	49.11± 9.14	44.71± 7.71	0.236
Baseline TAPSE (mm)	15.77 ± 4.55	15.45 ± 3.99	14.09 ± 4.88	0.412
Baseline RVFAC (%)	485.37 ± 7.99	44.3 ±10.04	42.34 ± 7.13	0.478
Pericardium closure	NA	0	23	<0.0001
STS score (%)	2.374 ± 0.781	2.418 ± 0.654	2.278 ± 0.417	0.752
EuroSCORE II	1.852 ± 0.681	1.729 ± 0.373	1.600 ± 0.183	0.188

Abbreviations: Afib, atrial fibrillation; Ao Xclamp, aortic cross-clamp; AR, aortic regurgitation; AS, aortic stenosis; BMI, body mass index; CAD, coronary artery disease; CKD, chronic kidney disease; COPD, chronic obstructive pulmonary disease; CPB, cardiopulmonary bypass; CVA, cerebrovascular disease; DM, diabetes mellitus; FFP, fresh frozen plasma; full-SAVR, full-sternotomy surgical aortic valve replacement; HLD, hyperlipidemia; HTN, hypertension; LVEF, left ventricular ejection fraction; mini-SAVR, mini-sternotomy surgical aortic valve replacement; MR, mitral regurgitation; MS, mitral stenosis; OSA, obstructive sleep apnea; PRBC, packed red blood cell; STS, Society of Thoracic Surgeons Score; TAVR, transcatheter aortic valve replacement; UOP, urine output.

widely used clinically [11, 12]. The benefit of this software is that it yields TAPSE, RVFAC, and RVEF consecutively. As pointed out in previous guidelines for RV echocardiographic assessments, 3D RVEF plays an important role in RV function assessment more than before [2]. Although 3D RVEF remains an ad hoc assessment that uses acquired images (i.e., not real-time), our division members could achieve the measurements within 3 min with appropriate training. Moreover, our data showed the great reproducibility of this measure.

Our finding of a higher % change in RV function indices in SAVR (mini- or full-SAVR) than in TAVR is in accordance with previous studies. Kempny et al. reported a significant decline in radial and longitudinal RV function in SAVR, although there was no

TABLE 2 | % change between each timing in RVEF, RVFAC, and TAPSE among TAVR, mini-SAVR, and full-SAVR.

	TAVR	Mini-SAVR	Full-SAVR	*p* value
% change in RVEF(timing #3 from #1)	4.51 ± 10.89	−13.67 ± 19.81[d]	−8.36 ± 18.24[e]	0.003[a]
% change in RVFAC(timing #3 from #1)	4.35 ± 12.33	−8.28 ± 23.88[f]	−9.49 ± 20.92[g]	<0.001[b]
% change in TAPSE(timing #3 from #1)	10.46 ± 24.17	−22.14 ± 32.48[h]	−32.48 ± 31.81[i]	<0.001[c]
% change in RVEF(timing #2 from #1)	NA	−16.75 [−27.98, −3.73]	−10.68 [−16.65, 5.60]	0.138
% change in RVFAC(timing #2 from #1)	NA	−15.54 [−20.5, −2.9]	−1.96 [−23.40, 5.84]	0.518
% change in TAPSE(timing #2 from #1)	NA	−36.11 [−45.2, −4.17]	−36.36 [−54.77, −15.66]	0.22
% change in RVEF(timing #3 from #2)	NA	2.29 [−6.70, 13.63]	0 [−12.61, 14.31]	0.532
% change in RVFAC(timing #3 from #2)	NA	3.97 [−5.03, 9.91]	0.98 [−4.06, 21.44]	0.865
% change in TAPSE(timing #3 from #2)	NA	8.33 [0, 23.66]	9.09 [0, 33.33]	0.792

Note: For ANCOVA, see Table 3.

Abbreviations: ANCOVA, analysis of covariance; full-SAVR, full-sternotomy surgical aortic valve replacement; mini-SAVR, mini-sternotomy surgical aortic valve replacement; RVEF, right ventricular ejection fraction; RVFAC, right ventricular fraction area change; TAPSE, tricuspid annular plane systolic excursion; TAVR, transcatheter aortic valve replacement.

[a] After adjusting for gender, age, RVEF, and CVP at timing #1 by ANCOVA.

