Comparative outcomes and risk analysis after cone repair or tricuspid valve replacement for Ebstein's anomaly

Rebekah Boyd, MD,[a] David Kalfa, MD, PhD,[a] Stephanie Nguyen, MD,[a] Matan Setton, MD,[b] Amee Shah, MD,[b] John Karamichalis, MD,[a] Matthew Lewis, MD,[c] Noa Zemer Wassercug, MD,[c] Marlon Rosenbaum, MD,[c] and Emile Bacha, MD[a]

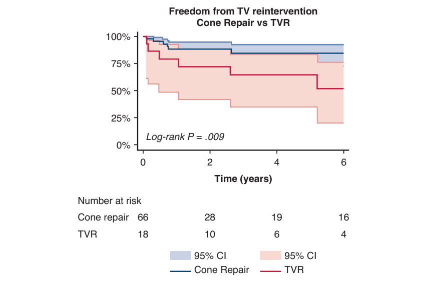
ABSTRACT

Objective: Ebstein's anomaly is a rare congenital heart malformation for which surgical and medical management are still controversial. The cone repair has transformed surgical outcomes in many of these patients. We aimed to present our results on the outcomes of patients with Ebstein's anomaly who underwent a cone repair or tricuspid valve replacement.

Methods: A total of 85 patients who underwent a cone repair (mean age, 16.5 years) or tricuspid valve replacement (mean age, 40.8 years) between 2006 and 2021 were included. Univariate, multivariate, and Kaplan–Meier analyses were used to evaluate operative and long-term outcomes.

Results: Residual/recurrent greater than mild-to-moderate tricuspid regurgitation at discharge was higher after cone repair compared with tricuspid valve replacement (36% vs 5%; *P* = .010). However, at last follow-up, the risk of greater than mild-to-moderate tricuspid regurgitation was not different between groups (35% in the cone group vs 37% in the tricuspid valve replacement group; *P* = .786). The tricuspid valve replacement group had a higher risk of tricuspid valve reoperation (37% vs 9%; *P* = .005) and tricuspid stenosis (21% vs 0%; *P* = .002) compared with the cone repair group. Kaplan–Meier freedom from reintervention was 97%, 91%, and 91% at 2, 4, and 6 years after cone repair, respectively, and 84%, 74%, and 68% at 2, 4, and 6 years after tricuspid valve replacement, respectively (*P* = .0191). At last follow-up, right ventricular function was significantly worse from baseline in the tricuspid valve replacement group (*P* = .0294). There were no statistical differences between age-stratified cohorts or surgeon volume in the cone repair group.

Conclusions: The cone procedure offers excellent results, with stable tricuspid valve function and low reintervention and death rates at last follow-up. The rate of greater than mild-to-moderate residual tricuspid regurgitation at discharge was higher after cone repair compared with tricuspid valve replacement, but this did not expose the patient to a higher risk of reoperation or death at last follow-up. Tricuspid valve replacement was associated with a significantly higher risk of tricuspid valve reoperation and tricuspid valve stenosis, and worse right ventricular function at last follow-up. (JTCVS Open 2023;14:372-84)



Cone repair shows significantly greater freedom from reintervention compared with TVR.

CENTRAL MESSAGE

Cone repair is associated with stable TV function long term and a significantly lower risk of TV stenosis, TV reoperation, and RV function worsening compared with valve replacement.

PERSPECTIVE

Cone repair has become the gold standard for TV repair for EA. In addition to stable long-term TV function and lower rates of reintervention, it also demonstrates improved RV function over time compared with valve replacement. The use of cone repair might be safely extended to use in older, sicker patients to improve RV remodeling.

From the [a]Section of Pediatric and Congenital and Cardiac Surgery, Division of Cardiac, Thoracic and Vascular Surgery, Department of Surgery, [b]Division of Pediatric Cardiology, Morgan Stanley Children Hospital New York-Presbyterian Hospital, Columbia University Vagelos College of Physicians and Surgeons, New York, NY; and [c]Division of Cardiology, New York Presbyterian Hospital, Columbia University Vagelos College of Physicians and Surgeons, New York, NY.

Drs Boyd and Kalfa contributed equally to this article.

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Address for reprints: Emile Bacha, MD, Columbia University College of Physicians and Surgeons, New York-Presbyterian Morgan Stanley Children's Hospital, 3959 Broadway, CHN-274, New York, NY 10032 (E-mail: eb2709@cumc.columbia.edu).

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Abbreviations and Acronyms

EA = Ebstein's anomaly
RV = right ventricle
TR = tricuspid regurgitation
TS = tricuspid stenosis
TV = tricuspid valve
TVR = tricuspid valve replacement

▶ Video clip is available online.

Ebstein's anomaly (EA) is among the rarest congenital heart defects with an approximate incidence of 1 per 200,000 live births, overall comprising less than 1% of all cases of congenital heart disease.[1,2] The anomaly was initially described in 1866 by Wilhelm Ebstein who identified failure of tricuspid leaflet delamination as the primary mechanism in the defect, resulting in a downward displacement of the tricuspid annulus.[2,3] This displacement leads to dilatation of the true tricuspid annulus, dilation of an atrialized portion of the right ventricle (RV), and progressive tricuspid regurgitation (TR) contributing to worsening RV enlargement and dysfunction.[3]

The first surgical repair of the tricuspid valve (TV) was reported in 1959; over the ensuing 50 years, multiple methods of surgical repair have been used including the Danielson and Carpentier methods.[2,4] As recently as 1998, however, these repair methods were not superior to traditional tricuspid valve replacement (TVR) in freedom from reoperation with up to 20% of patients requiring conversion to TVR or early reoperation.[5,6] In 1993, da Silva and colleagues[7] developed the cone repair technique that revolutionized the modern approach to TV repair in EA and quickly established dominance over other repair methods.[8] In this technique, the anterior, posterior, and septal tricuspid leaflets are surgically delaminated from the myocardium, brought up to the level of the tricuspid annulus, and rotated clockwise to create a "cone," offering an anatomic repair that creates a 360° of tricuspid leaflet tissue and affords leaflet-to-leaflet coaptation.[7,9,10]

Short- and midterm results at global major institutions using the cone repair technique have shown uniformly positive results with low morbidity and mortality.[6,7,11-20] However, long-term outcomes for the cone repair are still needed, and questions remain surrounding the effect of the cone repair on biventricular function and remodeling, valve durability, and echocardiographic follow-up with regard to residual and recurrent TR.[8,15,21] Of note, predictors of reoperation among those undergoing cone repair compared with those undergoing TVR are as yet unelucidated, and there are relatively few studies comparing midterm outcomes between cone repair and TVR. To that end, in this study we aimed to investigate the independent predictors of TV reintervention and reoperation among patients undergoing cone repair compared with TVR in addition to analyzing and comparing midterm TV function, RV size, and RV function between groups.

