Non-Contrast-Enhanced MR Angiography – Methods for Assessment of Morphology and Flow

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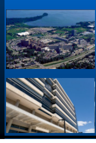
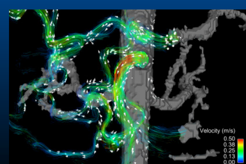
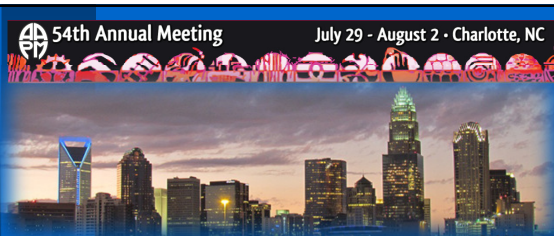






Declaration of Relevant Financial Interests or Relationships

Speaker Name: Oliver Wieben

I have the following relevant financial interest or relationship to disclose with regard to the subject matter of this presentation:

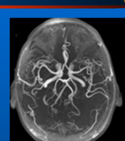
Company name: GE Healthcare
Type of relationship: Research Support

Outline

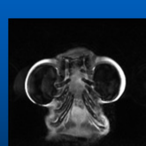
Motivation for Noncontrast-Enhanced (NCE)-MRA

NCE MRA Acquistion Methods
- Time-of-Flight (TOF)
- balanced SSFP
  - MRA
  - Arterial spin labeling (ASL)
- Phase Contrast (PC)
  - MRA
  - 4D PC MR - Hemodynamics
- Fast Spin Echo (FSE)
  - Fresh Blood Imaging (FBI)

Summary & Outlook

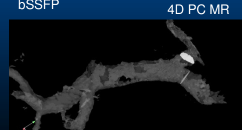


TOF



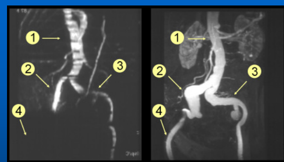
bSSFP

4D PC MR



Contrast-Enhanced (CE)-MRA

Advantages of CE-MRA
- Very high SNR
- Robust, insensitive to artifacts
  - Slow flow, suscetibility, etc.
- Well established – clinically proven
- Quantitative perfusion



TOF *CE-MRA*

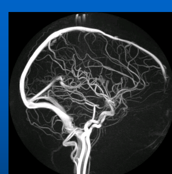
Disadvantages of CE-MRA
- Bolus Imaging
  - Arterial-venous window
  - limited scan time for first pass
    - *Limited SNR/spatial resolution/coverage*
  - synchronization with breathhold
  - Venous injection: bolus dispersion
- Use of Gd based contrast agents
  - Costs
  - Patients with compromised kidney function
    - *Nephrogenic Systemic Fibrosis*

SE Cowper et al., Lancet, 2000

Time-resolved CE-MRA

Why NCE-MRA

Advantages of NCE-MRA
- No Gd
  - *Cost reduction*
  - *Save Gd injection for other scan (e.g. perfusion)*
  - *No background enhancement from Gd*
  - *Provide alternative for patients at risk for NSF*
- Extended scan times
  - *Navigator/bellows instead of breathholds*
    - Improved patient comfort
  - *Aim for higher spatial resolution*
  - *Cardiac gating can be added*
- Functional information
  - *Arterial Spin Labeling*
    - ‚Virtal Arterial Injection'
    - Quantitative Perfusion Imaging
  - *PC MRI*
    - Velocity Vector Fields
    - Trans-stenotic Pressure Gradients
    - Vessel Stiffness (Pulse Wave Velocity)
    - Wall Shear Stress
    - ...

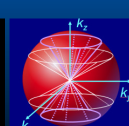


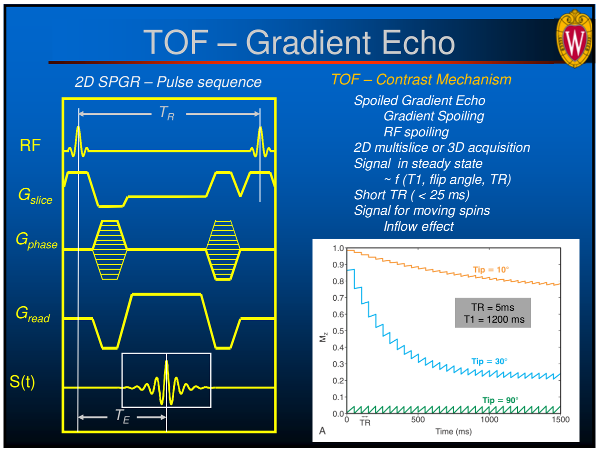
PC VIPR

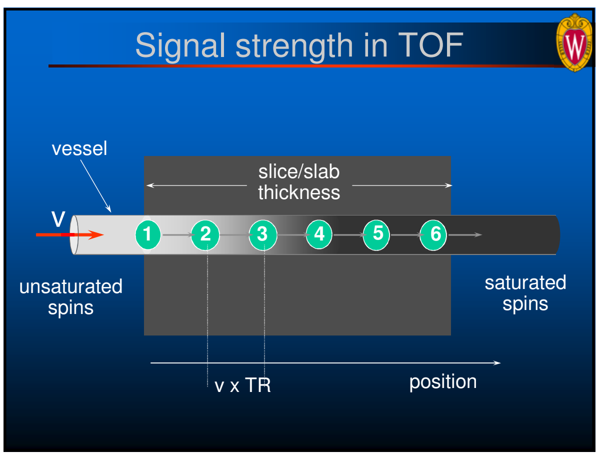
NCE MRA - Progress

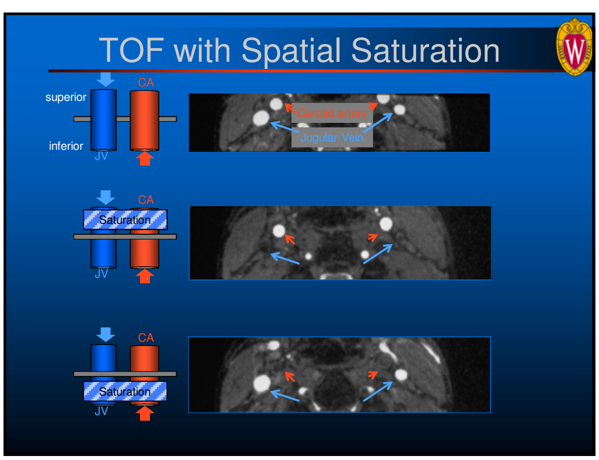
Hardware Advances
- Higher field strength (3T+)
  - Higher SNR
- Faster gradients
  - Fast imaging
  - Reduces artefacts
    - motion
    - dephasing from long TE
  - Enables balanced SSFP
- Multiple receiver coils
  - Higher SNR

Methodology Advances
- Novel reconstruction approaches
  - Parallel Imaging
    - SENSE, SMASH, GRAPPA, ARC, ...
  - Constrained Reconstruction
    - Compressed Sensing
    - HYPR, kt-BLAST, RIGR
- Novel contrast mechanisms
  - balanced SSFP
  - arterial spin labeling
  - Fresh Blood Imaging (FBI)
- Novel sampling strategies
  - Radial Undersampling, spiral trajectories, ...




