Techniques for More Accurate Characterization of the Fontan Circulation: Provocative Assessments

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Disclosures

- None related to this talk

- Consultant and/or Proctor for:
  - Edwards Lifesciences
  - Medtronic
  - W.L. Gore & Associates
  - St. Jude Medical
  - Philips Medical

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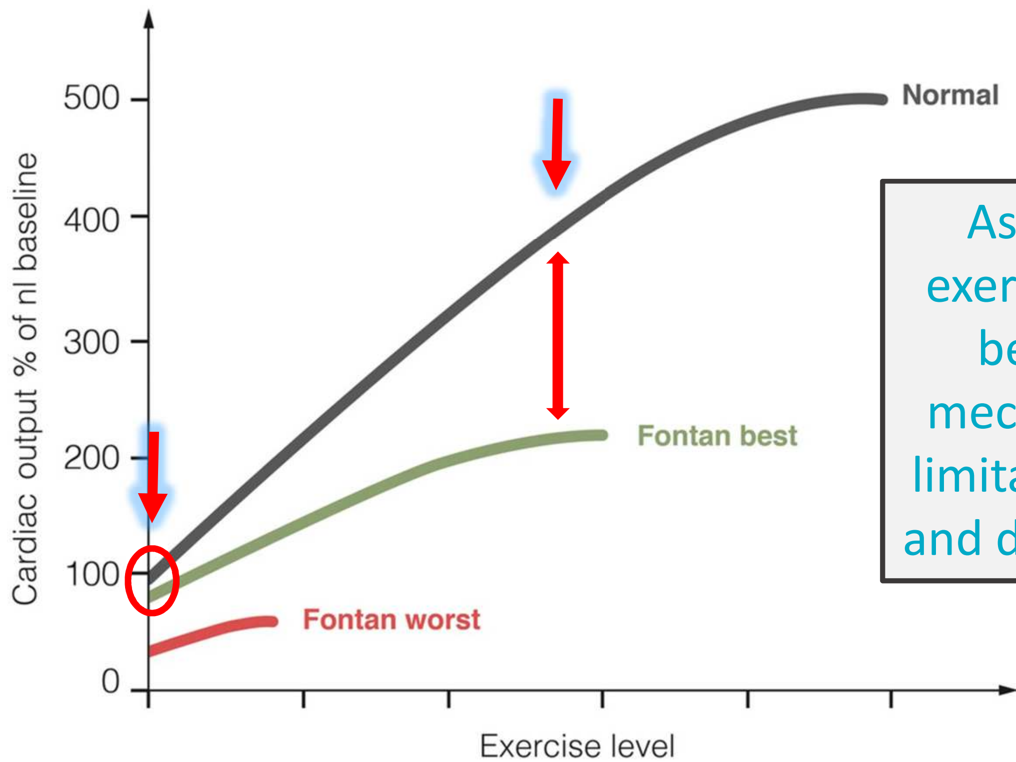
Objectives

- The problem with static testing
- Dynamic testing
  - Exercise stress
  - Pharmacologic stress
  - Implantable monitor
  - Dyssynchrony (if we have time)
- Conclusions

Cardiac Output: Rest vs. Exercise

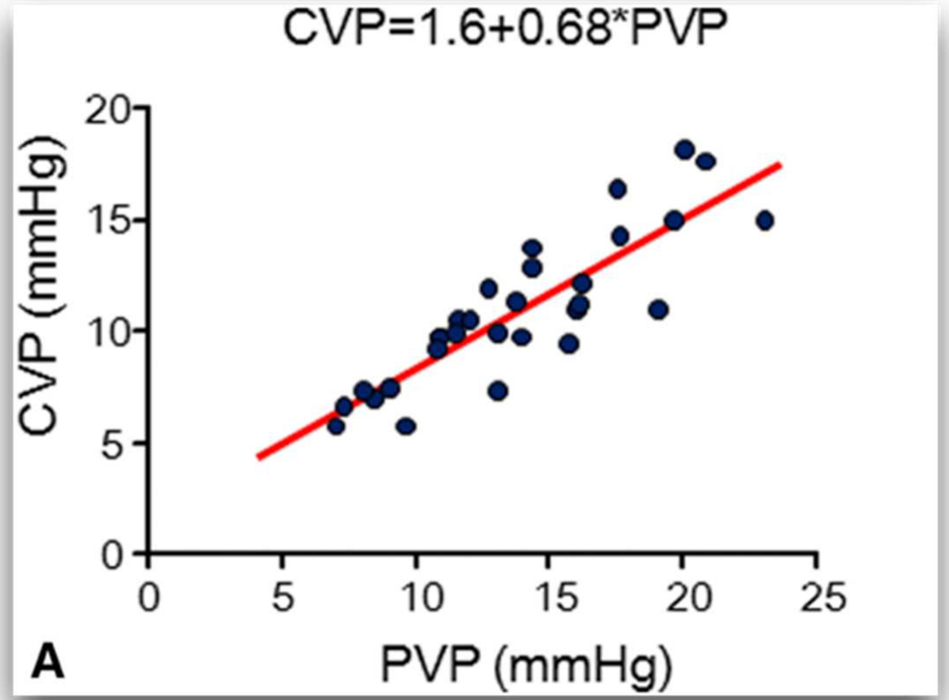


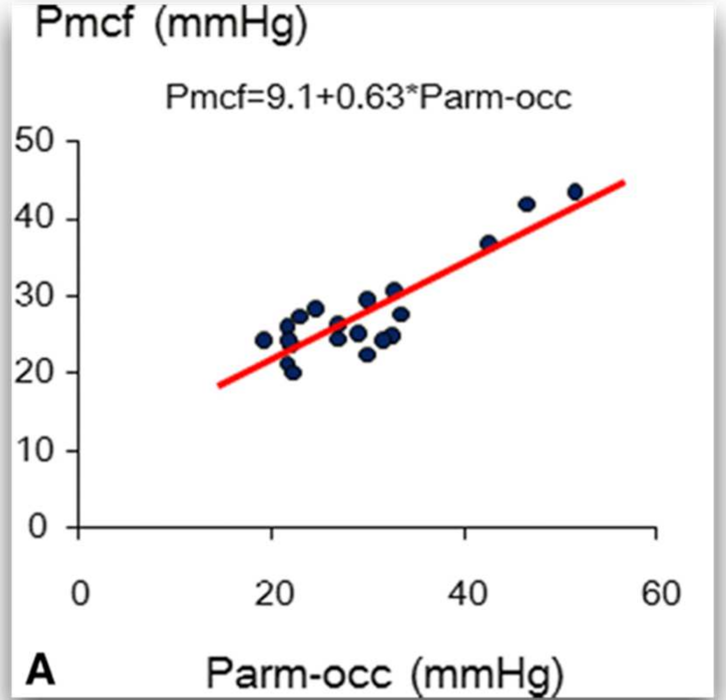
Assessment during exertion ought to offer better insight into mechanisms of Fontan limitations, including Rp and diastolic dysfunction

Adapted from Gewillig M and Goldberg DJ. *Heart Fail Clin* 2014;10:105-16.

Stressing the Already Stressed

Validation of PVP ≅ CVP

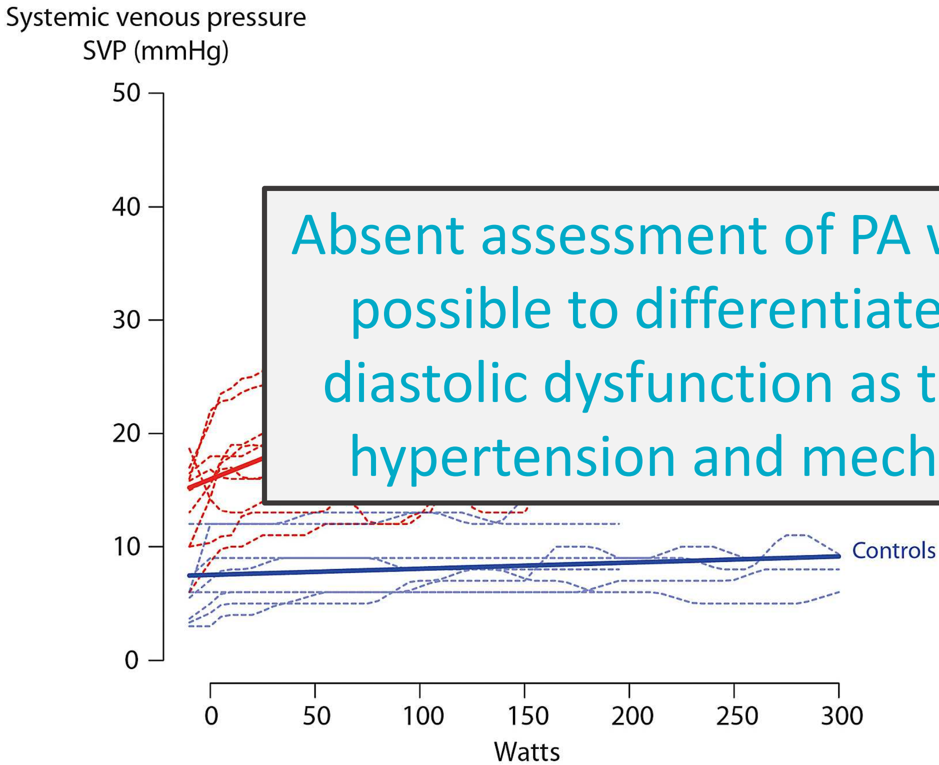


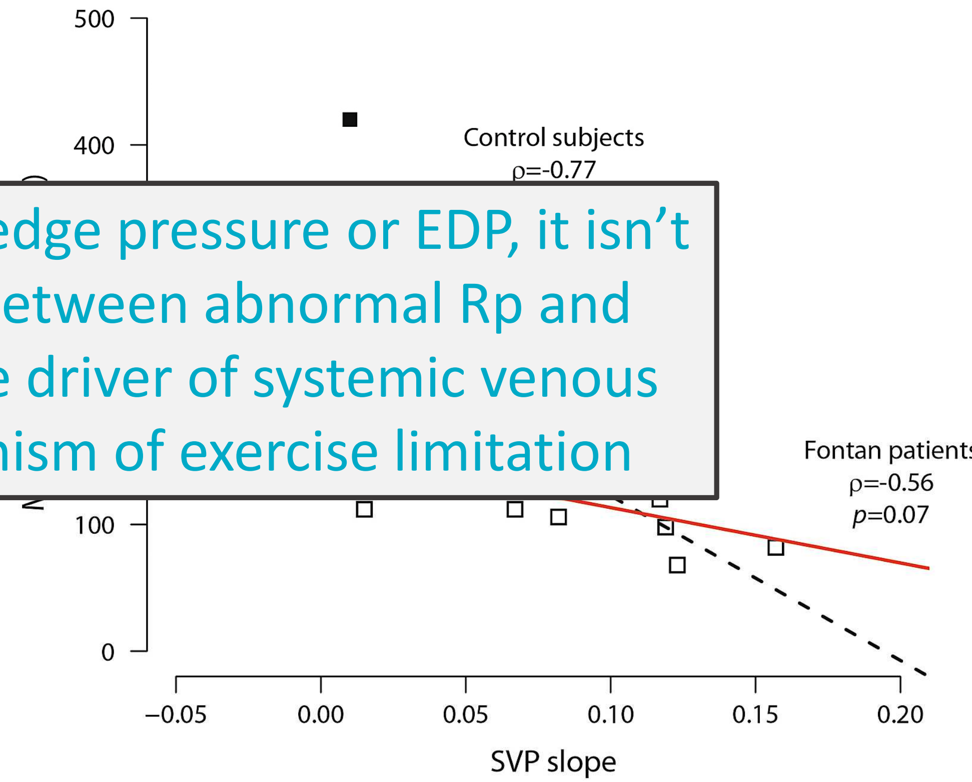


Musutani et al. *JTCVS* 2016


60
120 / 80
98
120 / 80
6.8
20

Exercise Induced Venous Hypertension

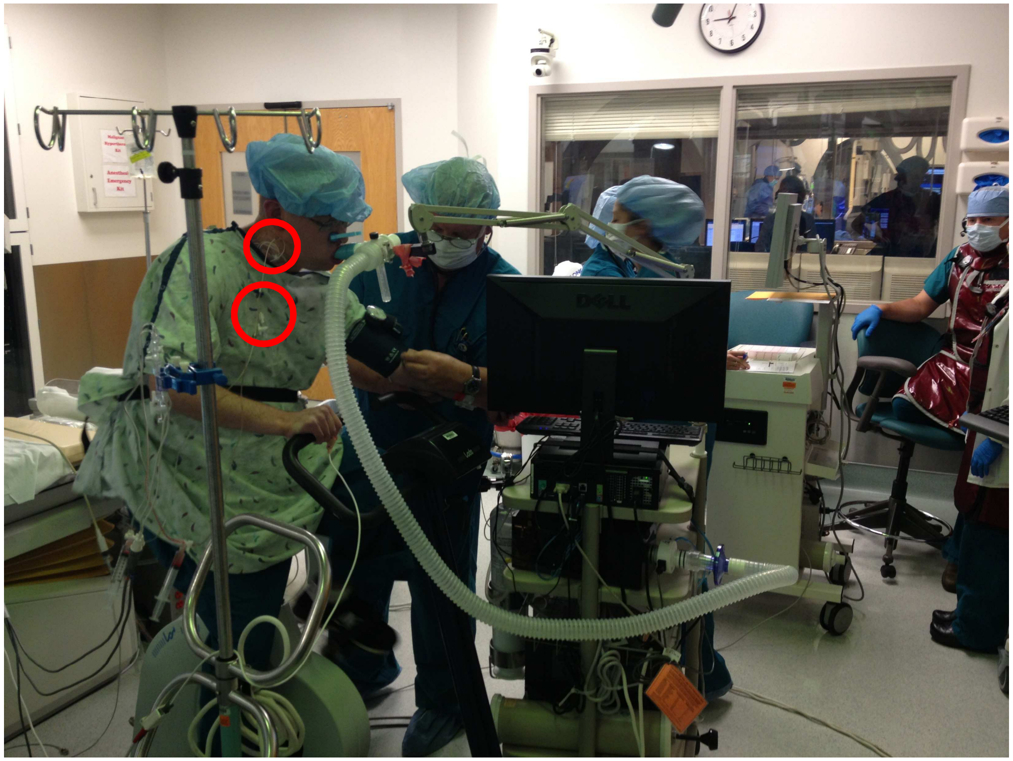




Absent assessment of PA wedge pressure or EDP, it isn't possible to differentiate between abnormal Rp and diastolic dysfunction as the driver of systemic venous hypertension and mechanism of exercise limitation

