Influence of Age on the Effect of Bidirectional Cavopulmonary Anastomosis on Left Ventricular Volume, Mass and Ejection Fraction

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Objectives. We sought to identify age-related differences in the ventricular response of patients after bidirectional cavopulmonary anastomosis (CPA) and to compare changes in the ventricular response among children <3 years of age who underwent CPA with that of age-matched control subjects who had a systemic to pulmonary artery shunt alone.

Background. Pre-Fontan CPA has been advocated over a systemic to pulmonary artery shunt alone in patients with a single ventricle to facilitate ventricular volume unloading and minimize risk of the Fontan operation.

Methods. Our study evaluated 23 patients who initially received a systemic to pulmonary artery shunt as an initial procedure before subsequent Fontan palliation. In eight of these patients (group I), bidirectional CPA was performed before age 3 years, and in four (group II), it was performed after age 10 years. The remaining 11 patients (group III, age and weight control group for group I) were maintained with their initial shunt until they underwent Fontan palliation. Serial echocardiographic analysis was used retrospectively to evaluate left ventricular volume and mass and systolic pump function (ejection fraction) before and after bidirectional CPA.

Results. Through 10 months of follow-up, group I patients showed significant decreases in indexed end-diastolic volume both after CPA (120 $ml/m^{1.5}$ body surface area vs. 78 $ml/m^{1.5}$, $p = 0.001$) and in comparison with values in patients in groups II and III, who showed no changes in end-diastolic volume ($p < 0.001$). Indexed ventricular mass decreased moderately after bidirectional CPA in group I (from 228 $g/m^{1.5}$ body surface area to 148 $g/m^{1.5}$) but remained unchanged in groups II and III. The differences in trends between groups I and III were significant ($p = 0.03$). Ejection fraction decreased significantly in group II versus group I patients (0.48 to 0.27 vs. 0.51 to 0.52, $p < 0.05$) after CPA. Oxygen saturation measurements before and after bidirectional CPA revealed a significant increase in group I (73% to 86%, $p < 0.001$) and a decrease in group II (82% to 73%, $p < 0.01$).

Conclusions. Bidirectional CPA facilitates ventricular volume unloading and promotes regression of left ventricular mass in younger children (<3 years) in preparation for a Fontan operation. In contrast, bidirectional CPA is of questionable value in older children as a staging procedure for Fontan palliation.

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The natural history of patients with unrepaired single ventricle is poor and is often complicated by the onset of dilated cardiomyopathy. The survival rates are <50% by age 15 years in patients who receive only palliative pulmonary artery banding or creation of a systemic to pulmonary artery shunt (1). The advent of "physiologic" separation of the systemic and pulmonary circulations for patients with tricuspid atresia by Fontan in 1969 initiated a new era in the treatment of patients with single ventricle physiology (2). With subsequent modifications, the Fontan procedure has significantly improved long-term survival among these patients (3,4).

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It is postulated that the modified Fontan procedure improves survival by reducing ventricular volume overload and mass and, possibly, by correcting the cyanosis (3,4). Unfortunately, short- and long-term mortality rates are high in patients with a single ventricle undergoing a modified Fontan procedure. These adverse results have been correlated with preoperative ventricular hypertrophy, ventricular dilation, small or distorted pulmonary arteries and very young age (4–7). Several investigators (8–11) have advocated use of the bidirectional cavopulmonary anastomosis (CPA) (bidirectional Glenn procedure) before completion of the modified Fontan operation to minimize ventricular volume overload and hypertrophy and to correct any residual pulmonary artery abnormalities.

The precise influence of the bidirectional CPA on ventricular volume and mass and its effect on ventricular function have been sparsely described, and control data in these studies are lacking (8–10,12). Although the detrimental influence of older age on myocardial contractile function after the modified Fontan operation has been documented (13), this relation has not been evaluated in patients undergoing bidirectional CPA.