TOF – Gradient Echo
2D SPGR – Pulse sequence
RF
G_{slice}
G_{phase}
G_{read}
S(t)
T_R
T_E
TOF – Contrast Mechanism
Spoiled Gradient Echo
Gradient Spoiling
RF spoiling
2D multislice or 3D acquisition
Signal in steady state
~ f (T1, flip angle, TR)
Short TR (< 25 ms)
Signal for moving spins
Inflow effect
Tip = 10°
TR = 5ms
T1 = 1200 ms
Tip = 30°
Tip = 90°
Time (ms)

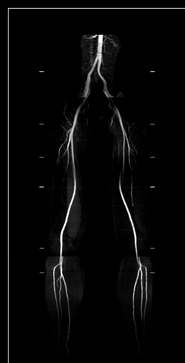

Signal strength in TOF
vessel
slice/slab
thickness
V
1
2
3
4
5
6
unsaturated
spins
saturated
spins
v x TR
position

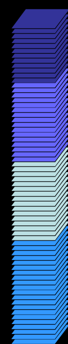

TOF with Spatial Saturation
superior
inferior
CA
JV
Saturation

Peripheral MRA with 2D TOF

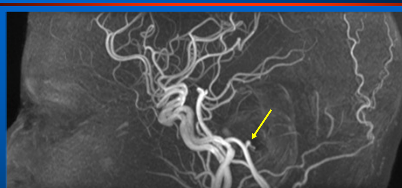
2D TOF at 1.5T

- Multistation exam
  - *up to 4 slabs*
- Magnetization transfer, fat saturation
- ECG gated, 32 views per segment
- TR/TE: 12.7/1.5 ms
- Flip angle = 70 deg
- FOV: 300 (360) x 150 (180) mm^2
- Matrix: 256 x 192
- Slice thickness: 3.0 mm
- Slices per slab: ~140-170
- Scan time: 5-7 min
- Acquired resolution:
  - 1.2 x 1.6 x 3 mm^2
- Reconstructed resolution
  - 0.6 x 0.6 x 3 mm^2





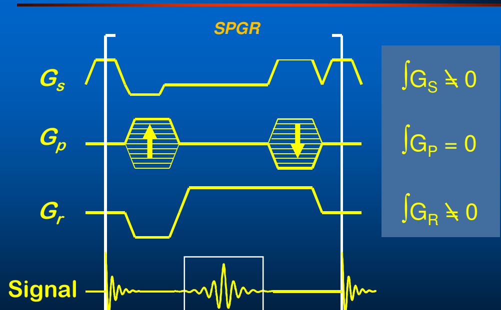
Cranial MRA with 3D TOF



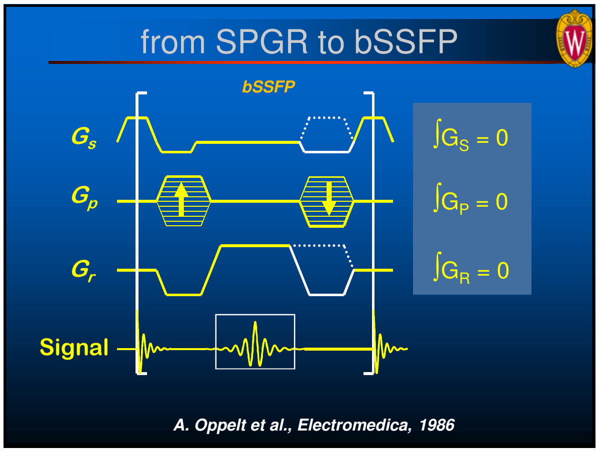
Intracranial 3D TOF – 38 y female volunteer
- Incidental finding of 2mm posterior-inferior cerebreallar artery (PICA) aneurysm

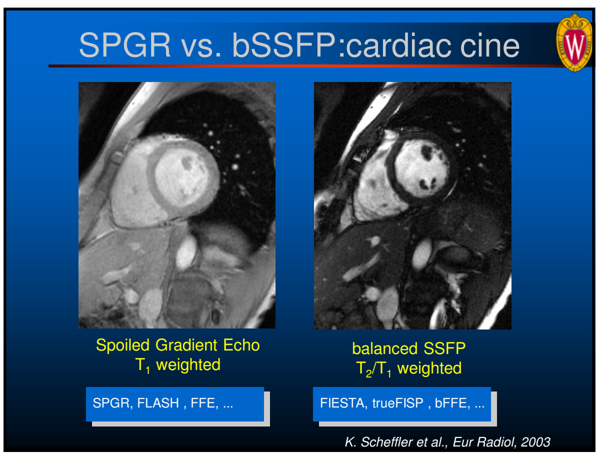
Typical Imaging Protocol
- 3 Tesla, magnetization transfer, flow compensation, fat sat, parallel imaging
- FOV = 22x16.5 cm;
- TR / TE = 24/2.4 ms; flip angle = 20 deg (ramped),
- Scan time = 4:30 min
- Acquired:
  - *imaging matrix = 512x224,*
  - *3 slabs, 42 slices per slab, 1mm slice thickness*
- Reconstructed:
  - *spatial resolution: 0.5 x 0.5 x 0.5 mm*
  - *192 slices – 9.6 cm coverage*

