Magnetic Resonance Angiography

Course: Advance MRI (BIOE 594)

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Overview

Magnetic Resonance Angiography (MRA)

1. Black Blood Angiography.
2. Bright Blood Angiography.
3. Phase Contrast MRA. (PC)
4. Contrast- Enhancement MRA (CEMRA).

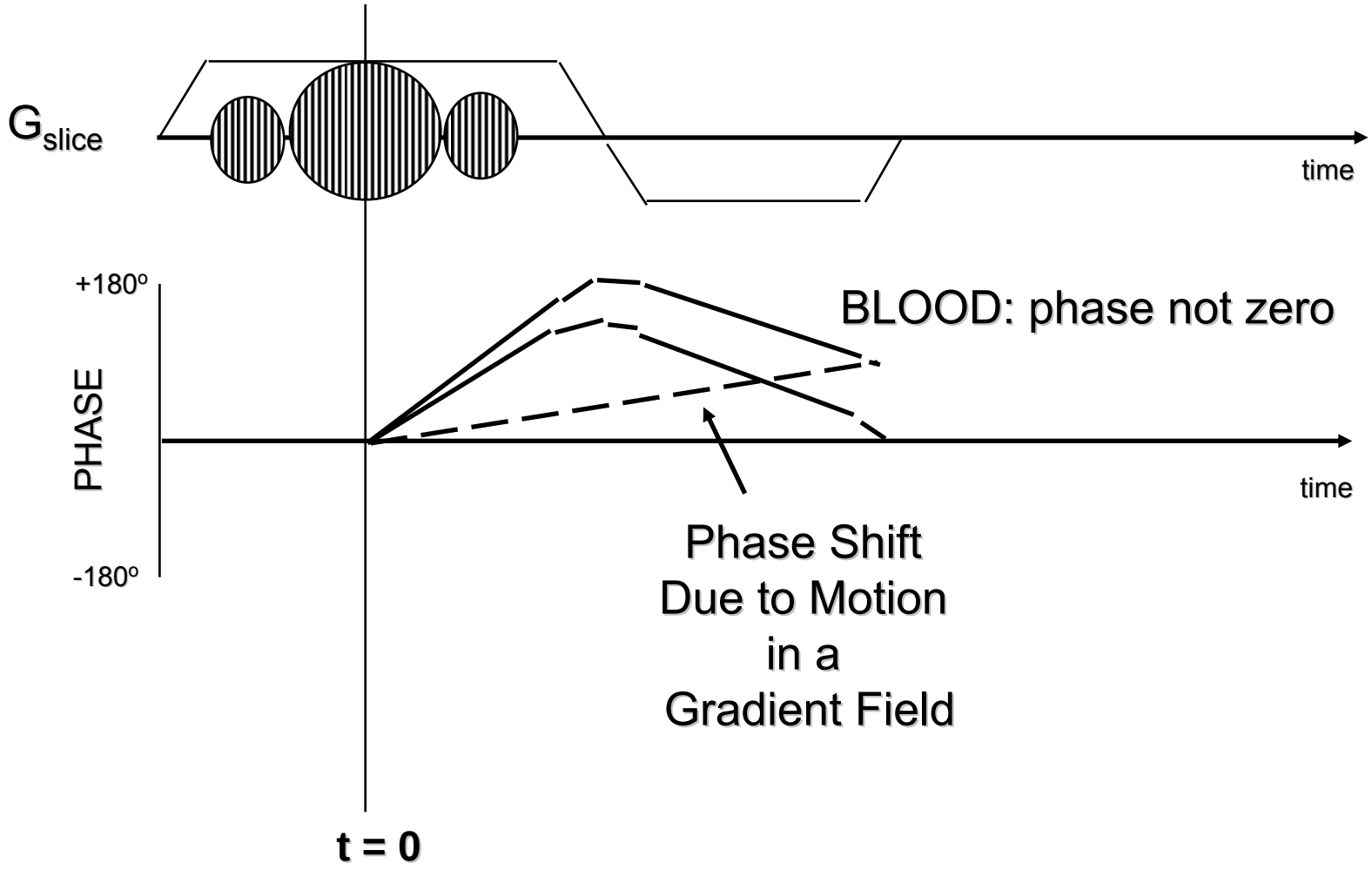
Phase Contrast

- Flow induced Phase Shift Phenomena
- Methods of Phase Sensitive Angiography
  - Incoherent phase sensitive methods.
    - Two images during systole and diastole.
    - Subtraction of the two images to obtain angiogram.
    - Another, Subtraction of Flow compensated and flow noncompensated images
  - Coherent phase sensitive methods.
    - Use of Flow encoding Bipolar gradients to obtain angiogram images.
    - Use of Phase-difference or complex difference methods.

