Right Ventricular and Tricuspid Valve Remodeling After Bidirectional Cavopulmonary Anastomosis

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Background: There are few investigations of the changes in tricuspid valve (TV) and right ventricular (RV) morphology following bidirectional cavopulmonary anastomosis (BCPA).

Methods and Results: The 2-D echocardiograms of 35 children (male, n=23; female, n=12; median age, 6 months; range, 3–10 months) with hypoplastic left heart syndrome, 1 month before and after BCPA performed between 2005 and 2011, were retrospectively reviewed. Patients who underwent TV repair at BCPA were excluded. From the 4-chamber view, the coaptation length, vena contracta width and RV end-diastolic area before and after BCPA were measured and indexed to surface area. The severity of tricuspid regurgitation was graded qualitatively. After BCPA, RV end-diastolic area decreased from 2,951±584 to 2,580±591 mm²/m² (P<0.001). The coaptation length of the anterior leaflet (8.8±5.8 vs. 11.0±6.2 mm²/m², P=0.0014) and of the septal leaflet (13.5±5.3 vs. 15.8±5.4 mm²/m², P=0.0072) increased after BCPA. The vena contracta width decreased (5.8±4.9 vs. 4.3±4.2 mm²/m², P=0.035), although there was no change in tricuspid regurgitation grade after BCPC (1.4±0.7 vs. 1.4±0.9, P=0.234).

Conclusions: In children with hypoplastic left heart syndrome after BCPA, the coaptation length of the anterior and septal leaflets of the TV improved concomitantly with vena contracta width and RV end-diastolic area despite unchanged tricuspid regurgitation grade. This suggests that favorable RV and TV remodeling accompanies the reduction in RV volume load following BCPA. (Circ J 2013; 77: 2514–2518)

Key Words: Bidirectional cavopulmonary anastomosis; Coaptation; Hypoplastic left heart syndrome; Right ventricle; Tricuspid valve

The outcome hypoplastic left heart syndrome (HLHS) has improved steadily as a result of better surgical techniques, cumulative experience and improved clinical understanding.1–6 Bidirectional cavopulmonary anastomosis (BCPA) is performed as the second stage of palliation for HLHS and theoretically should reduce ventricular volume load and improve effective pulmonary blood flow. Several reports have shown that BCPA has favorable effects on single ventricle geometry by decreasing the end-diastolic area and increasing wall thickness without impairing ventricular function.7–8 Michelfelder et al showed that BCPA decreased the tricuspid valve (TV) annular dilatation after stage 1 Norwood palliation.9 Understanding the morphology of the TV is crucial because development of tricuspid regurgitation (TR) is an important risk factor for increased mortality in children with HLHS.1–4 Recent advances in echocardiography and in the understanding of the mechanisms of atrioventricular valve regurgitation have made it possible to evaluate valve function and morphology both more accurately and quantitatively.11 We hypothesized that BCPA, by decreasing volume load, would increase the coaptation length of tricuspid leaflets and lead to favorable TV remodeling. The effect of BCPA, however, on coaptation length, TV and right ventricular (RV) remodeling in congenital heart disease involving systemic RV has not been reported to our knowledge. Therefore, we sought to quantify the changes in coaptation length and configuration of TV and RV morphology following BCPA in patients with HLHS.

Patients
We retrospectively reviewed all patients with classic HLHS who underwent BCPA after a stage 1 Norwood procedure at
RV and TV After BCPA

was graded as none, 0; trivial, 1; mild, 2; moderate, 3; and severe, 4. We measured the RV sphericity index from the ratio between the short diameter and the long diameter of RV at end-systole. All measurements were performed by 1 examiner (S.U.) who was blinded to patient profile.

Statistical Analysis
Continuous variables are described as mean ± SD and range if normally distributed, and median with range if not normally distributed. Categorical variables are described as frequencies and percentages. Two-sided paired sample t-test was used to compare changes in TV and RV measurements. Wilcoxon signed-rank test was used to compare changes in TR grade before and after BCPA. Two-sided unpaired t-test was used to compare data between groups. P<0.05 was considered to be statistically significant.

