Original Article

Prognostic value of cardiac CT parameters in patients undergoing surgical correction for tricuspid regurgitation: a prospective study

Young Joo Suh[1], Seung Hyun Lee[2], Sak Lee[2], Aaron Youngjae Kim[3,4], Young Jin Kim[1]

[1]Department of Radiology, Research Institute of Radiological Science, Center for Clinical Imaging Data Science, Severance Hospital, Yonsei University College of Medicine, Seoul, Korea; [2]Division of Cardiovascular Surgery, Department of Thoracic and Cardiovascular Surgery, Severance Cardiovascular Hospital, Yonsei University College of Medicine, Seoul, Korea; [3]Weill Cornell Medicine-Qatar, Doha, Qatar; [4]Department of Medicine, New York Presbyterian Brooklyn Methodist Hospital, Brooklyn, NY, USA

Contributions: (I) Conception and design: YJ Suh; (II) Administrative support: YJ Suh; (III) Provision of study materials or patients: All authors; (IV) Collection and assembly of data: YJ Suh, AY Kim; (V) Data analysis and interpretation: YJ Suh, AY Kim; (VI) Manuscript writing: All authors; (VII) Final approval of manuscript: All authors.

Correspondence to: Young Joo Suh, MD, PhD. Department of Radiology, Research Institute of Radiological Science, Center for Clinical Imaging Data Science, Severance Hospital, Yonsei University College of Medicine, 50-1 Yonsei-ro, Seodaemun-gu, Seoul 03722, Korea. Email: rongzusuh@gmail.com.

Background: Predictive value of perioperative cardiac computed tomography (CT) parameters, for long-term postoperative outcomes following tricuspid valve (TV) surgery is unclear. We investigated the prognostic value of perioperative cardiac CT-derived tricuspid annular and right ventricular (RV) parameters on long-term postoperative adverse outcomes after TV surgery.

Methods: We prospectively enrolled 66 patients who underwent corrective TV surgery for tricuspid regurgitation between June 2019 and January 2021 and had preoperative cardiac CT. Postoperative cardiac CT was performed 6 months after surgery. RV volume parameters were analyzed on the preoperative and postoperative cardiac CT images; the TV annulus diameter was measured from the preoperative CT. Postoperative adverse outcomes included death from any cause, unplanned postoperative admission, residual tricuspid regurgitation (≥ moderate), or RV systolic pressure >50 mmHg on postoperative echocardiography performed postoperative 6 months or later. Cox proportional hazard regression analyses were performed to identify significant imaging parameters associated with postoperative adverse outcomes. Restricted mean survival time was compared between groups at postoperative timepoints of 1 and 2 years.

Results: During postoperative follow-up period (mean 597.9±182.2 days), adverse outcomes occurred in 8 (12.1%) of 66 patients. Postoperative CT revealed RV volume changes of −21.6%±20.1% and −19.4%±23.3% for RV end-diastolic volume (RVEDV)/body surface area (BSA) and RV end-systolic volume (RVESV)/BSA, respectively. After adjusting for age, longer tricuspid annulus diameter $(TAD)_{4ch}$/BSA and larger RVEDV/BSA and RV stroke volume (RVSV)/BSA on preoperative CT, and a greater extent of postoperative RVEDV/BSA reduction showed significant association with adverse outcomes. Among imaging parameters, the largest intergroup difference was observed in comparison by preoperative RVSV/BSA (cutoff 37.2 mL/m^2) at postoperative 1-year timepoint (difference of 3.0 months, P<0.001) and RVEDV/BSA (cutoff 169.2 mL/m^2) at postoperative 2-year timepoint (difference of 8.7 months, P<0.001).

Conclusions: Perioperative cardiac CT imaging-based TAD and RV volume can provide independent prognostic information for postoperative adverse outcomes in patients undergoing TV surgery.

Keywords: Tricuspid valve (TV); right ventricle; cardiac surgery; multidetector computed tomography (multidetector CT)

Submitted Dec 22, 2024. Accepted for publication Apr 11, 2025. Published online Jun 24, 2025.
doi: 10.21037/qims-2024-2915
View this article at: https://dx.doi.org/10.21037/qims-2024-2915

Introduction

The association of tricuspid regurgitation (TR) severity with survival and the development of transcatheter tricuspid valve (TV) intervention has increased the focus on TV disease since several decades (1). Approximately 80% of significant TR cases are functional and associated with TV annular dilation and leaflet tethering in pressure and/or volume overload-related right ventricular (RV) remodeling (2). The 2020 American Heart Association/American College of Cardiology guideline for the management of patients with valvular heart disease includes TR severity and other factors, such as tricuspid annulus diameter (TAD), RV function, and pulmonary hypertension, as indications for TR intervention (3), and these should be included in imaging evaluation of TV disease.

Echocardiography is the primary investigation for assessing TV disease; however, multimodality imaging is preferred for comprehensive evaluation because cardiac magnetic resonance (CMR) imaging and computed tomography (CT) are complementary investigations to echocardiography (4). Compared to echocardiography, CMR provides a more accurate, reproducible assessment of RV volumes, systolic function, and other parameters, including TAD and the degree of leaflet tethering. Cardiac CT enables better anatomic visualization of TV apparatus and adjacent structures, thereby enabling transcatheter therapy planning (5). In case of arrhythmia and poor compliance, CMR image quality is often impaired; thus, cardiac CT constitutes a useful modality for RV functional evaluation.

A retrospective study demonstrated that preoperative cardiac CT-based TAD and RV volumes could predict immediate postoperative RV dysfunction (<7 days) after TV surgery (6). Nevertheless, the predictive value of perioperative cardiac CT parameters, including not only TAD and RV volume on preoperative CT but also the extent of postoperative RV volume decrease, for long-term postoperative outcomes is unclear. Therefore, we hypothesized that TAD and RV volume parameters measured on cardiac CT and the postoperative RV volume change could be associated with postoperative adverse outcomes after TV surgery.

The purpose of our study was to prospectively investigate the prognostic value of perioperative CT-derived TV annular and RV parameters in long-term postoperative adverse outcomes after TV surgery. We present this article in accordance with the STROBE reporting checklist (available at https://qims.amegroups.com/article/view/10.21037/qims-2024-2915/rc).

Methods

Patients

The study was conducted in accordance with the Declaration of Helsinki and its subsequent amendments. This prospective study was approved by the Institutional Review Board of Severance Hospital (No. 4-2018-0725) and informed consent was taken from all individual participants.

