Functional single ventricle and Fontan operation

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Diverse terminology of single ventricle type congenital heart disease

- Single ventricle
- Common ventricle
- Univentricular heart
- Functional / Functionally single ventricle

Spectrum of single ventricle

- Truly solitary ventricles, exceedingly rare
- Single well-developed ventricle + additional incomplete, rudimentary, or hypoplastic ventricle
- Two well-developed ventricles, not septatable

Recommended nomenclature & classification

• Hearts with double inlet AV connection	DILV / DIRV
• Hearts with absence of one AV connection	Mitral / Tricuspid atresia
• Hearts with a common AV valve and only one completely well-developed ventricle	Unbalanced AV canal defect
• Hearts with only one fully well-developed ventricle and heterotaxia syndrome	Heterotaxia syndrome
• Other rare forms of univentricular hearts	Others

Congenital Heart Surgery Nomenclature and Database Project: single ventricle
Marshall L. Jacobs and John E. Mayer, Jr Ann Thorac Surg 2000;69:197-204

Recommended nomenclature & classification

- Not included
  - HLHS
  - PA IVS
  - Biventricular hearts with straddling AV valves
  - Some complex forms of DORV

Congenital Heart Surgery Nomenclature and Database Project: single ventricle
Marshall L. Jacobs and John E. Mayer, Jr Ann Thorac Surg 2000;69:197-204

Epidermiology & Pathologic subtypes

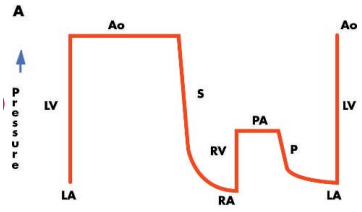
- Incidence of univentricular heart
  - 54 / million live births (New England, 1980)
- HLHS
  - 2.3 / 10,000 live births
- Tricuspid atresia
  - 1 / 10,000 live births
  - 2.9% to 1.4% of CHD autopsy & clinical series

Genetic factors

- Several subtypes, including DILV, single inlet, common inlet, complex single ventricle heterotaxy syndrome
  - Polygenic in nature
- Risk to siblings & offspring; 2% & 5%

Circulation by 2 ventricles

Normal mammal cardiovascular system
Double circuit - pulmonary & systemic
Double pump - right & left heart

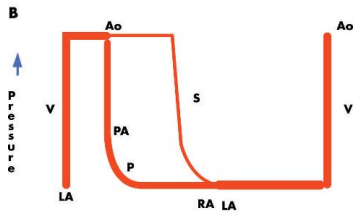


Pulmonary & systemic circulation in series

Gewilling M. Heart 2005;91:839–846

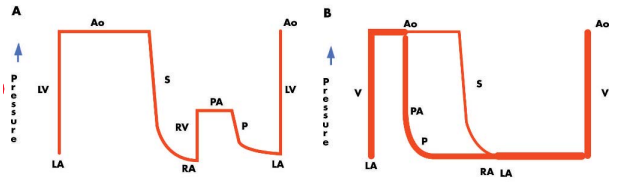
Circulation by functional SV

Only one functional SV
Pulmonary & systemic circulation in parallel



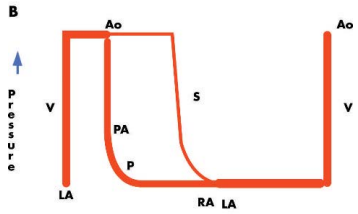
Gewilling M. Heart 2005;91:839–846

Comparison of 2 circulations



Gewilling M. Heart 2005;91:839–846

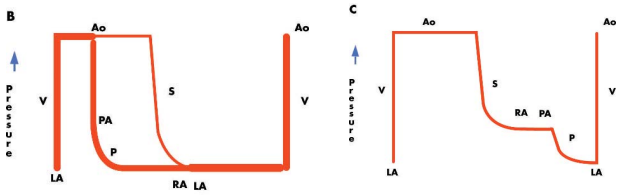
Circulation by functional SV



Arterial desaturation
Chronic volume overload to SV
→ Ventricular dysfunction

Gewilling M. Heart 2005;91:839–846

SV to Fontan circulation



Separating systemic & pulmonary circulation
- Systemic venous return to pulmonary arteries without interposition of adequate ventricle

