Tricuspid valve repair improves early right ventricular and tricuspid valve remodeling in patients with hypoplastic left heart syndrome

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Objective: Tricuspid regurgitation is a significant risk factor for reoperation and mortality in patients with hypoplastic left heart syndrome. The effects of tricuspid valve repair on quantitative measures of right ventricle and tricuspid valve remodeling have not been well documented.

Methods: We reviewed retrospectively the 2-dimensional echocardiograms of 17 tricuspid valve repairs (male, $n = 12$; female, $n = 5$; median age, 30 months; age range, 1.5-53 months) performed 1 month before and after tricuspid valve repair between 2005 and 2011. From the apical 4-chamber view, we measured right ventricle end-diastolic area, right ventricle fractional area change, and tricuspid valve leaflet coaptation length. The severity of tricuspid regurgitation was graded qualitatively. A 2-sided paired t test was used to compare changes in tricuspid valve and right ventricle outcomes, and the Wilcoxon signed-rank test was used to compare changes in tricuspid regurgitation grades.

Results: Right ventricle end-diastolic area decreased significantly after tricuspid valve repair from 14.1 ± 5.2 to $11.8 \pm 3.9 \text{ cm}^2$ ($P = .001$), whereas right ventricle fractional area change declined from $44.4\% \pm 6.4\%$ to $39.7\% \pm 8.5\%$ ($P = .016$). The coaptation length of the lateral and septal leaflet improved significantly after tricuspid valve repair ($0.4 \pm 2.4 \text{ mm}$ vs $3.1 \pm 2.7 \text{ mm}$, $P = .002$; 2.0 ± 2.7 vs $3.4 \pm 2.0 \text{ mm}$, $P = .036$; respectively). Furthermore, the tricuspid regurgitation grade improved after tricuspid valve repair (3.1 ± 0.6 to 1.7 ± 0.9 , $P < .001$).

Conclusions: Tricuspid valve repair improved significantly the tricuspid valve coaptation length and reduced right ventricle volume in children with hypoplastic left heart syndrome. Further follow-up of decreased right ventricle function is required to determine whether this is a temporary phenomenon related to reduced right ventricle preload, permanent right ventricle dysfunction from late repair of the tricuspid valve, or unavoidable sequelae of a right ventricle exposed to systemic vascular resistance. (J Thorac Cardiovasc Surg 2013;145:446-50)

The outcome of patients with hypoplastic left heart syndrome (HLHS) has improved significantly during the past 2 decades. However, there remain several factors that affect long-term survival negatively after the Norwood procedure. The development of tricuspid regurgitation (TR) is an ominous finding and is regarded as an important risk factor for increased mortality in children with HLHS.¹⁻⁴ Tricuspid regurgitation occurs in approximately 25% of survivors of the Norwood procedure within 10 years.⁴ Tricuspid regurgitation may occur because of congenital tricuspid valve (TV) dysplasia, malformation of support structures or secondary to right ventricle (RV) dilatation. Several reports have suggested that TV repair decreases the severity of TR and may improve the functional outcome of patients with HLHS.²⁻⁴ However, the

effects of TV repair on RV and TV remodeling have not been documented well in patients with HLHS.

Recent advances in echocardiography and understanding of the mechanisms of atrioventricular valve regurgitation have made it possible to evaluate valve function, before and after intervention, both more accurately and quantitatively. Mitral valve repair in adult patients with mitral regurgitation has been reported to increase the coaptation length of mitral valve leaflets and lead to favorable mitral valve remodeling.^{5,6} However, there is a paucity of data on the effect of TV repair on coaptation length, and TV and RV remodeling in congenital heart diseases with RVs exposed to the systemic circulation. Therefore, we sought to assess quantitatively the changes in TV and RV function and morphology after TV repair in patients with HLHS.