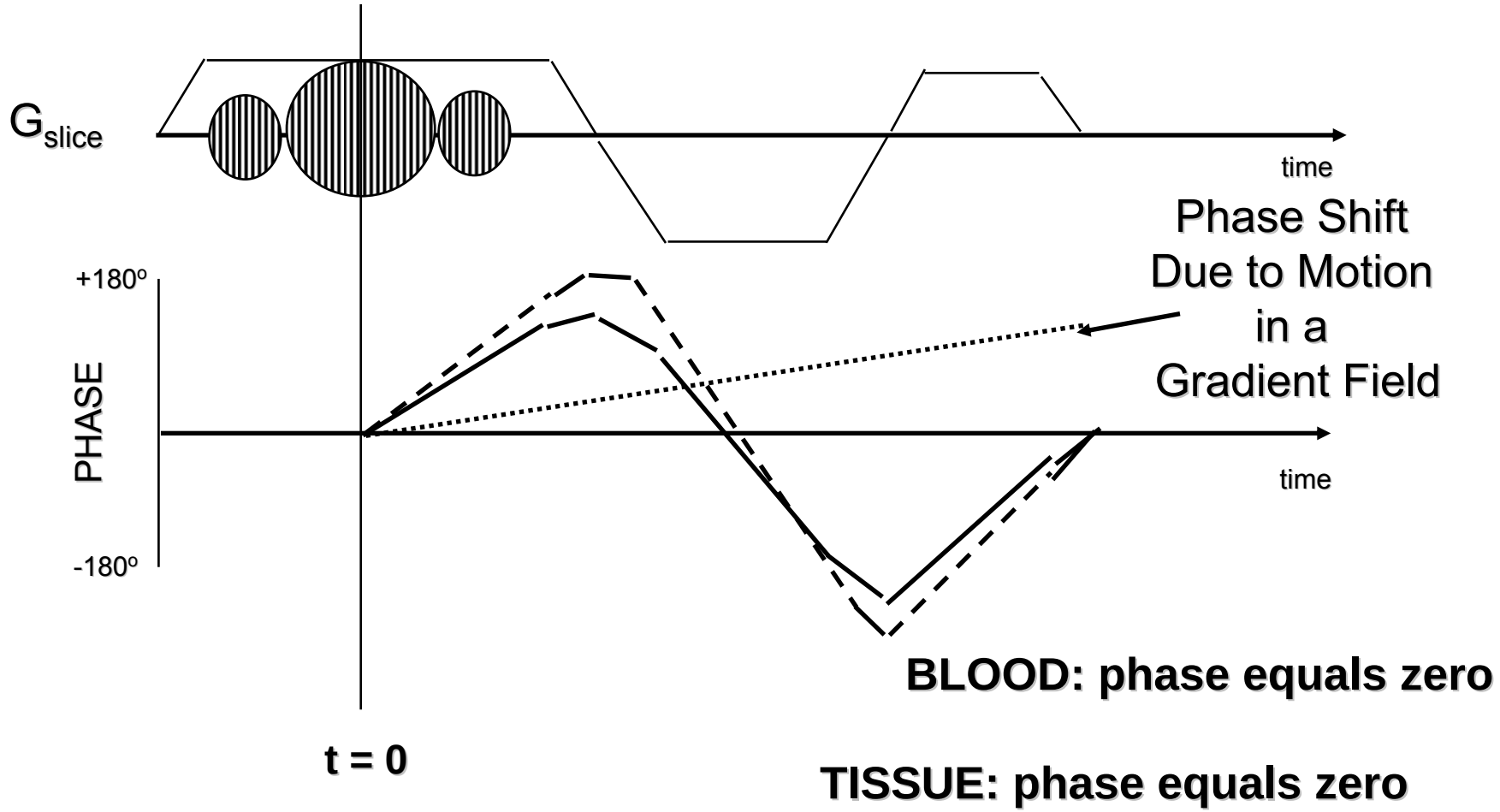
Phase Contrast Contd..

- 2D and 3D PC Angiography.
- Multiplexed Flow Encoding.
- Comparison of PCMRA and TOF angiography.

Dephasing Due to Motion



Motion Compensation Gradients



Motion Artifacts

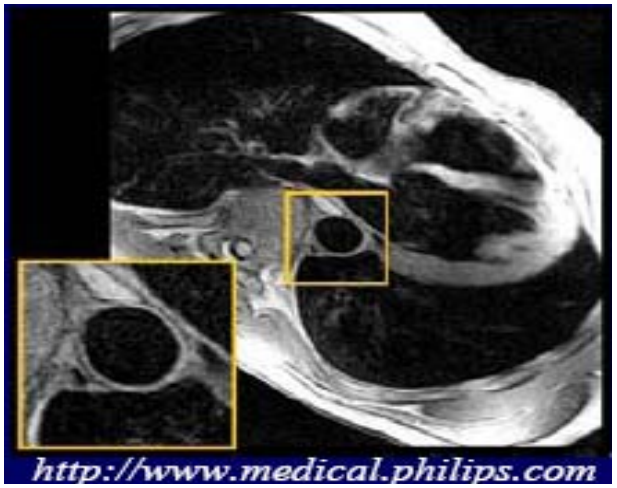
- in read-out direction
  - data acquired in time short compared to motion
  - blurring of edges
- in phase-encode direction
  - ghosting presenting as lines & smudges
- in slice-select direction
  - variable partial volume, difficult to detect

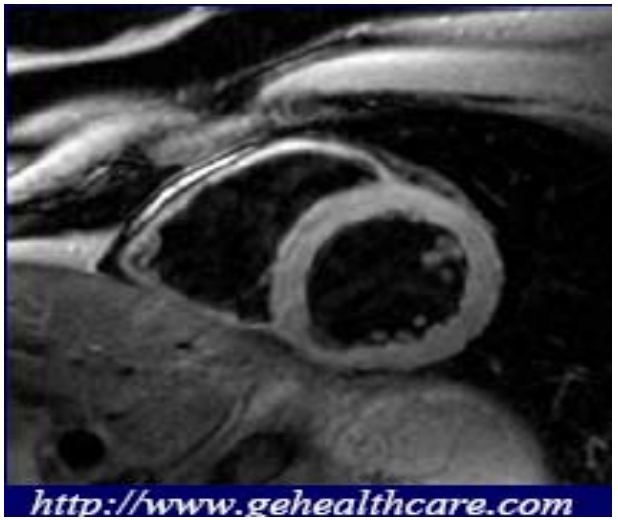
Flow Artifact Correction

- Spatial pre-saturation pulses prior to entry of the vessel into the slices
- Surface coil localization
- Shortened pulse sequences
- Cardiac & respiratory gating
- Motion Compensation Gradients

Black Blood Angiography

- As the name suggests, blood is seen dark as compared to other tissues.
- It is mainly used where TOF and PCMRA cannot be used.
- Mainly in distinguishing signal between fat and blood adjacent.





Black Blood Angiography (Contd..)

Methods:

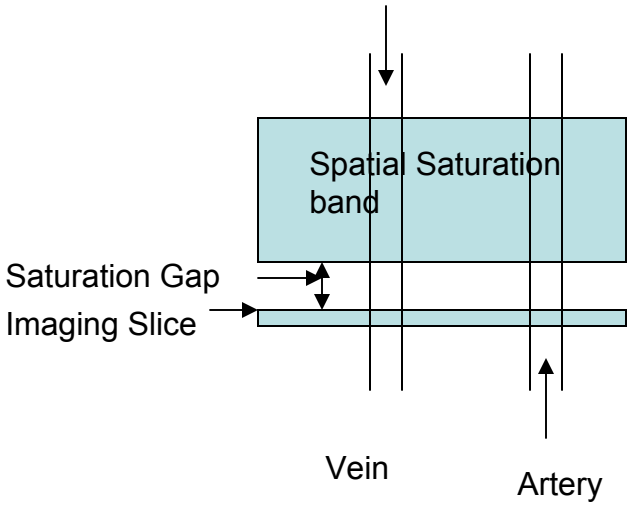
1. Spatial Saturation.
2. Spin Echo and RARE.
3. Inversion Recovery.
4. Preinversion Segmented turbo FLASH (PRESTO).

Black Blood Angiography (Contd..)

1. Saturation
   - Spatially selective 90^0 RF pulse.
   - Unlike excitation and refocusing spatial saturation pulses should have minimum transverse magnetization as possible.
   - RF pulse can be designed to produce phase dispersion and also spoiler gradient pulse is followed.
   - Before the magnetization recovers the saturation pulse is followed by the imaging sequence.