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Abbreviations and Acronyms

ACE = angiotensin-converting enzyme
ANOVA = analysis of variance
AV = atrioventricular
BSA = body surface area
CPA = cavopulmonary anastomosis
LV = left ventricular

Our hypothesis was that patients >10 years of age were less likely than younger children to benefit from bidirectional CPA.

The aims of our study were to determine the effect of bidirectional CPA on ventricular volume, mass and systolic function in patients with single ventricle physiology; to determine the influence of age on these processes; and to compare these effects with values in an age- and weight-matched control group of patients who did not undergo bidirectional CPA before undergoing a modified Fontan procedure.

Methods

Study patients. Patients with single ventricle physiology have a very heterogeneous group of specific diagnoses. To minimize some of the biologic variability inherent in this type of study, we included in our analysis only patients with left ventricular (LV) morphology who initially presented with decreased pulmonary flow requiring an aortopulmonary shunt. The need for the shunt was determined by the managing cardiologist, mainly on the basis of clinical status in conjunction with the cardiac morphology and systemic oxygen saturation. The specific diagnoses are given in Table 1.

The bidirectional CPA was performed with the patient on cardiopulmonary bypass and cooled to 28°C. The procedure was performed at Texas Children's Hospital between 1989 and 1994 and consisted of anastomosis of the superior vena cava to the right pulmonary artery in an end to side fashion, along with isolation of the main pulmonary artery and concurrent takedown of the aortopulmonary shunt.

The demographic features of our patients allowed us to perform this retrospective study by classifying the patients into three groups. All three groups had single LV morphology and restrictive pulmonary blood flow requiring placement of a systemic to pulmonary artery shunt before Fontan palliation. Group I consisted of eight patients receiving bidirectional CPA at <3 years of age before Fontan palliation. Group II consisted of four patients receiving bidirectional CPA at >10 years of age as a stage to a Fontan procedure. No bidirectional CPAs were performed on any patients between 3 and 10 years of age. Group III included 11 patients receiving only a systemic to pulmonary artery shunt before undergoing a modified Fontan procedure at Texas Children's Hospital between 1990 and 1993. This group served as age- and weight-matched control subjects for group I.

Sources and methods of data collection. The patients were identified by searching the echocardiographic data base at Texas Children's Hospital. By review of the charts and the stored echocardiographic data, we obtained the cardiac diagnoses, patient weight at the time of the echocardiograms, the location, type and diameter of the systemic to pulmonary artery shunt, systemic oxygen saturation levels before and after bidirectional CPA, as well as age at the time of CPA and Fontan palliation.

Table 1. Diagnoses, Prior Surgical Procedures and Patient Weights at Echocardiography in the Three Groups of Patients With a Single Left Ventricle and Restricted Pulmonary Blood Flow

	Group I (CPA <age 3 yr) (n = 8)	Group II (CPA >age 10 yr) (n = 4)	Group III (no CPA) (n = 11)
Age (yr at time of CPA)	1.4 ± 1.0	12.2 ± 2	NA
Type/size of shunt*			
5 mm	8	4	11
4 mm	0	0	1
W-C	1	1	0
Classic BT	1	0	1
Diagnosis			
TA	5	1	3
DILV with PVS	0	2	2
TGA with PVS/hypo RV	1	0	1
PA with IVS	3	1	5
Weight (kg) at time of echo			
Echo 1	7.2	—	5.1
Echo 2	9.3	68	7.0
Echo 3	9.5	71	—
Echo 4	12	73	9.1

*Some patients received more than one shunt. Unless otherwise stated, data presented are mean value ± SD or number of patients. BT = Blalock-Taussig shunt; CPA = bidirectional cavopulmonary anastomosis; DILV = double-inlet left ventricle; Echo = echocardiogram; hypo = hypoplastic; IVS = intact ventricular septum; NA = not applicable; PA = pulmonary atresia; PVS = pulmonary valve stenosis; RV = right ventricle; TA = tricuspid atresia; TGA = transposition of the great arteries; W-C = Waterston-Cooley shunt.

