Introduction to MR Angiography: Technical Details

Sagar Buch, Ph.D.

Department of Radiology

Wayne State University

What is Angiography?

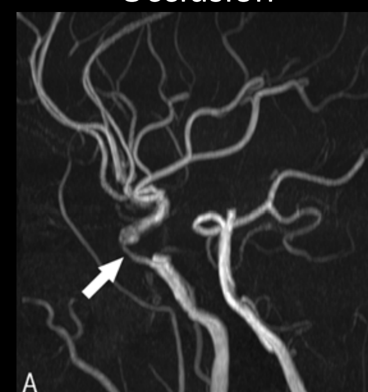
Angiography is an imaging procedure to visualize blood vessels from a given region

This is achieved by increasing the contrast between the blood vessels and surrounding tissues

Why is Angiography used?

- Find presence of narrowing – atherosclerosis
- Find obstruction in vessel lumen – embolism
- Find reduced/abnormal blood flow
- Monitoring changes over time

Occlusion



Choi CG *et al.*, AJNR. 2007 Mar;28(3):439-46.

Embolism

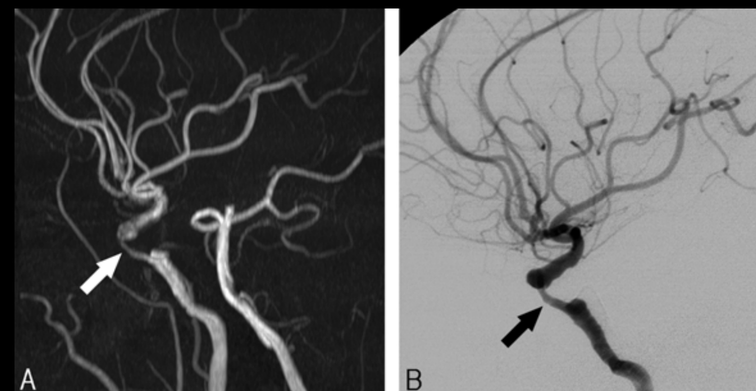
Pressacco J *et al.*, Eur J Radiol. 2019 Apr;113:165-173.

Catheter-based Angiography vs MR Angiography

- Traditionally, a radio-opaque contrast agent is used (*Coronary Angiogram)*
- Gold standard
- Disadvantages:
  - Exposure to ionizing radiation
  - Utilization of nephrotoxic contrast agent => chronic kidney disease

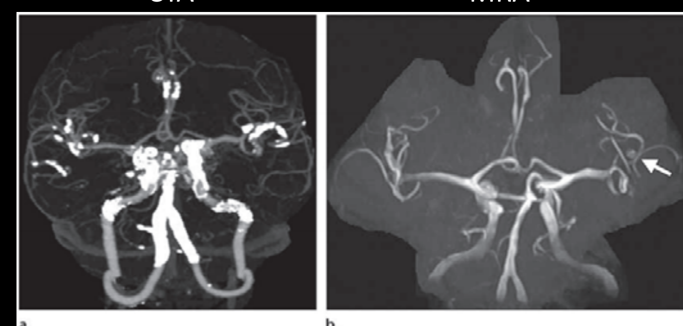
- Magnetic resonance angiography (MRA) has become the modality of choice
  - More informative => surrounding tissues
  - No ionizing radiation
  - Non-invasive options

MRA CA



Choi CG *et al.*, AJNR Am J Neuroradiol. 2007 Mar;28(3):439-46.

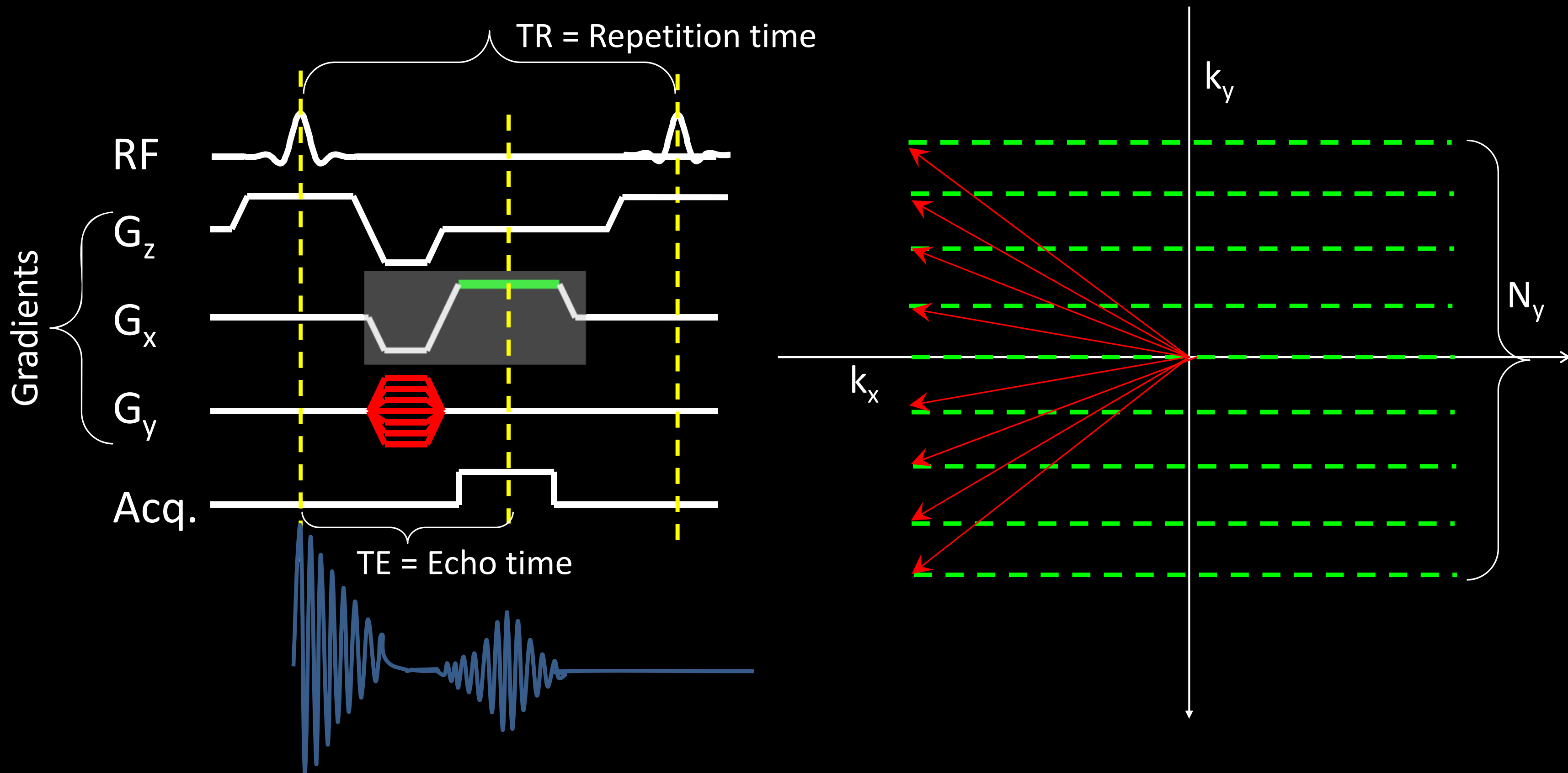
CTA MRA



Morita S *et al.*, Radiographics. 2011 Mar-Apr;31(2):E13-33.

Recap: A 2D Single Slice Acquisition

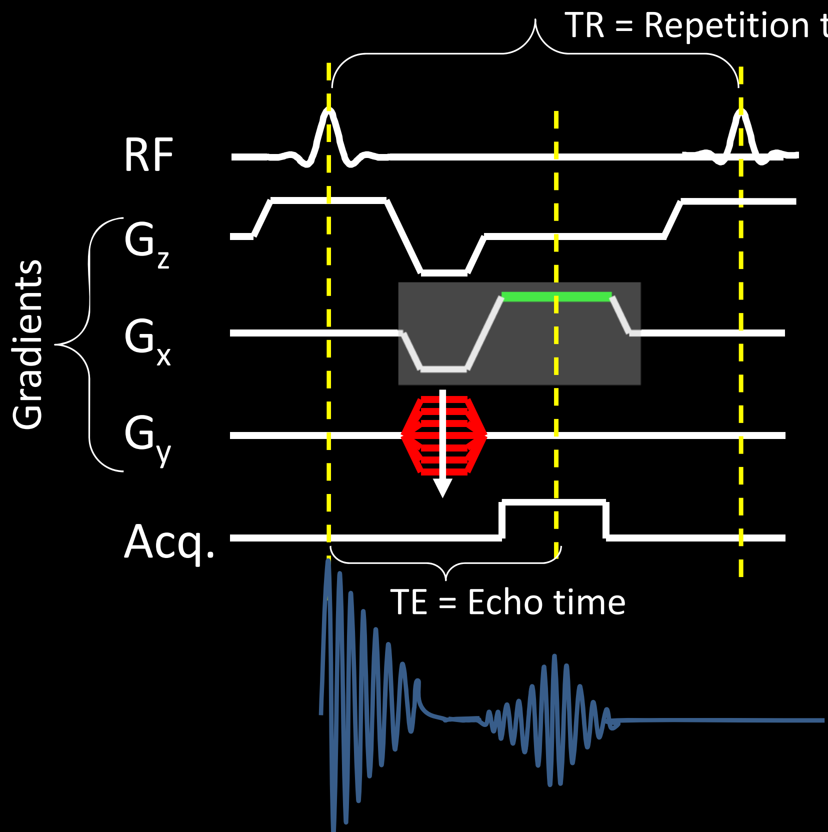
Typical Gradient Echo sequence:



Sampling of the signal in k-space line-by-line, forming the image in spatial domain

Recap: A 2D Single Slice Acquisition

Typical Gradient Echo sequence:



k-space

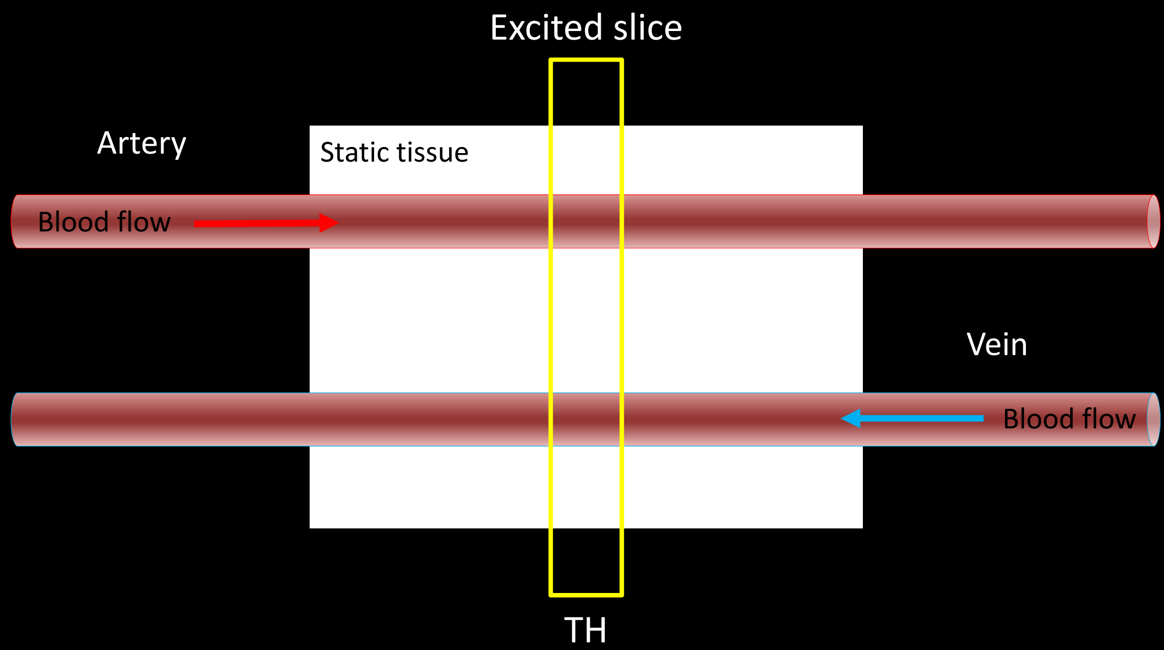
Image space

Sampling of the signal in k-space line-by-line, forming the image in spatial domain

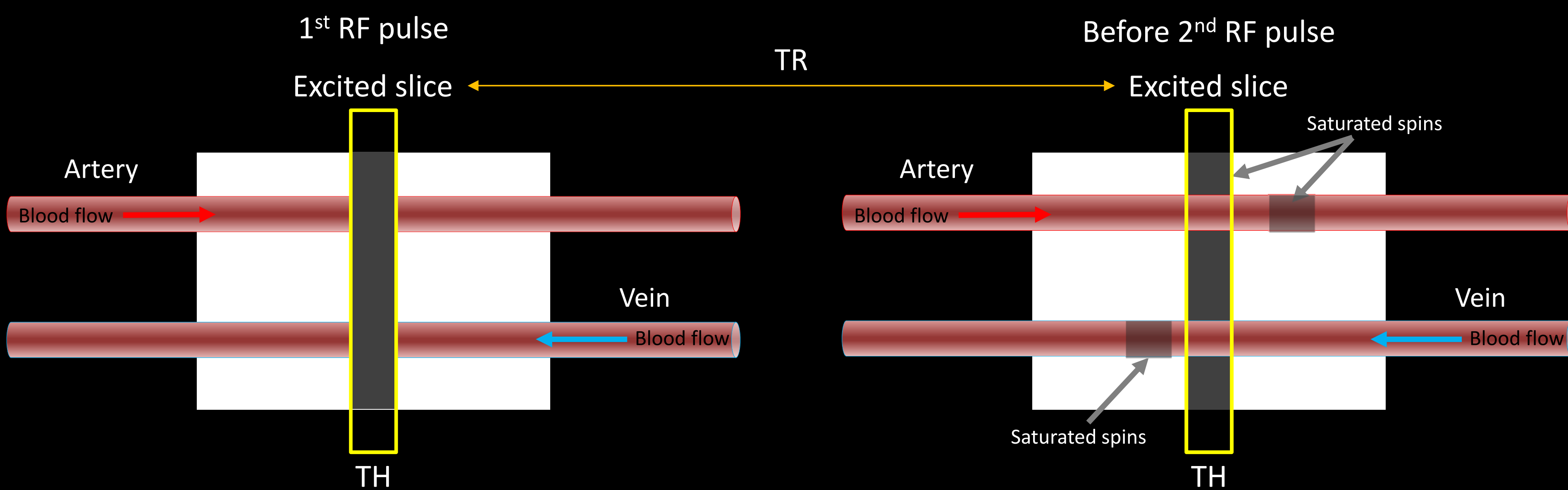
Time-of-Flight (TOF) Imaging

Principle of In-flow Enhancement

Let's take a simple model:

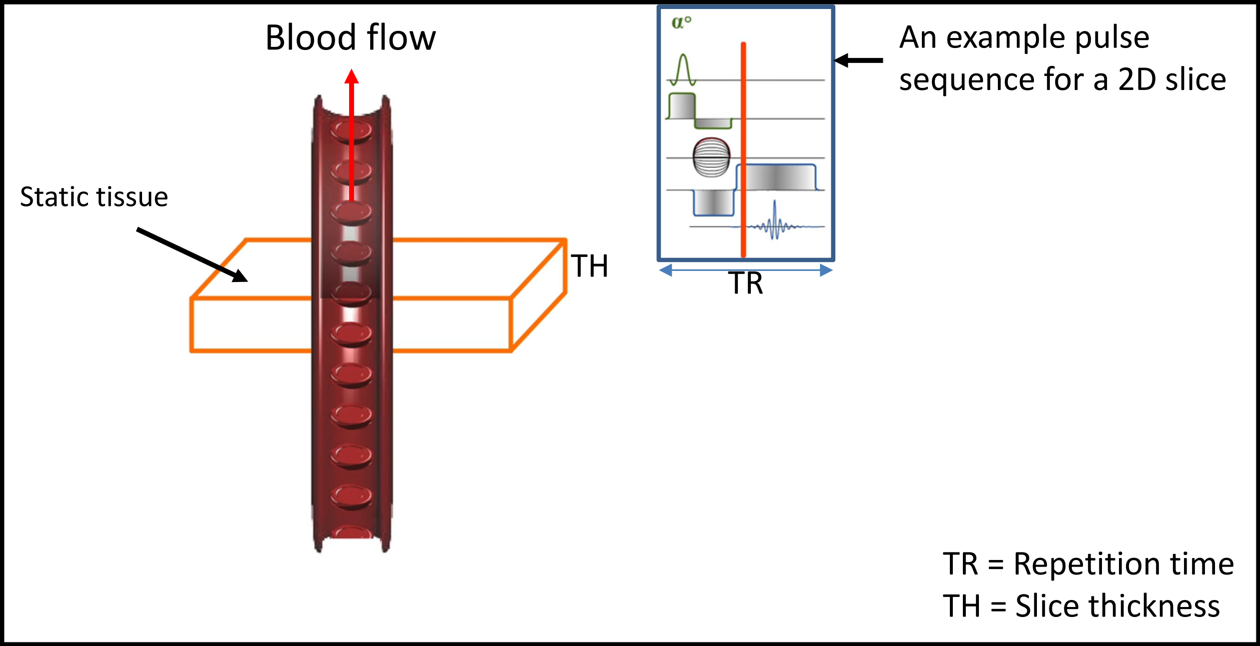


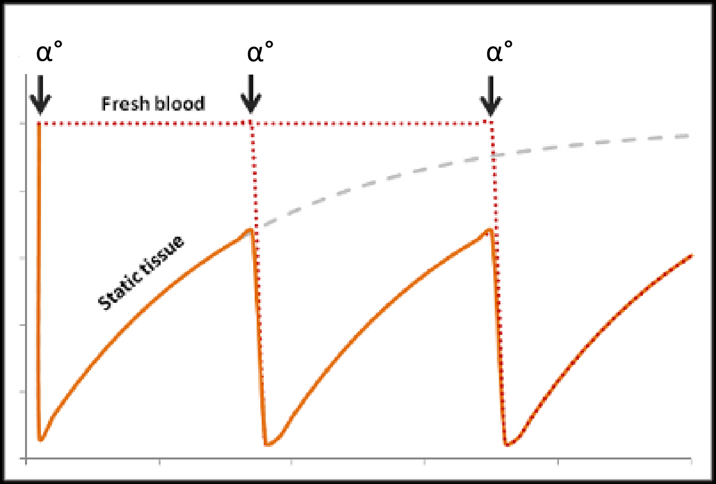
Principle of In-flow Enhancement



Due to fresh segment of blood (i.e. un-excited) entering into the slice every TR, the signal from blood is *effectively increased relative to surrounding tissue*

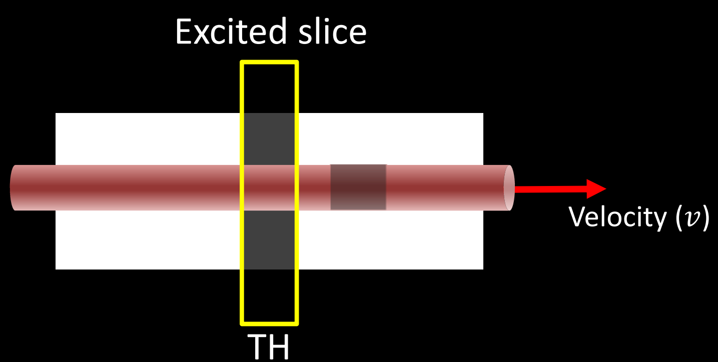
Time-of-Flight (TOF) Imaging





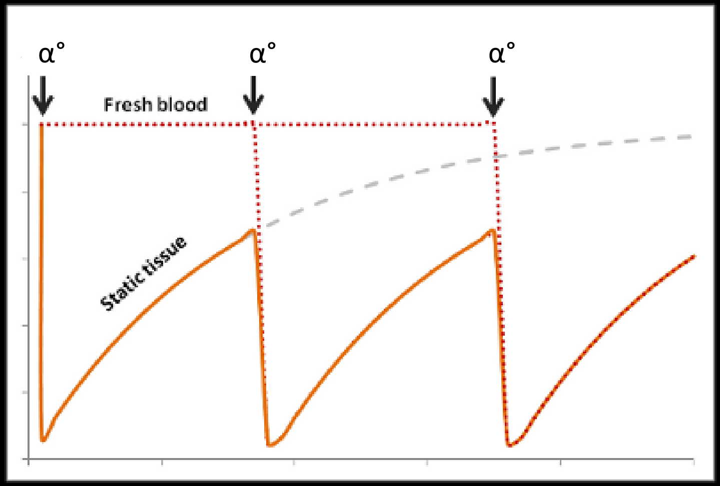
https://www.imaios.com/en/e-Courses/e-MRI/MR-Angiography-Flow-imaging/time-of-flight-mra

Time-of-Flight (TOF) Imaging



Fast flow: $\boxed{v \cdot TR \geq TH}$

- A complete new set of blood spins are entering the slice
- Effectively providing a T_1 recovery time of 0.