Navaratnam, Veldtman et al. *Am J Cardiol* 2016.

Invasive Exercise Hemodynamics



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Relation of Systemic Venous Return, Pulmonary Vascular Resistance, and Diastolic Dysfunction to Exercise Capacity in Patients With Single Ventricle Receiving Fontan Palliation

Bryan H. Goldstein, MD[a,b,*], Chad E. Connor, MD[c], Lindsay Gooding, BS[a,b], and Albert P. Rocchini, MD[a,b]

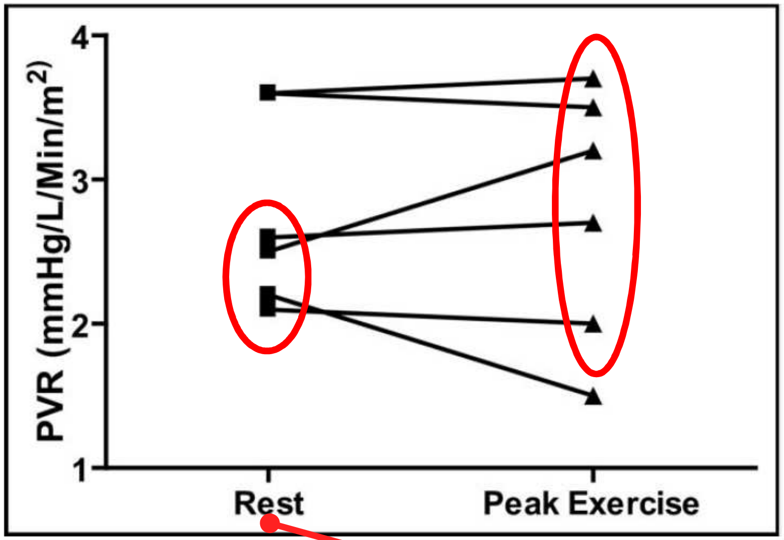
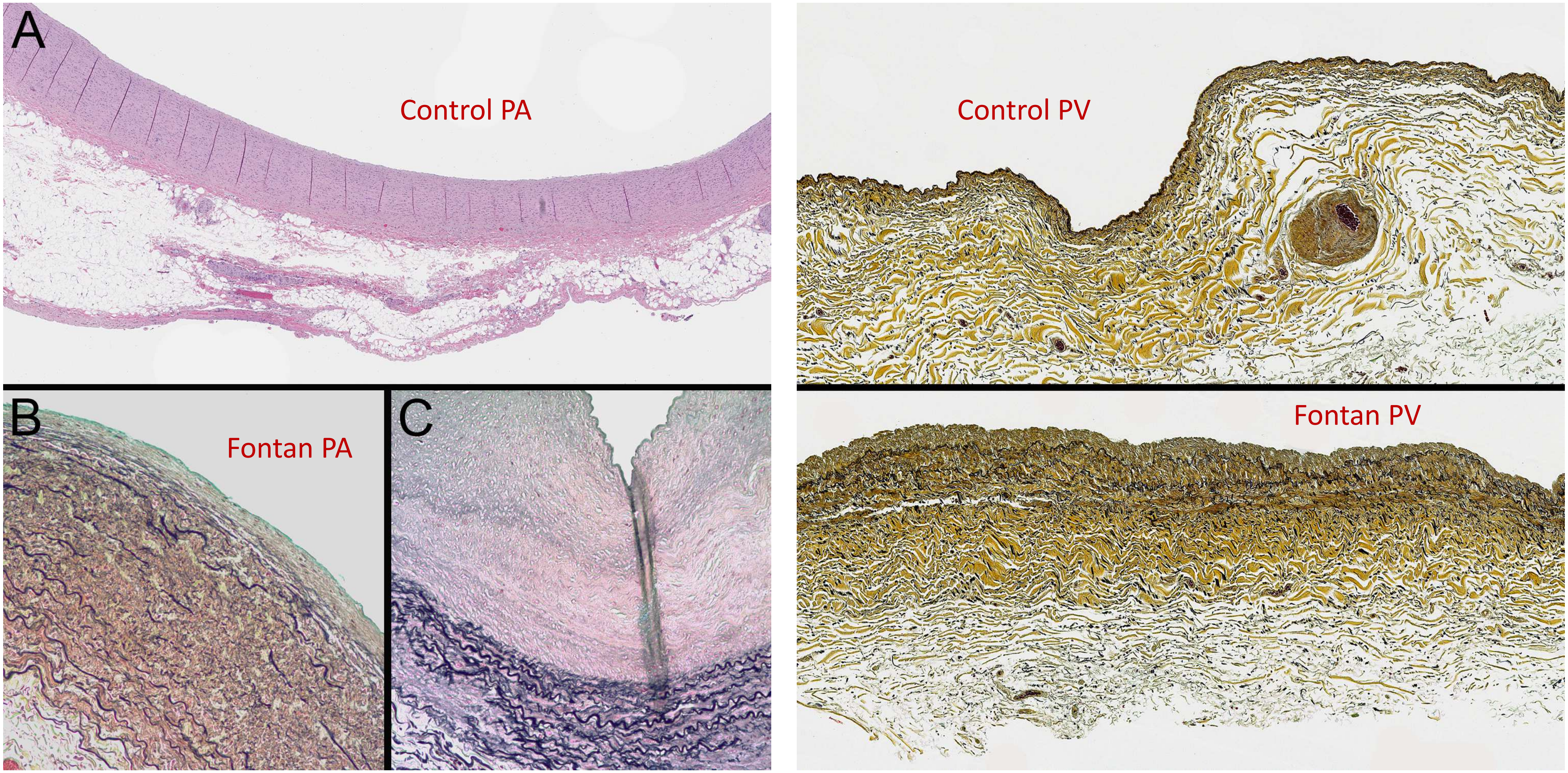


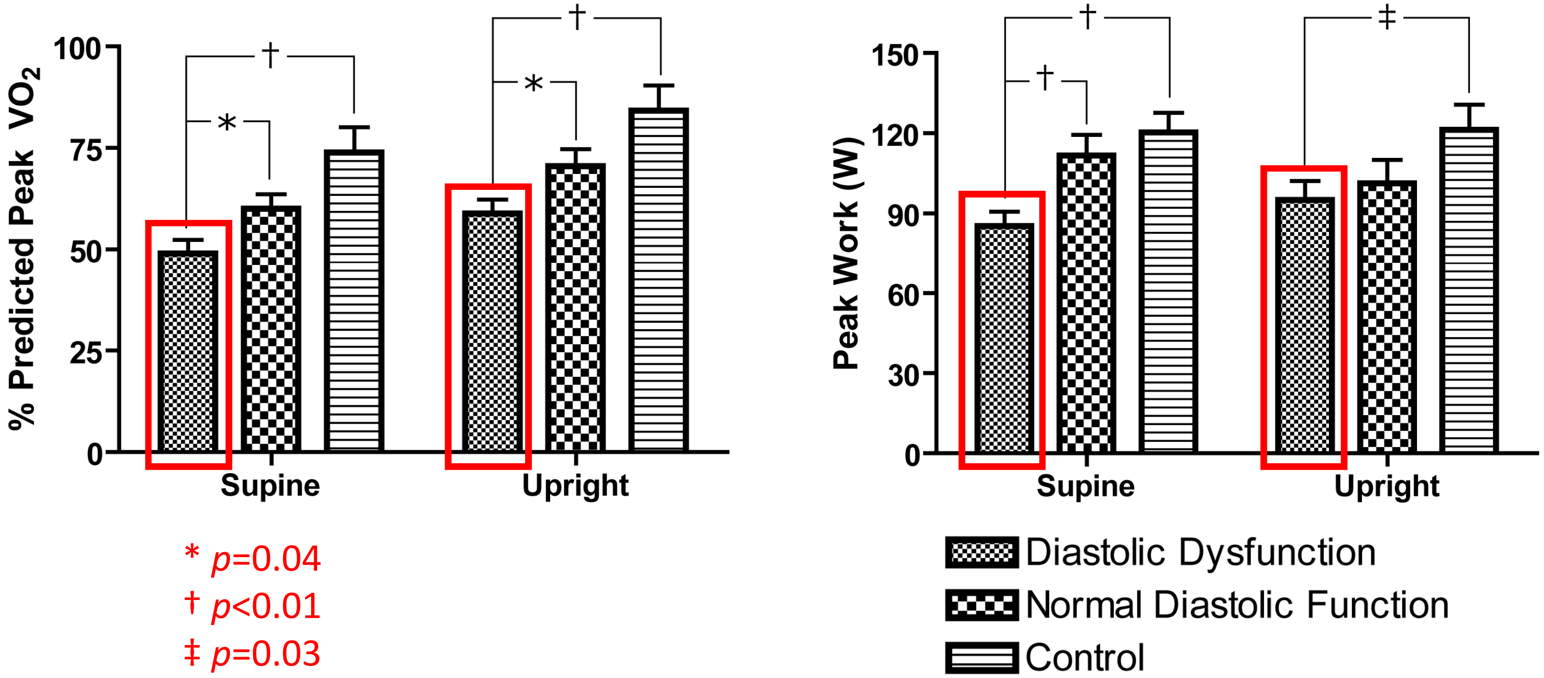
Figure 3. Change in PVR with supine exercise. Individual trends in PVR with supine exercise in 6 Fontan patients as assessed by invasive hemodynamic monitoring and determined using Fick principle.

Goldstein BH et al. *Am J Cardiol* 2010;105:1169-1175



Hays BS, Veldtman GR. *Heart*. 2017.

Diastolic Dysfunction & Exercise



* p=0.04
† p<0.01
‡ p=0.03

Goldstein BH, Rocchini A et al. *Am J Cardiol* 2010.