We prospectively enrolled patients who met all the following criteria: (I) received TV surgery between June 2019 and January 2021; (II) underwent cardiac CT before TV surgery; (III) did not receive concomitant coronary artery bypass-grafting with TV surgery; and (IV) informed consent for study participation. The exclusion criteria included: (I) serum estimated glomerular filtration rate <60 mL/min/1.73 m^2; (II) history of TV surgery before preoperative CT (*Figure 1*). Of the 84 eligible patients, 13 were excluded: two had decreased serum estimated glomerular filtration rate on follow-up study before the postoperative CT examination, 11 withdrew consent. Therefore, 71 patients underwent postoperative cardiac CT at 6 months after TV surgery. Among these 71 patients, five patients were excluded from analysis because four patients had primary TR etiology, and one patient had inadequate CT image quality for RV assessment. In total, 66 patients (36 women and 30 men; mean age 62.0±13.3 years) were included in the final analysis.

CT acquisition protocol

At our institution, cardiac CT is routinely performed to evaluate coronary artery and intra-/extracardiac structures before scheduling patients with valvular heart disease to receive valve surgery. All preoperative and postoperative CT scans were performed with a wide-coverage, 256-row (16 cm in the z-axis) CT scanner (Revolution CT, GE

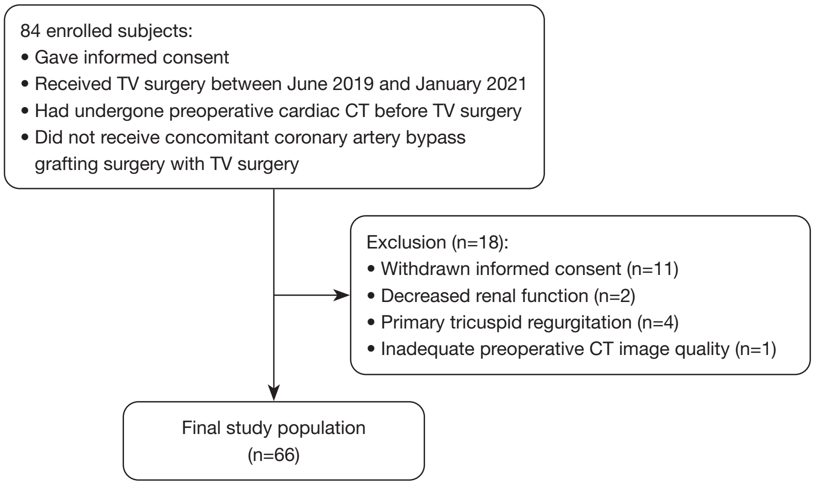

Figure 1 Flow chart of patient enrollment in this study. CT, computed tomography; TV, tricuspid valve.

Healthcare, Waukesha, WI, USA) with a tube rotation time of 280 ms (temporal resolution 140 ms). Patients were not premedicated with an oral beta-blocker for heart-rate control, and all CT angiography examinations were performed with prospective electrocardiogram-gating and single-beat acquisition (padding range of 20–120% of the R-R interval) to cover the whole cardiac cycle and alleviate the stair-step artifact (7,8). The triple-phase injection method (70 mL iopamidol, followed by 30 mL 50% blended iopamidol with saline, and 20 mL saline at 5 mL/s flow rate) was used to achieve sufficient RV enhancement. Scan delay times from contrast agent injection to scanning were determined individually using the bolus-tracking technique with a region-of-interest in the ascending aorta. All images were reconstructed with soft-tissue kernels and slice thickness of 0.625 mm, with 0.625-mm increments. Ten transverse datasets were reconstructed every 10% of the cardiac cycle and transferred to an image server for analysis using dedicated software (Aquarius iNtuition, Ver. 4.4.11, TeraRecon, San Mateo, CA, USA). The mean dose-length products of preoperative and postoperative cardiac CT were 257.3±71.4 and 310.4±78.2 mGy·cm, respectively.

CT image analysis

All CT analyses were performed by a cardiac radiologist, blinded to clinical information and echocardiographic results. On both preoperative and postoperative cardiac CT scans, RV volume was quantified with a semiautomatic three-dimensional region-growing method, both in end-diastolic and end-systolic phases (*Figure 2*) (9,10). The endocardial border was delineated using an attenuation-based thresholding method, with manual threshold adjustment until the appearances matched the visual assessment. Papillary muscles and trabeculations were excluded from the RV volume. End-diastolic and end-systolic volumes (EDV and ESV) were measured, and stroke volume (SV) was calculated as [EDV–ESV]. The RV ejection fraction (RVEF) was defined as “SV/EDV”.

Preoperative TV assessment comprised TAD measurement on multiplanar reformatted images in diastole showing maximal dimensions, as follows: (I) maximal diameter on four-chamber view (TAD_{4ch}); (II) maximal diameter on long-axis view (TAD_{LA}); and (III) average diameter derived from the TV annulus area on en-face (short-axis) view (TAD_{avg}) (6,11). For TAD and RV volume parameters, values indexed by body surface area (BSA) were analyzed. Postoperative RV volume changes were calculated for RVEDV/BSA, RVESV/BSA, RVSV/BSA as follows: 100 × (RV $volume_{post}$ – RV $volume_{pre}$)/RV $volume_{pre}$. The RVEF change was calculated as $RVEF_{post}$ – $RVEF_{pre}$.

Echocardiographic parameters

All patients underwent preoperative echocardiography (transthoracic or transesophageal echocardiography) within a median duration of 11 days (25^{th} to 75^{th} percentile, 2.8–34.0 days) from their TV surgery and underwent 6-month follow-up transthoracic echocardiography postoperatively at a median duration of 192.0 days (25^{th} to 75^{th} percentile, 183.0–199.0 days). Thereafter, further follow-up transthoracic echocardiography was performed annually