Echocardiographic data. We retrospectively analyzed all patients who satisfied the preceding criteria. Because of inadequate echocardiographic data, we excluded from our analysis one patient from group I and two patients from group III.

Ventricular volumes (Fig. 1) were measured from stored raw echocardiographic data obtained in all three groups. Echocardiographic studies were obtained in all but one group I patient two times before as well as two times after bidirectional CPA. The other patient had two echocardiographic studies before and one study after CPA just before undergoing Fontan palliation. Group II patients underwent an echocardiographic study one time before as well as two times after CPA. Among control group patients (group III), who did not undergo CPA, all but one patient underwent three echocardiographic studies before Fontan palliation; these studies corresponded temporally to the first, second and fourth echocardiograms in group I patients. The remaining patient underwent two echocardiographic studies before Fontan palliation that corresponded to the first and fourth echocardiograms of group I.

Using both a modified biplane Simpson's and a "bullet"

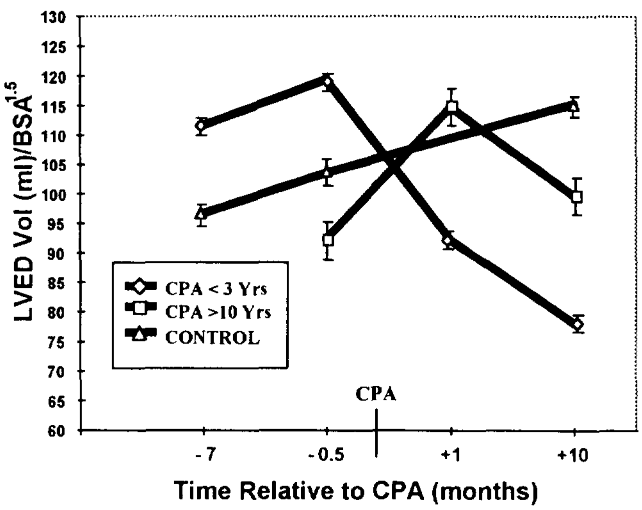

Figure 1. Left ventricular end-diastolic volume (LVED Vol) indexed to (body surface area)$^{1.5}$ (BSA$^{1.5}$). Group I, patients **(diamonds)** undergoing bidirectional cavopulmonary anastomosis (CPA) before 3 years of age as a stage to a Fontan procedure had echocardiographic examinations at 7 ± 4 months and 0.5 ± 0.5 month before and 1 ± 0.5 month and 10 ± 6 months after CPA. Group II patients **(squares)**, who underwent CPA after 10 years of age, had echocardiograms 1.3 ± 3 months before undergoing CPA, and 1 ± 0.5 month and 9.5 ± 4.3 months after CPA. Group III patients **(triangles)**, who did not undergo CPA, underwent three echocardiographic studies that corresponded (with regard to body weight) to the 7-month and 0.5-month studies obtained before CPA in group I, and with the study obtained 10 months after CPA in group I, just before Fontan palliation was performed.

technique (14), we digitized (Digisonics Inc. 1992) LV volume and mass using the apical, subcostal, and parasternal short-axis views obtained from two consecutive diastolic still frames, which were averaged. After the appropriate frames were chosen, two observers independently used both methods to measure LV volume and mass in 10 randomly chosen patients; the remainder of the studies were measured by one of us (T.J.F.). The modified Simpson's method yielded more consistent measurements with less intergroup and intragroup variability (r = 0.90 and r = 0.92, respectively). Ventricular volume and mass were indexed to the patient's (body surface area [BSA])$^{1.5}$, as this exponent has been shown (15) to most closely represent a linear relation between the patient's BSA and ventricular volume and mass. In all but two patients (both in group I), the subcostal views were used to obtain LV volume measurements. In the other two patients, the four-chamber apical view was used. The same view was used to obtain ventricular volume and mass measurements within each patient series. In patients who had a remnant right ventricle, that ventricle was not incorporated into our volumetric measurements. However, the entire ventricular septum was incorporated into our ventricular mass measurements. Ventricular volumes and mass were compared with those of children with normal anatomy by calculating a Z score for our study group. The Z score represents the variance in SD from the mean, with a Z score of 0 equaling no variance from the mean in a group with normal biventricular anatomy. In addition, the severity of atrioventricular (AV) and aortic valve regurgitation was determined by measuring the vena contracta from the apical and parasternal long-axis views and averaging the results (16).