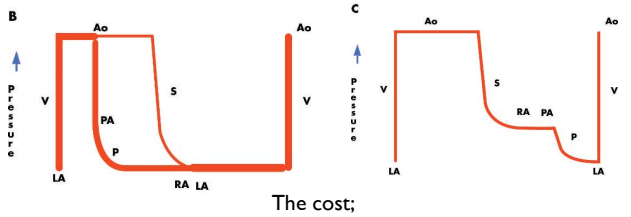
↓

Normalization of arterial saturation
Abolishment of chronic volume overload

Gewilling M. Heart 2005;91:839–846

Fontan circulation

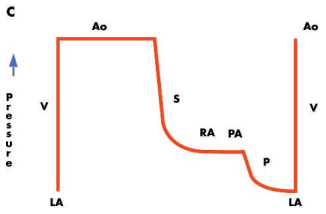
Normalization of arterial saturation
Abolishment of chronic volume overload



The cost;
Chronic hypertension & congestion of systemic veins
Decreased cardiac output

Gewilling M. Heart 2005;91:839–846

Fontan circulation



Typically, cardiac output is no longer determined by the heart, but rather by transpulmonary flow (itself mainly determined by pulmonary vascular resistance).

Gewilling M. Heart 2005;91:839–846

Hemodynamics of SV

- Key determinants
  - Obstruction to outflow, inflow ± flow across the atrial septum
  - Systemic & pulmonary venous return
  - Pulmonary vascular resistance (PVR)
  - AV valve regurgitation

Requirements of good hemodynamics of SV

- Good ventricular function
- No AV valve regurgitation
- Unrestrictive ASD
- Well-balanced systemic & pulmonary blood flow

Clinical features

Pulmonary outflow obstruction

No
↓
Large L to R shunting
↓
Congestive heart failure
Failure to thrive
↓
Aortic outflow obstruction combined
Worsen congenital heart failure

Yes
↓
Prevent pulmonary overcirculation
Hypoxemia & cyanosis

Natural history

- Poor prognosis in unrepaired univentricular heart
  - Moodie (1984)
    - 70% with well- formed single LV died before age 16, with annual attrition rate of 4.8%.
    - More unfavorable for patients with RV morphology, with 50% survival 4 years after diagnosis.
    - The most common causes of mortality
      - Arrhythmias, congestive heart failure, and sudden unexplained death

Natural history

- Survival into adulthood of patients with unoperated single ventricle
  - Ammash (1996)
  - Total 13 patients with DILV (12) or tricuspid atresia (1)
  - The oldest patient was 66 years old.
  - Moderate-to-severe PS or pulmonary hypertension (n=13)
  - LV EF normal (n=11) or mildly depressed (n=2)
  - Good functional capacity and worked full- or part-time (n=12)
  - Some adults with SV and well-balanced circulations may survive into their seventh decade with acceptable functional capacity and preserved ventricular function.

Diagnostic evaluation

- Radiological exam
- EKG
- Noninvasive imaging
  - EchoCG
- Cardiac catheterization

Diagnostic evaluation

- Objectives of cardiac catheterization
  - Assessment of
    - Hemodynamics
    - Systemic & pulmonary venous anatomy
    - AV & VA connections
    - Ventricular morphology & function
    - PVR
    - Aortic arch integrity
    - Systemic-pulmonary collaterals

Management of Cyanotic Patients With Univentricular Heart

- Chronic cyanosis in unoperated & partially palliated patients
- Hematologic derangements
  - Erythrocytosis, iron deficiency, thromboemboli, bleeding diathesis
- Neurological complications
  - Cerebral hemorrhage, thromboemboli from R-to-L shunting, cerebral abscesses
- Renal complications
- Rheumatological complications
- Cholelithiasis