[b] After adjusting for gender, age, RVFAC, and CVP at timing #1 by ANCOVA.

[c] After adjusting for gender, age, TAPSE, and CVP at timing #1 by ANCOVA.

[d] $p = 0.0081$, Bonferroni-adjusted post-hoc pairwise tests. Adjusted % change in RVEF between TAVR and mini-SAVR.

[e] $p = 0.0045$, Bonferroni-adjusted post-hoc pairwise tests. Adjusted % change in RVEF between TAVR and full-SAVR.

[f] $p = 0.006$, Bonferroni-adjusted post-hoc pairwise tests. Adjusted % change in RVFAC between TAVR and mini-SAVR.

[g] $p < 0.001$, Bonferroni-adjusted post-hoc pairwise tests. Adjusted % change in RVFAC between TAVR and full-SAVR.

[h] $p = 0.013$, Bonferroni-adjusted post-hoc pairwise tests. Adjusted % change in RVFAC between TAVR and mini-SAVR.

[i] $p < 0.001$, Bonferroni-adjusted post-hoc pairwise tests. Adjusted % change in RVFAC between TAVR and full-SAVR.

TABLE 3 | Results of the Type III analysis of covariance (ANCOVA) examining factors associated with % change in RV parameters.

	% change in RVEF				% change in RVFAC				% change in TAPSE			
	Sum square	df	F value	*p* value	Sum square	df	F value	*p* value	Sum square	df	F value	*p* value
(Intercept)	1014.5	1	5.08	0.028	1462.1	1	6.26	0.015	417.5	1	0.59	0.44
AVR	2595.3	2	6.50	0.003[a]	4301.6	2	9.21	<0.001[b]	166747.3	2	11.84	<0.001[b]
Gender	42.5	1	0.21	0.65	22.9	1	0.10	0.76	1408.5	1	2.00	0.16
Age	428.9	1	2.14	0.15	16.0	1	0.07	0.79	603.0	1	0.85	0.36
CVP[c]	45.1	1	0.23	0.64	663.2	1	2.84	0.10	44.0	1	0.06	0.80
NE equiv[d]	208.8	1	1.05		527.1	1	2.26	0.14	310.3	1	0.44	0.51
3D RVEF[c]	6027.2	1	30.20	<0.001[b]								
RVFAC[c]					7660.3	1	32.81	<0.001[b]				
TAPSE[c]									13484.0	1	19.01	<0.001[b]
Residuals	11774.0	59			13775.7	59			41646.1	59		

Note: AVR: TAVR = 0, mini-SAVR = 1, full SAVR = 2. Gender: male = 1, female = 0.

Abbreviations: CVP, central venous pressure; NE equiv, norepinephrine equivalent; NOR equiv, norepinephrine equivalent; RVEF, right ventricular ejection fraction; RVFAC, right ventricular fraction area change; TAPSE, tricuspid annular plane systolic excursion.

[a] $0.001 < p < 0.01$.

[b] $p < 0.001$.

[c] At timing #1,

[d] At timing #3.

correlation between RVEF decline and cardiopulmonary bypass (CPB) or aortic cross-clamp time [14].

Zhao et al. reported that echocardiography-assessed RV function was preserved in the TAVR cohort and decreased in the SAVR group [17]. The potential factors for this decline are considered to be the cardioplegia technique, ischemia, myocardial depression, hypothermia, and immune-mediated inflammation [18]. Between full and mini-SAVR, there was no significant difference in terms of % change in RVEF, RVFAC, and TAPSE (timing#3 from #1), and previous studies have reported inconsistent findings