Statistical analysis. Numeric data are expressed as mean value ± SD. Statistically significant differences within each of the three groups were determined by analysis of variance (ANOVA) and paired t tests, whereas intergroup comparisons were calculated with nonpaired t tests. Intergroup and intragroup comparisons reached statistical significance at $p < 0.05$.

Results

Patients in groups I and III were similar in terms of diagnosis, shunt size and weight at the time of the echocardiographic studies (Table 1). As part of our study design, patients in group II were older and larger than patients in the other two groups at the time of bidirectional CPA and Fontan palliation.

Ventricular volumes (Fig. 1) were measured from stored raw echocardiographic data in group I patients 7 ± 3 months and 0.5 ± 1 month before as well as 1 ± 0.5 month and 10 ± 3 months after bidirectional CPA. The older group II patients underwent echocardiography 1.2 ± 3 months before as well as 1 ± 0.5 month and 9.5 ± 4.3 months after CPA. Patients in the control group (group III), who did not undergo CPA, underwent three echocardiographic studies that were performed at 1 ± 0.5, 10 ± 5 and 23 ± 12 months of age; these ages corresponded to those of group I patients when they underwent their first, second and fourth echocardiograms.

Effect of bidirectional CPA on ventricular volume. Use of bidirectional CPA in the younger patients (group I) resulted in a progressive and significant decrease in indexed LV end-diastolic volume that persisted throughout the 10-month postoperative study period (Fig. 1, $p < 0.02$). In contrast, after CPA in older patients (group II), end-diastolic volume showed a significant early increase and remained increased 10 months postoperatively (Fig. 1). The effects of CPA on LV volumes were statistically different ($p < 0.02$) between groups I and II at 10 months after CPA. Group III patients, who received only an aortopulmonary shunt before Fontan palliation, had a progressive increase in end-diastolic volume (Fig. 1). Indexed end-diastolic volume in groups I and III diverged significantly, progressively decreasing in group I patients after CPA but showing an upward trend throughout the study in group III (Fig. 1, $p < .001$).

To further evaluate the effect of bidirectional CPA, we computed Z scores for LV end-diastolic volumes in the three groups, using a data base of age- and weight-matched children who had normal biventricular cardiac anatomy for reference values (Fig. 2). In this analysis, CPA reduced LV end-diastolic volume in the younger patients (group I) from a mean Z score of 4.0 to a score of <1.4 at 10 months after CPA, a value that is within the normal reference range. In contrast, LV end-diastolic volume Z scores increased postoperatively in the older patients (group II), remaining nearly 5 Z scores above the predicted mean for normal children. Group III patients