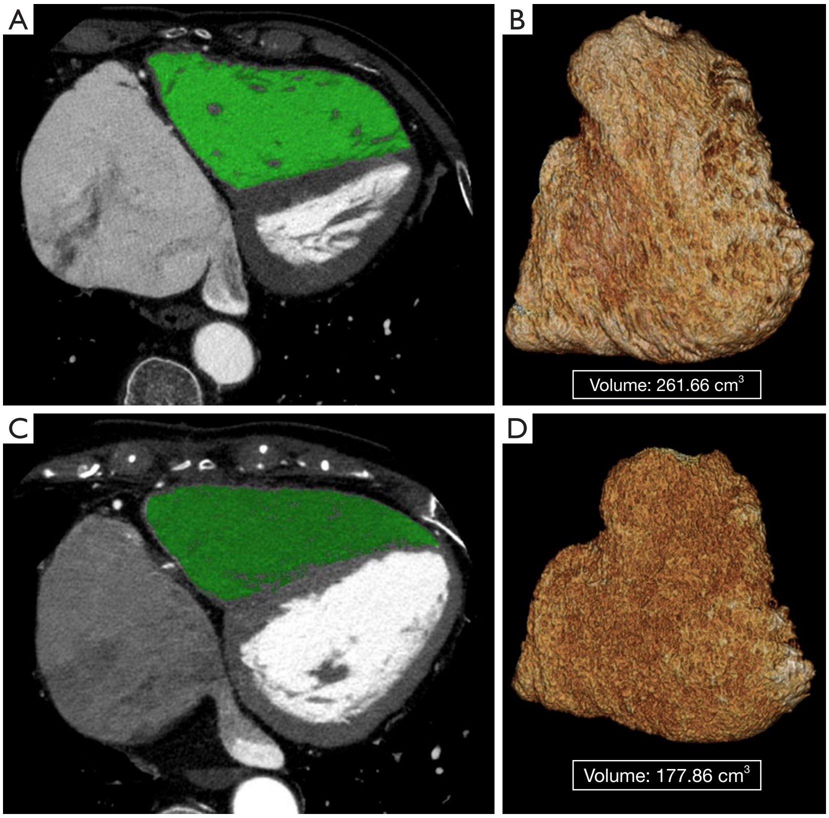

Figure 2 A representative case in a 73-year-old female for measurement of RV volume using cardiac CT. (A,B) The RVEDV/BSA was measured at 261.66 mL (201.3 mL/m^2) on preoperative cardiac CT, which was taken 5 days prior to the surgery. She had been diagnosed with prosthetic mitral valve dysfunction, native aortic valve steno-regurgitation, and severe TR. She subsequently underwent tricuspid valve repair using an annuloplasty ring, along with a redo-mitral valve replacement and aortic valve replacement. (C,D) Postoperative cardiac CT showed a decrease in RV volume [RVEDV 177.86 mL (134.7 mL/m^2)], resulting in postoperative RVEDV change of −33.0%. On postoperative follow-up echocardiography at 7 months, she had a moderate residual TR and right ventricular systolic pressure of 42 mmHg. (A,C) Axial CT images (RV cavity in green) and (B,D) 3-dimensional volume rending images depict RV volume measurement. BSA, body surface area; CT, computed tomography; EDV, end-diastolic volume; RV, right ventricle; TR, tricuspid regurgitation.

or bi-annually. TR severity was graded semi-quantitatively from color and continuous-wave Doppler data using a multiparametric approach: none or trivial (0–1+), mild (2+), moderate (3+), or severe (4+) (12,13). Preoperative TAD was measured in end-diastole in the apical four-chamber view (TAD_{echo}) (12). The RV systolic pressure (RVSP) was calculated from the maximum velocity of the TR jet on transthoracic echocardiography according to the modified Bernoulli equation (14).

TV surgery

TV surgery, indicated according to the current guideline (3), was performed by one of two experienced cardiothoracic surgeons. In detail, TV surgery was indicated for severe TR undergoing left-sided valve surgery, or non-severe but progressive TR undergoing left-sided valve surgery with (I) TAD dilatation (tricuspid annulus end-diastolic diameter >40 mm or 21 mm/m^2) on echocardiography or CT or (II) prior signs or symptoms from right-sided heart failure (3). Isolated TV surgery was considered in patients with signs and symptoms of right-sided heart failure and severe isolated secondary TR attributable to annular dilation (in the absence of pulmonary hypertension or left-sided disease) who are poorly responsive to medical therapy (3). In general, ring annuloplasty of TV was performed using either semi-rigid ring with flexible ends (Tri-AD; Medtronic, Minneapolis, MN, USA) or rigid (MC3; Edwards LifeScience, Irvine, CA, USA). In case of non-repairable valve morphology such as severe leaflet thickening and calcification, TV replacement was performed. During operation, the decision to occlude left atrial appendage was made in cases with persistent atrial fibrillation at the discretion of the surgeon, using one of following two methods: closure with an internal ligation method or amputation with a stapler device.

Data analysis

Clinical data were collected from medical records until the clinical follow-up end date of April 30, 2022 (mean postoperative follow-up period 597.9±182.2 days). Preoperative echocardiographic data included TR severity, TAD_{echo}, RVSP, and left ventricular ejection fraction. Postoperative follow-up transthoracic echocardiography data at least 6 months or later after surgery included residual TR severity and RVSP. In cases with preoperative TR with moderate to severe degree, type of TR was classified into atrial secondary functional TR and ventricular secondary functional TR, according to the recent proposed criteria (15). There was no cardiac implantable electronic device-related TR in our study population.

Study endpoint

The primary endpoint was the postoperative adverse outcome, including death from any cause, unplanned postoperative admission within postoperative follow-up period, or residual TR, or elevated RVSP >50 mmHg on postoperative transthoracic echocardiography after discharge (at least 6 months or later after TV surgery).

Statistical analysis

Statistical analyses were performed using computerized statistics programs (MedCalc for Windows, version 20.106; MedCalc Software, Mariakerke, Belgium, and R version 4.2.1, R Foundation for Statistical Computing, Vienna, Austria). Normally distributed data were identified using the Shapiro-Wilk W test. Continuous variables were presented as mean ± standard deviation and were compared using the independent *t*-test for normally distributed data or the Mann-Whitney *U* test for non-normally distributed data. Comparison of clinical, CT, and echocardiographic variables between patients with and without postoperative adverse outcomes was performed using the Chi-squared or Fisher's exact test for categorical variables, or the independent *t*-test or Mann-Whitney *U* test for continuous variables. Cumulative event rates were investigated by the Kaplan-Meier curve. Cutoffs of echocardiography or CT-derived parameters for comparison of survival curve were set by maximally selected rank statistics. Intergroup differences in event-free survival time were compared using the log-rank test. Restricted mean survival time was compared between groups at postoperative timepoints of 1 and 2 years. Cox proportional hazard regression analyses were performed to identify significant prognostic factors for postoperative adverse outcomes. Hazard ratios with 95% confidence intervals were used to ascertain risk estimations for unadjusted and adjusted analyses of clinical variables. Proportional hazard assumption of each variable was assessed using Schoenfeld residuals (16). Associations of postoperative volume change between clinical, echocardiographic, and CT parameters were assessed using logistic regression analysis. Probability values <0.05 were considered statistically significant.