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MATERIALS AND METHODS

Patients

We reviewed retrospectively all patients with classic HLHS who underwent TV repair after a stage 1 Norwood procedure at our institution between January 2005 and December 2011. The study was approved by the University of Alberta Institutional Review Board, and the need for parental consent was waived. We examined hospital records, surgical records, and echocardiographic data, and collected demographic information, diagnoses, surgical procedures, and data on the indications for TV repair, complications, and outcomes.

Abbreviations and Acronyms

ECMO	= extracorporeal membrane oxygenation
HLHS	= hypoplastic left heart syndrome
RV	= right ventricle
RVEDA	= right ventricular end-diastolic area
RVESA	= right ventricular end-systolic area
RVFAC	= right ventricular fractional area change
TR	= tricuspid regurgitation
TV	= tricuspid valve

Surgical Procedures

Several procedures for TV repair were used, depending on the mechanism of the TR (Table 1). Posterior annuloplasty was applied in patients with central regurgitation or regurgitant flow through the posterior leaflet of the TV. We performed this technique also if there was residual regurgitant flow after cleft closure or commissure closure. Posterior annuloplasty was accomplished by approximating the anteroposterior commissure with the septal–posterior commissure using mattress pledgeted sutures. Cleft closure was performed in patients with clefts, causing significant TR. Commissure closure was used if prolapsed leaflets, near the commissure, produced TR. The repaired TV was confirmed to have adequate tricuspid annular size. Posterior annuloplasty was performed in 14 patients, cleft closure in 5 patients, commissure closure in 4 patients, and with antero-septal annuloplasty in 2 patients. Fourteen children had concomitant procedures together with TV repair, including the modified Fontan operation in 10 patients, bidirectional Glenn in 3 patients, and aortic arch repair in 2 patients. Three children underwent TV repair after the bidirectional Glenn but before the Fontan completion. Tricuspid valve repair was performed a median of 4.0 months (range, 0.1–42.7 months) after the occurrence of significant TR.

In the latter part of the series, 3-dimensional echocardiography was helpful in preoperative evaluation and influenced intraoperative strategy.⁷ However, during the study period, not all patients underwent 3-dimensional echocardiography.

Echocardiographic Examination

A full 2-dimensional Doppler and color Doppler echocardiographic assessment was conducted routinely within 1 month before and after TV repair. The apical 4-chamber view was used to evaluate TV and RV outcomes. Right ventricular end-diastolic area (RVEDA) and RV end-systolic area (RVESA) were measured by tracing the area of the RV at end diastole and end systole, respectively. Right ventricular fractional area change (RVFAC) was calculated using the following equation:

$$\text{RVFAC (\%)} = \frac{\text{RVEDA} - \text{RVESA}}{\text{RVEDA}} \times 100$$

Tricuspid valve end-diastolic annular diameter was the distance between the insertion of the septal and the lateral leaflets at end diastole. The septal and lateral leaflet length (Ld) was measured from the tricuspid annulus to the tip of each leaflet during the diastole (Figure 1). The length of uncoapted segments of each leaflet (Lc) was the distance from the annulus to the coaptation point at end systole. Therefore, the coaptation length for each leaflet was calculated using the following equation:

$$\text{Coaptation length} = \text{Ld} - \text{Lc}$$

The TV tenting height was the distance between the septal and lateral annuli to the coaptation point of the tricuspid leaflet at end systole. The TV tenting area was calculated by multiplying the annular diameter at end systole by 0.5 times the tenting height. The vena contracta width

was measured at the narrowest region of the regurgitant flow just distal to the flow convergence area at mid systole.⁸ The degree of TR was determined qualitatively. TR was graded on the ratio of the color Doppler jet to the area of the atrium. TR was ranked as none (0), trivial (1), mild (2), moderate (3), and severe (4). The RV sphericity index was the ratio between the short diameter and the long diameter of the RV at end systole.

Data Analysis

Categoric variables are described as frequencies and percentages, and continuous variables are described as mean and standard deviation or median and range. A 2-sided paired sample *t* test was used to compare changes in TV and RV outcomes, and the Wilcoxon signed-rank test was used to compare changes in TR grades before and after TV repair. SAS/Base software version 9.3 (SAS Institute Inc, Cary, NC) was used for analysis.