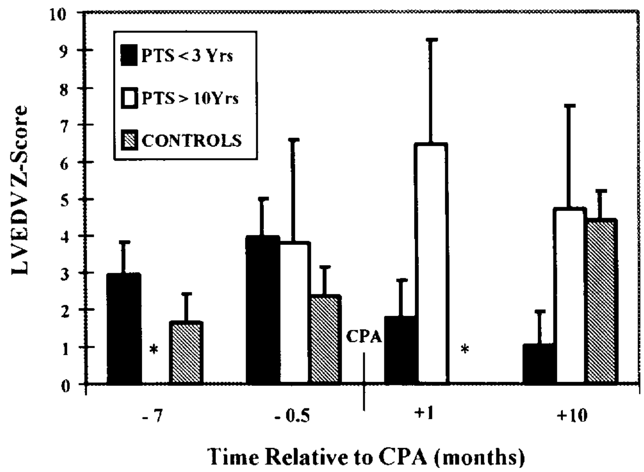

Figure 2. Left ventricular end-diastolic volume as indexed by Z scores (LVEDVZ-score) in groups I (**solid bars**), II (**open bars**) and III (**hatched bars**). The timing of the measurements in the three groups relative to bidirectional cavopulmonary anastomosis (CPA) was the same as in Figure 1. *Echocardiographic study not obtained for that group at the time period shown. PTS = patients.

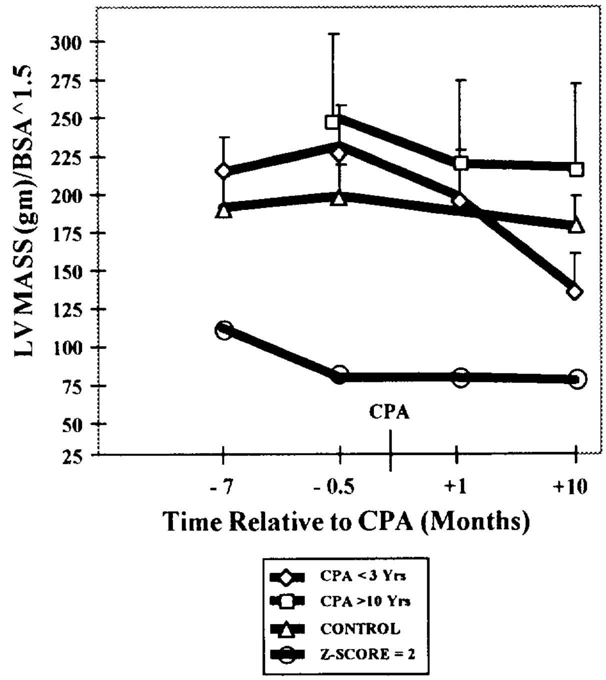

Figure 3. Left ventricular (LV) mass indexed to (body surface area)$^{1.5}$ (BSA$^{1.5}$) in groups I (**diamonds**), II (**squares**) and III (**triangles**). The timing of the measurements in the three groups relative to bidirectional cavopulmonary anastomosis (CPA) was the same as in Figure 1. **Circles** = 2 SD in indexed LV mass above the mean in children with normal biventricular anatomy (Z = 2.0).

showed a progressive increase in indexed LV end-diastolic volume by Z score analysis (Fig. 2).

Effect of bidirectional CPA on ventricular mass. The use of bidirectional CPA in the younger patients (group I) was associated with a progressive decrease in indexed LV mass for the 10-month postoperative period of observation ($p = 0.09$, Fig. 3). In group II patients, indexed LV mass decreased early postoperatively, remaining unchanged at 10 months after CPA (p = NS, Fig. 3). These potentially important differences in the intergroup trends between groups I and II did not reach statistical significance ($p = 0.1$). The LV mass of the control patients (group III), who did not undergo CPA, remained constant throughout the study period (p = NS, Fig. 3). The differences in indexed LV mass trends between groups I and III were significant ($p = 0.03$). Comparisons of LV mass in the three groups as they related to the upper limits for children with normal biventricular cardiac anatomy (signified as Z score = 2 in Fig. 3) showed that values in group I patients decreased toward but never reached normal ranges after CPA, whereas values in groups II and III remained significantly above the mean for normal children throughout the study period.

