Quantification of ventricular unloading by 3D echocardiography in single ventricle of left ventricular morphology following superior cavo-pulmonary anastomosis and Fontan completion – a feasibility study

Deepa Sasikumar, Bijulal Sasidharan, Baiju S Dharan[1], Arun Gopalakrishnan, Kavasseri M Krishnamoorthy, Sivasubramanian Sivasankaran

Departments of Cardiology and [1]Cardiothoracic Surgery, Sree Chitra Tirunal Institute for Medical Sciences and Technology, Thiruvananthapuram, Kerala, India

ABSTRACT

Background : **Three-dimensional echocardiography (3DE) is comparable to cardiac magnetic resonance imaging for estimating ventricular volume in congenital heart diseases. However, there are limited data on estimation of ventricular volumes by 3DE in univentricular heart and change in ventricular volumes after surgical creation of cavopulmonary connection. We sought to quantify the unloading of the single ventricle of left ventricular (LV) morphology by 3DE after superior cavopulmonary anastomosis (SCPA) or Fontan operation over a period of 3 months and thereby derive a preliminary 3DE data set on this patient subset.**

Patients and Methods : **Eighteen patients with functional single ventricle of LV morphology, who underwent SCPA or completion of Fontan circulation, were included in the study. Volume of the ventricle was estimated by 3DE before surgery and after surgery (in the early postoperative phase and 3 months after surgery), and indexed end-diastolic volume (EDV), end-systolic volume (ESV), and ejection fraction (EF) were derived.**

Results : **Twelve patients underwent SCPA and six patients underwent staged completion of Fontan circulation. Before surgery, EDV was similar in both groups. There was a significant fall in EDV immediately after SCPA (from 48.3 ± 14.9 ml/m^2 to 39.5 ± 12.3 ml/m^2). However, EDV increased at 3 months' follow-up to 41.3 ± 10.5 ml/m^2. There was no significant fall in EDV immediately after Fontan operation (47.2 ± 10.1 ml/m^2–46.6 ± 14.2 ml/m^2), but EDV continued to fall at 3 months of follow-up (44.7 ± 10 ml/m^2). There was no significant change in ESV in either group, but EF fell significantly after SCPA.**

Conclusions : **We provide preliminary information on 3DE volume data of single ventricle of LV morphology and the pattern of unloading after SCPA and Fontan operation. Immediate significant volume unloading occurred after SCPA which tended to catch-up after 3 months, whereas continued fall in ventricular volume with time was noted after Fontan.**

Keywords : Fontan operation, single ventricle, superior cavopulmonary anastomosis, three-dimensional echocardiography

Access this article online

Quick Response Code:

Website: www.annalspc.com

DOI: 10.4103/apc.APC_12_17

How to cite this article: Sasikumar D, Sasidharan B, Dharan BS, Gopalakrishnan A, Krishnamoorthy KM, Sivasankaran S. Quantification of ventricular unloading by 3D echocardiography in single ventricle of left ventricular morphology following superior cavo-pulmonary anastomosis and Fontan completion – a feasibility study. Ann Pediatr Card 2017;10:224-9.

Address for correspondence: Dr. Bijulal Sasidharan, Department of Cardiology, Sree Chitra Tirunal Institute for Medical Sciences and Technology, Thiruvananthapuram, Kerala, India. E-mail: bijulalsasidharan@gmail.com

INTRODUCTION

Assessment of ventricular volume and ventricular function in congenital heart disease is fraught with difficulties. Two-dimensional echocardiographic (2DE) assessment has significant limitations due to the geometrical assumptions of ventricular shape, which can lead to errors in assessment of ventricular volume in complex congenital heart diseases.[1,2] The gold standard for assessment of ventricular volume is cardiac magnetic resonance imaging (CMR),[3] which requires general anesthesia and is time consuming in the pediatric age group. In various studies, in patients with good acoustic window, 3DE was shown to provide volumetric data comparable to CMR[4]. However, normative 3DE values for ventricular volumes in children are limited to data from a few studies.[5,6,7]