RESULTS

Surgical Results

There were 19 consecutive patients who underwent TV repair for severe TR during the study period. Four of 19 children who received TV repair during the study period underwent a heart transplant a median of 6.5 months (range, 3–18 months) after TV repair. Heart transplantation was performed for 1 patient because of persistent TR and severe RV dysfunction, and was performed in 3 patients because of intractable protein-losing enteropathy despite mild TR and preserved RV function. Two patients were excluded. One patient died after TV repair. He could not be separated from cardiopulmonary bypass after the modified Norwood stage 1 operation because of severe RV dysfunction and TR, and he required extracorporeal membrane oxygenation (ECMO). This patient received 7 days of ECMO support with persistent, severe TR and RV dysfunction. Tricuspid valve repair was performed, but RV function remained severely depressed and the patient could not be weaned from ECMO. He developed mediastinitis, sepsis, and died. Thus, 1 of 19 patients died after TV repair, giving a hospital mortality of 5.3%. One patient had inadequate echocardiographic images. Therefore, 17 patients were included in the study. We studied 12 males and 5 females with a median age at tricuspid valve repair of 30 months (range, 1.5–53 months) and a median weight of 13 kg (range, 3.1–17.2 kg). Median myocardial ischemic time at TV repair was 22 minutes (range, 0–61 minutes). The median follow-up time was 31 months (range, 1–63 months).

Three patients underwent reoperation for persistent TV regurgitation. Two patients required a second posterior TV annuloplasty. In 1 of these patients, the cause of the TR was tethered TV chords. In the second patient, the TV leaked at the junction of the posterior and septal leaflet. In the third patient, a scallop of the posterior leaflet prolapsed and we closed with sutures the cleft between 2 scallops of the posterior leaflet. At reoperation we found an eccentric jet arising in the commissure between the posterior leaflet and the anterior leaflet adjacent to the previous repair. Subsequently, the cleft was closed between the anterior and

TABLE 1. The mechanisms of tricuspid valve regurgitation and type of repair

Patient	Primary diagnosis	Age at repair, month	Mechanisms of TR	Type of TV repair
1	HLHS (MA, AA)	1.5	Central regurgitation	Posterior annuloplasty
2	HLHS (MA, AA)	4	Central regurgitation	Posterior annuloplasty
3	HLHS (MA, AA)	5	Central regurgitation	Posterior annuloplasty
4	HLHS (MS, AS)	6	Central regurgitation	Posterior annuloplasty
5	HLHS (MA, AA)	20	Prolapse in the posterior leaflet	Posterior annuloplasty
6	HLHS (MS, AA)	20	Prolapse in the posterior leaflet	Cleft closure
7	HLHS (MS, AA)	26	Redundant scallops in the posterior leaflet	Commissure closure
8	HLHS (MA, AA)	33	Cleft in the anterior leaflet, central regurgitation	Posterior annuloplasty, cleft closure
9	HLHS (MA, AA)	30	Prolapse in the anterior leaflet	Anteroseptal annuloplasty
10	HLHS (MS, AA)	42	Central regurgitation	Posterior annuloplasty
11	HLHS (MS, AS)	53	Central regurgitation, regurgitation via the anteroseptal commissure	Posterior annuloplasty, cleft closure, commissure closure
12	HLHS (MS, AA)	31	Prolapse in the posterior leaflet	Posterior annuloplasty
13	HLHS (MA, AA)	28	Central regurgitation	Posterior annuloplasty
14	HLHS (MS, AA)	53	Prolapse in the anterior leaflet, cleft in the septal leaflet	Posterior annuloplasty, cleft closure, commissure closure
15	HLHS (MS, AA)	52	Cleft in the septal leaflet, regurgitant via the septal-posterior commissure	Posterior annuloplasty, anteroseptal annuloplasty, cleft closure
16	HLHS (MS, AA)	38	Central regurgitation	Posterior annuloplasty
17	HLHS (MA, AA)	36	Prolapse in the anterior leaflet	Posterior annuloplasty, commissure closure

TR, Tricuspid regurgitation; TV, tricuspid valve; HLHS, hypoplastic left heart syndrome; MA, mitral atresia; AA, aortic atresia; MS, mitral stenosis; AS, aortic stenosis.

posterior leaflets. The techniques used to repair the TV did not change over 6 years. The need for a second TV repair was spread evenly over the 6-year period.

