Understanding Hemodynamics: Optimizing the Cardiac Catheterization Laboratory in Complex Conditions

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Disclosures

- W.L. Gore & Associates: Consultant and Proctor
- Medtronic, Inc: Consultant and Proctor
- Mezzion Pharma: Consultant and Scientific Advisory Board Member
- PECA Labs: Consultant

Outline

- Ground rules
- Assumed vs. measured data
- Static vs. dynamic assessment
- Measurements we didn’t know we could obtain
- Conclusions

A common scenario

- 4 yo M with DCM undergoing pre-OHT evaluation
- Sats: PA 63%, DAO 96%
- Pressures: PA mean 16 mmHg, PCWP mean 6 mmHg
- Hgb 12.3, HR 115
- Assumed VO_2 165 ml/kg/min

- Qp=Qs=2.94 L/min/m^2
- Rp=2.72 U*m^2

A common scenario

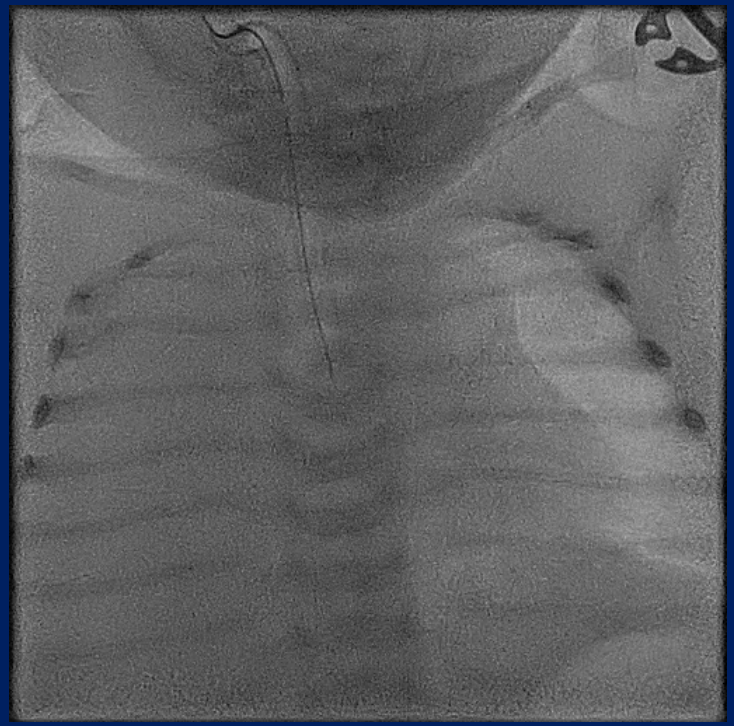
- 4 yo M with DCM undergoing pre-OHT evaluation
- Sats: PA 63%, DAO 96%
- Pressures: PA mean 16 mmHg, PCWP mean 6 mmHg
- Hgb 12.3, HR 115
- **Measured** VO_2 97 ml/kg/min

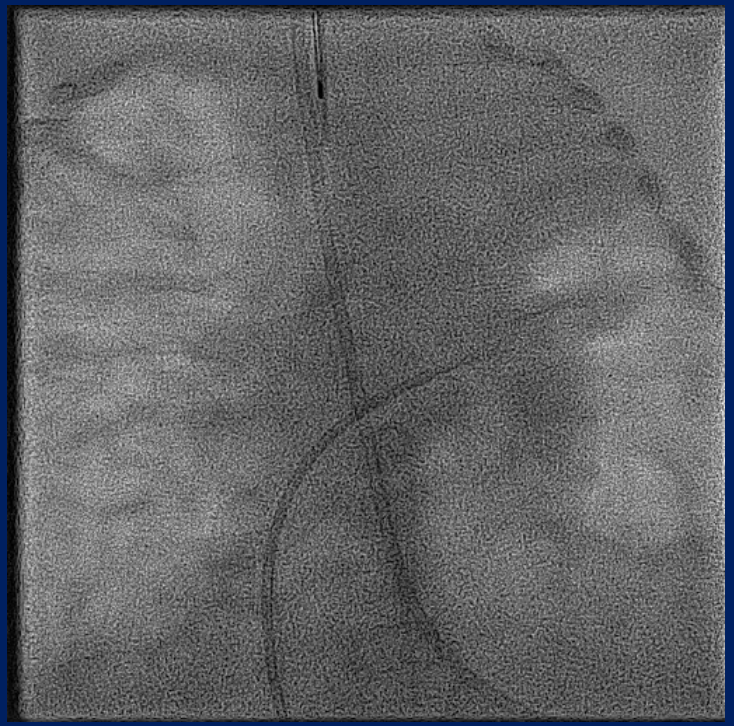
- Qp=Qs=1.76 L/min/m^2
- **Rp=5.68 U*m^2**

Ground Rules

- Catheterization reflects a moment in time
- Measured data are measured *whereas* assumed data are not
- Hemodynamic data are *typically* acquired in a sedated/anesthetized, supine, and somewhat volume unloaded state
- Airway management strategy, sedation/anesthetic agent selection, ventilation/acid-base homeostasis, extra-cardiac organ pathologies can all impact measured hemodynamics

Data are data, not truth





Accuracy in the measurement of cardiac output

Determination of Cardiac Output

- Integral to assessment of the critically ill patient
- Necessary for determination of vascular resistance
- Plays a major role in care delivery and decision making
- And yet…thermodilution determination of cardiac output (gold standard) cannot be used in the setting of very low output, shunt lesion(s) or valvar regurgitation
- Thus, we frequently rely on the Fick principle for determination of cardiac output

Determination of Cardiac Output

$$CO = \frac{VO_2}{(AO\text{-}PA)([Hgb])(1.36)(10)}$$

Oxygen Consumption

- Infrequently measured
- Difficult to assess in smaller/younger children or with GETA
- Historical reliance on formulae from LaFarge
- LaFarge data from 1960's
  - No GETA
  - No single ventricle palliation
  - No percutaneous interventions
  - No neonates, infants and young children
- Recent work has demonstrated LaFarge formulae to be inaccurate

LaFarge and Miettinen. *Cardiovasc Res*. 1970.

Validation of Cardiac Output Using Real-time Measurement of Oxygen Consumption during Cardiac Catheterization in Children Under 3 Years of Age

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ABSTRACT

Objective. To validate a method for determination of cardiac index (CI) using real-time measurement of oxygen consumption (VO_2) in young children undergoing cardiac catheterization.

Design. Retrospective review comparing thermodilution cardiac index (TDCI) to CI calculated by the Fick equation using real-time measured VO_2 (RT-VO_2) and VO_2 derived from 2 published predictive equations. Paired *t*-test and Bland-Altman analysis were used to compare TDCI to Fick CI. A survey to ascertain pediatric cardiac catheterization practices regarding VO_2 determination was also conducted.

Setting. Quaternary care children's hospital cardiac catheterization laboratory.

Patients. Children <3 years old with structurally normal hearts undergoing cardiac catheterization under general anesthesia with at least one set of contemporaneous TDCI and RT-VO_2 measurements.

Results. Thirty-six paired measurements of TDCI and RT-VO_2 were made in 27 patients over a 2-year period. Indications for catheterization included congenital diaphragmatic hernia postrepair (n = 13), heart disease post-orthotopic heart transplant (n = 13), and suspected cardiomyopathy (n = 1). Mean age was 21.5 ± 8 months; median weight was 9.9 kg (IQR 8.57, 12.2). RT-VO_2 was higher than VO_2 predicted by the LaFarge equation (190 ± 31 vs. 173.8 ± 12.8 mL/min/m^2, $P < .001$), but there was no difference between TDCI and Fick CI calculated using VO_2 from any method. Bland–Altman analysis showed excellent agreement between TDCI and Fick CI using RT-VO_2 and VO_2 predicted by the Lundell equation; Fick CI using VO_2 predicted by the LaFarge equation showed fair agreement with TDCI.

Conclusions. In children <3 years with a structurally normal heart, RT-VO_2 generates highly accurate determinations of Fick CI as compared with TDCI. Additionally, in this population, VO_2 derived from the LaFarge and Lundell equations generates accurate Fick CI compared with TDCI. Future studies are needed to identify factors associated with inaccurate VO_2 generated from these predictive equations.