Effect of bidirectional CPA on ejection fraction. Ejection fraction did not change significantly in group I patients after bidirectional CPA (Fig. 4). However, it decreased significantly immediately postoperatively ($p = 0.02$) in the older patients (group II), increasing toward preoperative levels 10 months after the procedure. Ejection fraction was significantly lower in group II patients than in group I patients both immediately and 10 months postoperatively ($p < 0.05$). It remained unchanged throughout the study in group III patients, who did not undergo CPA (Fig. 4). Although ejection fraction in group III graphically appeared to be consistently higher than that in group I, it was not significantly different from group I values at the time of Fontan palliation ($p = 0.2$).

Effect of bidirectional CPA on systemic oxygen saturations. As Table 2 depicts, group I systemic oxygen saturations (obtained a mean of 1.5 months before and 1 week after bidirectional CPA) increased significantly ($p < 0.001$) after CPA. In contrast, systemic oxygen saturations in group II

Figure 4. Ejection fraction in groups I (**diamonds**), II (**squares**) and III (**triangles**). The timing of the measurements in the three groups relative to the bidirectional cavopulmonary anastomosis (CPA) was the same as in Figure 1.

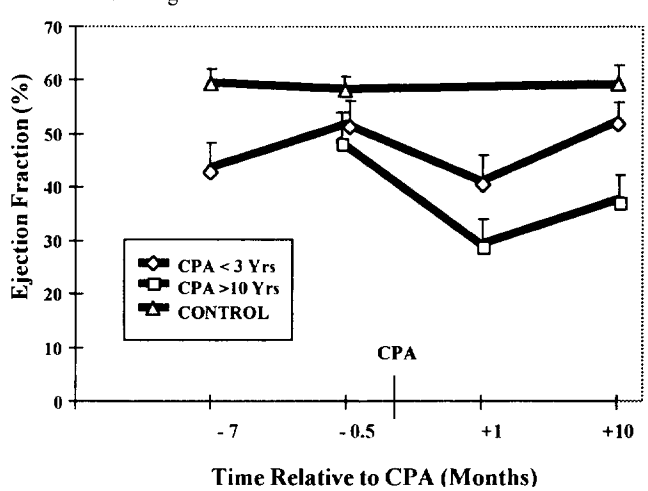

Table 2. Oxygen Saturations and Eventual Outcomes for the Three Patient Groups

	Group I (CPA <age 3 yr)	Group II (CPA >age 10 yr)	Group III (No CPA)
Oxygen saturations			
Before CPA	73.4 ± 3.4	82 ± 4.7	74 ± 5.1*
After CPA	83 ± 11.4	72.5 ± 2.1	76 ± 4.3*
Eventual outcome			
Received Fontan procedure	6	2	10
Referred for heart transplantation	2	1	0
Awaiting Fontan procedure	0	1	1

*Oxygen saturations in group III were obtained from the time periods corresponding to those of group I measurements before and after CPA. Data presented are mean value ± SD or number of patients. CPA = bidirectional cavopulmonary anastomosis.

(obtained a mean of 2.1 months before and 1 week after CPA) decreased significantly after CPA ($p = 0.009$). Oxygen saturations in group III did not change significantly throughout the study period. Intergroup comparisons between groups I and II and I and III were significant ($p < 0.001$).

Effect of bidirectional CPA on AV valve regurgitation. There were no significant differences in AV valve regurgitation between the three groups throughout the study period. The degree of regurgitation did not progress significantly in any patient during the study period.

Discussion

Previous studies. Patients with single LV physiology commonly experience progressive impairment of systolic function. Clinical data (17–19) had suggested an association between systolic and diastolic dysfunction and volume overload–induced increases in ventricular wall stress, subsequently causing cardiac hypertrophy. In turn, these factors have been associated with increased early and late postoperative morbidity and added mortality after a modified Fontan procedure. (5–7,19). Several investigators (20–22) have suggested that performing a Fontan operation at an earlier age minimizes volume overload and the subsequent development of hypertrophy, which often results from the initial shunting procedure. In addition, many studies (4,23) have noted younger age (<4 years) as a significant risk factor for nonsurvival after a modified Fontan procedure, with cited mortality rates as high as 36% in the early postoperative period, increasing to 54% at 10 years.