FIGURE 1. Illustration of the measurement of tricuspid valve leaflet coaptation length and tenting height.

Right Ventricular and Tricuspid Morphology

The changes in TV and RV morphology pre- and post-TV repair are summarized in (Table 2). The vena contracta width and the grade of TR diminished significantly after TV repair. Right ventricular end-diastolic area and TV end-diastolic annular diameter were also significantly decreased after TV repair, although RVFAC deteriorated after TV repair. The coaptation lengths of lateral and septal leaflets improved significantly after TV repair. In addition, TV repair decreased significantly the tenting height, area, and RV sphericity index.

DISCUSSION

In our experience, severe TV regurgitation may be improved by surgical valve repair in patients with HLHS in the majority of patients, with a low mortality rate. Our main findings were as follows: (1) TV repair improved the vena contracta width and the grade of TR; (2) TV repair resulted in decreased RVEDA and TV annulus, but unmasked reduced RV function; (3) TV repair improved coaptation length in both the septal and lateral leaflets, and normalized the coaptation points.

Changes in the Degree of Tricuspid Regurgitation and Right Ventricular Volume

There are many factors that cause TR in children with HLHS, including dysplastic TV leaflets, abnormal clefts, valve prolapse, chordal shortening, dilated annulus, and tethering caused by RV dilatation. During the early postoperative period after stage 1 Norwood procedures, patients have a volume-loaded RV, so they often develop increased

TABLE 2. Changes in tricuspid regurgitation, right ventricular variables, and tricuspid valve morphology before and after tricuspid valve repair

Variable	Pre-TV repair	Post-TV repair	P value
TR grade, 0-4	3.1 ± 0.6	1.7 ± 0.9	<.001*
Vena contracta width, mm	5.4 ± 1.3	2.7 ± 1.8	<.001
RVEDA, cm ²	14.1 ± 5.2	11.8 ± 3.9	.001
RVFAC, %	44.4 ± 6.4	39.7 ± 8.5	.016
TV end-diastolic annular diameter, mm	23.6 ± 3.9	19.8 ± 4.2	.001
Coaptation length of the lateral leaflet, mm	0.4 ± 2.4	3.1 ± 2.7	.002
Coaptation length of the septal leaflet, mm	2.0 ± 2.7	3.4 ± 2.0	.036
TV tenting height, mm	2.4 ± 2.3	1.2 ± 1.1	.014
TV tenting area, mm ²	23.7 ± 26.0	10.5 ± 9.8	.024
RV sphericity index	0.75 ± 0.16	0.66 ± 0.19	<.001

Data are described as mean ± standard deviation. TV, Tricuspid valve; TR, tricuspid regurgitation; RVEDA, right ventricular end-diastolic area; RVFAC, right ventricular fractional area change; RV, right ventricle. *The Wilcoxon signed-rank test was used for statistical analysis.