Results

Surgical Results
Forty-six children underwent BCPA after modified Norwood operation during the study period. All patients had RV to pulmonary artery shunt (RV-PA) using 5-mm expanded polytetrafluoroethylene graft at the first stage palliation. We excluded 11 patients: 3 because they underwent TV repair concomitantly with BCPA, and 8 because the echocardiographic images were inadequate. Therefore, data on 35 of 46 children (male, n=23; female, n=12) form the basis for this study. The median age at BCPA was 6 months (range, 3–10 months) and the median body weight was 6.4 kg (range, 3.7–8.7 kg). Concomitant procedures included repair of aortic recoarctation (n=4) and pulmonary arterioplasty (n=2). The RV-PA shunt was either completely divided or partially clipped depending on surgeon preference and was divided completely in 16 patients and partially closed in 19 children. One patient required
revision of BCPA because of stenosis at the anastomosis site and PA. One patient died 43 days after BCPA because of hypoxia caused by thrombus in the PA, which required extracorporeal membrane oxygenation. All other patients were discharged from hospital. The median hospital stay was 8 days (range, 4–196 days). In 11/35 patients who underwent preoperative cardiac catheterization, median Qp:Qs was 0.73:1 (range, 0.33–1.4:1).

**Changes in RV and TV Morphology After BCPA**

The changes in TV and RV morphology after BCPA are summarized in Table 1. The vena contracta width decreased significantly following BCPA (P=0.035), whereas TR grade did not change significantly (P=0.23). RV end-diastolic area decreased significantly after BCPA (P<0.001). There was no difference in RVFAC before and after BCPA (P=0.80). TV end-diastolic annular diameter decreased significantly after BCPA (P=0.0043). The coaptation lengths of anterior and septal leaflets recovered significantly after BCPA (P=0.0014 and P=0.0072, respectively). In addition, TV tenting height and area and RV sphericity index decreased significantly after BCPA (P<0.001).

**RV and TV Morphology Differences vs. RV-PA Shunt Patency**

The patients were grouped depending on whether RV-PA shunt was divided or partially closed. Table 2 summarizes the data on TV and RV morphology before and after BCPA between the 2 groups. There were no significant differences in all variables between divided and patent RV-PA shunts before BCPA. After BCPA, we found significant decreases in patients with divided RV-PA shunt in RVEDA (P=0.0035), coaptation lengths of the anterior leaflets (P=0.0044), tenting height (P<0.001) and area (P<0.001). After BCPA, in patients with patent RV-PA shunt, there was a significant improvement in RVEDA (P<0.001), RVESA (P=0.0029), TV annular diameter (P=0.014), coaptation lengths of the septal leaflets (P=0.013), tenting height (P=0.067) and area (P=0.028) and RV sphericity index (P<0.001). In addition, after BCPA, RVFAC was significantly better in patients whose shunts were patent at BCPA (P=0.021), but we found no significant differences in other variables between subjects with divided and patent RV-PA shunts.

**Table 1. Changes in TV and RV Morphology After BCPA**

|                  | Before BCPA | After BCPA | P-value |
|------------------|-------------|------------|---------|
| TR grade         | 1.4±0.7 (0–3) | 1.4±0.9 (0–3) | 0.23    |
| Vena contracta width (mm²/m²) | 5.8±4.9 (0–14.9) | 4.3±4.2 (0–12.5) | 0.035*  |
| RVEDA (mm²/m²)   | 2.95±1.684 (1.567–4.115) | 2.580±0.591 (1.359–3.591) | <0.001* |
| RVESA (mm²/m²)   | 1.69±0.455 (700–2.577) | 1.480±0.455 (538–2.600) | 0.0022* |
| RVFAC (%)        | 42.8±8.7 (27.1–57.7) | 42.6±8.8 (25.6–60.4) | 0.80    |
| TV end diastolic annular diameter (mm²/m²) | 60.3±9.8 (45.7–88.9) | 56.0±9.3 (30.2–81.5) | 0.0043* |
| Anterior leaflet coaptation length (mm²/m²) | 8.8±5.8 (–3.7 to 25.8) | 11.0±6.2 (–3.7 to 22.6) | 0.0014* |
| Septal leaflet coaptation length (mm²/m²) | 13.5±5.3 (2.1–23.3) | 15.8±5.4 (3.6–36.3) | 0.0072* |
| TV tenting height (mm²/m²) | 6.9±4.3 (–1.6 to 15.4) | 3.9±3.6 (–3.9 to 10.6) | <0.001* |
| TV tenting area (mm²/m²) | 55.8±3.97 (–20 to 151.5) | 32.3±3.32 (–39.3 to 124.2) | <0.001* |
| RV sphericity index | 0.69±0.18 (0.44–1.1) | 0.65±0.16 (0.4–1.1) | <0.001* |

Data given as mean±SD and range. *P<0.05 before BCPA vs. after BCPA; †P<0.05 divided shunt vs. patent shunt. BCPA, bidirectional cavopulmonary anastomosis; RV, right ventricle/ventricular; RVEDA, right ventricular end-diastolic area; RVESA, right ventricular end-systolic area; RVFAC, right ventricular fractional area change; TR, tricuspid regurgitation; TV, tricuspid valve.