Black Blood Angiography (Contd..)

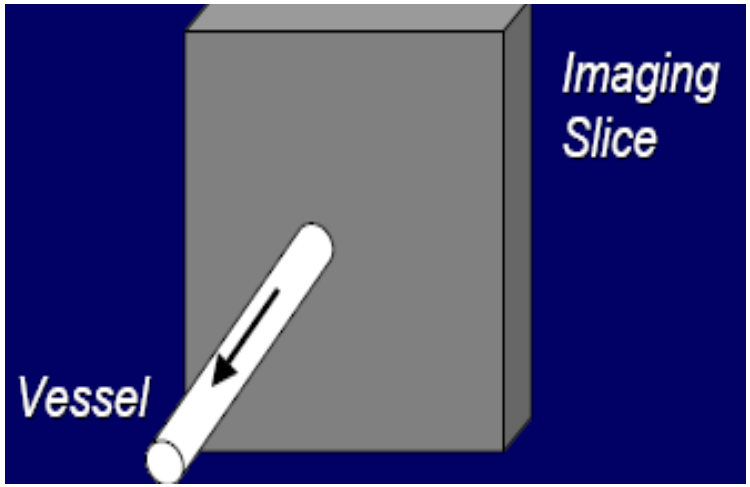
- Saturation band and the image slice are in the same plane.
- The position of the band depends on the type of flow to be saturated.
- To saturate venous flow in neck the saturation volume will be placed superior to the imaging slice.



Black Blood Angiography (Contd..)

SE and RARE

- Any pulse sequence with atleast one 180 refocusing pulse.
- Outflow of blood from the imaging slice in between 90 and 180 pulse.
- Time between 90 and 180 which is TE/2.
- Thus for complete outflow of blood from the slice, the velocity component perpendicular to the slice



$$v_{\perp} = \frac{2\Delta z}{TE}$$

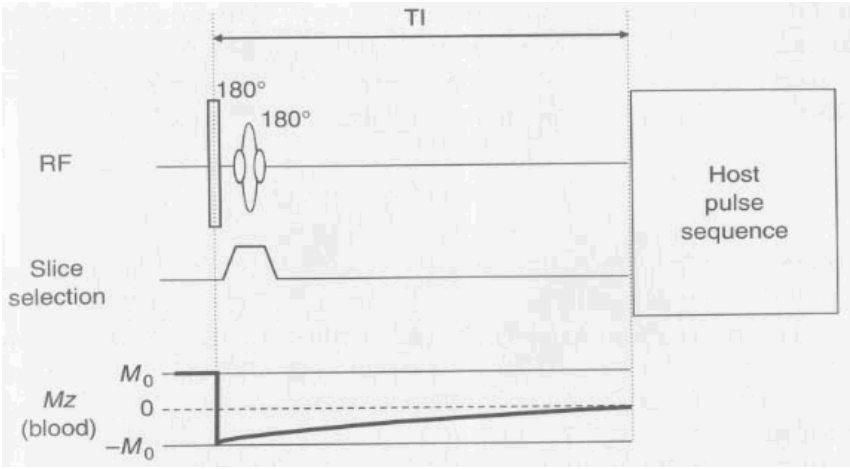
Black Blood Angiography (Contd..)

- For dual echo

$$v_{\perp} = \frac{2\Delta z}{TE_1 + TE_2}$$

Black Blood Angiography (Contd..)

3. Inversion Recovery Black Blood Method.
   - Invert longitudinal magnetization.
   - Image after a time TI so that magnetization recovers to zero.



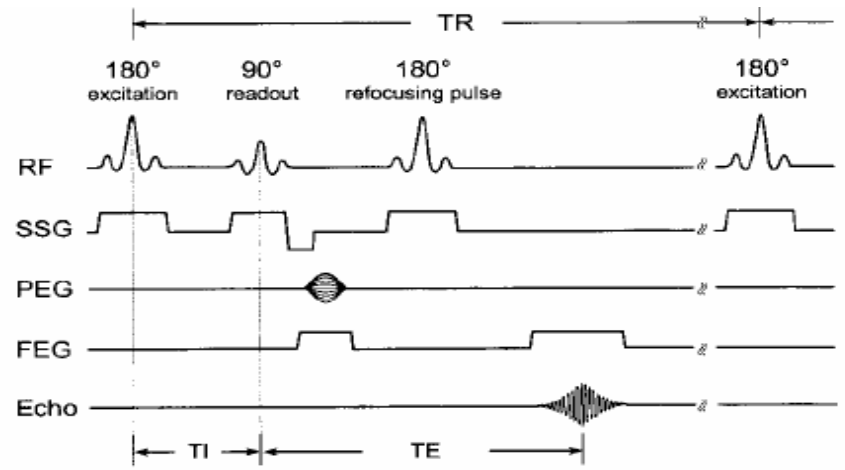
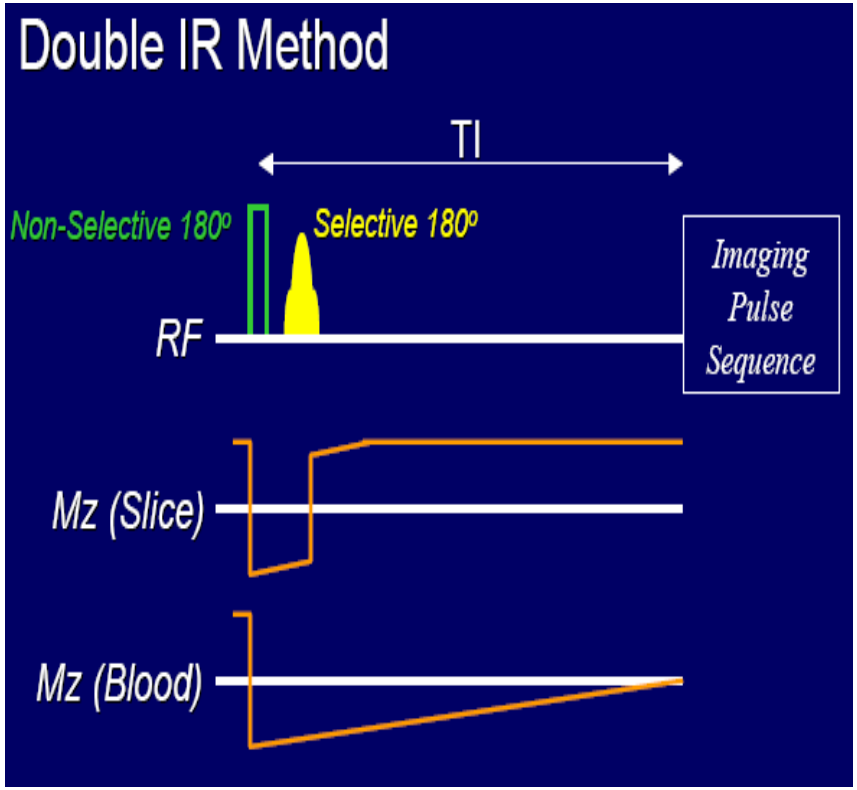


FIGURE 15-21. Inversion recovery pulse sequence uses an initial 180-degree pulse, followed by inversion time (TI) with 90-degree pulse and a second 180-degree pulse at a time TE/2.