The benefit of palliative surgeries in univentricular heart (superior cavopulmonary anastomosis [SCPA] and Fontan operation) is dependent to a large extent on the magnitude of ventricular unloading. Accurate assessment of ventricular volumes before and after surgery can be done by 3DE. However, there are very few studies, which estimated the volume of single ventricle by 3DE and compared it with CMR,[8,9,10] and no 3DE database exists for the changes in ventricular volumes following SCPA and Fontan operation. If such a 3DE database could be established, it would obviate the need for CMR and help future applications of 3DE in congenital heart disease. Therefore, this study was undertaken in a homogeneous subset of patients with single ventricle of left ventricular (LV) morphology, to quantify by 3DE the changes in ventricular volume and function following SCPA and Fontan operation.

PATIENTS AND METHODS

Patients with functional univentricular heart of LV morphology and pulmonary stenosis (tricuspid atresia with ventricular septal defect and pulmonary stenosis, single ventricle of LV morphology and pulmonary stenosis, and pulmonary atresia with intact ventricular septum [PAIVS]) were chosen to minimize variability in baseline values and variability in volume reduction after surgery. Eighteen patients with functional single ventricle of LV morphology who underwent SCPA or completion of Fontan circulation between January 2014 and December 2014 were prospectively studied. Patients with associated cardiac conditions predisposing to ventricular volume overload (aortopulmonary shunts, large aortopulmonary collaterals, and significant regurgitation of atrioventricular or semilunar valves) were excluded from the study. Patients requiring prolonged inotropic support after surgery and those patients with poor acoustic window were also excluded from the study. Informed consent was obtained from the parent/guardian/child as appropriate. This study was approved by the Institutional Ethical Committee.

Three-dimensional echocardiography

Echocardiography was performed by an experienced echocardiographer. After initial 2DE study, full-volume 3D image-gated data acquisition (five beats) was performed from apical four chamber view (Philips IE33, Philips Ultrasound Ltd., WA, USA) with a matrix array transducer (X5-1, X7-2). Children were sedated with oral chloral hydrate if they were not quiet during the study. Ventricular volumes and ejection fraction (EF) were measured off-line by summation of disc methodology with dedicated software. The data set was aligned in two orthogonal planes along the long axis of the ventricle with clear depiction of the mitral valve and the apex. End diastole was chosen as the largest chamber size and end systole as the smallest chamber size. Atrioventricular valve closure and opening also were noted, to improve delineation of end diastole and end systole. End-diastolic volumes (EDVs) and end-systolic volumes (ESVs) were measured thrice, and the average of the 3 values was selected and was indexed to body surface area (BSA) [Figure 1]. Changes in ventricular volume and function were assessed by 3DE 5–7 days after surgery and 3 months after surgery. Statistical analysis was done using the SPSS software program (version 21.0; SPSS Inc., Chicago, IL, USA). Continuous variables were expressed as mean ± standard deviation (SD) or median and range. Comparison between groups was analyzed using paired *t*-test. $P < 0.05$ was considered statistically significant.

RESULTS

Eighteen patients who satisfied the inclusion and exclusion criteria were included in the study. Twelve

Table 1: Baseline characteristics of patients who underwent superior cavopulmonary anastomosis and Fontan operation

Characteristics	Superior cavo-pulmonary anastomosis, *n*=12	Fontan operation, *n*=6
Age (years)	1.9 (0.3-5.3)	10.9 (8.7-17.3)
Females	7	5
BSA (ml/m^2)	0.4 (0.29-0.63)	1.1 (0.89-1.4)
Diagnosis	Pulmonary atresia, intact ventricular septum – 3 Tricuspid atresia, VSD, severe PS – 8 Single ventricle (LV), severe PS-1	Tricuspid atresia, VSD, severe PS, post SCPA – 3 Single ventricle (LV), severe PS, post SCPA -3

BSA : Body surface area, LV :left ventricle, PS :Pulmonary stenosis, SCPA: superior cavo-pulmonary anastomosis, VSD: Ventricular septal defect patients underwent SCPA and six patients underwent completion of Fontan circulation. Clinical and demographic data are provided in Table 1. Median age of patients who underwent SCPA was 1.9 years (range of 0.3–5.3 years) and Fontan operation was 10.9 years (range 8.75–17.3 years).