TV regurgitation. In the current study, TV repair was successful in reducing vena contracta width and the degree of TR. It is well reported that posterior annuloplasty is a reliable, simple, and reproducible procedure to alleviate TR and the subsequent RV dilatation.²⁻⁴ We used this technique in most children, which proved to be effective in reducing RV volume overload. However, there were a variety of mechanisms causing TR, and other techniques such as cleft and commissure closure were indispensable to repair dysplastic TV structures. In addition, in our experience, 3-dimensional echocardiography is a valuable adjunct to aid decision making before TV repair.⁷

Right Ventricle Function

The preservation of RV function is crucial to prevent symptoms and mortality in patients undergoing staged single-ventricle palliation. There have been reports suggesting that RV dysfunction and recurrent TR are closely linked.²⁻⁴ Several authors have suggested that TV repair preserved RV function in many patients with HLHS.^{2,3} Although, and in agreement with our study, Elmi and colleagues⁴ reported that RV performance deteriorated shortly after TV repair but improved during long-term follow-up. They measured RV function based primarily on the subjective evaluation of RV function, without quantification of the RV area before and after TV repair. Therefore, our method may represent more accurately the changes in RV function occurring in patients with HLHS and TV regurgitation. In the current study, RV function decreased after TV repair. There are several possible reasons for this finding. First, the effects of cardiopulmonary bypass and aortic crossclamp time may have contributed to myocardial ischemia. We evaluated RV function within 1 month of TV

repair; longer term follow-up would be necessary to investigate whether this was a reversible decrease in RV fractional area change. Second, TR may have underestimated RV dysfunction by reducing ventricular afterload, and TV repair may have unmasked an existing RV dysfunction. This phenomenon may be encountered in patients with prolonged mitral regurgitation or with severe TV regurgitation and RV dysfunction after the atrial switch operation.⁴ If this is the mechanism, then one may argue in favor of earlier TV repair to preserve RV function and improve long-term outcome.

Coaptation Changes After Tricuspid Valve Repair

Advances in echocardiography have made it possible to obtain more precise details of atrioventricular valve function and mechanisms of valvar dysfunction in young children. However, the changes in coaptation length of tricuspid leaflets caused by TV repair have not been documented previously. Our results suggest that TV repair remodels the TV effectively and favorably, because TV repair resulted in a reduction in the TV annulus, RV volume, and sphericity index, leading to improved coaptation lengths of the tricuspid leaflets. In addition, TV repair remodeled the coaptation point of the TV positively as a result of tethering caused by RV volume overload. Mitral valve repair has been reported to alleviate tethering of mitral valves, and our results demonstrate that TV repair can alleviate TV tethering in an RV exposed to systemic vascular resistance in a similar way.^{5,6} Last, the measurement of TV leaflet coaptation lengths may provide a more sensitive method to follow up and evaluate the TV in patients with systemic RVs because the changes in coaptation length occur before significant TR. Close evaluation and serial changes in coaptation lengths may help in decision making to repair a TV before significant decrease in RV function has occurred.

Limitations

This study has several limitations. It is retrospective, with a small number of patients, and it requires prospective evaluation in a larger cohort of patients. Precise measurements of leaflet length may be confounded by leaflet stretching with different ventricular loading conditions in the cardiac cycle. It is reported that normal mitral valves may increase their length by up to 15% through tension.⁶ However, we measured leaflet lengths only in mid diastole and end systole to avoid these changes as much as possible. In addition, most patients had concomitant procedures with TV repair that may have influenced morphology and function of TV and RV. Further study is required to evaluate the effects of TV repair on TV and RV after isolated TV repair. Also, our study focused on changes in TV and RV morphology and function within 1 month before and after TV repair. We acknowledge that longer follow-up is required to

evaluate whether the changes in the morphology and function of TV and RV were sustained. Last, the current study was based on 2-dimensional echo images and, conceivably, more accurate information may be available from 3-dimensional echocardiography and magnetic resonance imaging. However, the latter modalities, despite the potential for providing a deeper understanding of RV and TV morphology, are not suited for frequent, routine evaluation of children.

CONCLUSIONS

Tricuspid valve repair improved significantly the TV coaptation length and reduced RV volume in children with HLHS. Tricuspid valve repair impacted favorably on quantitative markers of RV and TV remodeling. Further follow-up of the decreased RV function is required to determine whether this is a temporary phenomenon related to reduced RV preload, permanent RV dysfunction from late repair of the TV, or an unavoidable consequence of an RV exposed to systemic vascular resistance.

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