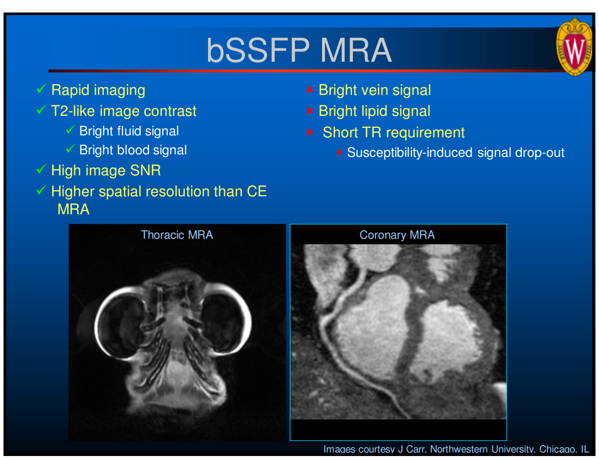
from SPGR to bSSFP



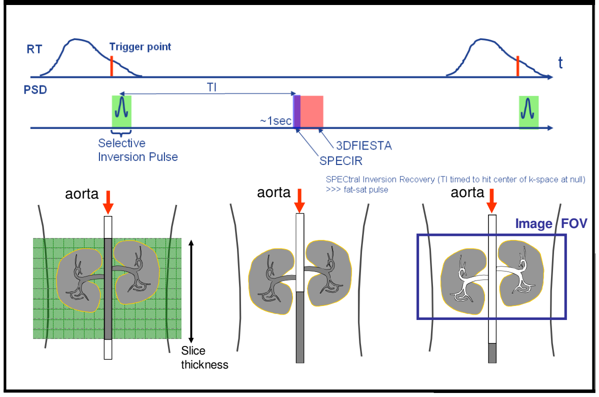
J. Frahm et al., MRM, 1986


from SPGR to bSSFP
bSSFP
G_s
G_p
G_r
Signal
$\int G_S = 0$
$\int G_P = 0$
$\int G_R = 0$
A. Oppelt et al., Electromedica, 1986


SPGR vs. bSSFP:cardiac cine
Spoiled Gradient Echo
T_1 weighted
balanced SSFP
T_2/T_1 weighted
SPGR, FLASH , FFE, ...
FIESTA, trueFISP , bFFE, ...
K. Scheffler et al., Eur Radiol, 2003


bSSFP MRA
✓ Rapid imaging
✓ T2-like image contrast
✓ Bright fluid signal
✓ Bright blood signal
✓ High image SNR
✓ Higher spatial resolution than CE MRA
× Bright vein signal
× Bright lipid signal
× Short TR requirement
• Susceptibility-induced signal drop-out
Thoracic MRA
Coronary MRA
Images courtesy J Carr, Northwestern University, Chicago, IL

bSSFP with inflow spin labeling



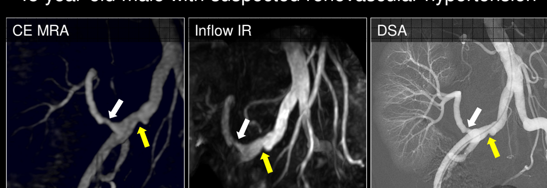
Inhance Inflow IR

Typical parameters at 1.5T
- TR/TE: 4.2/2.1 ms
- TI: 1300 ms
- Flip angle: 70°
- Prep Time: 200 ms
- FOV: 360 x 288 mm^2
- Matrix: 256 x 256
- Resolution: 1.40 x 1.13 mm^2
- ST: 2 mm
- Acquisition time: 4:17

Typical parameters at 3.0T
- TR/TE: 5.1/2.5 ms
- TI: 1300 ms
- Flip angle: 70°
- Prep Time: 240 ms
- FOV: 340 x 272 mm^2
- Matrix: 256 x 256
- Resolution: 1.32 x 1.06 mm^2
- ST: 2 mm
- Acquisition time: 3:18

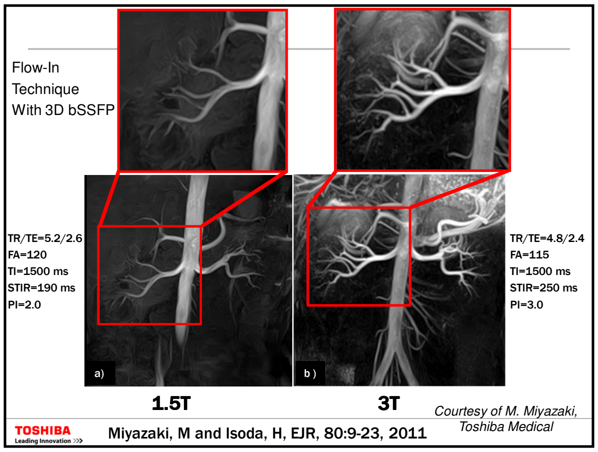
Inhance Inflow IR at 1.5T

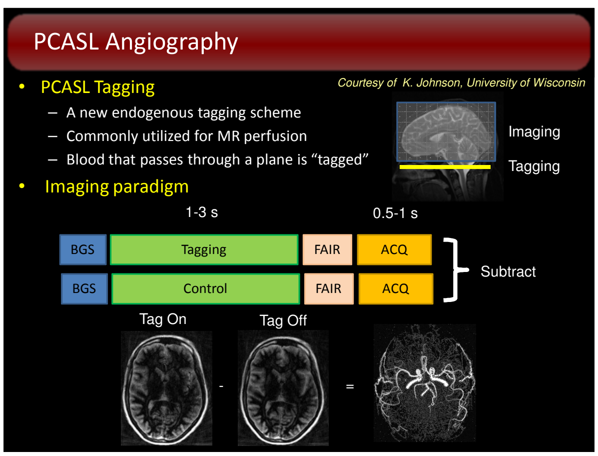
45 year-old male with suspected renovascular hypertension

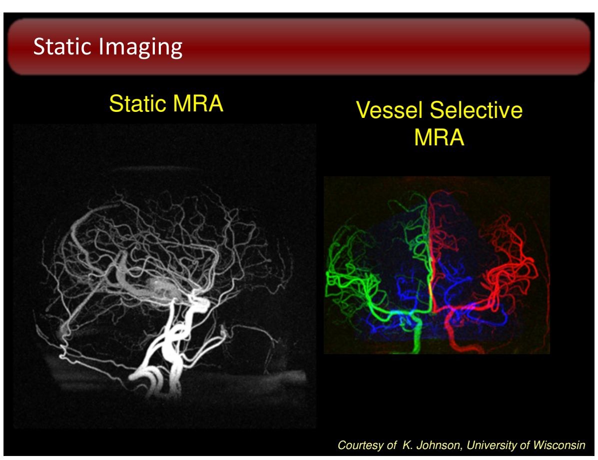


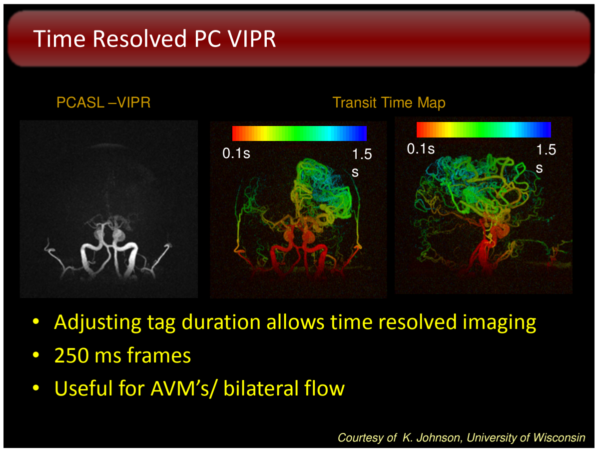
Trans-stenotic pressure gradient (TSPG) in DSA