MATERIALS AND METHODS

This is a single institution retrospective study analyzing all patients who underwent a TV repair or replacement for EA over a 15-year period from 2006 to 2021 (Figure 1). The cone repair was the only primary technique used for TV repair. Four surgeons performed the surgeries, with the majority performed by 2 surgeons. Exclusion criteria were (1) patients with a neonatal EA, (2) congenitally corrected transposition of the great arteries, or (3) single ventricle pathology. Medical records from index hospital stays, outpatient clinic follow-up visits, referring cardiologist notes, operative notes, discharge summaries, and echocardiographic data were reviewed for all patients. Indication criteria for TVR historically included mostly patients aged more than 50 years with significant RV dysfunction. The primary end points of the study were TV reoperation or reintervention and residual or recurrent greater than mild-to-moderate TR or tricuspid stenosis (TS). Secondary end points were residual or recurrent greater than moderate RV enlargement and systolic dysfunction.

Cone Repair Technique

With the use of standard aortic and bicaval cannulation and mild hypothermia, surgical delamination is performed starting with the anterior leaflet and then the posterior and septal leaflets, resecting every single abnormal attachment that would restrict the mobility of the leaflets (Video 1). Fenestrations are closed directly, creating the actual "cone," and the posterior leaflet is typically sutured to the septal leaflet, completing the cone. Following a clockwise rotation of the mobilized tissues, the cone is ready for reimplantation at the anatomic annulus. The atrialized portion of the RV is vertically plicated, starting from the apex and avoiding any injury to the right coronary artery. The annular size is reduced at 1 or multiple locations. The cone is reattached to the native annulus with reinforcement sutures. Stabilization of the annulus is performed in all adult-size patients and in those with a still enlarged neo-annulus, using a band. A pericardial patch augmentation of 1 of the leaflets (typically in the septal or anterior region) is performed in patients with a lack of native tissue to "complete the cone" without tension. A bidirectional Glenn may be performed in patients with significant preoperative or postoperative dysfunction or with TS after repair (>7 mm Hg).

Echocardiography

All patients had transthoracic echocardiographic evaluations preoperatively, before hospital discharge, and at last follow-up. TR and TS were qualitatively graded as none, mild, mild-to-moderate, moderate, and severe in keeping with prior studies.[21] Bilateral ventricle dysfunction was qualitatively graded as none, mild, mild-to-moderate, moderate, and severe. RV enlargement was similarly qualitatively graded as none, mild, mild-to-moderate, moderate, and severe, and included the atrialized portion. To assess late TR, TS, bilateral ventricle dysfunction, and RV enlargement, echocardiographic data from last available follow-up were analyzed. In patients who underwent TV reintervention, the data from the last available echocardiographic evaluation preceding the reintervention were used.

Anticoagulation After Tricuspid Valve Replacement

After TVR, patients were routinely placed on aspirin for anticoagulation therapy. Those deemed at higher risk for thrombosis were placed on warfarin therapy.

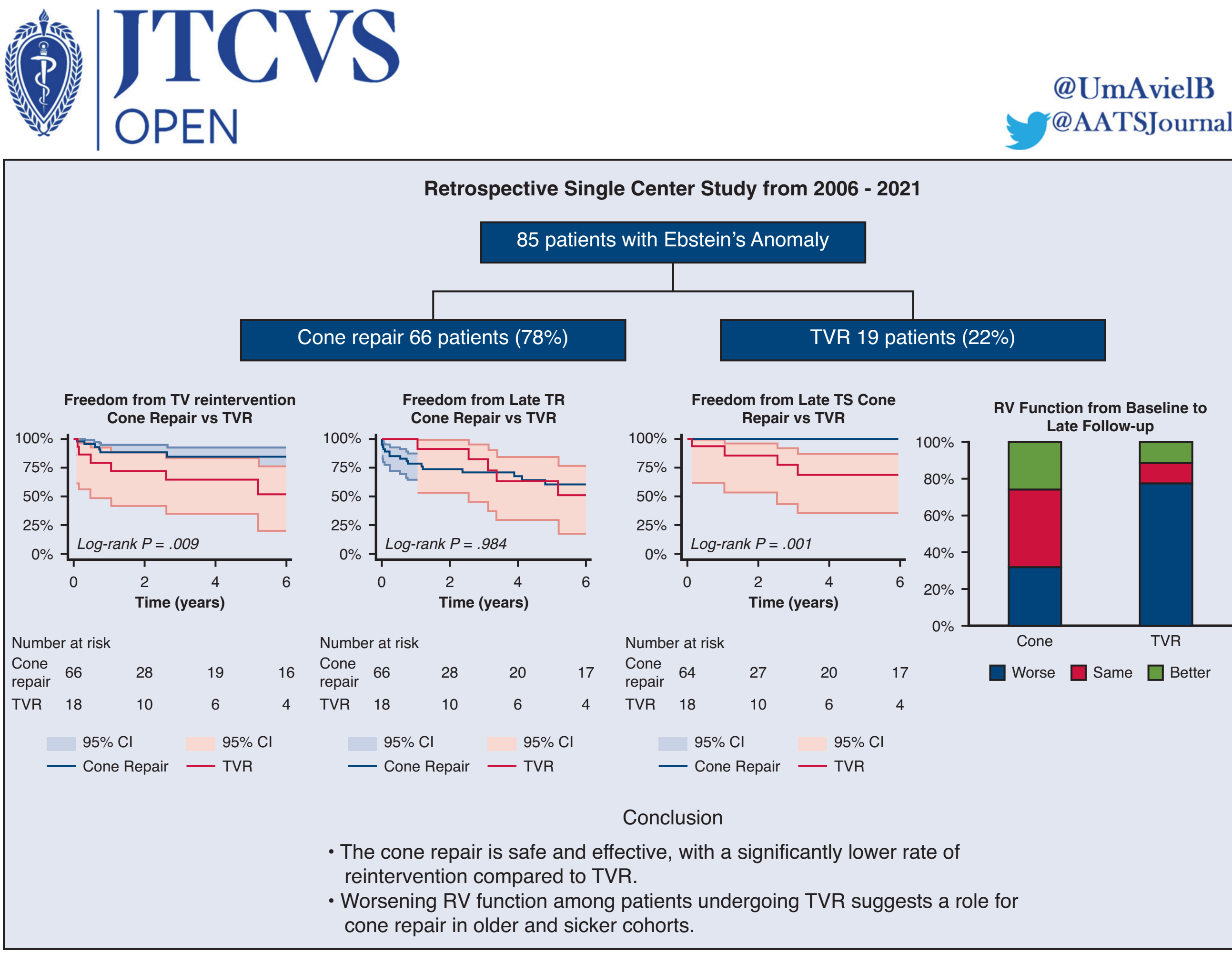

FIGURE 1. Graphical abstract. *TVR*, Tricuspid valve replacement; *TV*, tricuspid valve; *CI*, confidence interval; *TR*, tricuspid regurgitation; *TS*, tricuspid stenosis; *RV*, right ventricle.

