MR Angiography

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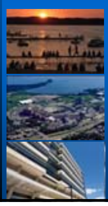
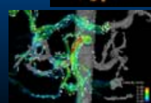
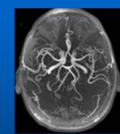




Outline

NCE MRA Acquistion Methods
- Time-of-Flight (TOF)
- balanced SSFP
  - MRA
  - Flow-prepared spin labeling
- Phase Contrast (PC)
  - MRA
  - Hemodynamics
- Fast Spin Echo (FSE)
- Black Blood MRA

Contrast Enhanced MRA
- Static Acquisition
- Dynamic Acquisition



(MR) Angiography Wishlist

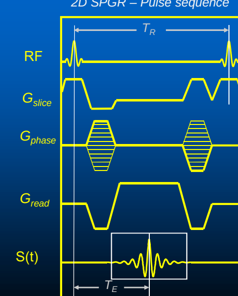
High contrast vessel vs background
(Dynamic) Volumetric Acquisition
Motion Robustness
- Respiratory Motion
- Cardiac Pulsatility
- Patient motion

Rapid Imaging
Quantitative Velocity / Flow Measures

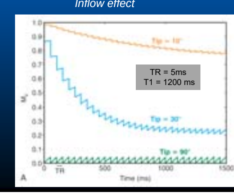
Digital Subtraction Angiography
2D projection
1024x1024 matrix, 30 frames per second
realtime

TOF – Gradient Echo

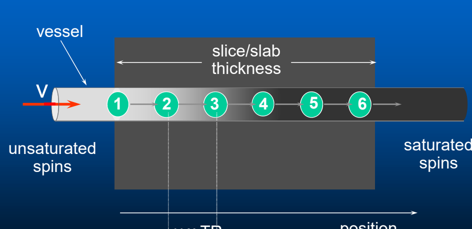
2D SPGR – Pulse sequence



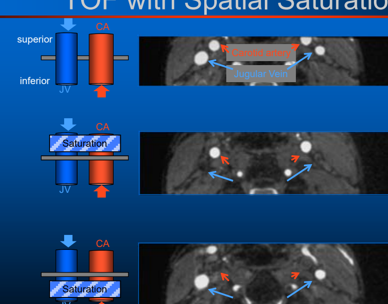
TOF – Contrast Mechanism
Spoiled Gradient Echo
Gradient Spoiling
RF spoiling
2D multislice or 3D acquisition
Signal in steady state
~ f (T1, flip, TR)
Short TR (< 10 ms)
Signal for moving spins
Inflow effect



Signal strength in TOF



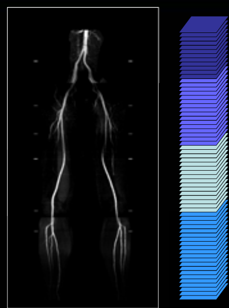
TOF with Spatial Saturation



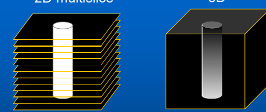
Peripheral MRA with 2D TOF

2D TOF at 1.5T

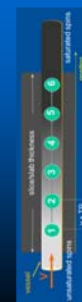
Multistation exam
up to 4 slabs
Magnetization transfer, fat saturation
ECG gated, 32 views per segment
TR/TE: 12.7/1.5 ms
Flip angle = 70 deg
FOV: 300 (360) x 150 (180) mm^2
Matrix: 256 x 192
Slice thickness: 3.0 mm
Slices per slab: ~140-170
Acquired resolution:
1.2 x 1.6 x 3 mm^2
Reconstructed resolution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



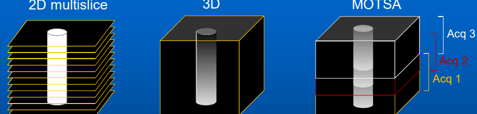
TOF – 2D vs 3D



2D multislice	3D
Advantages + High vessel contrast + Sensitive to Slow Flow	Advantages + High SNR + Thin slices
Disadvantages – Spin saturation for in-plane flow – Low SNR for thin 2D slices	Disadvantages – Spin saturation (decreasing vessel contrast in imaging volume)



TOF – 2D vs 3D

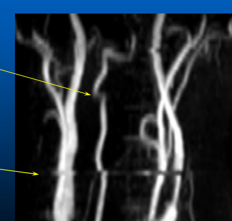


2D multislice	3D	MOTSA
Advantages + High vessel contrast + Sensitive to Slow Flow	Advantages + High SNR + Thin slices	Multiple Overlapping Thin Slab Acquisition D Parker et al. MRM 17, 1991
Disadvantages – Spin saturation for in-plane flow – Low SNR for thin 2D slices	Disadvantages – Spin saturation (decreasing vessel contrast in imaging volume)	

2D TOF - Artefacts

In-plane saturation

Motion artefacts (e.g. swallowing)



2D ToF MR Angiography

Advantages:

- High vessel contrast
- Sensitivity to slow flow
- Single acquisition – no subtraction
- Robust, easy to use

Disadvantages:

- Spin Saturation for in-plane flow
- Dephasing in regions of turbulent flow
  - Phase dispersion within voxels
  - Voxel size ~ 0.8x0.8x3.0mm
    - (larger than 3D ToF)
- Low SNR for thin slices

3D ToF MR Angiography

Advantages:

- Spatial resolution (thin slices)
- High SNR
- Single acquisition (relatively short acquisition times, no subtraction)

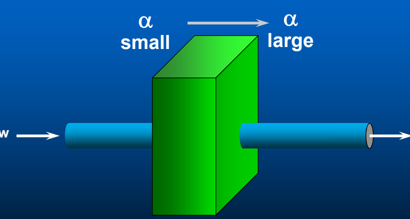
Distadvantages:

- Spin saturation (decreasing vessel contrast in imaging volume)
- T1 sensitivity (incomplete saturation of tissue with short T1)
- Incomplete suppression of signal from background tissues

Reducing Spin Saturation

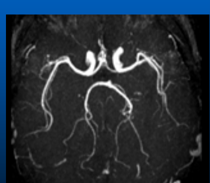
- **Spatially varying exscitation pulse (TONE)**
  - **Optimize signal along vessels in imaging volume**
- **Multiple Slabs (MOTSA)**
  - **Reduced spin saturation in thin slabs**
- **Magnetization Transfer Suppression (MTS)**
  - **Reduces signal of stationary tissues**
  - **No effect on blood signal**

Tilted RF Excitation (TONE)

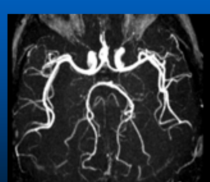


Courtesy of Klaus Scheffler, University Basel

Optimizing ToF MRA



standard



MTS & TONE

Cranial MRA with 3D TOF

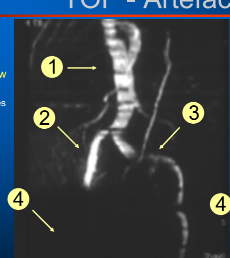
Intracranial 3D TOF – 38 y female volunteer
- Incidental finding of 2mm posterior-inferior cerebreallar artery (PICA) aneurysm

Typical Imaging Protocol
- 3 Tesla, magnetization transfer, flow compensation, fat sat
- FOV = 22x16.5 cm;
- TR / TE = 24/2.4 ms; flip angle = 20 deg (ramped),
- Scan time = 8 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*

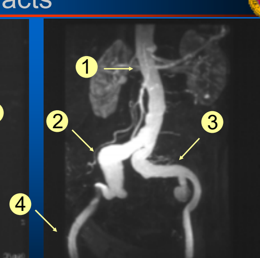
TOF - Artefacts

TOF is a standard gradient echo sequence tuned to maximize inflow
- Higher flip and long TR
- Several overlapping slabs or 2D slices

Assumptions:
- Flow is SI or IS
- Flow is fast
  - Arrival time is much less than T1



2D TOF



3D CE-MRA

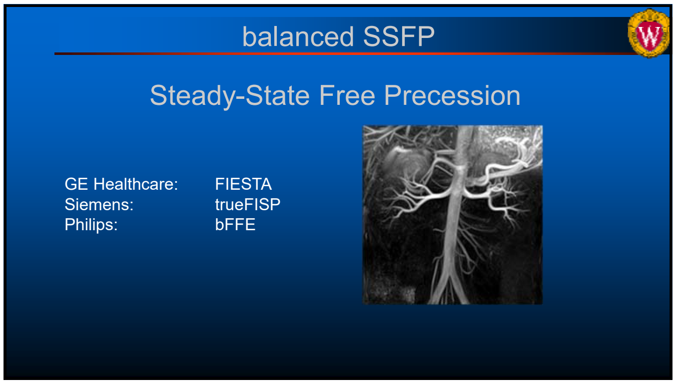
1. Cardiac pulsatility
2. Less sensitive to slow flow
3. In slice saturation
4. Sensitivity to magnetic susceptibility