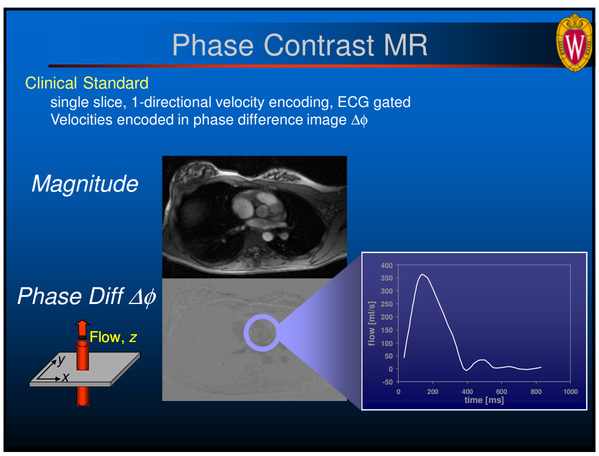
- Right common iliac artery > 10 mmHg → angioplasty
- Transplant renal artery < 10 mmHg → no treatment

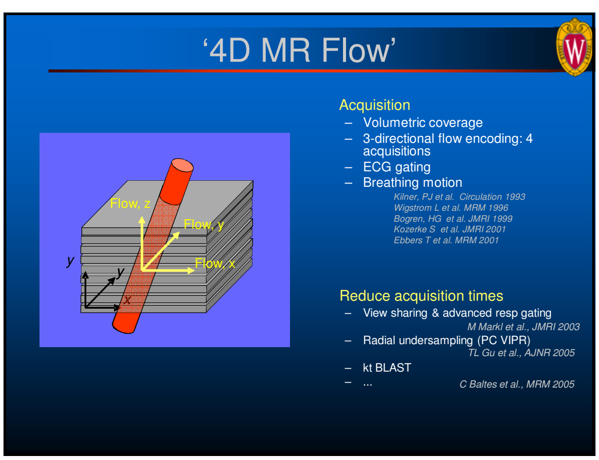

Flow-In
Technique
With 3D bSSFP
TR/TE=5.2/2.6
FA=120
TI=1500 ms
STIR=190 ms
PI=2.0
TR/TE=4.8/2.4
FA=115
TI=1500 ms
STIR=250 ms
PI=3.0
a)
b)
1.5T
3T
Courtesy of M. Miyazaki, Toshiba Medical
TOSHIBA
Leading Innovation
Miyazaki, M and Isoda, H, EJR, 80:9-23, 2011

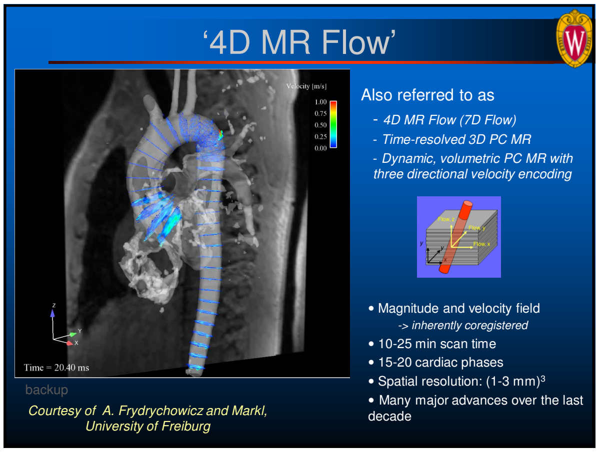

PCASL Angiography
Courtesy of K. Johnson, University of Wisconsin
• PCASL Tagging
– A new endogenous tagging scheme
– Commonly utilized for MR perfusion
– Blood that passes through a plane is "tagged"
Imaging
Tagging
• Imaging paradigm
1-3 s
0.5-1 s
BGS
Tagging
FAIR
ACQ
BGS
Control
FAIR
ACQ
Subtract
Tag On
Tag Off
-
=

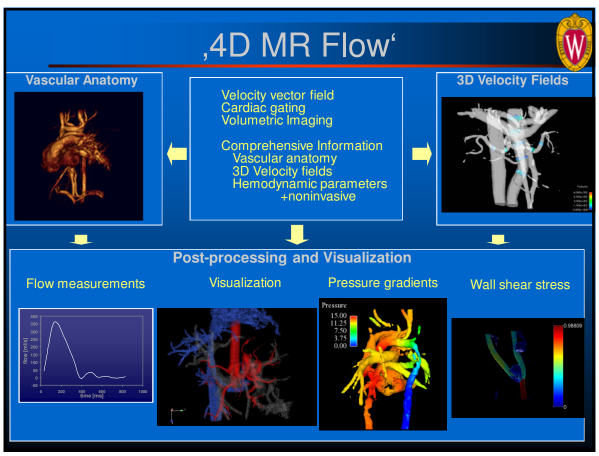

Static Imaging
Static MRA
Vessel Selective MRA
Courtesy of K. Johnson, University of Wisconsin

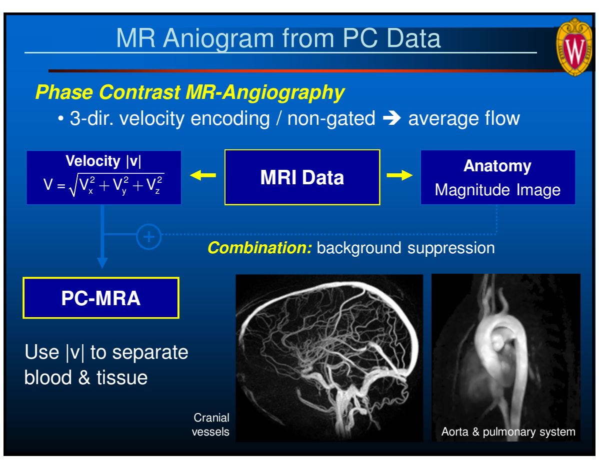

Time Resolved PC VIPR
PCASL –VIPR
Transit Time Map
0.1s
1.5
s
0.1s
1.5
s
• Adjusting tag duration allows time resolved imaging
• 250 ms frames
• Useful for AVM's/ bilateral flow
Courtesy of K. Johnson, University of Wisconsin