Preoperative indexed EDV was comparable in patients undergoing SCPA (48.3 ± 14.9 ml/m^2) and Fontan completion (47.2 ± 10.1 ml/m^2, P = 0.7). Preoperative indexed ESV was comparable in patients undergoing SCPA (18.5 ± 7.1 ml/m^2) and Fontan completion (19.4 ± 8.3 ml/m^2, P = 0.7).

Change in ventricular volume after superior cavopulmonary anastomosis

There was a significant fall in indexed EDV immediately after SCPA (39.5 ± 12.3 ml/m^2; P = 0.01). On 3 months' follow-up, there was increase in EDV, which was still lower compared with presurgical volume (41.3 ± 10.5 ml/m^2; P = 0.07) [Figure 2]. The changes in EDV after SCPA were similar in children <2 years of age and above 2 years of age.

ESV remained essentially unchanged in the immediate postoperative period (18.5 ± 7.1–17 ± 4.7) (P = 0.2) and 3 months after SCPA (18.4 ± 4.2) (P = 0.97); consequent to this, there was a significant fall in EF after SCPA, which persisted at 3 months' follow-up (P = 0.001) [Figure 3]. Changes in ESV and EF after SCPA were similar for children <2 years of age and >2 years of age (P = 0.9, 0.57, and 0.3 respectively).

Change in ventricular volume after Fontan operation

Although the reduction in EDV was not significant immediately after Fontan operation (46.6 ± 14.2 ml/m^2; P = 0.8), volumes decreased serially from presurgical values in Fontan patients at 3 months' follow-up (44.7 ± 10 ml/m^2; P = 0.4). Similar unchanged ESVs were observed immediately after Fontan operation (20.8 ± 7.4 ml/m^2; P = 0.3) and after 3 months (20.9 ± 5.3 ml/m^2; P = 0.5). There was nonsignificant fall in EF after Fontan completion. EF reduced from preoperative value of 60.1% ± 9.3% to 53.3% ± 4.6% after 3 months (P = 0.15) [Figure 3].

Among the subsets of univentricular hearts, least reduction in postoperative volumes was observed in children with PAIVS.

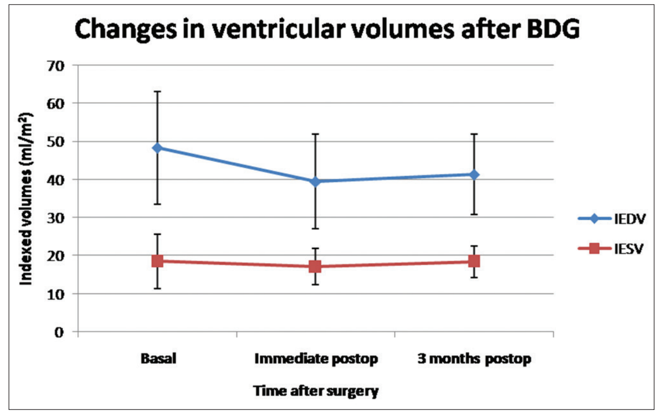

Figure 1: Graph showing the changes in indexed end-diastolic and end-systolic volumes after bidirectional Glenn