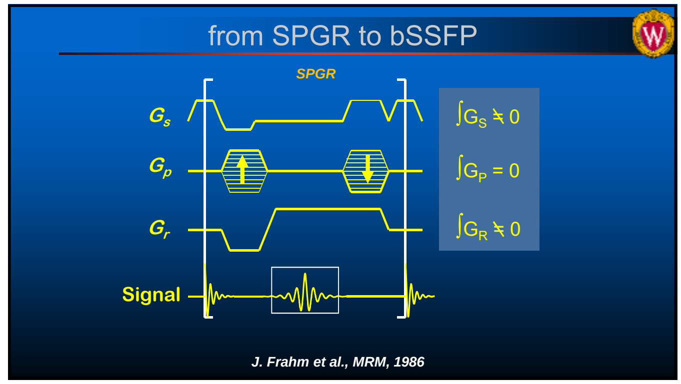
Prince, Grist, Debatin 'CE-MRA' 1997

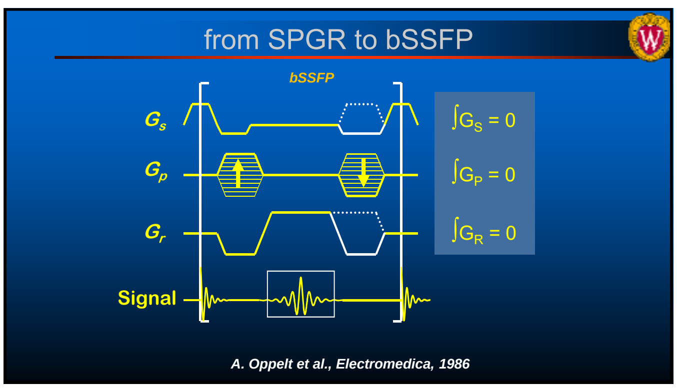
Time of Flight - Summary

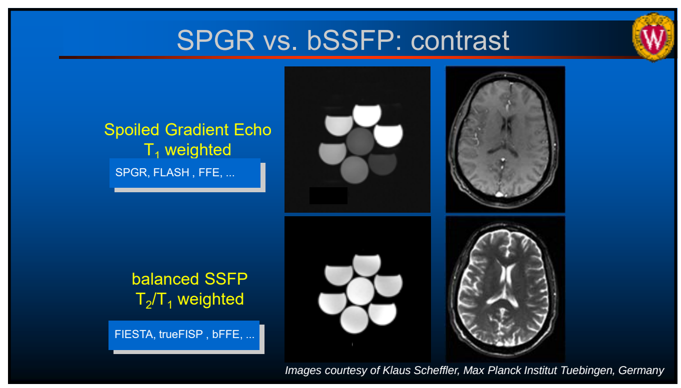
- Images usually high quality
  - Time of flight is good at detection of aneurysms
    - 96% Sensitivity, ~94% specificity in recent study
- Highly Inflow dependent
- Works well when
  - High inflow
  - Minimal in slice (slab) flow
- Challenging in areas of slow flow
  - Collateral filling
  - Tortuous geometry
  - Slow flow
- Due to above not very effective in many body applications

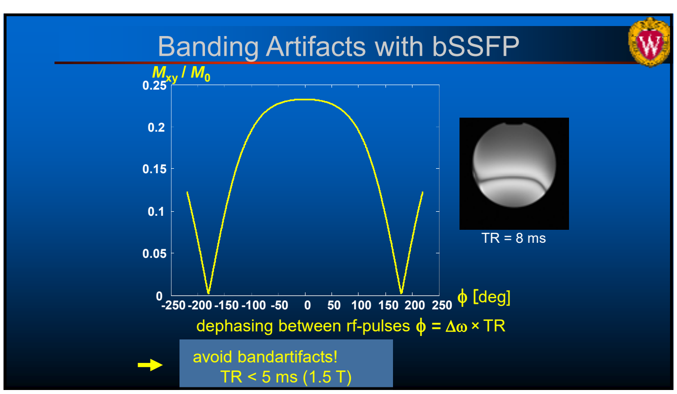
Li et al. 14' Radiology 271(2):
Buis et al. 12' AJNR 33:232
Takhtani et al. 14' Act Rad 10.1177
Kunimatsu et al. 13' MRMS 12(1):53-56

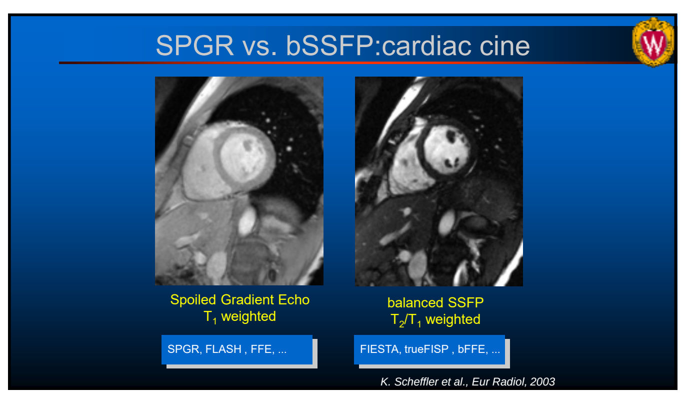

balanced SSFP
Steady-State Free Precession
GE Healthcare: FIESTA
Siemens: trueFISP
Philips: bFFE

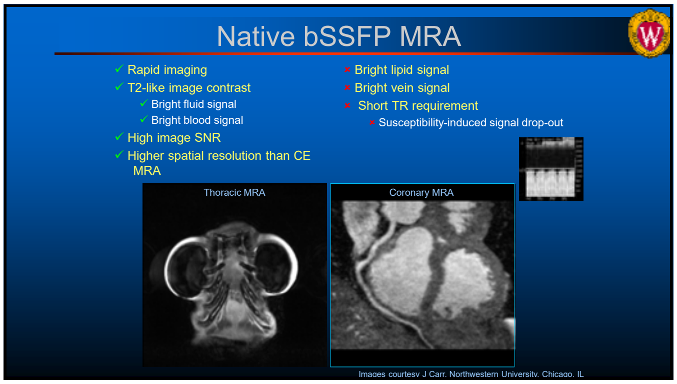

from SPGR to bSSFP
SPGR
G_s
G_p
G_r
Signal
$\int G_S \neq 0$
$\int G_P = 0$
$\int G_R \neq 0$
J. Frahm et al., MRM, 1986

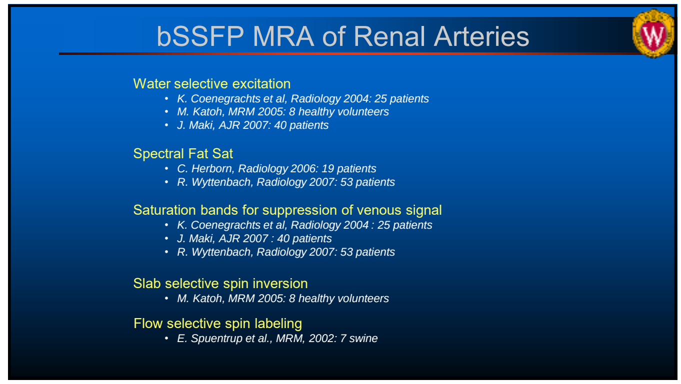

from SPGR to bSSFP
bSSFP
G_s
G_p
G_r
Signal
$\int G_S = 0$
$\int G_P = 0$
$\int G_R = 0$
A. Oppelt et al., Electromedica, 1986

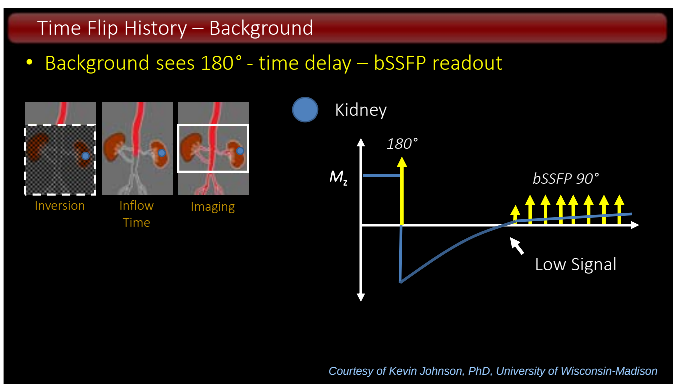

SPGR vs. bSSFP: contrast
Spoiled Gradient Echo
T_1 weighted
SPGR, FLASH, FFE, ...
balanced SSFP
T_2/T_1 weighted
FIESTA, trueFISP, bFFE, ...
Images courtesy of Klaus Scheffler, Max Planck Institut Tuebingen, Germany

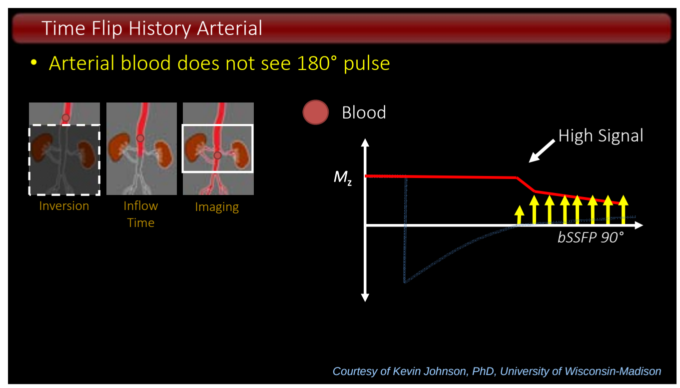

Banding Artifacts with bSSFP
M_{xy} / M_0
0.25
0.2
0.15
0.1
0.05
0
-250 -200 -150 -100 -50 0 50 100 150 200 250
ϕ [deg]
TR = 8 ms
dephasing between rf-pulses $\phi = \Delta\omega \times TR$
avoid bandartifacts!
TR < 5 ms (1.5 T)

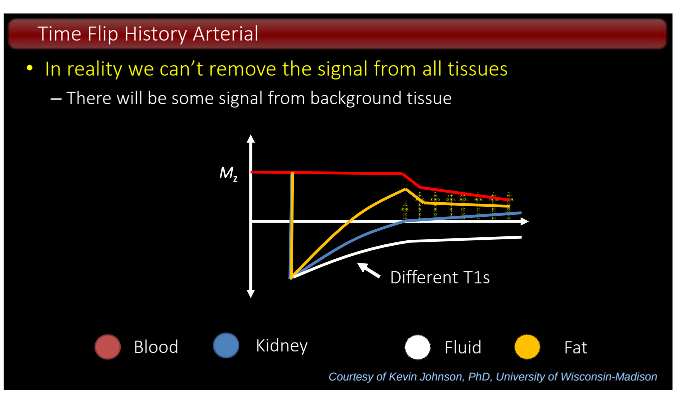

SPGR vs. bSSFP:cardiac cine
Spoiled Gradient Echo
T_1 weighted
SPGR, FLASH, FFE, ...
balanced SSFP
T_2/T_1 weighted
FIESTA, trueFISP, bFFE, ...
K. Scheffler et al., Eur Radiol, 2003