Phase Contrast MR
Clinical Standard
single slice, 1-directional velocity encoding, ECG gated
Velocities encoded in phase difference image Δϕ
Magnitude
Phase Diff Δϕ
Flow, z
y
x
flow [ml/s]
time [ms]


'4D MR Flow'
Flow, z
Flow, y
Flow, x
y
y
x
Acquisition
– Volumetric coverage
– 3-directional flow encoding: 4 acquisitions
– ECG gating
– Breathing motion
Kilner, PJ et al. Circulation 1993
Wigstrom L et al. MRM 1996
Bogren, HG et al. JMRI 1999
Kozerke S et al. JMRI 2001
Ebbers T et al. MRM 2001
Reduce acquisition times
– View sharing & advanced resp gating
M Markl et al., JMRI 2003
– Radial undersampling (PC VIPR)
TL Gu et al., AJNR 2005
– kt BLAST
– ...
C Baltes et al., MRM 2005


'4D MR Flow'
Also referred to as
- 4D MR Flow (7D Flow)
- Time-resolved 3D PC MR
- Dynamic, volumetric PC MR with three directional velocity encoding
• Magnitude and velocity field
-> inherently coregistered
• 10-25 min scan time
• 15-20 cardiac phases
• Spatial resolution: (1-3 mm)³
• Many major advances over the last decade
Time = 20.40 ms
backup
Courtesy of A. Frydrychowicz and Markl, University of Freiburg


„4D MR Flow"
Vascular Anatomy
Velocity vector field
Cardiac gating
Volumetric Imaging
Comprehensive Information
Vascular anatomy
3D Velocity fields
Hemodynamic parameters
+noninvasive
3D Velocity Fields
Post-processing and Visualization
Flow measurements
Visualization
Pressure gradients
Wall shear stress


MR Aniogram from PC Data
Phase Contrast MR-Angiography
• 3-dir. velocity encoding / non-gated ➔ average flow
Velocity |v|
$V = \sqrt{V_x^2 + V_y^2 + V_z^2}$
MRI Data
Anatomy
Magnitude Image
Combination: background suppression
PC-MRA
Use |v| to separate blood & tissue
Cranial vessels
Aorta & pulmonary system

PC VIPR – Cranial

Normal Volunteer

PC VIPR Parameters

- 3T (GE Healthcare)
- Dual Echo
- FOV: 20 x 20 x 20 cm
- Res: 0.6 x 0.6 x 0.6 mm
- 9000 Projections (36x)
- TR=15.9
- Bandwidth = 31.25
- VENC = 50 cm/s
- 5:07 min Scan Time

Same Cartesian PC

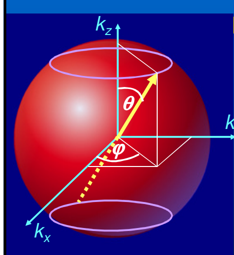
- 48+ min Exam (Partial)

Same TOF

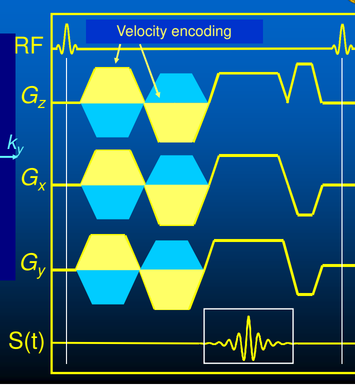
- 24+ min Exam (Partial)