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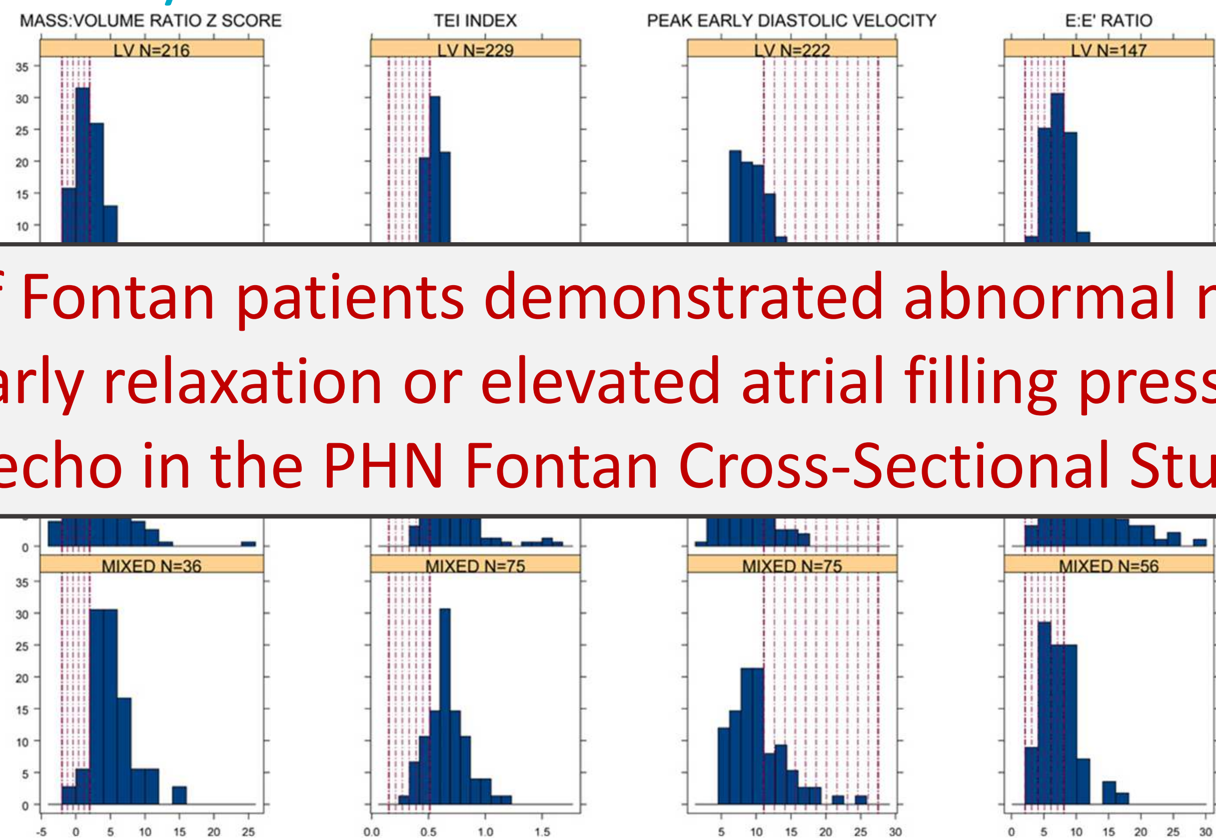
Diastolic Dysfunction: Prevalence



72% of Fontan patients demonstrated abnormal measures of early relaxation or elevated atrial filling pressure by echo in the PHN Fontan Cross-Sectional Study

Anderson et al. *J Am Coll Cardiol* 2008

Diastolic Dysfunction: Diagnosis

- The diagnosis of diastolic dysfunction in the Fontan patient is difficult, without population-specific validated non-invasive measures
- Invasive assessment of EDP, even in the symptomatic Fontan patient, is frequently unrevealing in the resting state

Fontan Fluid Challenge

Baseline Hemodynamic Assessment	
Include: Elective Fontan Cath	*Exclude: EDP ≥15 or PA ≥18 mmHg*

Averin K et al. *Heart.* 2016

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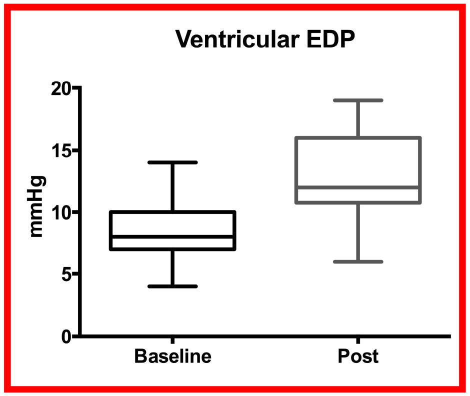
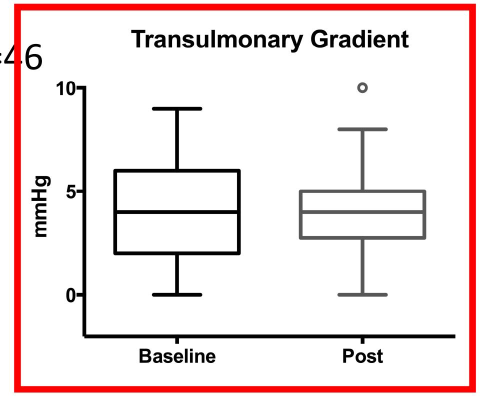
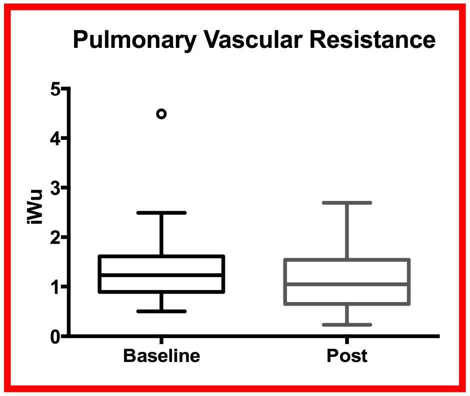
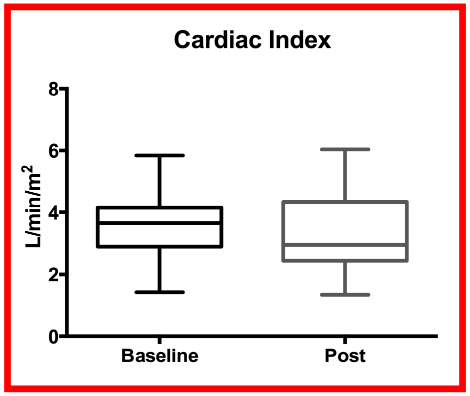
Occult Diastolic Dysfunction

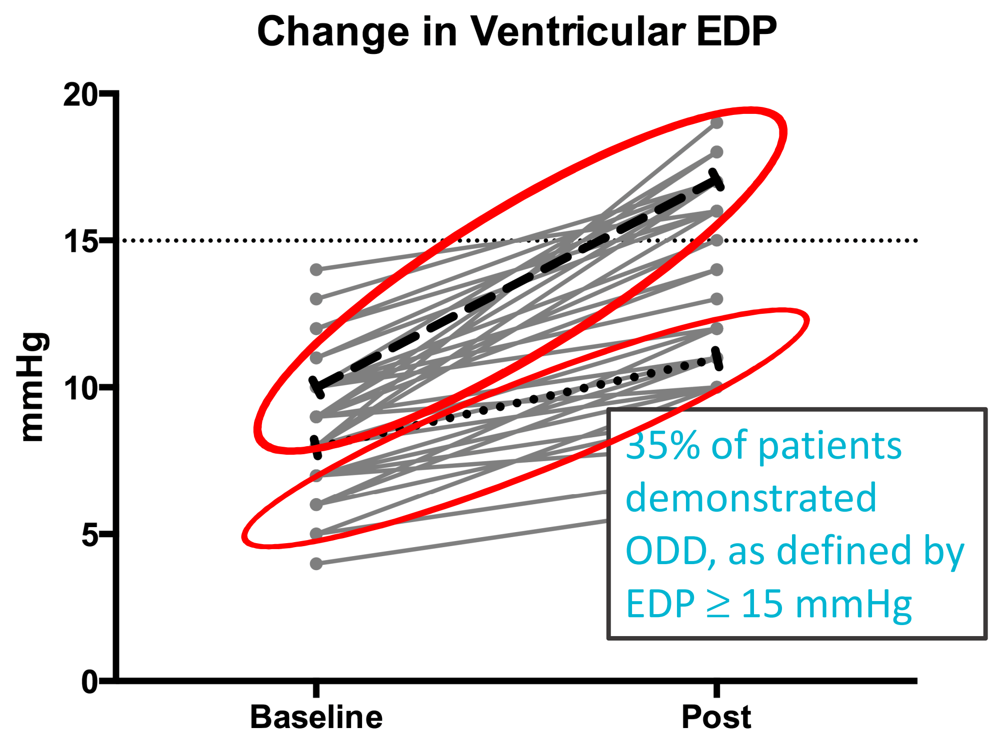


N=46







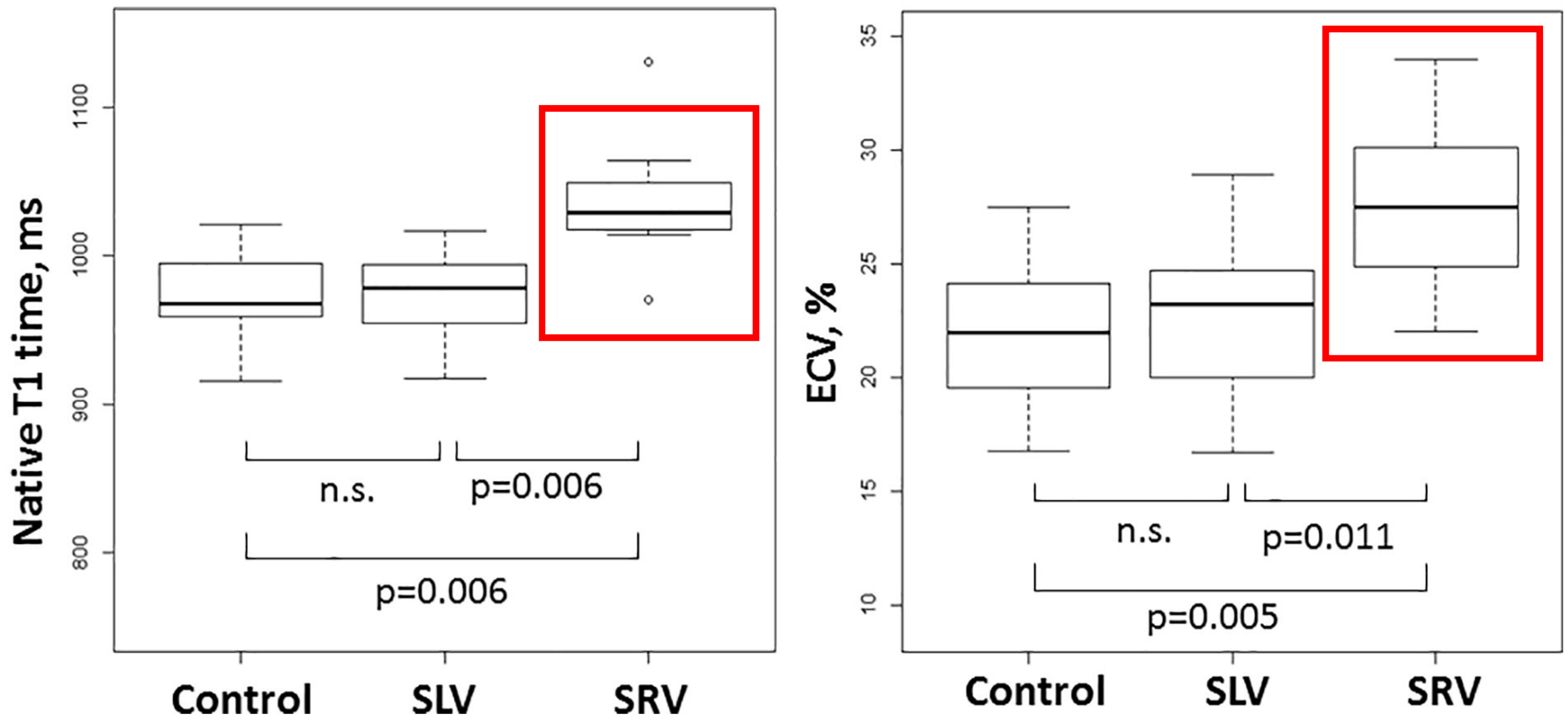


Factors Associated with ODD

- Higher baseline EDP, longer duration of Fontan circulation and lower baseline CI were associated with higher fluid challenge EDP
- Longer duration of Fontan circulation was associated with greater change (steeper rise) in EDP
- Ongoing efforts:
  - Identifying potential *causes* of ODD (e.g. myocardial fibrosis)
  - Association between fluid challenge EDP/compliance slope and mid-term clinical outcomes

Averin K et al. *Heart* 2016;14:1109-14

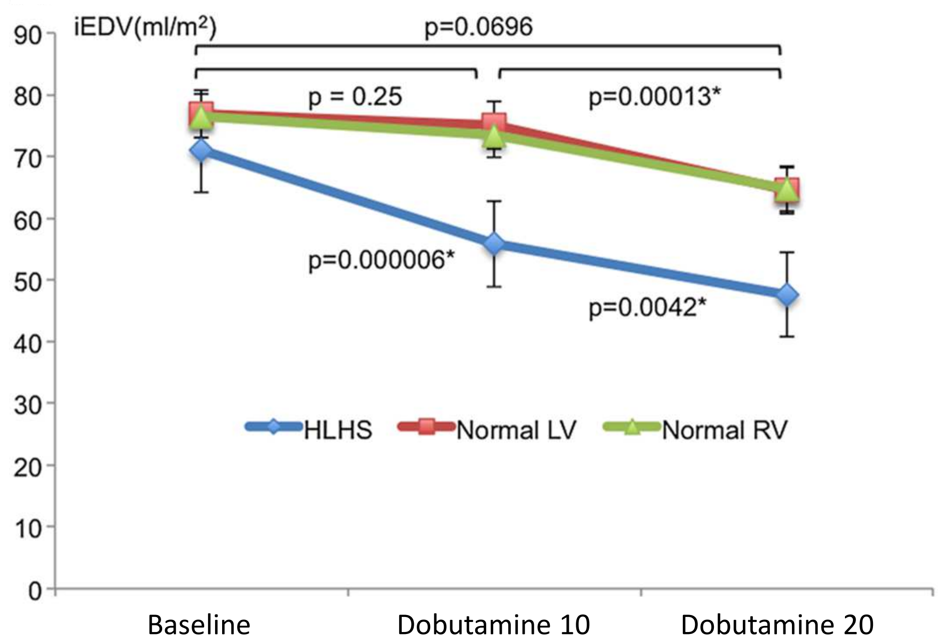
T1/ECV Assessment of Myocardial Fibrosis