Results

Baseline characteristics

Baseline clinical characteristics are summarized in *Table 1*. All patients received TV repair (ring annuloplasty) except one patient who underwent TV replacement due to severe leaflet thickening calcification. Three (4.5%) patients underwent isolated TV surgery: one due to secondary TR following prior left-sided valve correction and two due to atrial functional TR associated with atrial fibrillation. During postoperative follow-up, adverse outcomes occurred in 8 (12.1%) of 66 patients (1 unplanned admission after surgery, 6 residual TR, and 4 elevated RVSP >50 mmHg on at least 6 months follow-up postoperative transthoracic echocardiography); no death occurred. Two patients had both residual TR and elevation RVSP, and one patient had residual TR and unplanned admission after surgery due to chest pain. Patients with postoperative adverse outcome were significantly older than those without adverse outcomes (74.0±4.1 *vs.* 60.3±13.3 years, P<0.001). There were no significant intergroup differences in other demographic characteristics.

Echocardiography data and CT analysis results

Patients with postoperative adverse outcome had more

Table 1 Comparison of clinical characteristics between patients with and without postoperative adverse outcomes

Characteristics	All patients (n=66)	Patients without postoperative adverse outcome (n=58)	Patients with postoperative adverse outcome (n=8)	P value
Male	30 (45.5)	28 (48.3)	2 (25.0)	0.389
Age (years)	62.0±13.3	60.3±13.3	74.0±4.1	<0.001
Body surface area (m^2)	1.67±0.2	1.7±0.2	1.6±0.2	0.095
History of coronary artery disease	43 (65.2)	35 (60.3)	8 (100.0)	0.07
History of myocardial infarction	0 (0)	0 (0)	0 (0)	>0.999
History of atrial fibrillation	52 (78.8)	45 (77.6)	7 (87.5)	0.523
Prior valve surgery				0.553
AV repair	1 (1.5)	1 (1.7)	0 (0)	
MV replacement	7 (10.6)	5 (8.6)	2 (25.0)	
AV and MV replacement	5 (7.6)	4 (6.9)	1 (12.5)	
MV annuloplasty	5 (7.6)	5 (8.6)	0 (0)	
Classification of TV disease†				0.466
Atrial secondary functional TR	24 (55.8)	22 (62.9)	2 (25.0)	
Ventricular secondary functional TR	19 (44.2)	13 (37.1)	6 (75.0)	
Type of current TV surgery				0.722
Ring annuloplasty	65 (98.5)	57 (98.3)	8 (100.0)	
Replacement	1 (1.5)	1 (1.7)	0 (0)	
Type of annuloplasty ring‡				0.112
Semi-rigid ring with flexible ends	24 (36.9)	19 (33.3)	5 (62.5)	
Rigid	41 (63.1)	38 (66.7)	3 (37.5)	
Size of implanted ring (mm)‡				0.05
26	8 (12.3)	7 (12.3)	1 (12.5)	
28	8 (12.3)	8 (14.0)	0 (0)	
30	38 (58.5)	35 (61.4)	3 (37.5)	
32	11 (16.9)	7 (12.3)	4 (50.0)	
Concomitant other current surgery				
Valve surgery				0.386
TV surgery only	3 (4.5)	3 (5.2)	0 (0)	
MV surgery	46 (69.7)	41 (70.7)	5 (62.5)	
AV surgery	5 (7.6)	5 (8.6)	0 (0)	
MV, AV surgery	12 (18.2)	9 (15.5)	3 (37.5)	
Arrhythmia surgery	23 (34.8)	20 (34.5)	3 (37.5)	>0.999
Left atrial appendage surgery	28 (42.4)	25 (43.1)	3 (37.5)	>0.999

Table 1 (*continued*)

Table 1 (*continued*)

Characteristics	All patients (n=66)	Patients without postoperative adverse outcome (n=58)	Patients with postoperative adverse outcome (n=8)	P value
Echocardiographic parameter				
Time interval between preoperative echocardiography and TV surgery (days)	11.0 [2.0–34.0]	9.5 [2.0–34.0]	24.0 [2.0–40.5]	0.775
Preoperative TR grade				0.001
Mild	23 (34.8)	23 (39.7)	0 (0.0)	
Moderate	23 (34.8)	22 (37.9)	1 (12.5)	
Severe	20 (30.3)	13 (22.4)	7 (87.5)	
Preoperative TR grade (binary)				0.001
Mild to moderate	46 (69.7)	45 (77.6)	1 (12.5)	
Severe	20 (30.3)	13 (22.4)	7 (87.5)	
TV annulus				
TV annulus diameter (mm)	39.4±6.2	38.4±5.4	46.5±7.4	<0.001
TV annulus diameter/BSA (mm/m^2)	23.9±3.9	23.1±3.0	29.9±4.1	<0.001
Preoperative RVSP (mmHg)	45.0 [39.0–55.0]	44.0 [36.0–54.0]	59.0 [52.0–65.5]	0.018
LVEF (%)	64.0 [59.0–68.0]	64.0 [59.0–68.0]	61.5 [57.0–67.5]	0.616

Data are presented as the n (%), mean ± standard deviation, or median [25th to 75th percentile]. †, these are determined in cases with moderate severe degree of TR only; ‡, one patient who underwent TV replacement was not included in the analysis. AV, aortic valve; BSA, body surface area; LVEF, left ventricular ejection fraction; MV, mitral valve; RVSP, right ventricular systolic pressure; TR, tricuspid regurgitation; TV, tricuspid valve.

frequent severe TR grades, longer TAD_{echo}, and higher RVSP on echocardiography, compared to those without postoperative adverse outcome (P<0.05, *Table 1*). Preoperative cardiac CT was performed within 7.5 days (25th to 75th percentile, 3.0–21.0 days) from TV surgery; postoperative cardiac CT was performed at 193.8±12.9 days after TV surgery. Postoperative CT in one patient was inadequate to measure RV volume on diastolic phase because of arrhythmia during CT examination. Therefore, postoperative RV volume change could be measured for 65 patients (mean −21.6%±20.1% for RVEDV/BSA; −19.4%±23.3% for RVESV/BSA). In patients with postoperative adverse outcomes, TAD_{4ch}/BSA on CT was significantly longer than in those without postoperative adverse outcomes (P<0.05, *Table 2*). RVEDV/BSA, RVESV/BSA, and RVSV/BSA on both preoperative and postoperative CT scans were significantly larger in patients with postoperative adverse outcomes than in those without postoperative adverse outcomes (P<0.05, *Table 2*). RVEF on preoperative CT was significantly higher in patients with postoperative adverse outcomes (P=0.009). Patients with adverse outcomes had a greater extent of reduction in RV volume (RVEDV/BSA and RVESV/BSA) than those without postoperative adverse outcomes (P<0.05, *Table 2*).