KM Johnson et al.
ISMRM 2006 # 2384, 2958
ISMRM 2007 # 3116

PC VIPR – Sequence Design

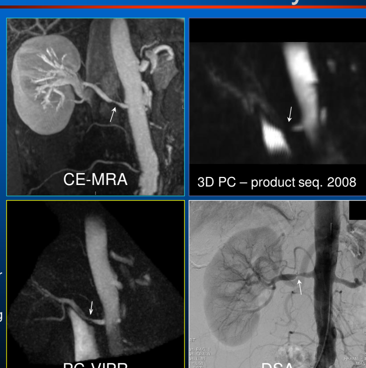


A Barger et. al, MRM 2002
TL Gu, AJNR 2005
KM Johnson, MRM 2008

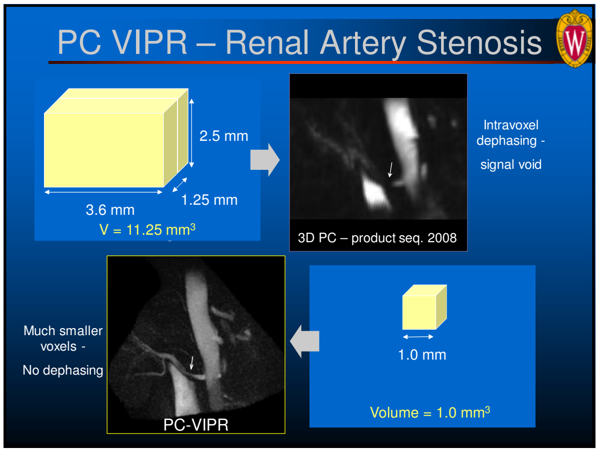


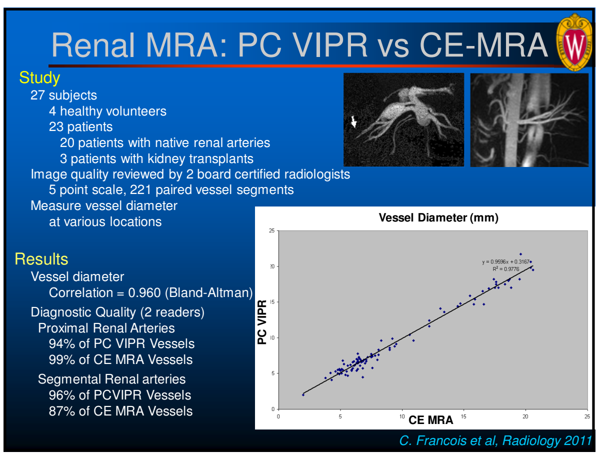
PC VIPR – Renal Artery Stenosis

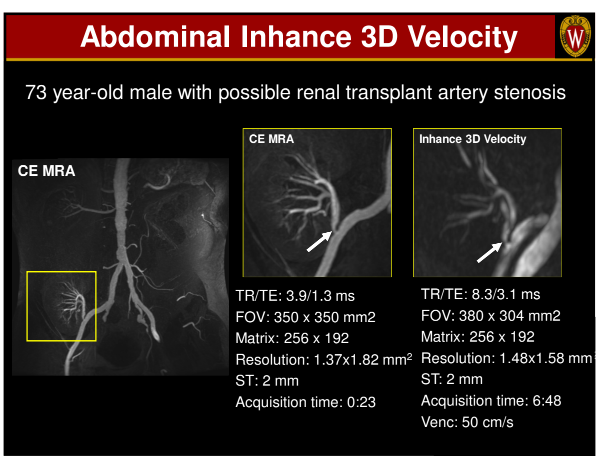
Much smaller voxels -
No dephasing

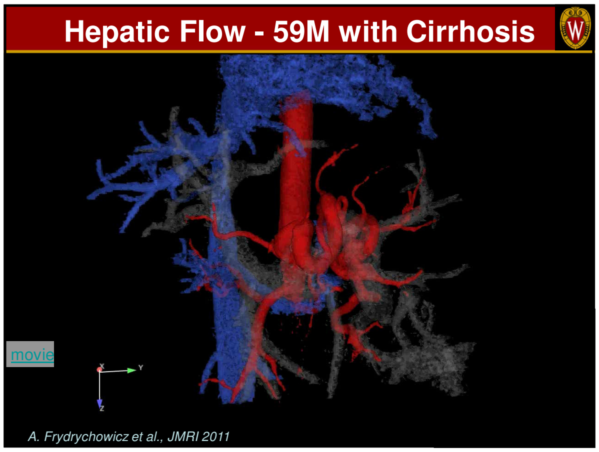


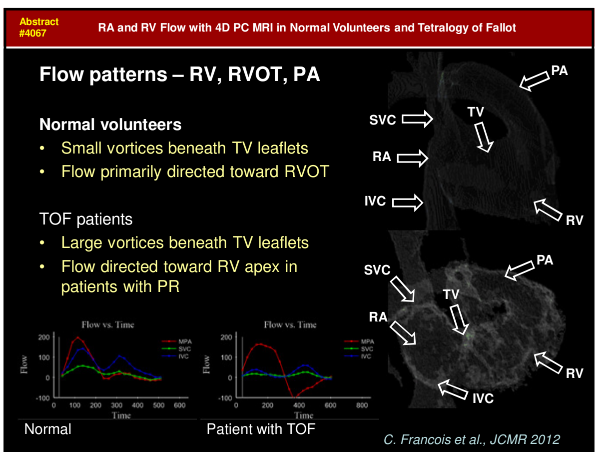
Intravoxel dephasing -
signal void

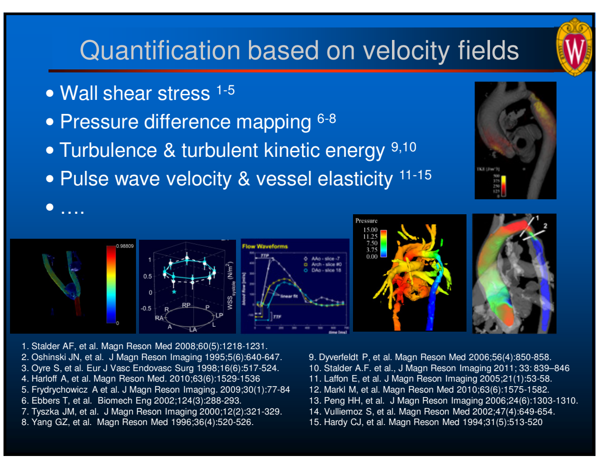

PC VIPR – Renal Artery Stenosis
2.5 mm
1.25 mm
3.6 mm
V = 11.25 mm³
Intravoxel dephasing -
signal void
3D PC – product seq. 2008
Much smaller voxels -
No dephasing
PC-VIPR
1.0 mm
Volume = 1.0 mm³


Renal MRA: PC VIPR vs CE-MRA
Study
27 subjects
4 healthy volunteers
23 patients
20 patients with native renal arteries
3 patients with kidney transplants
Image quality reviewed by 2 board certified radiologists
5 point scale, 221 paired vessel segments
Measure vessel diameter
at various locations
Vessel Diameter (mm)
PC VIPR
CE MRA
Results
Vessel diameter
Correlation = 0.960 (Bland-Altman)
Diagnostic Quality (2 readers)
Proximal Renal Arteries
94% of PC VIPR Vessels
99% of CE MRA Vessels
Segmental Renal arteries
96% of PCVIPR Vessels
87% of CE MRA Vessels
C. Francois et al, Radiology 2011


Abdominal Inhance 3D Velocity
73 year-old male with possible renal transplant artery stenosis
CE MRA
CE MRA
Inhance 3D Velocity
TR/TE: 3.9/1.3 ms
FOV: 350 x 350 mm2
Matrix: 256 x 192
Resolution: 1.37x1.82 mm²
ST: 2 mm
Acquisition time: 0:23
TR/TE: 8.3/3.1 ms
FOV: 380 x 304 mm2
Matrix: 256 x 192
Resolution: 1.48x1.58 mm²
ST: 2 mm
Acquisition time: 6:48
Venc: 50 cm/s


Hepatic Flow - 59M with Cirrhosis
movie
A. Frydrychowicz et al., JMRI 2011


Abstract #4067
RA and RV Flow with 4D PC MRI in Normal Volunteers and Tetralogy of Fallot
Flow patterns – RV, RVOT, PA
Normal volunteers
• Small vortices beneath TV leaflets
• Flow primarily directed toward RVOT
TOF patients
• Large vortices beneath TV leaflets
• Flow directed toward RV apex in patients with PR
PA
SVC
TV
RA
IVC
RV
Flow vs. Time
Flow
Time
MPA
SVC
IVC
Normal
Patient with TOF
C. Francois et al., JCMR 2012