Single ventricle
No pulmonary ventricle

Fontan operation

Management principles of SV

- Primum non nocere (Latin, First do no harm)
  - Intervention must be carried out so as to avoid injury to the heart, preserving ventricular systolic and diastolic function, preserving valvular function and preserving electrophysiologic function
- Optimization of pulmonary vascular circulation
  - Establishment and maintenance of the lowest possible PVR
- Keeping in mind about the potential for injury to other organs, particularly the brain, liver, kidneys and intestines as interventions are planned and carried out

Indications for Fontan circulation

- Functional single ventricle
- Very complex malformations
  - + High surgical risk morbidity
  - + Need for "high maintenance" (frequent conduit replacement)
  - Lower surgical risk and lower incidence of reinterventions for a similar clinical and functional long term result

Surgical management

- General objectives of initial surgical palliation
  - Unobstructed systemic & pulmonary venous return
  - Unobstructed systemic outflow
  - Controlled pulmonary blood flow

Why not Fontan initially?

- In the initial management of such children, after diagnosis and resuscitation, the dynamic aspect of the neonatal pulmonary vascular bed is a dominant factor.
- Because the PVR is so high initially, the goal of achieving pulmonary blood flow without a ventricular power source is not possible in the neonatal period.

Why not Fontan initially?

- Equally important though is the recognition that the initially high pulmonary resistance drops rapidly, falling to its nadir in a few weeks.
- So, we need to wait the variably paced maturation of the pulmonary resistance.
- Known as the reduction in PVR completed by approximately 6–12 weeks of age

Initial surgical palliation

- Except for those rare children with truly balanced circulation, virtually all children with single ventricle physiology will require intervention in the neonatal period to regulate pulmonary blood flow.

Initial surgical palliation

- Severe pulmonary stenosis or atresia
  - Aortopulmonary shunt
    - Modified BT shunt
  - Bidirectional cavopulmonary anastomosis
    - Glenn shunt

Initial surgical palliation

- Unrestrictive pulmonary blood flow
  - PA banding
  - PA division with creation of aortopulmonary shunt to limit PBF

Initial surgical palliation

- Aortic arch obstruction with unobstructed pulmonary blood flow
  - Aortic repair in the neonatal period
  - + Simultaneous PA banding or with pulmonary artery division and systemic to pulmonary shunt placement

Initial surgical palliation

- Potential for sub-aortic obstruction to develop if PA banding is performed
  - Damus–Kaye–Stansel (DKS) type of operation
  - Palliative arterial switch operation

Initial surgical palliation

- Regardless of form of first stage palliation of children with univentricular hearts, it must be emphasized that these children are left with a very inefficient circulation.
  - Associated with poor growth velocity, and in some anatomic subsets, especially HLHS and PA-IVS, a significant incidence of sudden death after hospital discharge

‘Interstage attrition’

- Home surveillance programs, consisting of daily monitoring of weight and oxygen saturation by parents or visiting nurses
- Although the results from such efforts are encouraging, interstage death has not been completely eliminated, emphasizing the fragility of SV patients with parallel circulation.

2nd stage palliation

Bidirectional Glenn or superior cavopulmonary shunt
Performed at about 6 mo of age

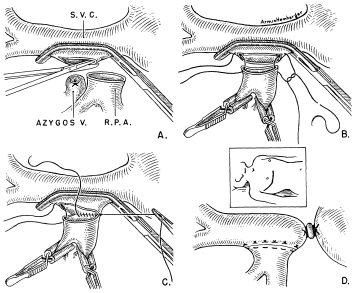
What is 'Glenn'?

Circulatory bypass of the right heart. I. Preliminary observations on the direct delivery of vena caval blood into the pulmonary artery circulation. Azygos vein-pulmonary artery shunt.
William W.L. Glenn, Patino, J. F.
Yale J. Biol. & Med. 27: 147, 1954.