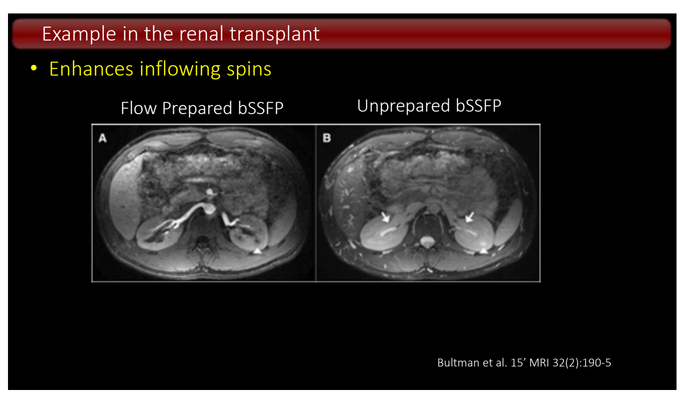

Native bSSFP MRA
✓ Rapid imaging
✓ T2-like image contrast
✓ Bright fluid signal
✓ Bright blood signal
✓ High image SNR
✓ Higher spatial resolution than CE MRA
× Bright lipid signal
× Bright vein signal
× Short TR requirement
× Susceptibility-induced signal drop-out
Thoracic MRA
Coronary MRA
Images courtesy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


bSSFP MRA of Renal Arteries
Water selective excitation
• K. Coenegrachts et al, Radiology 2004: 25 patients
• M. Katoh, MRM 2005: 8 healthy volunteers
• J. Maki, AJR 2007: 40 patients
Spectral Fat Sat
• C. Herborn, Radiology 2006: 19 patients
• R. Wyttenbach, Radiology 2007: 53 patients
Saturation bands for suppression of venous signal
• K. Coenegrachts et al, Radiology 2004 : 25 patients
• J. Maki, AJR 2007 : 40 patients
• R. Wyttenbach, Radiology 2007: 53 patients
Slab selective spin inversion
• M. Katoh, MRM 2005: 8 healthy volunteers
Flow selective spin labeling
• E. Spuentrup et al., MRM, 2002: 7 swine

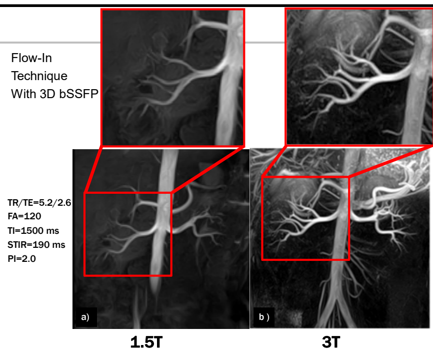

Time Flip History – Background
• Background sees 180° - time delay – bSSFP readout
Inversion
Inflow Time
Imaging
Kidney
180°
M_z
bSSFP 90°
Low Signal
Courtesy of Kevin Johnson, PhD, University of Wisconsin-Madison


Time Flip History Arterial
• Arterial blood does not see 180° pulse
Inversion
Inflow Time
Imaging
Blood
High Signal
M_z
bSSFP 90°
Courtesy of Kevin Johnson, PhD, University of Wisconsin-Madison


Time Flip History Arterial
• In reality we can't remove the signal from all tissues
– There will be some signal from background tissue
M_z
Different T1s
Blood
Kidney
Fluid
Fat
Courtesy of Kevin Johnson, PhD, University of Wisconsin-Madison


Example in the renal transplant
• Enhances inflowing spins
Flow Prepared bSSFP
Unprepared bSSFP
A
B
Bultman et al. 15' MRI 32(2):190-5

Flow-In Technique With 3D bSSFP

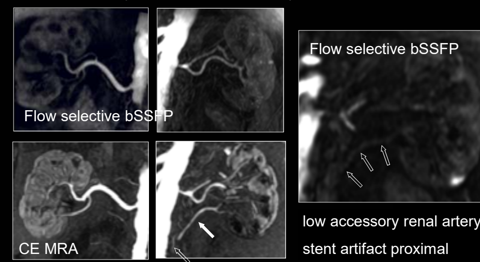


Courtesy of M. Miyazaki, Toshiba Medical

Miyazaki, M and Isoda, H, EJR, 80:9-23, 2011

Patients @ 1.5T

60 year-old female with hypertension



low accessory renal artery

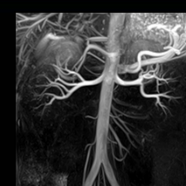
stent artifact proximal

Does nOt work well with long transit times

- None of this blood made it across a capillary bed

Courtesy of Kevin Johnson, PhD, University of Wisconsin-Madison

bSSFP with flow-prepared spin labeling - Summary



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

Inversion pulse
- Suppresses veins and background tissues

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
- Fast flow regions

Challenges
- Slow flow / long or varying transit times

Phase Contrast MRI

PC MR Angiogram
Velocity Encoding
2D, 3D, and 4D PC MRI

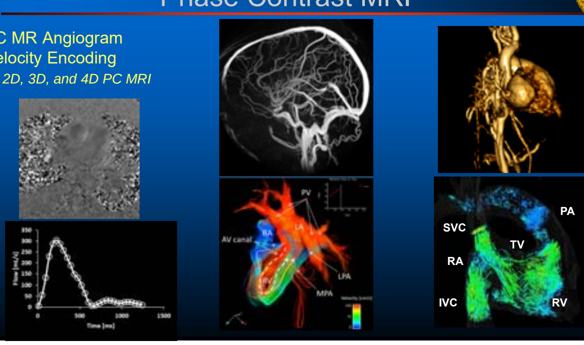
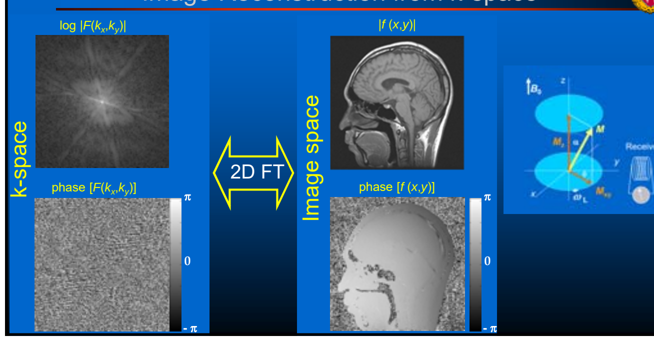
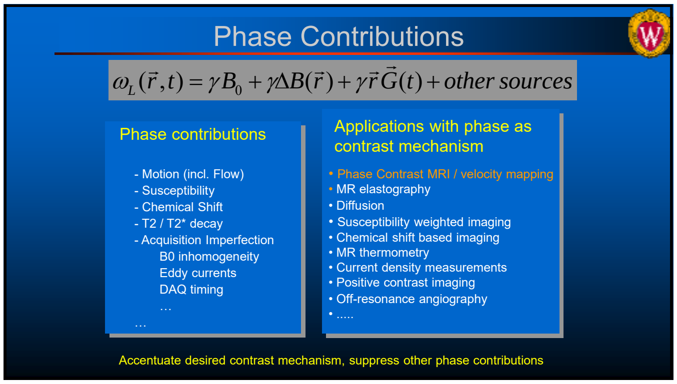
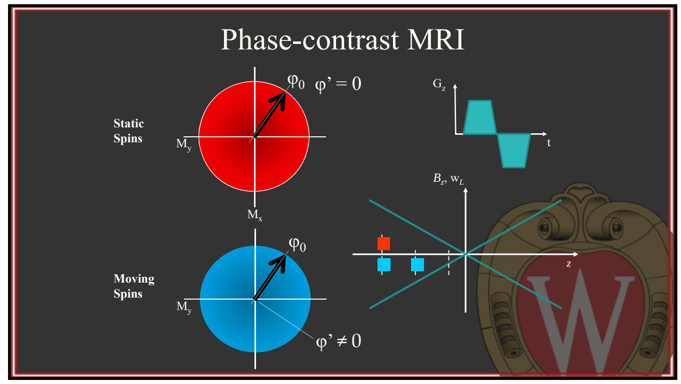
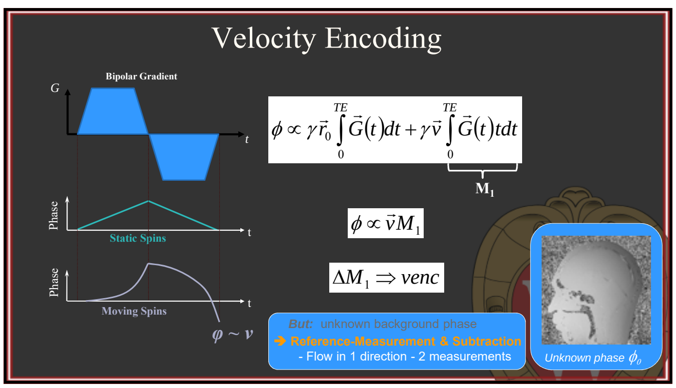