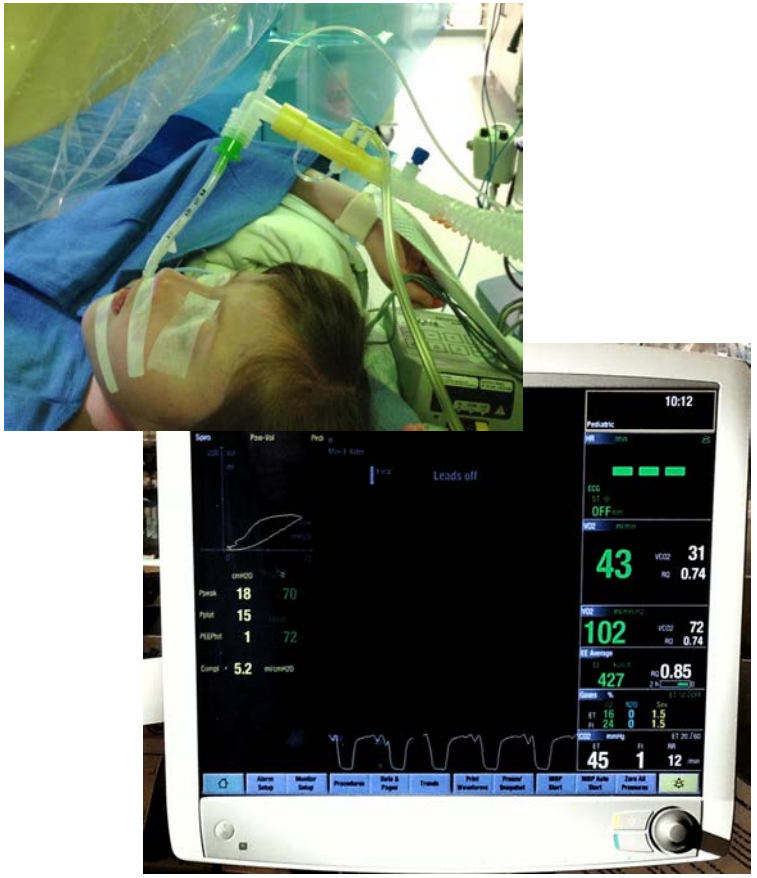
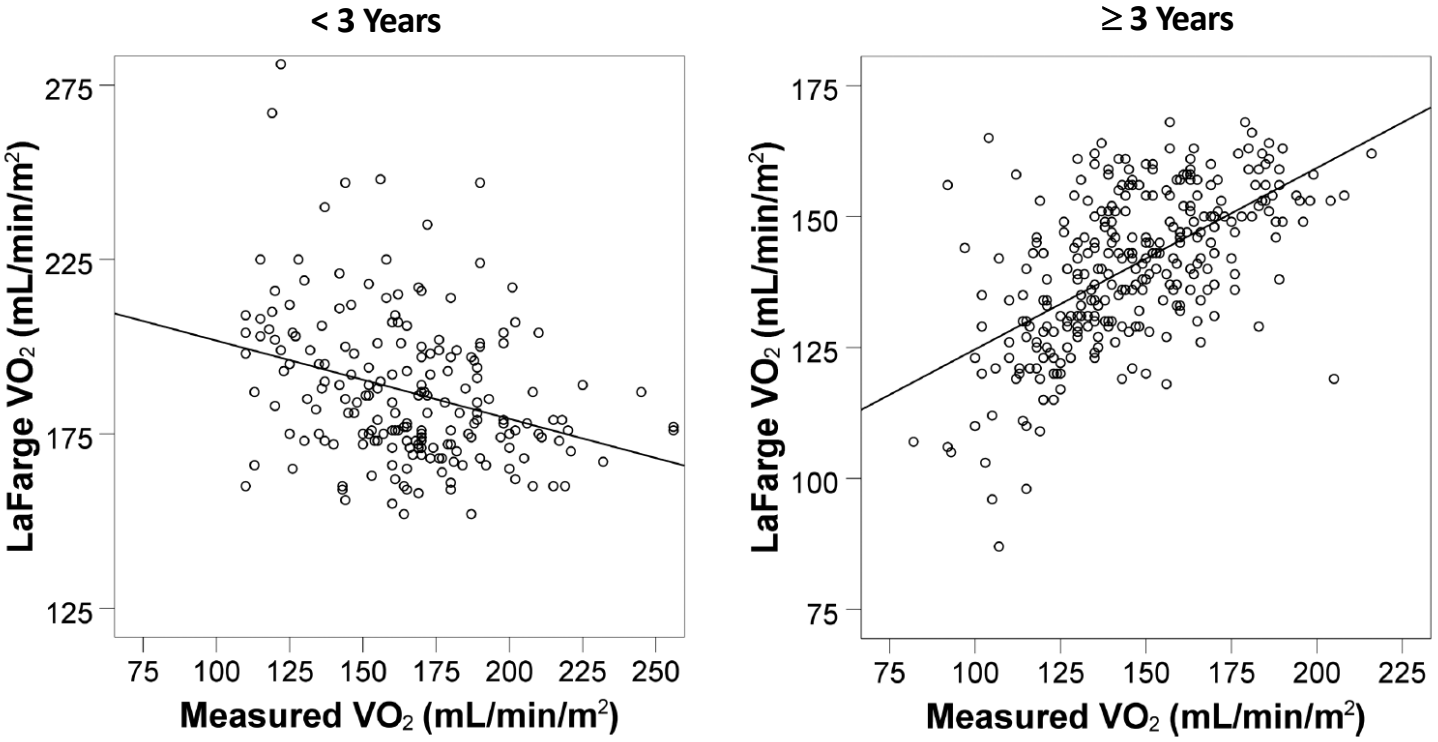


Table 1 Characteristics of the 502 patients in the baseline analysis

Factor	Group 1 (n=201)	Group 2 (n=301)	p Value
Age (years)	0.82 (0.35–1.64)	8.78 (4.8–12.26)	<0.001
Weight (kg)	7.5 (5.4–10.05)	27.5 (17–42.25)	<0.001
BSA (kg/m^2)	0.36 (0.28–0.46)	0.98 (0.69–1.38)	<0.001
Female gender	79 (39)	162 (54)	0.001
Heart rate (bpm)	116±21.4	88.5±17.8	<0.001
Haemoglobin (g/dL)	11.25±2.32	11.3±2.17	0.807
Critically ill status	59 (29)	21 (7)	<0.001
Diagnosis			
Structurally normal	2 (1)	13 (4)	0.034
Pulmonary arterial hypertension	19 (10)	19 (6)	0.192
Cardiomyopathy	2 (1)	13 (4)	0.034
Simple biventricular CHD	24 (12)	53 (18)	0.084
Complex biventricular CHD	43 (21)	54 (18)	0.337
Single ventricle	59 (29)	48 (16)	<0.001
Post Stage 1	42 (21)	0 (0)	<0.001
Post Stage 2	17 (9)	18 (6)	0.286
Post Stage 3	0 (0)	30 (10)	<0.001
Post heart transplant	52 (26)	101 (34)	0.067

Values are mean±SD, median (IQR) or n (%). Simple biventricular congenital heart disease (CHD) was defined as an isolated patent ductus arteriosus, atrial septal defect, ventricular septal defect, valvar aortic stenosis or valvar pulmonary stenosis. Complex biventricular CHD was defined as tetralogy of Fallot, pulmonary atresia/ventricular septal defect, atrioventricular septal defect or truncus arteriousus. A patent foramen ovale was considered a normal variant.
BSA, body surface area

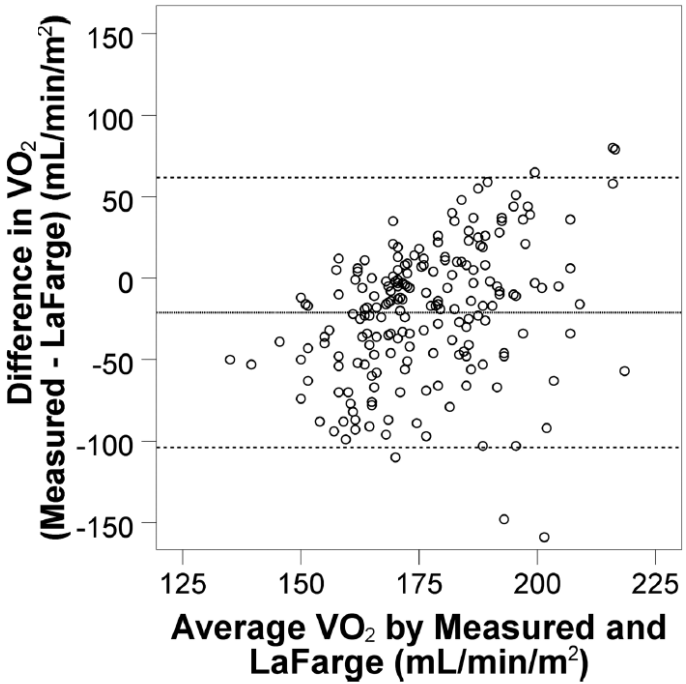
Oxygen Consumption



Seckeler et al. *Heart*. 2014

Oxygen Consumption

< 3 Years



≥ 3 Years

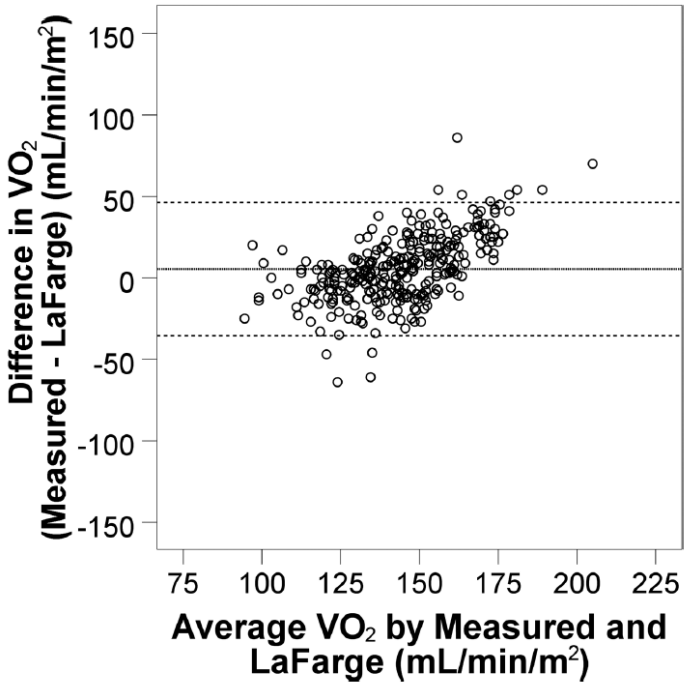


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Table 2 Results of simple and multiple logistic regression analyses to identify factors associated with an inaccurate LaFarge VO_2 for each group