Black Blood Angiography (Contd..)

Double Inversion Recovery.

- Unwanted suppression of the myocardium and other tissue with single inversion recovery can be reduced.
- As the name suggests implies two 180 pulses.



Black Blood Angiography (Contd..)

- DIR magnetization produces black blood signal because it flows into the imaging slice.
- Blood outside the slice recovers to zero.
- DIR relies on the inflow of the magnetization whereas the SE relies on outflow.
- DIR is more effective since TI is very large compared to TE (or TE_{eff}).

Black Blood Angiography (Contd..)

- Nonselective 180 pulse – Hard Pulse or Adiabatic (B1 inhomogeneity)
- Selective 180 pulse – SLR pulse or Slice selective Adiabatic pulse (hyperbolic secant).
- Slice of the second 180 pulse can be greater than the imaging slice to account for signal loss and imperfect slice profile.
- It has a limitation of single slice selection.
- Multiple echoes can be used to select different slices.

Black Blood Angiography (Contd..)

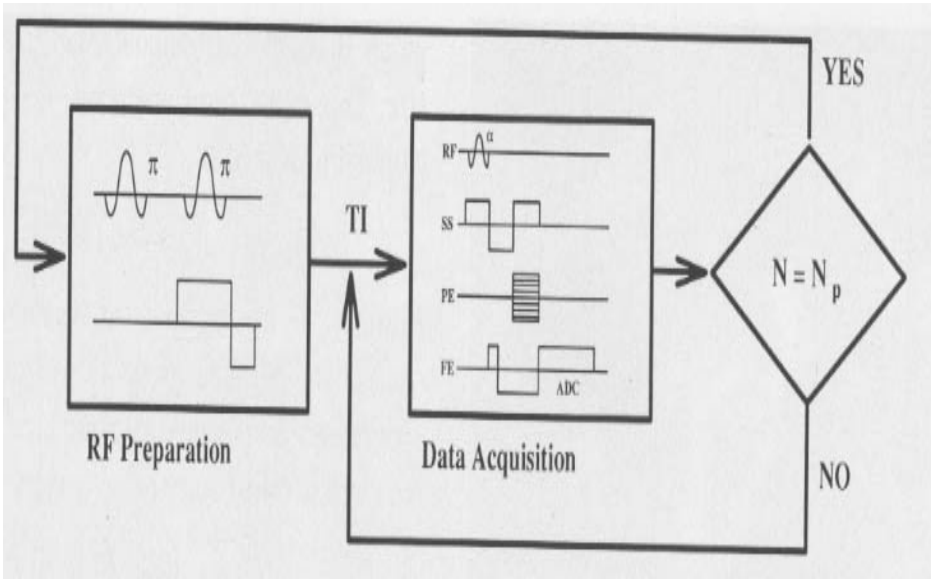
4. Preinversion Segmented turboFLASH (PRESTO):

Previous methods have following drawbacks:

- Long scan times making them sensitive to swallowing and other patient motion.
- Difficulty in imaging slow flowing and recirculating blood.
- These problems are solved by the PRESTO.

Black Blood Angiography (Contd..)

- RF preparatory pulse followed by a rapidly repeated GE sequence.
- 8 to 32 phase encoding steps can be acquired within a breath holding period.
- Unlike standard turbo PRESTO uses 180 inversion pulse affects tissue outside but not inside.



N = No. of phase encoding steps.

Np = No. of desired Phase encoding steps in the segment

Black Blood Angiography (Contd..)

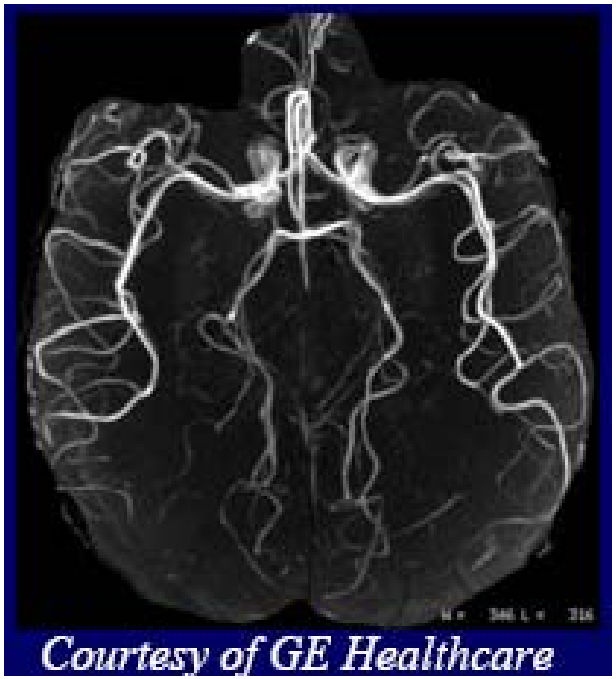
- Advantages:
  - Used in the case of stenoses and complex dephasing where bright blood methods cannot be used.
  - Provides better contrast between myocardium and blood signal as compared to other methods.
  - PRESTO method is useful for thoracic and abdominal imaging.
  - Intravoxel dephasing due to complex flow further reduces the signal.
  - Used when fat and blood vessel are in close vicinity.

Black Blood Angiography (Contd..)

- Disadvantages:
  - Since the technique is based on signal loss it is not preferable to use it unless required.
  - Recently for stenosis CEMRA is more readily used as compared to BBA.
  - Also since CEMRA is a bright blood method it is preferred.

Bright Blood Angiography (TOF)

- T_1 of flowing water is effectively shorter than the T_1 of stationary water
- Two contrast mechanisms are responsible:
  - **T_1 saturation** of the stationary tissue
  - **In-flow signal enhancement** from moving spins



Bright Blood Angiography (TOF)

- *Time-of-flight effect.*
  - Signal from the flowing spins first increased and then subsequently decreased.
  - Increase is due to the replacement of saturated spins by fully magnetized spins.
  - Decrease is due to spins spending insufficient time to become fully magnetized.
  - It has two kind of effects the Flow and Amplitude effect.