Statistical Analysis

The cohort was analyzed collectively and by groups stratified on the type of surgery (cone repair vs TVR). Subanalyses stratified by age were also conducted. Descriptive statistics included categorical variables described as frequency with percentage and continuous variables expressed as means ± standard deviation and range as applicable. Freedom from TV reintervention at last follow-up, TR greater than mild-to-moderate at last follow-up, and TS greater than mild-to-moderate at last follow-up were assessed using Kaplan–Meier methodology and log-rank statistic.

Comparisons between groups were performed using the Student *t* test for normally distributed variables and Fisher exact test for binominal variables given the small sample size. Wilcoxon matched-pairs signed-rank test was used to compare progression of RV dysfunction and enlargement from the preoperative period through hospital discharge and late follow-up. Univariate and multinomial logistic regression was used to estimate association between patient-related and procedure-related parameters and TV reintervention or reoperation. All statistical calculations were performed using STATA statistical software version 17.0 (StataCorp, LLC).

Institutional Review Board approval (AAAR3476 initial approval August 15, 2017; renewal approval February 10, 2022) was obtained from the Columbia University Irving Medical Center. Informed written consent was waived because of the retrospective nature of this study.

VIDEO 1. Demonstration of cone repair. Video available at: https://www.jtcvs.org/article/S2666-2736(23)00079-7/fulltext.

RESULTS

Patient Demographics and Preoperative Characteristics

A total of 85 patients met inclusion criteria over the study period. Of these, 66 (78%) underwent cone repair (from

2006-2021) and 19 (22%) had TVR (from 2007-2021). Of those who received TVR, 3 (16%) were converted from cone repair to TVR intraoperatively due to insufficient valvular tissue for adequate cone repair or persistent severe TR on intraoperative echocardiography. Patient demographics and preoperative characteristics are shown in Table 1. The mean age of the cohort overall was 21.9 years ± 17.5 years (range, 0.2-71.7 years); there was a statistically significant difference in mean age between those undergoing cone repair and those undergoing TVR (16.5 years vs 40.8 years; $P < .001$). Most patients were symptomatic at the time of surgery (n = 59; 69.4%). Preoperative symptoms of right heart failure and arrhythmia were significantly more frequent in patients undergoing TVR (n = 11 vs n = 0; $P < .001$ and n = 11 [58%] vs n = 16 [24%]; $P = .004$, respectively). Patients undergoing cone repair were significantly more likely to have other cardiac disease (n = 44 [66.7%] vs n = 3 [16%]; $P < .001$), the

TABLE 1. Preoperative patient characteristics and demographics

	All	Cone repair	TVR	*P* value
Patients	85	66 (78%)	19 (22%)	
BSA	1.41 ± 0.59	1.32 ± 0.60	1.75 ± 0.44	**.005**
Male	41 (48.2%)	35 (53%)	6 (32%)	.122
Age	21.9 ± 17.5	16.5 ± 12.23	40.8 ± 20.1	**.000**
Symptomatic	59 (69.4%)	44 (66.7%)	15 (79%)	.247
SOB/DOE	51 (60%)	38 (57.6%)	13 (68%)	.291
FTT	6 (7.1%)	6 (9.1%)	0 (0%)	.332
Edema	5 (5.9%)	0 (0%)	5 (26%)	**.000**
Syncope/presyncope	7 (8.2%)	5 (7.6%)	2 (11%)	.639
Cirrhosis	2 (2.4%)	0 (0%)	2 (11%)	**.044**
Pleural/pericardial effusion	4 (4.7%)	0 (0%)	4 (21%)	**.002**
Home oxygen	1 (1.1%)	1 (1.5%)	0 (0%)	1.000
Preoperative arrhythmia	27 (31.8%)	16 (24.2%)	11 (58%)	**.005**
SVT	12 (14.1%)	6 (9.1%)	6 (32%)	**.018**
Atrial fibrillation	5 (5.9%)	3 (4.5%)	2 (11%)	.290
Atrial flutter	3 (3.5%)	1 (1.5%)	2 (11%)	.115
WPW	7 (8.2%)	5 (7.6%)	2 (11%)	.639
Ventricular arrhythmia	1 (1.1%)	0 (0%)	1 (5%)	.217
First-degree block	1 (1.1%)	1 (1.5%)	0 (0%)	1.000
Other cardiac disease	47 (55.3%)	44 (66.7%)	3 (16%)	**.000**
		ASD n = 28 (42.4%)	ASD n = 2 (10.5%)	
		PFO n = 14 (21.2%)	PFO n = 1 (5.2%)	
		VSD n = 9 (13.6%)		
		Pulmonary atresia n = 3 (4.5%)		
		CoA n = 1 (1.5%)		
		PAPVR n = 2 (3.0%)		
		Hypoplastic arch n = 1 (1.5%)		
		Sinus of Valsalva aneurysm n = 1 (1.5%)		
Genetic syndrome	6 (7.1%)	6 (9.1%)	0 (0%)	.330
Trisomy 21		2 (3.0%)		
CHARGE syndrome		1 (1.5%)		
Tuberous sclerosis		1 (1.5%)		
Axenfeld-Rieger syndrome		1 (1.5%)		
Extracardiac abnormality	7 (8.2%)	5 (7.6%)	2 (11%)	.645
Previous intervention	9 (10.6%)	6 (9.1%)	3 (16%)	.412
Previous surgery	8 (9.4%)	8 (12.1%)	0 (0%)	.190
Preoperative moderate or more RV dysfunction	17 (20%)	9 (13.6%)	8 (42%)	**.009**
Preoperative moderate or more RV enlargement	67 (78.8%)	50 (75.8%)	17 (89%)	**.034**
Preoperative LV or more dysfunction	1 (1.2%)	0 (0%)	1 (5%)	.220

Bold is statistically significant. *TVR*, Tricuspid valve replacement; *BSA*, body surface area; *SOB*, shortness of breath; *DOE*, dyspnea on exertion; *FTT*, failure to thrive; *SVT*, supraventricular tachycardia; *WPW*, Wolff Parkinson White; *ASD*, atrial septal defect; *PFO*, patent foramen ovale; *VSD*, ventricular septal defect; *CoA*, coarctation of the aorta; *PAPVR*, partial anomalous pulmonary vein return; *RV*, right ventricle; *LV*, left ventricle.

most common of which was atrial septal defect (n = 28; 42.4%). A total of 20% of patients (n = 17) underwent a cardiac intervention/surgery before the index operation. Genetic syndromes were also only seen within the pediatric cone repair population (n = 6; 9.1%).

Patients who underwent TVR were significantly more likely to have moderate or greater RV dysfunction (n = 8 [42%] vs n = 9 [13.6%]; $P = .009$) and moderate or greater RV enlargement (n = 17 [89%] vs n = 50 [75.8%]; $P = .034$).