Quantification based on velocity fields
• Wall shear stress 1-5
• Pressure difference mapping 6-8
• Turbulence & turbulent kinetic energy 9,10
• Pulse wave velocity & vessel elasticity 11-15
• ….
Flow Waveforms
Pressure
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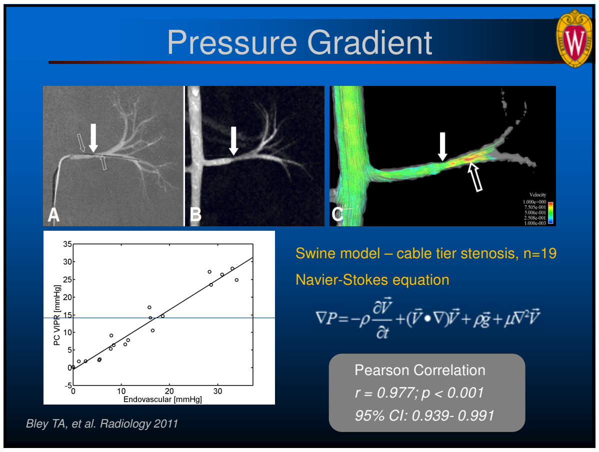
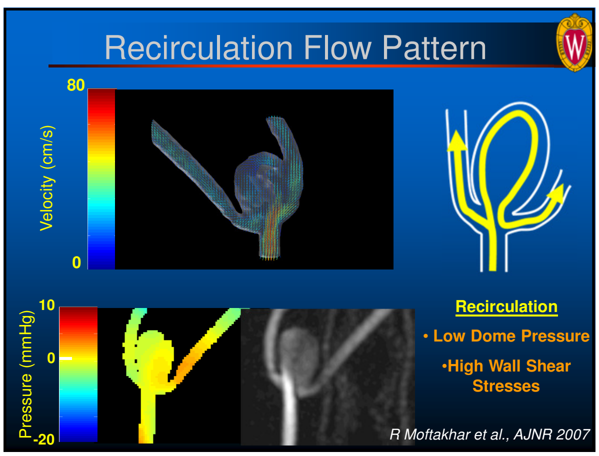
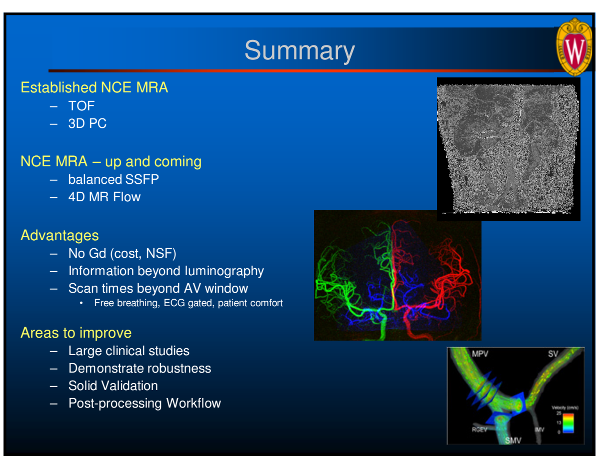

Pressure Gradient
A
B
C
PC VIPR [mmHg]
Endovascular [mmHg]
Swine model – cable tier stenosis, n=19
Navier-Stokes equation
$\nabla P = -\rho \frac{\partial \vec{V}}{\partial t} + (\vec{V} \bullet \nabla)\vec{V} + \rho\vec{g} + \mu\nabla^2\vec{V}$
Pearson Correlation
r = 0.977; p < 0.001
95% CI: 0.939- 0.991
Bley TA, et al. Radiology 2011


Recirculation Flow Pattern
80
Velocity (cm/s)
0
10
0
Pressure (mmHg)
-20
Recirculation
• Low Dome Pressure
•High Wall Shear Stresses
R Moftakhar et al., AJNR 2007


Summary
Established NCE MRA
– TOF
– 3D PC
NCE MRA – up and coming
– balanced SSFP
– 4D MR Flow
Advantages
– No Gd (cost, NSF)
– Information beyond luminography
– Scan times beyond AV window
• Free breathing, ECG gated, patient comfort
Areas to improve
– Large clinical studies
– Demonstrate robustness
– Solid Validation
– Post-processing Workflow
MPV
SV
SMV

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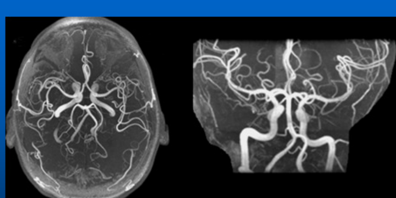
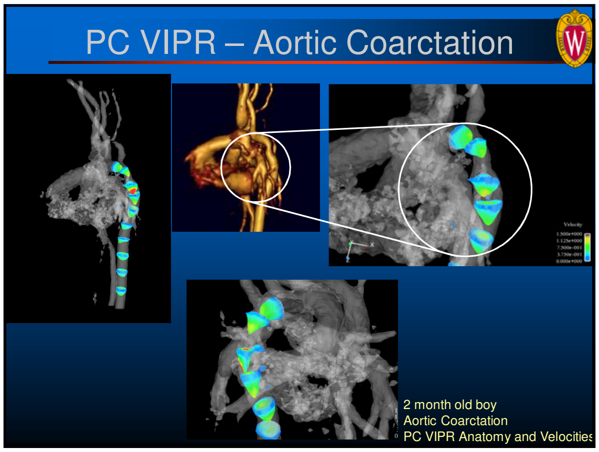
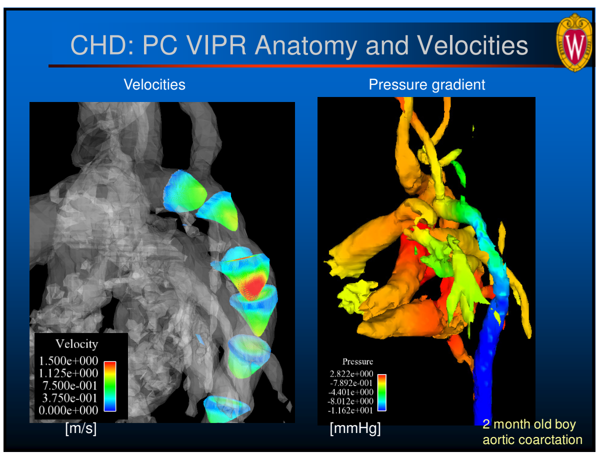
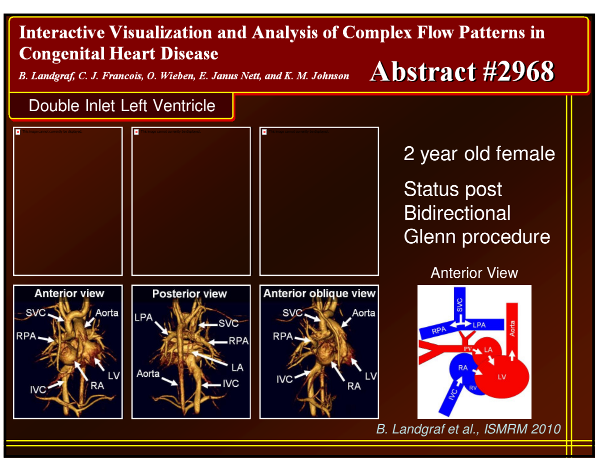
Arterial Spin Labeling