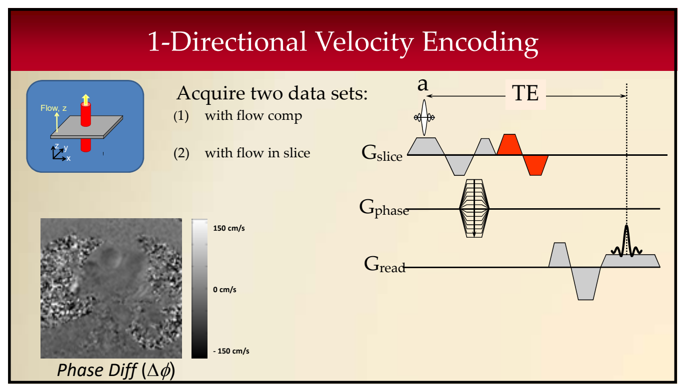
Image Reconstruction from k-space

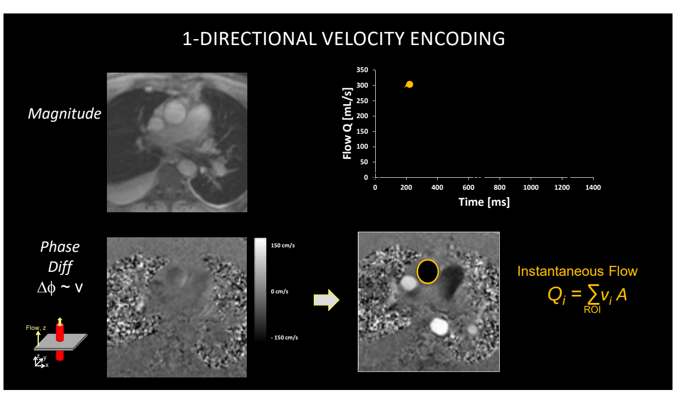


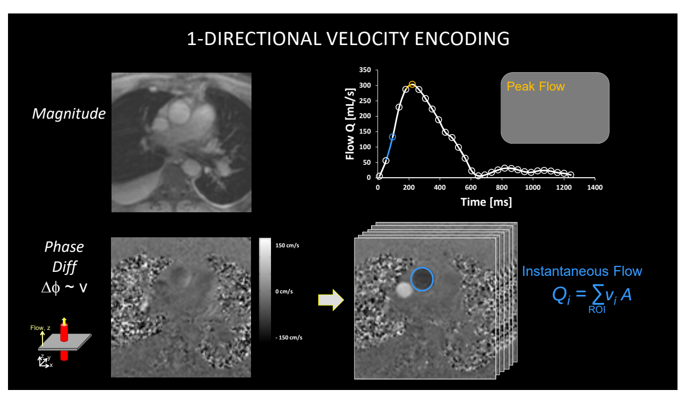

Phase Contributions
$\omega_L(\vec{r},t) = \gamma B_0 + \gamma\Delta B(\vec{r}) + \gamma\vec{r}\vec{G}(t) + other\ sources$
Phase contributions
- Motion (incl. Flow)
- Susceptibility
- Chemical Shift
- T2 / T2* decay
- Acquisition Imperfection
B0 inhomogeneity
Eddy currents
DAQ timing
…
…
Applications with phase as contrast mechanism
• Phase Contrast MRI / velocity mapping
• MR elastography
• Diffusion
• Susceptibility weighted imaging
• Chemical shift based imaging
• MR thermometry
• Current density measurements
• Positive contrast imaging
• Off-resonance angiography
• .....
Accentuate desired contrast mechanism, suppress other phase contributions

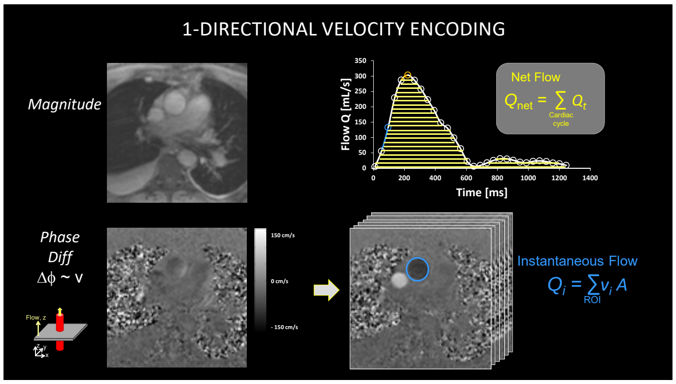

Phase-contrast MRI
Static Spins
Moving Spins
φ_0
$\varphi' = 0$
$\varphi' \neq 0$
M_y
M_x
G_z
t
B_z, w_L
z

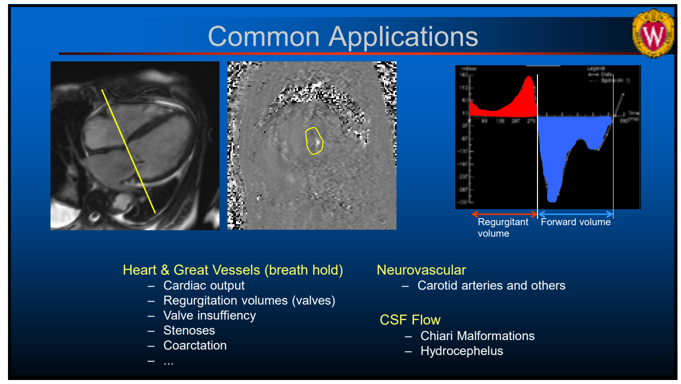

Velocity Encoding
Bipolar Gradient
G
t
Phase
Static Spins
Moving Spins
$\varphi \sim v$
$\phi \propto \gamma\vec{r}_0 \int_0^{TE} \vec{G}(t)dt + \gamma\vec{v}\int_0^{TE}\vec{G}(t)tdt$
M_1
$\phi \propto \vec{v}M_1$
$\Delta M_1 \Rightarrow venc$
But: unknown background phase
➔ Reference-Measurement & Subtraction
- Flow in 1 direction - 2 measurements
Unknown phase ϕ_0

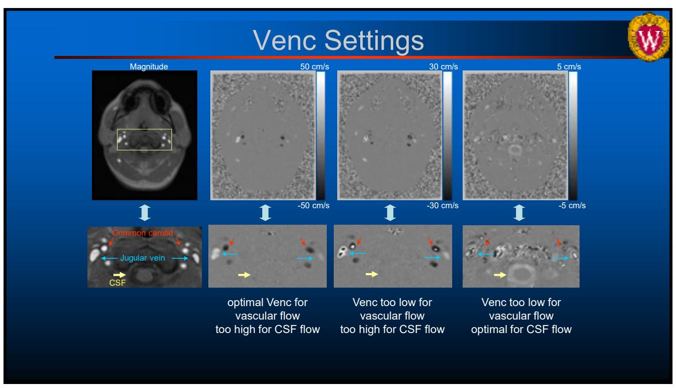

1-Directional Velocity Encoding
Acquire two data sets:
(1) with flow comp
(2) with flow in slice
a
TE
G_{slice}
G_{phase}
G_{read}
150 cm/s
0 cm/s
- 150 cm/s
Phase Diff ($\Delta\phi$)

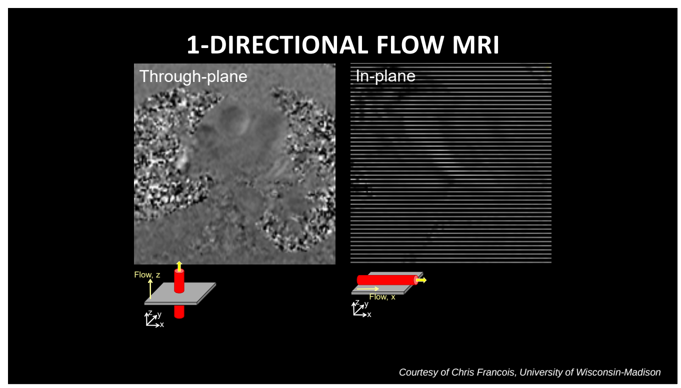

1-DIRECTIONAL VELOCITY ENCODING
Magnitude
Phase Diff
$\Delta\phi \sim v$
Flow Q [mL/s]
Time [ms]
Instantaneous Flow
$Q_i = \sum_{ROI} v_i A$

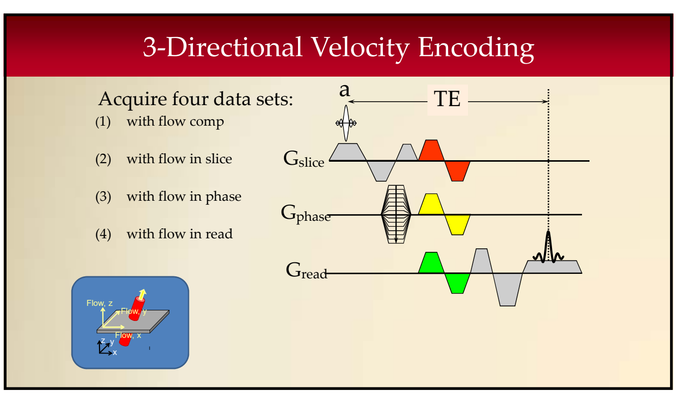

1-DIRECTIONAL VELOCITY ENCODING
Magnitude
Phase Diff
$\Delta\phi \sim v$
Peak Flow
Flow Q [mL/s]
Time [ms]
Instantaneous Flow
$Q_i = \sum_{ROI} v_i A$

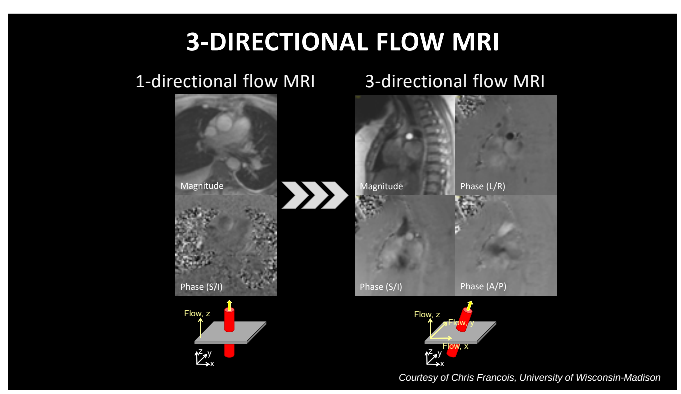

1-DIRECTIONAL VELOCITY ENCODING
Magnitude
Phase
Diff
Δφ ~ v
Flow Q [mL/s]
Time [ms]
Net Flow
$Q_{net} = \sum_{\text{Cardiac cycle}} Q_t$
Instantaneous Flow
$Q_i = \sum_{ROI} v_i A$
150 cm/s
0 cm/s
- 150 cm/s