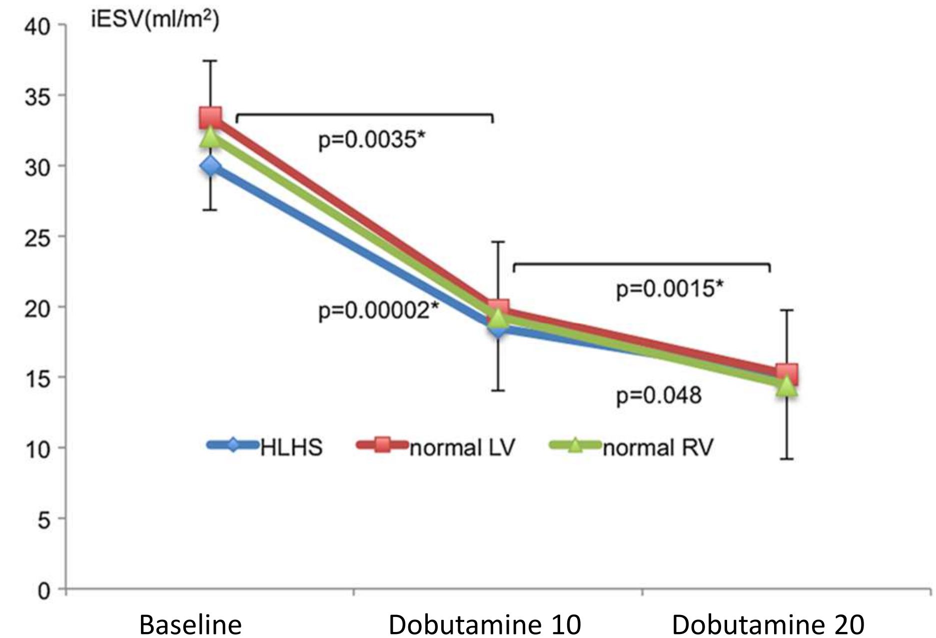


Kato et al. *Int J Cardiol* 2017.

Magnetic resonance imaging catheter stress haemodynamics post-Fontan in hypoplastic left heart syndrome

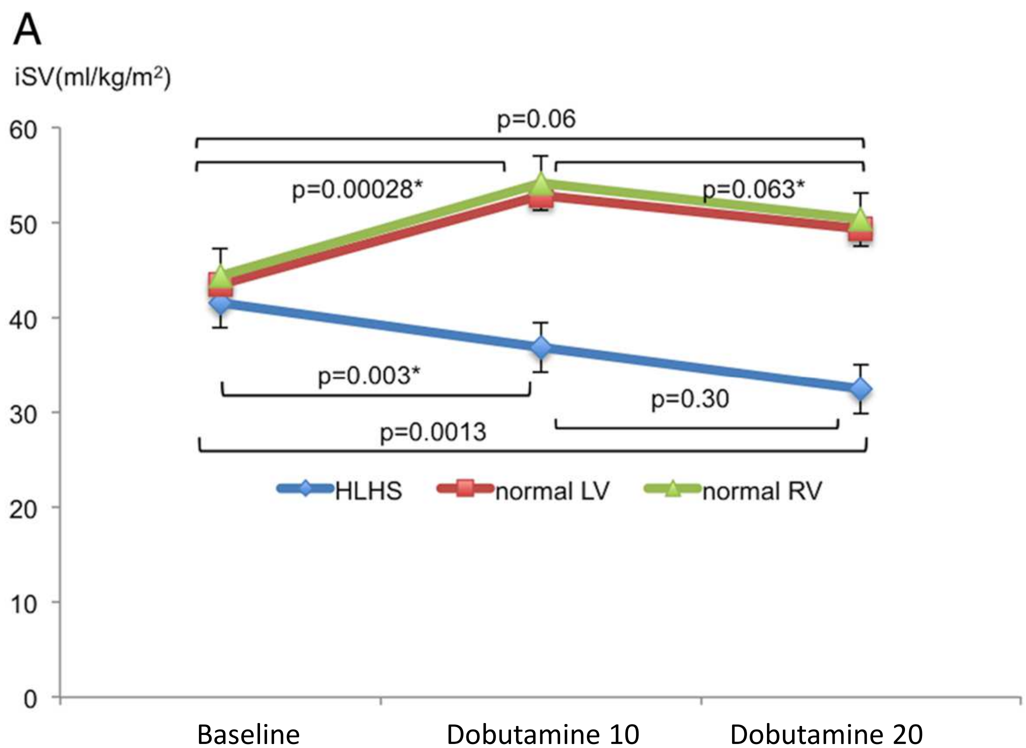
Kuberan Pushparajah[1,2], James K. Wong[1], Hannah R. Bellsham-Revell[2], Tarique Hussain[1,2], Israel Valverde[1], Aaron Bell[2], Aphrodite Tzifa[1], Gerald Greil[1,2], John M. Simpson[1,2], Shelby Kutty[3], and Reza Razavi[1,2,4*]

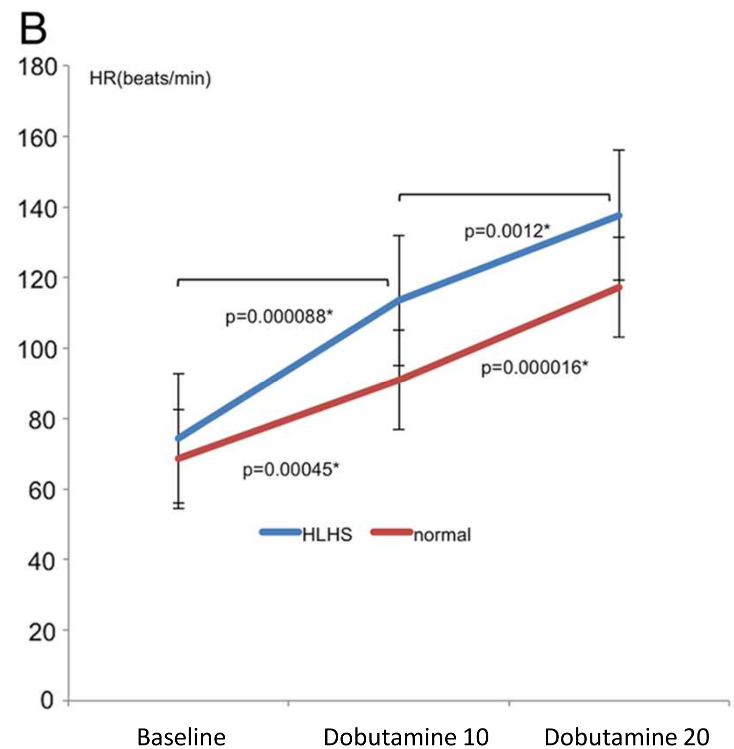




Pushparajah et al. *Eur Heart J Cardiovasc Imag* 2016.

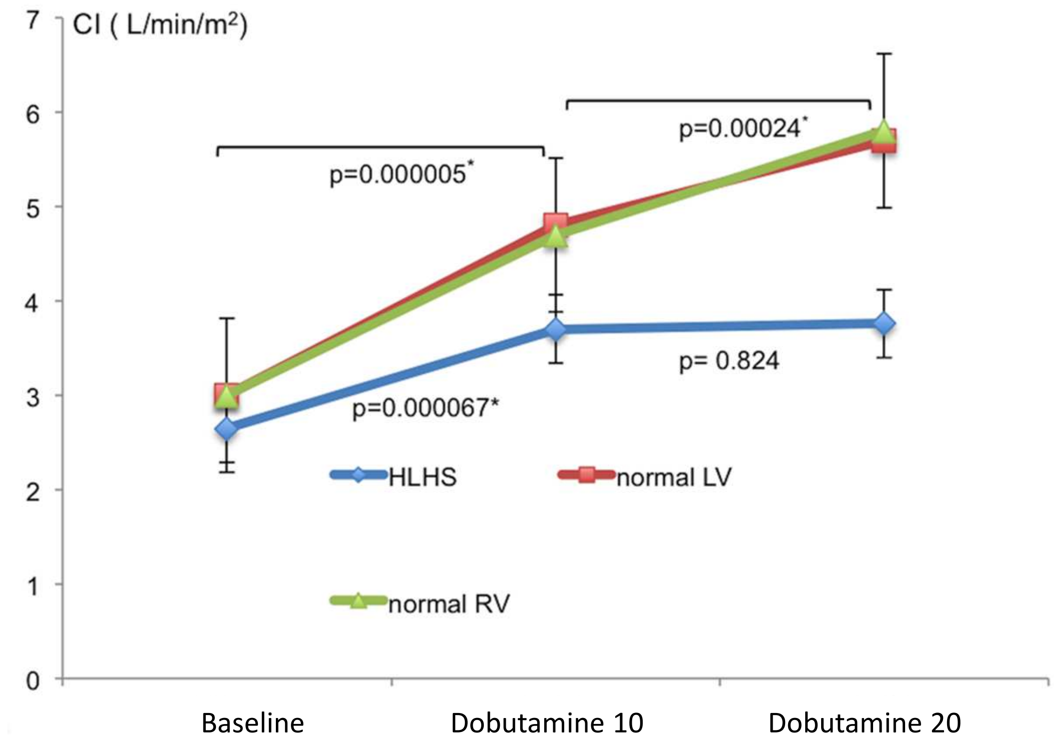
CMR Catheter Stress Hemodynamics

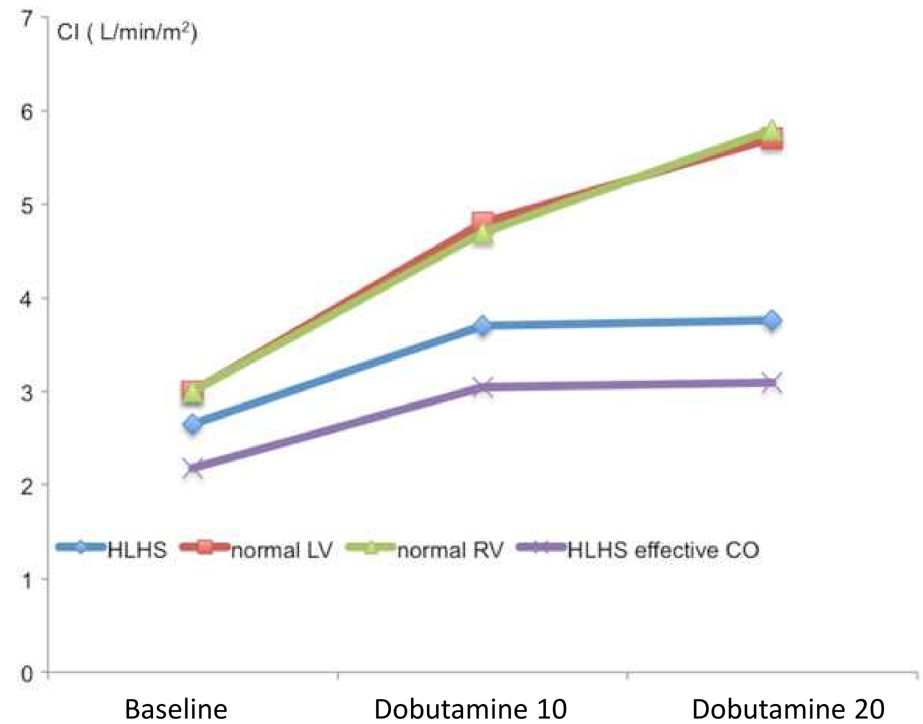




Pushparajah et al. *Eur Heart J Cardiovasc Imag* 2016.

CMR Catheter Stress Hemodynamics





Pushparajah et al. *Eur Heart J Cardiovasc Imag* 2016.