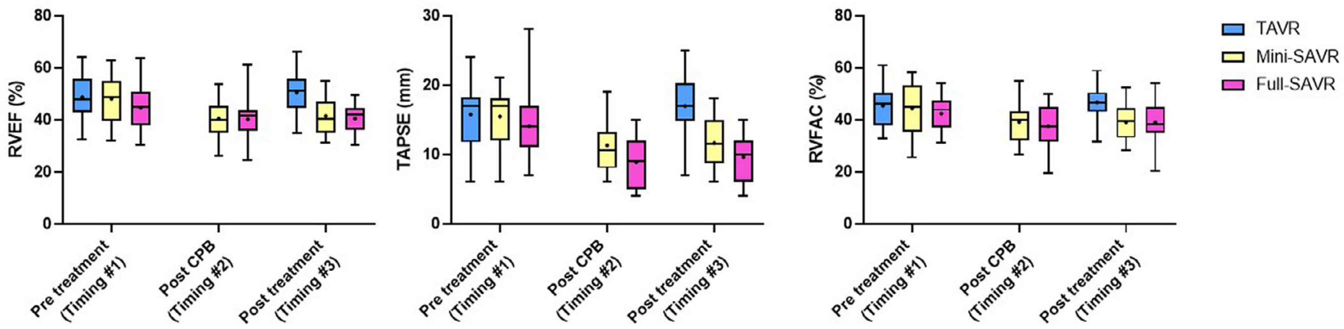

FIGURE 2 | The trends of RVEF, TAPSE, and RVFAC in the TAVR, mini-SAVR, and full-SAVR groups. CPB, cardiopulmonary bypass; full-SAVR, full-sternotomy surgical aortic valve replacement; mini-SAVR, mini-sternotomy surgical aortic valve replacement; RVEF, right ventricular ejection fraction; RVFAC, right ventricular fractional area change; TAPSE, tricuspid annular plane systolic excursion; TAVR, transcatheter aortic valve replacement; TEE, transesophageal echocardiography.

TABLE 4 | Odds ratio between each surgery technique and in-hospital MACCE.

TAVR			
(a) RVEF			
	aOR	95% CI	*p* value
Post RVEF	<1	0.851, 1.1	0.594
Post LVEF	<1	0.872, 1.04	0.257
Age	1.02	0.879, 1.19	0.777
(b) RVFAC			
	aOR	95% CI	*p* value
Post RVFAC	<1	0.845, 1.18	0.969
Post LVEF	<1	0.877, 1.04	0.272
Age	1.02	0.851, 1.1	0.799
(c) TAPSE			
	aOR	95% CI	*p* value
Post TAPSE	1.01	0.816, 1.25	0.935
Post LVEF	<1	0.871, 1.04	0.249
Age	1.02	0.878, 1.18	0.802
Mini-SAVR			
(a) RVEF			
	aOR	95% CI	*p* value
Post RVEF	<1	0.39, 0.983	0.0418[a]
Post LVEF	<1	0.595, 1.07	0.13
Age	<1	0.762, 1.1	0.35
(b) RVFAC			
	aOR	95% CI	*p* value
Post RVFAC	<1	0.597, 1.11	0.189
Post LVEF	<1	0.744, 1	0.0558

(Continues)

TABLE 4 | (Continued)

TAVR			
Age	<1	0.847, 1.08	0.466
(c) TAPSE			
	aOR	95% CI	*p* value
Post TAPSE	<1	0.842, 1.06	0.0838
Post LVEF	<1	0.704, 1.02	0.075
Age	<1	0.842, 1.06	0.354
Full-SAVR			
(a) RVEF			
	aOR	95% CI	*p* value
Post RVEF	<1	0.412, 0.953	0.029[a]
Post LVEF	<1	0.865, 1.1	0.702
Age	<1	0.938, 1.18	0.39
(b) RVFAC			
	aOR	95% CI	*p* value
Post RVFAC	<1	0.787, 1.02	0.0919
Post LVEF	<1	0.865, 1.08	0.557
Age	<1	0.903, 1.05	0.452
(c) TAPSE			
	aOR	95% CI	*p* value
Post TAPSE	1.11	0.855, 1.45	0.423
Post LVEF	<1	0.861, 1.07	0.435
Age	<1	0.908, 1.05	0.48

Abbreviations: aOR, adjusted odds ratio; CI, confidence interval; full-SAVR, full-sternotomy surgical aortic valve replacement; MACCE, major adverse cardiac and cerebrovascular events; mini-SAVR, mini-sternotomy surgical aortic valve replacement; TAVR, transcatheter aortic valve replacement.
[a]$p < 0.05$.

regarding this. Dalen et al. reported that the decline in RV global function (RVFAC) was comparable between full- and mini-SAVR, whereas longitudinal RV function (TAPSE) was more decreased in full-SAVR than in mini-SAVR [9]. Conversely, Hashemi et al. reported that the decline in RV contractility (RV-longitudinal strain rate) was more significant in full-SAVR than in mini-SAVR [10]. CPB and aortic cross-clamp time were longer in our study patients than in the previous study, and more aggressive pericardiotomy (leading to a loss of pericardial support to the RV)

TABLE 5 | Each covariate between TAVR, mini-SAVR, and full-SAVR.