Time-of-Flight (TOF) Imaging

Slow flow: $\boxed{v \cdot TR < TH}$

- Partial saturated spins are leftover in the excited slice.
- The resultant signal is composite of fresh and saturated blood

Recap:

Most MRA methods use GRE, which takes time to reach the equilibrium longitudinal magnetization value of:

$$M_{ze} = Mo(1 - e^{-TR/T1})/(1 - q)$$

where, $q = e^{-TR/T1} \cdot \cos\theta$

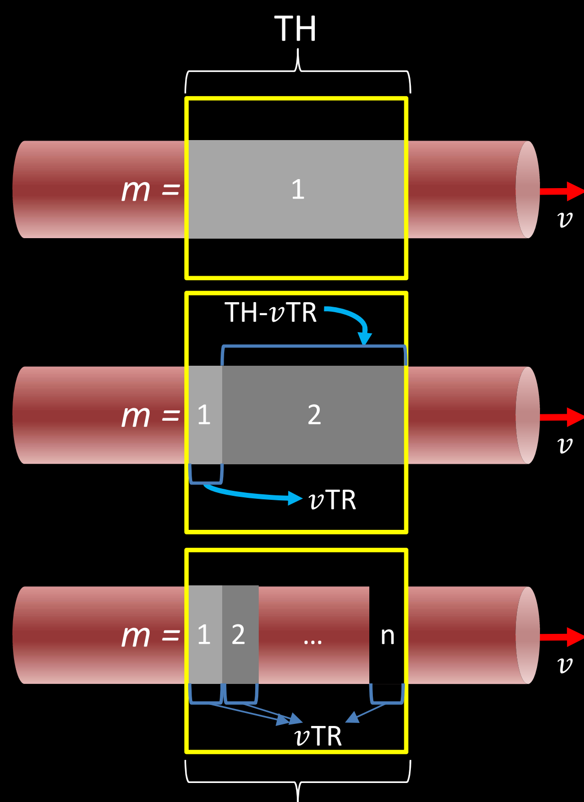
But, when equilibrium is not yet reached, the longitudinal magnetization just before the mth pulse is:

$$M_{ze}(m^-) = M_{ze} + q^{m-1}(M_o - M_{ze}) \qquad \text{(when } m \geq 1\text{)}$$

Time-of-Flight (TOF) Imaging

Slow flow: $\boxed{v \cdot TR < TH}$

- Partial saturated spins are leftover in the excited slice.
- The resultant signal is composite of fresh and saturated blood



After the first RF pulse, the transverse magnetization is:

$M_{XY}(1) = M_o \sin\theta$

After the second RF pulse, there will be two populations:

$$M_{XY}(2) = \left(\underbrace{\left(1-\frac{1}{n}\right)\left(M_{ze}+q(M_o-M_{ze})\right)}_{m=2} + \underbrace{\frac{1}{n}M_o}_{m=1}\right)\sin\theta$$

Hence, the variation of signal across n segments:

$$S_{\text{per segment}} = \left(M_{ze} + q^{m-1}(M_o - M_{ze})\right)\frac{\sin\theta}{n}$$

(when m ≥ 1)

Thickness of each individual segment:

$\boldsymbol{v}\cdot\mathbf{TR}$

Number of segments that fit into one slice *or the number of RF pulses applied*:

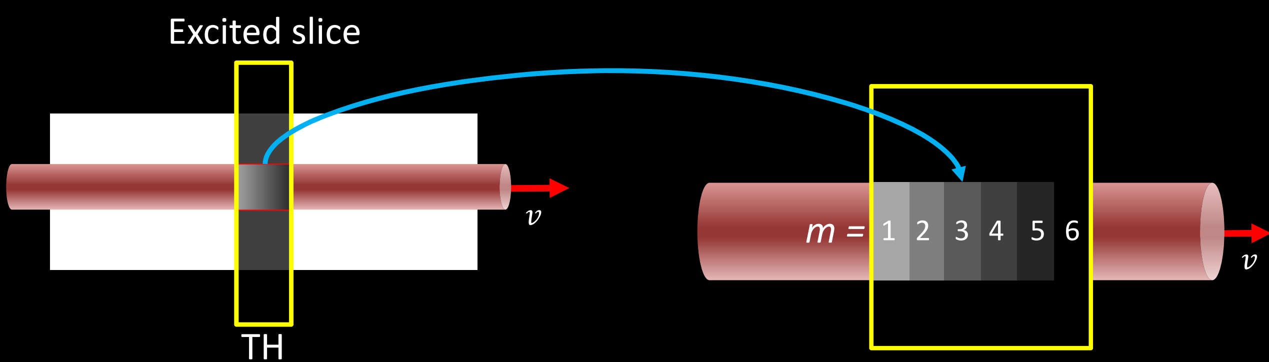
n = TH/(v·TR)

$$S_{\text{across the slice}} = \sum_{n-1}^{m} S_{\text{per segment}}$$

$$\boldsymbol{S_{\text{across the slice}} = \sin\theta\left(M_{ze} + (M_o - M_{ze})\left[\frac{1-q^n}{n(1-q)}\right]\right)}$$

Haacke EM et al., Magn Reson Med. 1990 May;14(2):202-21.

Time-of-Flight (TOF) Imaging



$$\boxed{v \cdot TR < TH}$$

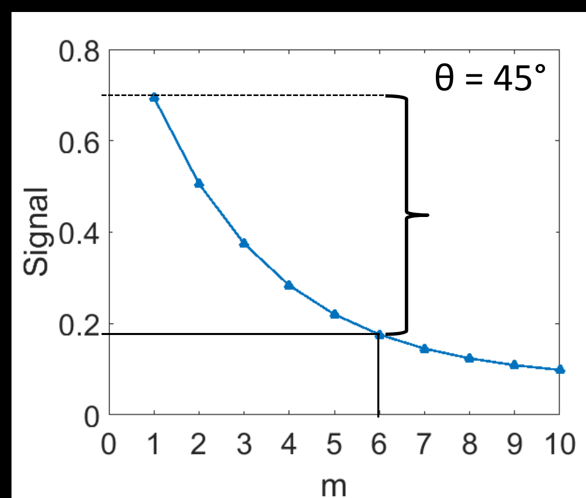
m = Number of pulses seen by spins

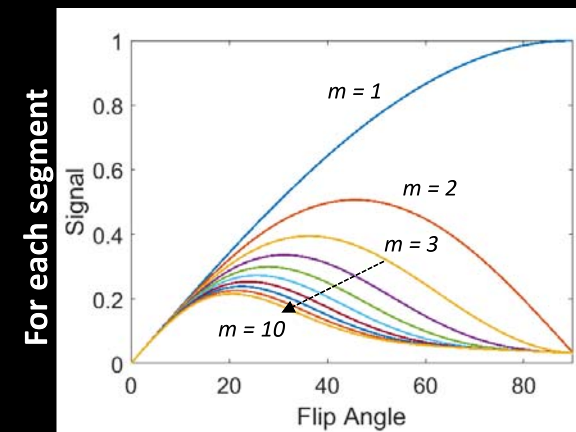
The variation of signal across n segments:

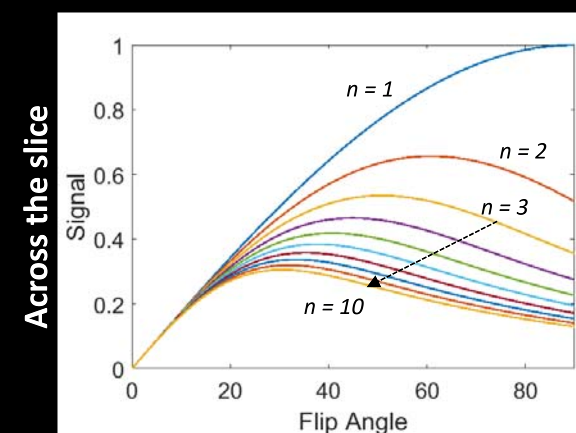
$$S_{\text{per segment}} = \left(M_{ze} + q^{m-1}(M_o - M_{ze})\right)\frac{\sin\theta}{n}$$

(when m ≥ 1)

$$S_{\text{across the slice}} = \sin\theta\left(M_{ze} + (M_o - M_{ze})\left[\frac{1-q^n}{n(1-q)}\right]\right)$$

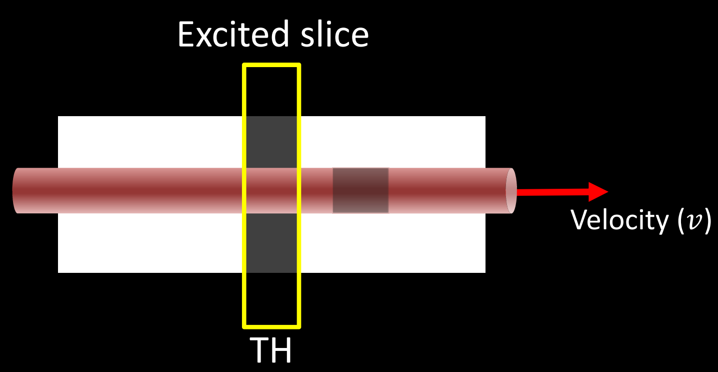






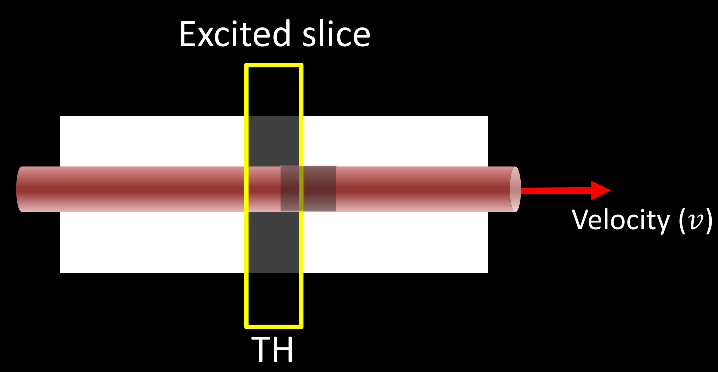
Useful for optimizing flip angle to achieve peak signal for different values of n

Time-of-Flight (TOF) Imaging



$$v \cdot TR \geq TH$$

- A complete new set of blood spins are entering the slice
- Effectively providing a T_1 recovery time of 0.

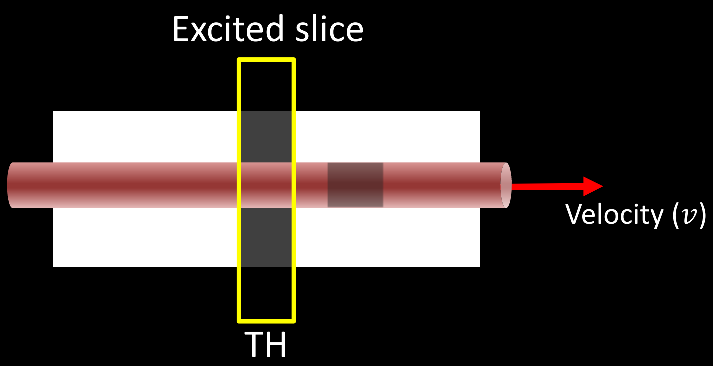


$$v \cdot TR < TH$$

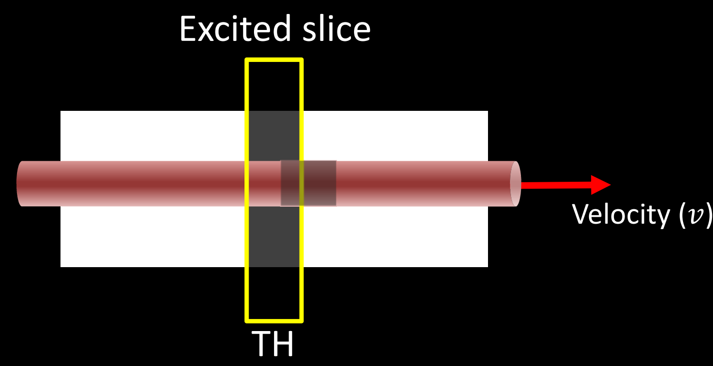
- Partial saturated spins are leftover in the excited slice.
- The resultant signal is composite of fresh and saturated blood

$$\boxed{\frac{1}{T_{1eff}} = \frac{1}{T_1} + \frac{v}{TH}}$$

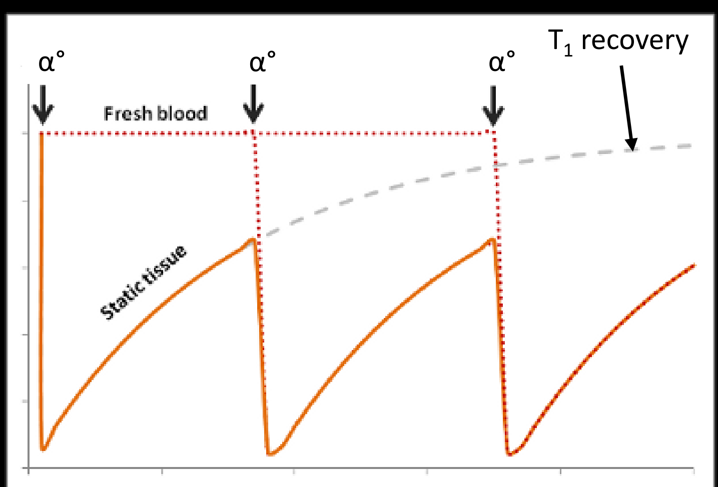
Time-of-Flight (TOF) Imaging



$$v \cdot TR \geq TH$$



$$v \cdot TR < TH$$



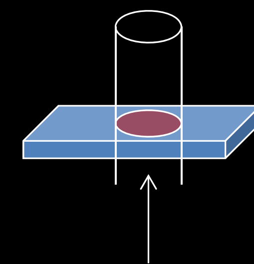
- Partial saturated spins are leftover in the excited slice.
- The resultant signal is composite of fresh and saturated blood

$$\boxed{\frac{1}{T_{1eff}} = \frac{1}{T_1} + \frac{v}{TH}}$$

- As v becomes small, T_{1eff} => T1
- As v > TH/TR, all signal is refreshed and $T1_{eff}$ => 0

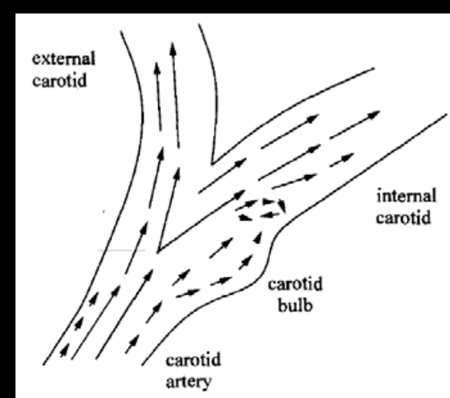
Time-of-Flight (TOF) Imaging

$$\frac{1}{T_{1eff}} = \frac{1}{T_1} + \frac{v}{TH}$$

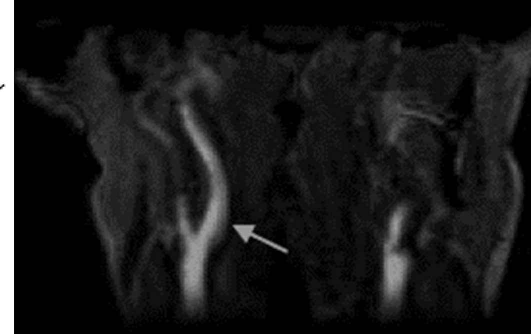


Through plane flow

For a given velocity, the *<u>thinner the slice the better is the T_1 enhancement</u>*

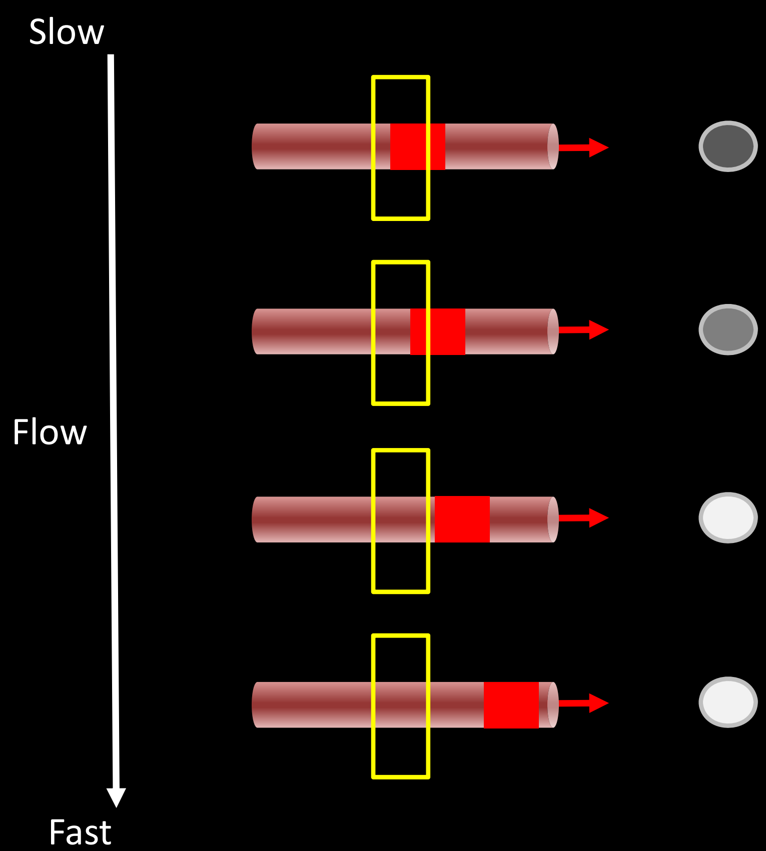


Vortex flow profile



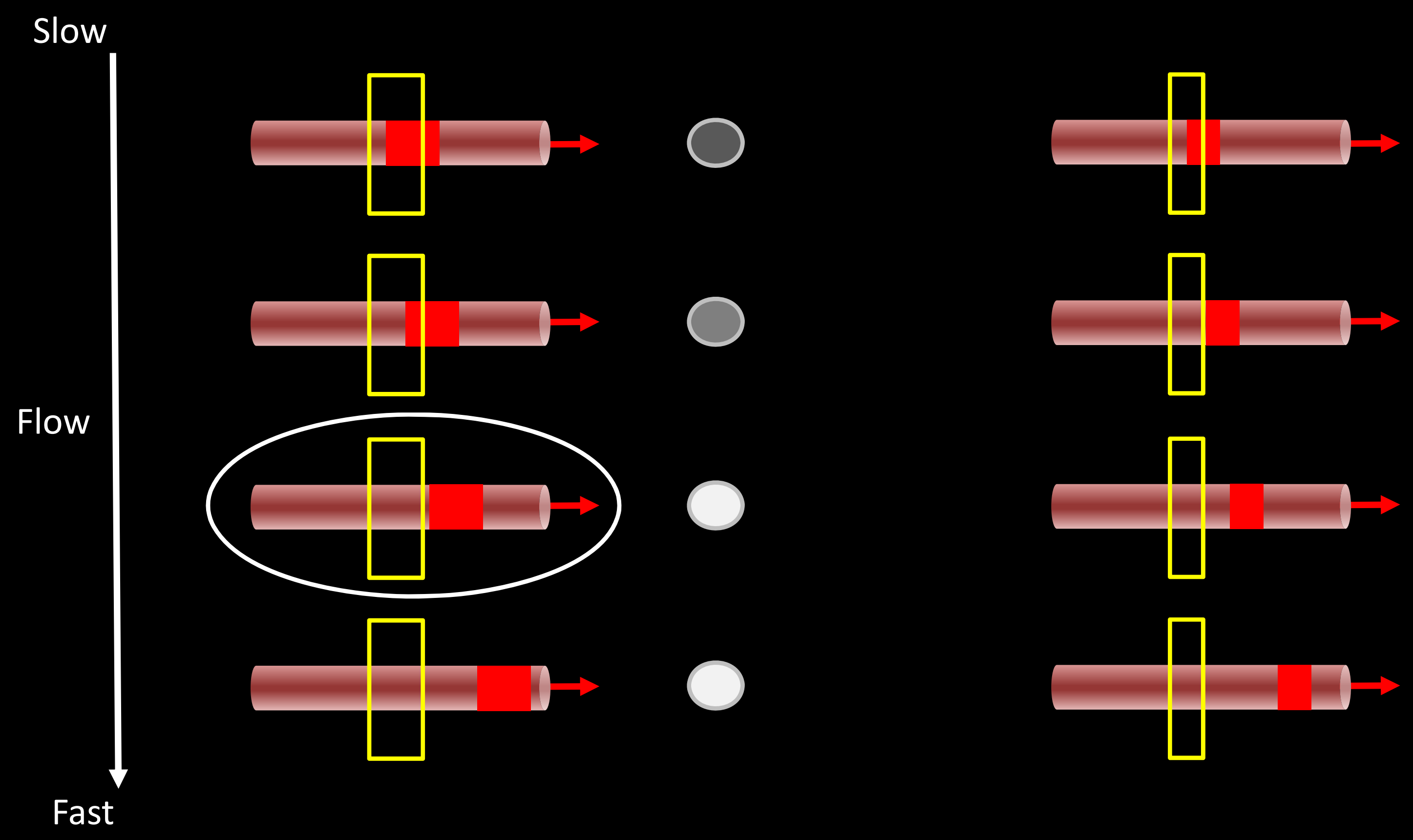
Carotids

What is the ideal TR?