	Group 1				Group 2			
	Univariate		Multivariable		Univariate		Multivariable	
Factor	OR (95% CI)	p Value	OR (95% CI)	p Value	OR (95% CI)	p Value	OR (95% CI)	p Value
Age (years)	0.32 (0.21 to 0.50)	<0.001	0.41 (0.20 to 0.82)	0.012	0.96 (0.90 to 1.02)	0.149		
Weight (kg)	0.82 (0.74 to 0.91)	<0.001	1.04 (0.90 to 1.19)	0.592	0.99 (0.97 to 1.00)	0.114		
BSA (kg/m^2)	0.01 (0.00 to 0.04)	<0.001			0.47 (0.20 to 1.13)	0.093		
Female gender	1.19 (0.67 to 2.10)	0.561			0.94 (0.48 to 1.83)	0.857		
Heart rate (bpm)	1.04 (1.02, 1.06)	<0.001	1.01 (0.99 to 1.02)	0.330	1.00 (0.99 to 1.02)	0.726		
Haemoglobin (g/dL)	1.16 (1.03 to 1.32)	0.019	0.93 (0.81 to 1.06)	0.265	0.83 (0.70 to 0.99)	0.036	0.84 (0.81 to 0.86)	<0.001
Critically ill status	3.40 (1.81 to 6.40)	<0.001	2.00 (0.96 to 4.18)	0.065	2.89 (1.05 to 7.97)	0.040	2.48 (0.90 to 6.82)	0.079
Structurally normal	0 (0)	0.999			2.04 (0.54 to 7.74)	0.297		
Pulmonary arterial hypertension	0.62 (0.22 to 1.70)	0.347			0.35 (0.05 to 2.67)	0.309		
Cardiomyopathy	1.40 (0.86, 22.7)	0.814			2.04 (0.54 to 7.74)	0.297		
Simple biventricular CHD	0.66 (0.27 to 1.63)	0.373			0.48 (0.16 to 1.41)	0.183		
Complex biventricular CHD	0.78 (0.39, 1.57)	0.493			1.17 (0.51 to 2.70)	0.716		
Single ventricle	3.07 (1.64 to 5.75)	<0.001			1.14 (0.47 to 2.75)	0.773		
Post Stage 1	5.64 (2.63 to 12.1)	<0.001	2.98 (1.14 to 7.55)	0.025	–	–		
Post Stage 2	0.55 (0.19 to 1.64)	0.285			1.96 (0.61 to 6.28)	0.257		
Post Stage 3	–	–			0.70 (0.20 to 2.43)	0.578		
Post heart transplant	0.59 (0.31 to 1.15)	0.124			1.08 (0.54 to 2.17)	0.835		

Body surface area (BSA) was not included in the final models as it was found to be collinear with age and weight. Simple biventricular congenital heart disease (CHD) was defined as an isolated patent ductus arteriosus, atrial septal defect, ventricular septal defect, valvar aortic stenosis or valvar pulmonary stenosis. Complex biventricular CHD was defined as tetralogy of Fallot, pulmonary atresia/ventricular septal defect, atrioventricular septal defect or truncus arteriousus.
VO_2, oxygen consumption

The Seckeler Equation for VO_2

$$VO_2 = 242.1 + [9.7 \times \ln \text{Age}] - [34 \times \ln \text{Weight}] - [9.6 \times \text{Single Ventricle}] - [11.2 \times \text{Critical Illness}]$$

Table 4 Intraclass correlation coefficients for the three predictive equations within the validation data set

Predictive equation	All patients (n=100)	<3 years old (n=41)	≥3 years old (n=59)
New	0.53 (0.31 to 0.69)	0.29 (−0.34 to 0.63)	0.61 (0.35 to 0.77)
LaFarge	0.17 (−0.23 to 0.44)	−1.10 (−3.22 to −0.12)	0.58 (0.30 to 0.75)
Lundell	0.45 (0.19 to 0.63)	0.56 (0.16 to 0.76)	0.42 (−0.06 to 0.68)

Values are intraclass correlation coefficient (95% CI).

Table 5 Predicted oxygen consumption (mL/min/m^2) by age and weight for not critically ill (top) and critically ill (below) patients with single ventricle anatomy

	2 kg	3 kg	4 kg	5 kg	7 kg	10 kg	15 kg	20 kg	25 kg	30 kg	35 kg	40 kg	45 kg	50 kg	60 kg	70 kg	80 kg	90 kg
0–6 months	187	176	169	167	159													
7–12 months				173	163	154	150											
2 years						161	147	137										
3 years						165	151	141	134									
4 years							154	144	137	130								
6 years							158	148	141	134	129	125						
8 years								151	143	137	132	127	123					
10 years									146	139	134	130	126					
12 years									147	141	136	131	127					
14 years										143	137	133	129					
16 years											139	134	130					
18 years													131					
20 years																		
25 years																		
30 years																		
0–6 months	175	165	158	156	147													
7–12 months				162	152	143	150											
2 years						150	136	126										
3 years						154	140	130	123									
4 years							143	133	125	119								
6 years							147	137	129	123	118	113						
8 years								140	132	126	121	116	112					
10 years									134	128	123	118	114					
12 years									136	130	125	120	116					
14 years										131	126	122	118					
16 years											128	123	119					
18 years													120					
20 years																		
25 years																		
30 years																		

Table 6 Predicted oxygen consumption (mL/min/m^2) by age and weight for not critically ill (top) and critically ill (below) patients with two ventricle anatomy

	2 kg	3 kg	4 kg	5 kg	7 kg	10 kg	15 kg	20 kg	25 kg	30 kg	35 kg	40 kg	45 kg	50 kg	60 kg	70 kg	80 kg	90 kg
0–6 months	196	186	178	177	168													
7–12 months				182	173	163	150											
2 years						171	157	147										
3 years						175	161	151	143									
4 years							164	154	146	140								
6 years							168	158	150	144	139	134						
8 years								161	153	147	142	137	133					
10 years									155	149	144	139	135	132	125			
12 years									157	151	146	141	137	133	127	122		
14 years										152	147	143	139	135	129	123	119	115
16 years											148	144	140	136	130	125	120	116
18 years													141	137	131	126	121	117
20 years														138	132	127	122	118
25 years														141	134	129	125	121
30 years														142	136	131	126	122
0–6 months	185	175	167	165	157													
7–12 months				171	162	152	150											
2 years						159	146	136										
3 years						163	150	140	132									
4 years							152	143	135	129								
6 years							156	147	139	133	128	123						
8 years								149	142	136	130	126	122					
10 years									144	138	133	128	124	120	114			
12 years									146	140	134	130	126	122	116	111		
14 years										141	136	131	127	124	118	112	108	104
16 years											137	133	129	125	119	114	109	105
18 years													130	126	120	115	110	106
20 years														127	121	116	111	107
25 years														129	123	118	113	109
30 years														131	125	120	115	111

Examples from UPMC Children's in 2023

Diagnosis	Age	Weight	Assumed VO_2 (LaFarge)	Assumed VO_2 (Seckeler)	Measured VO_2	Difference
Truncus (repaired), s/p CVA	19 months	16.2 kg	176 ml/min/m^2	147 ml/min/m^2	84 ml/min/m^2	

Directly measure oxygen consumption whenever possible.

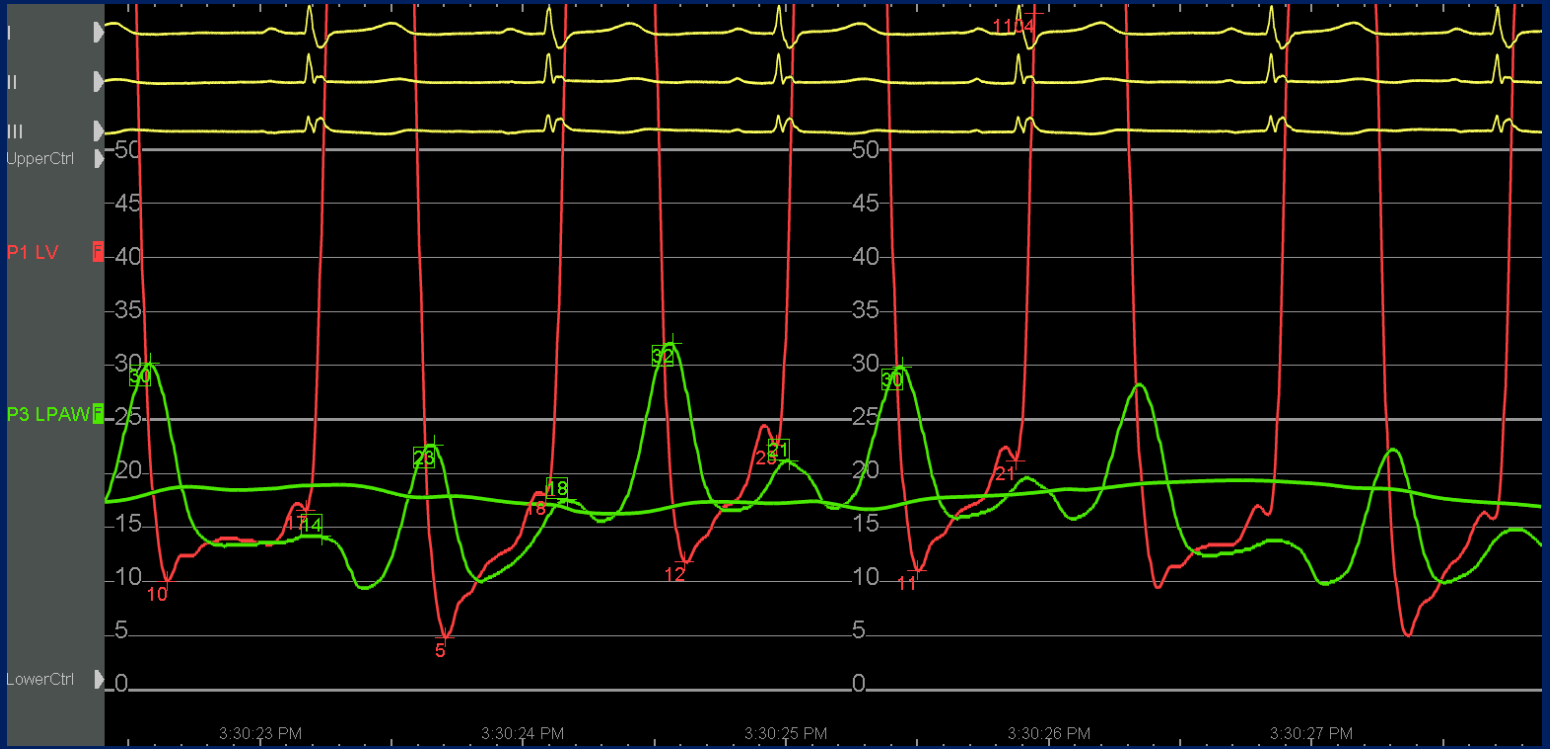
Resting hemodynamics may not be adequate in certain cases or populations