Bidirectional CPA has been increasingly used as a pre-Fontan staging procedure in patients who are at higher risk for undergoing a modified Fontan procedure because of abnormalities in ventricular function (both systolic and diastolic), mild elevation of pulmonary vascular resistance, significant AV valve regurgitation and young age (8–11). The guiding principle has been that bidirectional CPA reduces ventricular volume and mass, thereby preserving ventricular function and reducing patient risk factors for early postoperative and long-term survival after a modified Fontan operation. Bidirectional CPA has been shown (24) to decrease postoperative pleural effusions in patients undergoing completion of their Fontan operation and to improve survival in patients awaiting a stage III Norwood procedure (11). However, there are few data documenting its effects on ventricular volume, mass or function. Two recent publications (10,12) showed a modest decrease in volume and mass after bidirectional CPA, although no control data were provided.

Effect of bidirectional CPA on LV volume. Our data demonstrate clearly that ventricular volume decreases soon after a young patient with a single ventricle undergoes bidirectional CPA. The response appears to be sustained, at least during the initial 10 months after the procedure. This is not simply the natural history of these patients at this age, as demonstrated by previous studies (18,25) and by the progressive increase in LV volume observed in our weight-matched control subjects (group III), who did not undergo CPA before Fontan palliation.

Our data indicated that the beneficial effect of bidirectional CPA on LV volume appears to be age dependent. In patients undergoing CPA at <3 years of age (group I), LV end-diastolic volume was significantly reduced immediately after the procedure and by 10 months postoperatively had decreased to within 2 SD from the mean in children with normal biventricular anatomy. This effect was not demonstrable in patients >10 years of age (group II). This observation is consistent with the study of Sluysmans et al. (13), which noted a decrease in LV volume in three patients who underwent CPA before age 10 years but no change in end-diastolic volume in two patients who underwent the procedure after age 10 years. As we encountered no patients between 3 and 10 years of age in our study, the age range when the impact of CPA changes from beneficial to limited or possibly detrimental is unknown. Although we observed ventricular volumes decreasing to within normal ranges in the younger patients 10 months after CPA, the link between volume and performance is yet to be clearly established for single ventricle physiology.

Effect of bidirectional CPA on left ventricular mass. The trends in LV mass paralleled those of end-diastolic volume. This result reflects the relations wherein volume influences wall stress, thereby affecting mass. Group I patients showed a progressive decrease in mass after bidirectional CPA, whereas group II showed no appreciable changes in mass. This finding is consistent with previous reports (13,17) noting a decrease in wall stress and ventricular hypertrophy in patients undergoing Fontan palliation before 10 years of age, whereas wall stress was observed to increase postoperatively in patients undergoing Fontan palliation after age 10 years. Although we did not specifically quantitate wall stress, our results indirectly corroborate previous reports (13) of gradually decreasing wall stress among younger patients undergoing Fontan palliation. In group III patients, LV mass progressively increased through-

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out the study period, a finding consistent with the progressive volume overload observed in patients with a shunt (18,25).

There were no differences in medical therapy (particularly, use of angiotensin-converting enzyme [ACE] inhibitors) in the three patient groups before Fontan palliation was performed. We currently use ACE inhibitors in all patients with single ventricle. Although our study did not address the role of ACE inhibition in potentially minimizing the development of ventricular hypertrophy in the patient with single ventricle, future double-blind studies could provide data that would clarify the role of ACE inhibition in such patients.

Effect of bidirectional CPA on ejection fraction. We detected no significant change in the ejection fraction before or after bidirectional CPA in the younger patients (group I), suggesting that the operation in itself does not influence LV function. In contrast, ejection fraction in group II patients decreased significantly very soon after CPA but returned toward preoperative levels 10 months later. Our data suggest that before age 3 years, the ventricle is able to tolerate both operative cardiac bypass as well as the immediate decrease in preload. This observation raises the question of optimal timing for performing the Fontan procedure after CPA.