Operative Data and Postoperative Complications

Cone repair included a ring annuloplasty in 25% (n = 18), leaflet patch augmentation in 12% (n = 8), and a Glenn procedure in 4% (n = 3). All those who had TVR received a bioprosthetic valve: Carpentier-Edwards pericardial valve (n = 7; 37%), Epic St Jude porcine valve (n = 10; 53%), 1 Mosaic porcine valve (Medtronic), and 1 unspecified tissue valve. The majority of valves were 33 mm (n = 13; 68%); 3 patients had a 31-mm valve (16%) and 29-mm, 25-mm, and 19-mm valves were placed in 1 patient each (5%). Operative data are shown in Table 2. There was no difference in mean cardiopulmonary bypass time for TVR compared with cone repair (113.8 ± 39.3 minutes vs 113.7 ± 32.9 minutes; $P = .992$) after excluding the 3 cases that required conversion to TVR after attempted cone repair. However, mean crossclamp time was higher in the cone repair group (84.2 ± 29.5 minutes vs 71.5 ± 27.7 minutes; $P = .171$), although this did not reach statistical significance. Two patients in the TVR group required extracorporeal membrane oxygenation postoperatively; 1 was successfully weaned, but the second patient required early reoperation with biventricular assist device placement and subsequently died 6 days postoperatively of systemic thromboses. This patient had unexplained LV dysfunction immediately postoperatively. There was 1 additional early reoperation in the TVR group for valve thrombosis with repeat TVR performed 1 day after the index hospitalization.

Echocardiographic Evaluation at Discharge and Late Follow-up

Transthoracic echocardiographic findings were evaluated at hospital discharge and at late follow-up (censored at TV

TABLE 2. Operative data

	All	Cone repair	TVR	*P* value
Patients	85	66 (78%)	19 (22%)	
Glenn		3 (4.5%)		
Ring annuloplasty		18 (27.3%)		
Leaflet patch augmentation		8 (12.1%)		
CPB time (min)	113.7 ± 33.9	113.7 ± 32.9	113.8 ± 39.3	.992
Crossclamp time (min)	82.2 ± 29.4	84.2 ± 29.5	71.5 ± 27.7	.171
Concurrent procedure	59 (69.4%)	49 (74.2%)	10 (53%)	.092
Delayed chest closure	1 (1.2%)	1 (1.5%)	0 (0%)	1.000
ECMO	2 (2.4%)	0 (0%)	2 (11%)	**.049**
VAD	1 (1.1%)	0 (0%)	1 (5%)	.224
Early reoperation	2 (2.4%)	0 (0%)	2 (11%)	**.048**
Concurrent procedures	59 (69.4%)	49 (74.2%) ASD closure n = 27 (40.1%) PFO closure n = 11 (16.7%) VSD closure n = 6 (9.1%) Ablation n = 6 (9.1%) PDA ligation n = 4 (6.1%) PA patch repair n = 2 (3%) PVr n = 2 (3%) PVR n = 1 (1.5%) MVr n = 1 (1.5%) BTT shunt takedown n = 1 (1.5%) Repair sinus of Valsalva aneurysm n = 1 (1.5%) Ross n = 1 (1.5%) Warden procedure n = 1 (1.5%)	10 (52.6%) Ablation n = 5 (26%) PFO closure n = 2 (11%) ASD closure n = 2 (11%) RVOT resection n = 2 (11%) MVR n = 1 (5%) CABG n = 1 (5%)	.092

Bold is statistically significant. *TVR*, Tricuspid valve replacement; *CPB*, cardiopulmonary bypass; *ECMO*, extracorporeal membrane oxygenation; *VAD*, ventricular assist device; *ASD*, atrial septal defect; *PFO*, patent foramen ovale; *VSD*, ventricular septal defect; *PDA*, patent ductus arteriosus; *PA*, pulmonary artery; *PVr*, pulmonary valve repair; *PVR*, pulmonary valve replacement; *MVr*, mitral valve repair; *BTT*, Blalock-Thomas-Taussig; *RVOT*, right ventricular outflow tract; *MVR*, mitral valve replacement; *CABG*, coronary artery bypass grafting.

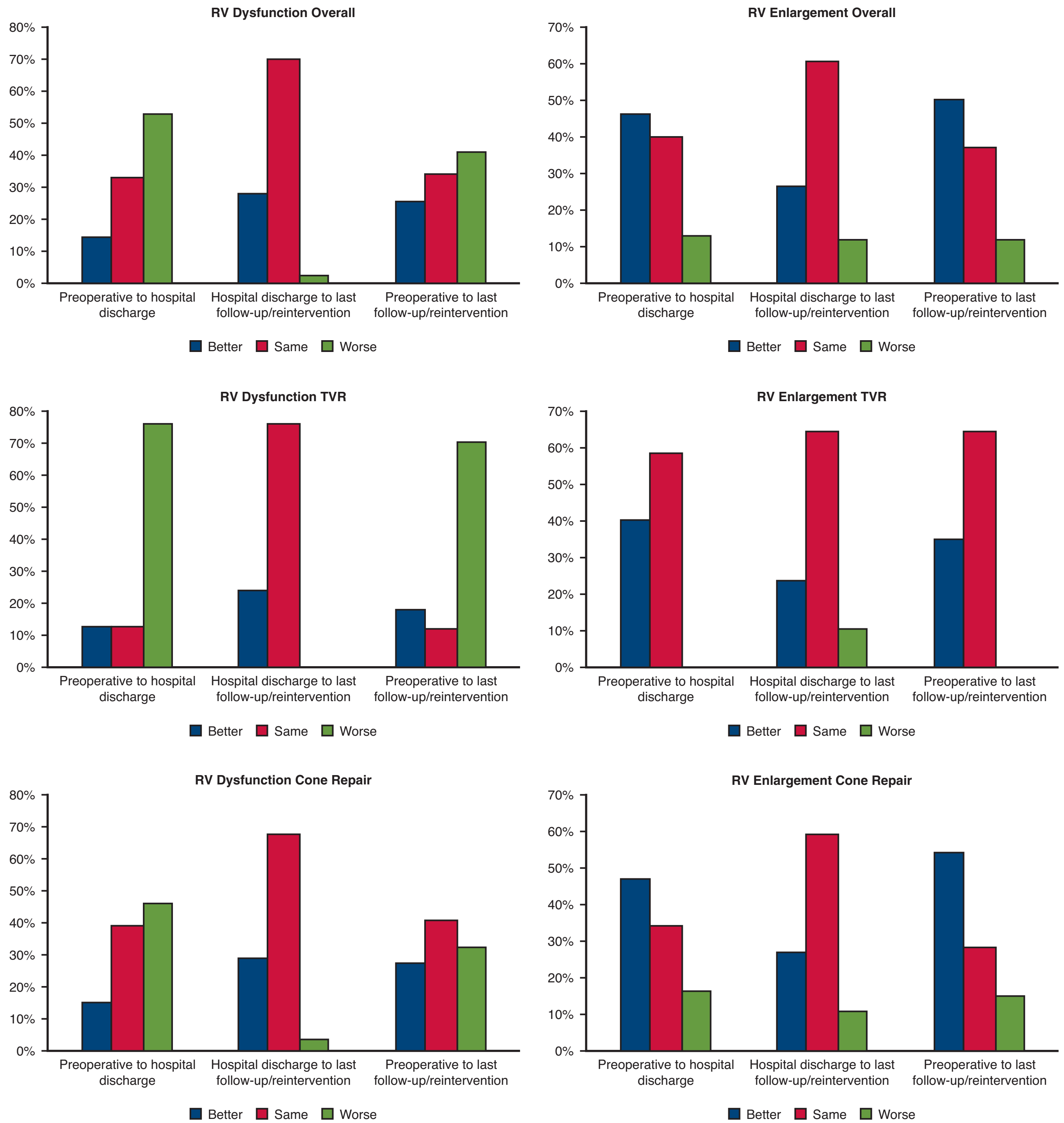

FIGURE 2. Evolution of RV dysfunction and enlargement by cohort and groups. *RV*, Right ventricle; *TVR*, tricuspid valve replacement.