Dynamic Assessment

- Many limitations to hemodynamic assessment in the volume unloaded, anesthetized, supine and paralyzed state
- Stress hemodynamics may unmask underlying pathology that is otherwise concealed
- Exercise hemodynamics – well described but frequently unachievable
- Other stressors include inotropic/chronotropic agents or volume loading

Restrictive Physiology: Classic Example

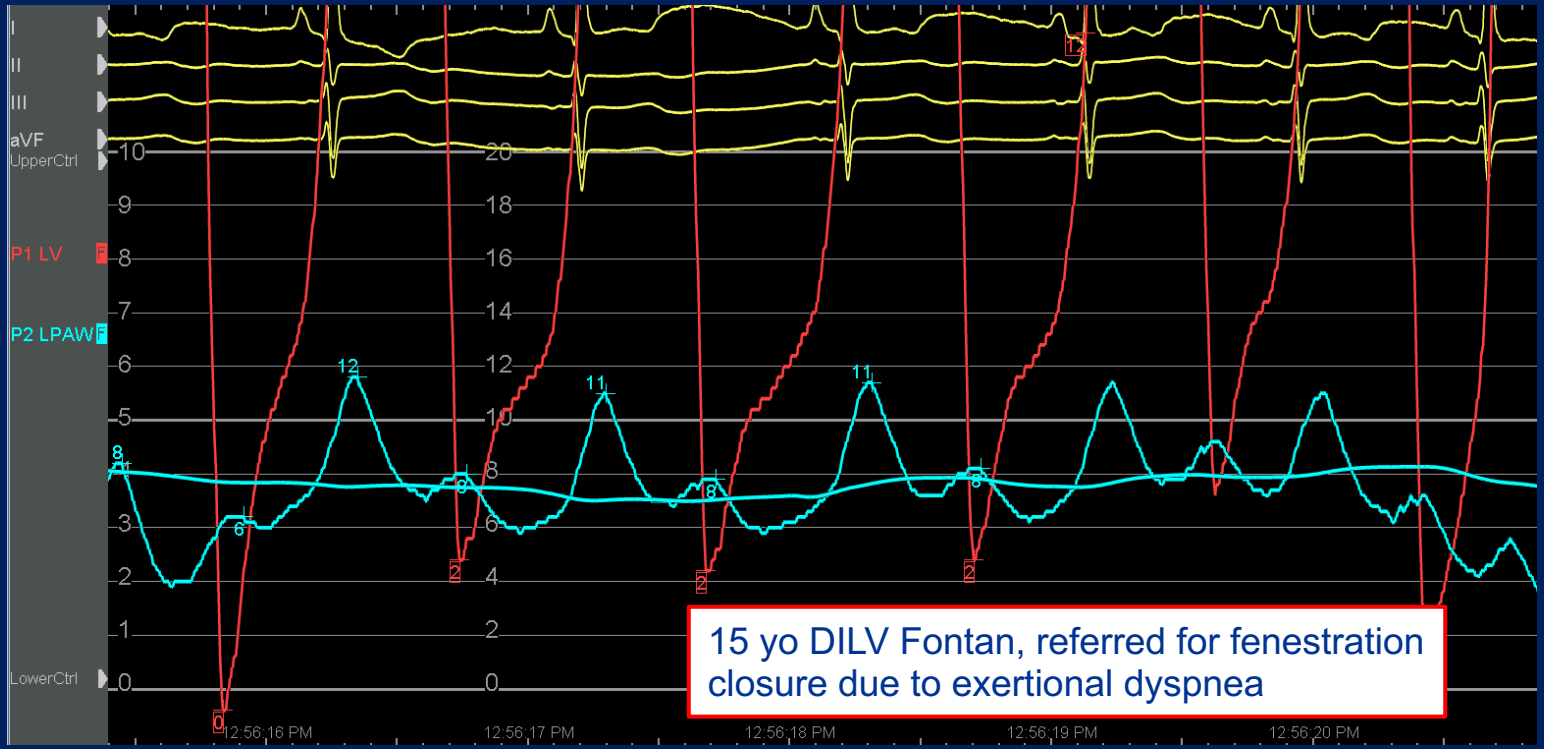
Restrictive Physiology: Classic Example



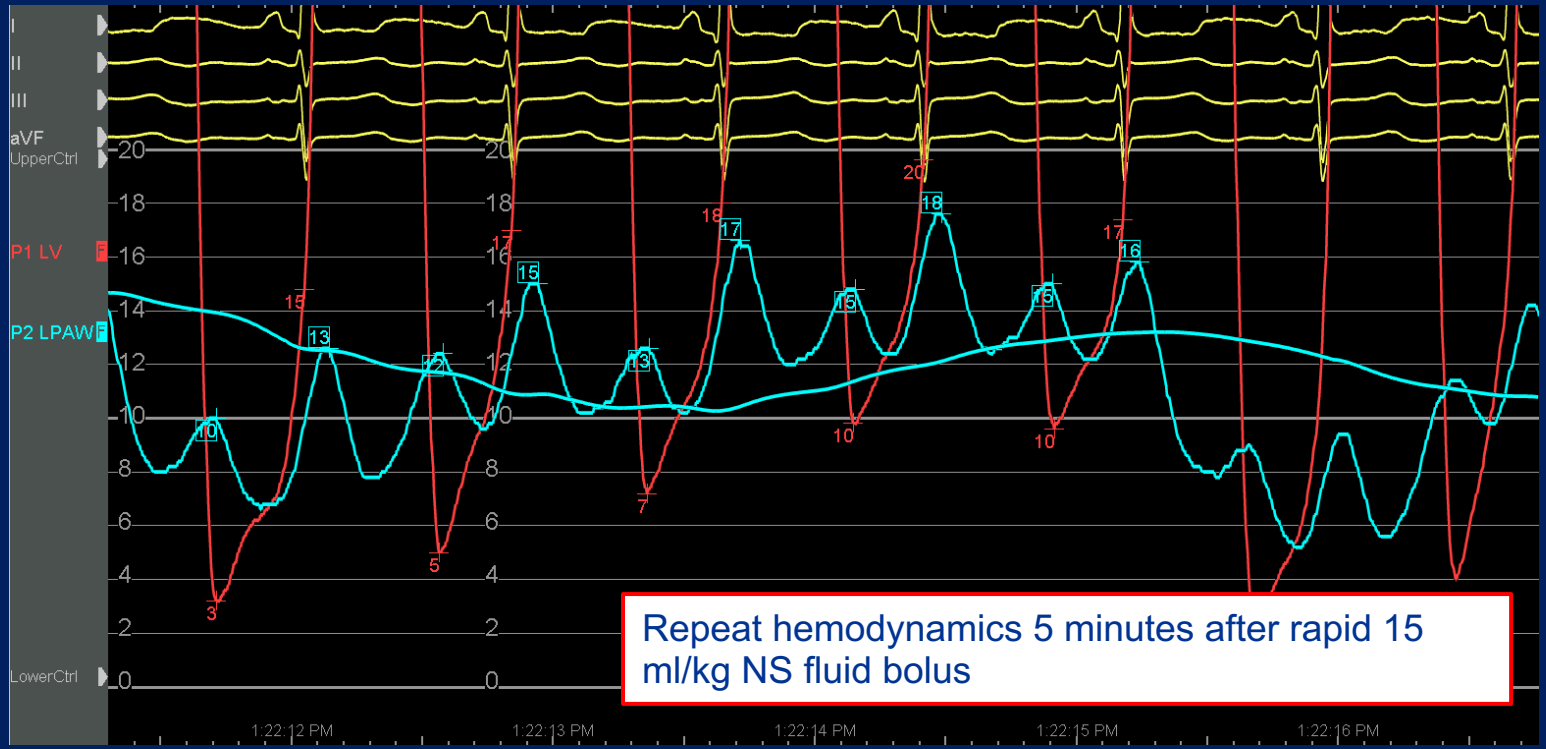
Volume Loading in CHD

- Limited role in hemodynamic assessment
- Fontan circulation offers an intriguing potential case for rapid volume expansion
- Population may be particularly prone to falsely low hemodynamics after NPO
- Patients are often symptomatic despite normal EDP, low PVR and preserved ventricular systolic function
- Only recently has diastolic dysfunction (FHFpEF) become accepted as frequent

