Applications of Phase Contrast Imaging in Congenital Heart Disease

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Conflicts of Interest

No conflicts of interest

Special thanks to
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Dr Davide Marini
Dr Mini Pakkal
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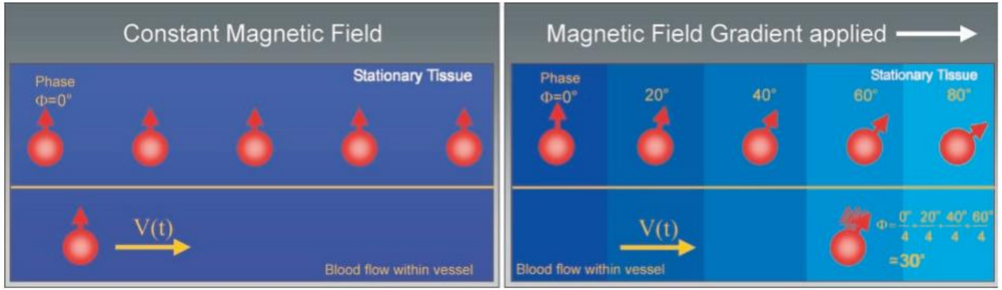


Figure 1. Diagrams show that spins moving along an external magnetic field gradient acquire a difference in the phase of their rotation (right), whereas nonmoving spins do not (left). The amount of phase difference is proportional to the velocity of the moving spin. t = time, V = velocity, Φ = phase shift.

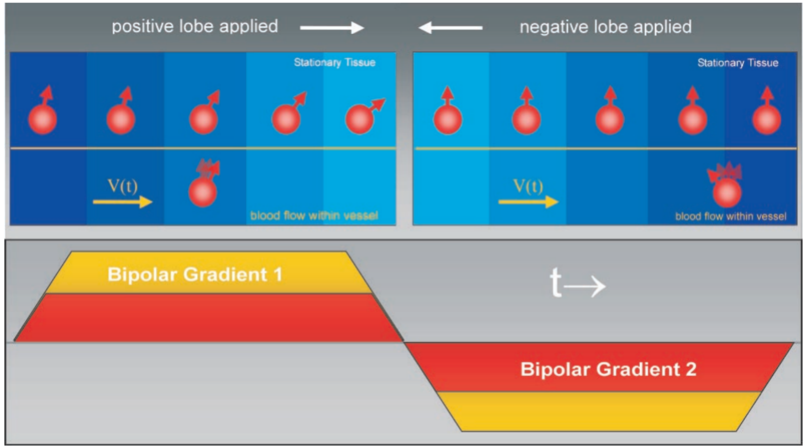
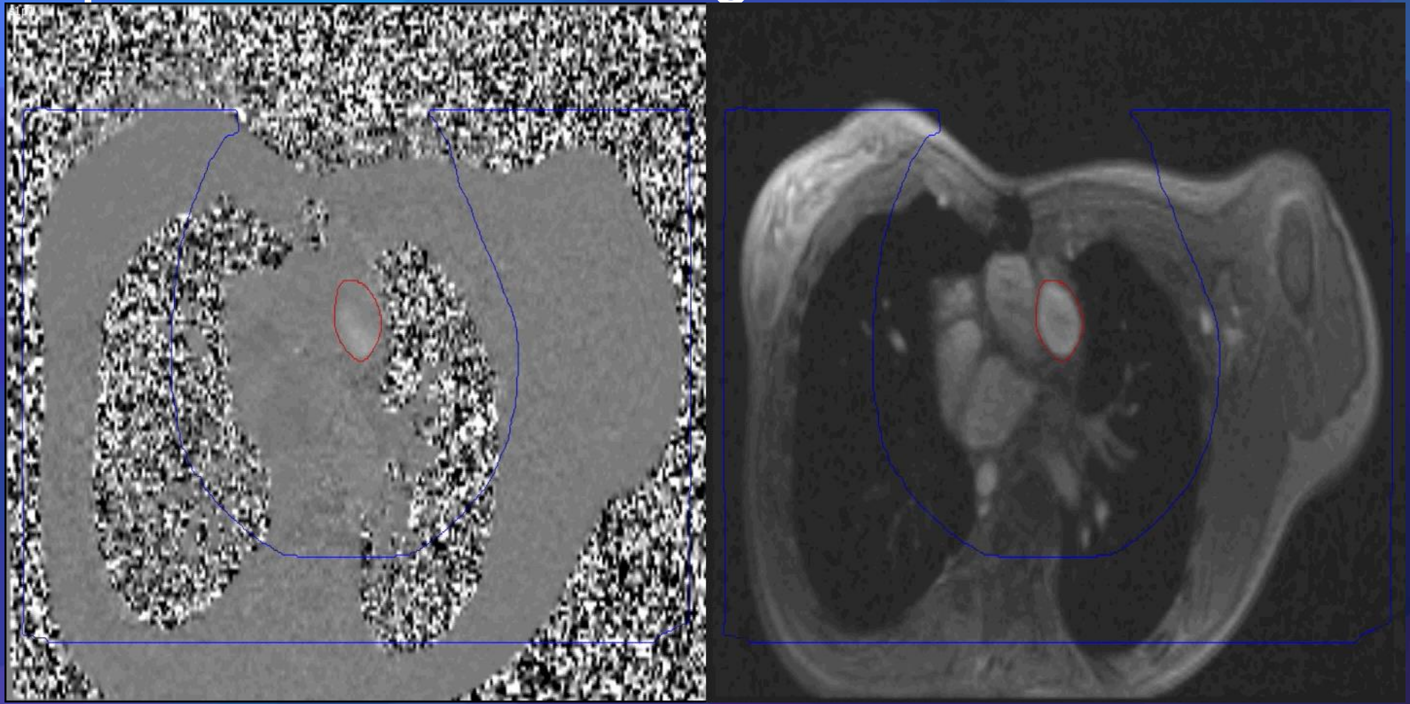


Figure 2. Principle of phase-contrast sequences available in most clinical MR imaging units. Diagram shows that two acquisitions are performed, each one with all parameters kept constant except for the flow-sensitizing bipolar gradients. The data of the two acquisitions are subtracted. The effective flow encoding is achieved by means of the difference in the bipolar gradients of the two acquisitions. This technique eliminates all phase shifts induced by imaging gradients. t = time, V = velocity.

Lotz J, Meier C, Leppert A, Galanski M. Cardiovascular flow measurement with phase-contrast MR imaging: basic facts and implementation. Radiographics. 2002 May-Jun;22(3):651-71

What phase contrast images look like



Phase image

Magnitude image

Paediatric considerations in CMR

1. Complex malformations and post-operative changes
2. Typical and atypical shunts
3. High and turbulent flows

Technical details

Retrospective ECG gating with free breathing

25-30 phases

Velocity encoding: Arteries: 150-200 cm/s, veins: 100-120 cm/s

Applications of phase contrast imaging

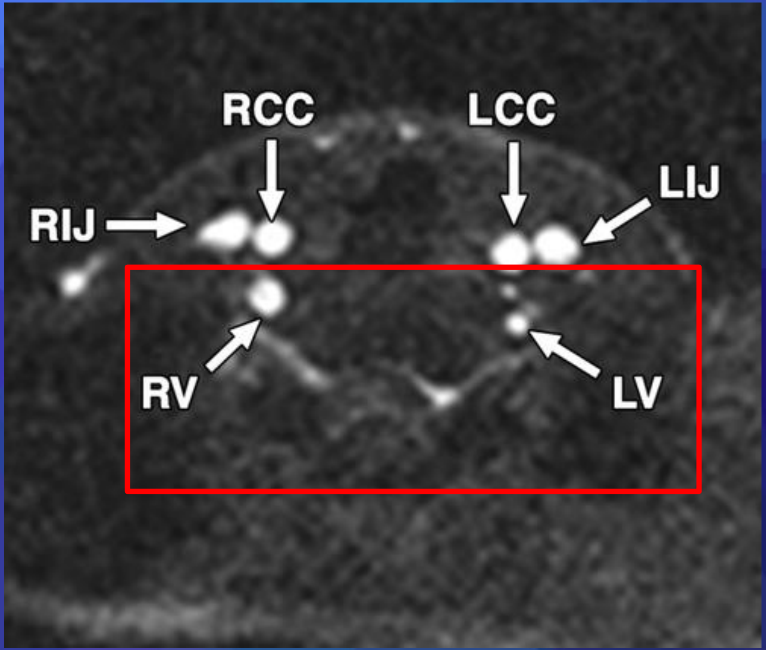
Information provided from phase contrast imaging

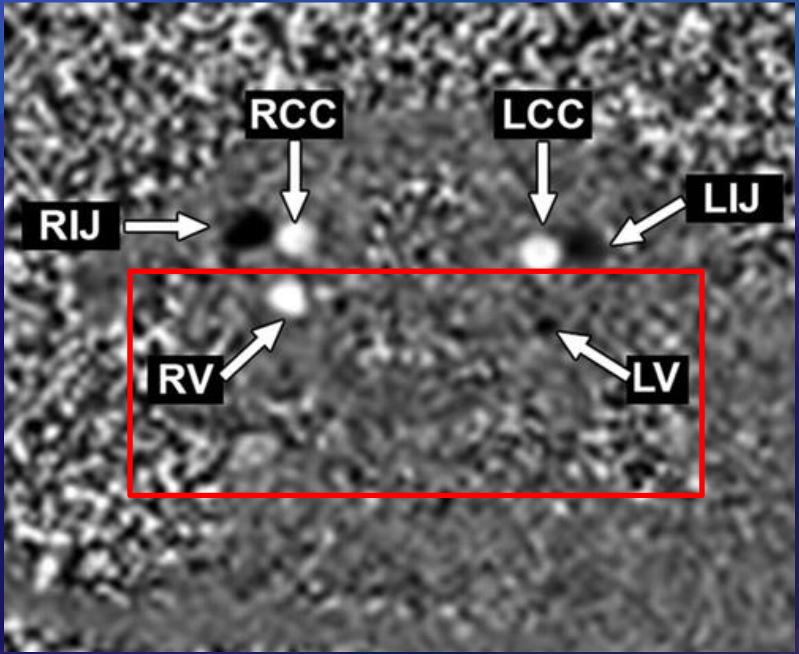
1. Flow volumes
2. Flow pattern
3. Direction of flow
4. (velocity)

Applications

1. Assessment of flow direction
2. Assessment of regurgitant fraction
3. Assessment of shunt volume
4. Assessment of pulmonary blood flow for calculation of pulmonary vascular resistance
5. Assessment of aortopulmonary collateral flow

1. Assessment of flow direction





Monvadi B et al. Cardiovascular Applications of Phase-Contrast MRI. American Journal of Roentgenology 2009 192:3, 662-675