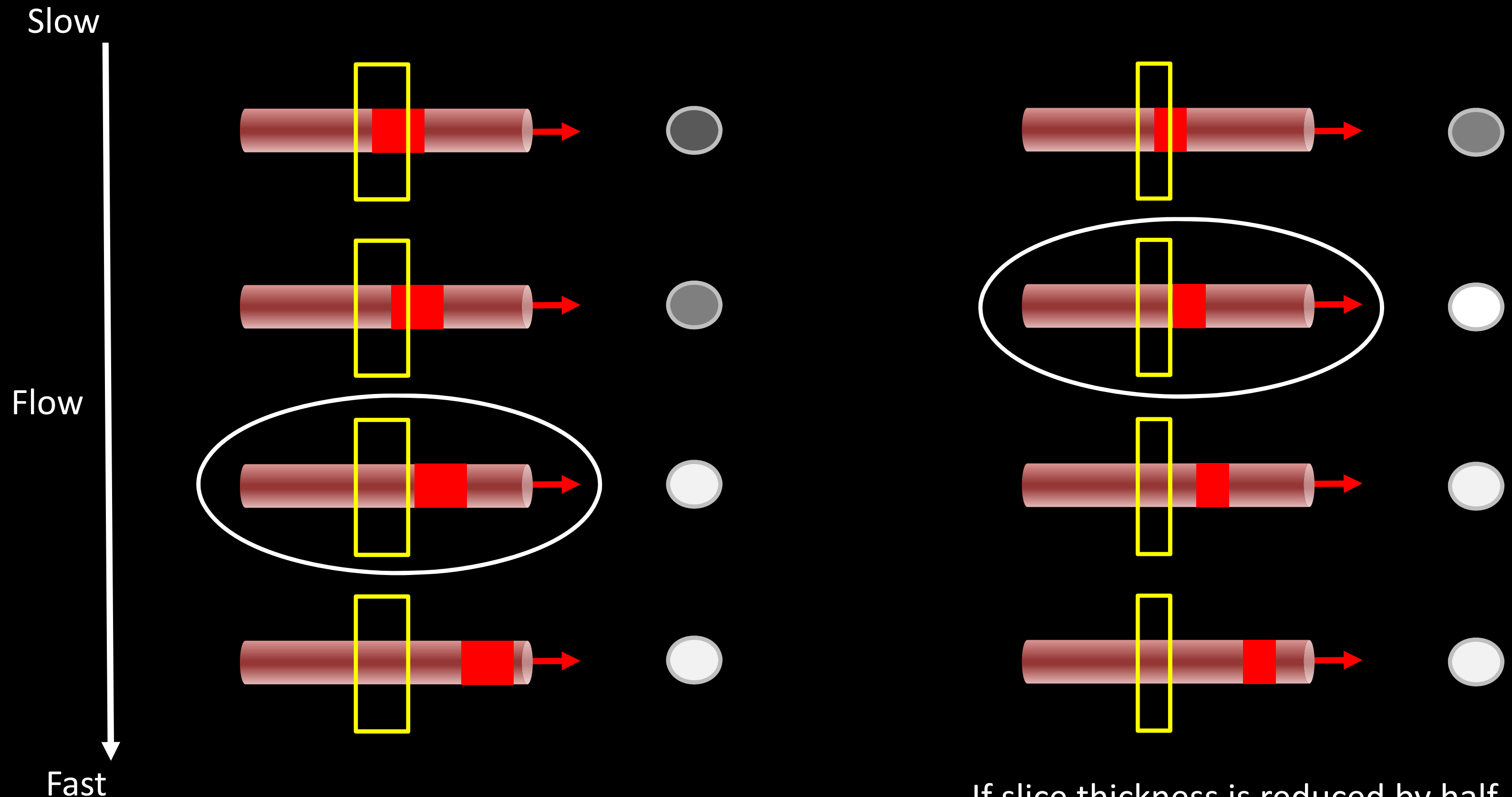


Short TR => insufficient time to flow out
Long TR => static tissues less saturated

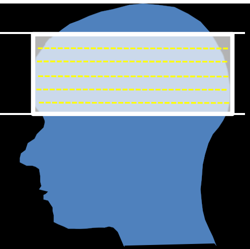
Ideal TR = TH/*v*



Ideal TR = TH/*v*

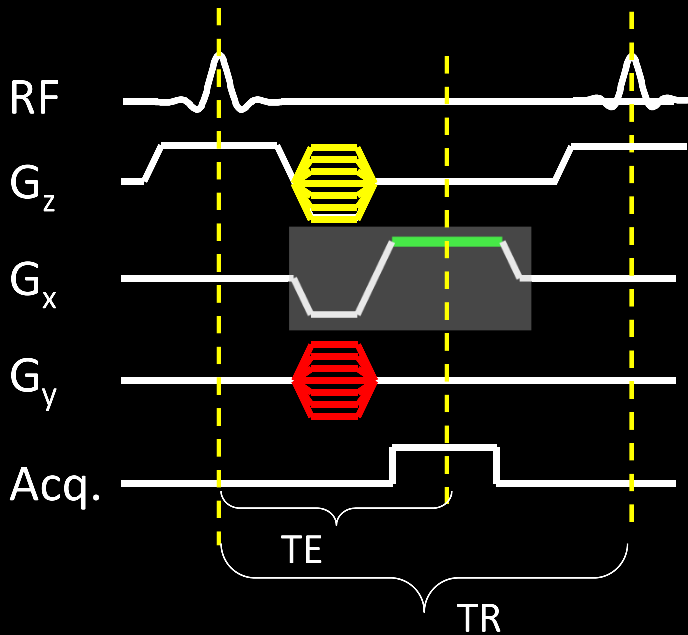


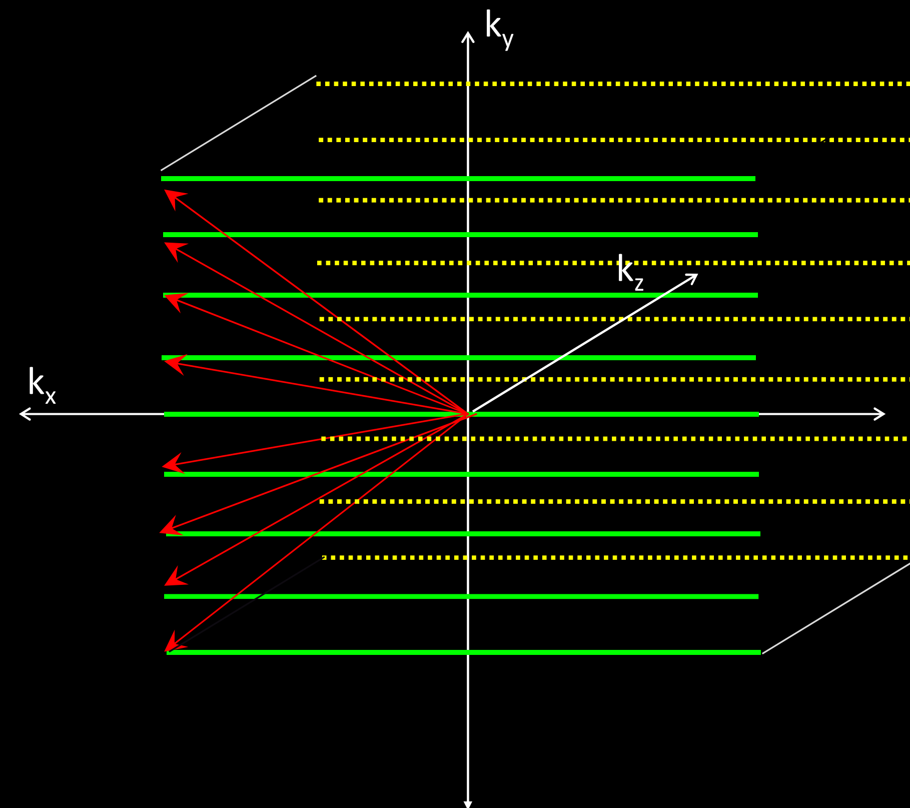
If slice thickness is reduced by half, the TR can also be reduced by half



3D imaging

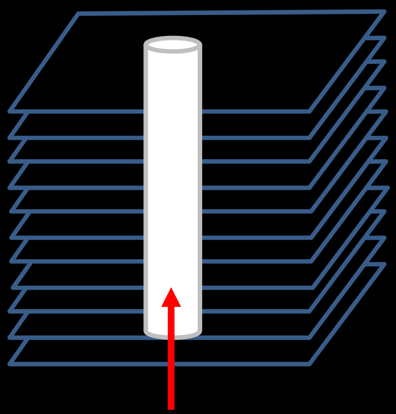
3D GRE - with slab excitation and partition encoding





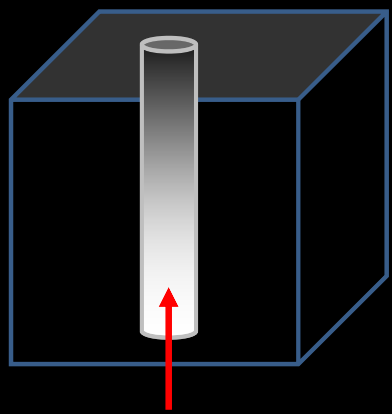
Slab Excitation and partition encoding in the z direction

2D vs 3D Acquisitions



Advantages:
+ High vessel contrast
+ Sensitive to slow flow

Disadvantages:
- Spin saturation for in-plane flow
- Low SNR for thin 2D slices
- More intravoxel dephasing due to high TE



Advantages:
+ High SNR
+ Thin slices
+ Low TE

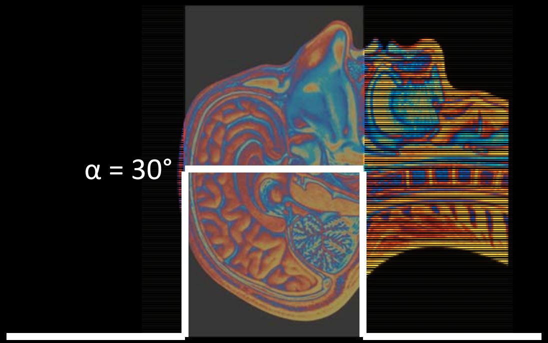
Disadvantages:
- Spin saturation (decreasing vessel contrast in imaging volume)

With a thick slab, Blood spends more time in the volume

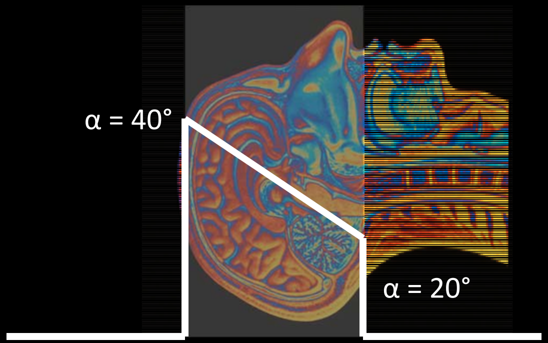
i.e. as you keep subjecting the volume to rf pulses, progressive saturation of the signal from blood occurs.

3D TOF: Conventional vs Variable FA

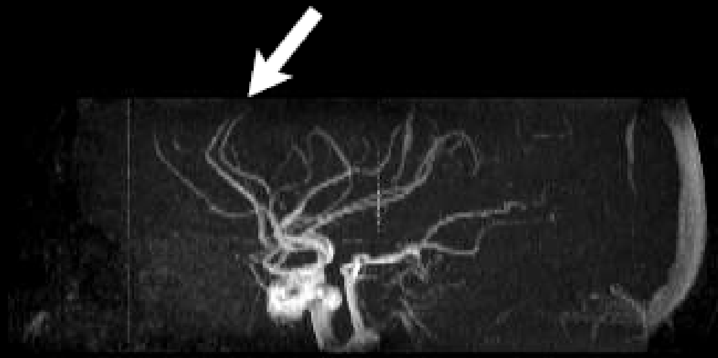
Conventional RF pulse



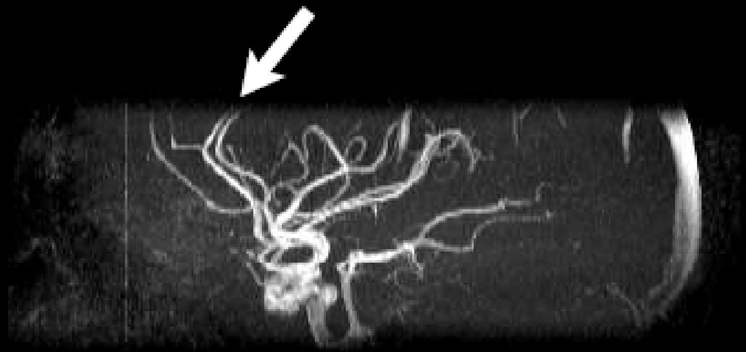
TONE RF pulse



To avoid this, a modified rf pulse which linearly **<u>increases the flip angle from one end of the volume to the other</u>** i.e., a TONE pulse (*tilted optimized non-saturating excitation*)

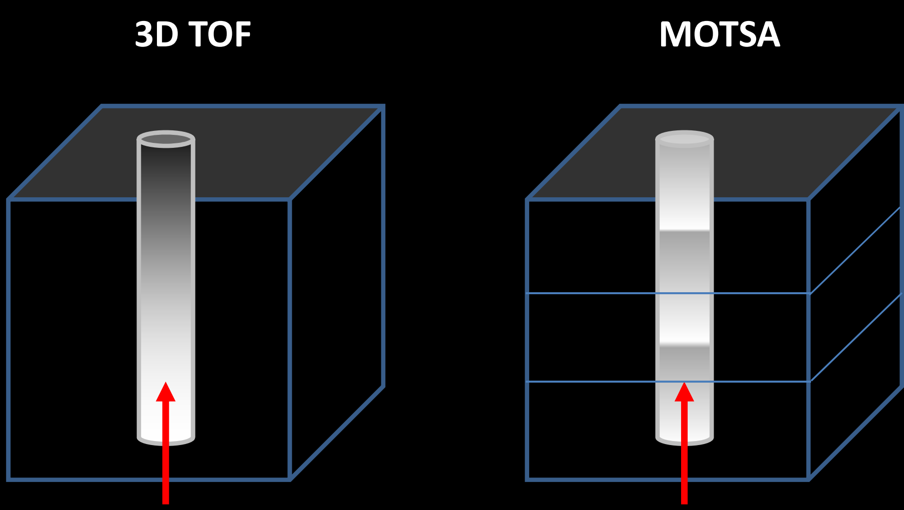


Normal 3D MRA

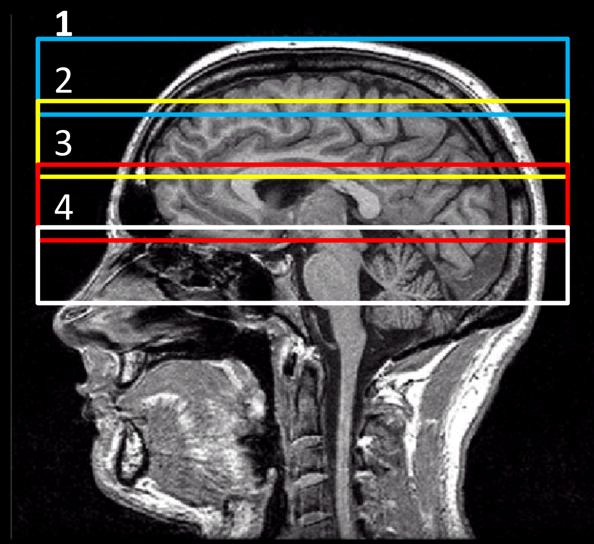


With TONE pulse

Multiple Overlapped Thin-Slab Acquisition (MOTSA)

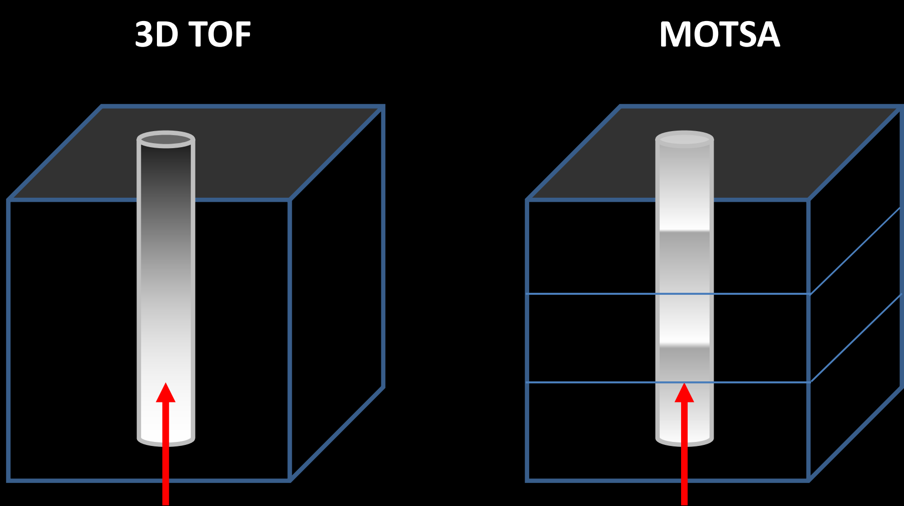


Parker DL *et al.*, Magn Reson Med. 1991 Feb;17(2):434-51.

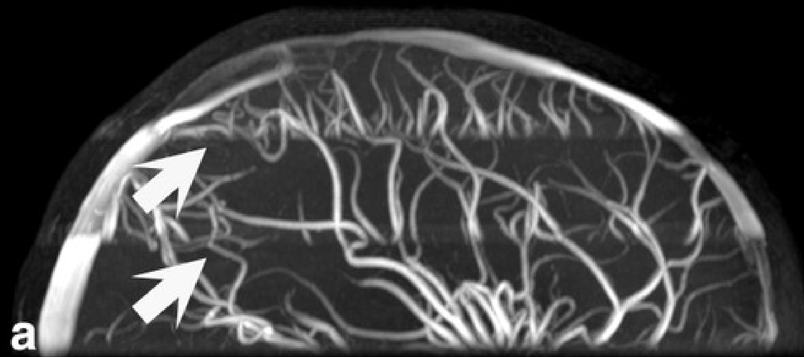


Because of this restricted slab thickness, loss of signal due to saturation effects is relatively limited, even at the exit slices.

Multiple Overlapped Thin-Slab Acquisition (MOTSA)



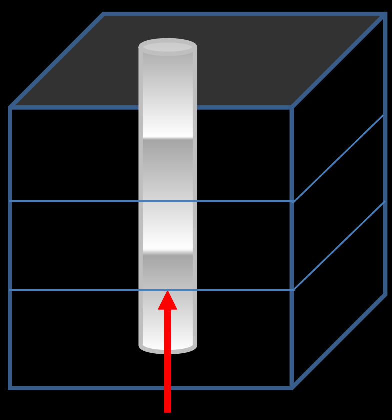
Parker DL *et al.*, Magn Reson Med. 1991 Feb;17(2):434-51.



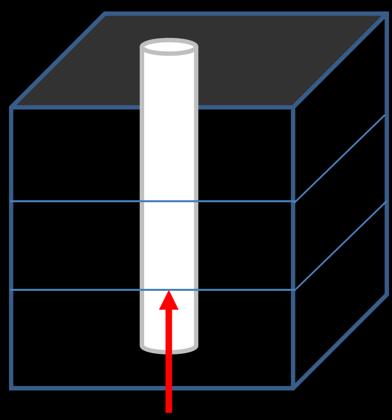
Morelli JN *et al.*, JMRI. 2013 Jun;37(6):1326-41.

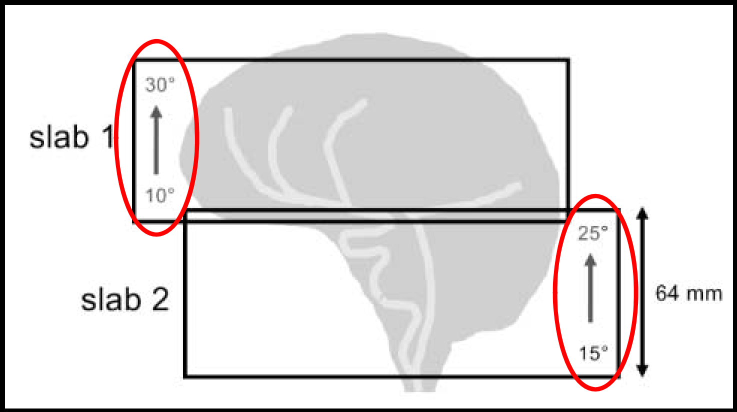
Reducing the Spin Saturation even more!

MOTSA



MOTSA + TONE RF pulse





Saïb et al., MRI 2019; 61: 104-115

Reducing the Spin Saturation even more!