Our older patients did not respond with any appreciable decrease in ventricular volume or mass after bidirectional CPA. One can postulate that the increase in ventricular mass in older patients has altered the usual compliance features of the ventricle, whose stroke volume becomes dependent on elevated preload to maintain adequate ventricular function. This balance apparently is immediately disturbed after CPA. Additionally, the significant decrease in oxygen saturation observed in the older patients (Table 2) results in a relatively increased degree of myocardial hypoxia, which may lead to the ventricular dysfunction observed after CPA. Finally, the stress of bypass may also have contributed to the immediate reduction in ventricular function observed in the older patients.

The preoperative indexed LV mass in the older patients (group II) was only minimally greater that in the younger patients (group I). This finding suggests that the often referenced adverse influence of mass on survival of patients with a single ventricle after a Fontan procedure may relate more to the type of cell in the myocardium than to the process of cardiac thickening. For example, fibroblast proliferation and increased collagen deposition have been demonstrated in several animal and human models of hypertrophy and cardiomyopathy (26). In combination with the limited postoperative ventricular remodeling seen in our older patients, this observation implies that bidirectional CPA has a dubious role in patients >10 years of age. The effects on morbidity and mortality of CPA on outcome of the Fontan procedure are currently being evaluated (manuscript in preparation).

Effect of bidirectional CPA on systemic oxygen saturations. The significant decrease in systemic oxygen saturations observed in the older group after bidirectional CPA is consistent with previous reports. The relative decrease in venous return through the superior vena cava (and thus the pulmonary bed), combined with the increase in inferior vena cava blood flow as the patient's body surface area increases, is thought to be the origin of the cyanosis (8,27).

Study limitations. There are inherent difficulties in attempting to measure volume and mass in any cardiac chamber, especially in a single LV. Because intragroup and intergroup comparisons correlated, and data trends in a patient series were emphasized rather than absolute volumes, this potential limitation was reduced. Furthermore, our volume and mass measurements were based on an assumed ventricular geometry, for which volume and mass calculations may not be strictly applicable. Nonetheless, we believe that our assumptions remain reasonable, especially when applied as serial studies in the same patients. Our results apply exclusively to patients with single LV physiology and initially reduced pulmonary blood flow. We cannot determine their applicability to the effect of bidirectional CPA in patients who underwent pulmonary artery banding after having initially increased pulmonary blood flow or in patients with single right ventricle physiology.

Another potential limitation to our study was the use of ejection fraction (a load-dependent measurement of systolic function) to evaluate LV performance in our patients. Because our study was retrospective, load-independent measures (wall stress analysis) of ventricular function were not available. However, even if wall stress analysis had been available, many investigators would challenge the validity of absolute data obtained with such analysis because the application constraints of the model (nonspheric short-axis geometry and frequent dyskinetic wall motion) are violated when contractility is assessed in hearts with a single ventricle. Future prospective studies analyzing longitudinal changes in wall stress trends within a patient series may be an important addition to the current data.

Conclusions. Use of bidirectional CPA facilitates LV volume unloading and mass regression in children <3 years of age with single ventricle physiology and initially restrictive pulmonary flow. This procedure can be performed in these patients without impairing ventricular function. These changes are progressive and suggest that completion of the Fontan circulation in selected patients can be delayed at least 10 months after bidirectional CPA. Additional follow-up is required to establish whether volume and mass continue to decrease after 10 months and whether these data are applicable to patients with other types of single ventricle anatomy and physiology. We could detect no benefit in performing CPA in patients older than 10 years. This finding suggests that older patients may be better managed with alternative approaches, perhaps by early triage toward heart transplantation before overt heart failure develops.

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