Prognostic value of cardiac CT-derived parameters

All clinical, echocardiographic, and CT-derived variables satisfied proportional hazard assumption before and after adjustment (Tables S1,S2). In the unadjusted Cox PH model, age, severe TR and longer TAD/BSA on preoperative echocardiography and longer TAD/BSA on preoperative CT, larger RV volume (RVEDV/BSA and RVSV/BSA) on preoperative and postoperative cardiac CT scans, higher RVEF on preoperative CT, and greater volume decrease in RVEDV were significant predictors of postoperative adverse outcomes (*Table 3*). After adjusting clinical variables (age), severe TR and the longer TAD/BSA on echocardiography, longer TAD_{4ch}/BSA on preoperative CT, larger RVEDV/BSA and RVSV/BSA on preoperative

Table 2 Comparison of CT parameters between patients with and without postoperative adverse outcomes

CT parameters	All patients (n=66)	Patients without postoperative adverse outcome (n=58)	Patients with postoperative adverse outcome (n=8)	P value
Preoperative CT parameter				
Interval between preoperative CT and TV surgery (days)	7.5 [3.0–21.0]	8.5 [3.0–21.0]	6.0 [2.5–23.0]	0.89
TV annulus				
TAD_{4ch} (mm)	42.2 [39.8–46.9]	42.0 [39.3–46.0]	47.4 [43.8–54.2]	0.015
TAD_{LA} (mm)	44.7±6.0	44.3±5.9	47.4±6.6	0.177
TAD_{avg} (mm)	44.2 [41.4–47.0]	44.0 [40.8–46.9]	44.3 [43.4–53.1]	0.259
TAD_{4ch}/BSA (mm/m^2)	26.4 [24.3–27.7]	25.6±2.9	31.6±4.3	<0.001
TAD_{LA}/BSA (mm/m^2)	27.1±4.0	26.6±3.6	30.7±4.5	0.005
TAD_{avg}/BSA (mm/m^2)	26.4 [25.1–28.9]	26.6±2.8	30.9±4.8	0.039
RV parameters				
RVEDV (mL)	214.6 [173.9–268.9]	200.0 [171.8–254.7]	313.0 [273.3–398.6]	<0.001
RVESV (mL)	109.7 [88.0–136.4]	108.1 [85.3–130.6]	144.7 [113.9–179.3]	0.021
RVSV (mL)	95.8 [80.4–128.2]	92.4 [79.2–113.9]	177.1 [156.9–183.1]	<0.001
RVEF (%)	47.8±8.7	46.8±8.3	55.3±8.0	0.009
RVEDV/BSA (mL/m^2)	122.8 [109.4–165.8]	119.2 [107.5–143.3]	203.5 [184.8–236.7]	<0.001
RVESV/BSA (mL/m^2)	66.8 [55.3–82.6]	60.6 [52.3–77.6]	92.2 [82.8–107.7]	0.002
RVSV/BSA (mL/m^2)	29.3±6.9	28.3±6.2	36.2±8.1	0.002
Postoperative CT parameter				
Interval between postoperative CT and TV surgery (days)	193.8±12.9	193.5±12.1	195.8±18.6	0.646
RV parameters				
RVEDV (mL)†	164.0 [142.3–184.0]	162.7±30.4	200.0±57.4	0.111
RVESV (mL)	89.3±23.9	87.8±23.6	100.5±24.6	0.16
RVSV (mL)†	71.9 [63.6–86.0]	71.0 [62.7–83.2]	90.4 [74.0–115.5]	0.052
RVEF (%)†	46.7±8.7	46.5±8.7	48.7±9.1	0.49
RVEDV/BSA (mL/m^2)†	100.0 [86.2–109.1]	98.2±15.9	131.8±37.5	0.04
RVESV/BSA (mL/m^2)	54.4±13.5	52.8±13.0	65.5±12.6	0.012
RVSV/BSA (mL/m^2)†	44.2 [40.1–53.7]	42.5 [40.0–50.8]	68.0 [47.9–73.7]	0.012
Perioperative change in RV parameters				
Change in RVEDV/BSA (%)†	−21.6±20.1	−19.0±19.6	−40.6±9.4	<0.001
Change in RVESV/BSA (%)	−19.4±23.3	−17.5±24.0	−32.1±9.0	0.003
Change in RVSV/BSA (%)†	61.4 [24.3–88.6]	61.4 [24.3–87.9]	57.9 [29.02–150.2]	0.746
Change in RVEF (%)†	−0.9±11.3	−0.2±11.5	−6.5±8.3	0.136

Data are presented as median [25th to 75th percentile] or mean ± standard deviation. †, values can be measured for 65 patients because postoperative CT in one patient is inadequate to measure RV volume on diastolic phase because of arrhythmia during CT examination. 4ch, four-chamber; avg, average; BSA, body surface area; CT, computed tomography; EDV, end-diastolic volume; EF, ejection fraction; ESV, end-systolic volume; LA, long-axis; RV, right ventricle; SV, stroke volume; TAD, tricuspid annulus diameter; TV, tricuspid valve.

Table 3 Cox proportional hazard model for the prediction of postoperative adverse outcomes