MOTSA + uniform RF

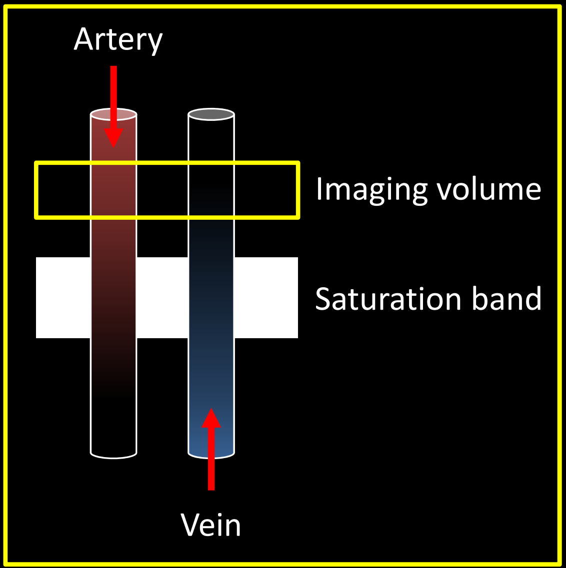
MOTSA + TONE RF

Saïb et al., MRI 2019; 61: 104-115

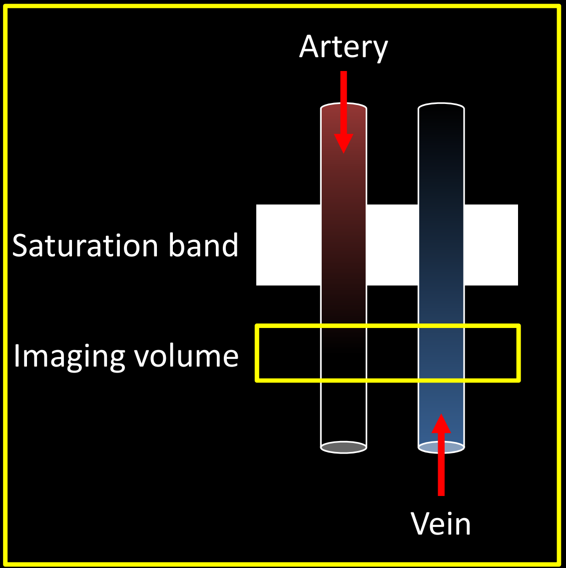
Saturation Pulses to obtain MRA and MRV

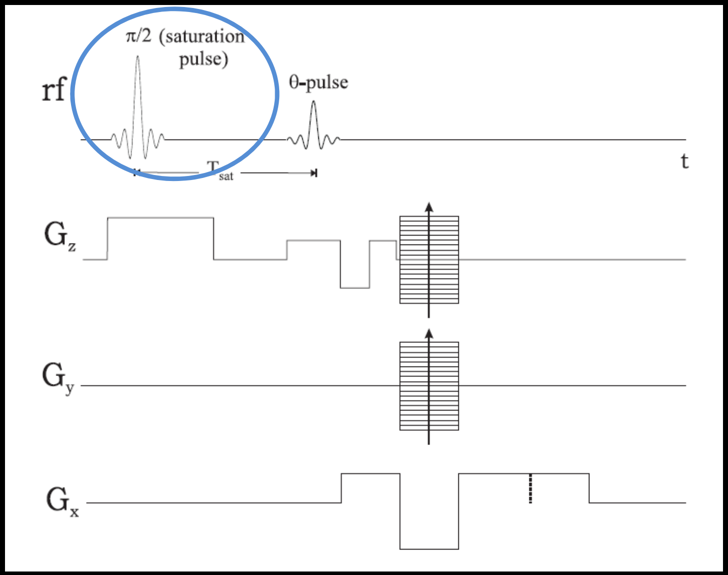
MR Arteriogram

MRA: Venous Saturation

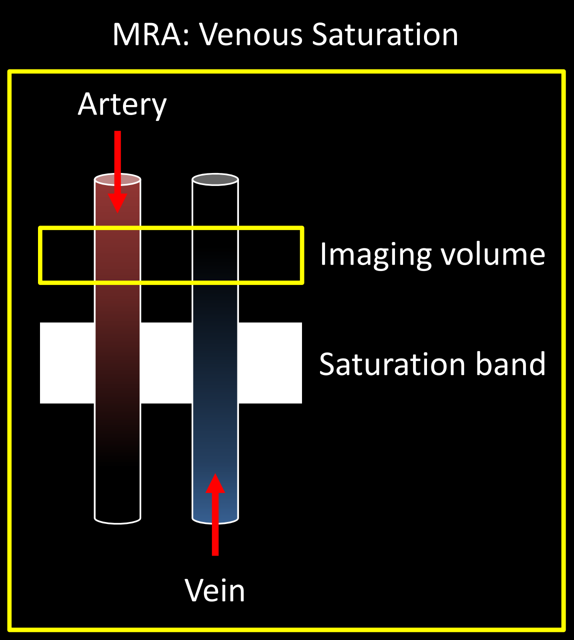


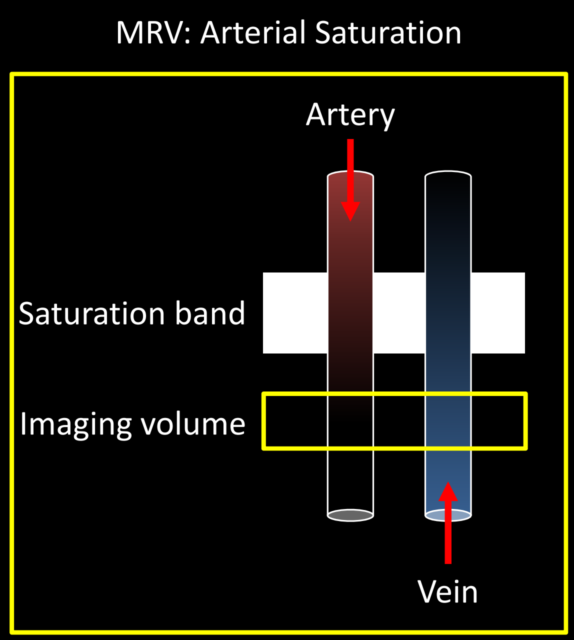
MRV: Arterial Saturation

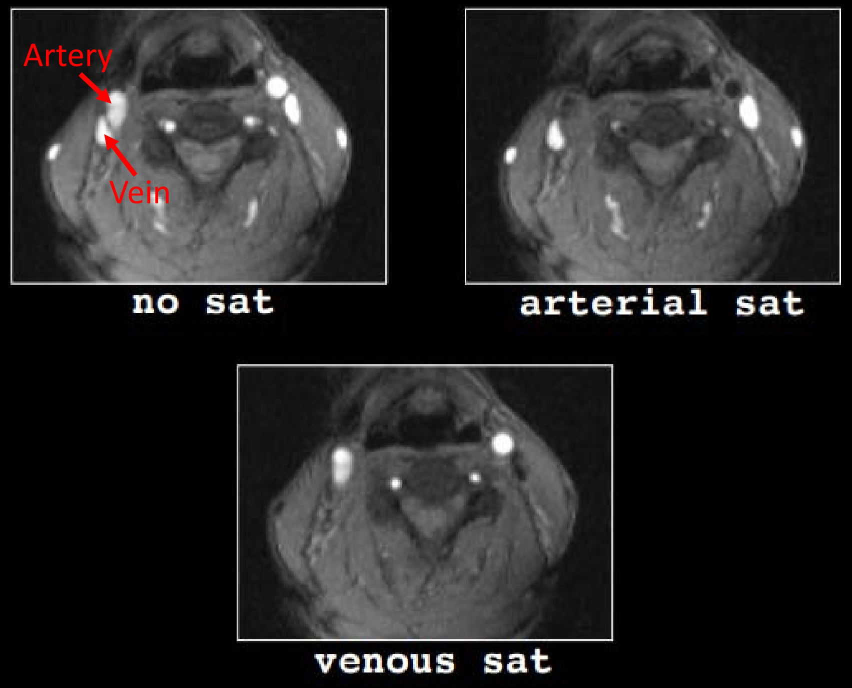




Saturation Pulses to obtain MRA and MRV







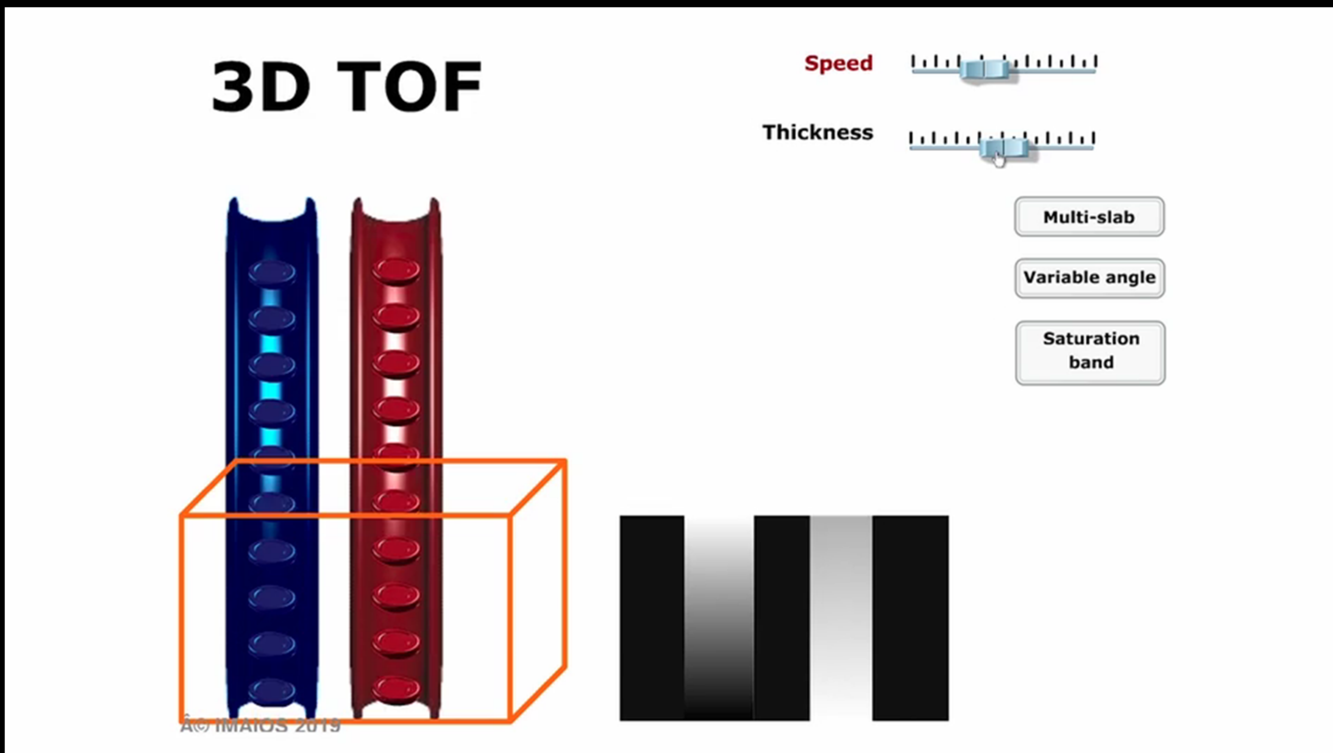
Saturation Pulses to obtain MRA and MRV

Removing the signal from superior sagittal sinus
using the saturation pulse

Without Saturation

With Saturation

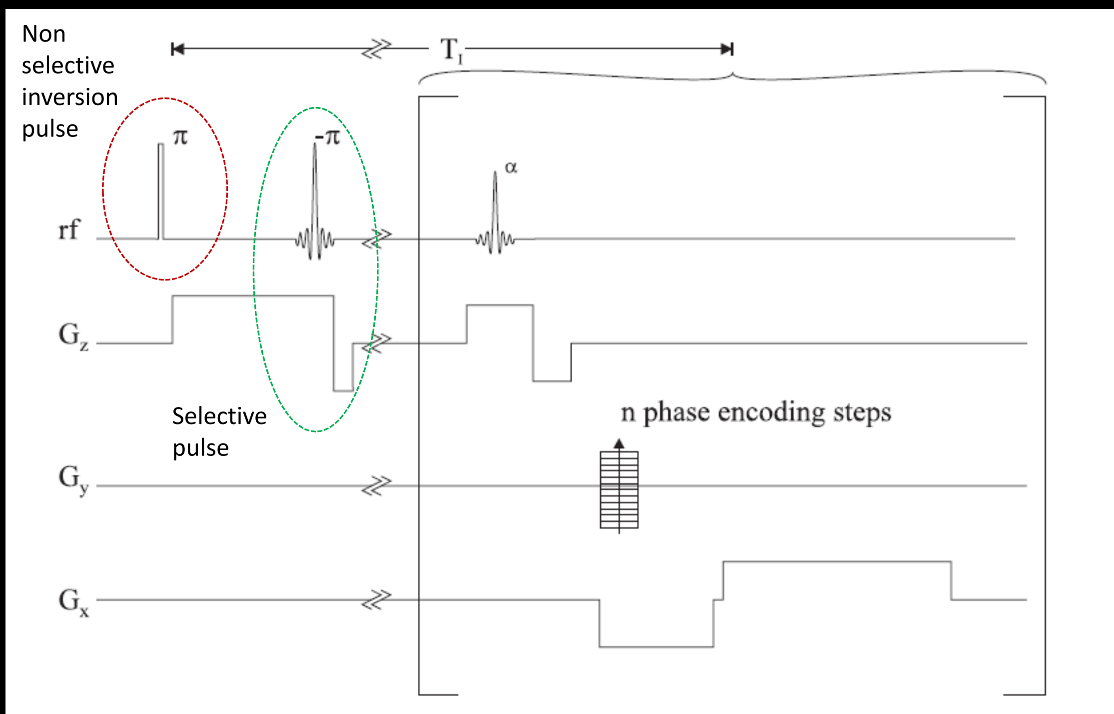
Summary of TOF methods



- Robust and highly inflow dependent
- Main application: imaging the cerebral arteries (3D) and carotid arteries (2D)
- Takes ≈5mins to acquire
- Prone to saturation effects due to slow flow and signal loss in turbulent/vortex flow or tortuous geometry

https://www.imaios.com/en/e-Courses/e-MRI/MR-Angiography-Flow-imaging/time-of-flight-mra

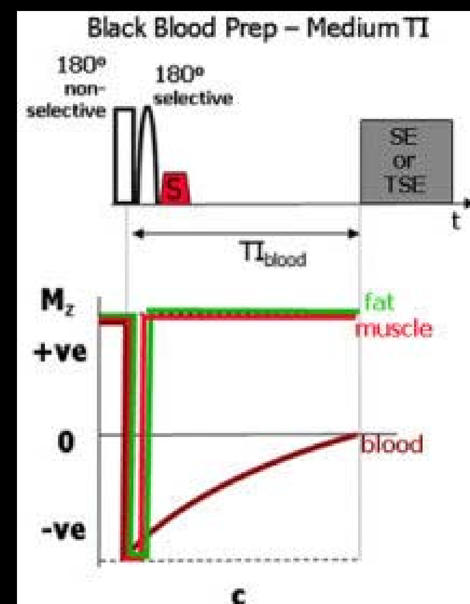
Inversion Recovery: Using relaxation properties of blood



- The first π pulse inverts all magnetization

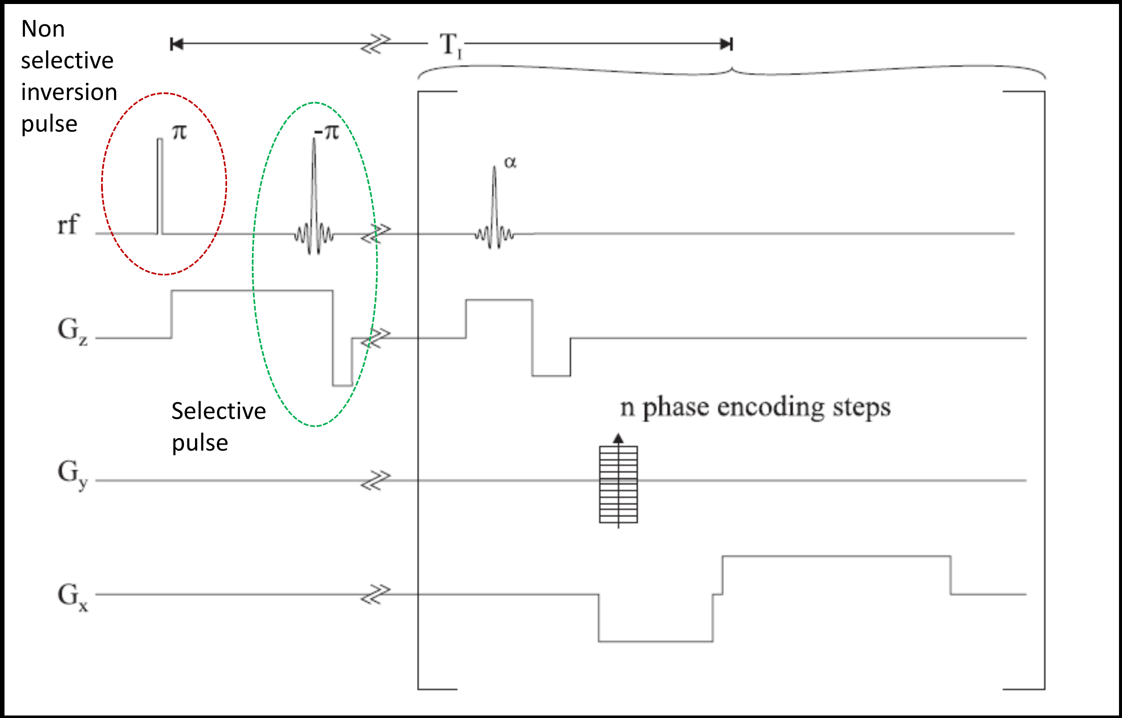
i.e., a non-selective pulse

- Then the next $-\pi$ pulse (which is slice selective) reverts the magnetization back to its original position along the z axis

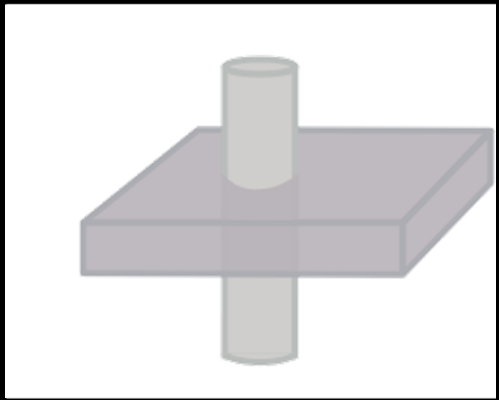


Biglands et al. JCMR, 2012, 14:66

Inversion Recovery: Using relaxation properties of blood



- The first π pulse inverts all magnetization i.e., a non-selective pulse
- Then the next $-\pi$ pulse (which is slice selective) reverts the magnetization back to its original position along the z axis



http://xrayphysics.com/cv_mri.html

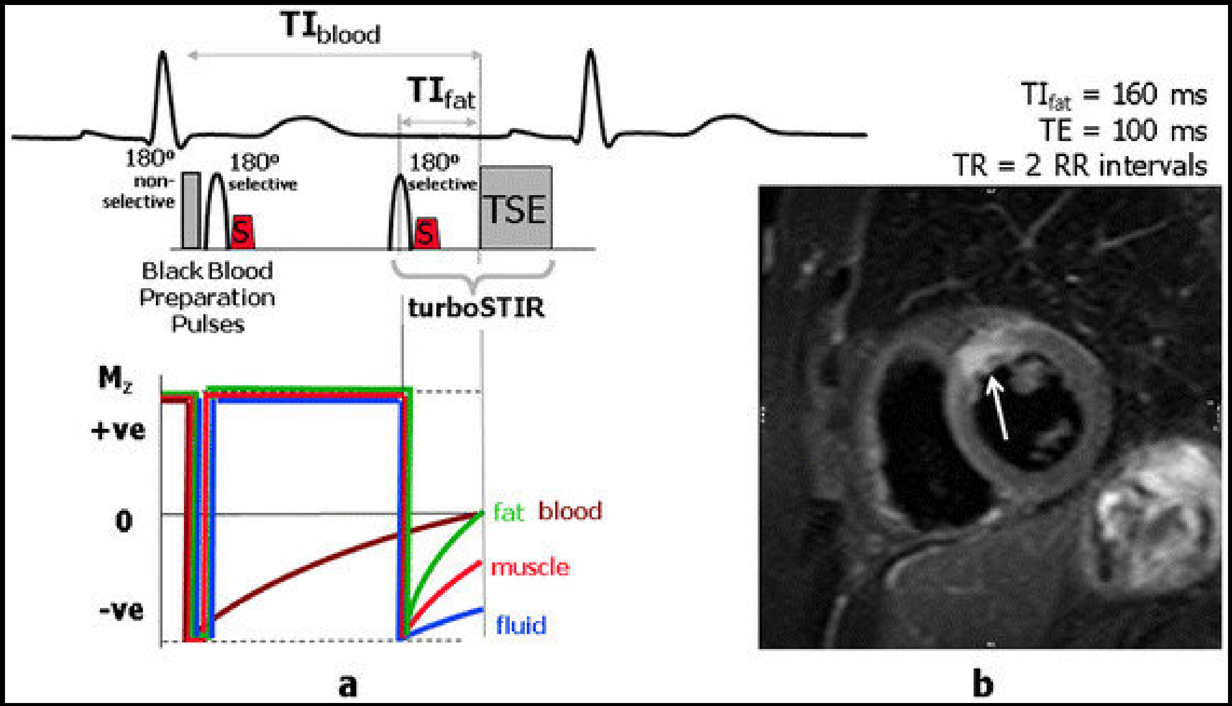
Inversion Recovery: Black blood imaging

2D TOF

Black blood image

Useful for visualizing the walls of the cardiac chambers and blood vessels

Inversion Recovery: Black blood imaging

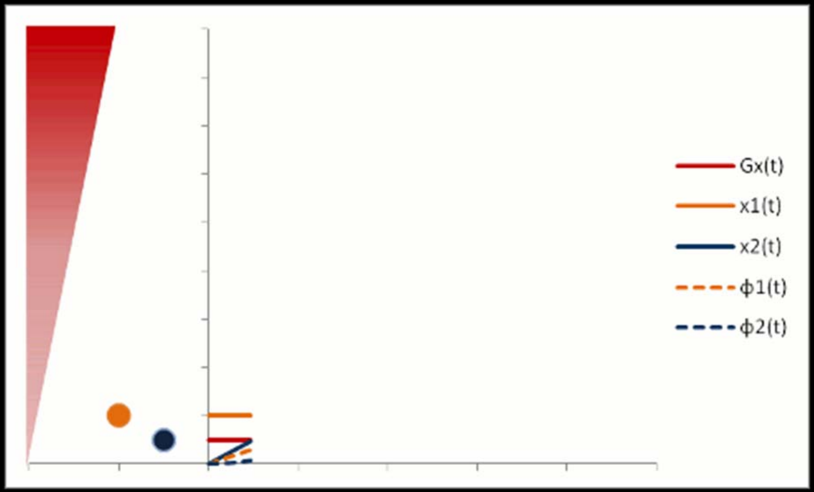


Triple IR Preparation scheme for Oedema imaging

Biglands et al. JCMR, 2012, 14:66

Phase Contrast Angiography

Phase Accumulation over time



Moving (**blue**) and stationary (**orange**) protons in the presence of a constant gradient Gx (**red**)