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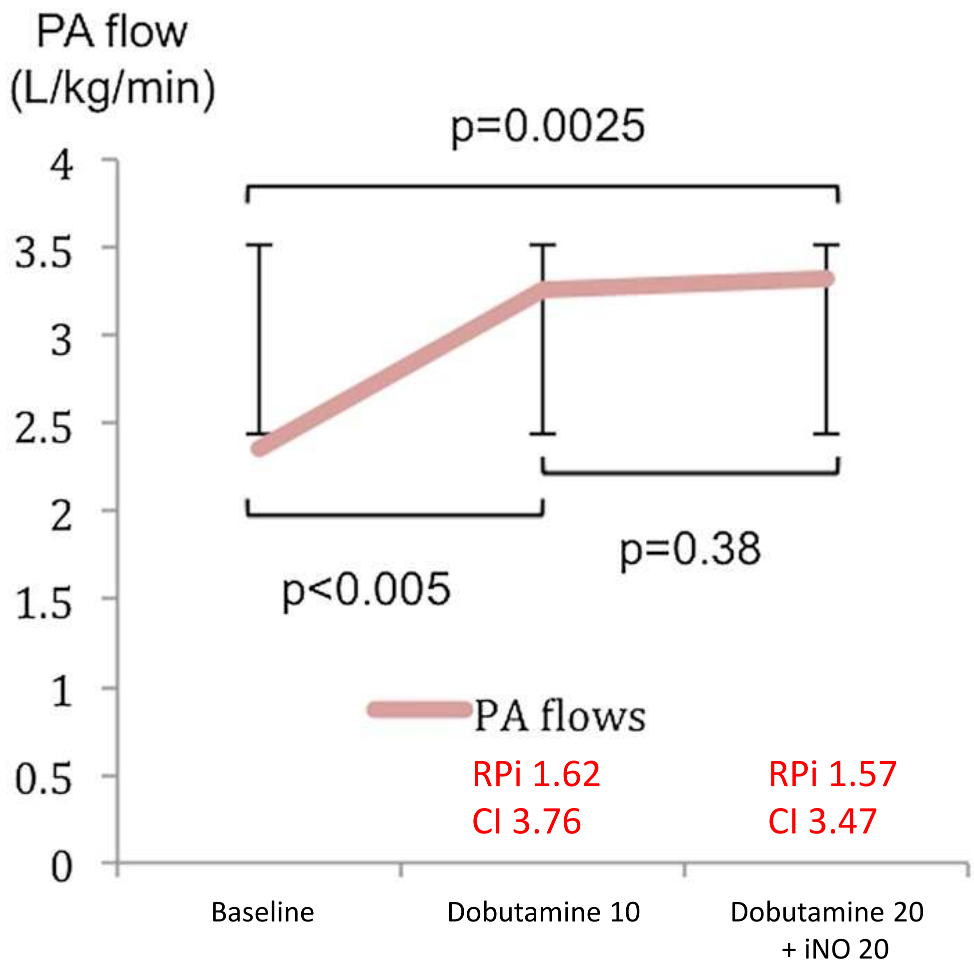
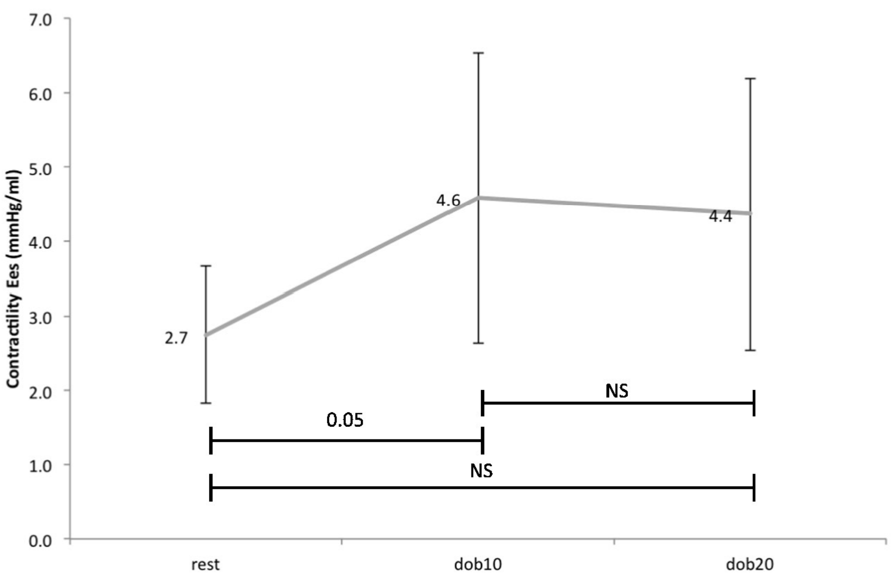


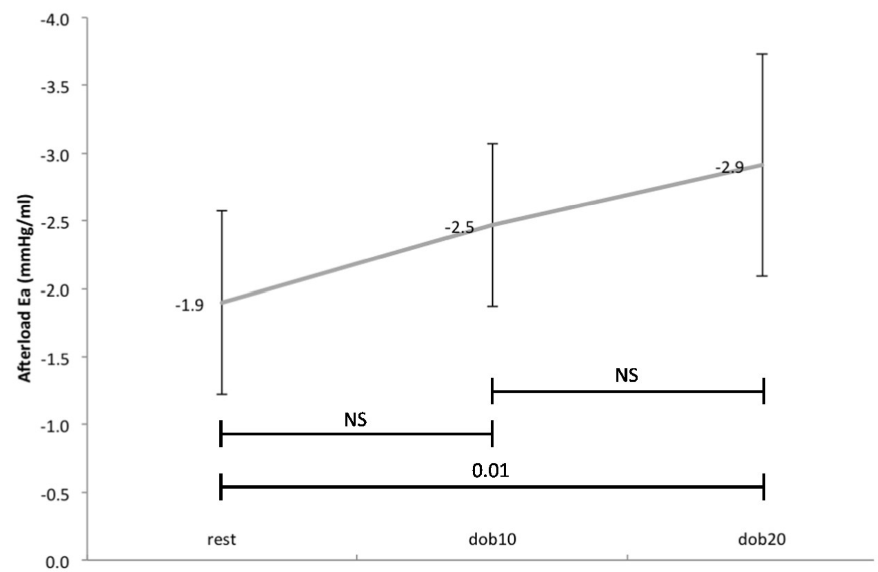
Pushparajah et al. *Eur Heart J Cardiovasc Imag* 2016.

Pressure–volume loop-derived cardiac indices during dobutamine stress: a step towards understanding limitations in cardiac output in children with hypoplastic left heart syndrome☆

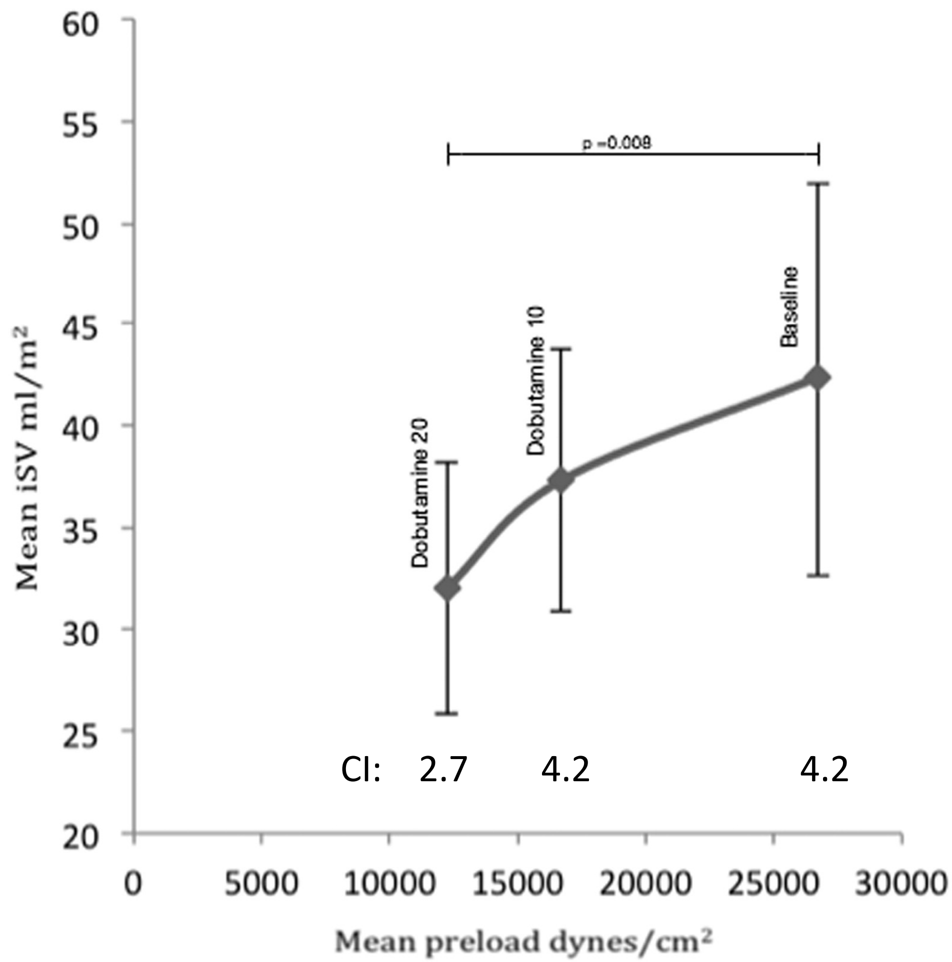
James Wong, Kuberan Pushparajah, Adelaide de Vecchi, Bram Ruijsink, Gerald F. Greil, Tarique Hussain, Reza Razavi *

Division of Imaging Sciences and Biomedical Engineering, King's College London, St. Thomas' Hospital, London SE1 7EH, United Kingdom





Wong et al. *Int J Cardiol* 2017.



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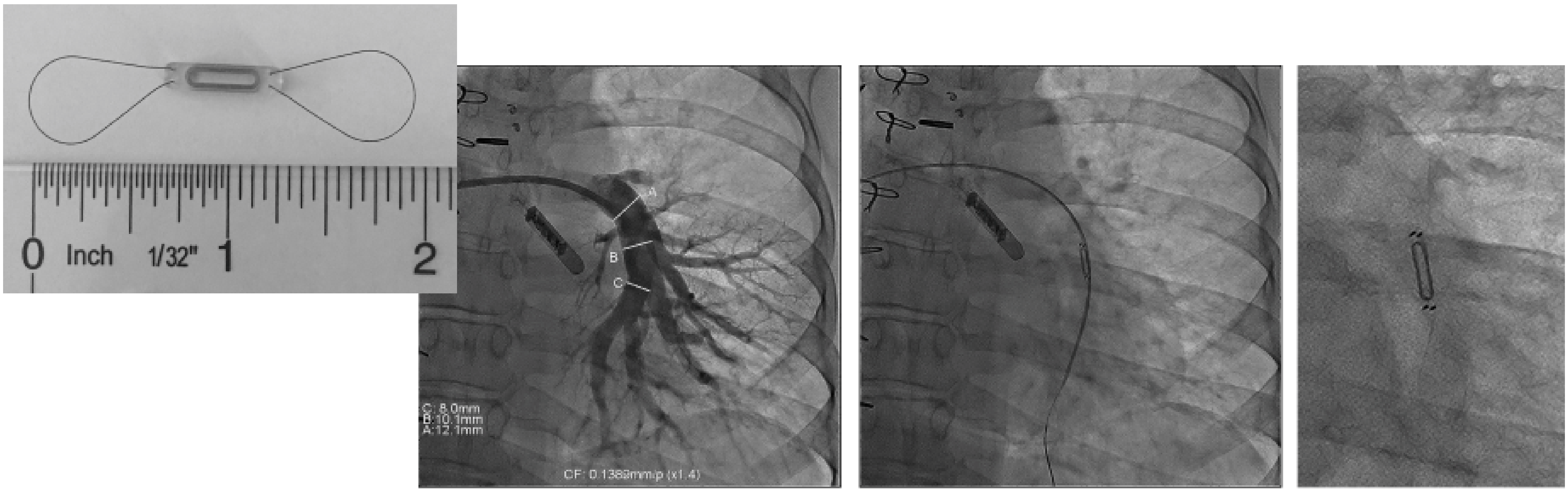
ID	EDP (mmHg)			Tau			Preload $\times 10^3$ dynes/cm^2			PVR (WU.m^2)		
	Rest	Dob10	Dob20	Rest	Dob10	Dob20	Rest	Dob10	Dob20	Rest	Dob10	Dob20
1	8.0	4.8	7.0	28.9	22.8	17.7	80	33	28	0.9	1.7	1.7
2	7.5	9.5	6.0	12.5	6.4	4.3	68	61	27	0.9	0.42	2.0
3	12.5	11.5	10.5	45.7	22.0	18.5	77	53	28	0.8	1.5	1.6
4	4.5	4.5	4.0	28.7	27.0	8.8	37	27	25	2.1	2.5	2.1
5	12.0	9.0	10.7	28.6	12.4	4.6	81	41	36	1.0	0.5	0.5
6	3.5	4.0	6.0	18.0	13.0	6.3	19	18	16	0.9	0.8	0.8
7	10.7	9.5	11.0	62.5	18.8	27.0	89	70	46	0.95	0.9	1.1
8	5.0	2.0	2.0	18.4	18.8	14.2	36	46	36	1.5	1.8	1.7
9	10.0	10.0	7.0	28.8	23.4	19.8	42	31	22	1.9	1.8	1.5
10	6.5	6.3	3.8	22.6	30.7	21.6	32	16	19	4.4	3.7	3.4
Mean	8.1	7.4	7.1	30.1	19.3	13.8 *	52	36	26 †	1.7	1.7	1.8
±SD	±3.1	±2.8	(±2.7)	(14.3)	(7.4)	(8.0)	(30)	(19)	(10)	(±1.2)	(±1.1)	(±0.8)
ANOVA *p* value	0.72			0.005			0.037			0.97		
Post hoc compared to rest				* denotes $p < 0.01$			† denotes $p < 0.05$					

EDP indicates end-diastolic pressure, Tau is the early relaxation constant, PVR pulmonary vascular resistance.