2. Assessment of regurgitant fraction

4.3.5. Tetralogy of Fallot

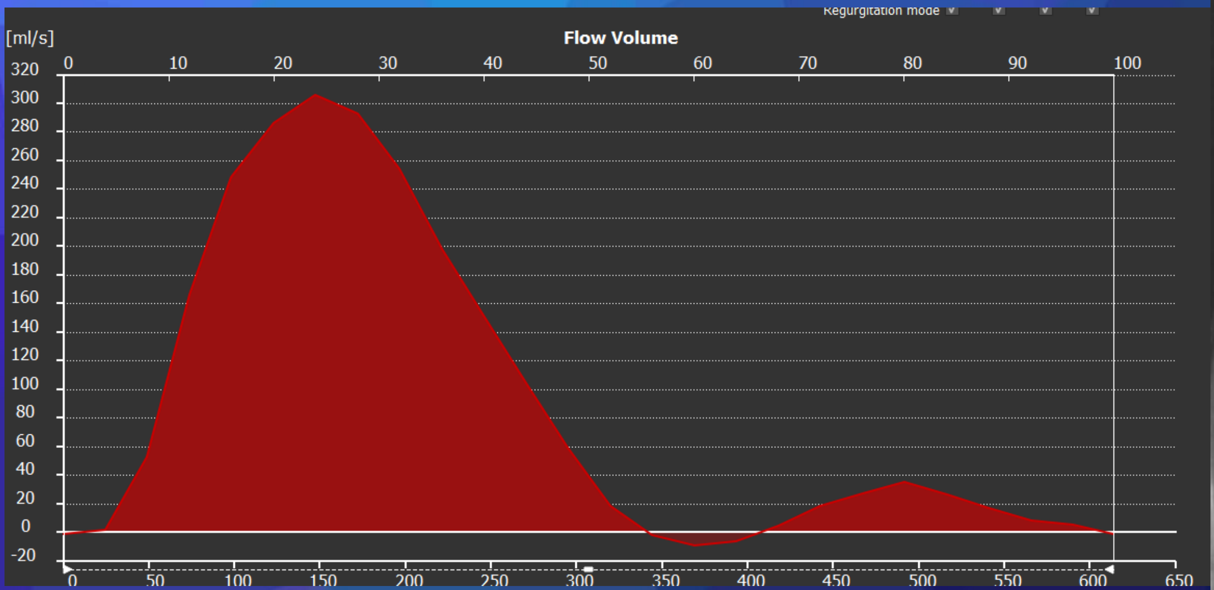
Recommendations for TOF
Referenced studies that support recommendations are summarized in Online Data Supplement 43. (See Section 4.3.6. for recommendations regarding evaluation and management of right ventricle–to-PA conduits.)

COR	LOE	Recommendations
Diagnostic		
I	B-NR	1. CMR is useful to quantify ventricular size and function, pulmonary valve function, pulmonary artery anatomy, and left heart abnormalities in patients with repaired TOF.[S4.3.5-1]
I	B-NR	2. Coronary artery compression testing is indicated before right ventricle–to-PA conduit stenting or transcatheter valve placement in repaired TOF.[S4.3.5-2]
IIa	B-NR	3. Programmed ventricular stimulation can be useful to risk-stratify adults with TOF and additional risk factors for SCD.[S4.3.5-3–S4.3.5-8]
IIa	C-EO	4. In patients with repaired TOF, cardiac catheterization with angiography, if indicated, is reasonable to assess hemodynamics when adequate data cannot be obtained noninvasively in the setting of an arrhythmia, HF, unexplained ventricular dysfunction, suspected pulmonary hypertension or cyanosis.

Recommendations for TOF (Continued)

COR	LOE	Recommendations
Therapeutic		
I	B-NR	5. Pulmonary valve replacement (surgical or percutaneous) for relief of symptoms is recommended for patients with repaired TOF and moderate or greater PR with cardiovascular symptoms not otherwise explained.[S4.3.5-9–S4.3.5-11]
IIa	B-NR	6. Pulmonary valve replacement (surgical or percutaneous) is reasonable for preservation of ventricular size and function in asymptomatic patients with repaired TOF and ventricular enlargement or dysfunction and moderate or greater PR.[S4.3.5-1,S4.3.5-9,S4.3.5-12–S4.3.5-14]
IIa	B-NR	7. Primary prevention ICD therapy is reasonable in adults with TOF and multiple risk factors for SCD.[S4.3.5-15–S4.3.5-17]
IIb	C-EO	8. Surgical pulmonary valve replacement may be reasonable for adults with repaired TOF and moderate or greater PR with other lesions requiring surgical interventions.
IIb	C-EO	9. Pulmonary valve replacement, in addition to arrhythmia management, may be considered for adults with repaired TOF and moderate or greater PR and ventricular tachyarrhythmia.

2018 AHA/ACC Guideline for the Management of Adults With Congenital Heart Disease: A Report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines


Regurgitation mode
[ml/s]
Flow Volume
0 10 20 30 40 50 60 70 80 90 100
320 300 280 260 240 220 200 180 160 140 120 100 80 60 40 20 0 -20
0 50 100 150 200 250 300 350 400 450 500 550 600 650

Forward flow volume: 85.29 ml   7.48 l/min

Backward flow volume: 37.00 ml   3.25 l/min

Regurgitant fraction: 43 %

Background correction method: Stationary Flow Fit

2. Estimation of regurgitant fraction

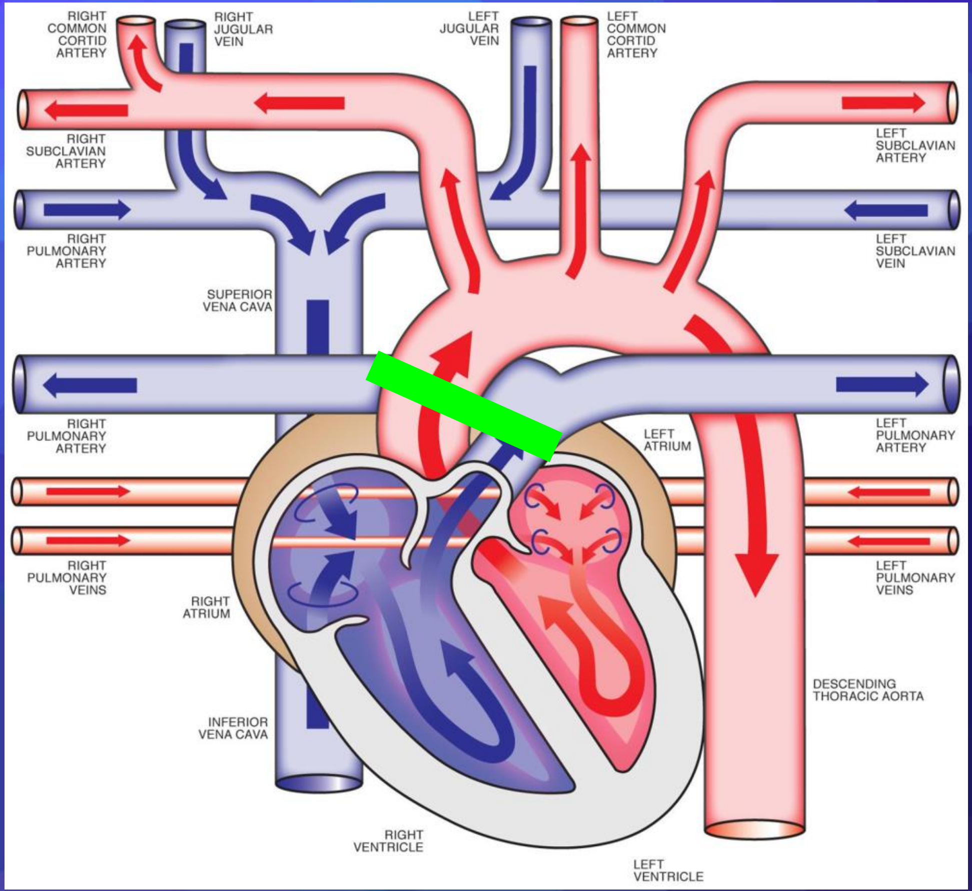
1. Pulmonary regurgitation: Backward flow/Forward flow
2. Aortic regurgitation: (AOV forward flow - Qp)/ AOV forward flow
3. Tricuspid regurgitation: RVCI-MPAf/ (RVCI -MPAf) + Qs
4. Mitral regurgitation: LVCI - AAOf/ (LVCI - AAOf) + Qp

Local practice, no established consensus

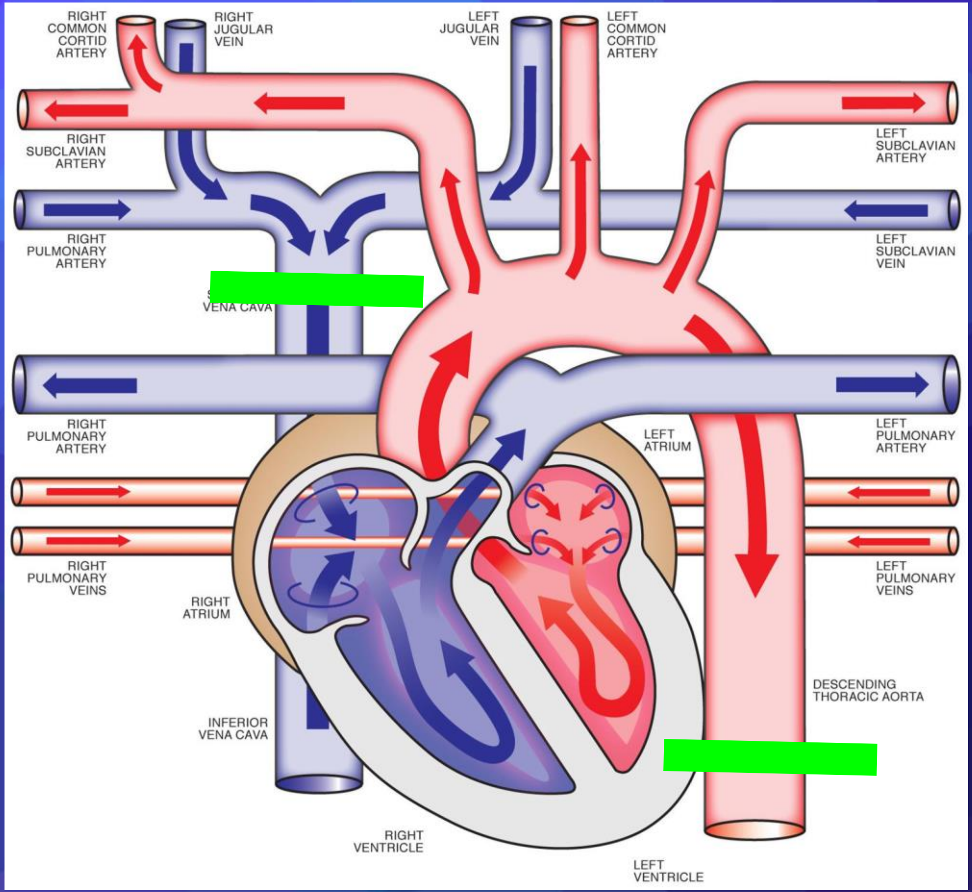
3. Assessment of shunt volume

Qp/Qs

(pulmonary blood flow/systemic blood flow)