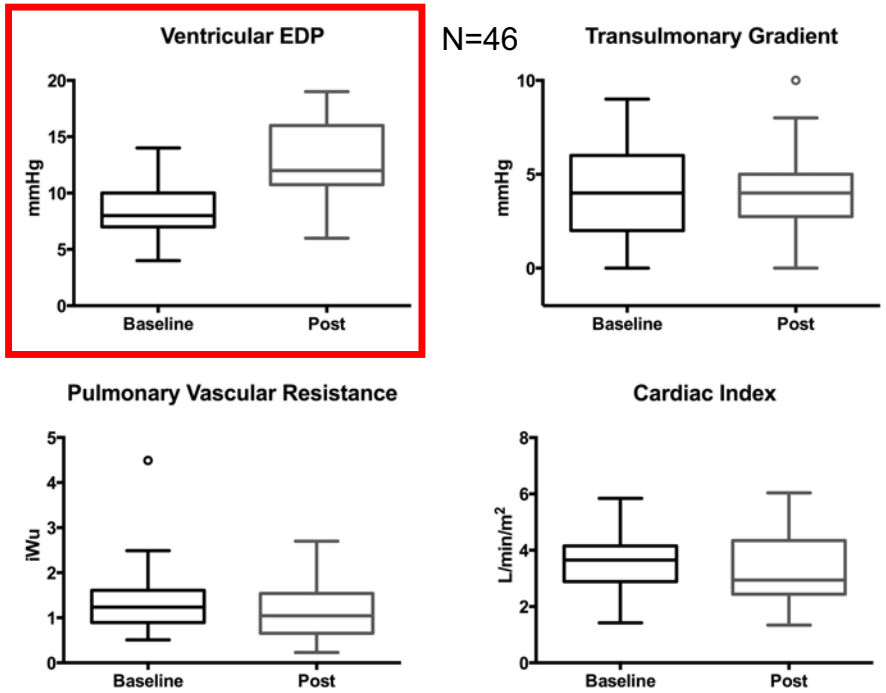
Impact of Volume Loading in Fontan

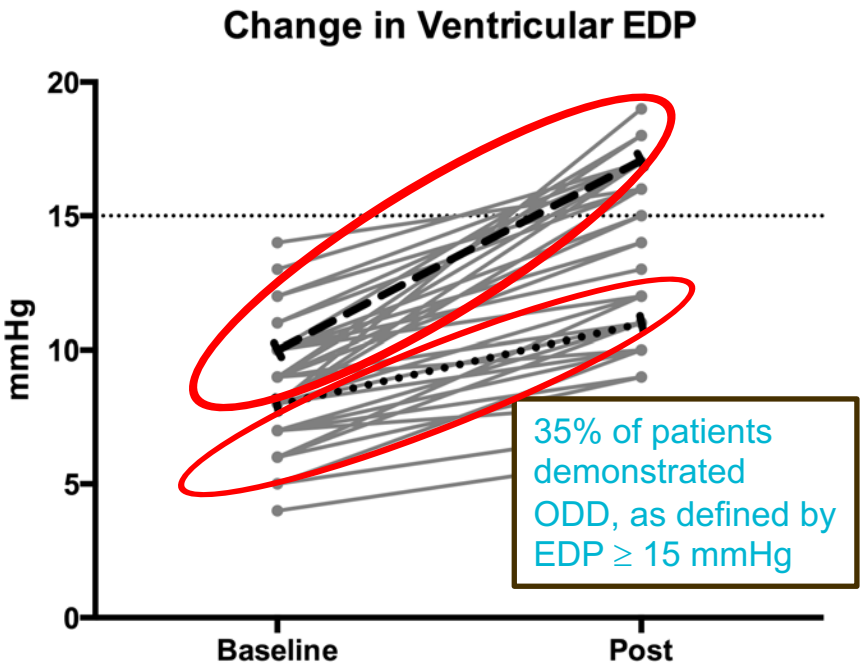


Impact of Volume Loading in Fontan



Occult Diastolic Dysfunction: Fontan





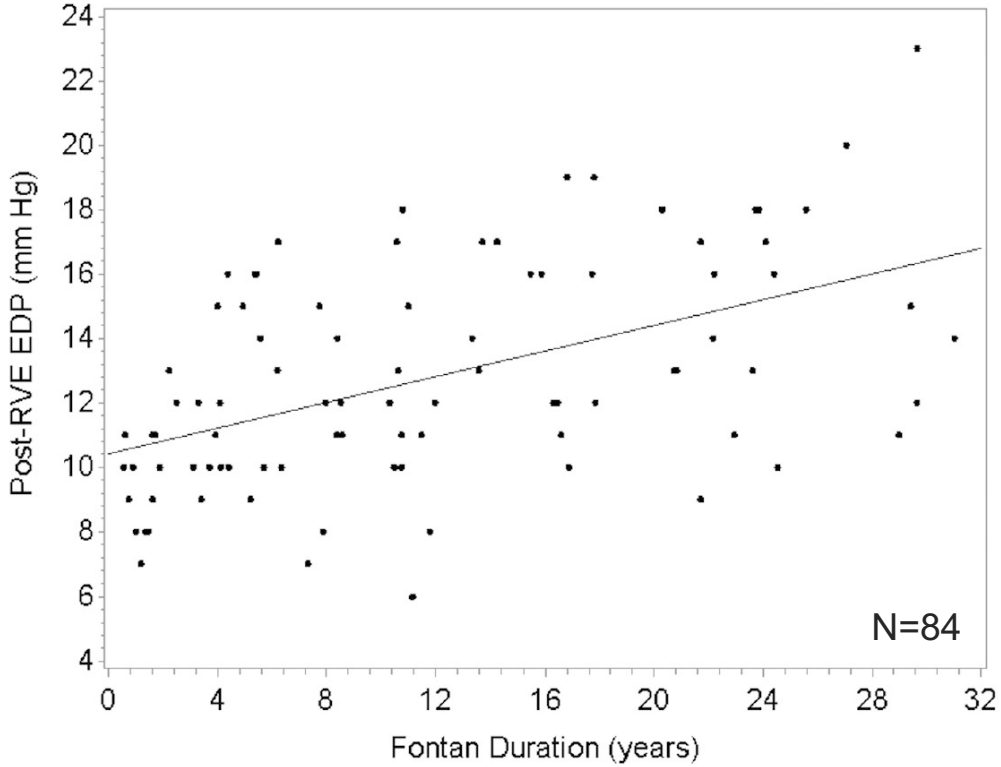
Averin K et al. *Heart.* 2016

Occult Diastolic Dysfunction in Fontan

- In univariate analysis, higher baseline EDP ($p<0.001$), longer duration of Fontan circulation ($p=0.02$) and lower baseline CI ($p=0.03$) were associated with higher fluid challenge EDP
- Longer duration of Fontan circulation ($p=0.04$) was associated with greater change in EDP
- In multivariable analysis, only higher baseline EDP ($p<0.001$) was significantly associated with higher fluid challenge EDP

Averin K et al. *Heart.* 2016

Occult Diastolic Dysfunction in Fontan



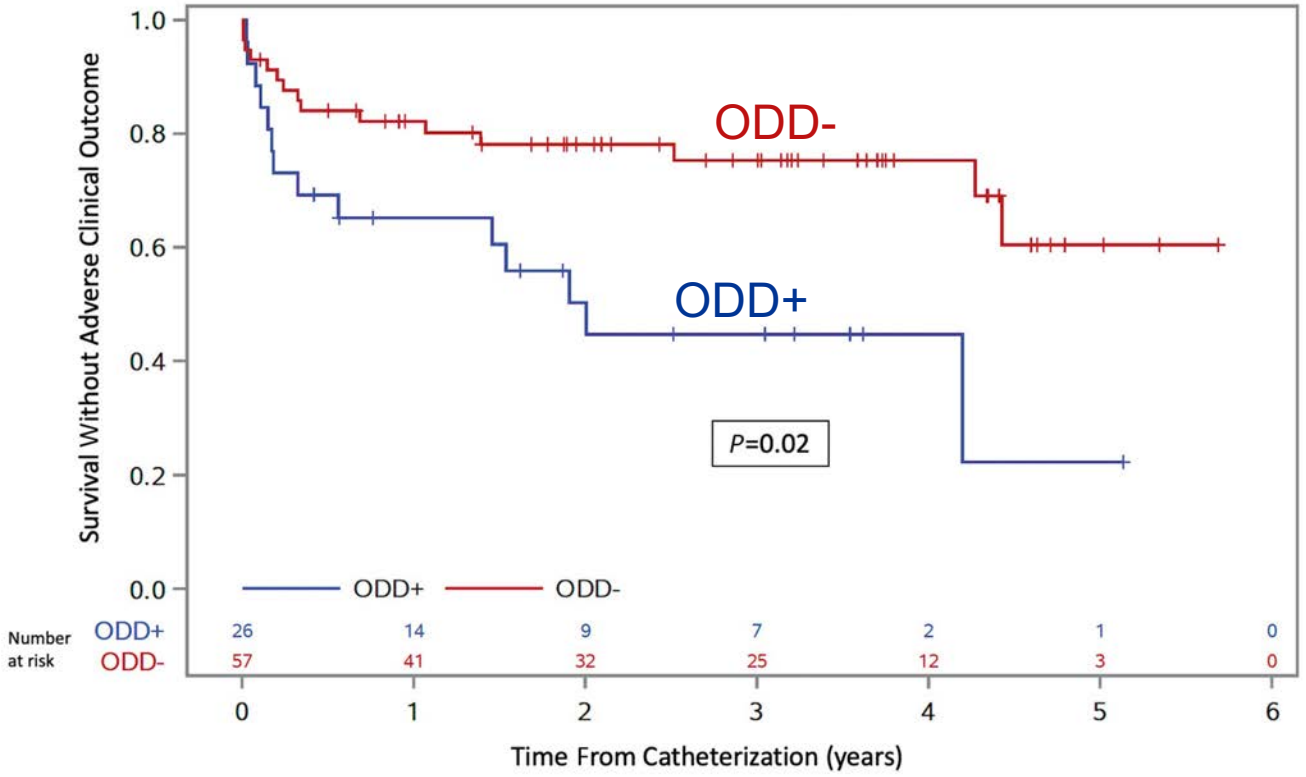
Peck D et al. *J Am Heart Assoc.* 2023.