- Phase effect:
  - Additional phase experienced by the transverse magnetization of spins flowing as compared to their stationary counterparts.
  - This phase change occurs when the spins giving rise to transverse magnetization move along the axis defined by the gradient.

$$\Phi(t) = \gamma \int x(t)G(t)\, dt$$

-where x(t) is the position along the axis as a function of time (moving spins).

G(t) – magnetic field gradient

Now, $x(t) = x_0 + vt$

Where v is the velocity of the flowing spins

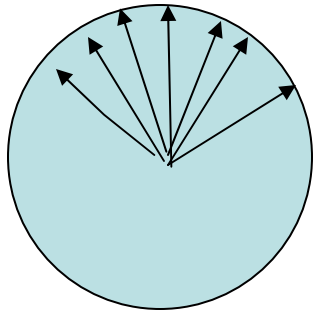
$$\Phi(t)=\gamma \int G(t)(x_0 + vt)\, dt$$

$$= \gamma G x_0 \tau + \gamma G v\, \tau^2/2$$

Thus we can see that the phase increases quadratically with time.

- Intravoxel Phase Dispersion
  - Flow inside a vessel is laminar i.e the velocity across the voxel section varies in a parabolic path.
  - In this the distribution of flow velocities in a voxel exists in a concomitant distribution.

- This causes signal loss due to destructive interference.
- This effect is the principal cause of flow void in spin echo sequences.
- The phase shifts and concomitant losses occur during echo time.
- But only the shifts which do not alter their positions rephase to zero at the echo time.
- Since the blood is flowing the spins will change their location and also the phase builds quadratically thus further causing the signal reduction.



- Gradient Moment Nulling:
  - If the function x(t) includes motion other than constant velocity x(t) can be expanded as follows:

$$x(t) = x(0) + x'(0)t + \frac{x''(0)\,t2}{2!} + \frac{x'''(0)\,t3}{3!} + \ldots.$$

Where x'(0) – velocity

x"(0) – acceleration and higher order motions.

Thus the phase can be expressed as

$$\Phi(t) = \gamma x_0 M(0) + \gamma v M(1) + \tfrac{1}{2}\gamma a M(2) + \ldots.$$

Where the M's are different order gradient moments.

- The key to nulling the phase of spins moving at constant velocity is to devise a gradient waveform that has no first moment i.e

  $M(1) = \int_0^{TE} G(t)\, dt = 0$
- Such a strategy is known as *Gradient Moment Nulling.*
- To Null the first moment the gradient waveform has to have a ratio of 1:-2:1 as shown

$$\Phi(t) = \int_0^{3\tau} \acute{\omega}(t)t\,dt$$

$$= \int_0^{\tau} \acute{\omega}(t)t\,dt + \int_{\tau}^{2\tau} \acute{\omega}(t)t\,dt + \int_{2\tau}^{3\tau} \acute{\omega}(t)t\,dt$$

$$\Phi = \gamma G v \tau^2/2 - 3\gamma G v \tau^2 + \gamma G v\, \tau^2\, 5/2$$

$$= 0$$

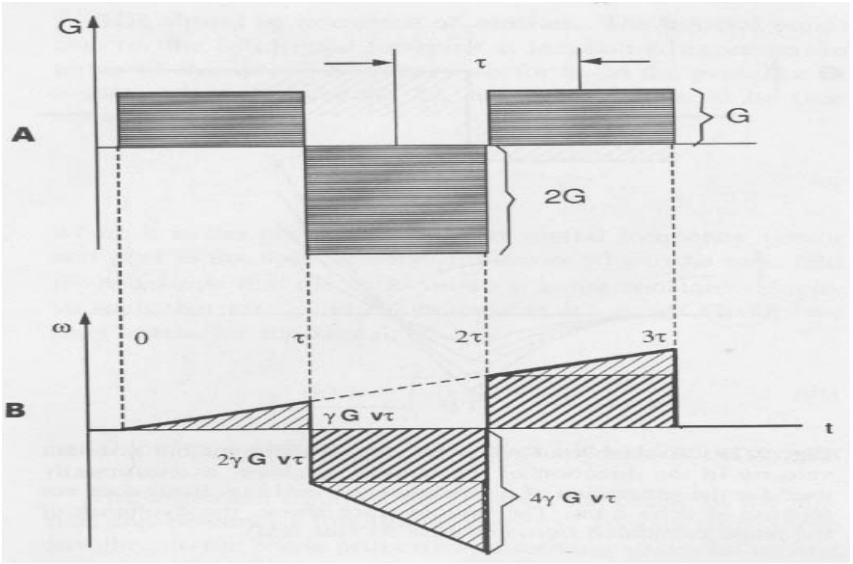
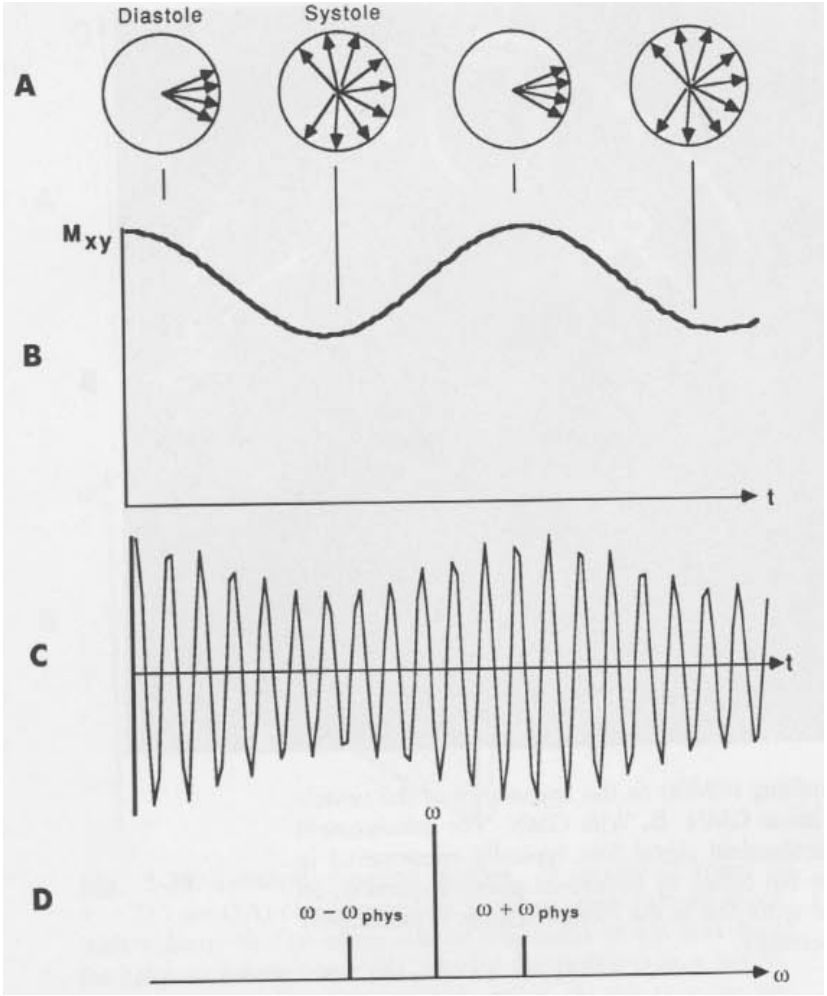