Variables	Unadjusted model			Adjusted model		
	HR (95% CI)	P value	C-index (95% CI)	HR (95% CI)	P value	C-index (95% CI)
Clinical finding						
Female sex	5.374 (0.643–44.93)	0.122	0.648 (0.506–0.791)	N/A	N/A	N/A
Age (per 1 year increase)	1.155 (1.028–1.297)	0.015	0.835 (0.737–0.932)	N/A	N/A	N/A
BSA (per 1 m^2 increase)	0.011 (0.0001–1.147)	0.057	0.718 (0.514–0.922)	N/A	N/A	N/A
Echocardiographic parameter						
TR severity			0.778 (0.635–0.922)			0.892 (0.836–0.949)
TR grade (≤ moderate)	1 (reference)			1 (reference)		
TR grade (severe)	15.078 (1.812–125.487)	0.012		9.491 (1.085–83.044)	0.042	
TV annulus diameter						
TV annulus diameter/BSA (per 1 mm/m^2 increase)	1.365 (1.169–1.594)	<0.001	0.909 (0.856–0.962)	1.275 (1.077–1.510)	0.005	0.925 (0.885–0.965)
Preoperative RVSP (mmHg)	1.032 (0.988–1.079)	0.160	0.693 (0.496–0.890)	N/A	N/A	N/A
Preoperative CT parameter						
TV annulus diameter						
TAD_{4ch}/BSA (per 1 mm/m^2 increase)	1.336 (1.138–1.570)	<0.001	0.844 (0.738–0.950)	1.232 (1.029–1.475)	0.023	0.875 (0.786–0.965)
TAD_{LA}/BSA (per 1 mm/m^2 increase)	1.255 (1.029–1.530)	0.025	0.732 (0.518–0.947)	1.156 (0.966–1.383)	0.114	0.848 (0.728–0.968)
TAD_{avg}/BSA (per 1 mm/m^2 increase)	1.289 (1.075–1.545)	0.006	0.736 (0.503–0.970)	1.168 (0.965–1.413)	0.111	0.850 (0.737–0.964)
RV parameter						
RVEDV/BSA (per 1 mm/m^2 increase)	1.020 (1.010–1.030)	<0.001	0.903 (0.846–0.960)	1.015 (1.005–1.026)	0.005	0.913 (0.854–0.973)
RVESV/BSA (per 1 mm/m^2 increase)	1.018 (0.999–1.037)	0.070	0.781 (0.666–0.896)	N/A	N/A	N/A
RVSV/BSA (per 1 mm/m^2 increase)	1.264 (1.110–1.438)	<0.001	0.831 (0.678–0.984)	1.186 (1.047–1.344)	0.007	0.903 (0.812–0.994)
RVEF (per 1% increase)	1.223 (1.077–1.390)	0.002	0.843 (0.733–0.952)	1.164 (1.027–1.320)	0.018	0.921 (0.878–0.965)
Postoperative CT parameter						
RV parameter						
RVEDV/BSA (per 1 mm/m^2 increase)	1.034 (1.012–1.057)	0.002	0.765 (0.566–0.965)	1.018 (0.994–1.043)	0.143	0.859 (0.757–0.961)
RVESV/BSA (per 1 mm/m^2 increase)	1.046 (0.990–1.094)	0.116	0.723 (0.576–0.870)	N/A	N/A	N/A
RVSV/BSA (per 1 mm/m^2 increase)	1.048 (1.018–1.080)	0.002	0.723 (0.470–0.975)	1.027 (0.994–1.062)	0.111	0.856 (0.734–0.978)
RVEF (per 1% increase)	1.036 (0.950–1.129)	0.425	0.628 (0.399–0.857)	N/A	N/A	N/A
Postoperative change in RV parameters						
Change in RVEDV/BSA (%) (per 1% increase)	0.923 (0.869–0.980)	0.008	0.829 (0.730–0.928)	0.901 (0.28–0.981)	0.017	0.923 (0.878–0.967)
Change in RVESV/BSA (%) (per 1% increase)	0.975 (0.941–1.012)	0.180	0.661 (0.547–0.776)	N/A	N/A	N/A
Change in RVSV/BSA (%) (per 1% increase)	0.998 (0.987–1.010)	0.779	0.525 (0.272–0.779)	N/A	N/A	N/A
Change in RVEF (%) (per 1% increase)	0.928 (0.857–1.005)	0.067	0.692 (0.534–0.850)	N/A	N/A	N/A

4ch, four-chamber; avg, average; BSA, body surface area; CI, confidence interval; CT, computed tomography; EDV, end-diastolic volume; EF, ejection fraction; ESV, end-systolic volume; HR, hazard ratio; LA, long-axis; N/A, not applicable; RV, right ventricle; RVSP, right ventricular systolic pressure; SV, stroke volume; TAD, tricuspid annulus diameter; TR, tricuspid regurgitation; TV, tricuspid valve.

CT were significant predictors of postoperative adverse outcomes. Greater postoperative RVEDV/BSA change showed a significant association after adjustments.

For classifying groups for survival comparison, optimal cutoff values were calculated for five echocardiographic or CT parameters variables that were significant predictors on adjusted Cox proportional hazard model (Table S3). The best cutoff values for preoperative RVEDV/BSA and postoperative RVEDV decrease were 169.2 mL/m^2 and −40.5%, respectively.

When restricted mean survival time was compared between groups, patients with longer TAD for both echocardiography and CT showed smaller restricted mean survival time at 1- and 2-year time point, than patient with shorter TAD (*Figure 3A*), indicating worse event-free survival. Patients with larger RVEDV/BSA and RVSV/BSA on preoperative CT and greater decrease in postoperative RVEDV/BSA showed worse event-free survival at 1- and 2-year timepoints (*Figure 3B,3C*). Among five parameters, the largest intergroup difference was observed in comparison by preoperative RVSV/BSA (cutoff 37.2 mL/m^2) at postoperative 1-year timepoint (difference of 3.0 months, P<0.001) and RVEDV/BSA (cutoff 169.2 mL/m^2) at postoperative 2-year timepoint (difference of 8.7 months, P<0.001). In patients with preoperative RVEDV/BSA ≤169.2 mL/m^2, no event occurred (*Figure 3C*). In patients with preoperative RVEDV/BSA >169.2 mL/m^2, there was no significant difference in overall event-free survival in comparison by postoperative RVEDV change, but a small difference in restricted mean survival time was seen at 1-year was noted between groups showing longer restricted mean survival time in patients with RVEDV change >−40.5% (difference of 1.0 month, P<0.001; *Figure 3C*).

Parameters associated with postoperative RV volume change

Greater volume reduction of RVEDV/BSA (≤−40.5%) was associated with severe TR, longer TAD/BSA, and higher RVSP on preoperative echocardiography, and longer TAD_{4ch}/BSA, larger RVEDV/BSA on preoperative CT (*Table 4*). No clinical variable was associated with greater RVEDV/BSA volume decrease. Comparison of clinical, echocardiographic, and CT parameters according to the RV volume-decrease extent and preoperative RV volume is presented in Table S4. In patients without preoperative RVEDV enlargement (RVEDV/BSA ≤169.2 mL/m^2), severe TR on preoperative echocardiography was the only significant predictor of marked postoperative RVEDV/BSA volume reduction [odds ratio (OR) 17.571, P=0.019]. In patients with preoperative RV enlargement, no imaging parameter was associated with the extent of RVEDV/BSA change.

Discussion

This prospective study shows that preoperative and postoperative cardiac CT-based TAD and RV volume parameters can predict postoperative adverse outcomes after TV surgery. Longer TAD and RVEDV/BSA and RVESV/BSA on preoperative cardiac CT are independent predictors of postoperative adverse outcome. Greater extent of postoperative RVEDV/BSA change is associated with small increase in postoperative adverse outcome at 1-year follow-up, in case of enlarged preoperative RV volume.

Assessment of RV systolic function is crucial in preoperative planning in TR patients as impaired RV systolic function negatively impacts functional and survival outcomes following TV surgery (2,17). The prognostic value of preoperative CMR-based RV volume and functional parameters in severe TR for prediction of postoperative outcomes after TV surgery was investigated (18-20). A large preoperative RV volume or low RVEF is an adverse prognostic factor in postoperative death or major adverse cardiac events after TV surgery. Timely surgical correction of severe TR improves functional capacity and clinical outcomes (17), and CMR-based RV volume measurement helps determine the optimal timing for TR surgery (18,19). Despite our endpoint parameter partly differing from those of previous studies (e.g., death or major adverse cardiovascular event), the results showed that large preoperative RV volume on CT was associated with increased postoperative adverse outcomes and can be a determinant for the timing of TV surgery.