Circulatory bypass of the right side of the heart. IV. Shunt between superior vena cava and distal right pulmonary artery; report of clinical application.
Glenn, W.W.
N Engl J Med 259: 117-120, 1958

Circulatory Bypass of the Right Side of the Heart: VI. Shunt between Superior Vena Cava and Distal Right Pulmonary Artery; Report of Clinical Application in Thirty-eight Cases
Glenn WW, Ordway NK, Talner NS, Call,jr EP.
Circulation 31:172-189, 1965

What is 'Glenn'?



What is 'Glenn'?

Indications for Cava-pulmonary Artery Anastomosis

1. Tricuspid atresia
2. Defective development of right ventricle with intact ventricular septum
3. Tetralogy of Fallot (certain cases)
4. Corrected transposition of great vessels with pulmonary stenosis
5. Transposition of the great vessels with ventricular septal defect and pulmonary stenosis
6. Single ventricle with rudimentary outflow to pulmonary artery
7. Origin of both great vessels from right ventricle with pulmonary stenosis
8. Ebstein's anomaly

Circulation 1965;31;172-189

What is 'bidirectional' Glenn?

Thorax (1972), **27**, 111.

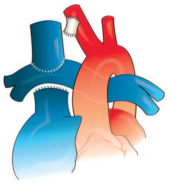
Tricuspid atresia: Experience in surgical management with a modified cavopulmonary anastomosis

G. AZZOLINA, S. EUFRATE, and P. PENSA

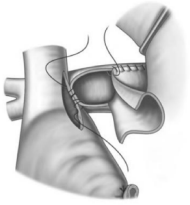
Department of Paediatric Cardiothoracic Surgery, Ospedale Generale Provinciale, Massa, Italy

2nd stage palliation

Bidirectional Glenn shunt



Hemi-Fontan operation



2nd stage palliation

- Bidirectional superior cavopulmonary anastomosis
  - Volume unloading effect of converting from parallel to series circulation provided salutary effects on coronary blood flow and ventricular energetics
  - Standard to proceed from initial palliation to the Fontan circulation by means of an intermediate operation

2nd stage palliation

- Controversies on 2nd stage palliation
  - Antegrade source of additional pulmonary blood flow
  - Optimal timing

2nd stage palliation

- Antegrade source of additional pulmonary blood flow
  - Advocates of antegrade flow point out the higher oxygen saturations that result, as well as the theoretical effect of pulsatile flow on enhancing pulmonary artery growth.
  - Proponents of eliminating antegrade blood flow report a reduction in the extent and duration of postoperative pleural effusions as well as the difficulty in establishing how much antegrade blood flow is too much.

2nd stage palliation

- Optimal timing
  - Proponents of early operation point to the shortening of the risky interstage period.
  - Other theoretic benefits include early achievement of the salutary effects of volume unloading on the ventricle, the establishment of more normal growth patterns, as well as studies showing equivalent survival outcomes as in patients having later second stage operation.

2nd stage palliation

- Optimal timing
  - Opponents of early second stage operation point to significant early postoperative cyanosis in younger patients, as well as increased resource utilization and longer hospitalization in younger children.
  - In general, the age at second stage operation has decreased slightly over the past several years.

3rd stage palliation

Fontan operation

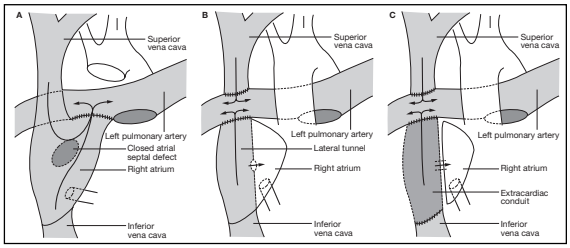
3rd stage palliation

- For children with single ventricle physiology, the ultimate physiologic goal is attained with the performance of the Fontan operation.
- This operation results in near normal arterial oxygen saturation as a result of the diversion of all of the systemic venous return to the pulmonary vascular bed before its return to the heart, with the exception of coronary sinus effluent that may not be routed to the lungs (depending on the type of Fontan construction).