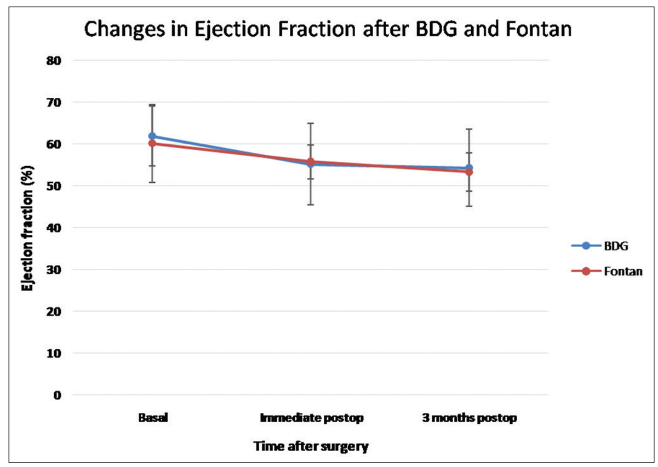

Figure 2: Graph showing the changes in ejection in fraction following bidirectional Glenn and Fontan

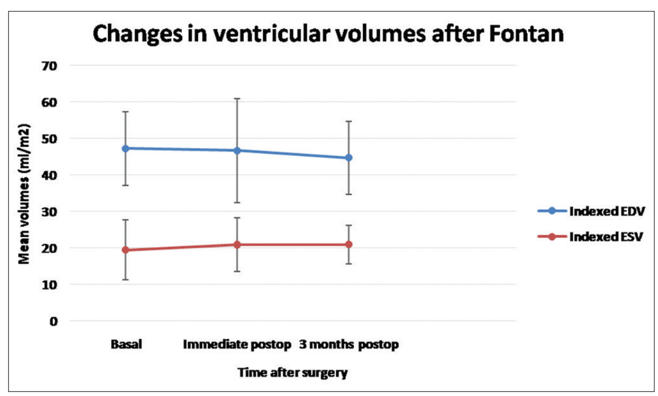

Figure 3: Graph showing the changes in indexed end-diastolic and end-systolic volumes after Fontan

DISCUSSION

3DE reference values for normal LV volumes are yet to be derived for diverse population groups; in preliminary studies, values for normal EDV calculated from 3DE range between 50 and 66 ml/m^2 and ESV range between 19 and 29 ml/m^2.[1] 3DE and CMR data for normal ventricular volumes in children <18 years are limited. In a study that attempted to establish normal values for chamber volumes by 3DE in children, the EDV ranged from 50.1 ml/m^2 for children having BSA 0.5–0.75 m^2 to 64.4 ml/m^2 for children with BSA >1.5 m^2. The ESVs ranged from 19.9 to 26.6 ml/m^2, respectively.[11] In a similar study that attempted to formulate normative ventricular volume values for children by CMR, the mean LVEDV was 77.5 ml/m^2 for male children and 67.8 ml/m^2 for female children (SD 0.04) while LVESV was 29.7 ml/m^2 for male children and 26.1 ml/m^2 for female children (SD 0.06).[12] Biplane angiograms have shown that univentricular hearts have 110% of normal ventricular volumes (EDV index ranged from 72 to 282 ml/m^2 (average 131 ml/m^2).[13]

Chamber volumes estimated by 3DE, though comparable to values estimated by CMR, have consistently been shown to be less than CMR-obtained values.[8] In a study that assessed single ventricle volumes (both single right and left ventricle) by 3DE and compared it to CMR, the mean EDV was 41.4 ± 22.7 ml/m^2; mean ESV was 19.9 ± 12.1, and the values were comparable to those derived from CMR.[14] In another study that assessed ventricular volumes of 32 children with functional single left ventricle by 3DE and CMR, the average LV EDV was 23.78 ± 10.99 ml, LV ESV of 11.19 ± 4.89 ml,[7] which when corrected for BSA were within the range of normal LV volumes.