RIGHT COMMON CORTID ARTERY
RIGHT JUGULAR VEIN
LEFT JUGULAR VEIN
LEFT COMMON CORTID ARTERY
RIGHT SUBCLAVIAN ARTERY
LEFT SUBCLAVIAN ARTERY
RIGHT PULMONARY ARTERY
LEFT SUBCLAVIAN VEIN
SUPERIOR VENA CAVA
RIGHT PULMONARY ARTERY
LEFT ATRIUM
LEFT PULMONARY ARTERY
RIGHT PULMONARY VEINS
LEFT PULMONARY VEINS
RIGHT ATRIUM
DESCENDING THORACIC AORTA
INFERIOR VENA CAVA
RIGHT VENTRICLE
LEFT VENTRICLE

$Q_S = Q_{AAO}$

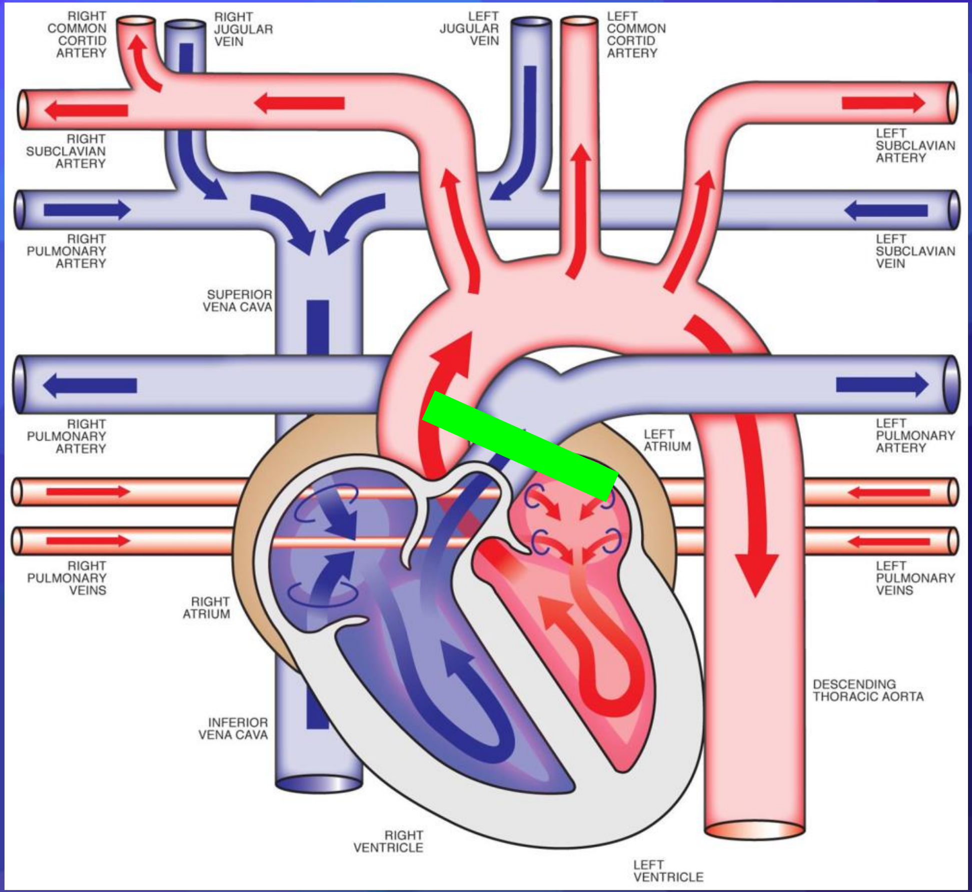


Qs =

QSVC (all the venous return from the upper body)

+ QDAO (all the systemic supply to the lower body)

(more reliable than direct measurement of AAO due to presence of turbulent flow)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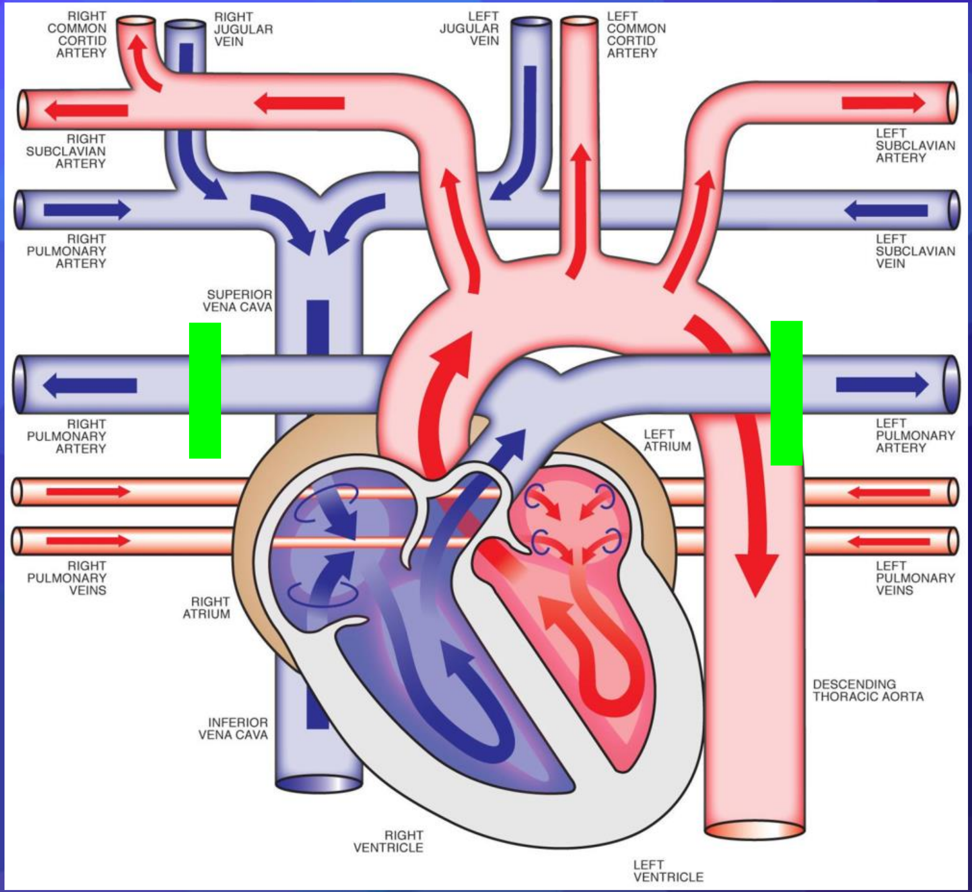
RIGHT PULMONARY VEINS
LEFT PULMONARY VEINS
RIGHT ATRIUM
DESCENDING THORACIC AORTA
INFERIOR VENA CAVA
RIGHT VENTRICLE
LEFT VENTRICLE

Qpa = Qmpa

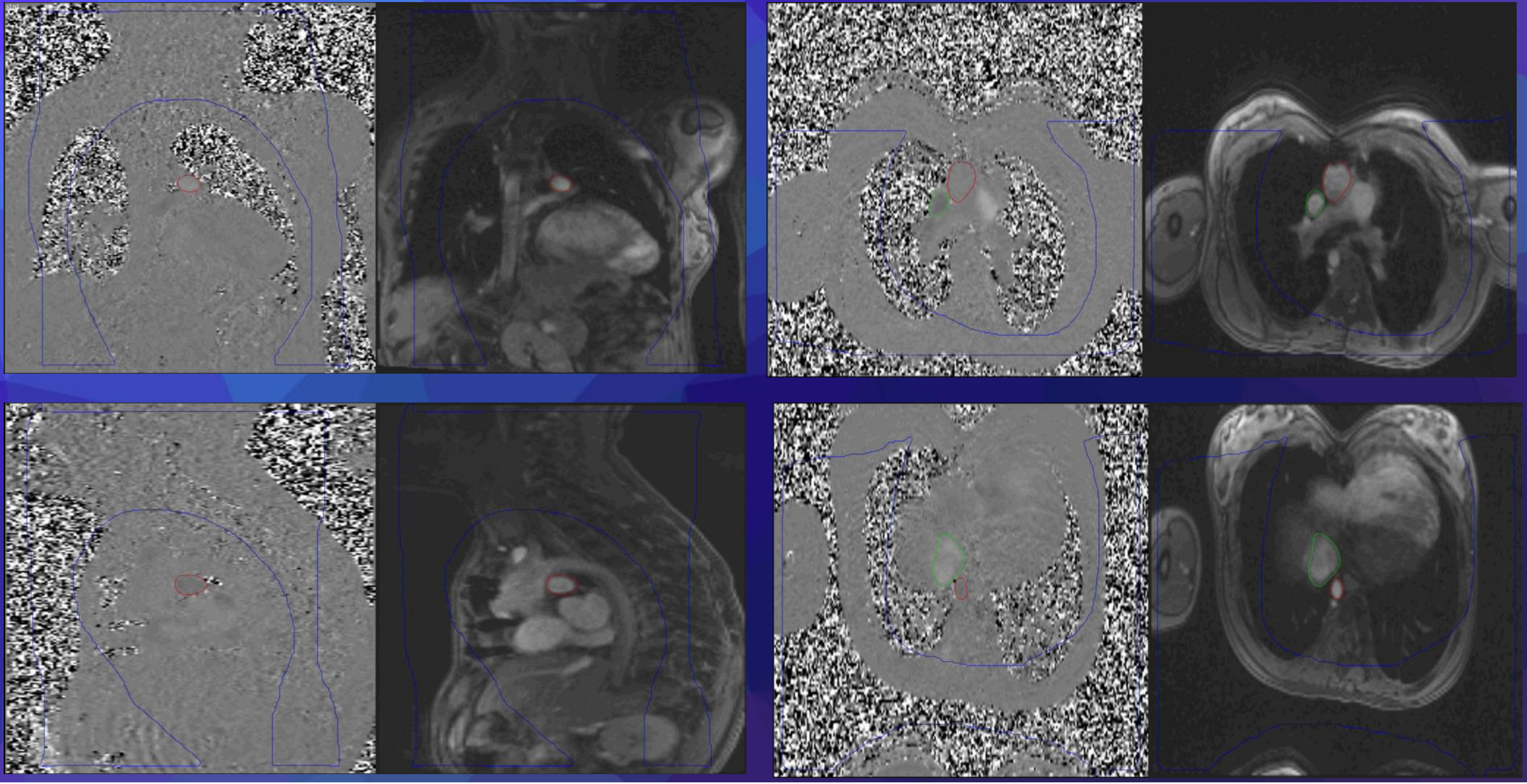


Qpa = $Q_{RPA} + Q_{LPA}$

(more reliable than direct measurement of MPA due to turbulent flow and cardiac motion)

Example case

- 12 year old girl with history of valve sparing repair of Tetralogy of Fallot
- Previous echocardiography showed absence of residual left to right shunting
- Follow-up cardiac MRI to assess:
  - Ventricular volumes and function
  - Pulmonary regurgitation