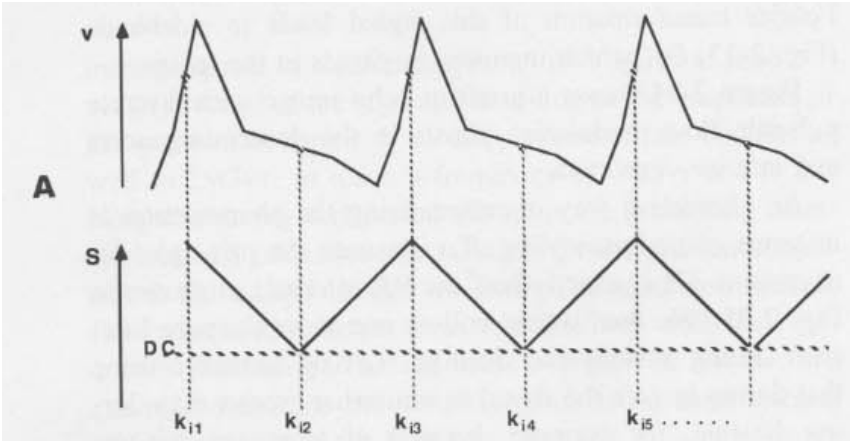
Fig. 2-30. Gradient moment nulling. A gradient triplet of 1:(−2):1 area **(A)** compensates the phase of spins moving at constant velocity v. The phase can be calculated as the area under the frequency-time curve **(B).** During the period 0 to τ the frequency increases linearly to a value $\gamma G v \tau$. At this time the amplitude of the gradient is doubled and its polarity reversed. The spins now precess counterclockwise at a rate $-2\gamma G v \tau$, to reach a frequency $-4\gamma G v \tau$ at time $t = 2\tau$. At this time the polarity of the gradient is reversed a second time. Immediately after polarity reversal, the precession frequency is $2\gamma G v \tau$, to reach a final value $3\gamma G v \tau$ at $t = 3\tau$. One can see that the net area under the frequency-time curve is zero, thus showing that the phase, regardless of the spins' velocity, is nulled.

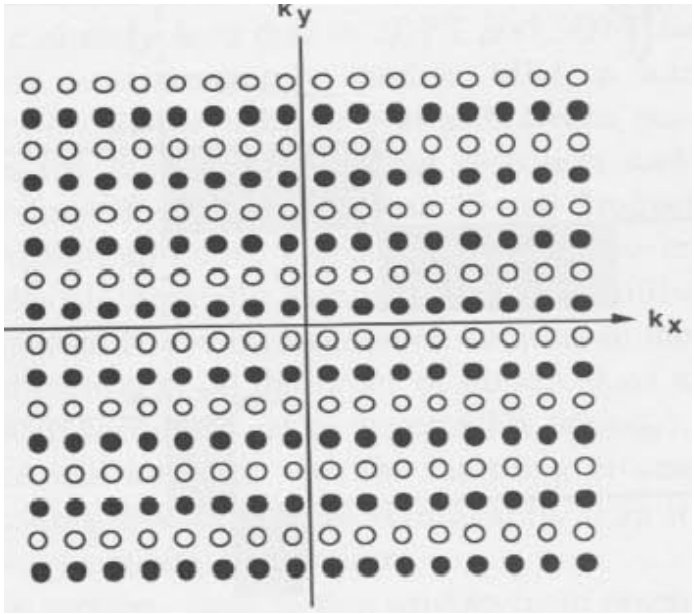
- Pulsatile Motion:
  - Blood and CSF flow have variations in the flow velocity due to pulsatile motion.
  - Also we know that sampling time between successive samples in frequency encoding direction is less as compared to the phase encoding.
  - Entire frequency encoding line is obtained in few milliseconds where as time between successive sample in PE direction is of the order of milliseconds.
  - Thus motion interferes with the sampling in the PE direction more than in FE.

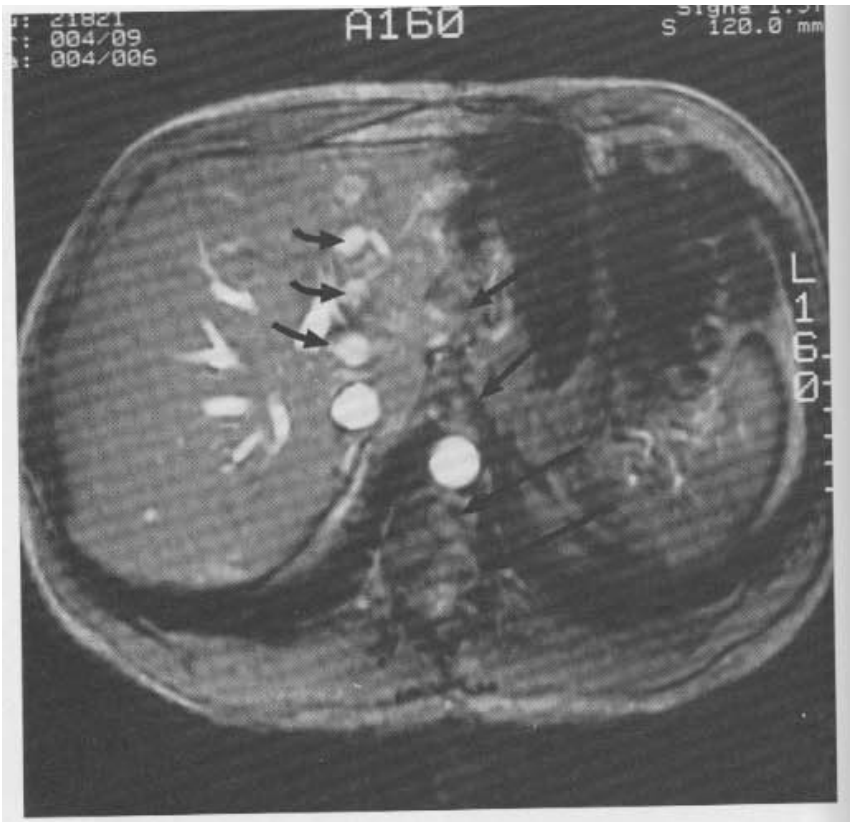
- Phase dispersion effect causes modulation in the transverse magnetization.
- The fig. shows how phase modulation transforms in Amp. Modulation.