reintervention if occurred). Mean follow-up time was 4.01 years ± 4.00 years (range, 3 days to 12.9 years). Overall, 78% of patients (n = 66) had follow-up echocardiographic studies completed after the immediate 30-day postoperative window with a mean time to late echocardiographic study of 3.1 ± 3.6 years. Evolution of paired RV dysfunction and RV enlargement from the preoperative period through hospital discharge and late follow-up are presented in Figures 2 and 3, and Table 3.

Collectively, greater than moderate RV dysfunction and RV enlargement were higher among those undergoing TVR at discharge (n = 12 [63%] vs n = 26 [39.4%]; *P* = .039 and n = 15 [79%] vs n = 38 [57.6%]; *P* = .045), and this difference persisted through late follow-up (n = 11 [58%] vs n = 16 [24.2%]; P = .019 and n = 14 [74%] vs n = 30 [45.5%]; P = .031). In terms of the evolution of individual patient RV volume and function over time, Wilcoxon paired signed-rank test demonstrated worsening RV dysfunction at hospital discharge in the cone repair group (P = .0001) and the TVR group (P = .0036). However, at late follow-up, RV dysfunction remained significantly worse from baseline only in the TVR group (P = .0294 vs P = .4136). RV enlargement was significantly improved at hospital discharge in both the cone repair group (P < .001) and TVR group (P = .0084), which persisted at late follow-up.

At hospital discharge, those undergoing cone repair were more likely to have greater than mild-to-moderate TR on transthoracic echocardiographic evaluation (n = 24 [36.4%] vs n = 1 [5%]; P = .010). However, this difference dissipated over time with no difference in prevalence of residual or recurrent greater than mild-to-moderate TR on late follow-up (n = 23 [34.8%] vs n = 7 [37%]; P = .786). Although there was no residual or recurrent TS within either group at hospital discharge, patients who underwent TVR were more likely to show greater than mild-to-moderate stenotic pathology at late follow-up (n = 4 [21%] vs n = 0 [0%; P = .002).

Reintervention and Reoperation

In total, there were 13 reinterventions in the cohort. The rate of reintervention was significantly higher among those who underwent TVR compared with cone repair (n = 7 [37%] vs n = 6 [9%]; P = .005). Among those who underwent cone repair, 4 patients (6%) required re-repair and 2 patients (3%) ultimately underwent TVR. In the TVR group, 2 patients underwent orthotopic heart transplant (11%), 2 patients had repeat TVR (11%), 2 patients had percutaneous valve-in-valve placement (11%), and 1 patient underwent balloon valvuloplasty for stenosis.

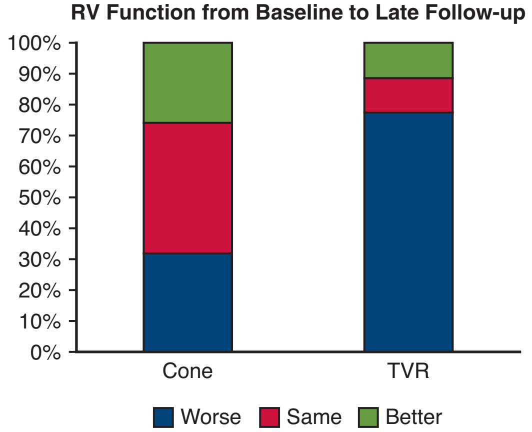

FIGURE 3. Proportions of worsening, improving, and stable RV function by groups. *RV*, Right ventricle; *TVR*, tricuspid valve replacement.

Average time to reintervention was longer in the TVR group at 3 years ± 3.56 years (range, 42 days to 10.5 years) compared with 0.86 years ± 0.91 years (range, 35 days to 2.6 years) for those who received cone repair; however, this difference was not significant (P = .175).

Survival Analyses

Kaplan–Meier survival analysis curves were estimated for freedom from TV reintervention/reoperation, greater than mild-to-moderate TR at late follow-up, and greater than mild-to-moderate TS at late follow-up as shown in Figure 4. Kaplan–Meier freedom from reintervention was 97%, 91%, and 91% at 2, 4, and 6 years after cone repair, respectively, and 84%, 74%, and 68% at 2, 4, and 6 years after TVR, respectively. Long-term survival was 100% in both groups.

Predictors of Reintervention and Reoperation

In the cohort overall, univariate analysis showed that factors associated with reintervention or reoperation were TVR versus cone repair (P = .002), greater than or equal to moderate preoperative RV dysfunction (P = .009), postoperative inotrope requirement more than 24 hours (P = .007), and ultimate requirement of pacemaker (P = .012). On multivariate regression in the cohort overall, only postoperative inotrope requirement greater than 24 hours (P = .019) remained significant (Table 4).

Modifications of Cone Repair

Modifications of the cone repair procedure (leaflet patch augmentation, ring annuloplasty, and Glenn) were analyzed to detect any impact on outcomes. Ring annuloplasty was noted have a positive trend in decreasing the progression to greater than mild-to-moderate TR at late follow-up. Only 4 of the 18 patients who underwent annuloplasty progressed to greater than moderate TR at late follow-up compared with 19 of the 48 patients who did not (22% vs 40%; P = .187). Leaflet patch augmentation and Glenn procedure were not found to be associated with rates of reoperation or progression to greater than mild-to-moderate TR or TS at hospital discharge or late follow-up.

Analysis by Age

Age-stratified outcomes of cone repair were also analyzed (Table E1). Patients were grouped into the following age cohorts: age less than 1 year, age 1 to 12 years, age 12 to 18 years, age 18 to 21 years, and age more than 21 years. There were no statistical differences in primary or secondary end points across these cohorts.