3rd stage palliation

- Fontan procedure
  - Completed btw 18 mo & 4 yr of age
  - Separates pulmonary from systemic circulations

Different types of Fontan circulation



(A) Atriopulmonary connection. (B) Intracardiac total cavopulmonary connection (lateral tunnel). (C) Extracardiac total cavopulmonary connection

de Leval, M. R. (2005). "The Fontan circulation: a challenge to William Harvey!" Nature Clinical Practice Cardiovascular Medicine 2(4): 202-208.

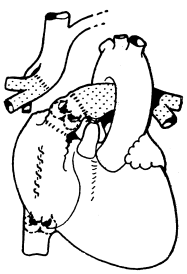
Thorax (1971), **26,** 240.

Surgical repair of tricuspid atresia

F. FONTAN and E. BAUDET

Centre de Cardiologie, Université de Bordeaux II, Hôpital du Tondu, Bordeaux, France

Original Fontan op.



1. Glenn shunt to right lung
2. Harvest of MPA from RVOT
3. Anastomosis of MPA to RA with an interposed homograft valve
4. Placement of a homograft valve in IVC-RA junction
5. Closure of ASD

Fontan F, Baudet E, Thorax 1971;26:240

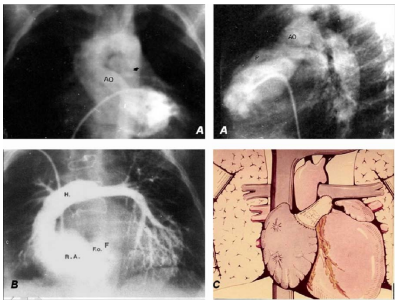
Pediatric Cardiac Surgery Annual

The Fontan/Kreutzer Procedure At 40: An Operation for the Correction of Tricuspid Atresia

Guillermo O. Kreutzer, MD,[a] Andrés J. Schlichter, MD,[b] and Christian Kreutzer, MD[c]

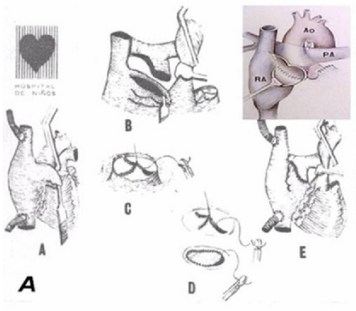
Seminars in Thoracic and Cardiovascular Surgery: Pediatric Cardiac Surgery Annual 2010;13: 84-90

Atriopulmonary anastomosis (Kreutzer)



J Thorac Cardiovasc Surg 1973;66:613-621

Modification of APA



J Thorac Cardiovasc Surg 1982;83:427-436

Original Criteria Proposed for Fontan Completion (Choussat A, 1978)

1. Age ≥4 years to <15 years
2. Normal sinus rhythm
3. Normal systemic venous return
4. Normal right atrial volume
5. Mean pulmonary artery pressure ≤15 mm Hg
6. Pulmonary arteriolar resistance <4 Wood units/m^2
7. Pulmonary artery to aortic diameter ratio ≥0.75
8. Left ventricular ejection fraction ≥0.60
9. Competent mitral valve
10. Absence of pulmonary artery distortion

Advances in Fontan procedure

- Total cavopulmonary connections
  1. Lateral tunnel Fontan
     - Puga FJ (1987), de Leval MR (1988)
     - End-to-side anastomosis of SVC to undivided RPA + intra-atrial tunnel to channel IVC to transected SVC
  2. Extracardiac conduit Fontan
     - Marcelletti C (1990)

Advances in Fontan procedure

- Fenestrated Fontan
  - Bridges ND (1990)
  - Fontan pathway "fenestrated" by creation of an ASD in baffle or patch
  - Provides R-to-L shunting
  - Maybe beneficial early after the Fontan
  - If hemodynamics are favorable, fenestrations can later be closed by transcatheter approach.