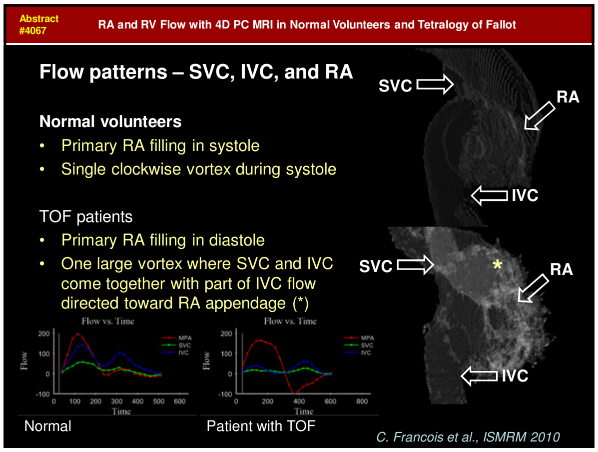
Time of Flight (TOF) MRA

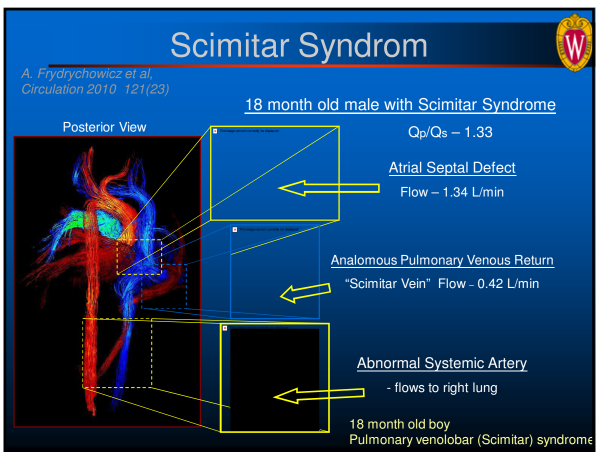


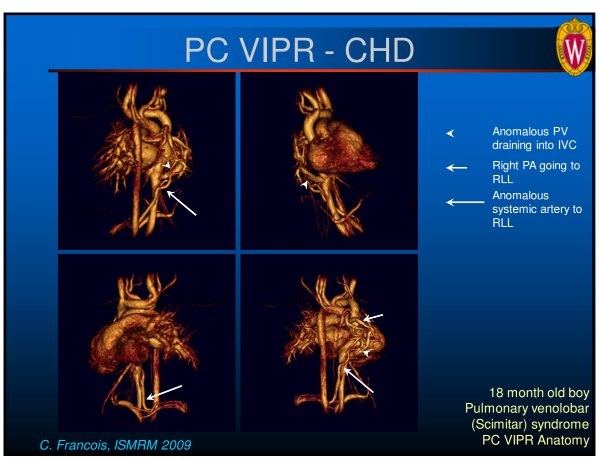

PC VIPR – Aortic Coarctation
2 month old boy
Aortic Coarctation
PC VIPR Anatomy and Velocities


CHD: PC VIPR Anatomy and Velocities
Velocities
Pressure gradient
Velocity
1.500e+000
1.125e+000
7.500e-001
3.750e-001
0.000e+000
[m/s]
Pressure
2.822e+000
-7.892e-001
-4.401e+000
-8.012e+000
-1.162e+001
[mmHg]
2 month old boy
aortic coarctation


Interactive Visualization and Analysis of Complex Flow Patterns in Congenital Heart Disease
B. Landgraf, C. J. Francois, O. Wieben, E. Janus Nett, and K. M. Johnson
Abstract #2968
Double Inlet Left Ventricle
2 year old female
Status post Bidirectional Glenn procedure
Anterior View
Anterior view
Posterior view
Anterior oblique view
SVC
Aorta
RPA
LV
IVC
RA
LPA
LA
SVC
LPA
RPA
Aorta
RA
LA
LV
IVC
B. Landgraf et al., ISMRM 2010


Abstract #4067
RA and RV Flow with 4D PC MRI in Normal Volunteers and Tetralogy of Fallot
Flow patterns – SVC, IVC, and RA
Normal volunteers
• Primary RA filling in systole
• Single clockwise vortex during systole
TOF patients
• Primary RA filling in diastole
• One large vortex where SVC and IVC come together with part of IVC flow directed toward RA appendage (*)
SVC
RA
IVC
*
Flow vs. Time
Flow
Time
MPA
SVC
IVC
Normal
Patient with TOF
C. Francois et al., ISMRM 2010


Scimitar Syndrom
A. Frydrychowicz et al, Circulation 2010 121(23)
18 month old male with Scimitar Syndrome
Posterior View
Qp/Qs – 1.33
Atrial Septal Defect
Flow – 1.34 L/min
Analomous Pulmonary Venous Return
"Scimitar Vein" Flow – 0.42 L/min
Abnormal Systemic Artery
- flows to right lung
18 month old boy
Pulmonary venolobar (Scimitar) syndrome

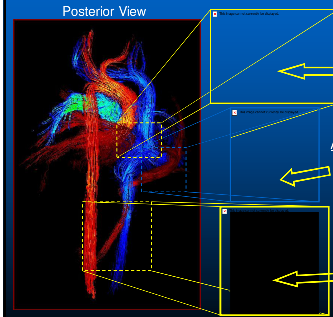

PC VIPR - CHD
Anomalous PV draining into IVC
Right PA going to RLL
Anomalous systemic artery to RLL
18 month old boy
Pulmonary venolobar (Scimitar) syndrome
PC VIPR Anatomy
C. Francois, ISMRM 2009

Scimitar Syndrom

A. Frydrychowicz et al, Circulation 2010 121(23)

18 month old male with Scimitar Syndrome

Posterior View



Q_p/Q_s – 1.33

Atrial Septal Defect

Flow – 1.34 L/min

Analomous Pulmonary Venous Return

"Scimitar Vein" Flow – 0.42 L/min

Abnormal Systemic Artery

- flows to right lung

18 month old boy
Pulmonary venolobar (Scimitar) syndrome

bSSFP with inflow spin labeling

Balanced SSFP (FIESTA)
- Provides high blood signal with T2/T1 contrast

Inflow effect is utilized to visualize vessels

Inversion pulse
- Suppresses veins and background tissues
- Select any vessels you want to depict

Advantages
- High blood signal
- Artery and venous separation
- Depiction of blood flow in any direction
- Free breathing (respiratory triggered with bellows)

Works well in abdomen and pelvis