Timing#1	TAVR	Mini-SAVR	Full-SAVR	*p* value
PEEP (cmH2O)	5.5 ± 1.1	5.23 ± 0.69	5.26 ± 0.86	0.55
EtCO2 (mmHg)	35.1 ± 2.25	34.45 ± 1.71	35.78 ± 2.17	0.105
Nor equiv	0.012 ± 0.0234	0.0095 ± 0.019	0.01 ± 0.0198	0.896
HR (bpm)	73.95 ± 7.68	72.36 ± 5.55	71.22 ± 6.09	0.372
MAP (mmHg)	66.86 ± 4.12	67.14 ± 4.0.	66.17 ± 3.64	0.699
CVP (mmHg)	6.09 ± 1.69	6.22 ± 1.95	6.18 ± 1.70	0.963
mPAP (mmHg)	NA	30.05 ± 3.33	27.87 ± 3.56	0.0412
Timing#2				
PEEP (cmH2O)	NA	6.41 ± 1.82	6.00 ± 1.60	0.426
EtCO2 (mmHg)	NA	34.45 ± 1.71	35.48 ± 2.04	0.0759
Nor equiv	NA	0.056 ± 0.041	0.064 ± 0.045	0.44
HR (bpm)	NA	70.59 ± 4.02	67.43 ± 14.3	0.324
MAP (mmHg)	NA	65.86 ± 5.71	66.83 ± 3.43	0.495
CVP (mmHg)	NA	11.14 ± 2.38	11.22 ± 2.07	0.903
mPAP (mmHg)	NA	29.9 ± 3.54	27.87 ± 3.66	0.0644
Timing#3				
PEEP (cmH2O)	5.77 ± 1.31	5.32 ± 0.89	6.09 ±1.28	0.0966
EtCO2 (mmHg)	34.59 ± 2.04	34.95 ± 1.59	34.30 ± 2.8	0.577
Nor equiv	0.0289 ± 0.031	0.0568 ± 0.041	0.0659 ± 0.044	0.00723[a]
HR (bpm)	77.91 ± 9.53	78.86 ± 9.39	76.61 ± 9.72	0.73
MAP (mmHg)	66.73 ± 4.31	65.86 ± 5.71	64.95 ± 3.99	0.457
CVP (mmHg)	11.95 ± 2.57	11.18 ± 2.17	11.86 ± 2.88	0.55
mPAP (mmHg)	NA	29.66 ± 4.35	27.13 ± 4.30	0.0908

Notes: TAVR patients did not have pulmonary artery catheter or Timing#2 measurements. There is no significant difference between each group in all covariates.
Abbreviations: CVP, central venous pressure; $EtCO_2$, end-tidal carbon dioxide; full-SAVR, full-sternotomy surgical aortic valve replacement; HR, heart rate; MAP, mean arterial pressure; mPAP, mean pulmonary arterial pressure; mini-SAVR, mini-sternotomy surgical aortic valve replacement; Nor equiv, norepinephrine equivalent; PEEP, positive end-expiratory pressure; TAVR, transcatheter aortic valve replacement.
[a] $p < 0.05$.

was noted in full-SAVR than in mini-SAVR [10, 19]. Moreover, the cardioplegia technique was different in the two groups. The RV is predominantly drained by the Thebesian and small cardiac veins. Thebesian veins empty directly into the RV, and small cardiac veins open close to the coronary sinus ostium. These anatomical features of the RV make retrograde cardioplegia less effective in protecting the RV myocardium than antegrade cardioplegia [20]. These factors may have led to a greater decline in RV function in full-SAVR than in mini-SAVR. However, the full-SAVR group required a higher dose of epinephrine than the mini-SAVR group (Table 2), which might have counteracted the factors listed above. Thus, we can say that the decline in RV function in full-SAVR was more significant than that in mini-SAVR, given that our % change was comparable, with more inotropes used in full-SAVR. Our RV echocardiographic indices are load-dependent [1–3] and may have been affected by intraoperative fluid shifts [16]. The timing of echocardiographic assessment is also important. Postoperative mediastinal adhesions, which were not relevant in our study, may have contributed to the postoperative decline in RV function in previous studies.[7, 8]

The difference in the drop in longitudinal and global RV function between SAVR (mini- or full-) and TAVR was not observed in our study population [7, 8]. This might be due to differences in measurement timing between our study and previous studies, or the limitation of TAPSE in cardiac surgery settings [4, 5, 16].