Outcomes after Fontan procedure

Authors	Study period	No of Pt.	Type of Fontan	Early survival	Late survival
Stamm (2001)	1987-1991	220	LT 100%	95%	91% (10yr)
Petrossian (2006)	1992-2005	285	EC 100%	98.9%	91% (10yr)
Giannico (2006)	1988-2003	221	EC 100%	90%	85% (15yr)
Lee JR (2006)	1995-2006	165	LT 67 / EC 98	97%	LT/ EC 92% / 89% (10yr)
Jacobs (2008)	1996-2006	100	EC 100%	100%	1 late death
Kim SJ (2008)	1996-2006	200	EC 100%	97%	92% (10yr)
Hirsch (2008)	1992-2007	636	LT 92% / EC 8%	96%	97% (50mo)
Brown (2010)	1992-2008	220	LT 100%	99.5%	95% (10yr)
Robbers-Visser (2010)	1988-2008	209	LT 102 / EC 107	96%	10 late deaths
Total		2256		97%	

* LT; lateral tunnel Fontan, EC; extracardiac conduit Fontan, mo; months, yr; years

Functional status and exercise tolerance after Fontan

- Despite the abnormality of the circuit, clinicians are frequently impressed by the ability of most patients with a Fontan circulation to lead a nearly normal life, including mild to moderate sport activities.
- More than 90% of all hospital survivors are in NYHA Fc I or II.
- Most patients progress through the education system just like the standard population and can pursue a wide variety of professional careers.

Functional status and exercise tolerance after Fontan

- However, with time there is a progressive decline of functional status in some subgroups.
- A Fontan circulation is palliative in nature, with good results in patients with an ideal hemodynamic profile, but with significant ongoing morbidity and mortality if some criteria are not met.

Post-Fontan complications and mechanisms of Fontan failure

- Early postoperative failure
- Late Fontan failure
- Progressive exercise intolerance ± cyanosis

Late Fontan failure

- Single-ventricular dysfunction
- Elevated PVR
- Valve dysfunction & subvalvular stenosis
- Lymphatic derangements: protein-losing enteropathy & plastic bronchitis
- Pulmonary arteriovenous fistulae/ malformations
- Thrombotic circuit occlusion
- Intractable arrhythmias

Single-ventricular dysfunction

- Several factors contribute to ventricular dysfunction
- Underlying CHD associated with some degree of cardiomyopathy and ventricular morphology not well-suited for long-term "systemic work."
- While the morphologic RV is capable of adapting to long-term function at systemic pressures, it has a higher incidence of failure over decades than systemic LV.

Single-ventricular dysfunction

- Accumulated effect of multiple surgeries (often with periods of myocardial ischemia) likely contributes to worsening systolic and diastolic function.
- Periods of neonatal and childhood palliation with a volume-loaded ventricle may negatively impact long-term ventricular function.
- Although the volume work of the ventricle is reduced with the TCPC, the ventricle must drive cardiac output through two resistance beds, resulting in a chronic increase in pressure work that likely contributes to eventual ventricular dysfunction.

Single-ventricular dysfunction

- Ventricular failure in patients with a Fontan circulation is particularly problematic because even slight increases in ventricular end-diastolic pressure lead to higher Fontan circuit pressures, likely increasing the risk for all of the various complications associated with the Fontan circuit.
- Unfortunately, ventricular failure in Fontan patients is often refractory to standard medical treatments including afterload reduction, beta-blockade, and inotropy.

Single-ventricular dysfunction

- In theory, chronic afterload reduction may attenuate the impact of the pressure load, but no clear benefit has been demonstrated through the use of ACE inhibition.
- Incompetence of the systemic AV valve volume loads the overworked ventricle, further reducing its efficiency.
- Loss of sinus rhythm impairs ventricular mechanics and, although data is limited, some evidence supports the idea that dual-chamber pacing and ventricular resynchronization via multi site pacing may improve Fontan function and resolve some of the symptoms of a failing Fontan.