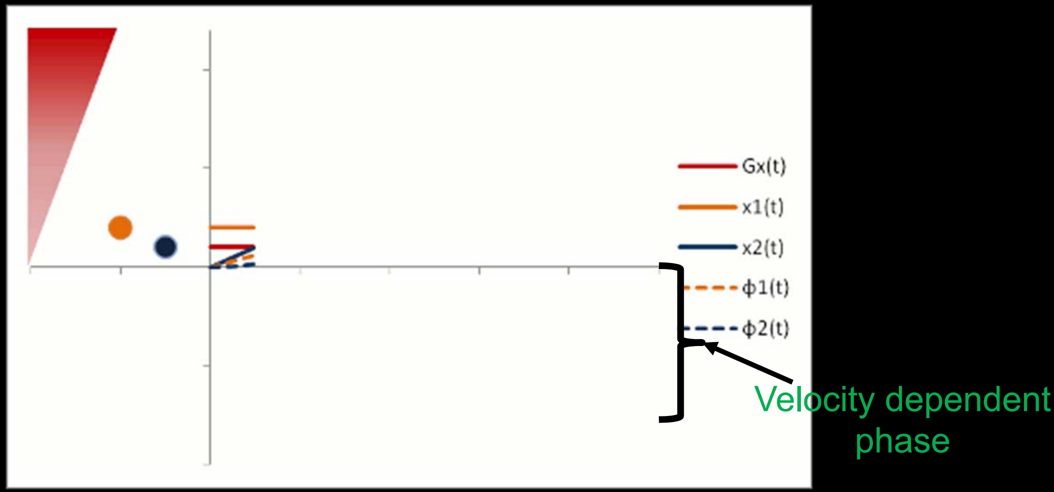
In presence of a gradient (G_x), the phase accumulation (φ) for spins moving with a constant velocity (v_x):

$$\varphi = \gamma G_x v_x \tau^2$$

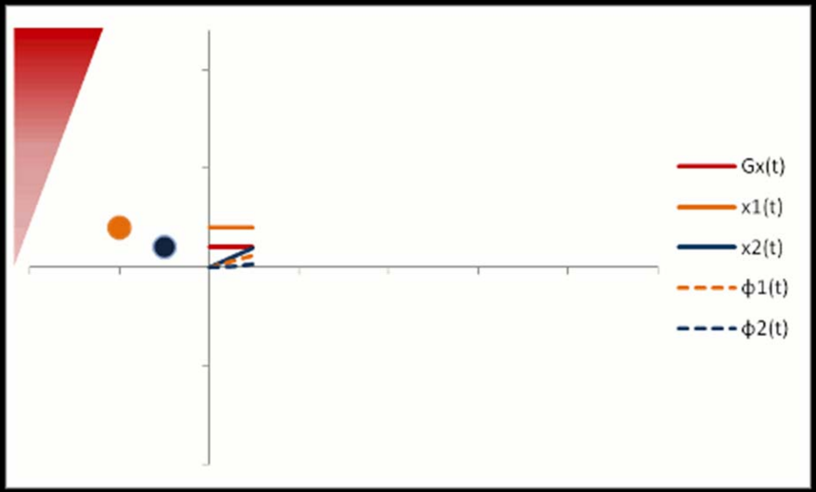
γ = gyromagnetic ratio (constant)
τ = the amount of time the gradient is ON

http://xrayphysics.com/mr_flow.html#frd

Velocity encoding vs velocity compensation



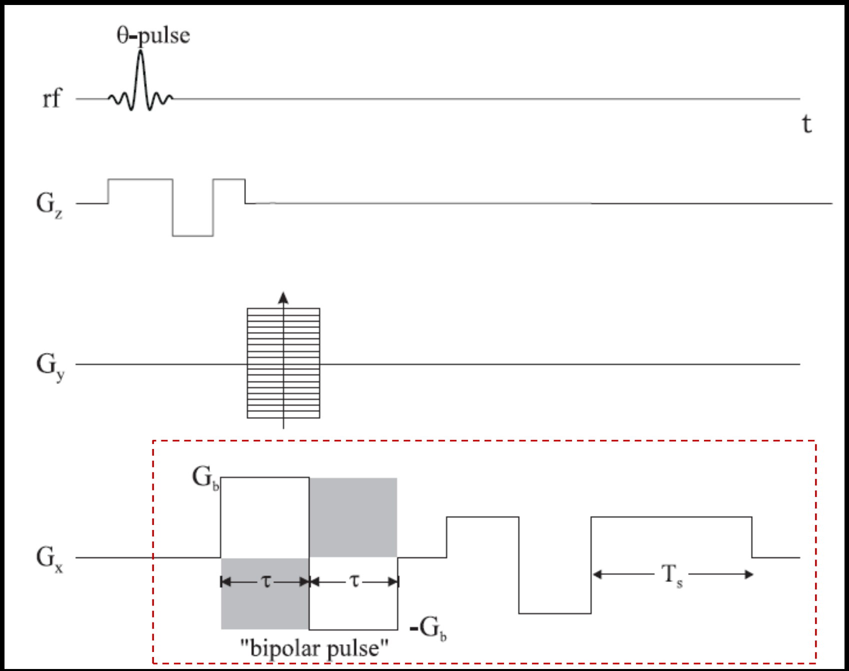
Moving (**blue**) and stationary (**orange**) protons in the presence of the bipolar gradients (**red**)



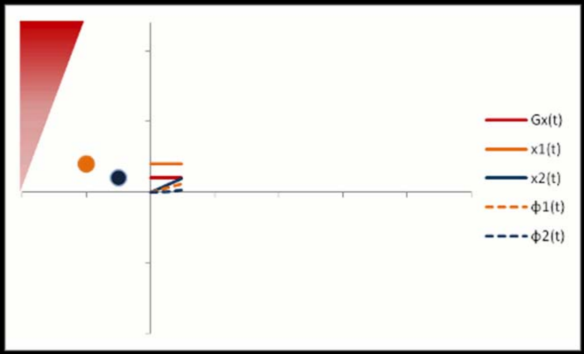
Moving (**blue**) and stationary (**orange**) protons in the presence of the flow encoding gradients (**red**)

http://xrayphysics.com/mr_flow.html#frd

Bipolar Pulses for Velocity Encoding



Introducing bipolar gradients to impart a specific velocity dependent phase <u>followed by a flow-compensated read-out</u>

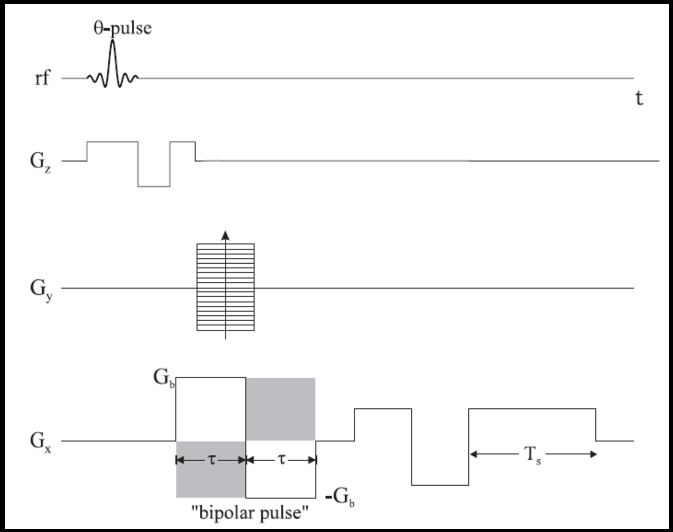


For extracting the flow (in the direction of bipolar gradients), the images are subtracted, which gives us:

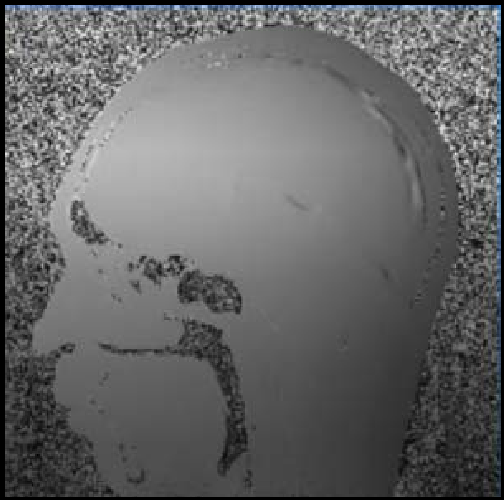
$$\Delta\varphi = 2\gamma G v_x \tau^2$$

This allows us to quantify the velocity (v_x)

Background Removal using a Reference Scan

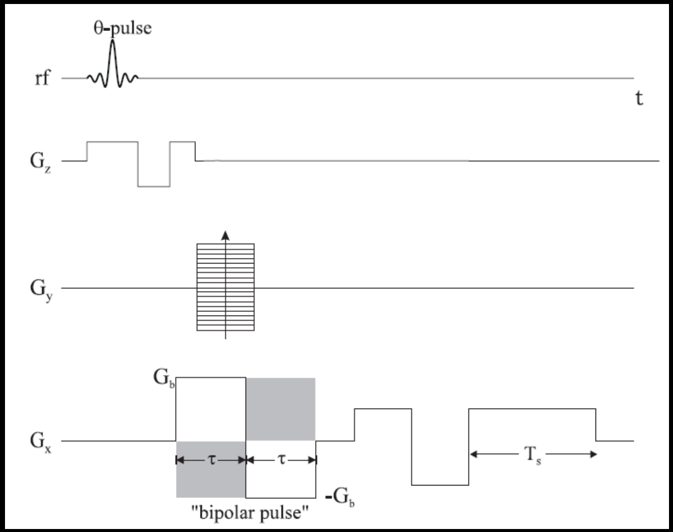


With velocity encoding

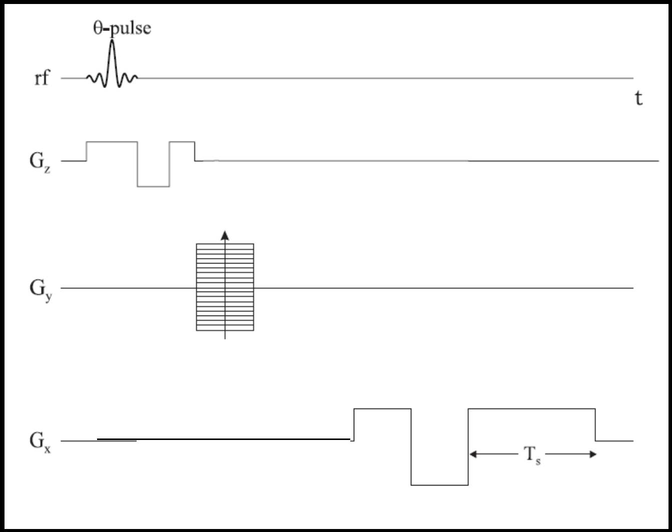


Unknown background phase

Background Removal using a Reference Scan



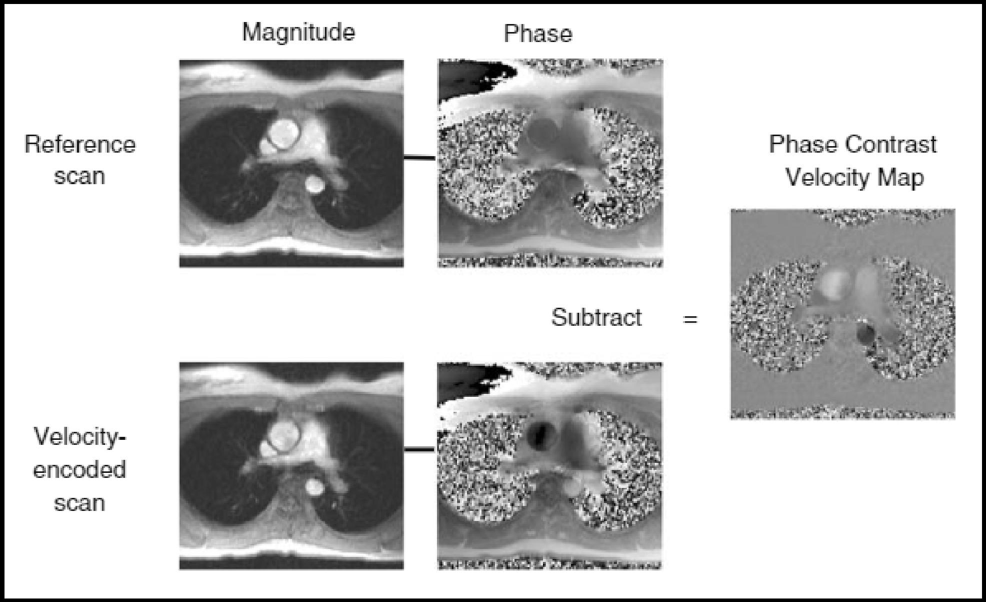
With velocity encoding



Without velocity encoding (Reference)

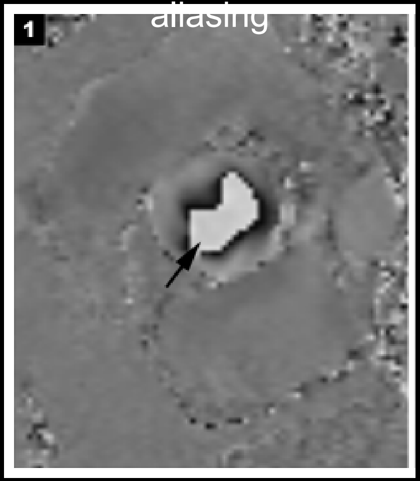
Subtracting an acquisition with and without bipolar pulse removes any background tissue effects and just highlights the moving spins, and along the way provides with a velocity image

Background Removal using a Reference Scan



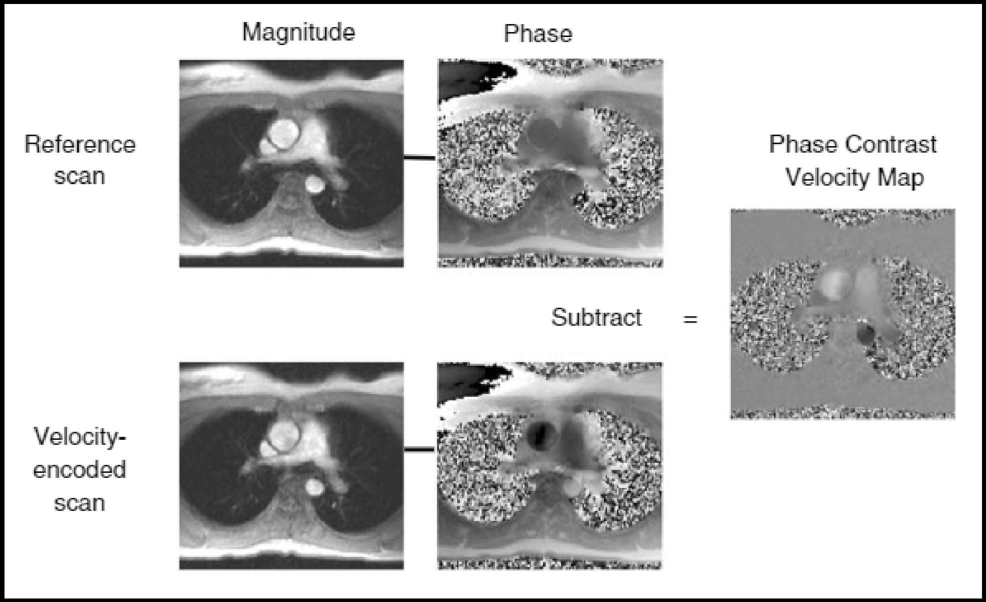
Gatehouse PD *et al.*, Eur Radiol. 2005 Oct;15(10):2172-84.

Practical issue: Phase aliasing



Subtracting an acquisition with and without bipolar pulse removes any background tissue effects and just highlights the moving spins, and along the way provides with a velocity image

Background Removal using a Reference Scan



Gatehouse PD *et al.*, Eur Radiol. 2005 Oct;15(10):2172-84.

If the phase exceeds π, it aliases back to a phase between –π to π

This occurs when the phase due to the bipolar pulse ($\varphi_{bipolar}$) is such that

$$\varphi_{bipolar} = \gamma G v_x \tau^2 > \pi$$

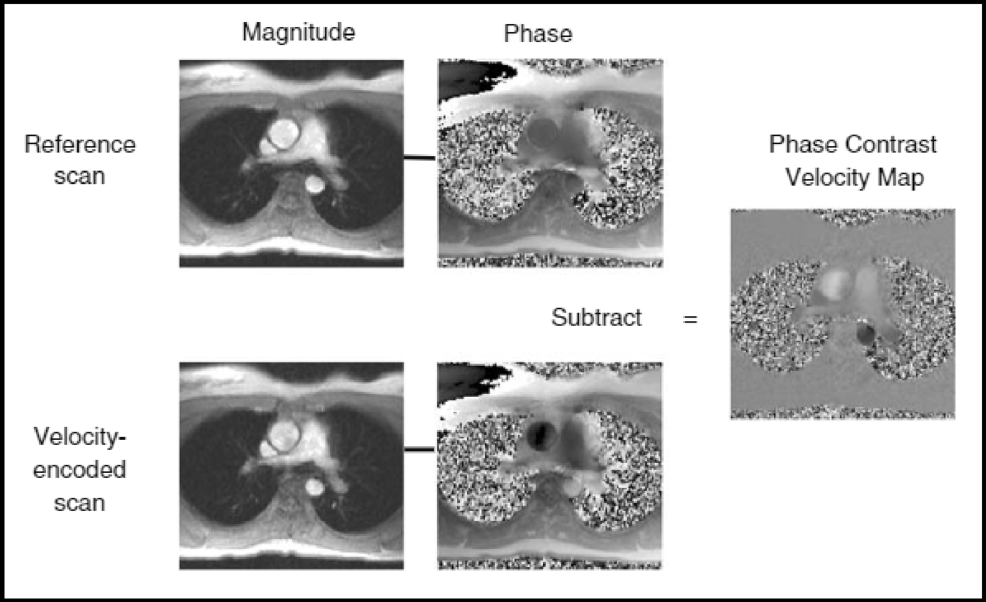
Therefore, we can define v_{enc} as the velocity that produces a phase shift of π radians, where

$$v_{enc} = \pi/(\gamma G \tau^2)$$

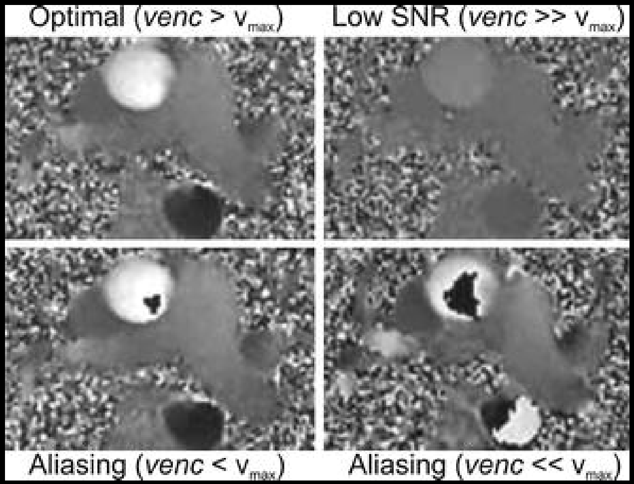
By increasing the v_{enc}, we can increase the velocity limit for phase accumulation without aliasing

$$v_x = \frac{\text{Phase shift} \cdot v_{enc}}{\pi}$$

Background Removal using a Reference Scan

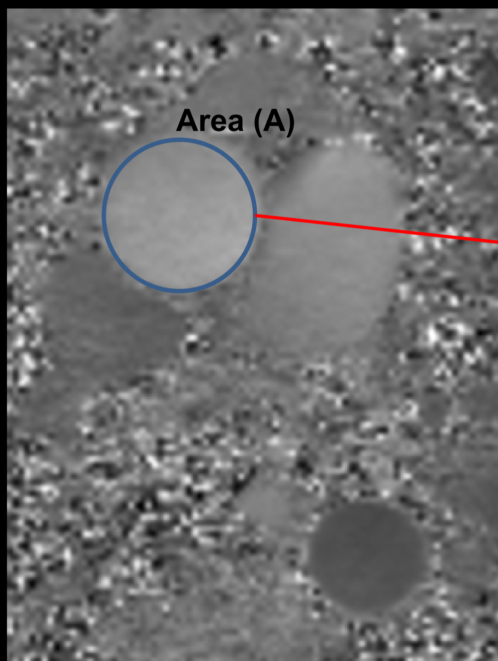


Gatehouse PD *et al.*, Eur Radiol. 2005 Oct;15(10):2172-84.