Notably, a marginal correlation was observed between the pre-chest closure CVP (timing #2) and the % change in RVEF (timing #3 from #2) in full-SAVR and mini-SAVR. To further isolate the potential impact of chest closure, a sensitivity analysis comparing full-SAVR timing #2 (post-CPB, pre-chest closure) and TAVR timing #3 (post-valve deployment, pre-chest closure) demonstrated that RVEF remained significantly lower in full-SAVR than in TAVR (40.24 ± 8.02 vs. 50.48 ± 7.61, $p < 0.0001$). This finding suggests that the decline in RVEF observed in SAVR cannot be attributed solely to chest closure, but is more likely due to intraoperative factors such as CPB, myocardial ischemia-reperfusion, and pericardial manipulation. Nevertheless, chest closure itself may further modulate preload and ventricular interdependence, particularly in patients with elevated CVP and limited cardiac reserve.[21]

Several reports have described a good correlation between perioperative RV function and postoperative outcomes [22–26]. Our data also suggests that postoperative RVEF is correlated with in-hospital MACCE, while postoperative TAPSE or RVFAC was not. This might be because of the postoperative geometry change in RV, which was not fully assessed with TAPSE or RVFAC. These findings should be investigated with a bigger study, because this study's scale was not intended for that purpose.

The great reproducibility of 3D RVEF, RVFAC, and TAPSE was also notable, which is inconsistent with a report by Tolvaj et al. that indicated that the guideline-recommended cutoff values of conventional echocardiographic parameters of RV systolic function are only modestly associated with RVEF-based assessment [27]. We owe this advantage to 4D RVQ package, which measures TAPSE and RVFAC using the same 3D reconstruction from which 3D RVEF was calculated [11, 12]. This 4D RVQ software should enable us to obtain constant measurements as long as quality images are obtained.

Schneider et al. reported that the most common methods of RV function assessment remain "eye-balling" (72%) and TAPSE (69%) in clinical settings [3]. We hope this study encourages anesthesia providers to consider using 3D echocardiography to routinely assess RV volume and function, which would help them consider RV function in different AVR techniques.

4.1 | Future Directions

Larger-scale clinical trials are needed to better understand the effects of different surgical techniques. RV regional function assessment using strain echocardiography may be added. In addition, echocardiographic assessment should include the postoperative period so that future studies can assess the trend of gradual changes in RV geometry after cardiac surgery.

4.2 | Limitations

This study had some limitations. First, the single-center, prospective study design may limit the generalizability of our findings. Second, our observations were limited to the intraoperative period and might not have been long enough to assess the surgical effects on the RV. Third, the number of enrolled patients was small. Finally, because our study was an echocardiographic study, its outcomes may not translate to clinical outcomes.

In conclusion, this study demonstrated that SAVR (mini- or full-) was associated with a greater decline in RV function than TAVR pre- and post-procedure. Overall, negative odds ratios were noted between post-procedure RV function and in-hospital MACCE. Additionally, great reproducibility was noted in the echocardiographic RV function indices using the 4D RVQ software. Further research is required to refine the differences and mechanisms of changes in RV function with different AVR procedures.

Acknowledgments

J.L. and S.S. helped with IRB application and participant enrolment.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Our research data cannot be shared because it includes sensitive or confidential information, such as patient data.

References

1. L. G. Rudski, W. W. Lai, J. Afilalo, et al., "Guidelines for the Echocardiographic Assessment of the Right Heart in Adults: A Report From the American Society of Echocardiography Endorsed by the European Association of Echocardiography, a Registered Branch of the European Society of Cardiology, and the Canadian Society of Echocardiography," *Journal of the American Society of Echocardiography* 23 (2010): 685–713, https://doi.org/10.1016/j.echo.2010.05.010.

2. R. M. Lang, L. P. Badano, and V. Mor-Avi, "Recommendations for Cardiac Chamber Quantification by Echocardiography in Adults: An Update From the American Society of Echocardiography and the European Association of Cardiovascular Imaging," *Journal of the American Society of Echocardiography* 28, no. 1 (2015): 1–39, e14, https://doi.org/10.1016/j.echo.2014.10.003.