- This can be explained as follows:
  - Let TR be half of RR interval.
  - We take one k-space line during each systole and diastole.
  - Also the signal during systole is greater than during diastole.
  - Image can be regarded as superposition of two data sets.
  - Thus the data set look like we are undersampling the systolic component (every other line).
  - This is what leads to the aliasing







- This figure shows the Aliasing effects due to Pulsatile motion.

Amplitude Effects

- Saturation Effects in Gradient Echo:
  - In flow effect in gradient echo are much more prominent.
  - Gradient echo has much simpler velocity dependence than spin echo imaging.
  - Unlike the spin echo which is governed by inflow of unsaturated spins and signal reduction due to exit of spins between the 90 and 180 pulses. Grdaient echo signal increases monotonically.

- This increasing velocity reaches a maximum when complete washout of the spins with an RF history.
- 2D imaging uses a 90^0 flip angle for maximum inflow enhancement.
- 3D uses a lower flip angle.
- Also if the velocity decreases or slab thickness increases (or lower TR) spins will see more number of RF pulses.
- For slab thickness z, spins moving with velocity v will experience

$$n = z / v * TR$$

Magnetization M_n just before application of n+1th pulse is

$$M_n = A^n M_0 + \frac{(1- A^n)B M_0}{1-A}$$

Where $A = E_1 \cos\alpha$, $B = 1 - E_1$

$$E_1 = \exp(-TR/T_1) \text{ and } \frac{B M_0}{1 – A} = M_s$$

$$\Delta S_{blood} = (M_0 – M_s) A^{z/vTR} e^{-TE/T2} \sin \alpha$$

- Spatial presaturation:
  - In multi slice spin echo luminal enhancement may or may not occur, which is undesirable from imaging view point.
  - It can falsely imply thrombus.
  - This can be suppress with the use of a spatial presaturating the spins outside the imaging slice.
  - Also we need to know about the frequency of saturation pulses, slab thickness and choice of flip angle.

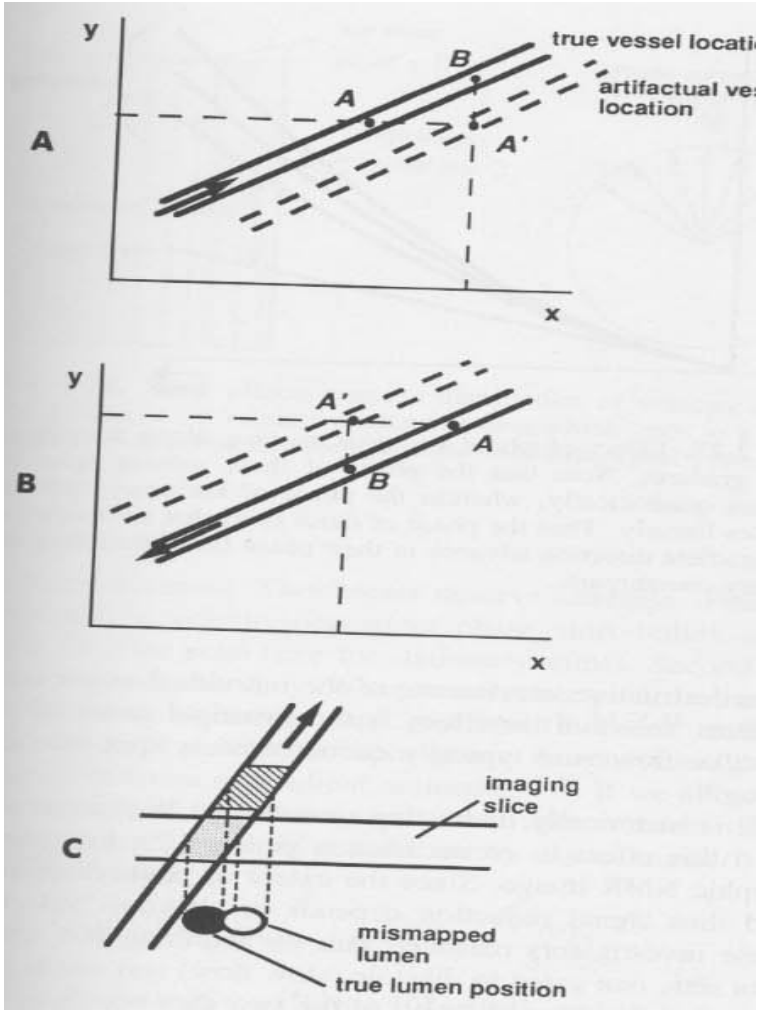
- Spins have to be saturated frequently to avoid recovery between saturation and detection which will be proportional $(1- e^{-T/T1})$ where T is the time between two saturation pulses.
- Saturation slab must be thick enough that the spins don't pass the slab and enter the imaging slice without being excited.

- Spin Misregistration:
  - Frequently observed artifact due to noncoincidence of phase and frequency encoding.
  - It occurs for oblique flow to one of the axes.
  - For stationary spins the time difference between PE and FE is immaterial.
  - However if the spins are moving misregistration will ensue.

– If Δt between two encoding steps the spins will have traveled from location A to B acc. To

R(B) = r(A) + vΔt and the spins will be mismapped by

$\Delta x = v_x \Delta t$



2D Time-Of-Flight Advantages

- Good stationary tissue to blood
- flow contrast
- Sensitive to flow
- Minimal saturation effects
- Short scan times
- Can be used with low flow rate