**Table 2. Changes in TV and RV Morphology vs. RV-PA Shunt Patency**

|                  | Divided (n=16) | Patent (n=19) | Divided (n=16) | Patent (n=19) |
|------------------|---------------|---------------|---------------|---------------|
| TR grade         | 1.4±0.8 (0–2.5) | 1.4±0.7 (0–3) | 1.4±0.8 (0–3) | 1.5±0.9 (0–3) |
| Vena contracta width (mm²/m²) | 5.3±5.0 (0–14.9) | 6.2±4.9 (0–14.8) | 3.7±3.7 (0–10.0) | 4.8±4.6 (0–12.5) |
| RVEDA (mm²/m²)   | 2.88±1.569 (1.567–3.571) | 3.009±0.607 (1.771–4.115) | 2.495±0.557* (1.359–3.200) | 2.652±0.623* (1.436–3.581) |
| RVESA (mm²/m²)   | 1.686±0.509 (700–2.552) | 1.705±0.418 (1.114–2.577) | 1.513±0.459 (538–2.143) | 1.453±0.462* (853–2.600) |
| RVFAC (%)        | 42.4±9.4 (28.2–57.7) | 43.1±8.3 (27.1–56.6) | 38.8±8.6 (25.6–60.4) | 45.5±7.8* (26.0–55.6) |
| TV end-diastolic annular diameter (mm²/m²) | 59.1±8.1 (45.7–75.9) | 61.4±11.2 (45.7–88.9) | 54.7±9.5 (30.2–88.0) | 57.1±9.2* (41.0–81.5) |
| Anterior leaflet coaptation length (mm²/m²) | 9.1±6.4 (0–25.8) | 8.6±5.5 (–3.7 to 18.1) | 11.4±6.7* (0–22.6) | 10.6±5.8 (–3.7 to 22.5) |
| Septal leaflet coaptation length (mm²/m²) | 13.9±5.3 (2.1–23.3) | 13.1±5.4 (5.4–21.1) | 15.6±6.8 (3.6–36.3) | 15.9±3.9* (10.3–23.8) |
| TV tenting height (mm²/m²) | 7.1±3.7 (0–13.9) | 6.7±4.8 (–1.6 to 15.4) | 4.4±2.9* (–1.2 to 10.6) | 3.5±4.2* (–3.9 to 10.3) |
| TV tenting area (mm²/m²) | 61.3±40.0 (0–151.5) | 51.1±40.0 (–20 to 146.4) | 37.9±30.2* (–5.9 to 124.2) | 27.6±34.1* (–39.3 to 84.4) |
| RV sphericity index | 0.68±0.18 (0.44–1.1) | 0.69±0.18 (0.47–1.0) | 0.65±0.15 (0.42–0.93) | 0.64±0.18* (0.40–1.0) |

Data given as mean±SD and range. *P<0.05 before BCPA vs. after BCPA; †P<0.05 divided shunt vs. patent shunt. Other abbreviations as in Table 1.
RV and TV Morphology and Preservation of Function