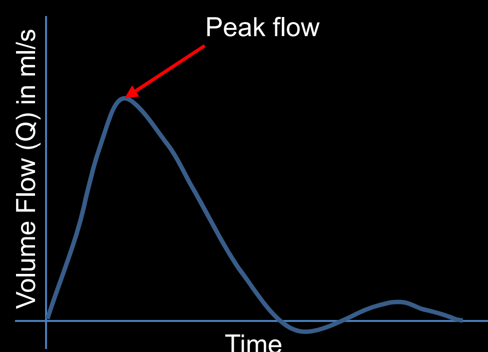
Carr JC, Carroll TJ, Magnetic Resonance Angiography: Principles and Applications. Springer-Verlag, Heidelberg/New York, 2012. 412 pp.

Directional Velocity Encoding

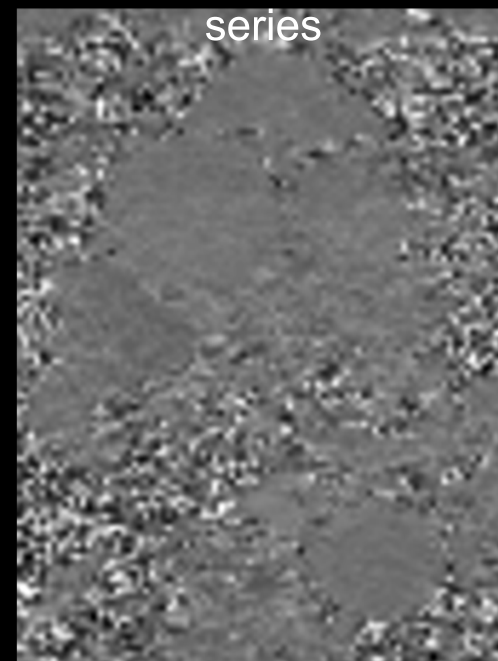


Volume Flow:

$$Q_i = \sum v_{x,i} \cdot A$$

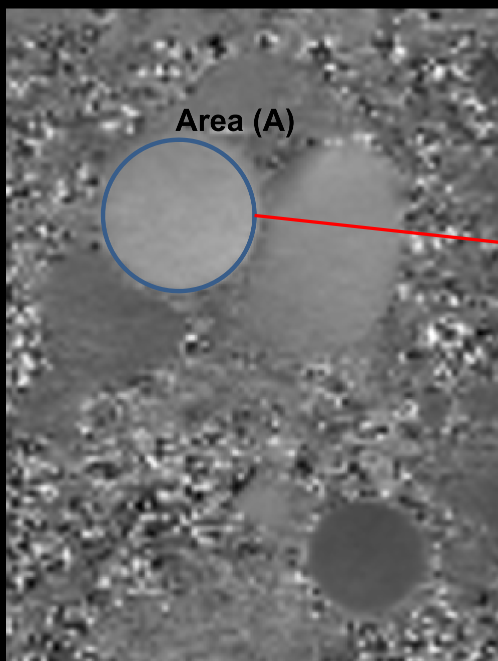


PCA Time series



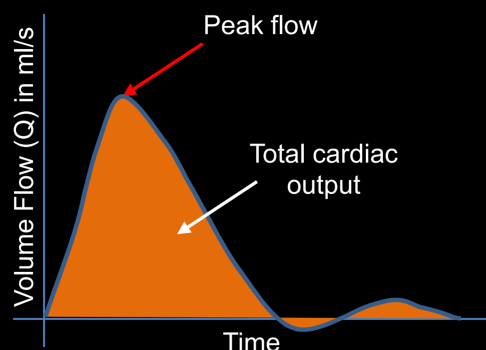
http://www.xinapse.com/Manual/roi_propagate_pwv.html

Directional Velocity Encoding

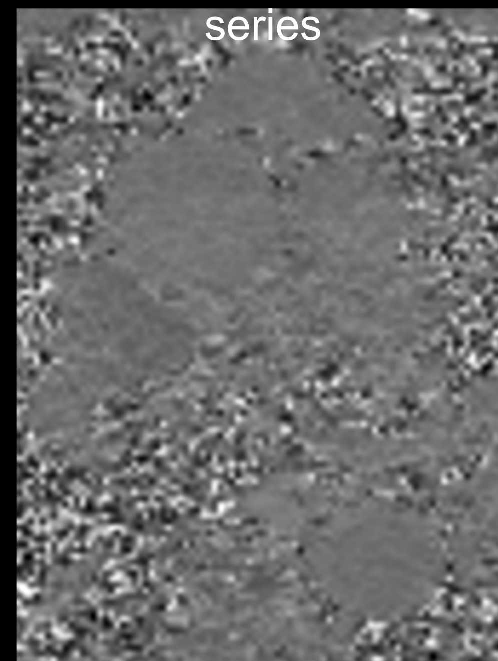


Volume Flow:

$$Q_i = \sum v_{x,i} \cdot A$$

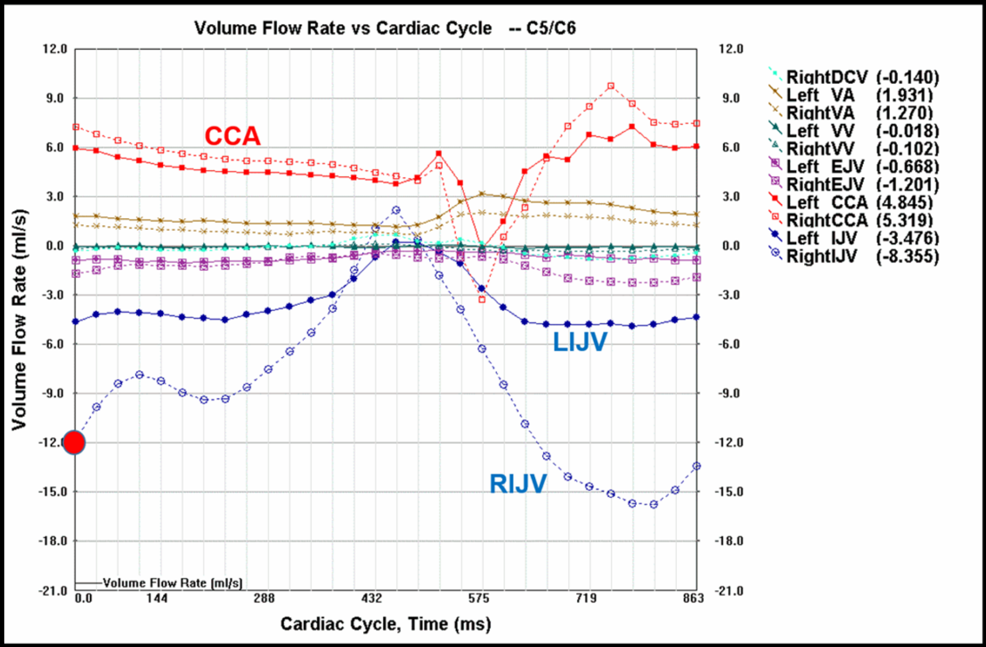


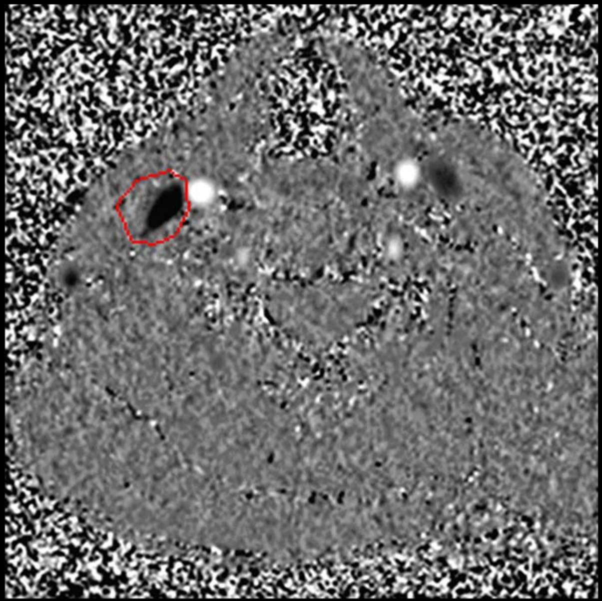
PCA Time series



http://www.xinapse.com/Manual/roi_propagate_pwv.html

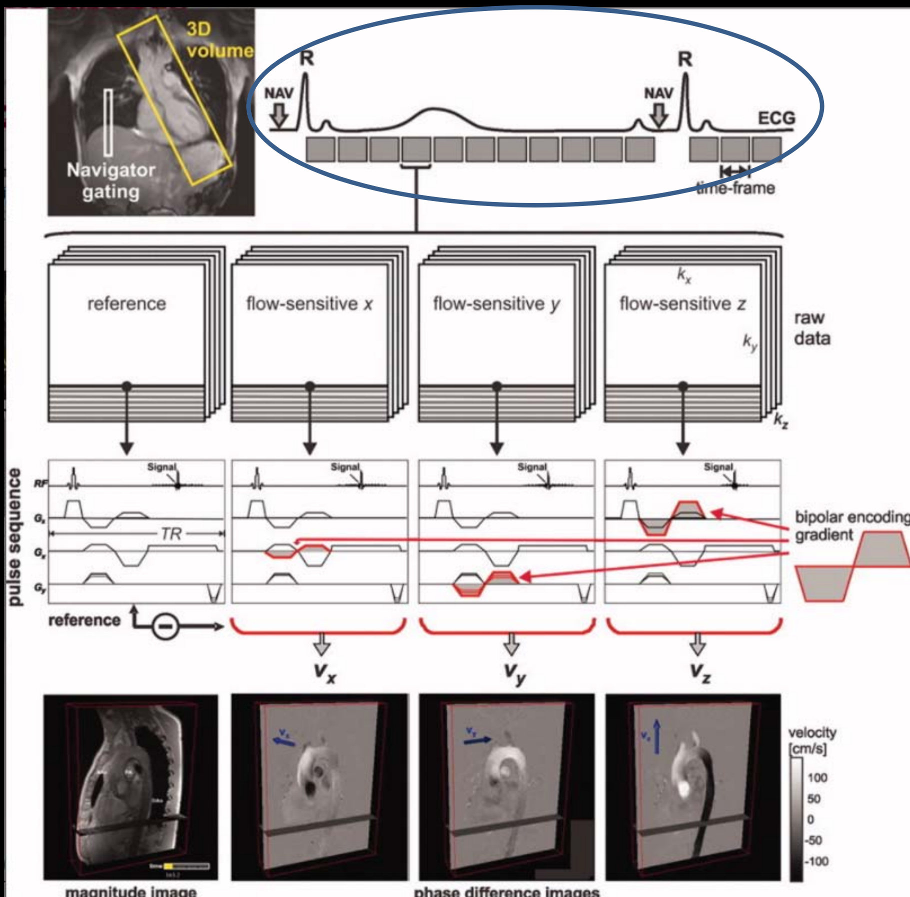
Quantification of Cerebral Blood Supply and Output



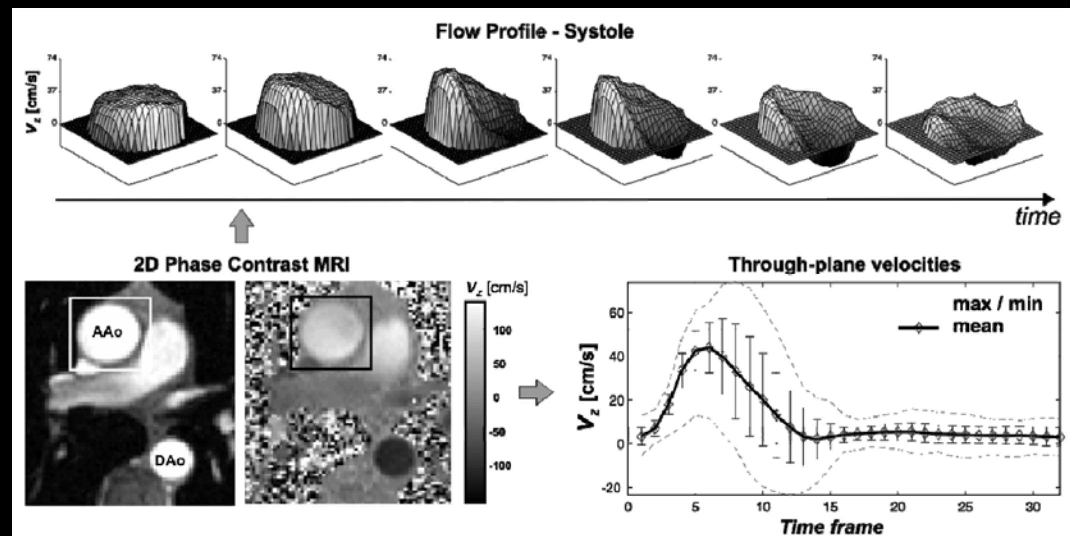


This is performed on one plane, but we can even do this in 3D!

ECG-gated 3D PCA

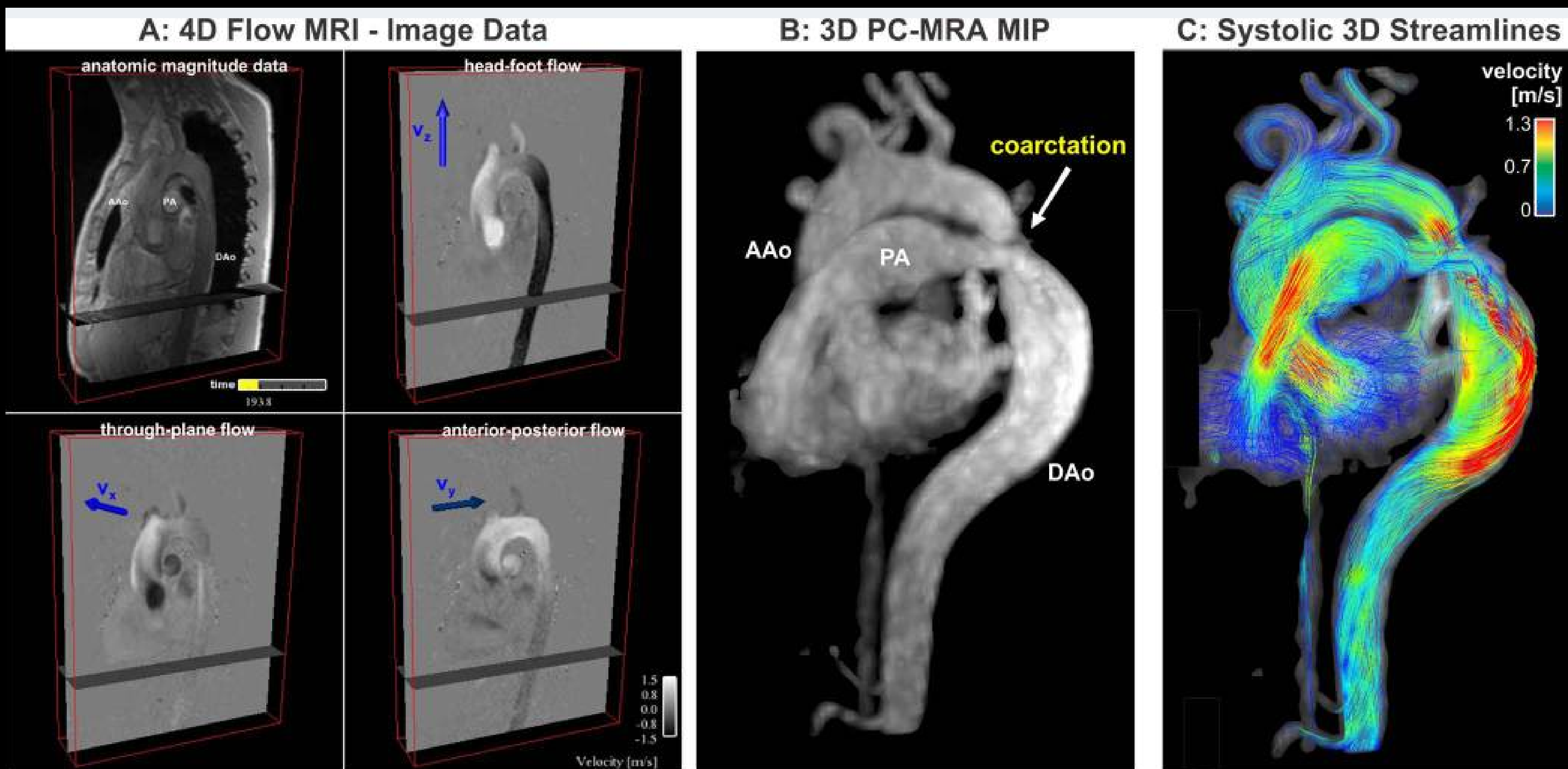


Analysis plane flow profile for 3D projections



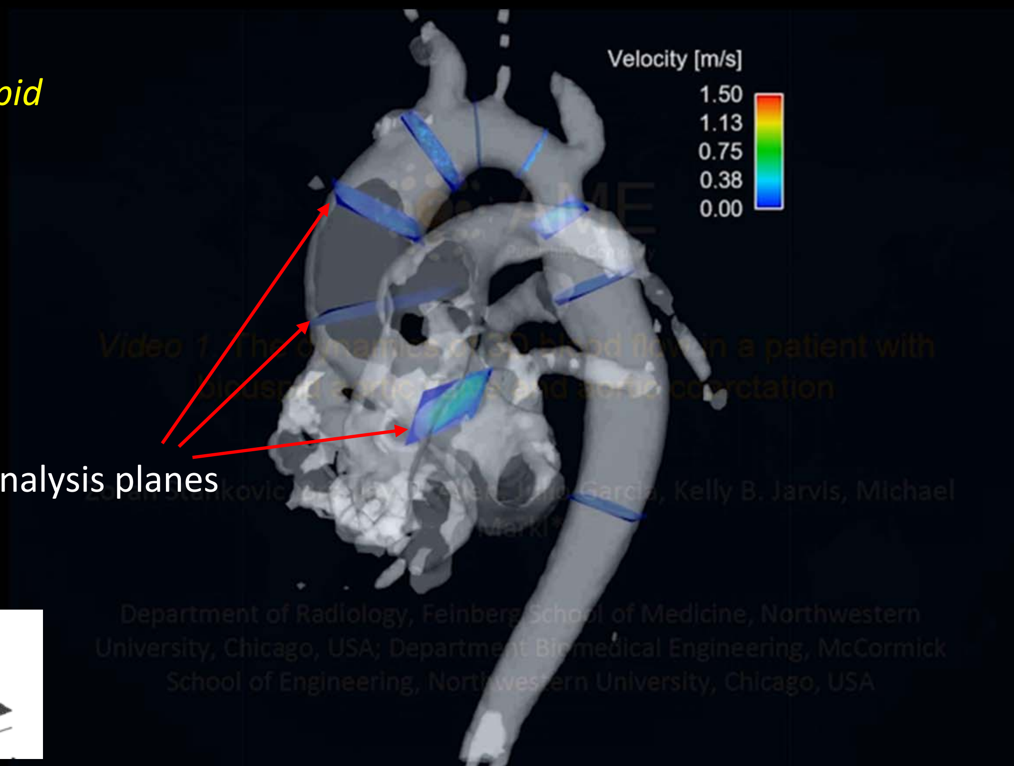
http://ee-classes.usc.edu/ee591/library/Markl-FlowImaging.pdf

Cardiac-gated 3D PCA



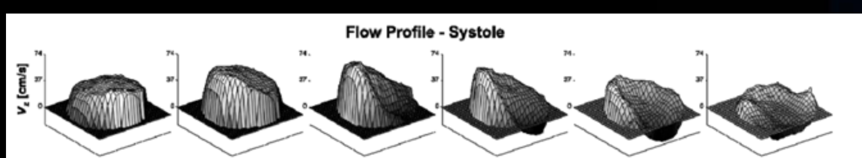
Dynamics of 3D Blood Flow using PCA

Time-resolved streamlines in a patient with *bicuspid aortic valve* and *aortic coarctation (narrowing)*



Analysis planes

Analysis plane flow profile for 3D projections



Stankovic Z *et al.*, *Cardiovasc Diagn Ther*. 2014;4(2):173-192.