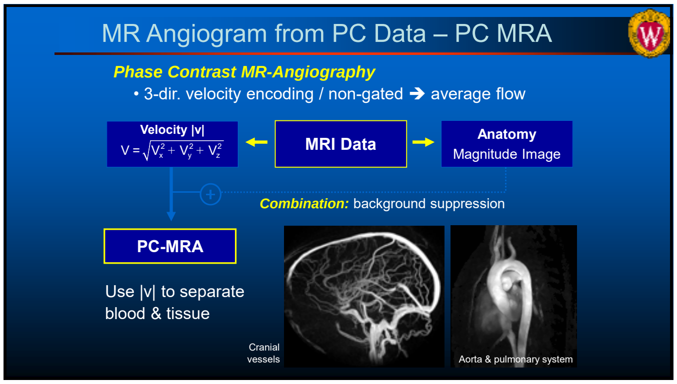

Common Applications
Regurgitant volume
Forward volume
Heart & Great Vessels (breath hold)
– Cardiac output
– Regurgitation volumes (valves)
– Valve insuffiency
– Stenoses
– Coarctation
– …
Neurovascular
– Carotid arteries and others
CSF Flow
– Chiari Malformations
– Hydrocephelus

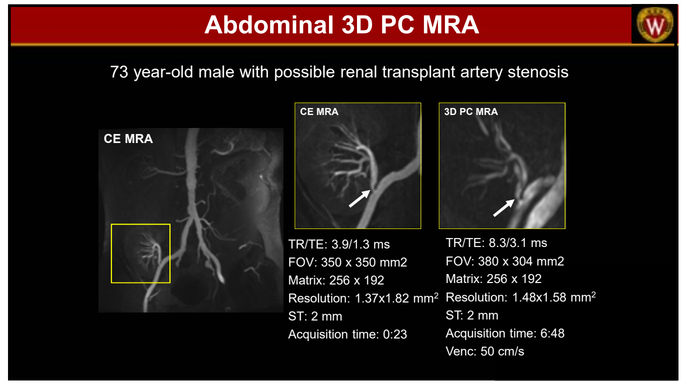

Venc Settings
Magnitude
50 cm/s
30 cm/s
5 cm/s
-50 cm/s
-30 cm/s
-5 cm/s
Common carotid
Jugular vein
CSF
optimal Venc for vascular flow too high for CSF flow
Venc too low for vascular flow too high for CSF flow
Venc too low for vascular flow optimal for CSF flow

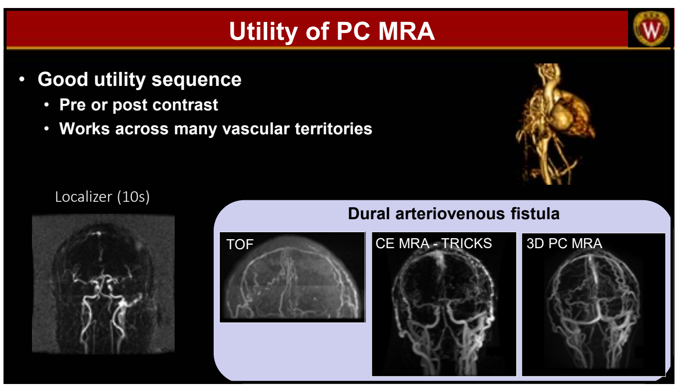

1-DIRECTIONAL FLOW MRI
Through-plane
In-plane
Flow, z
Flow, x
Courtesy of Chris Francois, University of Wisconsin-Madison

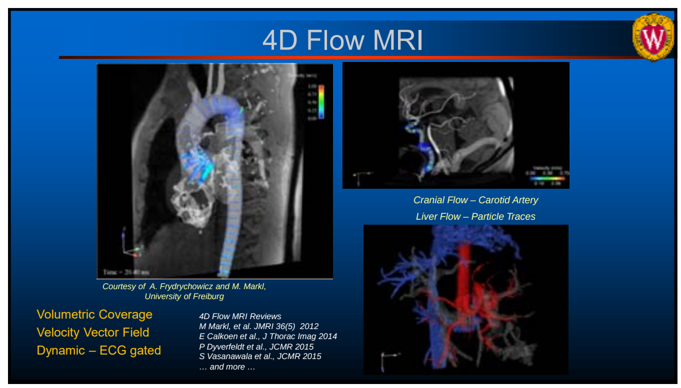

3-Directional Velocity Encoding
Acquire four data sets:
(1) with flow comp
(2) with flow in slice
(3) with flow in phase
(4) with flow in read
a
TE
G_{slice}
G_{phase}
G_{read}
Flow, z
Flow, y
Flow, x

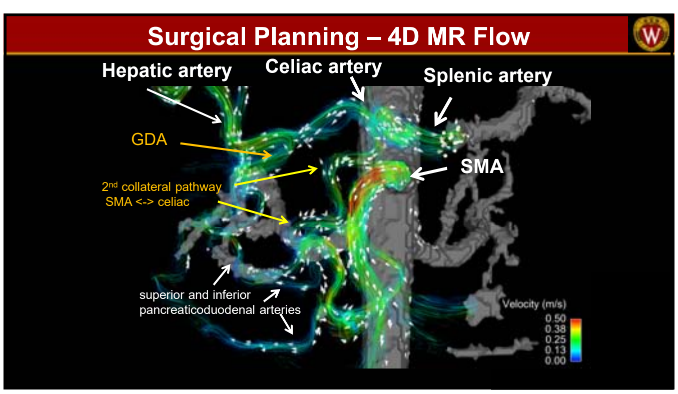

3-DIRECTIONAL FLOW MRI
1-directional flow MRI
3-directional flow MRI
Magnitude
Phase (S/I)
Magnitude
Phase (L/R)
Phase (S/I)
Phase (A/P)
Flow, z
Flow, y
Flow, x
Courtesy of Chris Francois, University of Wisconsin-Madison

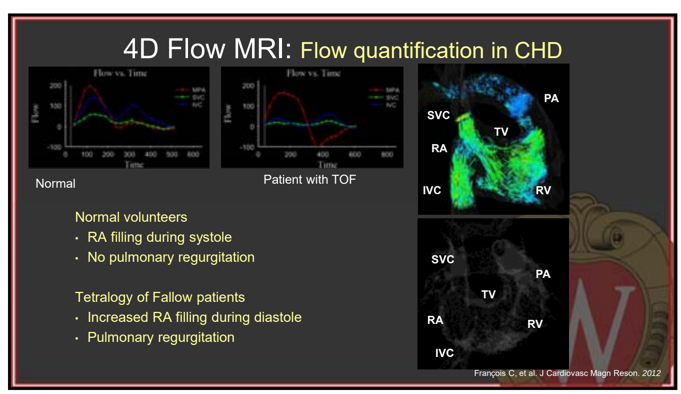

MR Angiogram from PC Data – PC MRA
Phase Contrast MR-Angiography
• 3-dir. velocity encoding / non-gated → average flow
Velocity |v|
$V = \sqrt{V_x^2 + V_y^2 + V_z^2}$
MRI Data
Anatomy
Magnitude Image
Combination: background suppression
PC-MRA
Use |v| to separate blood & tissue
Cranial vessels
Aorta &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

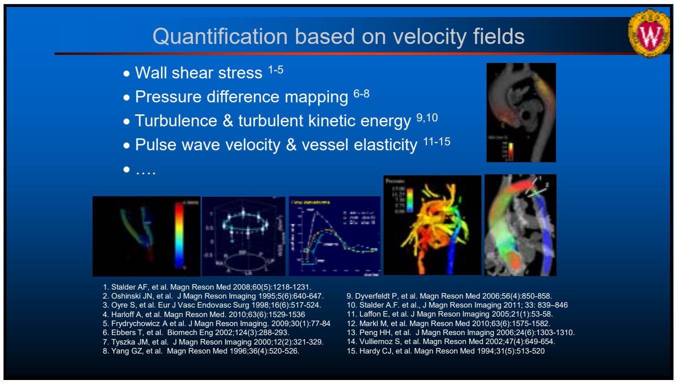

Abdominal 3D PC MRA
73 year-old male with possible renal transplant artery stenosis
CE MRA
CE MRA
3D PC MRA
TR/TE: 3.9/1.3 ms
FOV: 350 x 350 mm2
Matrix: 256 x 192
Resolution: 1.37x1.82 mm²
ST: 2 mm
Acquisition time: 0:23
TR/TE: 8.3/3.1 ms
FOV: 380 x 304 mm2
Matrix: 256 x 192
Resolution: 1.48x1.58 mm²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

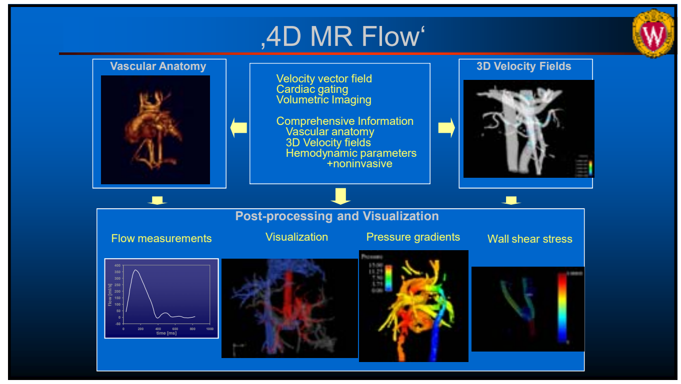

Utility of PC MRA
• Good utility sequence
• Pre or post contrast
• Works across many vascular territories
Localizer (10s)
Dural arteriovenous fistula
TOF
CE MRA - TRICKS
3D PC MRA