Wong et al. *Int J Cardiol* 2017.

First Implantable Hemodynamic Monitoring Device Placement in Single Ventricle Fontan Anatomy

Elisa A. Bradley,* MD, Darren Berman, MD, and Curt J. Daniels, MD



(a) (b) (c)

Bradley et al. *Catheter Cardiovasc Interv* 2016.

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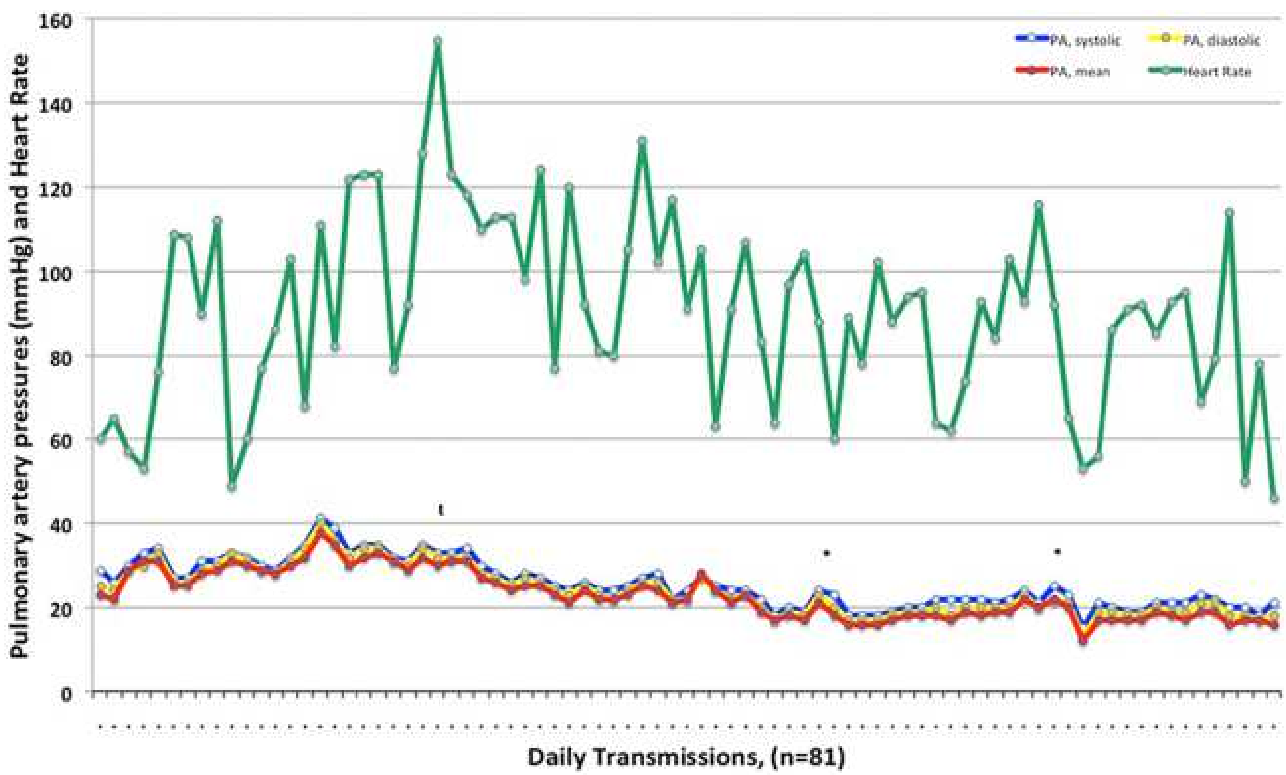
“Continuous” Hemodynamic Assessment



Bradley et al. *Catheter Cardiovasc Interv* 2016.

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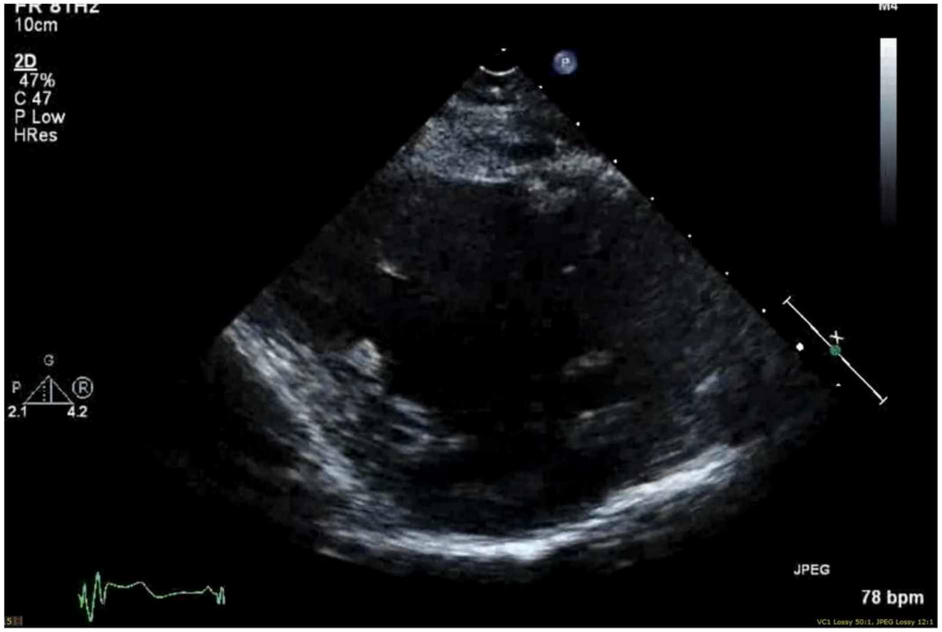
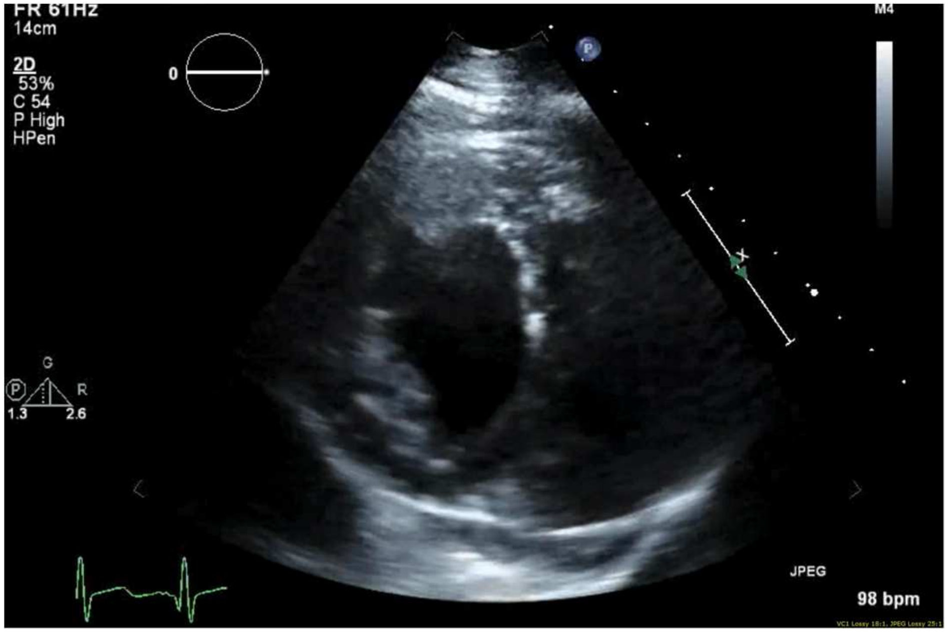
What About Systolic Dysfunction?





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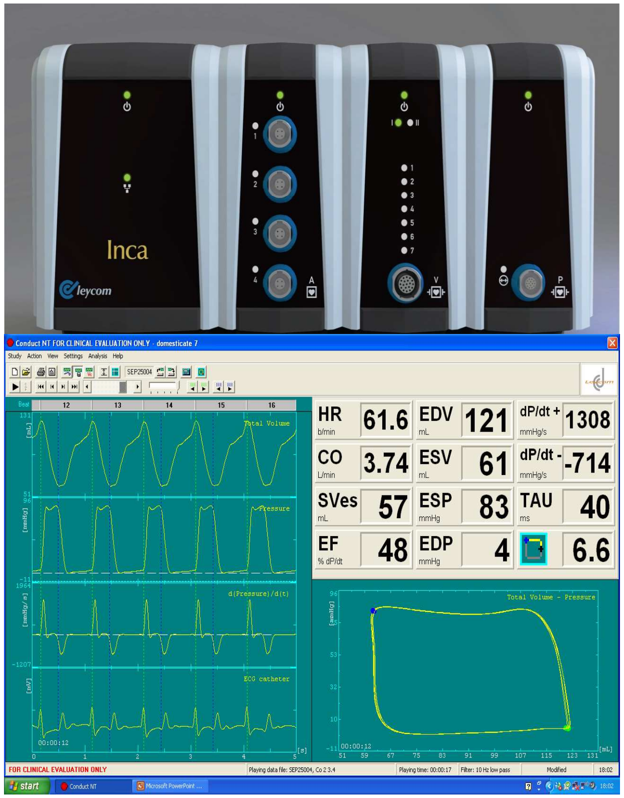
Mechanical Dyssynchrony

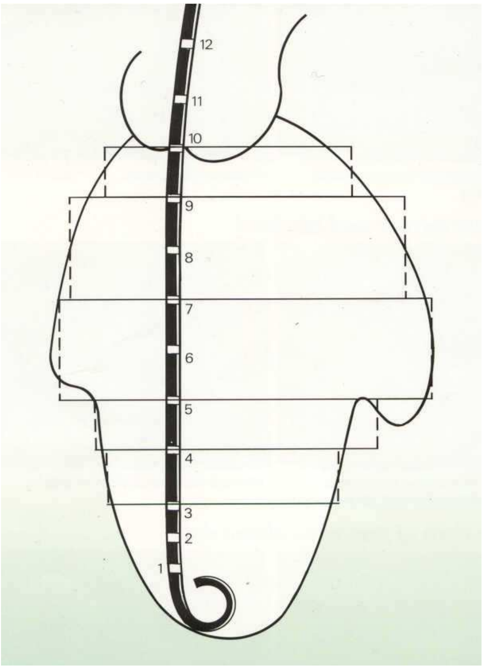
- Fontan patients may have mechanical dyssynchrony without electrical dyssynchrony
- Mechanical dyssynchrony contributes to overall ventricular dysfunction (systolic and diastolic), which in turn contributes to symptomatic Fontan failure
- Reducing mechanical dyssynchrony may improve ventricular mechanics which in turn could improve symptomatic Fontan failure

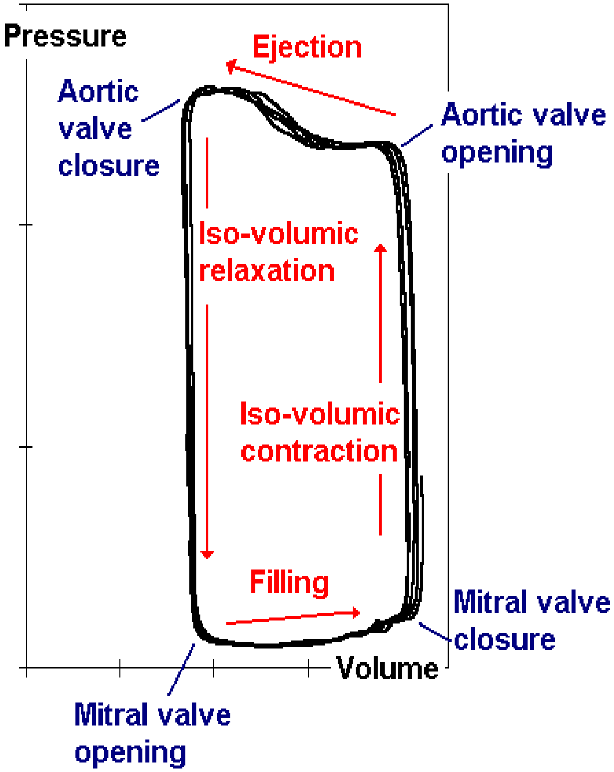
Mechanical Dyssynchrony

- Single/multi-site pacing may improve mechanical dyssynchrony
- We can measure acute impact of “proposed” pacing sites on ventricular mechanics and mechanical dyssynchrony
- Acute improvements in ventricular mechanics predict long term benefit to ventricular function