In our cohort of patients who underwent SCPA, presurgical EDV was 48.3 ± 14.9 ml/m^2 and ESV was 18.5 ± 7.1 ml/m^2, which falls within the normal described range. Although we did not find significant volume overload in our single ventricle patients before SCPA, the LV volumes are notably higher than those derived in another 3DE study on children with left-sided obstructive lesions (EDV 13.1 ± 9.8 ml and ESV 7.1 ± 4.5 ml).[14]

We noticed a significant fall in indexed EDV soon after SCPA (39.5 ± 12.3 ml/m^2; $P = 0.001$), but at 3 months' follow-up, EDV rose to 41.3 ± 10.5 ml/m^2 ($P = 0.08$). Most studies show a significant volume unloading of the ventricle after SCPA,[15] but initial fall and later rise in volumes have also been noted.[16-20] This is hypothesized to be due to blood flow redistribution to head and neck vessels causing compensatory increase in total blood volume, adaptive response of the ventricle to chronic hypoxia, and development of aortopulmonary collaterals contributing to volume overload.[16,21] We found that ESV remained unchanged after SCPA, resulting in significant decrease of EF immediately after surgery (61.9% ± 7.1% reduced to 55.2% ± 9.7%) ($P = 0.002$) and at 3 months (54.3% ± 9.2%) ($P = 0.001$). This is in contrast to previous studies, which showed reduction in ESV with preservation of EF after SCPA.[15] Our study population were older than the usual age of SCPA (due to logistic reasons), and this could have contributed to altered hemodynamics.

A study on effect of age on SCPA showed that SCPA promotes significant ventricular volume unloading and regression of LV mass in younger children (<3 years) compared to older children (120 ml/m$^{1.5}$ BSA vs. 78 ml/m$^{1.5}$, $P = 0.001$).[22] All the children in that study had undergone systemic to pulmonary artery shunt before SCPA. In our study, there was no significant difference in ventricular volume unloading between children <2 years ($n = 6$) and children >2 years ($n = 6$) of age ($P = 0.2$). None of the children in our study group had a prior systemic to pulmonary artery shunt, which might explain the lack of influence of age on volume reduction in our study.

SCPA and Fontan have been shown to have inferior effect on contractility in patients with PAIVS when compared to those of patients with tricuspid atresia.[23] This is proposed to be due to the high-pressure right ventricle which impairs the LV performance of patients with PAIVS. Three patients in our SCPA group had PAIVS. There was a less reduction in volume of single ventricle in these patients, which was not statistically significant.

All our patients in the Fontan group had undergone prior bidirectional Glenn procedure. Studies have shown that volume reduction with prior SCPA leads to improved ventricular energetics after Fontan.[18,24] The basal EDV in the six patients who underwent Fontan operation was 47.2 ± 10.1 ml/m^2 and ESV was 19.4 ± 8.3 ml/m^2, which was similar to that of the patients before SCPA, indicating that the volume reduction after SCPA does not persist up to Fontan completion. We also found that there was no significant volume unloading after Fontan completion though EDV continued to fall at 3 months' follow-up. ESV and EF remained relatively unchanged after Fontan. The significant fall in EF after SCPA was not noted in the Fontan subset. Our findings contrasted with that of a study of 35 patients with functional single ventricle at various stages of Fontan reconstruction who underwent angiographic and CMR assessment of ventricular volumes pre-Fontan, post-hemi-Fontan, and post-Fontan, in which no significant volume changes were noted 6–9 months after hemi-Fontan, though there was significant volume unloading 1–2 years after Fontan.[18] In our study, the median age of patients undergoing Fontan procedure (10.9 years) was higher than in other studies. It has been postulated that significant volume unloading may not be seen if there was preexisting chronic volume overload, perioperative myocardial damage, or prolonged cyanosis, and these factors could have resulted in delayed ventricular remodeling in our study group and the unloading may take longer time.