The patients were grouped depending on preoperative RV FAC >40% (n=22) and <40% (n=13). Table 3 summarizes the data on TV and RV morphology before and after BCPA between these 2 groups. Before BCPA, patients with decreased RV function had significantly larger RVESA compared with those with preserved RV function (P<0.001), but there were no significant differences in other variables in patients with preserved RV function (P=0.023), but we found no significant differences in other variables in patients with preserved RV function (P=0.001), coaptation lengths of anterior leaflets (P=0.014), tenting height (P=0.0011) and area (P=0.0074) and RV sphericity index (P=0.011) in patients with RV FAC >40%. After BCPA, we found significant improvement in RVEDA (P=0.0048), RVESA (P=0.0034), TV annular diameter (P=0.014), coaptation lengths of anterior (P=0.029) and septal leaflets (P=0.001), tenting height (P=0.015) and area (P=0.017) and RV sphericity index (P=0.019) in patients with RV FAC <40%. In addition, TR grade was significantly better in patients with RV FAC >40% (P=0.019), tenting height (P=0.015) and area (P=0.017) and RV sphericity index (P=0.019) in patients with RV FAC >40%. After BCPA, there was significant improvement in RVEDA (P<0.001), coaptation lengths of anterior leaflets (P=0.014), tenting height (P=0.0011) and area (P=0.0074) and RV sphericity index (P=0.011) in patients with RV FAC >40%. After BCPA, the vena contracta width decreased despite no change in regurgitant area of color flow Doppler. We agree with previous studies, which attest to the superiority of vena contracta width as an assessment of TV functional competence. The regurgitant color flow jet area may be confused by changes in vascular resistance, color Doppler velocity settings, the Venturi effect and the size, loading conditions and compliance of the atrium. The present results, however, were collected only 1 month after BCPA and further study with longer follow-up may be necessary to evaluate whether the change in vena contracta width predicts more consistent improvement in color Doppler regurgitant jet area.

Coaptation Changes After TV Repair

Advances in echocardiography have enabled us to obtain more precise detail of atrioventricular valve function and mechanisms of valve dysfunction in small children. The changes in coaptation length of the tricuspid leaflets produced by BCPA, however, have not been documented to our knowledge. The present results suggest that BCPA effectively and favorably remodels the morphology of TV as a result of reduction in RV volume and RV sphericity index, leading to improved coaptation lengths of the TV leaflets. In addition, BCPA satisfactorily normalized the coaptation point of the tethered TV caused by RV volume overload after stage 1 Norwood palliation. In adult studies, mitral valve repair has been reported to alleviate tethering of mitral valves by decreasing the annular size and left ventricular volume. The present study suggests that BCPA can improve TV tethering in a morphological RV exposed to systemic vascular resistance. Preliminary data suggest that TV repair markedly improved coaptation lengths of TV in patients with HLHS. Even though the measured changes in TV coaptation length were smaller after BCPA than those after TV repair, BCPA had a favorable impact on TV apparatus.

The measurement of TV leaflet coaptation lengths may be a useful measurement in the follow-up and evaluation of TV in patients with systemic but morphological RV because the changes in TV coaptation lengths were smaller after BCPA.

Discussion

The main finding is that BCPA quantitatively improved RV and TV remodeling based on the following: (1) decreased vena contracta width; (2) decreased RV end-diastolic area, TV annular diameter and RV sphericity index; and (3) increased coaptation length in both septal and anterior leaflets and normalized coaptation points. Favorable RV and TV remodeling occurred after BCPA irrespective of preoperative RV function and regardless of whether RV-PA shunt was divided or left patent.

Changes in Degree of TR and RV Volume

After stage 1 Norwood procedure, the RV volume is loaded to a variable degree, which may lead to ventricular dilatation, decreased ventricular function and TR, especially if there are congenital abnormalities of the TV such as dysplasia and chordal tethering. Michelfelder et al reported that the rate of TV annulus dilatation exceeds the rate of normal TV annulus growth after stage 1 Norwood operation. The present study is in agreement with previous reports that the size of RV and the TV annulus decrease after BCPA in response to a decrease in ineffective pulmonary blood flow. After BCPA, the vena contracta width decreased despite no change in regurgitant area of color flow Doppler. We agree with previous studies, which attest to the superiority of vena contracta width as an assessment of TV functional competence. The regurgitant color flow jet area may be confused by changes in vascular resistance, color Doppler velocity settings, the Venturi effect and the size, loading conditions and compliance of the atrium. The present results, however, were collected only 1 month after BCPA and further study with longer follow-up may be necessary to evaluate whether the change in vena contracta width predicts more consistent improvement in color Doppler regurgitant jet area.