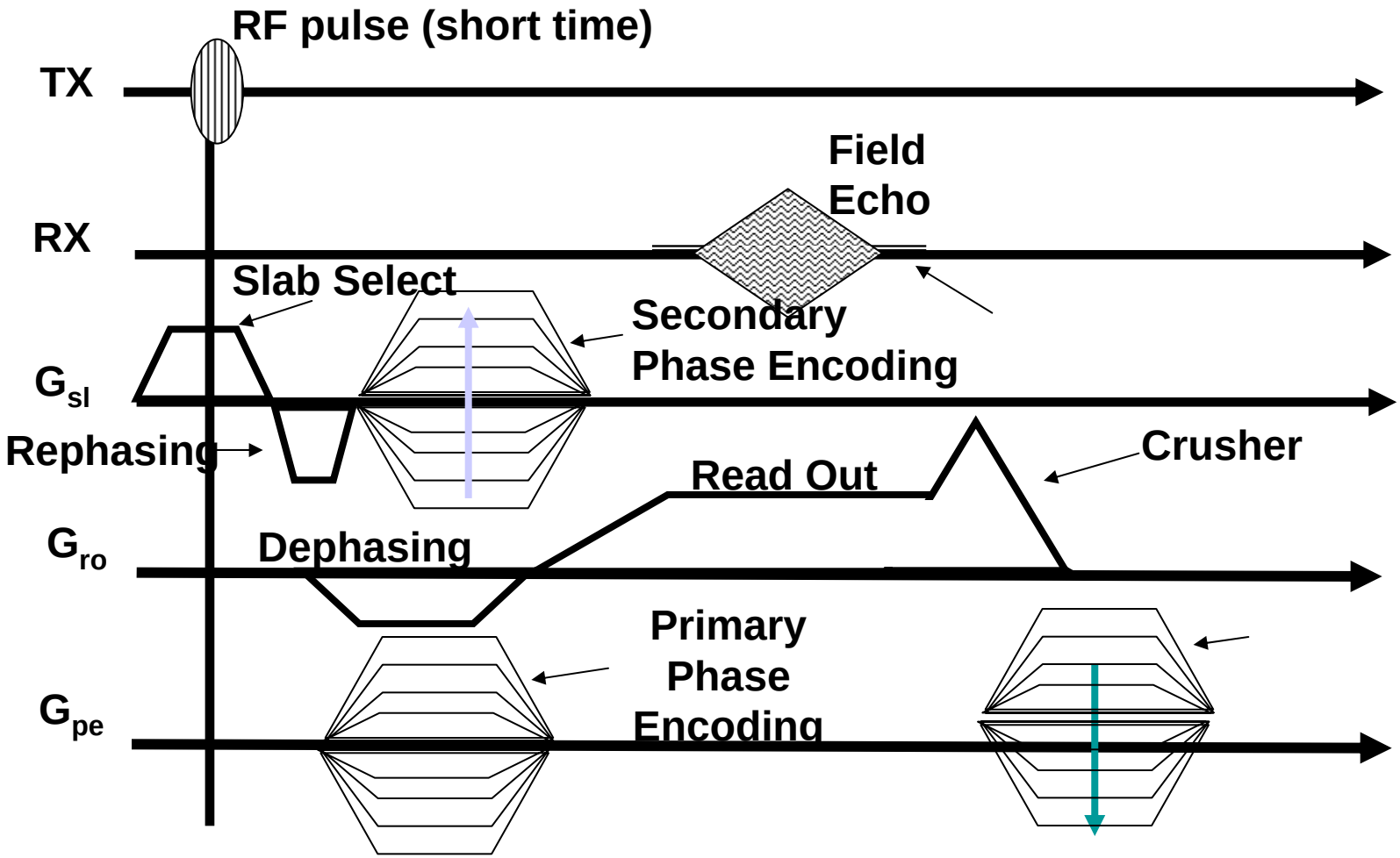
2D Time-of-Flight MRA Limitations

- Relatively poor SNR
- Poor in-plane flow sensitivity
- Relatively thick slices
- Long echo times (TE)
- Sensitive to short T1 species

3D Time-of-Flight MRA Conditions

- Uses two phase encode gradients and volume excitation
- Maximum volume thickness limited by flow velocity
- Use minimum TR, adjust flip angle for best contrast

Three Dimensional Gradient Refocused Echo Imaging



3D Time-of-Flight MRA Advantages

- Higher resolution (thinner slices) available allowing for delineation of smoother edges
- Higher signal-to-noise than 2D methods
- Lower slice select gradient amplitudes results in fewer phase effect artifacts than 2D method
- Short duration RF pulses can be used to excite slab – TE can be reduced

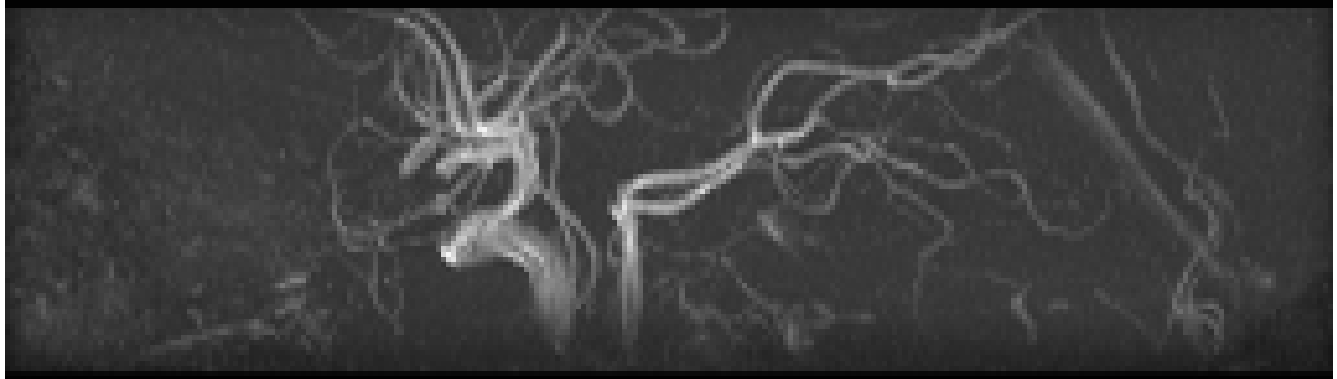
3D Time-of-Flight MRA Limitations

- Blood signal is easily saturated with slow flow
- Relatively poor background suppression
- Short T_1 tissues may be mistaken for vessels

3D-TOF Application:
Cerebral Arteries – Circle of WIllis

- TR /TE = 40 / 4.7 ms
- 64 partitions, 48 mm slab, 0.75 mm per partition
- Flip angle = 25^{o}
- 256 x 256, 18 cm FOV, 0.78 x 1.56 mm pixel
- MTC contrast
- Venous Presaturation

Circle of Willis



90°

Time of Flight MRA

Multi-Slab 3D TOF MRA

Hybrid of 2D and 3D methods:

- Thin 3D slabs used
  - Good inflow enhancement
- Multiples slabs to cover volume of interest
  - High resolution
  - Short TE
- Relatively time inefficient

- Advantages of 3D over 2D:
  - 2D
    - Long Scan time for volume coverage
  - 3D
    - Faster than 2D (~ 10 min)
    - Higher Spatial Resolution
    - But one disadvantage of saturation of arterial flow