Analysis by Surgeon Volume

Outcomes of cone repair by surgeon volume were also analyzed (Table E2). There were no statistical differences

TABLE 3. Postoperative complications and operative outcomes

	All	Cone repair	TVR	*P* value
Postoperative complications	64 (75.3%)	48 (72.7%)	16 (84.2%)	.379
Arrhythmia	32 (37.6%)	24 (36.4%)	8 (42.1%)	.789
Inotrope requirement ≥24 h	43 (50.6%)	31 (47%)	12 (63.2%)	.299
Cardiac tamponade	3 (3.5%)	1 (1.5%)	2 (10.5%)	.124
Transient pHTN	7 (8.2%)	5 (7.6%)	2 (10.5%)	.650
Anemia requiring transfusion	16 (18.8%)	9 (13.6%)	7 (36.8%)	**.041**
Infection	8 (9.4%)	4 (6.1%)	4 (21%)	.070
CVA	3 (3.5%)	1 (1.5%)	2 (10.5%)	.124
Pacemaker requirement	9 (10.6%)	2 (3%)	7 (36.8%)	**.000**
New renal dialysis	1 (1.2%)	0 (0%)	1 (5.3%)	.224
Valve thrombosis	2 (2.4%)	0 (0%)	2 (10.5%)	**.048**
Multiorgan failure	1 (1.2%)	0 (0%)	1 (5.3%)	.224
Early mortality	1 (1.2%)	0 (0%)	1 (5.3%)	.224
Late mortality	0 (0%)	0 (0%)	0 (0%)	
Echocardiographic findings at hospital discharge				
Greater than mild-to-moderate TR	25 (29.4%)	24 (36.4%)	1 (5.3%)	**.010**
Greater than mild-to-moderate TS	0 (0%)	0 (0%)	0 (0%)	
Moderate or greater RV dysfunction	38 (44.7%)	26 (39.4%)	12 (63%)	**.039**
Moderate or greater RV enlargement	53 (62.4%)	38 (57.6%)	15 (79%)	**.045**
Moderate or greater LV dysfunction	2 (2.4%)	0 (0%)	2 (10.5%)	**.044**
Length of follow-up (mean ± SD, y)	4.0 (4.0)	3.6 (3.8)	5.7 (4.2)	.624
Echocardiographic findings at last follow-up				
Greater than mild-to-moderate TR	30 (35.3%)	23 (34.8%)	7 (37%)	.786
Greater than mild-to-moderate TS	4 (4.7%)	0 (0%)	4 (21%)	**.002**
Moderate or greater RV dysfunction	26 (30.6%)	16 (24.2%)	11 (52.6%)	**.019**
Moderate or greater RV enlargement	44 (51.8%)	30 (45.5%)	14 (74%)	**.031**
TV reintervention/reoperation	13 (15.3%)	6 (9.1%) Re-repair n = 4 (6.1%) TVR n = 2 (3%)	7 (37%) OHT n = 2 (11%) TVR n = 2 (11%) ViV n = 2 (11%) Valvuloplasty n = 1 (5%)	**.005**

Bold is statistically significant. *TVR*, Tricuspid valve replacement; *pHTN*, pulmonary hypertension; *CVA*, cerebrovascular accident; *TR*, tricuspid regurgitation; *TS*, tricuspid stenosis; *RV*, right ventricle; *LV*, left ventricle; *SD*, standard deviation; *OHT*, orthotopic heart transplant; *ViV*, valve-in-valve.

in primary or secondary endpoints by surgeon volume in this series.

DISCUSSION

Introduction of the cone repair technique has changed the global landscape of TV repair in the population with EA. Our series redemonstrates the excellent long-term overall survival of patients undergoing cone repair, in keeping with other large institutions.[3,6,11-18,20,21] We showed excellent long-term survival with no early or late mortalities in our cohort. Additionally, we demonstrated acceptable levels of TR that remained stable over time and the feasibility of using annuloplasty rings as a protective measure without increasing the risk of TS. Our cone cohort also demonstrated durable long-term RV remodeling and ultimately a lower rate of reintervention than TVR.

There may be a higher mortality risk associated with conservative management of asymptomatic or mildly symptomatic patients with EA when compared with surgical repair.[20] In Belli and colleagues' series,[20] an 8% (2/24) mortality rate was noted among those with mild TR who were delegated to nonoperative management, including percutaneous atrial septal defect closure. Although this finding delineates the importance of surgical management in this population, it raises the question of the impact of cone repair specifically on recurrent or residual TR, late RV remodeling and function, and long-term survival compared with TVR. Although other studies have reported outcomes for cone repair cohorts, this is one of the few that have examined differences in outcomes between cone repair and TVR in a larger cohort.

Notably, our series demonstrated significantly higher greater than mild-to-moderate TR at hospital discharge among those undergoing cone repair compared with TVR (36% vs 5%; $P = .010$). However, in terms of overall improvement, both groups demonstrated improvement in TR grade from the preoperative period to hospital discharge (n = 45 [75%] cone repair $P < .0001$; n = 16 [84%] TVR