Cardiac CT is a useful, accurate modality for evaluating RV volume and function (21); however, the prognostic value of cardiac CT parameters for predicting outcomes after TV surgery was rarely investigated. In a previous study, TAD, tethering angles, and tethering height on preoperative cardiac CT correlated with preoperative TR severity; tethering height was an independent risk factor for recurrent TR (≥ mild) (22). In another study, longer TAD and larger RV volume on preoperative cardiac CT were independent predictors of immediate postoperative RV dysfunction (6). Our study assessed long-term prognostic value of perioperative cardiac CT parameters in TR

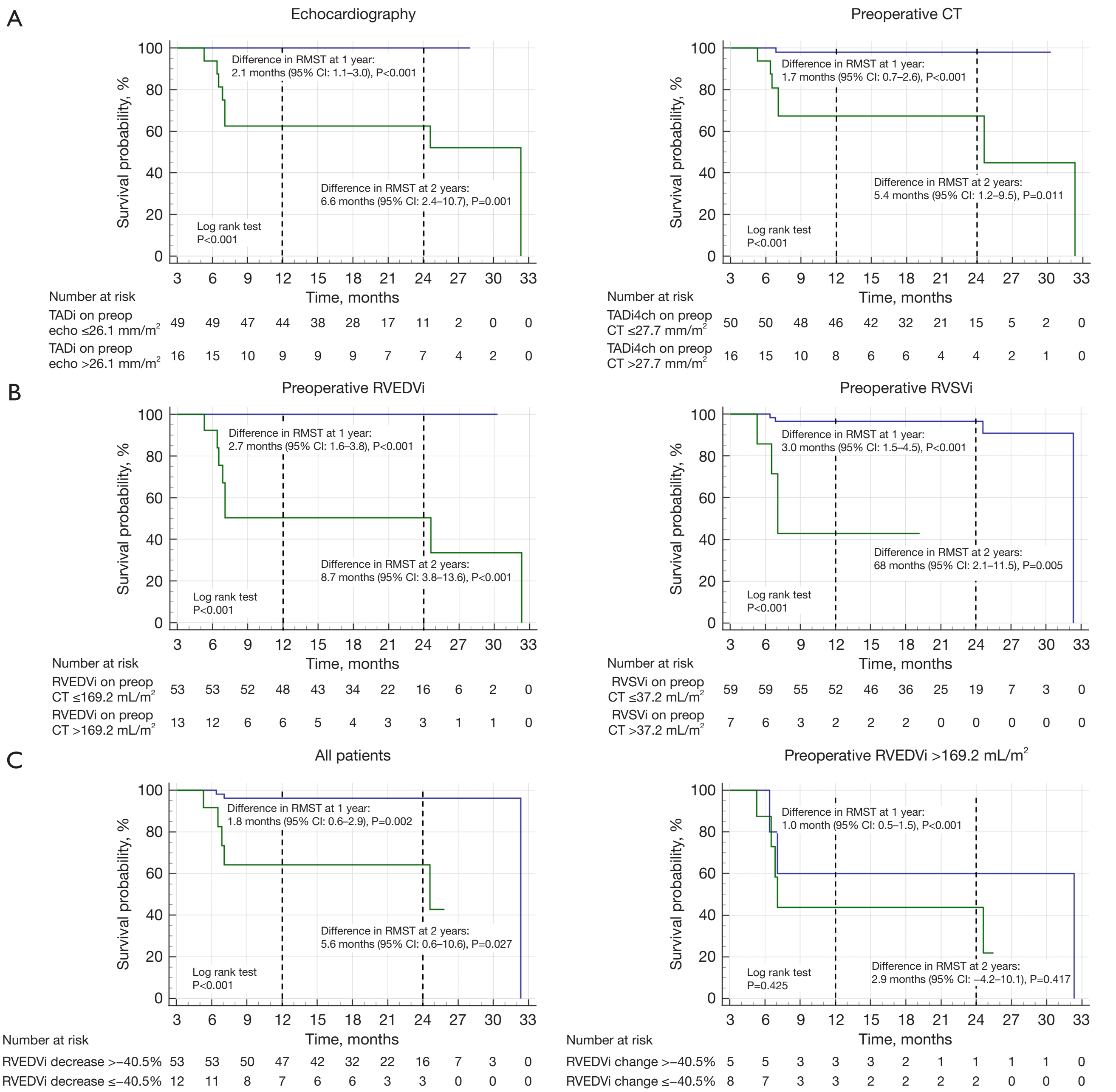

Figure 3 Kaplan-Meier curves show postoperative event-free survival and restricted mean survival time, stratified by echocardiography or CT parameters. Green lines represent patients with TAD or RV volume above the cutoffs and RV volume change below the cutoff, whereas blue lines represent those with TAD or RV volume below the cutoffs and RV volume change above the cutoff. Overall event-free survival and restricted mean survival time at 1- and 2-year time point were significantly shorter (A) in patients with longer preoperative TAD that shorter TAD (left, TAD/BSA on preoperative echocardiography; right, TAD_{4ch}/BSA on preoperative CT), (B) in patients with larger RV volume on preoperative CT (left, RVEDV/BSA; right, RVSV/BSA), and (C) patients with greater postoperative RV volume decrease (left, postoperative decrease in RVEDV/BSA in the entire study population). (C) In patients with preoperative RVEDV/BSA >169.2 mL/m^2, there was no significant difference in overall event-free survival in comparison by postoperative RVEDV change, but a small difference in restricted mean survival time was seen at 1-year was noted between groups (right, postoperative decrease in RVEDV/BSA in the subgroup with preoperative RVEDV/BSA >169.2 mL/m^2). 4ch, four-chamber; BSA, body surface area; CT, computed tomography; EDV, end-diastolic volume; RMST, restricted mean survival time; RV, right ventricle; RVEDVi, indexed right ventricular end-diastolic volume; RVSVi, indexed right ventricular stroke volume; SV, stroke volume; TAD, tricuspid annulus diameter; TADi, indexed tricuspid annulus diameter.