Our study is the first to assess the change of ventricular volumes by 3DE in single ventricle of LV morphology with pulmonary stenosis following SCPA and Fontan. The baseline volumes were similar to that of 3D- and CMR-derived volumes of univentricular hearts of LV morphology in other studies.[7] SCPA showed better volume reduction in the immediate postoperative period than Fontan though EF fell significantly after

SCPA. However, Fontan patients demonstrated better hemodynamics with time, with continuing fall in ventricular volumes and relatively unchanged EF in the Fontan group. This may partly be attributed to the fact that all Fontan patients in our study were primed with a prior SCPA, which allowed for correction of afterload mismatch, translating to better ventricular energetics after Fontan. 3DE data in similar larger group of patients are needed to provide valuable information regarding volume changes and contractility after SCPA/Fontan and to provide more insight into the hemodynamics of post-SCPA/Fontan circulation. It may also help to prognosticate as to the group of patients who are unlikely to do well after SCPA/Fontan.

CONCLUSIONS

Pattern and magnitude of unloading of the single ventricle of LV morphology differs after SCPA and completion of Fontan circulation. 3DE provides reliable estimation of volume of the single ventricle, which is comparable with published values. This 3DE data set can serve as a useful tool to compare and validate in various morphologies of congenital heart defects.

Limitations

Small sample size prevented us from drawing firm conclusions on magnitude and pattern of volume unloading after SCPA and Fontan completion. Greater age at surgery in both groups may have adversely affected the pattern of unloading of the single ventricle.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

REFERENCES

1. Lang RM, Badano LP, Mor-Avi V, Afilalo J, Armstrong A, Ernande L et al. Recommendations for Cardiac Chamber Quantification by Echocardiography in Adults: An Update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. J Am SocEchocardiogr 2015;28:1-39.
2. Monaghan MJ. Role of real time 3D echocardiography in evaluating the left ventricle. Heart 2006;92:131-136.
3. Alfakih K, Reid S, Jones T, Sivananthan M. Assessment of ventricular function and mass by cardiac magnetic resonance imaging. EurRadiol 2004;14:1813-22.
4. Wood PW, Choy JB, Nanda NC, BecherH. Left Ventricular Ejection Fraction and Volumes: It Depends on the Imaging Method. Echocardiography 2014;31:87-100.
5. Hoffmann R, BarlettaG, vonBardelebenS, Vanoverschelde JL, Kasprzak J, Greis C, *et al*. Analysis of Left Ventricular Volumes and Function: A Multicenter Comparison of Cardiac Magnetic Resonance Imaging, Cine Ventriculography, and Unenhanced and Contrast-Enhanced Two-Dimensional and Three-Dimensional Echocardiography. J Am SocEchocardiogr 2014;27:292-301.
6. Dorosz JL, LezotteDC,Weitzenkamp DA, Allen LA, Salcedo EE. Performance of 3-dimensional echocardiography in measuring left ventricular volumes and ejection fraction: A systematic review and meta-analysis. J Am CollCardiol 2012;59:1799-808.
7. Zhong SW, Zhang Y-Q,Chen L-J, Wang S-S, Li W-H. Evaluation of Left Ventricular Volumes and Function by Real Time Three-Dimensional Echocardiography in Children with Functional Single Left Ventricle: A Comparison between QLAB and TomTec. Echocardiography 2015;32:1554-63.
8. Bu L, Munns S, Zhang H, Disterhoft M, Dixon M, Stolpen A, *et al*. Rapid full volume data acquisition by real-time 3-dimensional echocardiography for assessment of left ventricular indexes in children: a validation study compared with magnetic resonance imaging. J Am SocEchocardiogr 2005;18:299-305.
9. Riehle TJ, Mahle WT, Parks WJ, Sallee D, Fyfe DA. Real-time three-dimensional echocardiographic acquisition and quantification of left ventricular indices in children and young adults with congenital heart disease: comparison with magnetic resonance imaging. J Am SocEchocardiogr 2008;21:78-83.
10. Shimada YJ, Shiota T. A meta-analysis and investigation for the source of bias of left ventricular volumes and function by three-dimensional echocardiography in comparison with magnetic resonance imaging. Am J Cardiol 2011;107:126-38.
11. Poutanen T, Jokinen E, Sairanen H, Tikanoja T. Left atrial and left ventricular function in healthy children and young adults assessed by three dimensional echocardiography. Heart 2003;89:544-9.
12. Buechel EV, Kaiser T, Jackson C, Schmitz A, Kellenberger CJ. Normal right- and left ventricular volumes and myocardial mass in children measured by steady state free precession cardiovascular magnetic resonance. J CardiovascMagnReson. 2009;11:19.
13. Shimazaki Y, Kawashima Y, Mori T, Kitamura S, Matsuda H, Yokota K. Ventricular volume characteristics of single ventricle before corrective surgery. Am J Cardiol. 1980;45:806-10.
14. Friedberg MK, Su X, Tworetzky W, Soriano BD, Powell AJ and Marx GR. Validation of 3D Echo Assessment of LV Volumes, Mass, and EF in Neonates and Infants With CHD -A Comparison Study With CMR. CircCardiovasc Imaging. 2010;3:735-742.
15. Lemes V, Ritter SB, Messina J, Gold JP. Enhancement of ventricular mechanics following bidirectional superior cavopulmonary anastomosis in patients with single ventricle. J Card Surg 1995;10:119-24.
16. Fogel MA, Weinberg PM, Chin AJ, Fellows KE, Hoffman EA. Late Ventricular Geometry and Performance Changes of Functional Single Ventricle Throughout Staged Fontan Reconstruction Assessed by Magnetic Resonance Imaging