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Qp = Q(RPA+LPA)

RPA 3.2 L/min/m2
LPA 2.8 L/min/m2

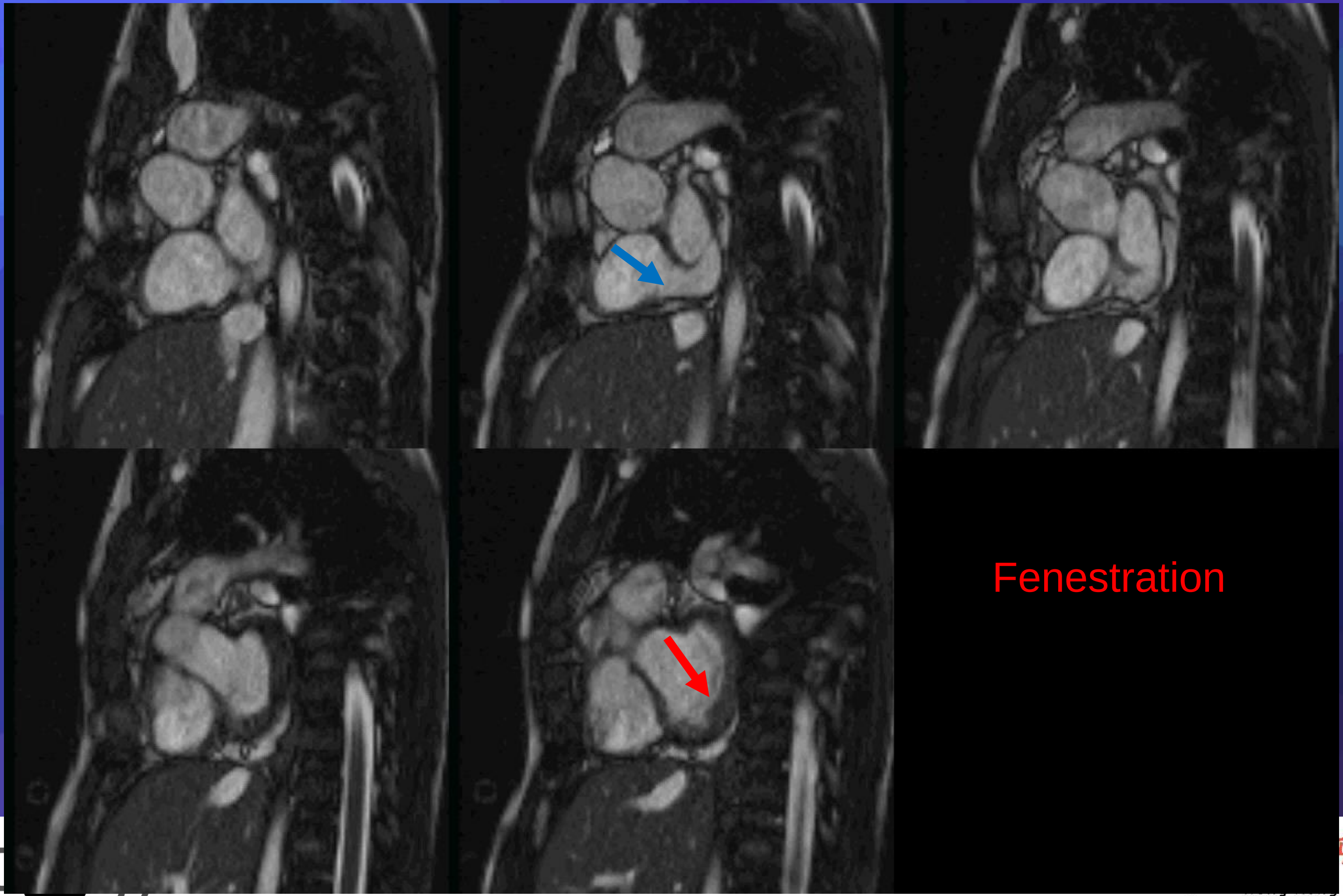
Qp = 6 L/min/m2

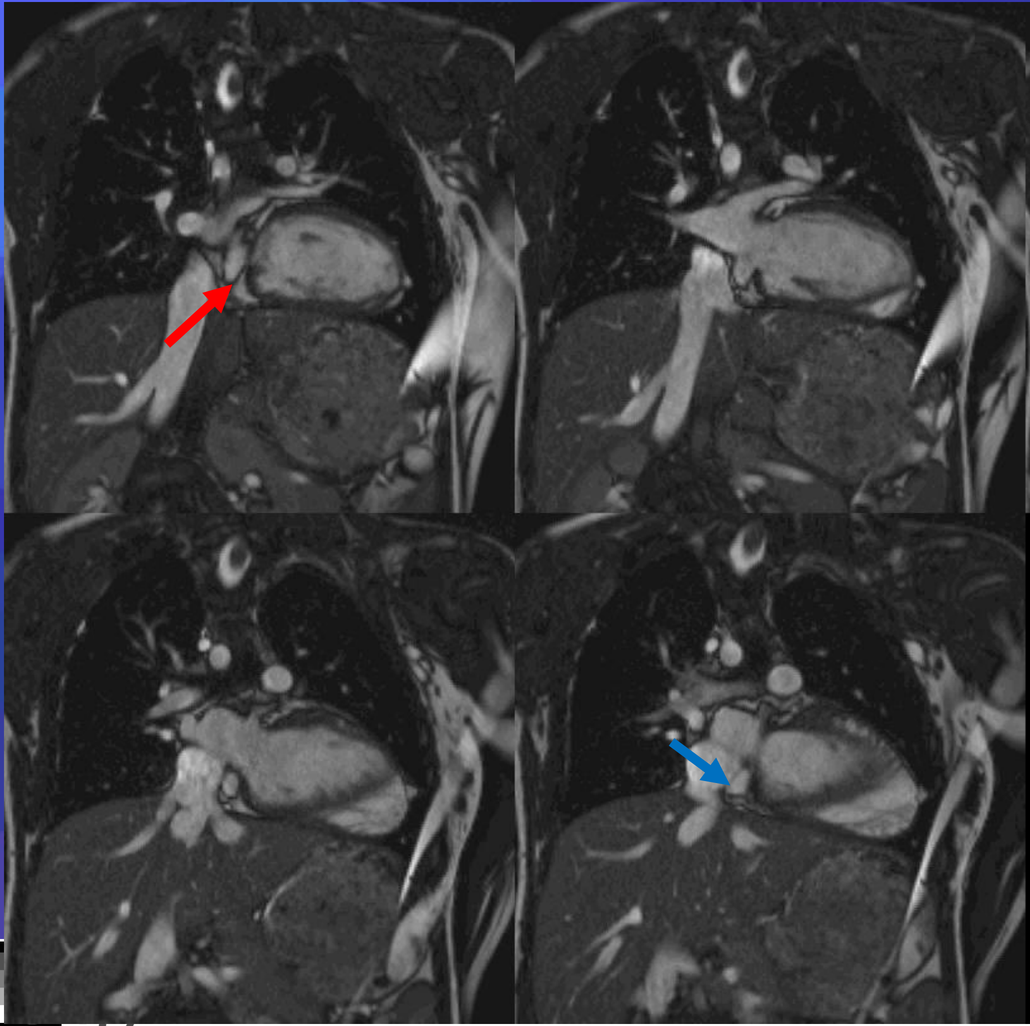
Qs = Q(SVC+DAO)

SVC= 1.4 L/min/m2
DAO = 2.5 L/min/m2

Qs = 3.9 L/min/m2

Qp / Qs = 1.6


Fenestration



Fenestration

Defect = 12 x 17 mm

Retrospective analysis of all the follow up echocardiograms

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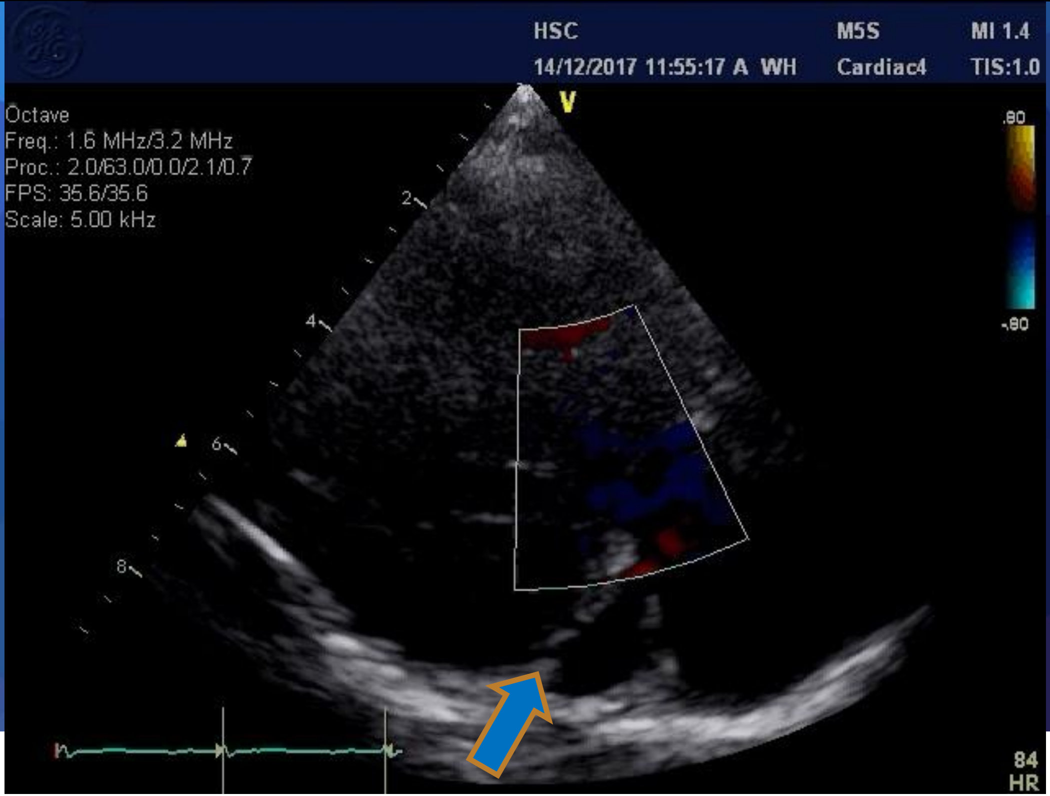
Retrospective analysis of all the follow up echocardiograms