Table 4 Univariable logistic regression model for predicting greater RV volume decrease (change in RVEDV/BSA ≤−40.5%)

Variables	All patients (n=65)		Patients with preoperative RVEDV/BSA ≤169.2 mL/m^2 (n=52)		Patients with preoperative RVEDV/BSA >169.2 mL/m^2 (n=13)	
	OR (95% CI)	P value	OR (95% CI)	P value	OR (95% CI)	P value
Female sex	1.786 (0.479–6.657)	0.388	2.760 (0.268–28.452)	0.394	1.111 (0.112–10.987)	0.928
Age (per 1 year increase)	0.990 (0.945–1.037)	0.665	0.942 (0.876–1.013)	0.103	0.985 (0.899–1.079)	0.739
History of coronary artery disease	1.677 (0.404–6.951)	0.476	1.645 (0.159–17.066)	0.677	2.000 (0.181–22.057)	0.571
History of atrial fibrillation	0.786 (0.181–3.402)	0.747	N/A*	N/A	N/A*	N/A
Severe TR on preoperative echocardiography	7.636 (1.937–30.100)	0.004	17.571 (1.593–193.880)	0.019	0.417 (0.030–5.708)	0.512
TAD/BSA on echocardiography (per 1 mm/m^2 increase)	1.328 (1.077–1.637)	0.004	1.163 (0.821–1.647)	0.396	1.186 (0.871–1.614)	0.280
Preoperative RVSP (per 1 mmHg increase)	1.026 (0.9845–1.0691)	0.223	0.987 (0.903–1.079)	0.768	0.964 (0.898–1.035)	0.313
TAD_{4ch}/BSA on preoperative CT (per 1 mm/m^2 increase)	1.196 (1.005–1.425)	0.044	1.021 (0.715–1.459)	0.910	0.982 (0.756–1.276)	0.893
RVEDV/BSA on preoperative CT (per 1 mL/m^2 increase)	1.041 (1.018–1.064)	<0.001	1.125 (1.027–1.233)	0.012	1.005 (0.9788–1.0317)	0714
RVEDV/BSA on postoperative CT (per 1 mL/m^2 increase)	1.007 (0.981–1.034)	0.611	0.935 (0.859–1.018)	0.123	0.977 (0.938–1.019)	0.282

*, not assessable due to data separation issue (no event in a specific subgroup). 4ch, four-chamber; BSA, body surface area; CI, confidence interval; CT, computed tomography; EDV, end-diastolic volume; N/A, not applicable; OR, odds ratio; RV, right ventricle; RVSP, right ventricular systolic pressure; TAD, tricuspid annulus diameter; TR, tricuspid regurgitation.

patients who underwent TV surgery and this has not been previously investigated. Given the low event rate (12.1%), the survival curve with restricted mean survival time, rather than meticulous adjustment for Cox proportional hazard regression analysis, was presented. A longer TAD and larger preoperative volume on preoperative CT showed worse event-free survival at 1- and 2-year timepoints. Preoperative RVEDV/BSA (cutoff 169.2 mL/m^2) and RVSV/BSA (cutoff 37.2 mL/m^2) discriminated event-free survival with the largest difference among imaging-derived parameters.

A greater post-TV surgery RV volume decrease was associated with increased postoperative adverse outcomes, which was unexpected as successful TR surgery can remarkably reduce RV volumes and preserve RV systolic function (18). The clinical impact of the postoperative RV volume-reduction extent was unclear, partly owing to the lack of follow-up imaging studies with uniform postoperative intervals. Postoperative CMR-indicated RV volume and function changes at 10–52 months in patients operated for severe functional TR showed that RVEDV/BSA, RVESV/BSA, and RVEF decreased [27.2%±26.6%, 19.9%±33.8%, and 5.9%±34.5%, respectively] (18). We showed that on cardiac CT at 6 months after TV surgery, RVEDV/BSA and RVESV/BSA decreased by 21.6%±20.1% and 19.4%±23.3%, respectively. The greater postoperative RV-volume decrease was associated with some preoperative echocardiographic or CT parameters and was an adverse prognostic factor in our cohort. Cautious interpretation of these results is required, given that the parameter is closely associated with the preoperative RV volume. In patients with RVEDV/BSA <169.2 mL/m^2, no event occurred; thus, the extent of RVEDV/BSA change was not significant. Conversely, in 13 patients with preoperative RVEDV >169.2 mL/m^2, 5 and 8 patients with smaller and larger RVEDV/BSA decrease, respectively, showed significant but small (1.0 months) difference in restricted mean survival time at 1-year follow-up, but had no significant difference in clinical characteristics, imaging parameters, and long-term outcomes. Therefore, large preoperative RVEDV is an important risk factor for postoperative adverse outcomes, irrespective of the extent of RVEDV change.

Higher RVEF on preoperative CT correlated with increased postoperative adverse outcomes, which was inconsistent with previous CMR-based studies. The difference in volumetric methods (e.g., Simpson's method *vs.* 3D-based method, or exclusion *vs.* inclusion of papillary muscle and trabeculation within endocardial border) between CT and CMR may have affected the results (21). Moreover, RVEF on CT might not entirely reflect RV systolic function in significant TR as the TR regurgitant fraction is not considered.

Our study has several limitations. First, selection bias exists as we prospectively enrolled patients after TV surgery. Postoperative mortality ranged from 6.7% to 25% (19,23,24), but only survivors who could undergo postoperative CT examinations were enrolled; thus, the participants had good general condition and normal renal function. Consequently, the overall event rate of adverse outcomes was not high; especially, hard events, including mortality, did not occur in the participants. Therefore, our study results cannot be generalized for all patients undergoing TV surgery. Nevertheless, this study shows the prognostic value of cardiac CT-derived parameters in survivors of TV surgery. Second, the postoperative RV volumes and volume change in one case were excluded from analysis due to poor image quality caused by arrhythmia. Finally, the potential hazard of radiation exposure by CT and the risk from iodinated contrast agent constitute limitations.

Conclusions

Perioperative assessment of cardiac CT imaging-based TAD and RV volume can provide independent prognostic information for postoperative adverse outcomes in patients undergoing TV surgery. Preoperative RVEDV/BSA is the most useful parameter for predicting postoperative adverse outcomes after TV surgery.

Acknowledgments

None.

Footnote

Reporting Checklist: The authors have completed the STROBE reporting checklist. Available at https://qims.amegroups.com/article/view/10.21037/qims-2024-2915/rc

Funding: This study was supported by the DongKook Life Science, Co., Ltd., Korea (No. 4-2018-0725) to Y.J.S.

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://qims.amegroups.com/article/view/10.21037/qims-2024-2915/coif). Y.J.S. reports the funding from DongKook Life Science, Co., Ltd., Korea. The other authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki and its subsequent amendments. The study was approved by the Institutional Review Board of Severance Hospital (No. 4-2018-0725), and informed consent was taken from all individual participants.

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Cite this article as: Suh YJ, Lee SH, Lee S, Kim AY, Kim YJ. Prognostic value of cardiac CT parameters in patients undergoing surgical correction for tricuspid regurgitation: a prospective study. Quant Imaging Med Surg 2025;15(7):5940-5954. doi: 10.21037/qims-2024-2915