Elevated PVR

- Despite acceptable PVR at the time of TCPC, some patients may develop elevations in the transpulmonary gradient, resulting in Fontan failure.
- Surgical or percutaneous interventions are indicated to treat focal stenoses of the pulmonary arteries or veins.
- However, diffuse changes in pulmonary vascular physiology as the result of the Fontan circulation may also play a role in the development of pulmonary hypertension.

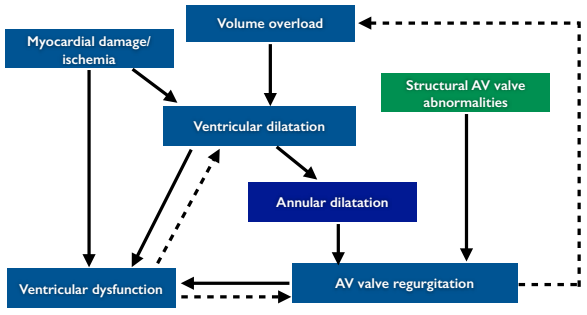
Elevated PVR

- Mechanism of pulmonary arterial dysfunction; not certain
  - Lack of pulsatility
  - Pulmonary microemboli
  - Elevated pulmonary lymphatic pressure
  - Disordered pulmonary vascular bed in nitric oxide synthesis & endothelial dysfunction

Elevated PVR

- Improvements in conduit hemodynamics may help to reduce some of the derangements resulting in elevated PVR.
- Fontan revision, including RA reduction, pulmonary arterioplasty, or conversion to an extracardiac TCPC, may streamline flow and reduce resistance within the Fontan circuit.

Mechanisms of development of significant AV valve insufficiency



Honjo O et al (2011). "Atrioventricular Valve Repair in Patients With Single-ventricle Physiology: Mechanisms, Techniques of Repair, and Clinical Outcomes." Seminars in Thoracic and Cardiovascular Surgery: Pediatric Cardiac Surgery Annual **14**(1): 75-84.

Protein-losing enteropathy (PLE)

- 3% - 15% of patients following Fontan
- Presents as vague GI symptoms progressing to ascites, pleural effusions, and peripheral edema.
  - Diarrhea; common with the onset of severe gut edema

Protein-losing enteropathy (PLE)

- Pathophysiology; not well understood
- Contributing factors
  - Abnormal mesenteric vascular pressure & inflammation
  - Lymphatic hypertension from elevated SVC pressures
  - Low cardiac output
  - Enterocyte membrane dysfunction

Protein-losing enteropathy (PLE)

- Serum proteins are lost in the intestinal tract, including coagulation factors and immunoglobulins that may incite infections and thromboembolic events.
- Particularly frustrating to caregivers is the fact that patients with hemodynamically well-functioning Fontan circuits may develop PLE, and determination of pre-Fontan risk factors for post-Fontan PLE has been elusive.
- Medical therapy with heparin has on occasion been helpful.
- Correctable causes of PLE are rare.

Pulmonary arteriovenous malformations (PAVMs)

- Complicate the course of a number of patients following second-stage palliation for SV lesions
- Etiology, not entirely clear
  - Lack of pulsatility in pulmonary circulation
  - Lack of some hepatic-derived factor in pulmonary arterial supply to lungs

Pulmonary arteriovenous malformations (PAVMs)

- Management
  - Conversion from BCPS to TCPC
  - If PAVMs persist following TCPC
    - Surgical revision of cavopulmonary connection for even distribution of hepatic flow to lungs
  - Percutaneous closure of large PAVMs
  - Lung transplantation

Options for treatment of Fontan circuit failure

- Fontan Revision/Conversion
  - Focal anatomic issues
    - Pulmonary artery stenosis, pulmonary venous obstruction, AV valve insufficiency, subaortic stenosis etc
  - Atrioventricular or atriopulmonary type Fontan
- Cardiac Transplantation