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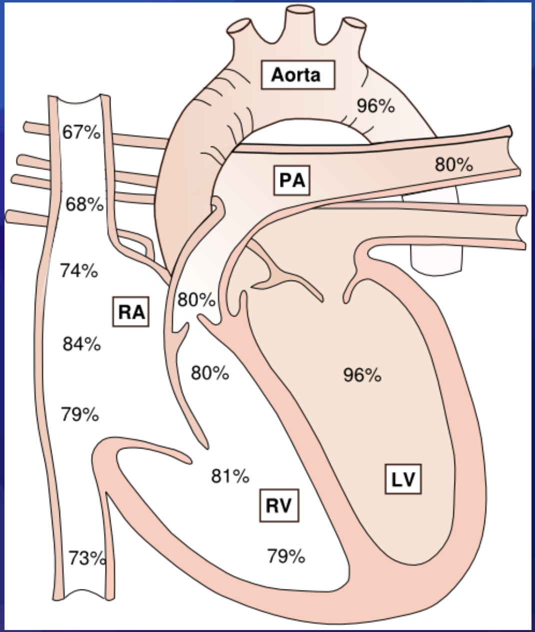
4. Assessment of pulmonary blood flow for calculation of pulmonary vascular resistance

Fick Principle

Thermodilution



https://www.pcipedia.org/

Limitations of the Fick principle

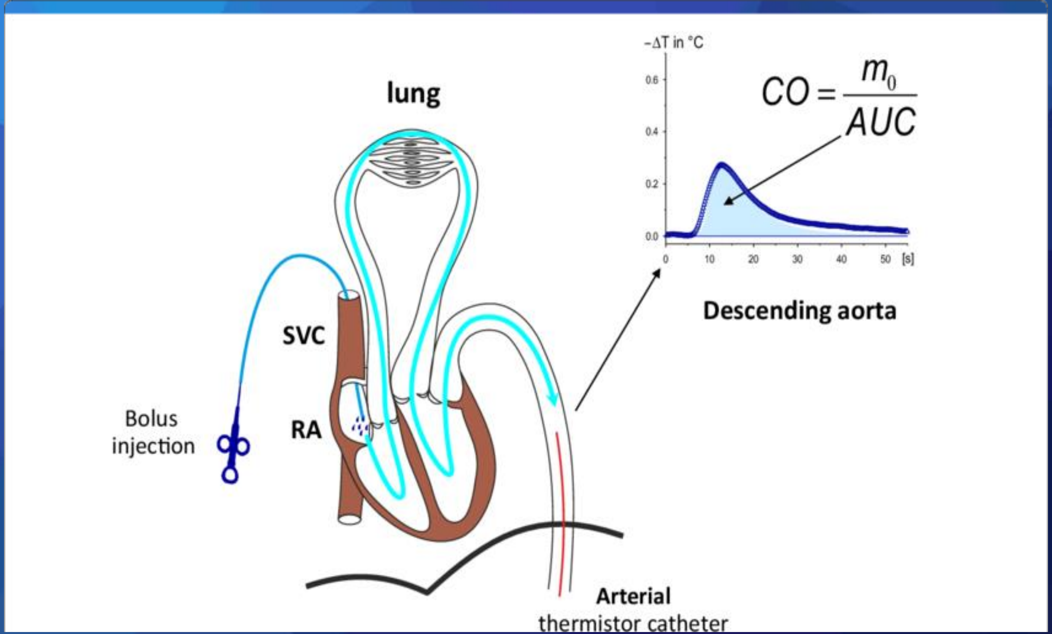
The Fick principle requires measurement of

- Haemoglobin
- aortic and pulmonary artery oxygen saturations and partial pressures
- oxygen consumption.

Accumulation of errors due to multiple individual measurement errors

Reduced accuracy in patients with large intra-cardiac shunts and high pulmonary blood flow

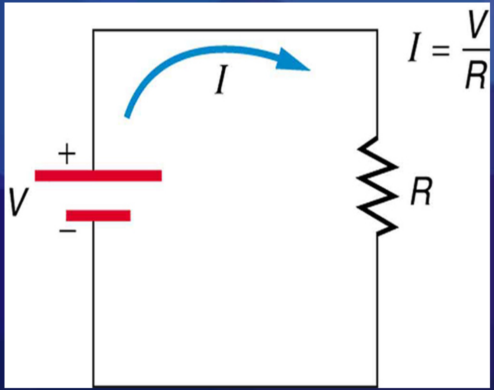
Thermodilution



Teboul JL, Saugel B, Cecconi M, De Backer D, Hofer CK, Monnet X, Perel A,Pinsky MR, Reuter DA, Rhodes A, Squara P, Vincent JL, Scheeren TW. Less invasive hemodynamic monitoring in critically ill patients. Intensive Care Med. 2016 Sep;42(9):1350-9.

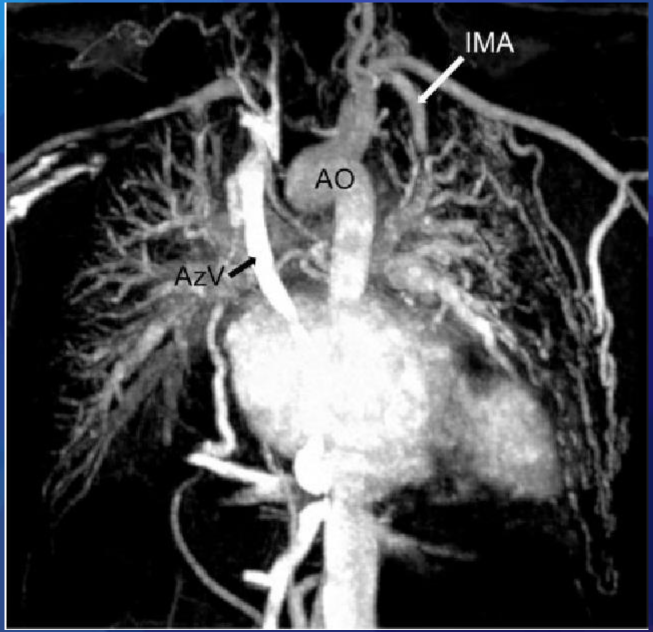
Use of CMR

1. Direct measurement of pulmonary blood flow
   a. QRPA + QLPA
   b. Q (RUPV + RLPV + LUPV + LLPV) in cases of turbulence
2. Catheter pressure measurement



Muthurangu V et al. Novel method of quantifying pulmonary vascular resistance by use of simultaneous invasive pressure monitoring and phase-contrast magnetic resonance flow. Circulation. 2004; 110:826-834.

5. Assessment of aortopulmonary collateral flow



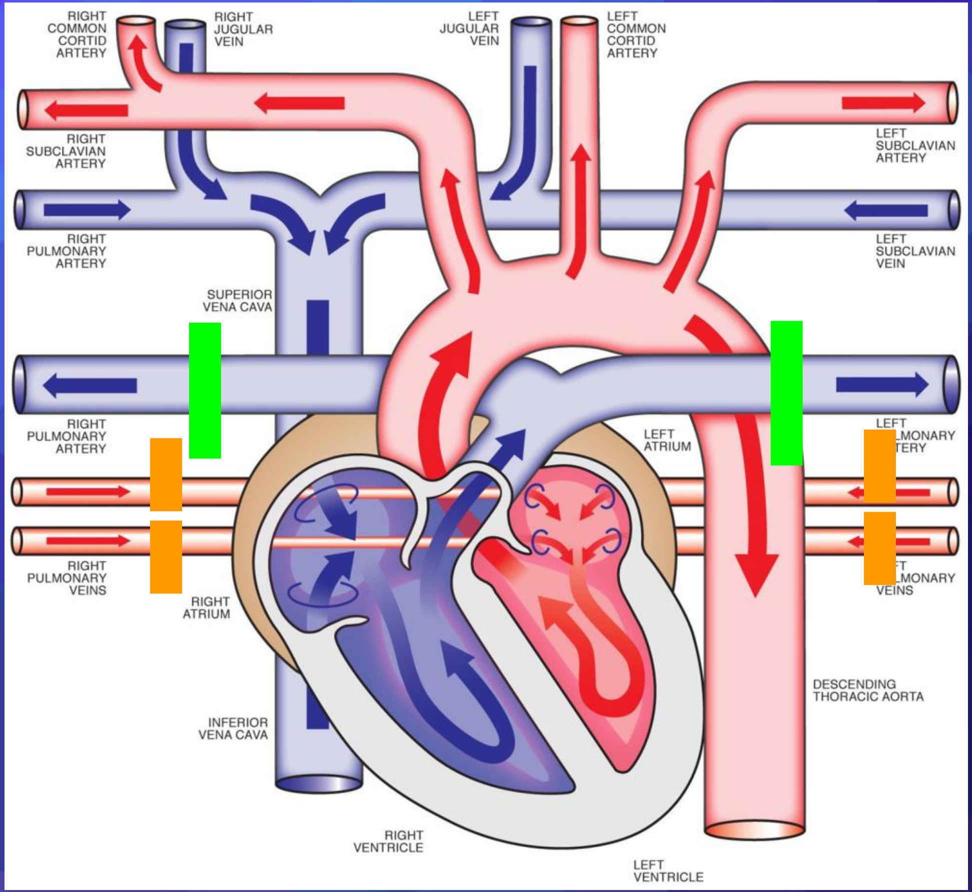
Grosse-Wortmann L, Al-Otay A, Yoo SJ. Aortopulmonary collaterals after bidirectional cavopulmonary connection or Fontan completion: Quantification with magnetic resonance

Perioperative management of APCs prior to Fontan completion

The aortopulmonary collateral flow (relative to the cardiac index) correlated with

- the duration of hospital stay (P = .02)
- and pleural drainage (P = .03).

Grosse-Wortmann, Lars et al. Aortopulmonary collateral flow volume affects early postoperative outcome after Fontan completion: A multimodality study. The Journal of Thoracic and Cardiovascular Surgery , Volume 144 , Issue 6 , 1329 - 1336



$$Q_{pa} = Q_{RPA} + Q_{LPA}$$

$$Q_{pv} = Q_{PVs}$$

$$Q_{APC} = Q_{pv} - Q_{pa}$$

BCPC

MRN_______________ **NAME**____________________ **AGE**___________

Date of Exam:____________________ **Date of Birth:**______________________

Weight ________ **kg** **Height** __________ **cm** **BSA** _________ **m²**

OBJECTIVES:

1. Pulmonary blood flow
2. Aortopulmonary collaterals
3. Ventricular function

PROTOCOL:

	SEQUENCE	REF IMAGES	#	REMARKS
	SSFP scout – 3 planes			
	SSFP localizer – 3 planes	Scout		
	Cine – 2CV	Axial	5	
	MOLLI – SA - precontrast	Axial / 2CV	3	basal and midventricular
	3D IR FLASH Angio with ECG-gating and respiration navigation	Axial / Sag / Cor		Gadovist 0.2 mmol/kg Slow infusion, starting 45 sec before the start of contrast and finishing 45 sec before the expected end of the scan.
	Cine – 4CV	AVV / 2CV	1	
	Cine – SA	2CV / 4CV	10-14	3rd plane should align on the AV junction.
	T1 scout for LGE - SA	2CV / 4CV	1	At 10 min after injection of Gadovist
	LGE – SA single shot	2CV / 4CV		Cover entire ventricles
	Cine – 4CV (60 phases low resolution for 3D prescrip)			
	LGE – axial single shot	Coronal / Sagittal		Cover entire LV
	MOLLI – SA - postcontrast	Same as pre	3	
	PC – AAO	Coronal / Sagittal		Use angio when needed
	PC – SVC	Coronal / sagittal		Use angio when needed
	PC - DAO	Coronal / Sagittal		Also target IVC if possible
	PC - LPA	IR FLASH		
	PC - RPA	IR FLASH		Consider upper and main branch separately
	PC – RUPV	IR FLASH		
	PC – RLPV	IR FLASH		
	PC – LUPV	IR FLASH		
	PC – LLPV	IR FLASH		