Occult Diastolic Dysfunction in Fontan

Table 3. Adverse Clinical Outcomes

	All, N=84	ODD-positive, N=27	ODD-negative, N=57	*P* value
Composite clinical outcome*	29 (35)	14 (52)	15 (26)	0.03
Death, VAD, or transplant	9 (11)	3 (11)	6 (11)	1
Clinical outcome				
Mortality	4 (5)	1 (4)	3 (5)	1
Heart transplant†	5 (6)	2 (7)	3 (5)	0.65
VAD	1 (1)	0	1 (2)	1
Heart failure	10 (12)	5 (19)	5 (9)	0.28
Arrhythmia	10 (12)	4 (15)	6 (11)	0.72
CVA (including TIA)	4 (5)	2 (7)	2 (4)	0.59
Protein-losing enteropathy	2 (2)	2 (7)	0	0.1
Plastic bronchitis	3 (4)	1 (4)	2 (4)	1
Thrombus	1 (1)	0	1 (2)	1
Hemoptysis	2 (2)	1 (4)	1 (2)	0.52
Endocarditis	1 (1)	1 (4)	0	0.32
Seizure	1 (1)	0	1 (2)	1
Follow-up duration, y‡	2.9 (1.4–3.8)	2.5 (0.6–3.6)	3.0 (1.5–3.8)	0.44

Occult Diastolic Dysfunction in Fontan



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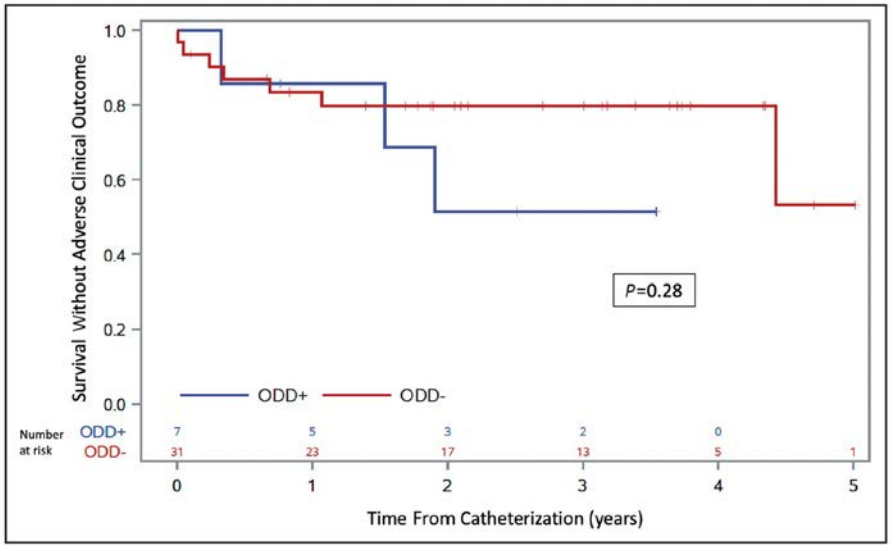
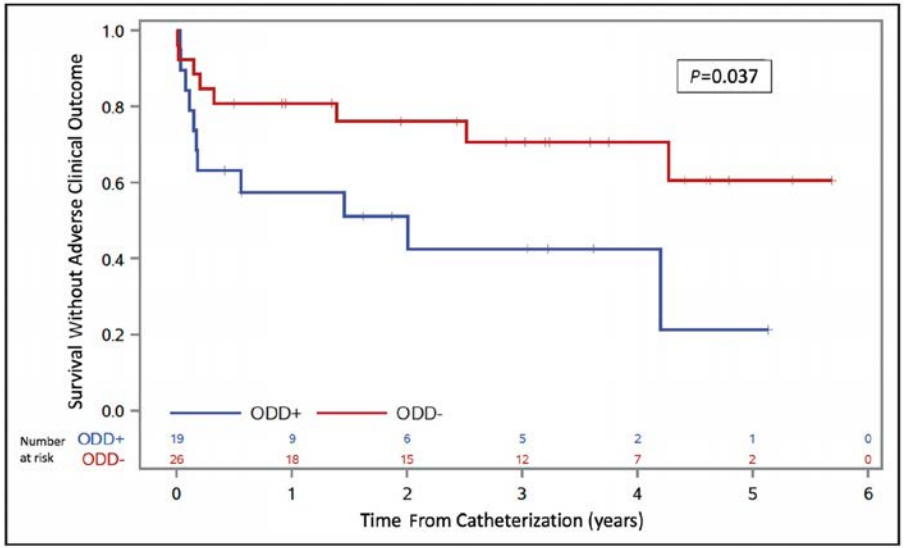
Occult Diastolic Dysfunction in Fontan

< 10 Year Fontan Duration



≥ 10 Year Fontan Duration



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Dynamic Evaluation of Fontan Circulation

Dynamic Evaluation of Fontan Circulation

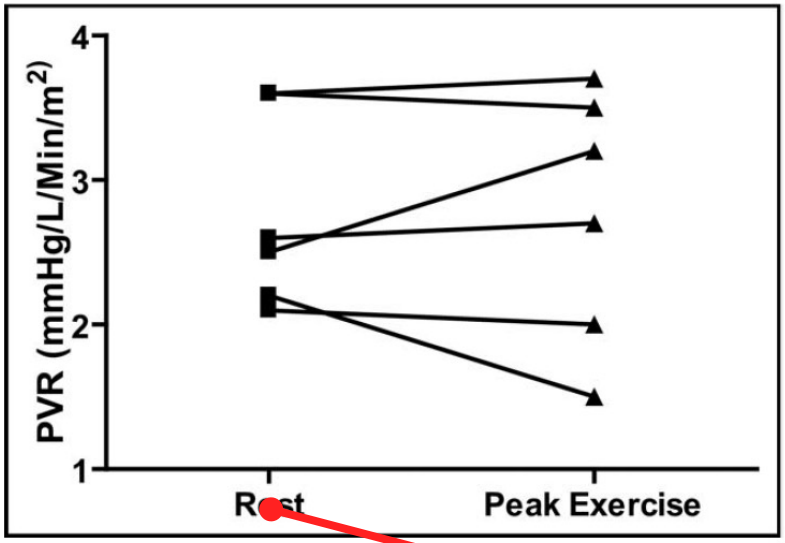
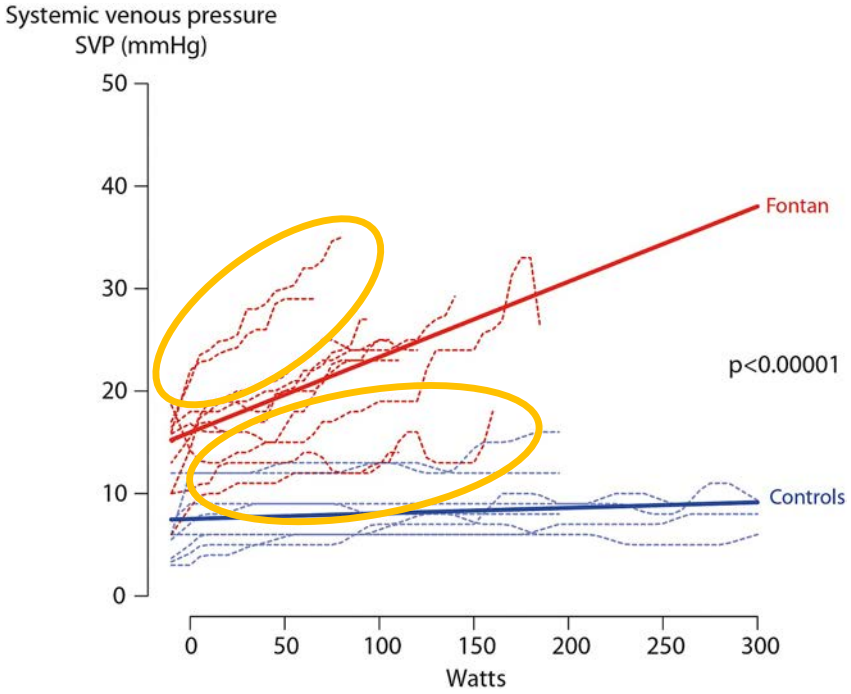


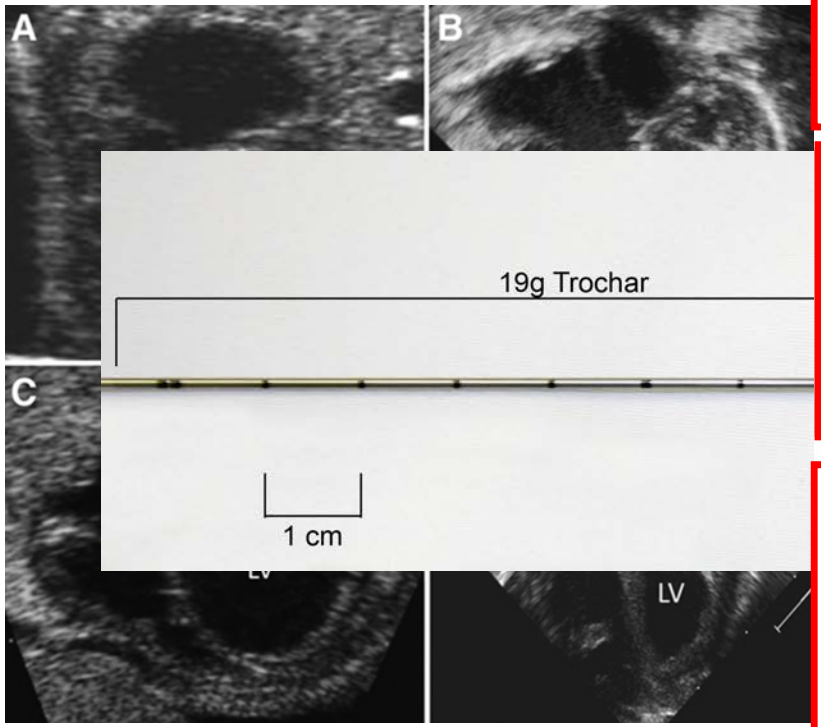
Figure 3. Change in PVR with supine exercise. Individual trends in PVR with supine exercise in 6 Fontan patients as assessed by invasive hemodynamic monitoring and determined using Fick principle.