| Table 3. Changes in RV and TV Morphology vs. Preservation of Function |
|---------------------------------------------------------------|
| **Before BCPA** | **After BCPA** | **Before BCPA** | **After BCPA** |
| **TR grade** | 1.3±0.8 (0–3) | 1.2±0.9 (0–3) | 1.9±0.7* (1–3) |
| **Vena contracta width (mm/mm²)** | 5.9±5.4 (0–14.9) | 5.7±4.1 (0–11.1) | 3.8±4.2* (0–12.5) | 5.3±4.2 (0–11.1) |
| **RVEDA (mm²/m²)** | 2.84±509 (1567–3935) | 3.13±677 (1771–4115) | 2.51±558* (1359–3581) | 2.68±651* (1436–3514) |
| **RVESA (mm²/m²)** | 1.480±313 (700–2222) | 2.06±428 (1114–2577) | 1.37±423 (538–2370) | 1.661±466* (923–2600) |
| **RVFAC (%)** | 48.0±6.0 (40.0–57.7) | 33.9±4.2* (27.1–38.7) | 45.0±8.3 (31.0–60.4) | 38.1±7.9* (25.6–48.4) |
| **RV end diastolic annular diameter (mm/mm²)** | 58.4±7.2 (45.7–71.0) | 63.6±12.8 (45.7–88.9) | 55.7±6.4 (45.4–70.4) | 56.6±6.3* (30.2–81.5) |
| **Anterior leaflet coaptation length (mm/mm²)** | 9.4±6.5 (–3.7–25.8) | 7.8±4.5 (0–14.3) | 11.9±6.8* (–3.7–22.6) | 9.4±4.6* (0–17.7) |
| **Septal leaflet coaptation length (mm/mm²)** | 13.0±5.8 (2.1–23.3) | 14.2±4.4 (7.4–21.0) | 15.0±6.1 (3.6–36.3) | 17.1±3.7* (10.3–23.8) |
| **TV tenting height (mm/mm²)** | 7.3±4.3 (–1.6–15.4) | 6.2±4.4 (0–13.9) | 4.2±3.6* (–2.7–10.3) | 3.5±3.8* (–3.9 to 10.6) |
| **TV tenting area (mm²/m²)** | 54.1±36.7 (9.2–146.4) | 58.6±45.7 (0–151.5) | 31.4±26.8* (–15.4–84.4) | 33.8±41.3* (–39.3 to 124.2) |
| **RV sphericity index** | 0.65±0.19 (0.44–1.1) | 0.74±0.15 (0.47–1.0) | 0.62±0.15* (0.41–0.89) | 0.69±0.18* (0.40–1.0) |

Data given as mean±SD and range. *P<0.05 before BCPA vs. after BCPA; #P<0.05 RVFAC >40% vs. <40%. Abbreviations as in Table 1.
changes in coaptation length may occur before significant TR. Close evaluation and serial changes in coaptation lengths may help predict deteriorating TV function before an important decrease in RV function has occurred and provide further data to support early intervention to correct TV dysfunction.

Early Effects of Additional Pulmonary Flow on TV and RV Morphology

It is controversial whether additional sources of pulmonary blood flow are advantageous to patients undergoing BCPA. Several benefits have been reported including improved growth and may unload the single ventricle and potentially improve valve regurgitation. In the present study, similar to other reports, TV and RV morphology were similar between subjects with divided and patent shunts. Interestingly, the present study suggests that RV function (RVFAC) was better in patients with patent RV-PA shunt. Berdat et al showed that fractional shortening in patients with antegrade pulmonary blood flow was well preserved, but that fractional shortening in those without additional pulmonary flow deteriorated during follow-up after BCPA. Further follow-up until completion of total cavopulmonary surgery is required to confirm this finding.

Study Limitations

This study is retrospective and the results require validation in a prospective evaluation in a larger cohort of patients. Precise measurements of leaflet length may be confounded by leaflet stretching with different ventricular loading conditions and the cardiac cycle. It is reported that normal mitral valves may increase their length by up to 15% as a result of tension. We measured leaflet lengths only in mid-diastole and end-systole, however, to avoid these changes as much as possible. Finally, the current study was based on 2-D echocardiographic images, and conceivably more accurate information may be available from 3-D echocardiography and magnetic resonance imaging. The latter modalities, however, are not suited for frequent, routine evaluation of children despite potentially providing a deeper understanding of RV and TV function and morphology.

Conclusions

In children with HLHS following BCPA, the coaptation lengths of the anterior and septal leaflets of TV improved concomitantly with vena contracta width and RV end-diastolic area despite unchanged TR grade estimated by the area of the color Doppler regurgitant jet. This suggests that favorable RV and TV remodeling accompanies the reduction in RV volume load following BCPA.

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