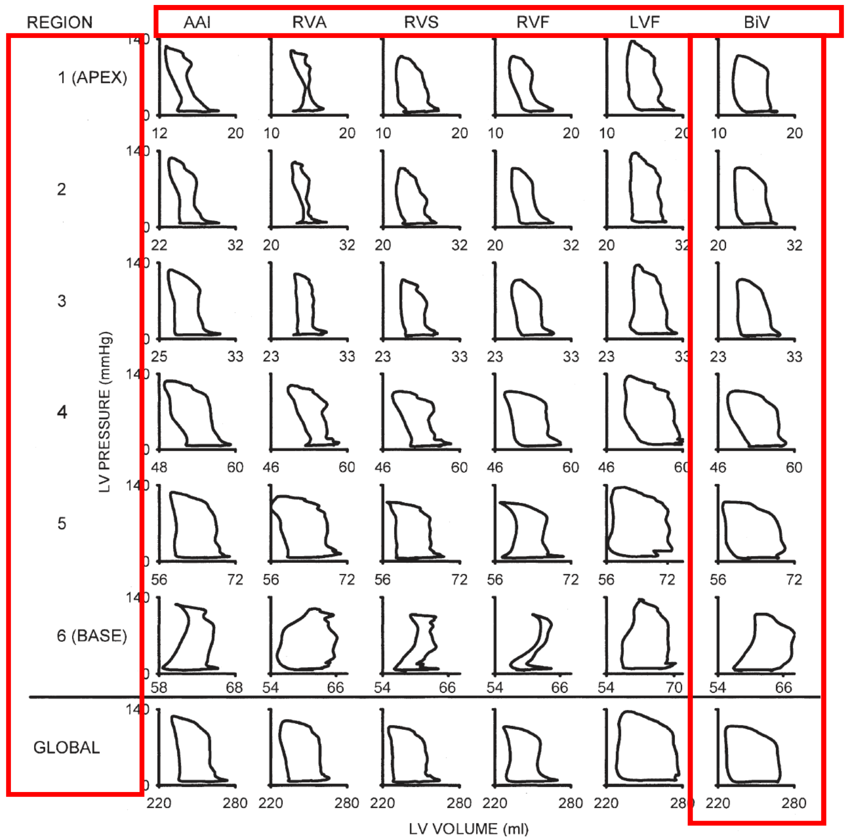
Pressure Volume Loops



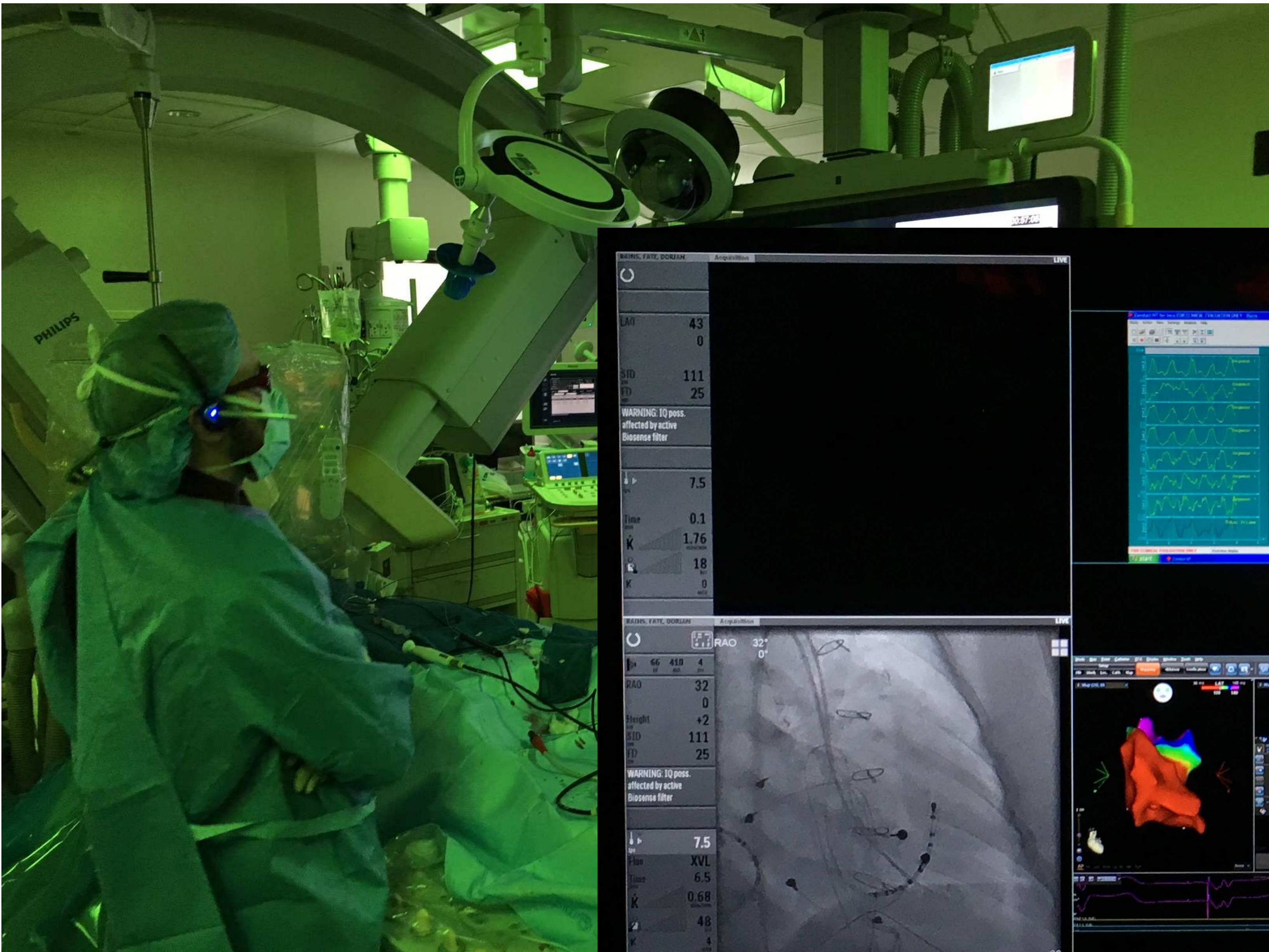
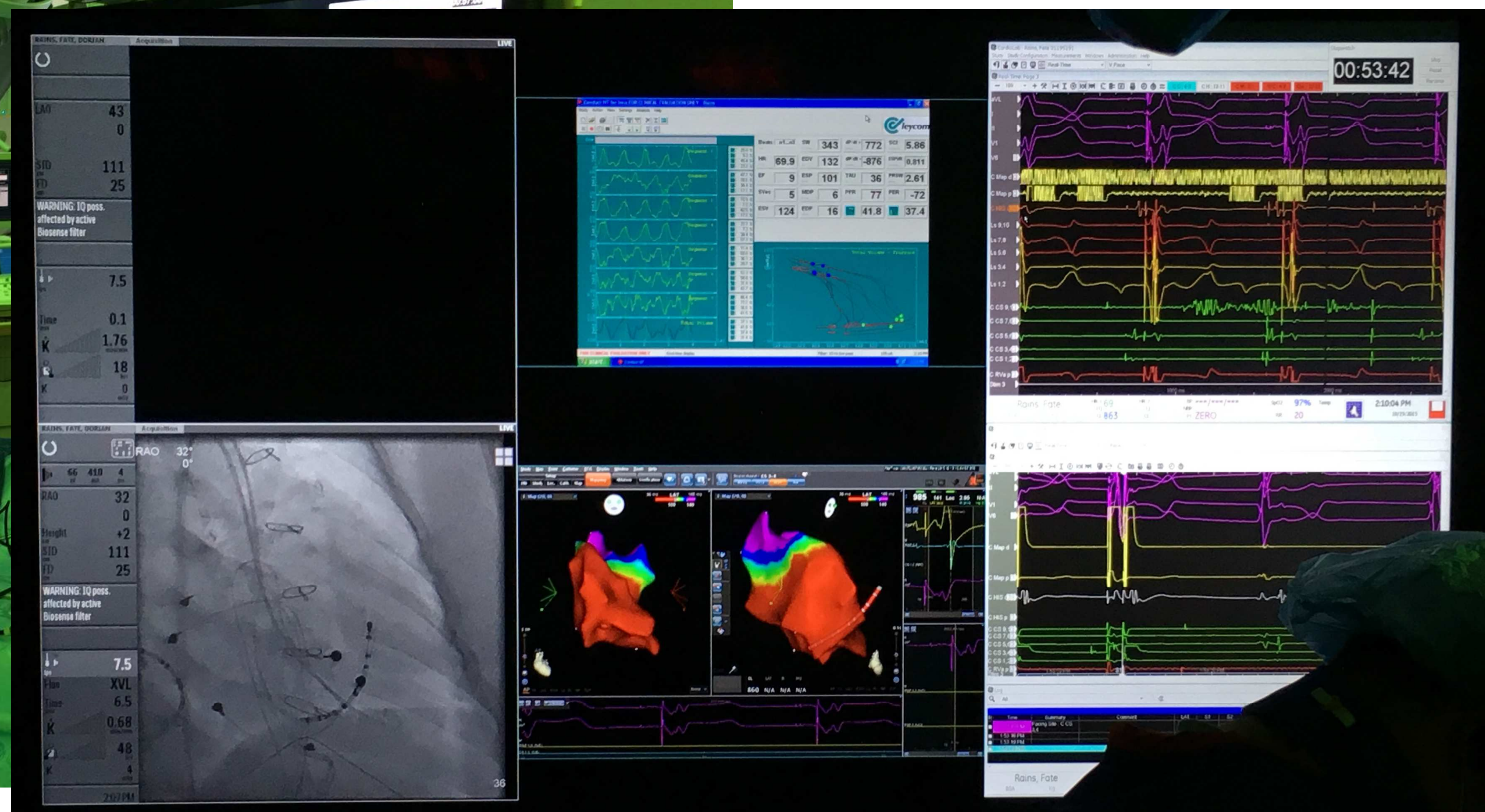




PV Loops and Dyssynchrony



Lieberman et al, *J Amer Coll Cardiol*. 2006.