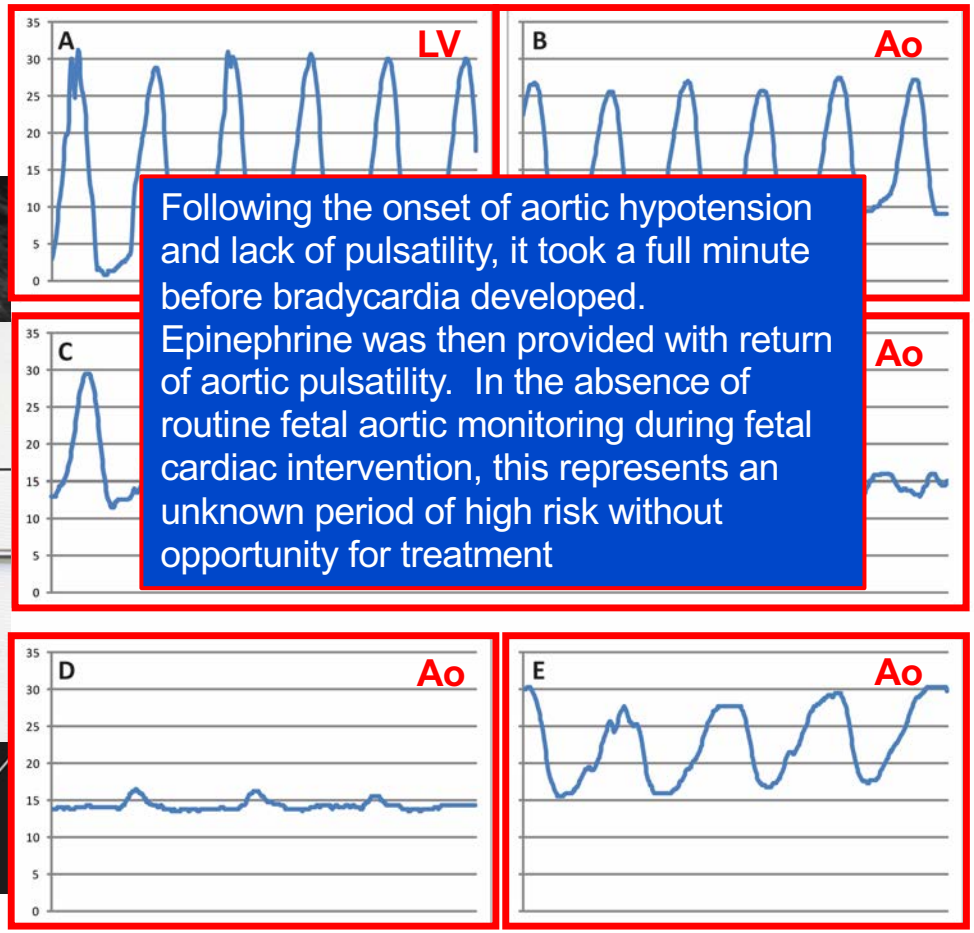


Goldstein B et al. *Am J Cardiol.* 2011
Navaratnam and Veldtman et al. *Am J Cardiol*. 2016

Use of novel technologies to acquire standard data

Fetal Critical AS with





Following the onset of aortic hypotension and lack of pulsatility, it took a full minute before bradycardia developed. Epinephrine was then provided with return of aortic pulsatility. In the absence of routine fetal aortic monitoring during fetal cardiac intervention, this represents an unknown period of high risk without opportunity for treatment

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Freud et al. *Circulation*. 2014.
Goldstein et al. *Pediatr.* 2011

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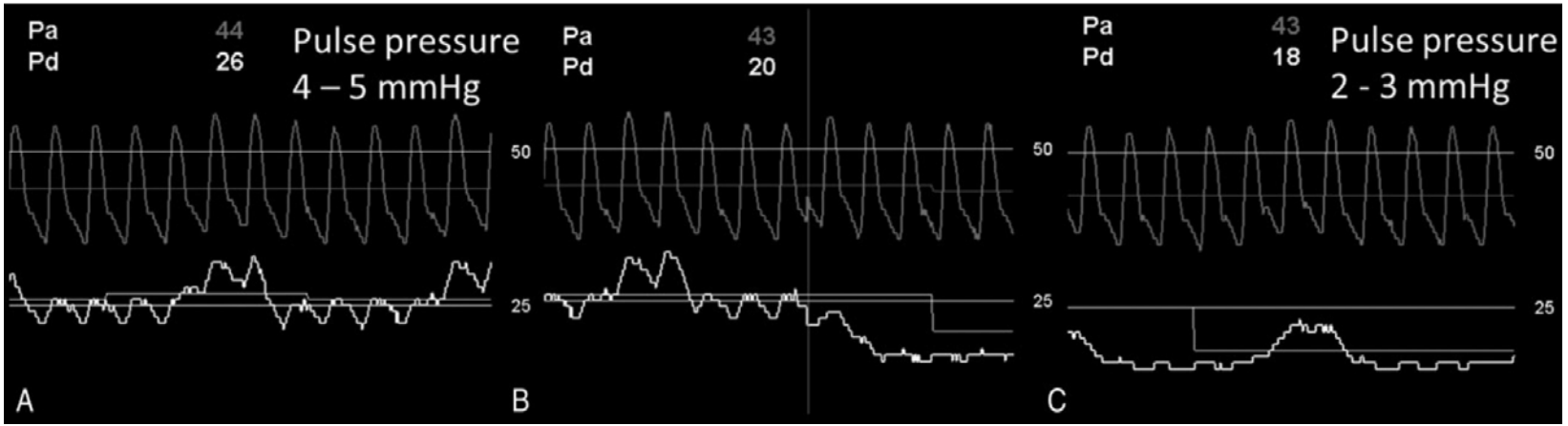
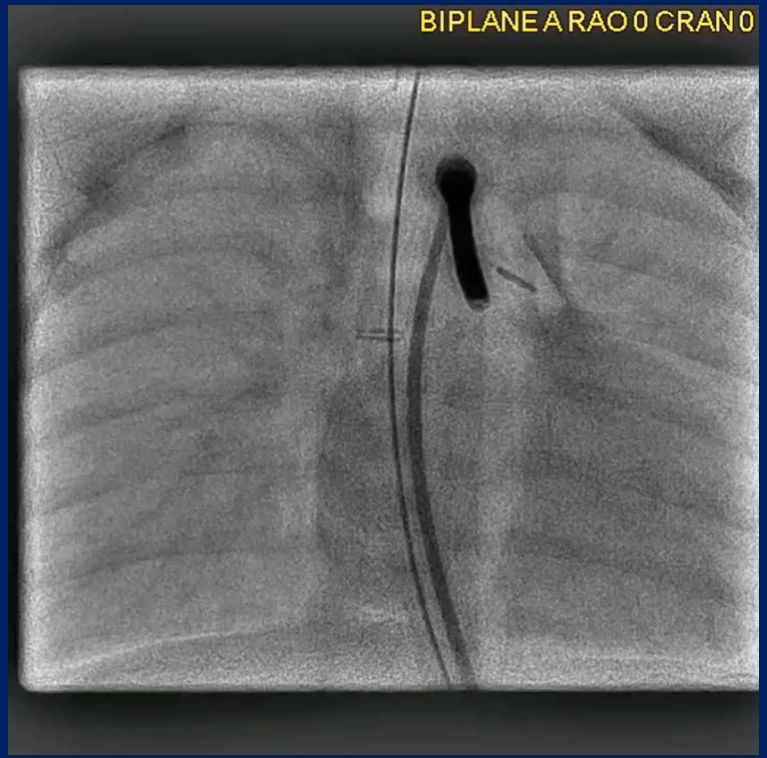
Use of a Pressure Guidewire to Assess Pulmonary Artery Band Adequacy in the Hybrid Stage I Procedure for High-risk Neonates with Hypoplastic Left Heart Syndrome and Variants

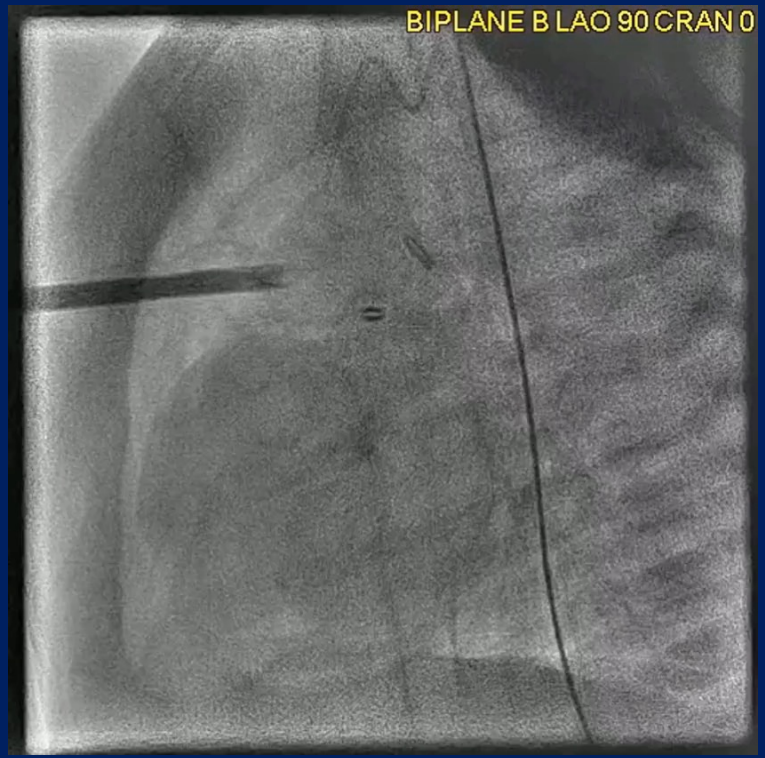
Jeffrey D. Zampi, MD,* Jennifer C. Hirsch, MD, MS,† Bryan H. Goldstein, MD,‡ and Aimee K. Armstrong, MD*



Zampi J et al. *Congenit Heart Dis.* 2013.