.JACC 1996;28:212-21.

17. Seliem MA, BaEa JM, Vetter JM, Chen SL, Chin Al, Norwood WI. Changes in right ventricular geometry and heart rate early after hemi-Fontan procedure. Ann Thorac Surg 1993;55:1558-12.
18. Tanoue Y, Sese A, Ueno Y, Joh K, HijiiT. Bidirectional Glenn procedure improves the mechanical efficiency of a total cavopulmonary connection in high-risk fontan candidates. Circulation. 2001;103:2176-80.
19. Tanoue Y, Sese A, Imoto Y, JohK. Ventricular Mechanics in the Bidirectional Glenn Procedure and Total Cavopulmonary Connection.Ann ThoracSurg 2003;76:562-6.
20. Gewillig M, Daencn W, Aubert A, Van der Hauwaert L. Abolishment of chronic volume overload. Implications for diastolic function of the systemic ventricle immediately after Fontan repair. Circulation 1992;86Suppl ll:b-93-9.
21. Triedman IK, Bridget ND, Maker JE, Lock JE. Prevalence and risk factors for aortopulmonary collateral vessels after Fontan and hdirectmnal Glenn procedure. J Am CollCardiol 1993:22:207-15.
22. Forbes TJ, Gajarski R, Johnson GL, Reul GJ, Ott DA, Drescher K, *et al*. Influence of Age on the Effect of Bidirectional Cavopulmonary Anastomosis on Left Ventricular Volume, Mass and Ejection Fraction. J Am Coll Cardiol 1996;28:1301-7.
23. Tanoue Y, Kado H, Maeda T, ShiokawaY,Ishikawa F, Ishikawa S. Left ventricular performance of pulmonary atresia with intact ventricular septum after right heart bypass surgery.J Thorac Cardiovasc Surg 2004;128:710-7.
24. GewilligaM, Brownb SC, HeyingaR, EyskensaB, GanameaJ, Boshoffa DE, Budtsa W, Gorenfloa M. State-of-the-art -Congenital Volume load paradox while preparing for the Fontan: not too much for the ventricle, not too little for the lungs .Interactive CardioVascular and Thoracic Surgery 2010;10:262-5.