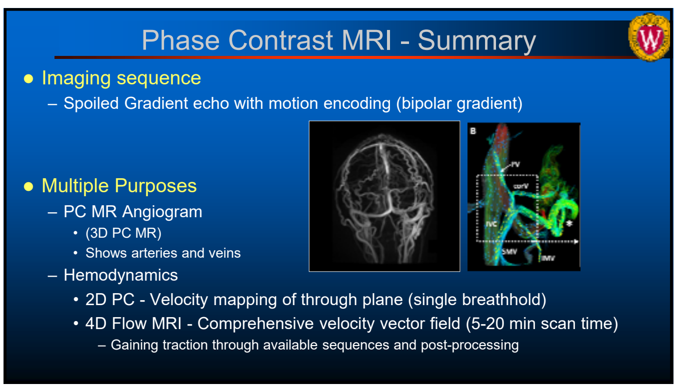

4D Flow MRI
Courtesy of A. Frydrychowicz and M. Markl, University of Freiburg
Cranial Flow – Carotid Artery
Liver Flow – Particle Traces
Volumetric Coverage
Velocity Vector Field
Dynamic – ECG gated
4D Flow MRI Reviews
M Markl, et al. JMRI 36(5) 2012
E Calkoen et al., J Thorac Imag 2014
P Dyverfeldt et al., JCMR 2015
S Vasanawala et al., JCMR 2015
… and more …

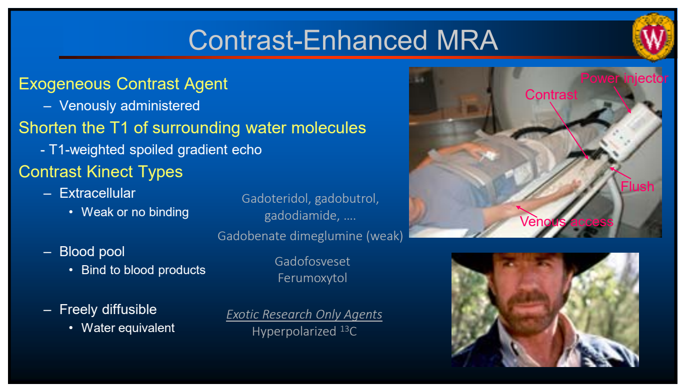

Surgical Planning – 4D MR Flow
Hepatic artery
Celiac artery
Splenic artery
GDA
SMA
2nd collateral pathway
SMA <-> celiac
superior and inferior
pancreaticoduodenal arteries
Velocity (m/s)
0.50
0.38
0.25
0.13
0.00

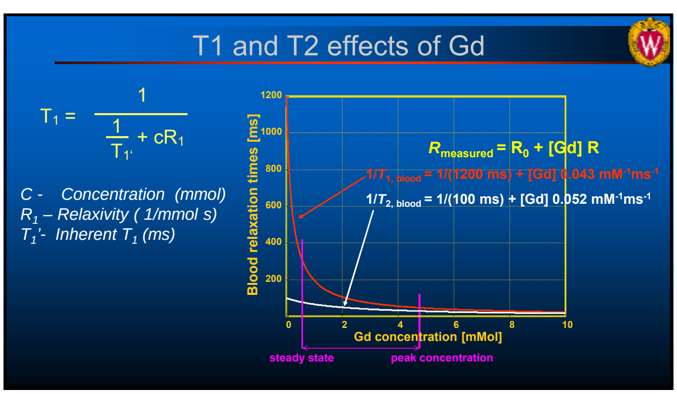

4D Flow MRI: Flow quantification in CHD
Normal
Patient with TOF
Normal volunteers
• RA filling during systole
• No pulmonary regurgitation
Tetralogy of Fallow patients
• Increased RA filling during diastole
• Pulmonary regurgitation
SVC
PA
TV
RA
IVC
RV
François C, et al. J Cardiovasc Magn Reson. 2012

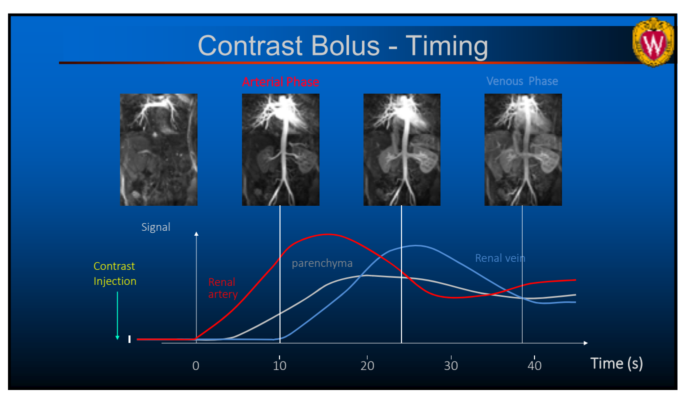

Quantification based on velocity fields
• Wall shear stress [1-5]
• Pressure difference mapping [6-8]
• Turbulence & turbulent kinetic energy [9,10]
• Pulse wave velocity & vessel elasticity [11-15]
• ….
1. Stalder AF, et al. Magn Reson Med 2008;60(5):1218-1231.
2. Oshinski JN, et al. J Magn Reson Imaging 1995;5(6):640-647.
3. Oyre S, et al. Eur J Vasc Endovasc Surg 1998;16(6):517-524.
4. Harloff A, et al. Magn Reson Med. 2010;63(6):1529-1536
5. Frydrychowicz A et al. J Magn Reson Imaging. 2009;30(1):77-84
6. Ebbers T, et al. Biomech Eng 2002;124(3):288-293.
7. Tyszka JM, et al. J Magn Reson Imaging 2000;12(2):321-329.
8. Yang GZ, et al. Magn Reson Med 1996;36(4):520-526.
9. Dyverfeldt P, et al. Magn Reson Med 2006;56(4):850-858.
10. Stalder A.F. et al., J Magn Reson Imaging 2011; 33: 839–846
11. Laffon E, et al. J Magn Reson Imaging 2005;21(1):53-58.
12. Markl M, et al. Magn Reson Med 2010;63(6):1575-1582.
13. Peng HH, et al. J Magn Reson Imaging 2006;24(6):1303-1310.
14. Vulliemoz S, et al. Magn Reson Med 2002;47(4):649-654.
15. Hardy CJ, et al. Magn Reson Med 1994;31(5):513-520

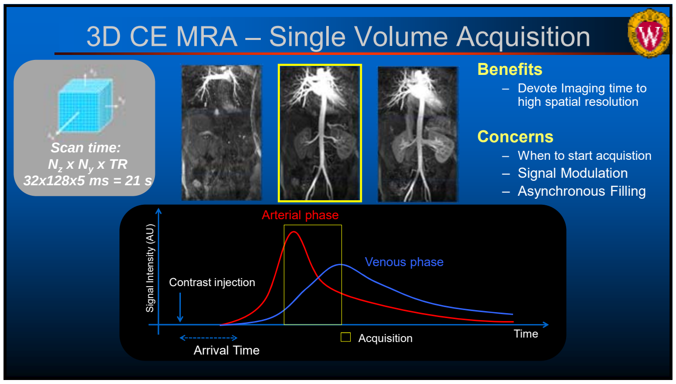

‚4D MR Flow‘
Vascular Anatomy
Velocity vector field
Cardiac gating
Volumetric Imaging
Comprehensive Information
Vascular anatomy
3D Velocity fields
Hemodynamic parameters
+noninvasive
3D Velocity Fields
Post-processing and Visualization
Flow measurements
Visualization
Pressure gradients
Wall shear stress

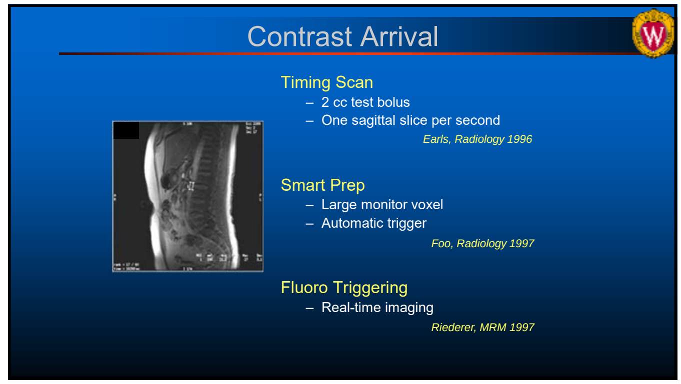

Phase Contrast MRI - Summary
● Imaging sequence
– Spoiled Gradient echo with motion encoding (bipolar gradient)
● Multiple Purposes
– PC MR Angiogram
• (3D PC MR)
• Shows arteries and veins
– Hemodynamics
• 2D PC - Velocity mapping of through plane (single breathhold)
• 4D Flow MRI - Comprehensive velocity vector field (5-20 min scan time)
– Gaining traction through available sequences and post-processing

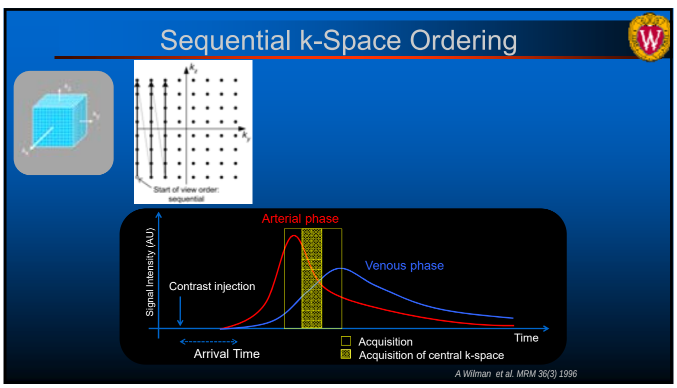

Contrast-Enhanced MRA
Exogeneous Contrast Agent
– Venously administered
Shorten the T1 of surrounding water molecules
- T1-weighted spoiled gradient echo
Contrast Kinect Types
– Extracellular
• Weak or no binding
Gadoteridol, gadobutrol, gadodiamide, ….
Gadobenate dimeglumine (weak)
– Blood pool
• Bind to blood products
Gadofosveset
Ferumoxytol
– Freely diffusible
• Water equivalent
Exotic Research Only Agents
Hyperpolarized 13C
Power injector
Contrast
Flush
Venous access