- PC of large venous decompressing channels, if present

Fontan Operation

PROTOCOL:

	SEQUENCE	REF IMAGES	#	REMARKS
	SSFP scout – 3 planes			
	SSFP localizer – 3 planes	Scout		High resolution for coronal
	Cine – 2CV	Axial	5	
	MOLLI – Ax – precontrast	Coronal / Sagittal	1	
	MOLLI – SA - precontrast	Axial / 2CV	2	basal and midventricular
	Flash in-out of phase imaging	Axial liver only		Please refer to protocol at the end of this document
	HASTE T2 Abd	Axial		
	HASTE T2 Abd	Coronal		
	GRE T1 or 3D VIBE	Axial /Coronal		
	Static contrast angio – 5 runs	Axial / Sag / Cor		MultiHance 0.15 mmol/kg, injection over 70% of scan time, trigger the 1st run when contrast arrives in descending aorta.
	Cine – 4CV	AVV / 2CV	1	
	Cine – SA	2CV / 4CV	10-14	3rd plane should align on the AV junction.
	GRE T1 or 3D VIBE	Coronal		
	T1 scout for LGE - SA	2CV / 4CV	1	At 10 min after injection of MultiHance
	LGE – SA single shot	2CV / 4CV		Cover entire LV
	LGE – axial single shot	Coronal / Sagittal		Cover entire LV
	Cine – 4CV (60 phases low resolution for 3D prescrip)			
	MOLLI – Ax – postcontrast	Same as pre	1	At 15 minutes after injection of MultiHance
	MOLLI – SA - postcontrast	Same as pre	2	
	Inject Ablavar 0.03 mmol/kg			
	3D IR FLASH - coronal	Axial / Sagittal		
	PC – AAO	Coronal / Sagittal		Use angio when needed
	PC – SVC	Coronal / sagittal		Use angio when needed
	PC - DAO	Coronal / Sagittal		Also target IVC if possible
	PC - LPA	IR FLASH		
	PC - RPA	IR FLASH		Consider upper and main branch separately
	PC – RUPV	IR FLASH		
	PC – RLPV	IR FLASH		
	PC – LUPV	IR FLASH		
	PC – LLPV	IR FLASH		
	PC-Fontan below fenest	IR FLASH		
	PC-Fontan above fenest (when present)	IR FLASH		
	PC-Fenestration (when present)	2CV / axial		VENC of 200cm/s
	PC-SMA/SMV	IR FLASH		
	PC-celiac axis	IR FLASH		
	PC-portal vein	IR FLASH		
	PC-IVC above renal veins	IR FLASH		
	PC-IVC and DAO above bifurcation	IR FLASH		

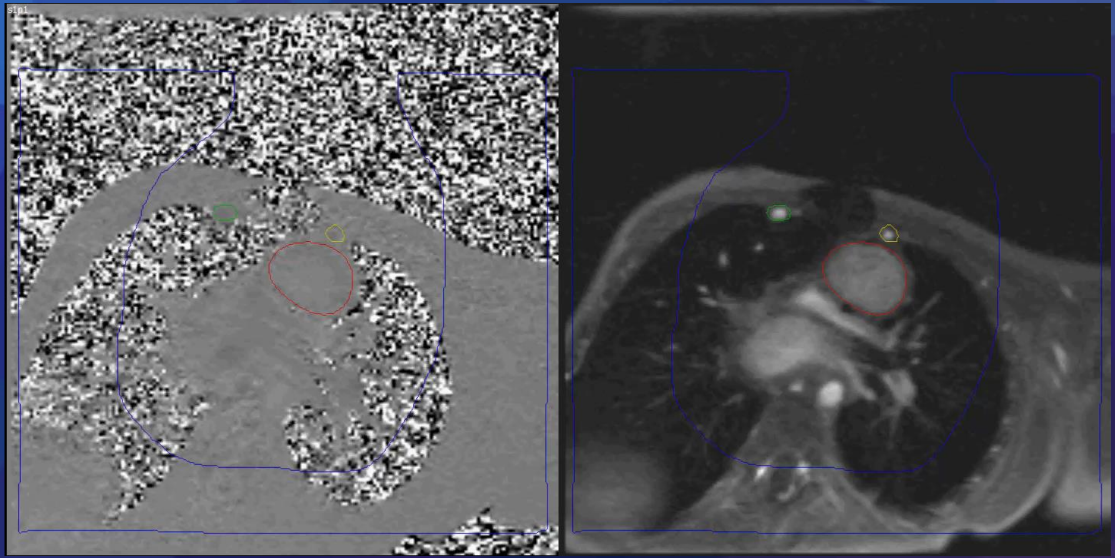
Workflow at SickKids

1. MRI performed at Cardiac Diagnostic Imaging Unit
2. Invasive angiography performed
3. Flows derived from MRI
4. Embolisation of collaterals if presence of significant APCs (~>50%)


Radiologist
Cardiothoracic surgeon
Cardiologist
Interventional cardiologist

Limitations of phase contrast imaging

1. Motion artefacts
2. Partial volume artefacts
3. Turbulence or stenotic jets



Future directions

4D Flow

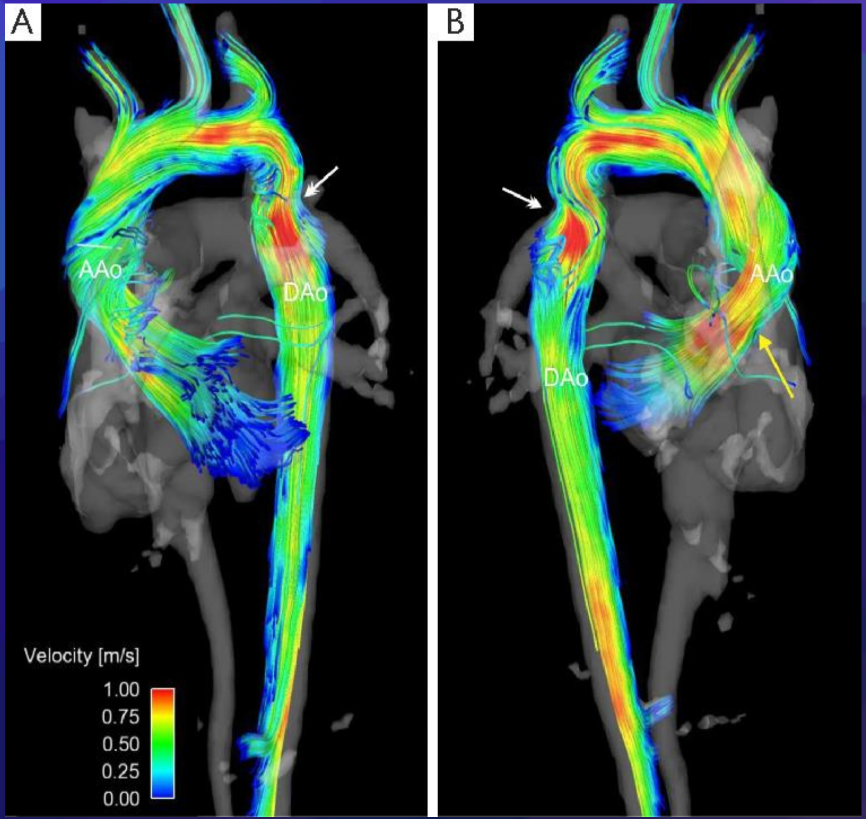
Additional information on

Wall shear stress

Turbulent kinetic energy

Vortex flows

Pressure gradient



4D flow MRI. Michael Markl et al. Journal of magnetic resonance imaging : JMRI 2012

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Questions?

Thank you!

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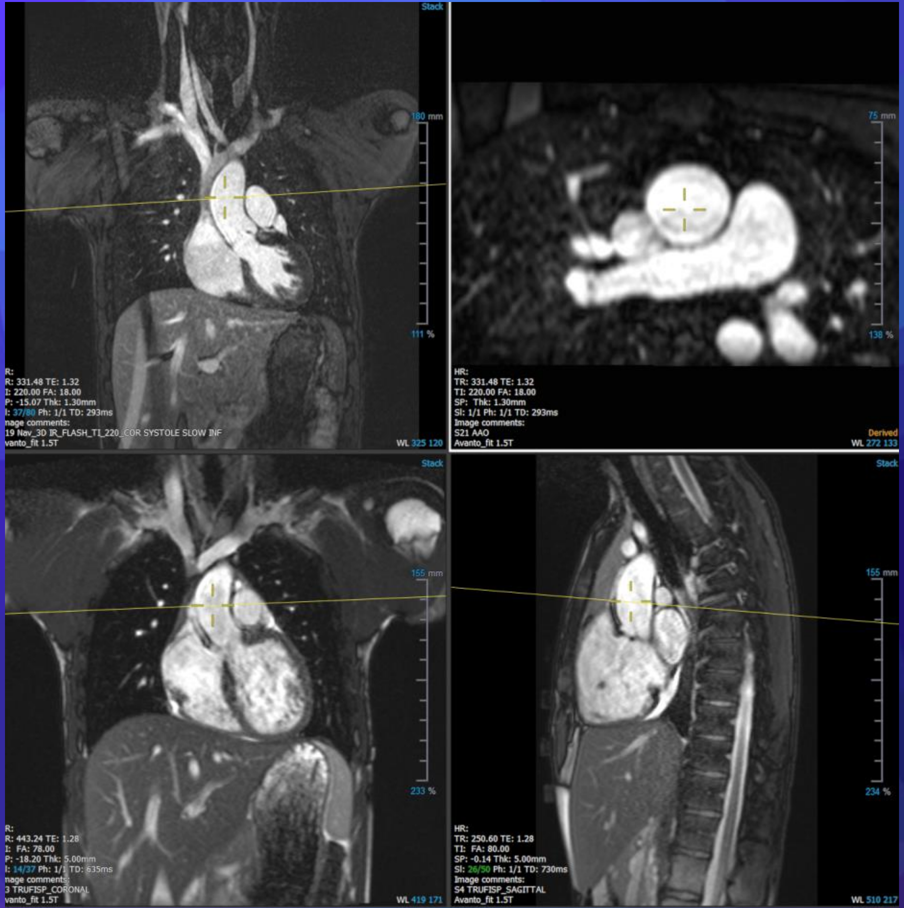
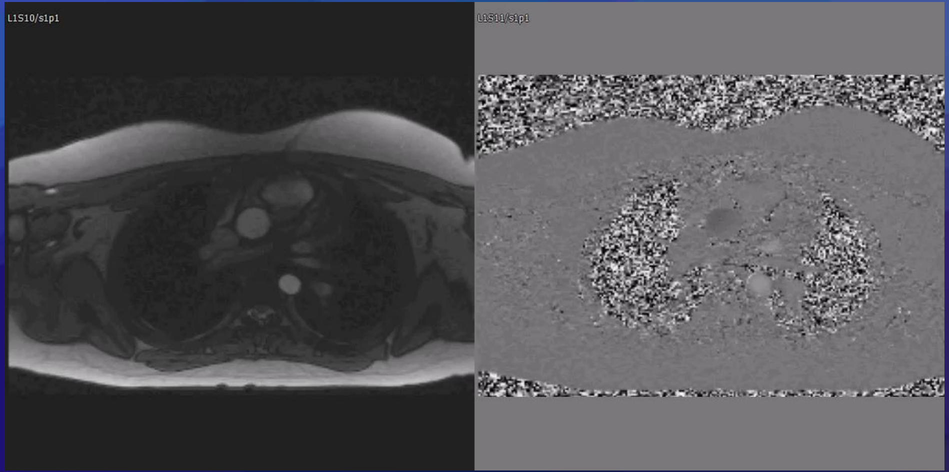
Appendix