3. M. Schneider, S. Aschauer, J. Mascherbauer, et al., "Echocardiographic Assessment of Right Ventricular Function: Current Clinical Practice," *International Journal of Cardiovascular Imaging* 35 (2019): 49–56, https://doi.org/10.1007/s10554-018-1428-8.

4. F. Haddad, P. Couture, C. Tousignant, et al., "The Right Ventricle in Cardiac Surgery, a Perioperative Perspective: I. Anatomy, Physiology, and Assessment," *Anesthesia and Analgesia* 108 (2009): 407–421, https://doi.org/10.1213/ane.0b013e31818f8623.

5. F. Haddad, P. Couture, C. Tousignant, et al., "The Right Ventricle in Cardiac Surgery, a Perioperative Perspective: II. Pathophysiology, Clinical Importance, and Management," *Anesthesia and Analgesia* 108 (2009): 422–433, https://doi.org/10.1213/ane.0b013e31818d8b92.

6. B. Ren, E. Spitzer, M. L. Geleijnse, et al., "Right Ventricular Systolic Function in Patients Undergoing Transcatheter Aortic Valve Implantation: A Systematic Review and Meta-Analysis," *International Journal of Cardiology* 257 (2018): 40–45, https://doi.org/10.1016/j.ijcard.2018.01.117.

7. P. C. Cremer, Y. Zhang, and M. Alu, "The Incidence and Prognostic Implications of Worsening Right Ventricular Function After Surgical or Transcatheter Aortic Valve Replacement: Insights From PARTNER IIA," *European Heart Journal* 39 (2018): 2659–2667, https://doi.org/10.1093/eurheartj/ehy251.

8. C. Keyl, J. Schneider, F. Beyersdorf, et al., "Right Ventricular Function After Aortic Valve Replacement: A Pilot Study Comparing Surgical and Transcatheter Procedures Using 3D Echocardiography," *European Journal of Cardio – Thoracic Surgery* 49 (2016): 966–971, https://doi.org/10.1093/ejcts/ezv227.

9. M. Dalén, C. Oliveira Da Silva, U. Sartipy, et al., "Comparison of Right Ventricular Function After Ministernotomy and Full Sternotomy Aortic Valve Replacement: A Randomized Study," *Interactive CardioVascular and Thoracic Surgery* 26 (2018): 790–797, https://doi.org/10.1093/icvts/ivx422.

10. N. Hashemi, J. Johnson, L. A. Brodin, et al., "Right Ventricular Mechanics and Contractility After Aortic Valve Replacement Surgery: A Randomised Study Comparing Minimally Invasive Versus Conventional Approach," *Open Heart* 5 (2018): e000842, https://doi.org/10.1136/openhrt-2018-000842.

11. 4D Auto RVQ. GE Healthcare. (Assessed May 2025), https://www.gehealthcare.com/-/jssmedia/7b06403306dc4aca9cb894b4f39b6a48.pdf.

12. R. Aubert, C. Venner, and O. Huttin, "Three-Dimensional Echocardiography for the Assessment of Right Ventriculo-Arterial Coupling," *Journal of the American Society of Echocardiography* 31 (2018): 905–915, https://doi.org/10.1016/j.echo.2018.04.013.

13. Y. Kotani, A. Di Gioia, G. Landoni, et al., "Correction: An Updated "Norepinephrine Equivalent" Score in Intensive Care as a Marker of Shock Severity," *Critical Care (London, England)* 29 (2025): 104, https://doi.org/10.1186/s13054-025-05250-9.

14. A. Kempny, G. P. Diller, G. Kaleschke, et al., "Impact of Transcatheter Aortic Valve Implantation or Surgical Aortic Valve Replacement on Right Ventricular Function," *Heart* 98 (2012): 1299–1304, https://doi.org/10.1136/heartjnl-2011-301203.

15. P. E. Shrout and J. L. Fleiss, "Intraclass Correlations: Uses in Assessing Rater Reliability," *Psychological Bulletin* 86 (1979): 420–428, https://doi.org/10.1037//0033-2909.86.2.420.