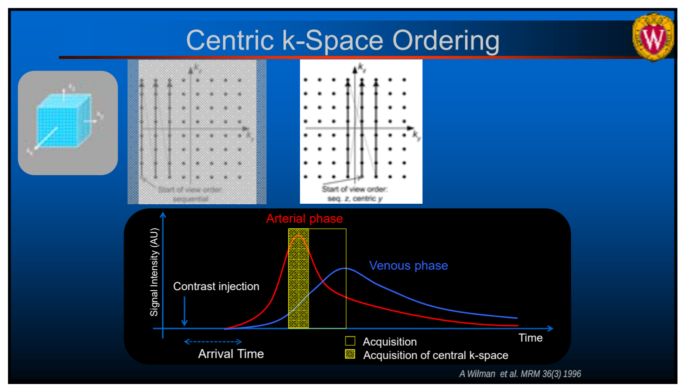

T1 and T2 effects of Gd
$T_1 = \dfrac{1}{\dfrac{1}{T_{1'}} + cR_1}$
C - Concentration (mmol)
R_1 – Relaxivity (1/mmol s)
T_1'- Inherent T_1 (ms)
Blood relaxation times [ms]
$R_{measured} = R_0 + [Gd] R$
$1/T_{1,\,blood} = 1/(1200\ ms) + [Gd]\ 0.043\ mM^{-1}ms^{-1}$
$1/T_{2,\,blood} = 1/(100\ ms) + [Gd]\ 0.052\ mM^{-1}ms^{-1}$
Gd concentration [mMol]
steady state
peak concentration

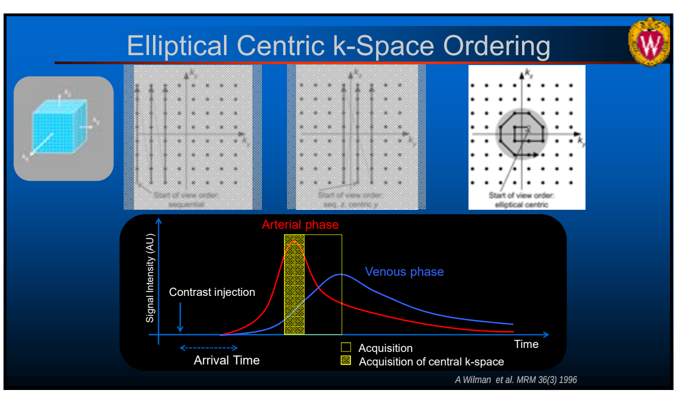

Contrast Bolus - Timing
Arterial Phase
Venous Phase
Signal
Contrast Injection
Renal artery
parenchyma
Renal vein
Time (s)

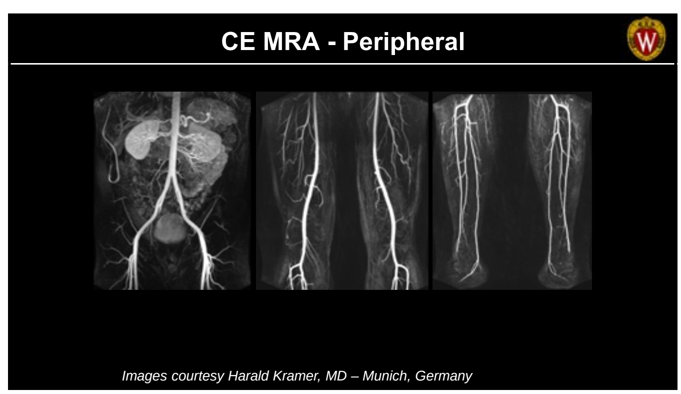

3D CE MRA – Single Volume Acquisition
Scan time:
N_z x N_y x TR
32x128x5 ms = 21 s
Benefits
– Devote Imaging time to high spatial resolution
Concerns
– When to start acquistion
– Signal Modulation
– Asynchronous Filling
Arterial phase
Venous phase
Signal Intensity (AU)
Contrast injection
Acquisition
Time
Arrival Time

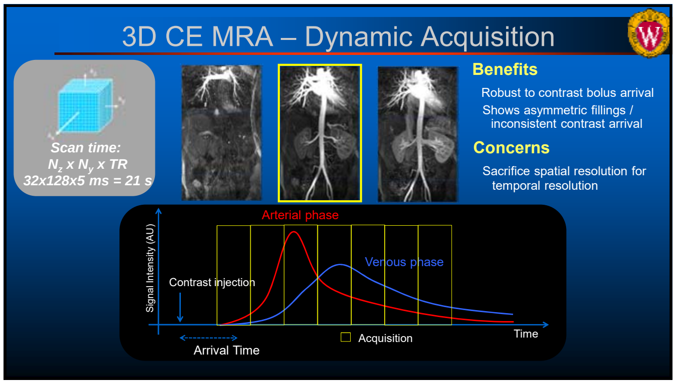

Contrast Arrival
Timing Scan
– 2 cc test bolus
– One sagittal slice per second
Earls, Radiology 1996
Smart Prep
– Large monitor voxel
– Automatic trigger
Foo, Radiology 1997
Fluoro Triggering
– Real-time imaging
Riederer, MRM 1997

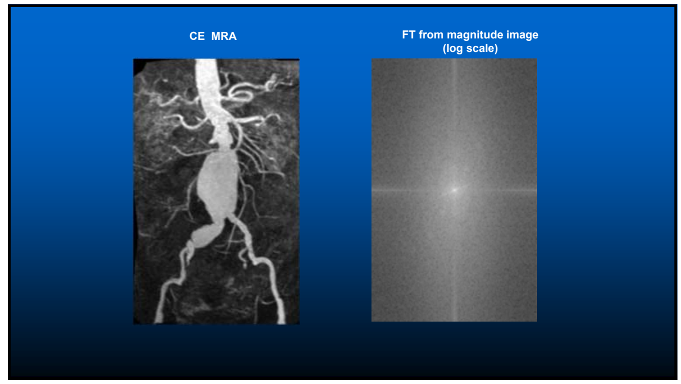

Sequential k-Space Ordering
Start of view order: sequential
Arterial phase
Venous phase
Signal Intensity (AU)
Contrast injection
Acquisition
Acquisition of central k-space
Time
Arrival Time
A Wilman et al. MRM 36(3) 1996

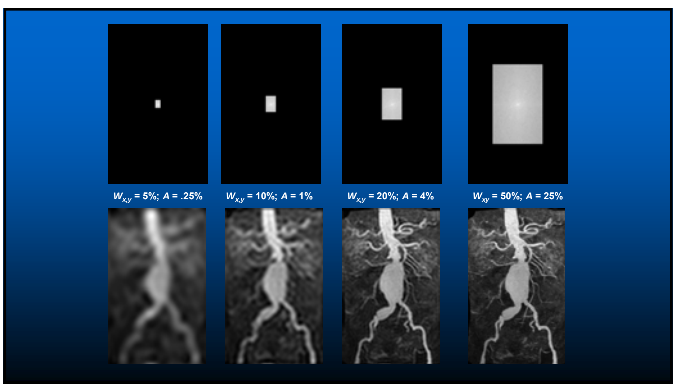

Centric k-Space Ordering
Start of view order: seq. z, centric y
Arterial phase
Venous phase
Signal Intensity (AU)
Contrast injection
Acquisition
Acquisition of central k-space
Time
Arrival Time
A Wilman et al. MRM 36(3) 1996

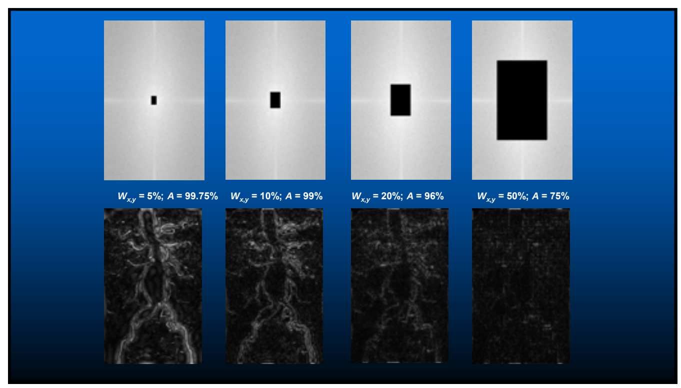

Elliptical Centric k-Space Ordering
Start of view order: elliptical centric
Arterial phase
Venous phase
Signal Intensity (AU)
Contrast injection
Acquisition
Acquisition of central k-space
Time
Arrival Time
A Wilman et al. MRM 36(3) 1996

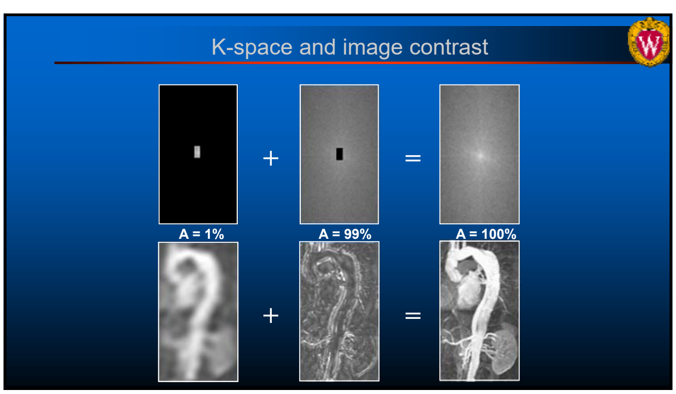

CE MRA - Peripheral
Images courtesy Harald Kramer, MD – Munich, Germany

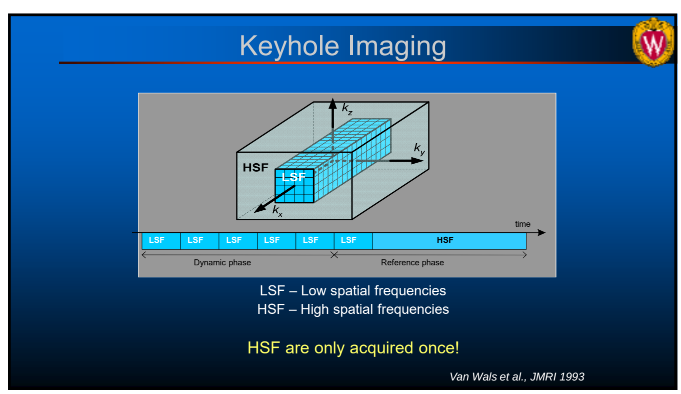

3D CE MRA – Dynamic Acquisition
Scan time:
$N_z \times N_y \times TR$
32x128x5 ms = 21 s
Benefits
Robust to contrast bolus arrival
Shows asymmetric fillings / inconsistent contrast arrival
Concerns
Sacrifice spatial resolution for temporal resolution
Arterial phase
Venous phase
Signal Intensity (AU)
Contrast injection
Acquisition
Time
Arrival Time