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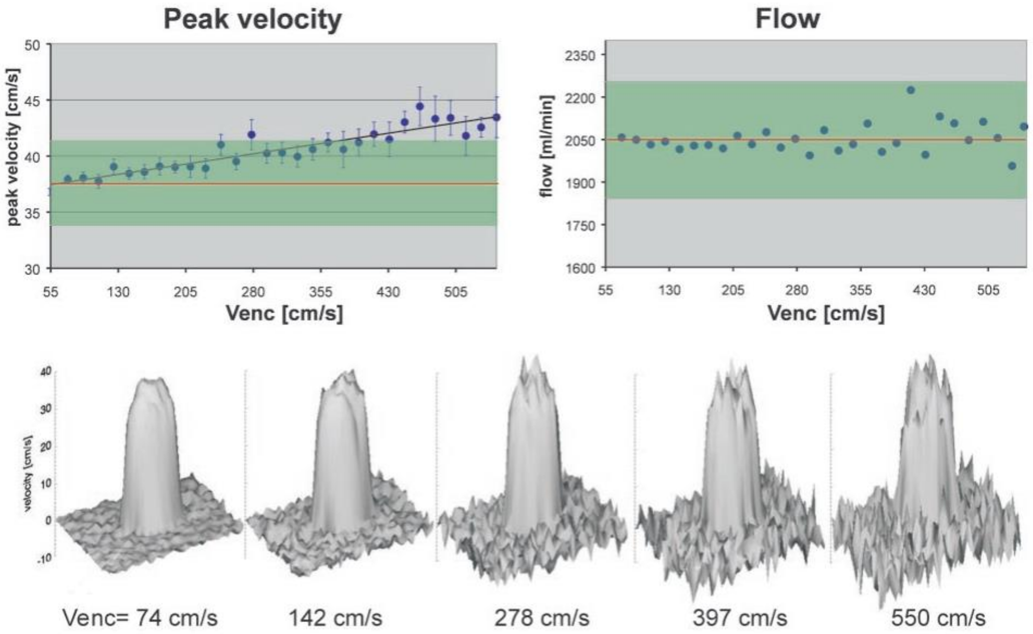
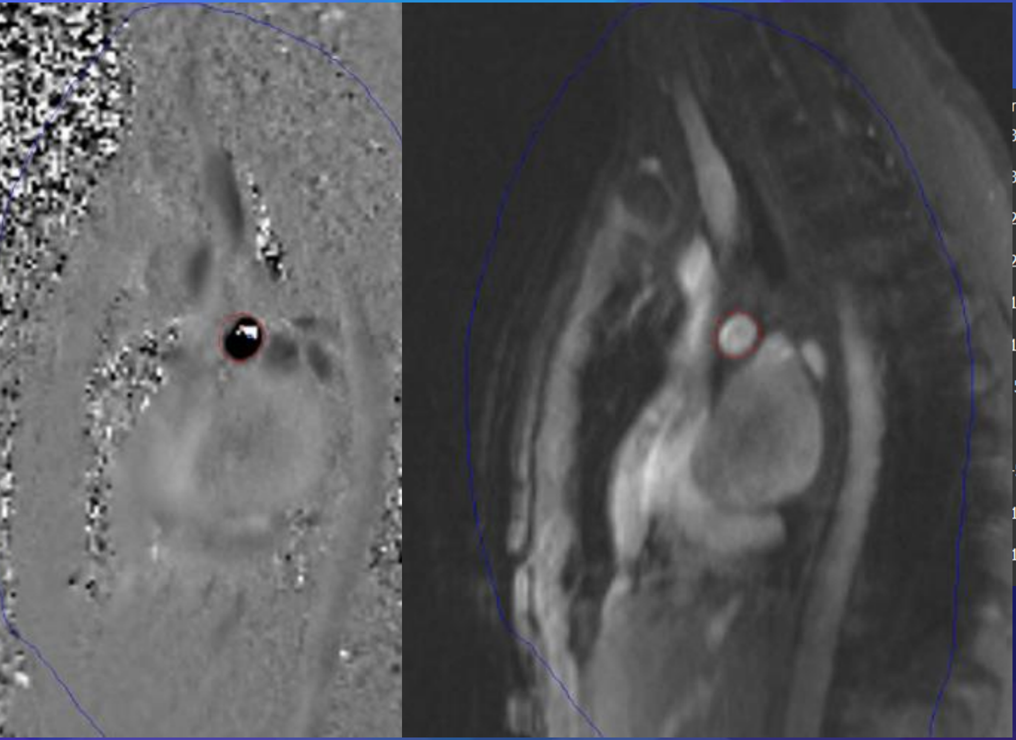
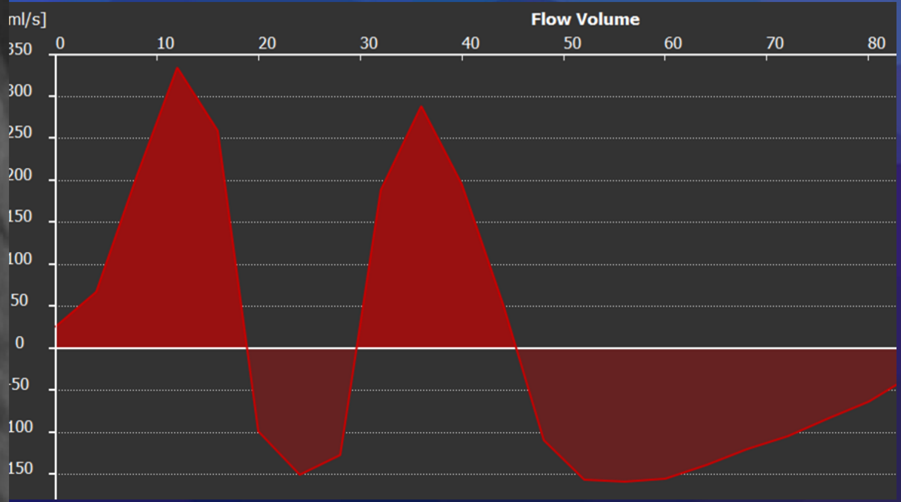


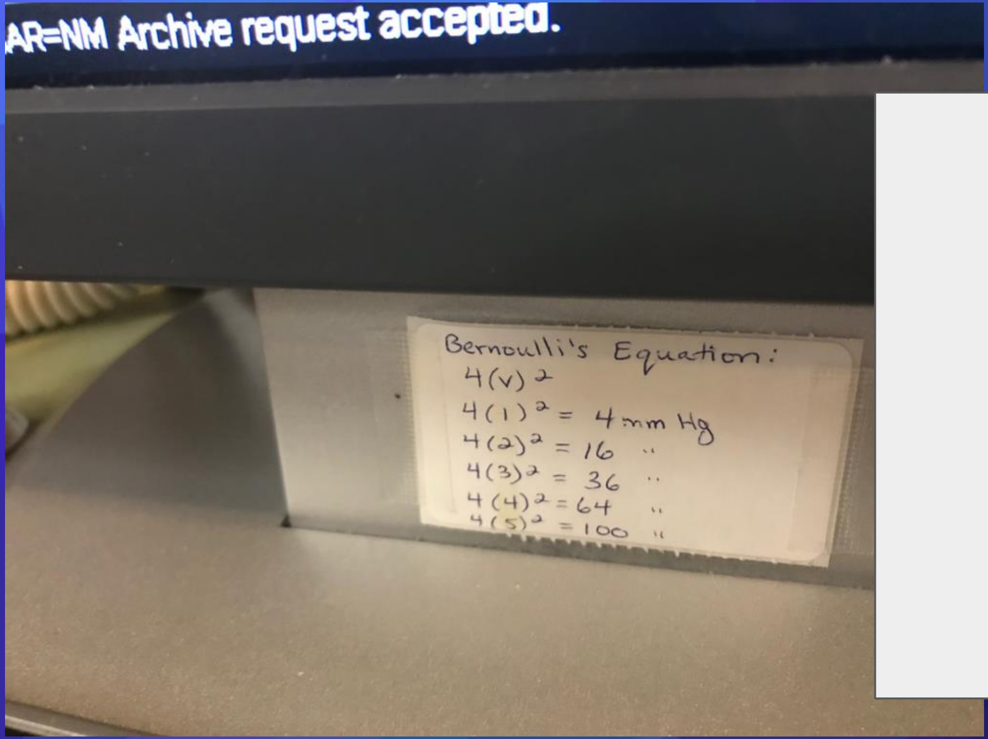
Figure 4. Effect of a mismatched V_{enc} on noise. Top: Graphs show that, in an experimental setting, estimates of peak velocity demonstrate a deviation of more than 10% if V_{enc} increases by more than three times the velocity in the vessel (left), whereas estimates of flow are largely preserved (right). Red line indicates the true peak velocity or true flow. Green area indicates a deviation of 10% from the true peak velocity or true flow. Bottom: Surface renderings of data from velocity images obtained at different values of V_{enc} show how increasing noise may mask the true peak velocity values. (The experimental setting consisted of the following: laminar steady flow of 2.05 L/min, gadolinium-doped saline solution, and a 1.5-cm-diameter glass tube. The real flow rate was monitored with an inductive flowmeter. The imaging parameters were kept constant while V_{enc} was varied between 57 cm/sec and 550 cm/sec.)