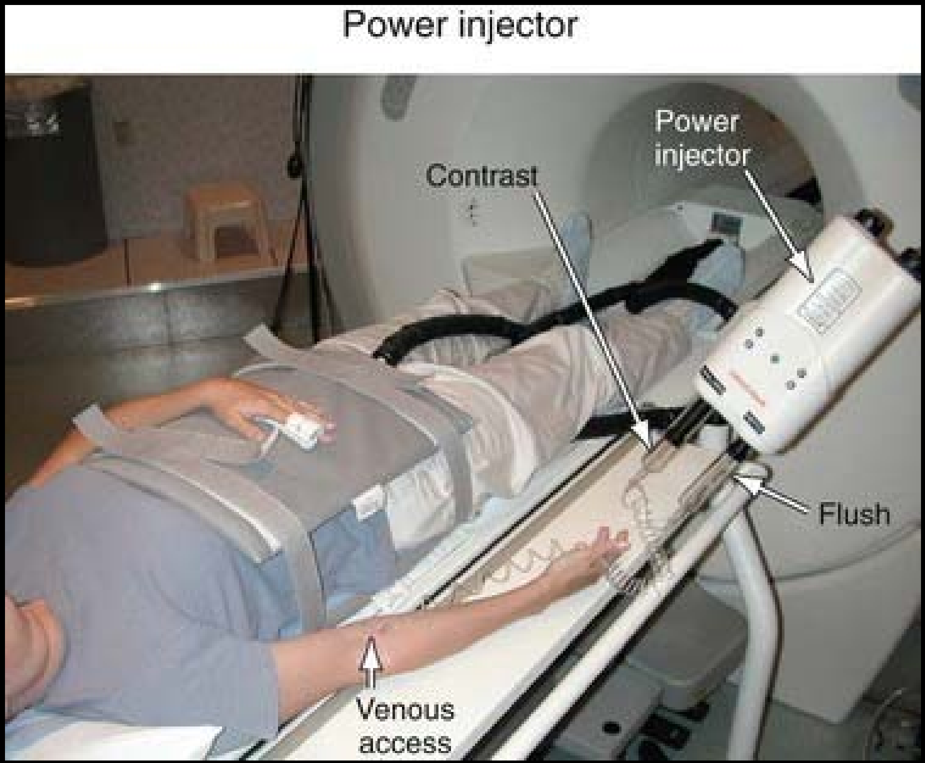
Summary of PC Angiography

- Suppressed background
- Allows acquiring a 2D time-series with high temporal resolution
- Flow quantification
- Direction independent (3D)
- 4D flow MRI:
  - Comprehensive velocity vector field to study cardiac hemodynamics
  - Long imaging time
- Main applications: Cerebral, heart and carotid vessels (2D); and hemodynamic evaluation (such as for congenital heart defects) (3D/4D)

Contrast-Enhanced MRA

Administering Exogenous Contrast Agent

T_1 modifying MRI contrast agent – Gadolinum chelates (Gadoteridol, Gadobutrol, gadodiamide)



https://radiologykey.com/magnetic-resonance-angiography-physics-and-instrumentation/

Effect of Exogenous Contrast Agent on T_1 Relaxation

In case of TOF:

$$\frac{1}{T_{1eff}} = \frac{1}{T_1} + \frac{v}{TH}$$

T_1 modifying MRI contrast agent – Gadolinum chelates (Gadoteridol, Gadobutrol, gadodiamide)

$$\frac{1}{T_{1eff}} = \frac{1}{T_1} + \alpha[c]$$

$[c]$ is the contrast agent concentration
α is the T_1 relaxivity of the contrast agent
≈ 4 L/mmol/sec for Gd

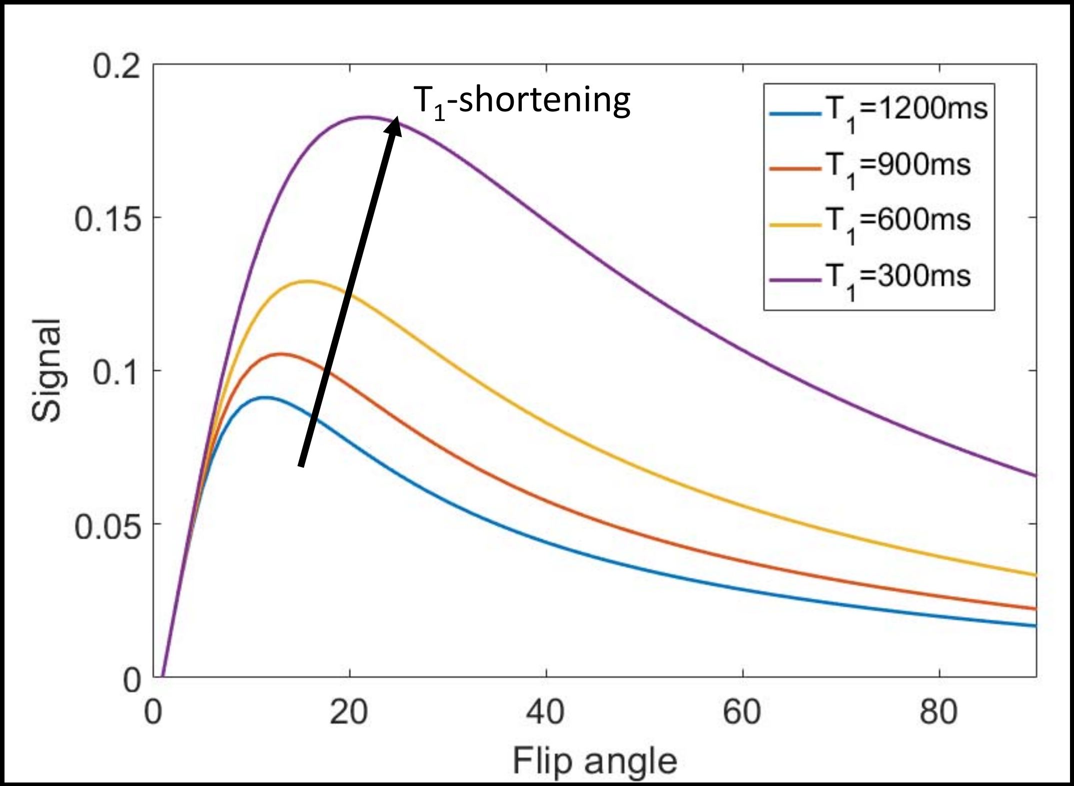
Typical $[c]$ value achieved in a clinical study is 1mM (millimoles/liter)

By estimating the total blood volume in a person through his weight, the amount of contrast to be injected intravenously is calculated. This typically turns out to be 0.1mM/kg

Effect of Exogenous Contrast Agent on T1 Relaxation

Steady-state Signal (m→∞)

$$S(\mathrm{TR}, T1, \theta) = \sin\theta \frac{1-e^{-\frac{\mathrm{TR}}{\mathrm{T1}}}}{1-e^{-\frac{\mathrm{TR}}{\mathrm{T1}}}\cdot\cos\theta}$$



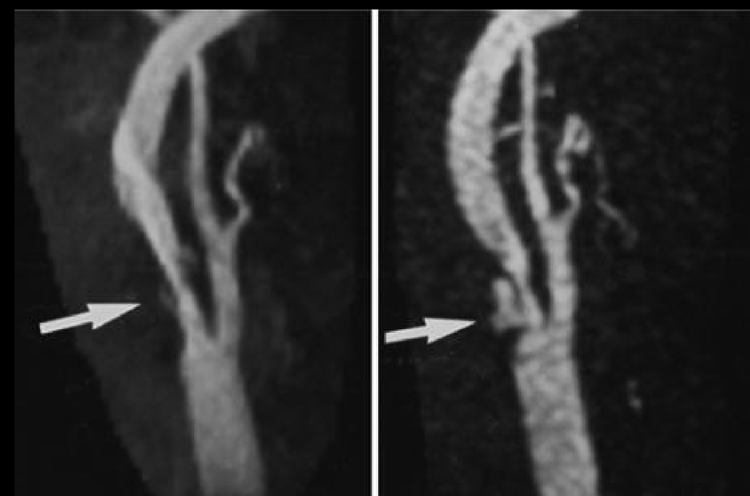
T1-reducing contrast agents play a key role **in** enhancing vascular information

Contrast-Enhanced MRA (CE MRA)

TOF MRA CE MRA

Koktzoglou I *et al. J Cardiovasc Magn Reson* **18,** 18 (2016).

TOF MRA CE MRA

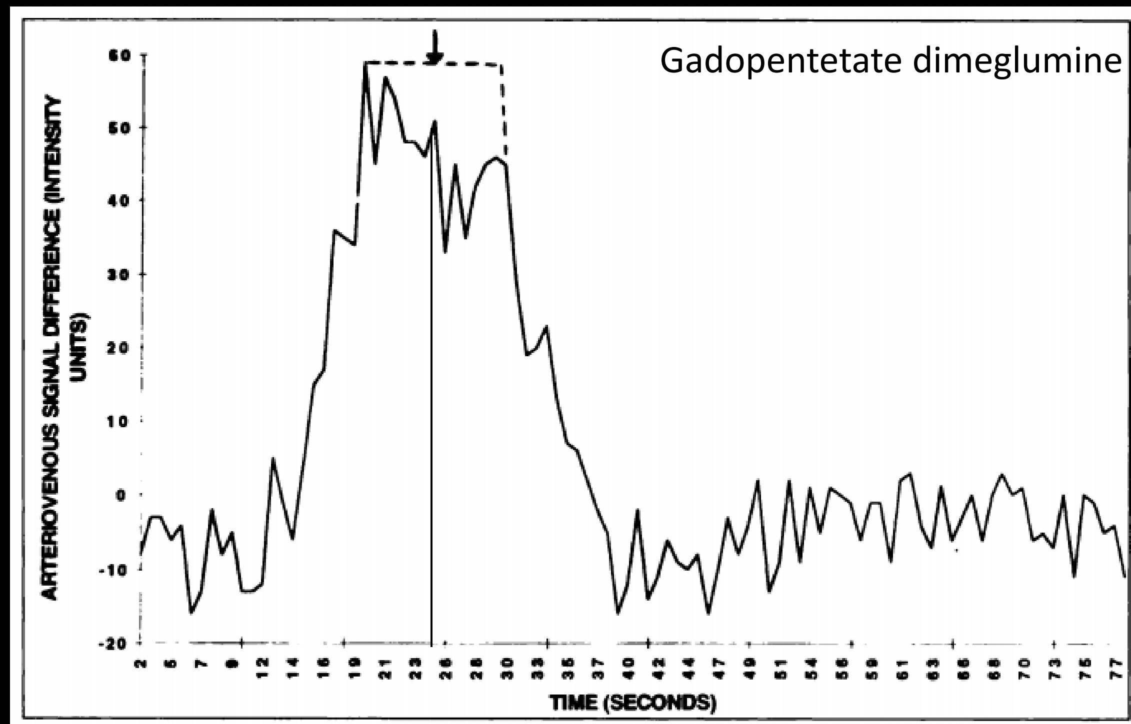


Tong E *et al.*, Neurosurg Focus. 2014 Jan;36(1):E3.

CE MRA provides higher intravascular signal and is independent of saturation due to slow flow or vortex flow

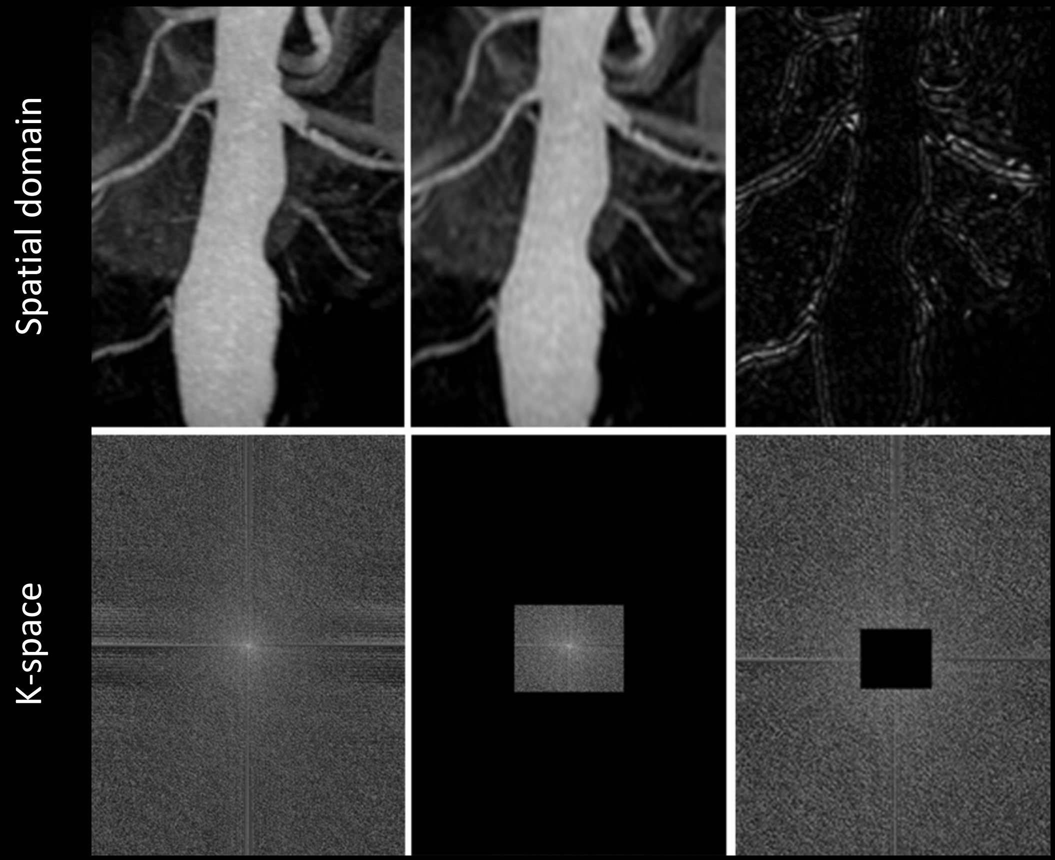
Contrast Bolus: Timing the Acquisition

- 20 sec after the injection => A 10-sec 'window' indicates maximum signal-intensity difference.
- Hence, the imaging must be timed for central k-space to be acquired during midpoint of interval of maximum signal difference



Levy RA, Prince MR. Arterial-phase three-dimensional contrast-enhanced MR angiography of the carotid arteries. AJR Am J Roentgenol. 1996 Jul;167(1):211-5.

Bolus Arrival and Center of K-space



Morelli JN *et al.*, JMRI. 2013 Jun;37(6):1326-41.

- **With only center of k-space preserved:**

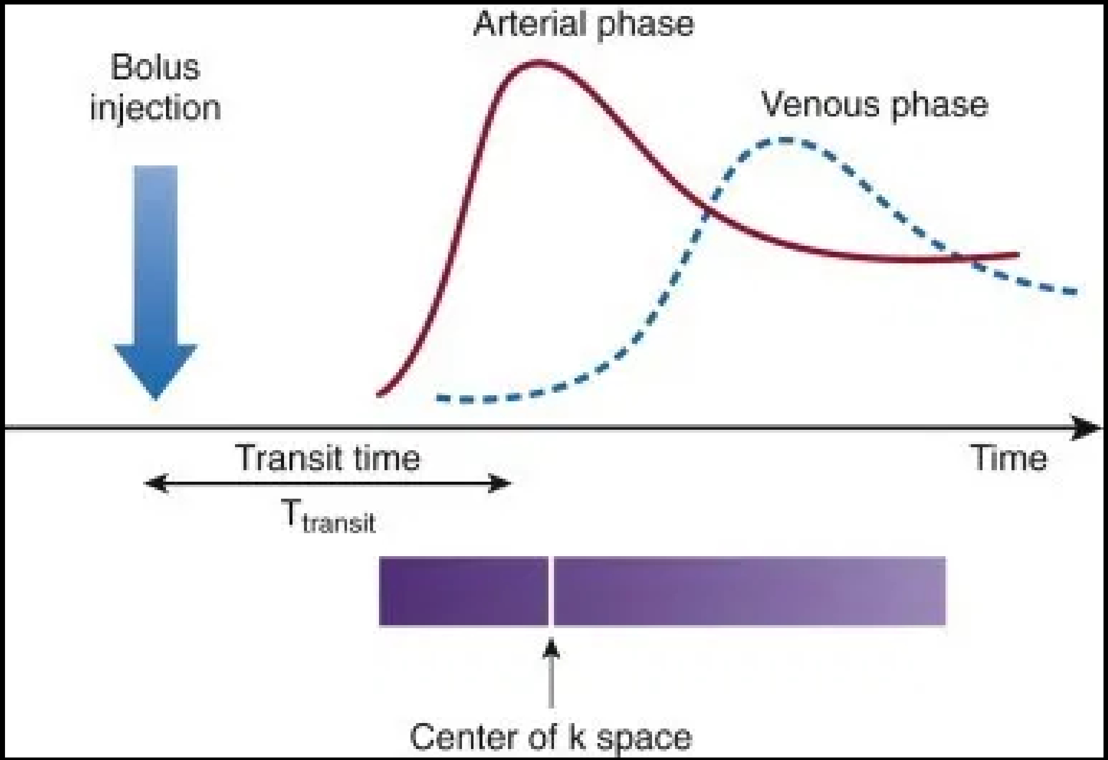
The image is blurry but overall contrast between vasculature and background is preserved

- **With the central elements removed:**

Only the high frequency components (boundaries) are highlighted

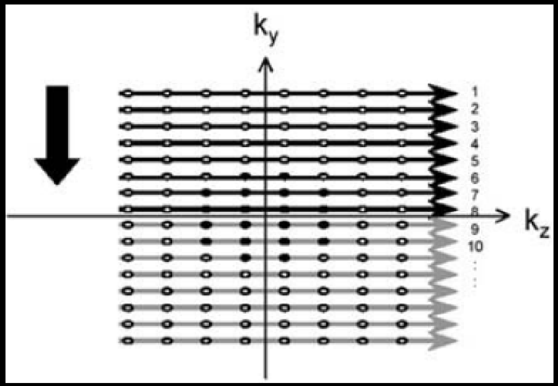
Bolus Arrival and Center of K-space

Arterial depiction relies on the ***synchronization of acquiring the center of k-space with the arterial phase of the Gd bolus***

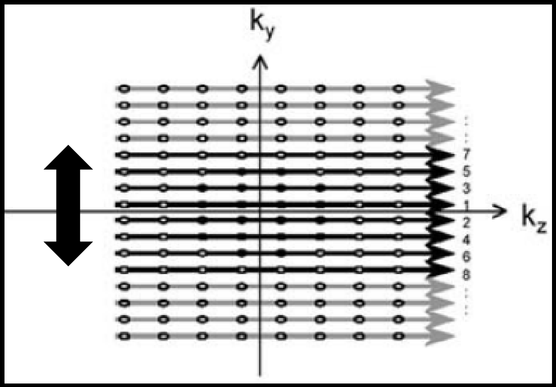


K-space Acquisition Schemes

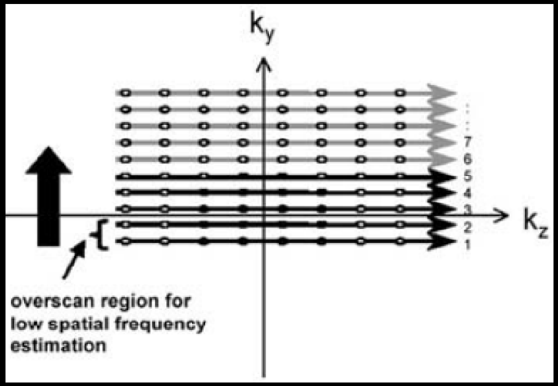
Conventional sequential



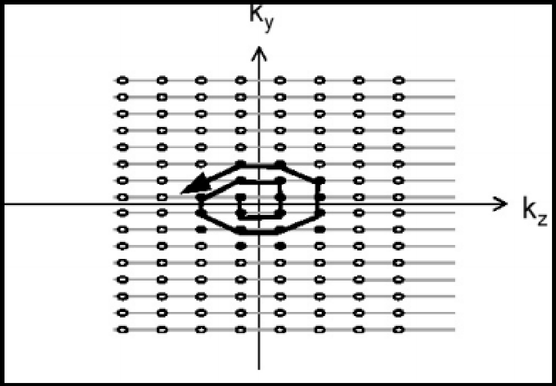
Centric sequential



Partial Fourier reverse sequential

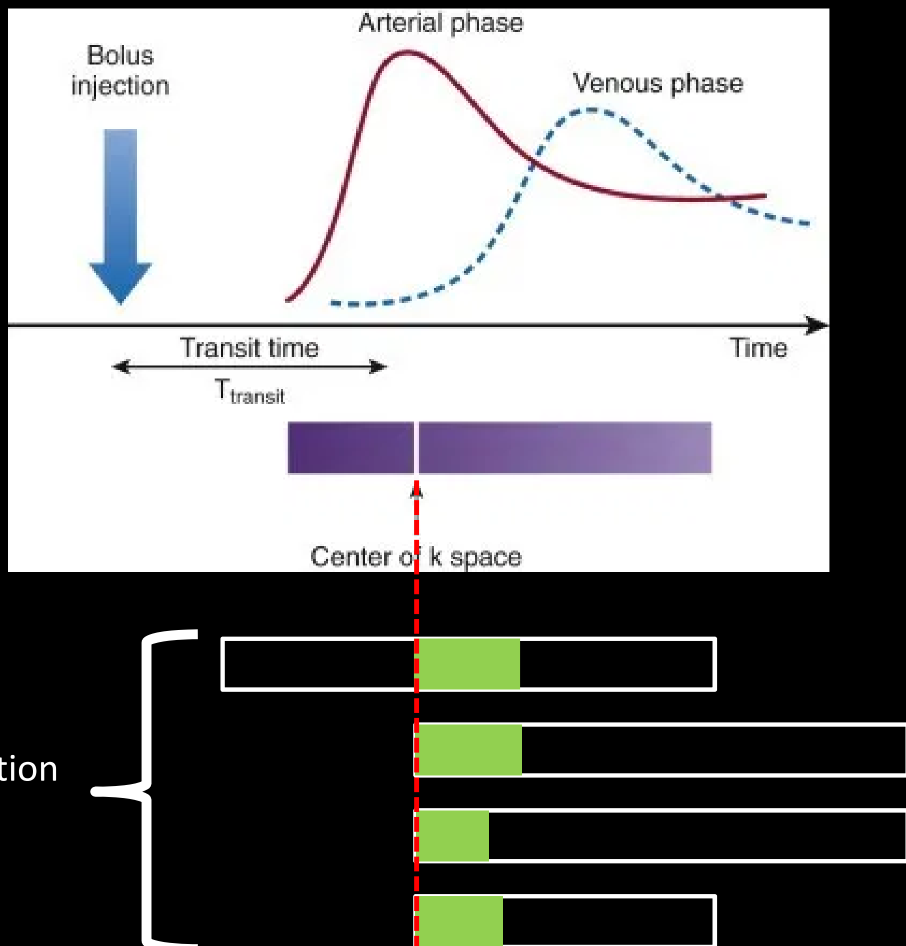


Elliptical centric



Ho VB et al., Contrast-Enhanced MR Angiography: Theory and Technical Optimization. In: Schneider G., Prince M.R., Meaney J.F.M., Ho V.B. (eds) Magnetic Resonance Angiography.