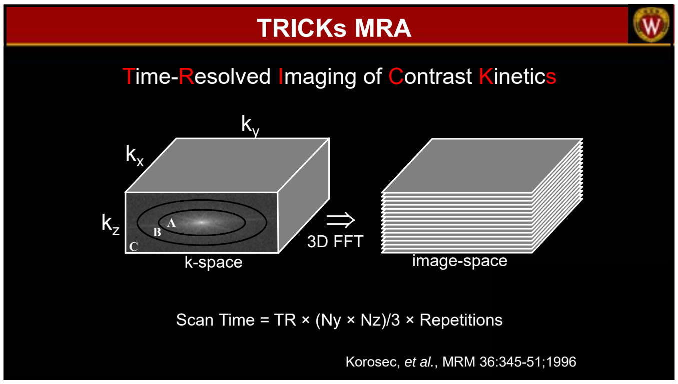

CE MRA
FT from magnitude image
(log scale)

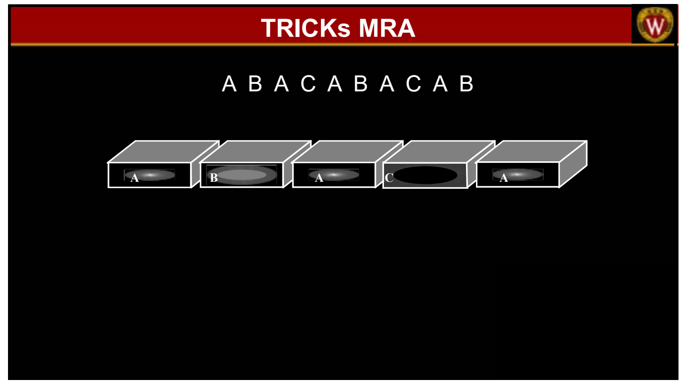

$W_{x,y}$ = 5%; A = .25%
$W_{x,y}$ = 10%; A = 1%
$W_{x,y}$ = 20%; A = 4%
$W_{x,y}$ = 50%; A = 25%

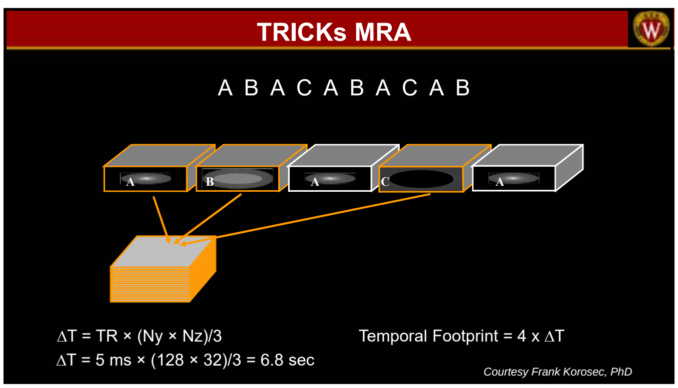

$W_{x,y}$ = 5%; A = 99.75%
$W_{x,y}$ = 10%; A = 99%
$W_{x,y}$ = 20%; A = 96%
$W_{x,y}$ = 50%; A = 75%

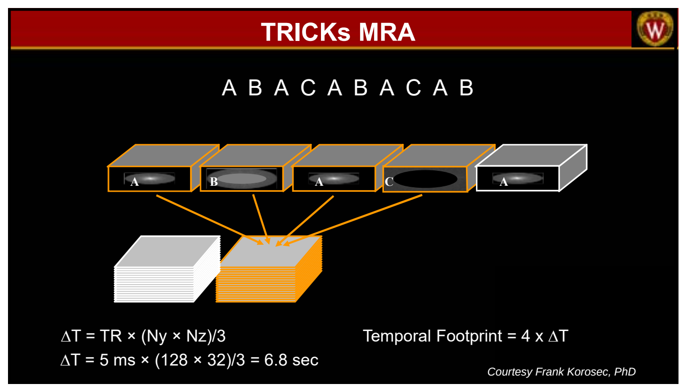

K-space and image contrast
+
=
A = 1%
A = 99%
A = 100%

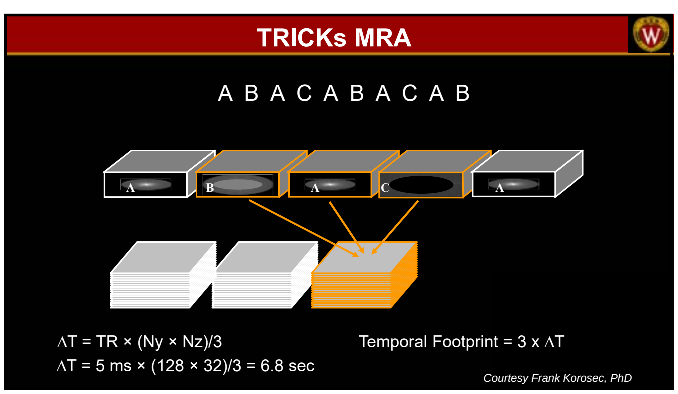

Keyhole Imaging
k_z
k_y
k_x
HSF
LSF
time
Dynamic phase
Reference phase
LSF – Low spatial frequencies
HSF – High spatial frequencies
HSF are only acquired once!
Van Wals et al., JMRI 1993

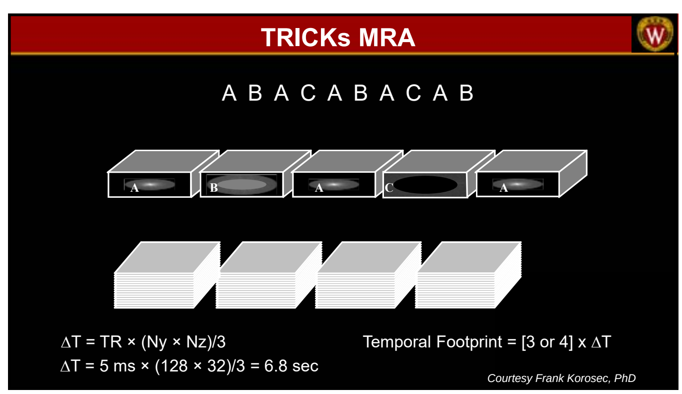

TRICKs MRA
Time-Resolved Imaging of Contrast Kinetics
k_y
k_x
k_z
A
B
C
k-space
⇒
3D FFT
image-space
Scan Time = TR × (Ny × Nz)/3 × Repetitions
Korosec, *et al.*, MRM 36:345-51;1996


TRICKs MRA
A B A C A B A C A B
A
B
A
C
A

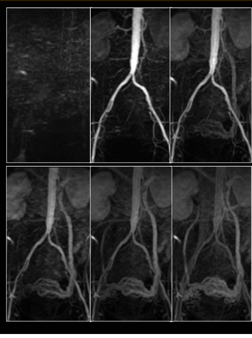

TRICKs MRA
A B A C A B A C A B
A
B
A
C
A
ΔT = TR × (Ny × Nz)/3
ΔT = 5 ms × (128 × 32)/3 = 6.8 sec
Temporal Footprint = 4 x ΔT
Courtesy Frank Korosec, PhD

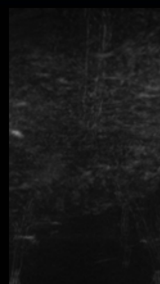

TRICKs MRA
A B A C A B A C A B
A
B
A
C
A
ΔT = TR × (Ny × Nz)/3
ΔT = 5 ms × (128 × 32)/3 = 6.8 sec
Temporal Footprint = 4 x ΔT
Courtesy Frank Korosec, PhD


TRICKs MRA
A B A C A B A C A B
A
B
A
C
A
ΔT = TR × (Ny × Nz)/3
ΔT = 5 ms × (128 × 32)/3 = 6.8 sec
Temporal Footprint = 3 x ΔT
Courtesy Frank Korosec, PhD


TRICKs MRA
A B A C A B A C A B
A
B
A
C
A
ΔT = TR × (Ny × Nz)/3
ΔT = 5 ms × (128 × 32)/3 = 6.8 sec
Temporal Footprint = [3 or 4] x ΔT
Courtesy Frank Korosec, PhD

time-resolved MRA





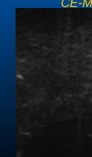
Contrast-Enhanced (CE)-MRA

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
- Need for contrast agents
  - Costs
  - Gd-based agents: Patients with compromised kidney function
    - *Nephrogenic Systemic Fibrosis*

SE Cowper et al., Lancet, 2000



Time-resolved CE-MRA

Summary

MRA has many contrast mechanisms

Endogeneous
- Native (bSSFP)
- Inflow (TOF, flow-prepared bSSFP)
- Motion (Phase Contrast)

Exogeneous
- Extracellular (Gd-based)
- Blood Pool (Gd-based and Ferahin)

MRA can provide
- Anatomy
- Hemodynamics