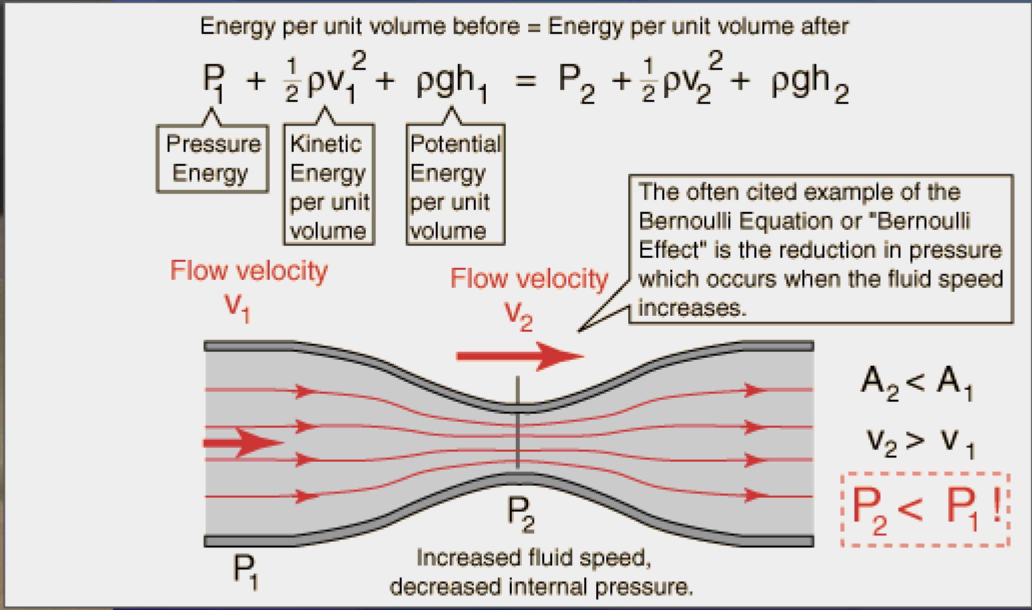
Lotz J et al. Cardiovascular flow measurement with phase-contrast MR imaging: basic facts and implementation. Radiographics. 2002 May-Jun;22(3):651-71





ml/s]
Flow Volume
0
10
20
30
40
50
60
70
80
350
300
250
200
150
100
50
0
-50
100
150





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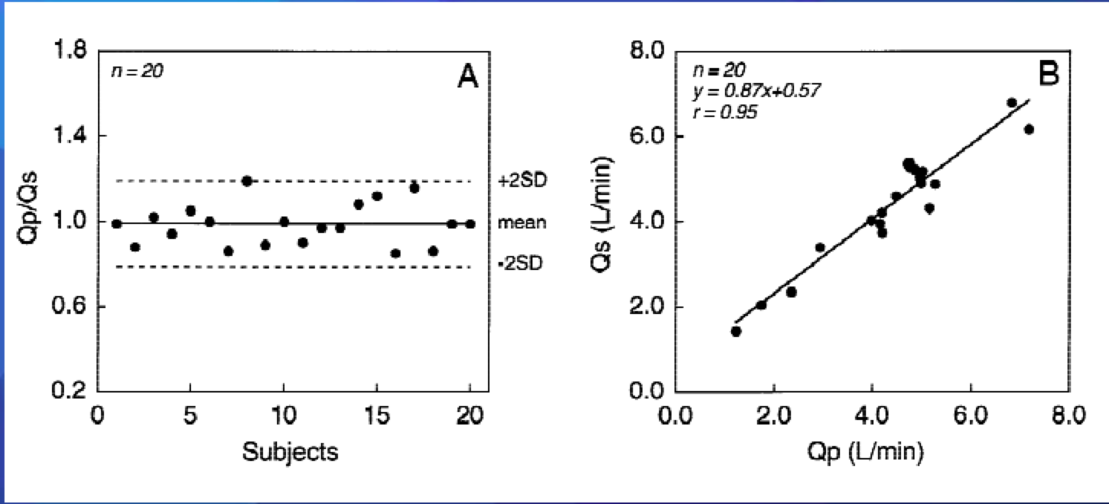
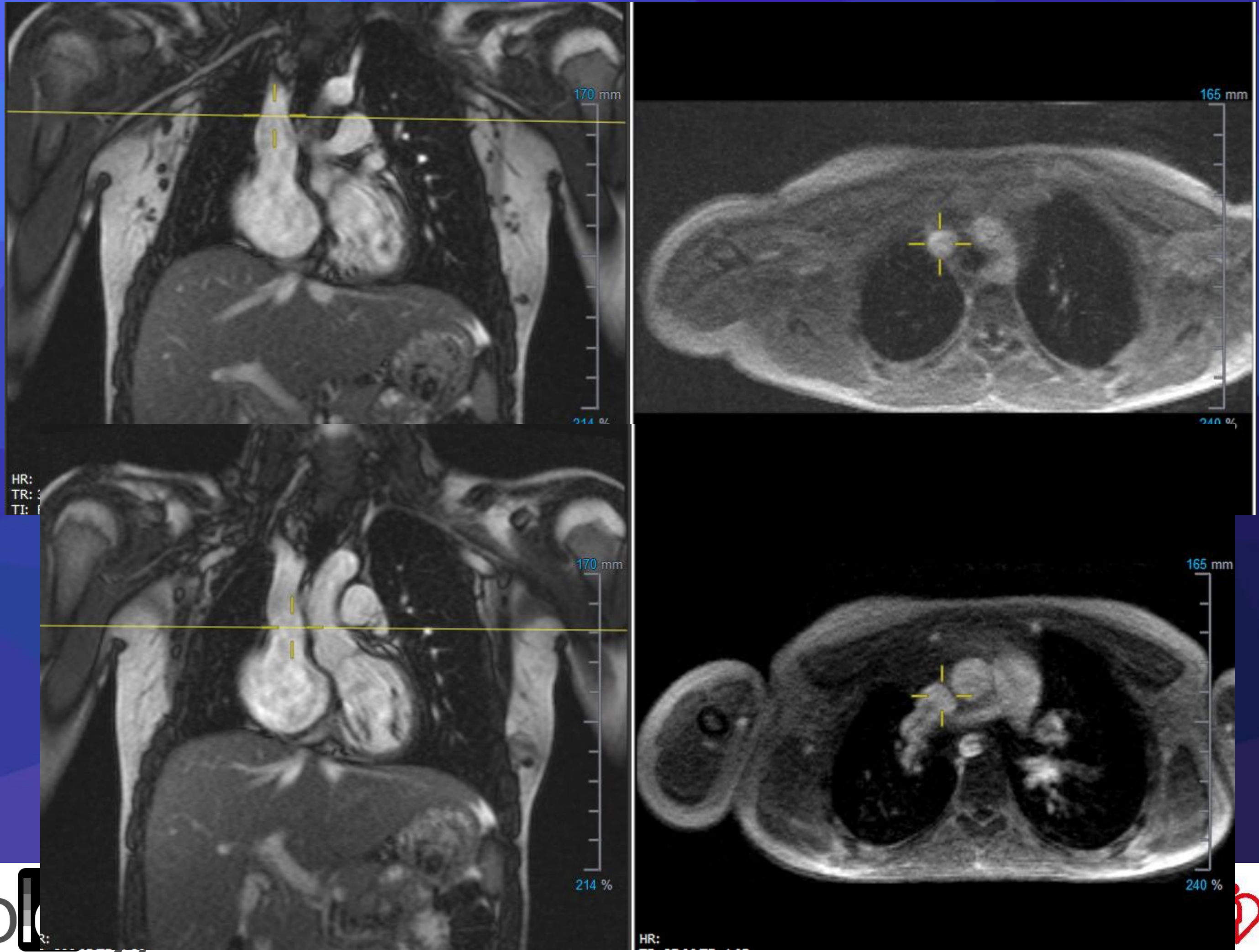


Powell AJ et al. Phase-velocity cine magnetic resonance imaging measurement of pulsatile blood

flow in children and young adults: in vitro and in vivo validation. Pediatr Cardiol.

Commonly encountered flow patterns

1. PAPVC
   a. Simple numbers game: Qsvc above Qsvc below



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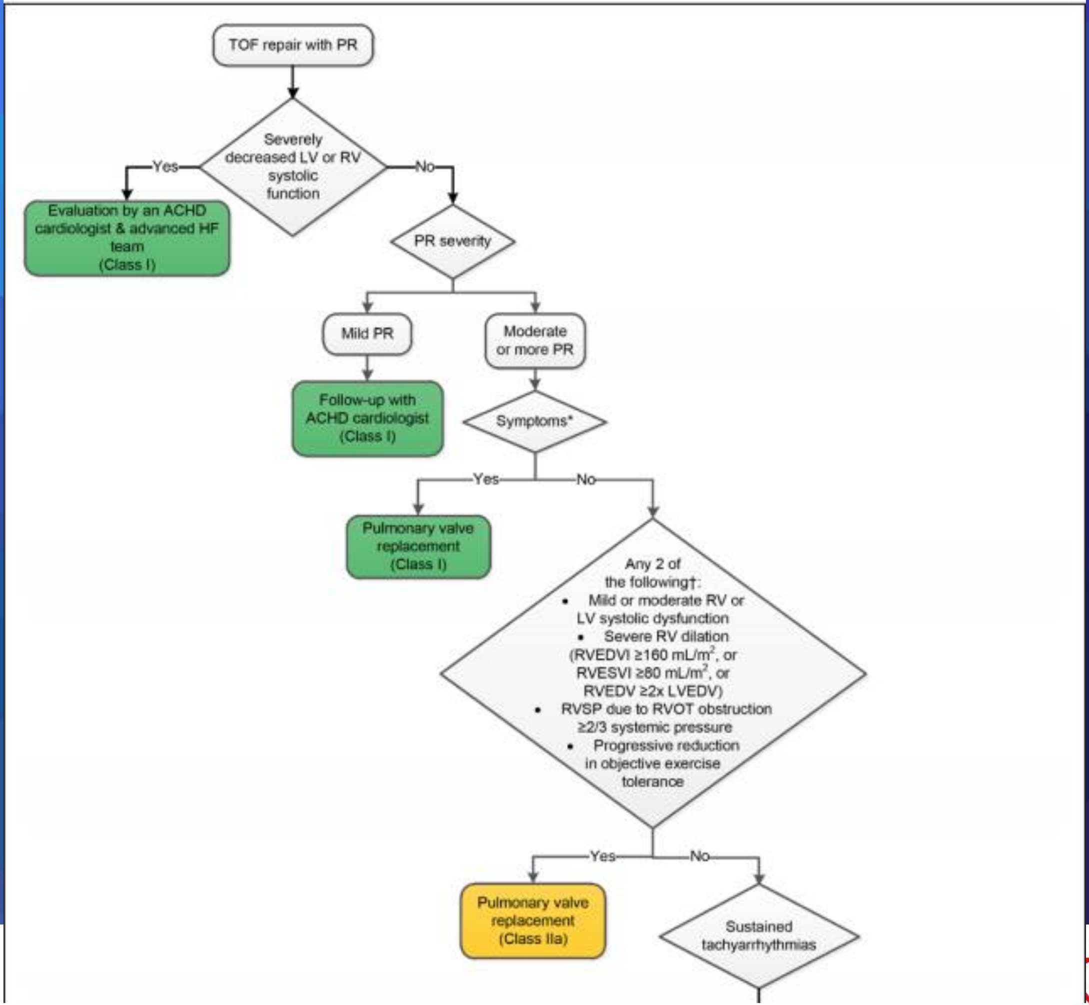

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