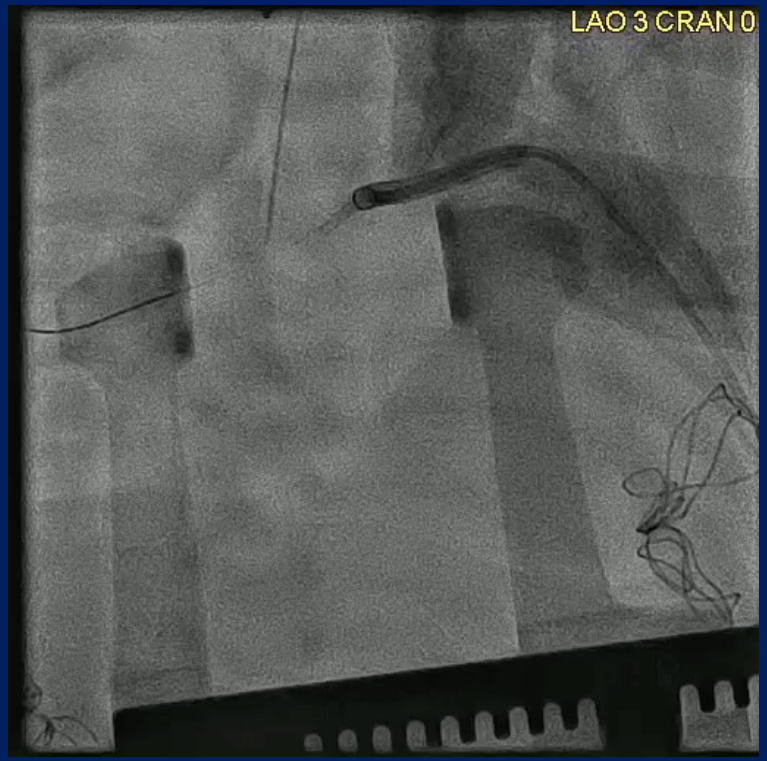
Hybrid PA Band Placement in HLHS

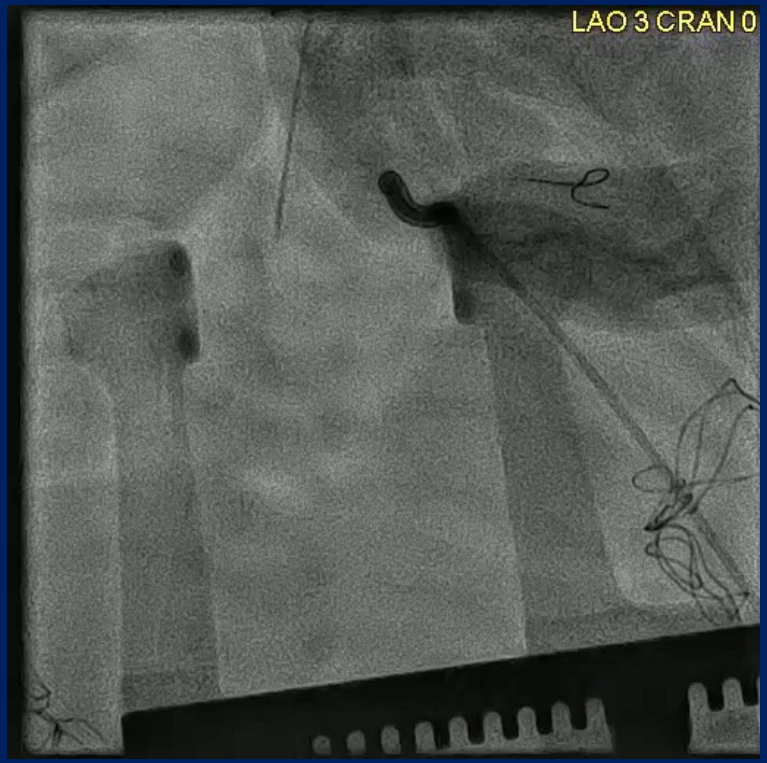




Pacella J and Batlivala SP et al. *In Preparation.*

Hybrid PA Band Placement in HLHS





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Pacella J and Batlivala SP et al. *In Preparation.*

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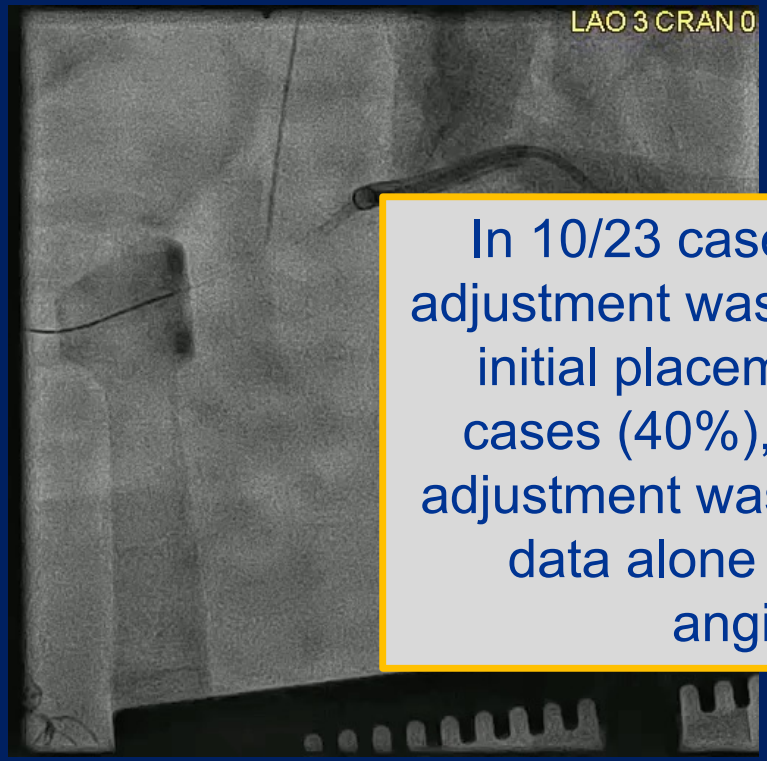
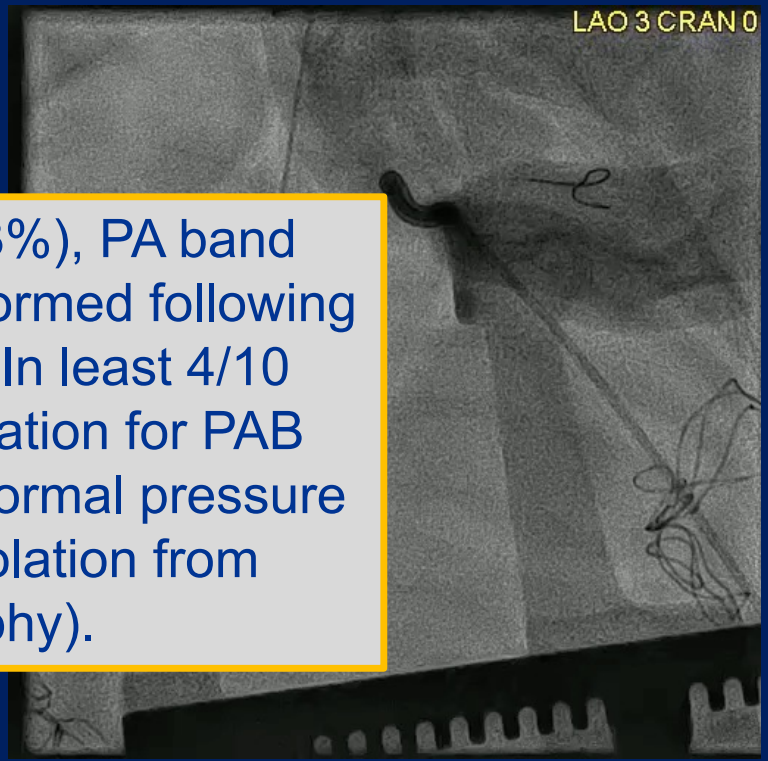
Hybrid PA Band Placement in HLHS





In 10/23 cases (43%), PA band adjustment was performed following initial placement. In least 4/10 cases (40%), indication for PAB adjustment was abnormal pressure data alone (in isolation from angiography).

Conclusions

- “There is no magic in magic, it’s all in the details”
  -Walt Disney
- Catheterization data are highly dependent upon the circumstances (state) at the time of data acquisition
- Assumed data are just that
- Dynamic testing (volume, exercise, pharmacologic) increases the likelihood of identifying occult pathology – e.g. Fontan ODD
- Even in an era where catheterization-related “press” is dominated by interventional procedures, nuanced hemodynamic interrogations still matter

Thank You

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