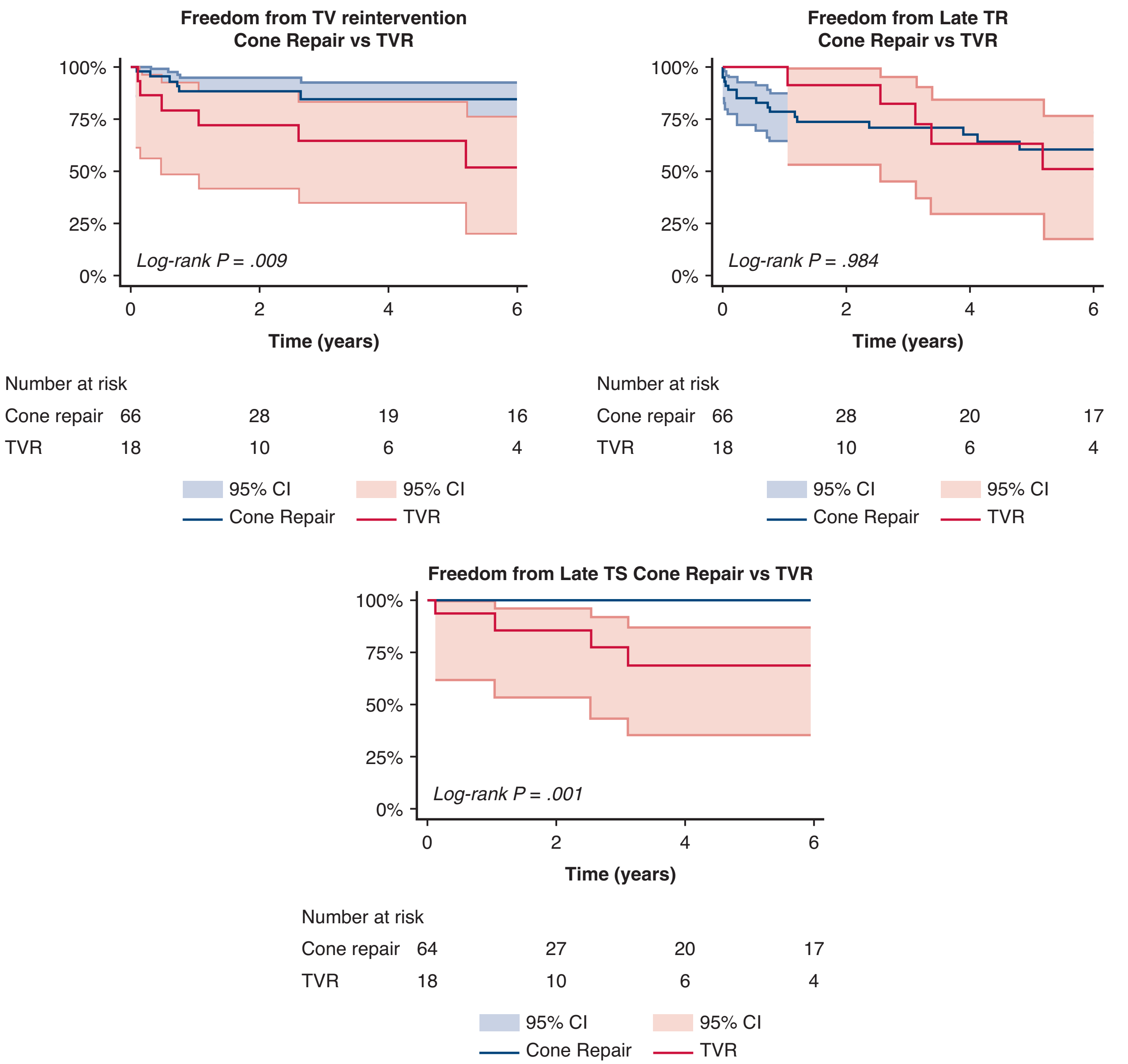

FIGURE 4. Kaplan–Meier survival curves from TV reintervention, late TR, and late TS by cohort and groups. *TV*, Tricuspid valve; *TVR*, tricuspid valve replacement; *CI*, confidence interval; *TR*, tricuspid regurgitation; *TS*, tricuspid stenosis.

P = .0001) in keeping with the significant decline in TR fraction reported in da Silva and colleagues' index series.[7] Of note, this initial disparity between residual/recurrent mild-to-moderate TR completely dissipated by late follow-up indicating an overall worsening of TR among those undergoing TVR compared with ongoing stabilization among those in the cone repair group. This finding may indicate a more durable repair with the

TABLE 4. Univariate and multivariate analyses of factors associated with tricuspid valve reintervention

Cohort overall	OR (95% CI)	*P* value	B (95% CI)	*P* value
Cone repair or TVR	6.4 (1.6-24.6)	.002	0.16 (−0.04 to 0.35)	.114
Moderate or greater baseline RV dysfunction	4.9 (1.3-19.1)	.009	0.19 (−0.17 to 0.41)	.072
Inotrope requirement >24 h	7.1 (1.3-37.4)	.007	0.18 (0.02-0.33)	.019
Pacemaker requirement	5.9 (1.2-27.9)	.012	0.16 (−0.11 to 0.43)	.237

OR, Odds ratio; *CI*, confidence interval; *TVR*, tricuspid valve repair; *RV*, right ventricle.

anatomic cone technique that translates over time to sustained valvular function when compared with the use of a bioprosthetic. An additional notable finding is the reduction in progression to greater than mild-to-moderate TR among those in the cone group who underwent ring annuloplasty (22% vs 40%; $P = .187$). The use of an annular ring to support the true tricuspid annulus is controversial, with da Silva and colleagues[7] initially recommending against use of ring annuloplasty to prevent TS. However, Dearani[10] at the Mayo Clinic routinely uses pericardial strip annular reinforcement in children and an annuloplasty band in older children and adults, and has not demonstrated a higher incidence of TS in the cohort. Similarly in our series, there was no evidence of TS among those who received ring annuloplasty. When coupled with the improvement in terms of late follow-up residual or recurrent greater than mild-to-moderate TR, this may cautiously indicate a role for ring annuloplasty, particularly among those deemed at considerable risk for annular dilatation and recurrent TR after cone repair.

The importance of residual/recurrent TR lies in its predilection to causing right heart enlargement, dysfunction, and right heart failure in the setting of an abnormal RV myocardium related to the EA itself. As demonstrated by Attenhofer and colleagues[22] in a study of patients with EA over 4 decades, the risk of sudden death is more than 6 times higher among those with heart failure after TV surgery. To that end, we studied the evolution of RV dysfunction and enlargement over time in our cohort. Those who underwent TVR had greater preoperative RV dysfunction and enlargement compared with those in the cone repair cohort, although this difference is likely explained by the fact that the TVR cohort was significantly older and had longer time exposure to the deleterious effects of ongoing TR, RV enlargement, and progressive RV dysfunction. In both groups, there was an initial decline in RV function at hospital discharge, which may be due to increased right-sided afterload and closure or partial closure of interatrial communication. At late follow-up, those undergoing cone repair showed improved RV function from baseline, whereas those in the TVR group had significantly worsened RV function compared with preoperative baseline ($P = .03$). Given the significant age difference between cohorts, this finding may indicate the need for earlier referral to surgery and consideration of surgical repair before long-term deleterious effects of TR and RV enlargement leading to RV dysfunction.[23] This is particularly true when noting that in our series, this failure to improve RV function after TVR occurred despite the significant improvement in RV volume postoperatively both at discharge and late follow-up ($P = .008$).

One of the most important findings of our series is the significant increase in exposure to TV reintervention/reoperation among those undergoing TVR compared with cone repair (n = 7 [37%] vs n = 6 [9%]; $P = .005$). This finding indicates that the initially higher rate of residual or recurrent greater than mild-to-moderate TR in the cone repair group ultimately did not expose patients to a higher risk of reoperation. TVR was associated with a significantly higher risk of TV stenosis and less improvement in RV function over time, which may have led to the higher rates of reoperation observed and the ultimate need for orthotopic heart transplantation among 2 patients in the TVR cohort who failed to regain adequate right-sided heart function. Although we did not find a significant association between age at the time of surgery and reintervention ($P = .82$), the longer time exposure to RV dysfunction among the TVR group (mean age at surgery 40.8 years vs 16.5 years $P < .0001$) may further point to the need to establish an optimal time for TV repair, even in those with mild TR and symptoms.

In patients with greater than mild-to-moderate TR at late follow-up, there was a significant increase in RV enlargement with 69.5% (n = 16) of patients with late TR having greater than moderate RV enlargement compared with 33.3% (n = 14) of those without TR ($P = .009$). However, this finding did not apply to RV dysfunction; there was no statistical difference between those with late TR and greater than moderate RV dysfunction (n = 7, 30.4%) and those without late TR who also had RV dysfunction (n = 9, 20.9%; $P = .547$).

A cavopulmonary Glenn shunt was used sparingly in this series, more in line with da Silva's approach,[18] as opposed to the Mayo clinic approach.[21] This is likely related to our institutional bias to leave a small atrial "pop-off" communication to deal with postoperative diastolic RV dysfunction. The Glenn's main purpose is to get the "sicker" patients through their operation. With an excellent early and late survival, and in the absence of evidence that a Glenn is truly protective, we will likely continue to be restrictive in our Glenn use. However, because one of the main conclusions of this study is that the cone procedure should be used more liberally in older patients with RV dysfunction, it is possible that our use of the Glenn will increase in this older/sicker cohort.