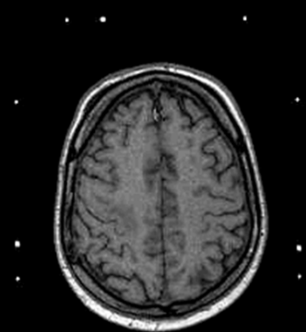
Contrast Bolus: Timing the Acquisition

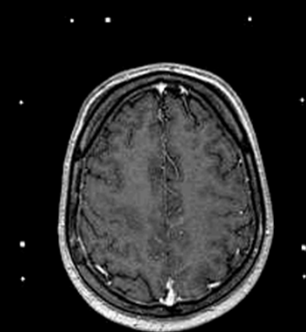


Contrast Enhanced Tumor Imaging (3D T_1 weighted)

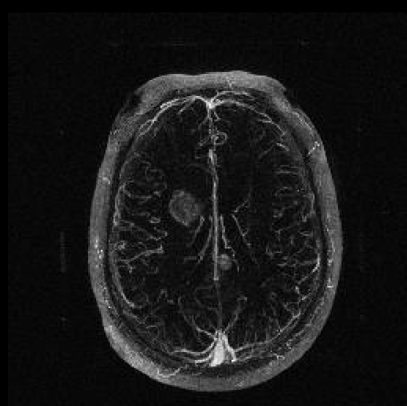
Pre- and post-contrast imaging allows exact subtraction revealing enhanced regions and in some cases even feeding/draining vessels.

Pre-contrast

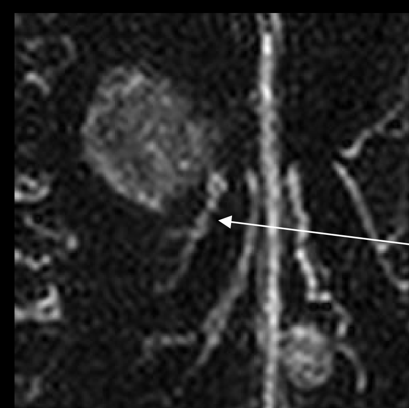




Post-contrast

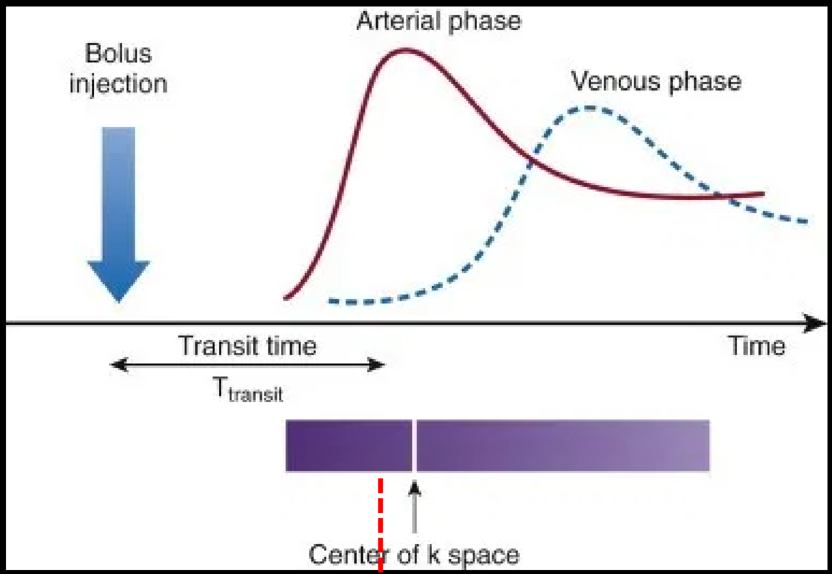


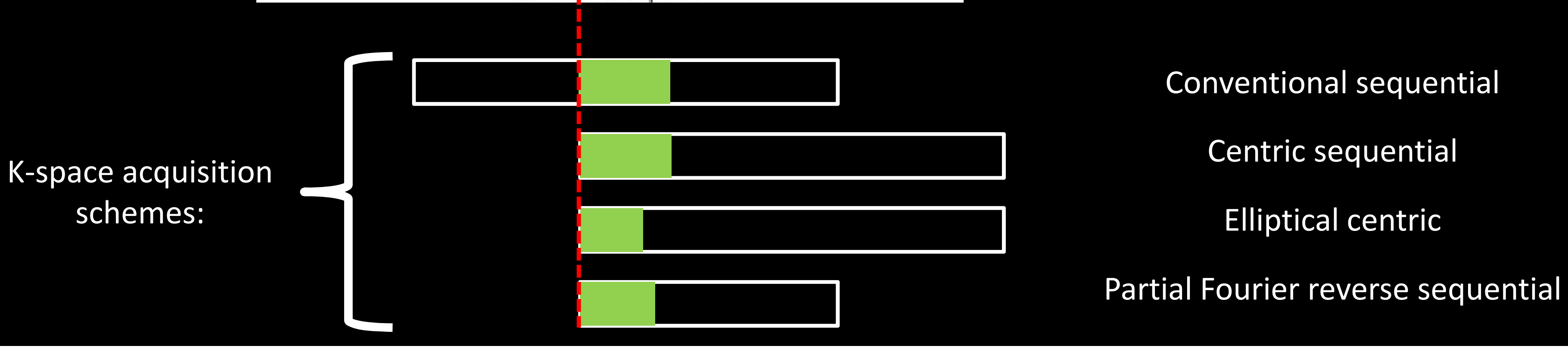
T_1 subtraction maximum intensity projection image



Tumor draining/feeding vessels

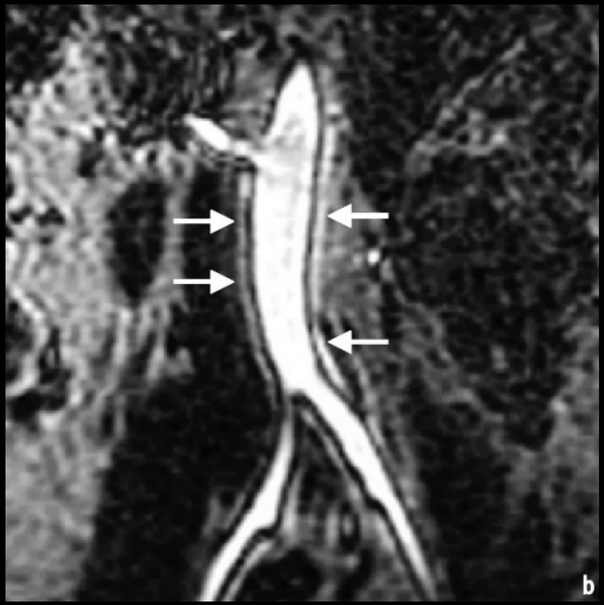
Contrast Bolus: Premature Acquisition





Contrast Bolus: Premature Acquisition

Gibbs Ringing artifact can be caused by the premature acquisition of the central k-space



This artifact can be avoided by obtaining the low spatial frequencies during the plateau phase of the arterial enhancement

Ho VB et al., Contrast-Enhanced MR Angiography: Theory and Technical Optimization. In: Schneider G., Prince M.R., Meaney J.F.M., Ho V.B. (eds) Magnetic Resonance Angiography. Springer, Milano.

Time-Resolved MRA

- CE-MRA approach discussed up to now obtain *a single point* in time after injection

Time-resolved MRA sequences, known under acronyms such as ***TRICKS*** and ***TWIST***, obtain a *<u>series</u>* of images to display the passage of the contrast bolus.

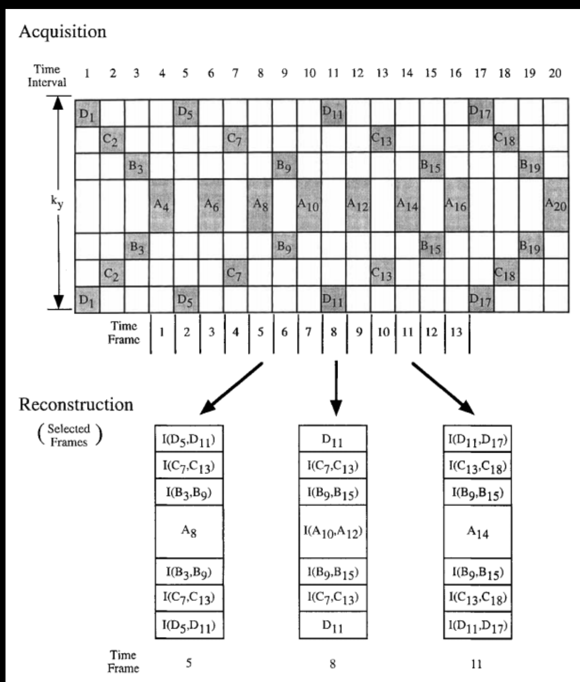
- Typically, 20+ images are acquired (1-2 frames/second)

- An inherent trade-off exists between spatial and temporal resolution

  a. Increasing spatial resolution thus requires that more *k*-space points be sampled
  b. However, sampling more points requires additional imaging time, adversely impacting temporal resolution

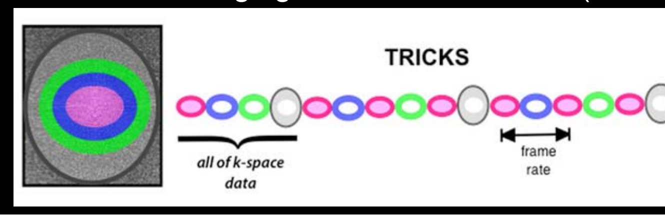
Solution: Use rapid acquisition by temporally sampling different k-space sections in order to reconstruct the time-resolved image sets

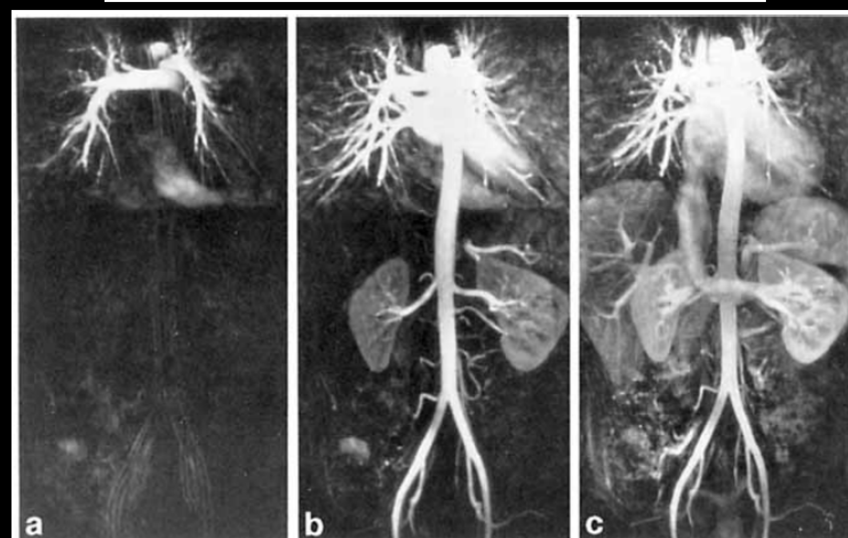
Time-Resolved MRA



Korosec FR *et al.*, Magn Reson Med. 1996 Sep;36(3):345-51.

Time Resolved Imaging of Contrast KineticS (TRICKS)



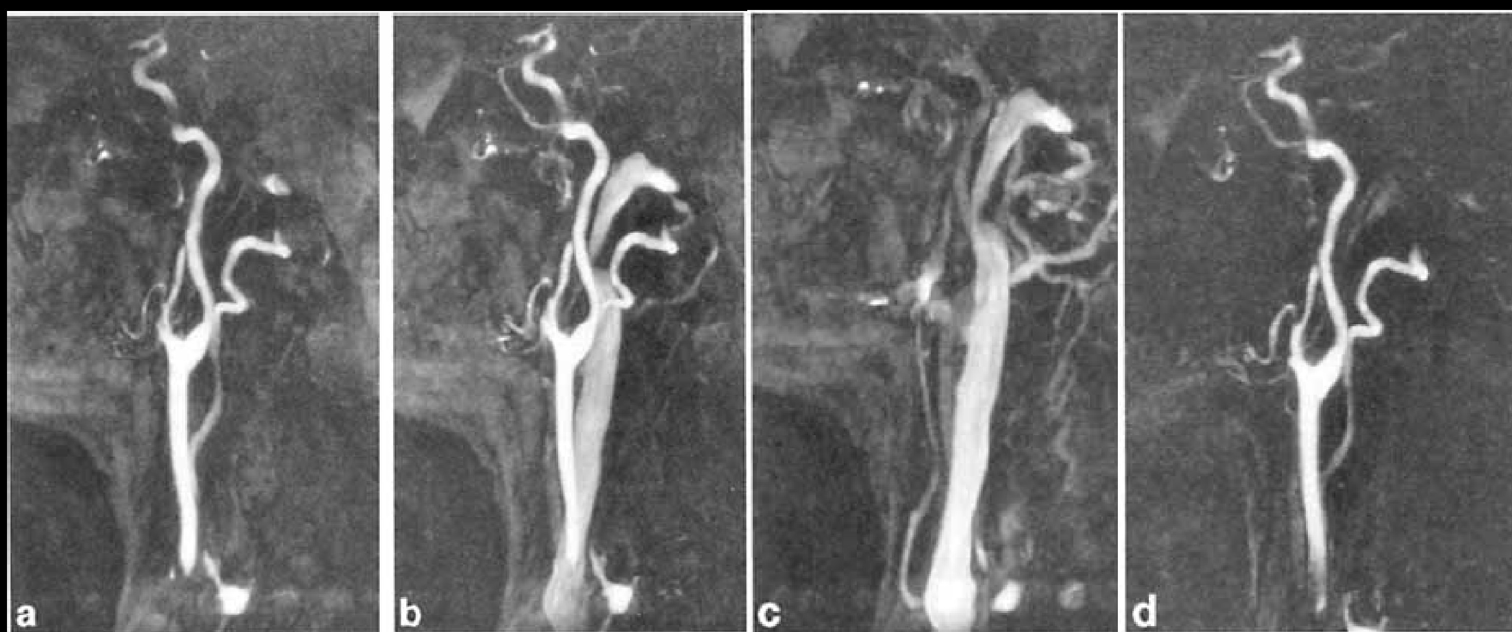


Early Phase
Pulmonary vessels

Intermediate Phase
Aorta and renal arteries

Late Phase
All major vessels (including veins)

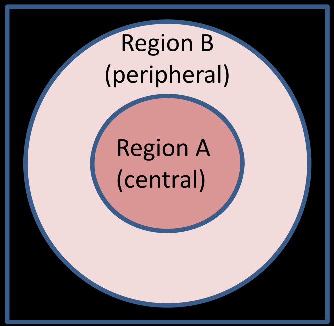
Time-Resolved MRA



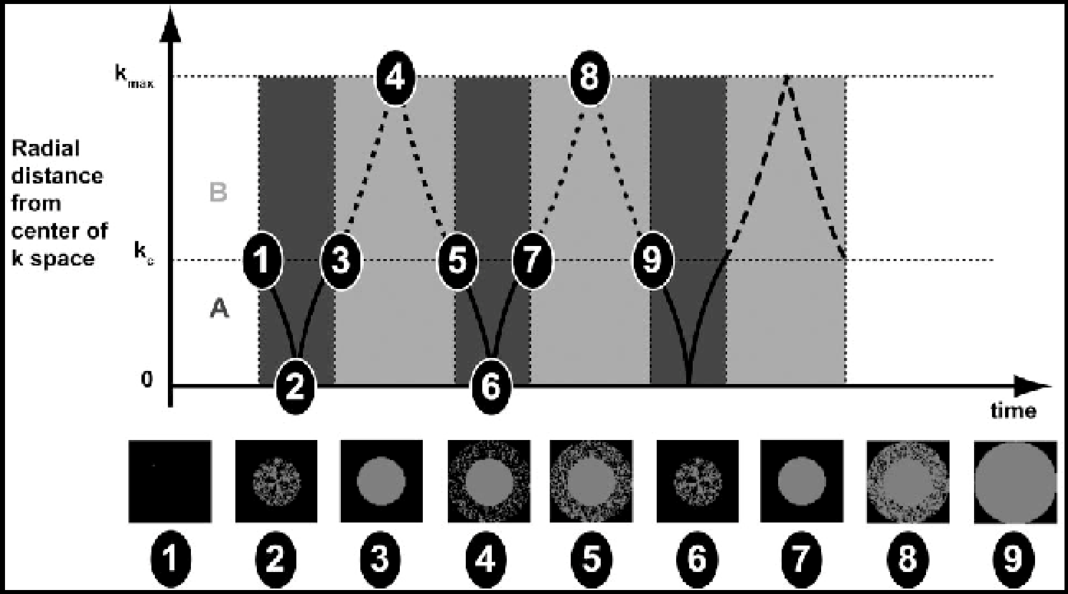
Korosec FR, Frayne R, Grist TM, Mistretta CA. Time-resolved contrast-enhanced 3D MR angiography. Magn Reson Med. 1996 Sep;36(3):345-51. doi: 10.1002/mrm.

Time-Resolved MRA

Time-resolved angiography With Interleaved Stochastic Trajectories (TWIST)



In region B, *a bigger, variable stepping rate* is used as compared to region A



Lim RP *et al.*, AJNR. 2008 Nov;29(10):1847-54.

Results of Dynamic CE-MRA

Time series of Dynamic contrast enhanced imaging used to visualize the time course of contrast agent uptake in the vessels and tissue.

https://www.siemens-healthineers.com/magnetic-resonance-imaging/options-and-upgrades/clinical-applications/twist

Summary of CE-MRA

- Very high SNR
- Robust and insensitive to artifacts such as slow flow, turbulent flow, etc.
- Well established and clinically proven
- Limitations:
  - Requires careful acquisition timing based on arterial-venous window or one can use time-resolved techniques
  - Costs of the contrast agent
  - Invasive
  - Gd-based agents: patients with compromised kidney function => Nephrogenic systemic fibrosis

Summary of MRA Techniques

- MRA helps in evaluate blood vessels, hemodynamics and help identify abnormalities

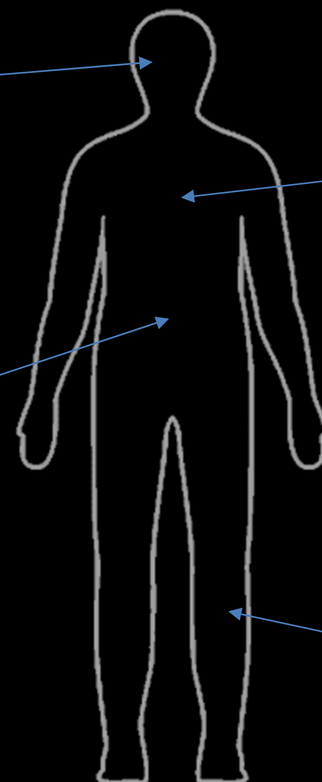
Endogenous (non-invasive):
- Inflow (TOF)
- Motion (Phase contrast)
- Relaxation property (Inversion recovery)

Exogenous:
- Contrast (CEMRA)

- MRA can also be complemented by anatomical scans and quantitative metrics to further strengthen a study

Head and Neck:
Inflow (TOF)
Motion (PCA)
Contrast (CEMRA)

Cardiopulmonary:
Contrast (CEMRA)
Motion (PCMRA)
Inversion recovery



Abdomen:
Contrast (CEMRA)
Inflow (TOF)

Peripherals:
Inflow (TOF)
Contrast (CEMRA)
Motion (PCMRA)

Any questions?

See you next Wednesday!

MICRO Imaging

SWI
(Dark blood MRV)

Ferumoxytol enhanced
SWI