16. M. Dandel and R. Hetzer, "Echocardiographic Assessment of the Right Ventricle: Impact of the Distinctly Load Dependency of Its Size, Geometry and Performance," *International Journal of Cardiology* 221 (2016): 1132–1142, https://doi.org/10.1016/j.ijcard.2016.07.014.

17. Y. Zhao, P. Lindqvist, J. Nilsson, et al., "Trans-Catheter Aortic Valve Implantation–Early Recovery of Left and Preservation of Right Ventricular Function," *Interactive CardioVascular and Thoracic Surgery* 12 (2011): 35–39, https://doi.org/10.1510/icvts.2010.251348.

18. L. E. Dobson, T. A. Musa, and J. P. Greenwood, "Aortic Valve Replacement and the Right Ventricle – The Plot Thickens," *Journal of Thoracic and Cardiovascular Surgery* 150 (2015): 742–743, https://doi.org/10.1016/j.jtcvs.2015.05.027.

19. P. Lindqvist, A. Holmgren, Y. Zhao, et al., "Effect of Pericardial Repair After Aortic Valve Replacement on Septal and Right Ventricular Function," *International Journal of Cardiology* 155 (2012): 388–393, https://doi.org/10.1016/j.ijcard.2010.10.049.

20. B. S. Allen, J. W. Winkelmann, H. Hanafy, et al., "Retrograde Cardioplegia Does Not Adequately Perfuse the Right Ventricle," *Journal of Thoracic and Cardiovascular Surgery* 109 (1995): 1116–1124, https://doi.org/10.1016/S0022-5223(95)70195-8.

21. F. Schiefenhövel, R. F. Trauzeddel, M. Sander, et al., "High Central Venous Pressure After Cardiac Surgery Might Depict Hemodynamic Deterioration Associated With Increased Morbidity and M Ortality," *Journal of Clinical Medicine* 10 (2021): 3945, https://doi.org/10.3390/jcm10173945.

22. A. A. Sayour, M. Tokodi, C. Celeng, et al., "Association of Right Ventricular Functional Parameters With Adverse Cardiopulmonary Outcomes: A Meta-Analysis," *Journal of the American Society of Echocardiography* 36 (2023): 624–633, e8, https://doi.org/10.1016/j.echo.2023.01.018.

23. F. Haddad, A. Y. Denault, P. Couture, et al., "Right Ventricular Myocardial Performance Index Predicts Perioperative Mortality or Circulatory Failure in High-Risk Valvular Surgery," *Journal of the American Society of Echocardiography* 20 (2007): 1065–1072, https://doi.org/10.1016/j.echo.2007.02.017.

24. J. Kjaergaard, E. M. Snyder, C. Hassager, et al., "Impact of Preload and Afterload on Global and Regional Right Ventricular Function and Pressure: A Quantitative Echocardiography Study," *Journal of the American Society of Echocardiography* 19 (2006): 515–521, https://doi.org/10.1016/j.echo.2005.12.021.

25. J. Boldt, B. Zickmann, M. Ballesteros, et al., "RETRACTED: Right Ventricular Function in Patients With Aortic Stenosis Undergoing Aortic Valve Replacement," *Journal of Cardiothoracic and Vascular Anesthesia* 6 (1992): 287–291, https://doi.org/10.1016/1053-0770(92)90141-S.

26. T. C. Tan, A. W. Flynn, and A. Chen-Tournoux, "Risk Prediction in Aortic Valve Replacement: Incremental Value of the Preoperative Echocardiogram," *Journal of the American Heart Association* 4 (2015): e002129, https://doi.org/10.1161/JAHA.115.002129.

27. M. Tolvaj and A. Kovács, "Significant Disagreement Between Conventional Parameters and 3D Chocardiography-Derived Ejection Fraction in the Detection of Right Ventricular Systolic Dysfunction and Its Association With Outcomes," *Journal of the American Society of Echocardiography* 37 (2024): 677–686, https://doi.org/10.1016/j.echo.2024.04.005.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Table S1. Norepinephrine equivalent, epinephrine, and nicardipine dose at each timing. Table S2. Hemodynamics at each timing. Table S3. Post-hoc pairwise comparisons in the analysis of covariance of RVEF, RVFAC, and TAPSE. Table S4. Intraclass correlations of pre-procedural 3D RVEF, RVFAC, and TAPSE Figure S1. Bland-Altman plot for ICC.