Study Limitations

This study was a retrospective single-center study, and assignment to cone repair or TVR was not randomized; thus, our findings are likely confounded by underlying differences in morbidity and anatomy that led to selection of TVR over cone repair. Specifically, the higher rate of preoperative RV dysfunction and enlargement in the TVR group is a confounding factor on outcomes at last follow-up. However, our analysis of the evolution of these criteria over time takes this limitation into consideration in the way we interpret our results. Our echocardiographic findings relied on review of written findings in the electronic medical record, and the images were not reviewed. This may lead to differences in interrater variation in grading of TR, RV dysfunction, and RV enlargement. Echocardiographic limitations in measuring RV function and size are well known compared with magnetic resonance studies.[8] Finally, there were gaps in length of follow-up within our cohort with 15 patients (18%) having a follow-up time of less than 30 days, which may significantly impact our findings despite being censored at the date of last follow-up.

CONCLUSIONS

The cone procedure offers excellent results with stable valve function long term, with low reintervention (9%) and death (0%) rates at last follow-up. The rate of greater than mild-to-moderate residual TR at discharge was higher after the cone procedure compared with TVR, but this tended to improve with time and did not expose patients to a higher risk of reoperation or death at last follow-up. TVR was associated with a significantly higher risk of TV stenosis and reoperation/reintervention compared with the cone procedure. We recommend the use and expansion of the cone repair technique in EA, with strong consideration for a ring annuloplasty when possible.

Conflict of Interest Statement

The authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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Key Words: cone repair, congenital, Ebstein's anomaly

TABLE E1. Age-stratified outcomes of cone repair

	Age <1 year	1-12 years	12-18 years	18-21 years	Age >21 years	*P* value
Patients	5 (8%)	24 (36%)	7 (11%)	7 (11%)	23 (35%)	
Male	2 (40%)	14 (58%)	3 (43%)	3 (43%)	12 (52%)	
Postoperative complications						
Arrhythmia	1 (20%)	9 (38%)	3 (43%)	3 (43%)	8 (35%)	.949
Inotrope requirement ≥24 h	4 (80%)	15 (63%)	4 (57%)	2 (29%)	6 (26%)	.044
Cardiac tamponade	0 (0%)	0 (0%)	0 (0%)	1 (14%)	0 (0%)	.288
Transient pHTN	1 (20%)	4 (17%)	0 (0%)	0 (0%)	0 (0%)	.120
Anemia requiring transfusion	1 (20%)	3 (13%)	2 (29%)	1 (14%)	2 (9%)	.624
Infection	0 (0%)	2 (8%)	0 (0%)	0 (0%)	2 (9%)	1.000
CVA	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (4%)	.636
Pacemaker requirement	0 (0%)	1 (4%)	0 (0%)	0 (0%)	1 (4%)	1.000
Early mortality	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	N/A
Late mortality	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	N/A
Echocardiographic findings at hospital discharge						
Greater than mild-to-moderate TR	3 (60%)	9 (38%)	3 (43%)	2 (29%)	7 (30%)	.799
Greater than mild-to-moderate TS	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Moderate or greater RV dysfunction	1 (20%)	6 (25%)	2 (29%)	3 (43%)	14 (61%)	.107
Moderate or greater RV enlargement	3 (60%)	14 (58%)	3 (43%)	4 (57%)	14 (61%)	.966
Moderate or greater LV dysfunction	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Length of follow up, y; mean (SD)	3.7 (3.5)	2.9 (3.9)	4.7 (3.2)	4.9 (4.0)	4.5 (4.3)	.906
Echocardiographic findings at last follow-up						
Greater than mild-to-moderate TR	3 (60%)	7 (29%)	4 (57%)	1 (14%)	8 (35%)	.366
Greater than mild-to-moderate TS	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	
Moderate or greater RV dysfunction	1 (20%)	3 (13%)	1 (14%)	2 (29%)	9 (39%)	.269
Moderate or greater RV enlargement	2 (40%)	11 (46%)	4 (57%)	2 (29%)	11 (48%)	.947
TV reintervention/reoperation	2 (40%)	2 (8%)	0 (0%)	0 (0%)	2 (9%)	.224

pHTN, Pulmonary hypertension; *CVA*, cerebrovascular accident; *N/A*, not available; *TR*, tricuspid regurgitation; *TS*, tricuspid stenosis; *RV*, right ventricle; *LV*, left ventricle; *SD*, standard deviation; *TV*, tricuspid valve.

TABLE E2. Outcomes of cone repair by surgeon volume

	Highest-volume surgeon (Bacha)	Second highest-volume surgeon (Quaeberger)	*P* value
Patients	44	21	
Male	26 (59.1%)	8 (38.1%)	.150
Age (y)	17.0 ± 13.0	14.6 ± 10.2	
Postoperative complications			
Arrhythmia	17 (38.6%)	7 (33.3%)	.864
Inotrope requirement ≥24 h	19 (43.2%)	11 (52.4%)	.506
Cardiac tamponade	1 (2.3%)	0 (0%)	1.000
Transient pHTN	5 (11.4%)	0 (0%)	.229
Anemia requiring transfusion	8 (18.2%)	1 (4.8%)	.353
Infection	3 (6.8%)	1 (4.8%)	1.000
CVA	0 (0%)	1 (4.8%)	.333
Pacemaker requirement	2 (4.5%)	0 (0%)	1.000
Early mortality	0 (0%)	0 (0%)	N/A
Late mortality	0 (0%)	0 (0%)	N/A
Echocardiographic findings at hospital discharge			
Greater than mild-to-moderate TR	14 (31.8%)	10 (47.6%)	.386
Greater than mild-to-moderate TS	0 (0%)	0 (0%)	N/A
Moderate or greater RV dysfunction	20 (45.5%)	6 (28.6%)	.333
Moderate or greater RV enlargement	28 (63.6%)	9 (42.9%)	.181
Moderate or greater LV dysfunction	0 (0%)	0 (0%)	N/A
Echocardiographic findings at last follow-up			
Greater than mild-to-moderate TR	15 (34.1%)	8 (38.1%)	.861
Greater than mild-to-moderate TS	0 (0%)	0 (0%)	N/A
Moderate or greater RV dysfunction	12 (27.3%)	4 (19%)	.660
Moderate or greater RV enlargement	22 (50%)	7 (33.3%)	.286
TV reintervention/reoperation	4 (9.1%)	2 (9.5%)	1.000

pHTN, Pulmonary hypertension; *CVA*, cerebrovascular accident; *N/A*, not available; *TR*, tricuspid regurgitation; *TS*, tricuspid stenosis; *RV*, right ventricle; *LV*, left ventricle; *TV*, tricuspid valve.