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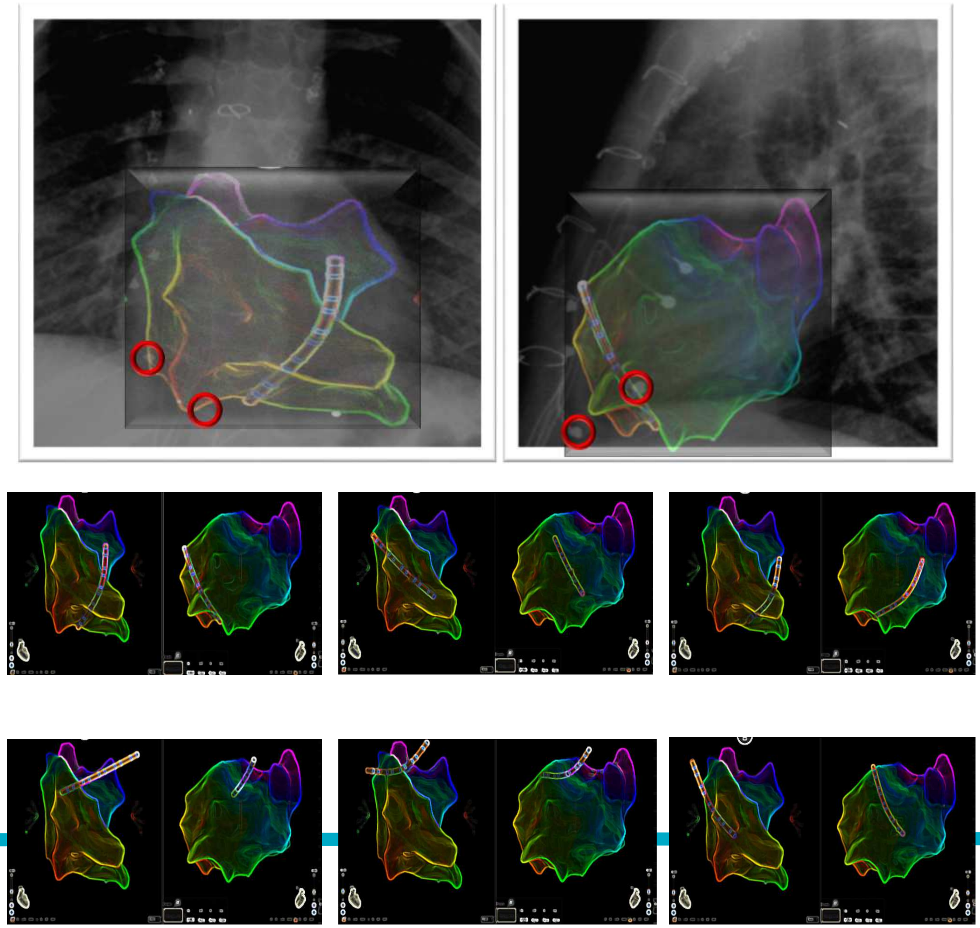
Index Fontan Patient



Site	dP/dT (% Δ)	EDP (% Δ)
BL	750	21 mmHg
#1	852 (+14%)	15 mmHg (-25%)
#2	776 (+4%)	13 mmHg (-35%)
#3	774 (+3%)	13 mmHg (-35%)
#4	818 (+9%)	14 mmHg (-30%)
#5	680 (-9%)	14 mmHg (-30%)
#6	852 (+14%)	12 mmHg (-40%)

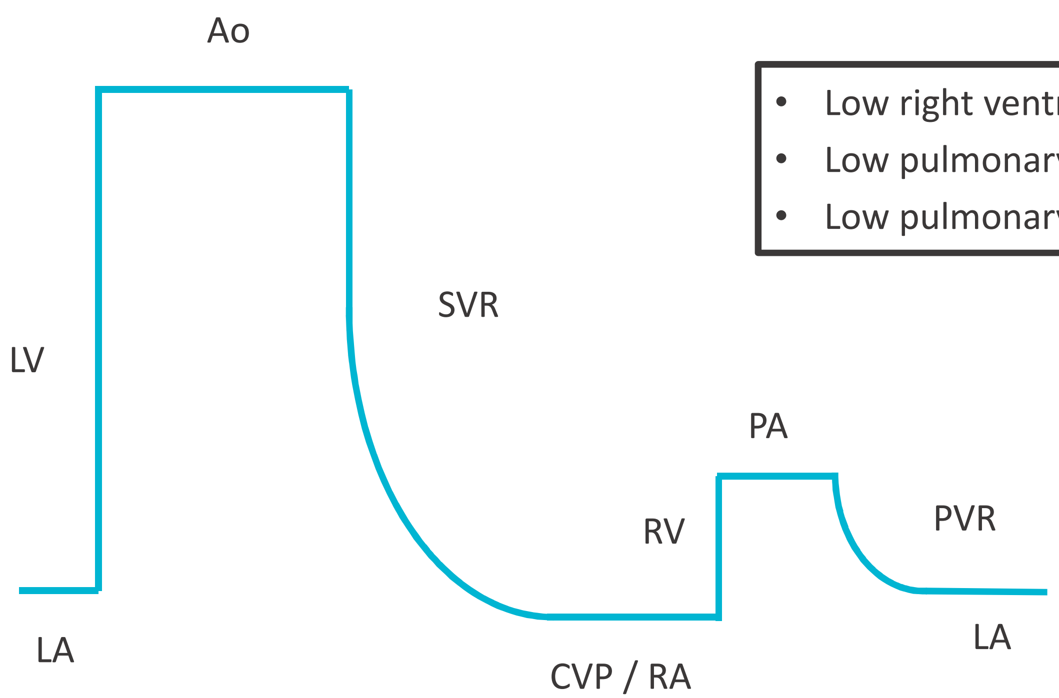
Conclusions

- Dynamic assessment of the Fontan circulation *may* provide substantial insight into patient-specific pathologies beyond what can be obtained in the resting state
- By combining disciplines, we may be able to offer Fontan patients improved insight into mechanisms of failure – and hopefully potential therapies to improve functionality and QOL
- Pathologies in the pulmonary vadculature *and* diastolic function – even those that aren't easily measurable with advanced techniques – likely play critical roles in Fontan limitations

Thank You!

Bryan.Goldstein@cchmc.org

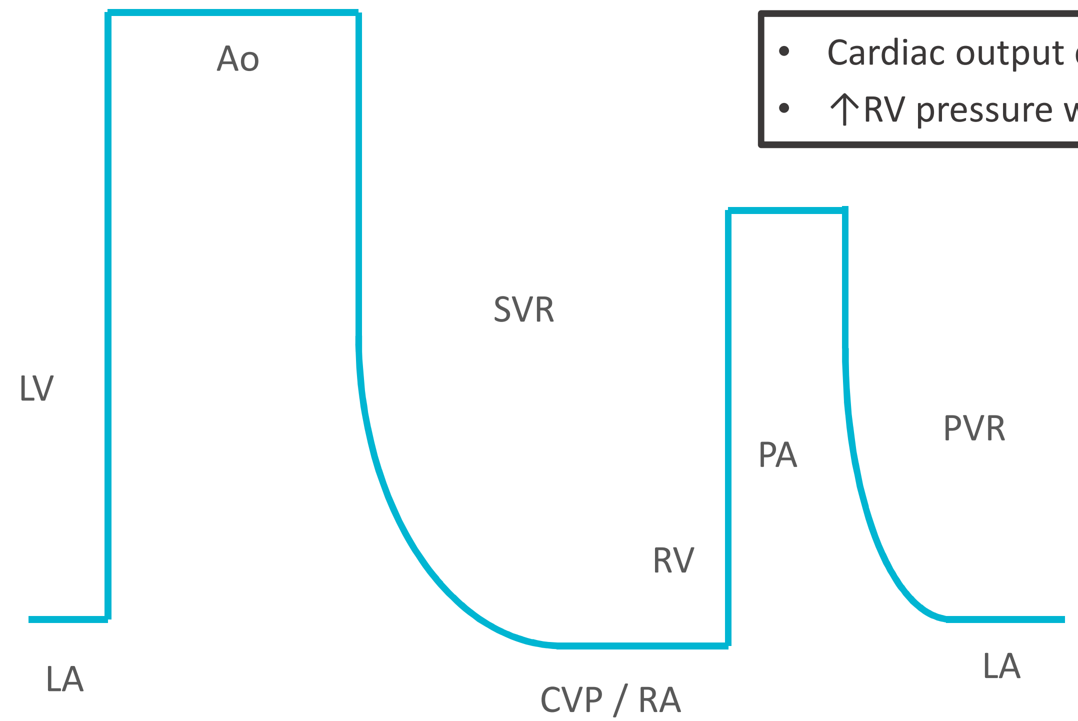
Biventricular Circulation: Rest



- Low right ventricular pressure
- Low pulmonary arterial pressure
- Low pulmonary vascular resistance

Adapted from Gewillig M and Goldberg DJ. *Heart Fail Clin* 2014;10:105-16.

Biventricular Circulation: Exercise



- Cardiac output can increase to >5x baseline
- ↑RV pressure while ↓R_p

Adapted from Gewillig M and Goldberg DJ. *Heart Fail Clin* 2014;10:105-16.

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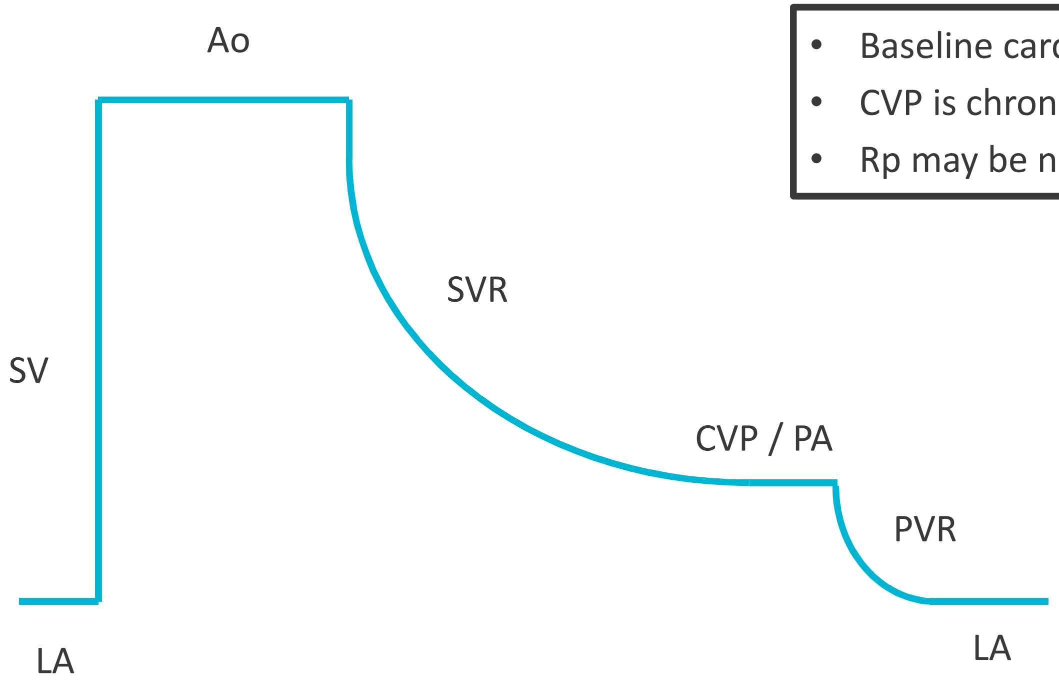
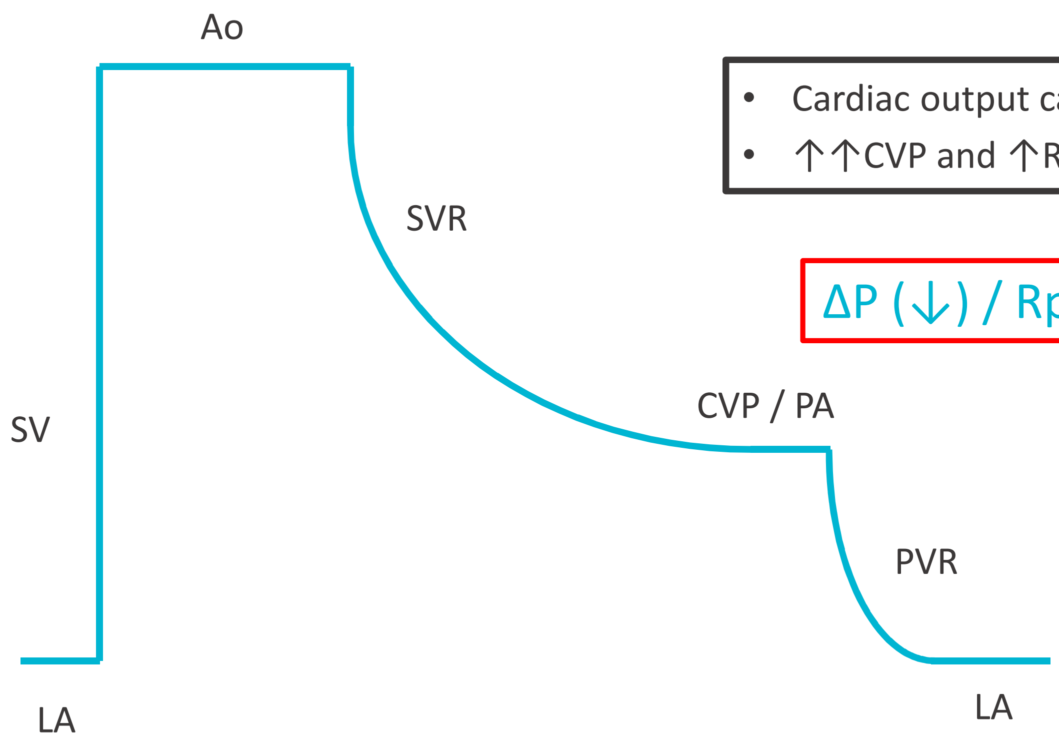
Fontan Circulation: Rest



- Baseline cardiac output ~70% of BiV
- CVP is chronically elevated
- Rp may be normal to mildly elevated

Adapted from Gewillig M and Goldberg DJ. *Heart Fail Clin* 2014;10:105-16.

Fontan Circulation: Exercise



- Cardiac output can increase to ~2x baseline
- ↑↑CVP and ↑Rp

ΔP (↓) / Rp (↑) = Qp (↓↓)

Adapted from Gewillig M and Goldberg DJ. *Heart Fail Clin* 2014;10:105-16.