Magnetic Resonance Angiography

Course: Advance MRI (BIOE 594)
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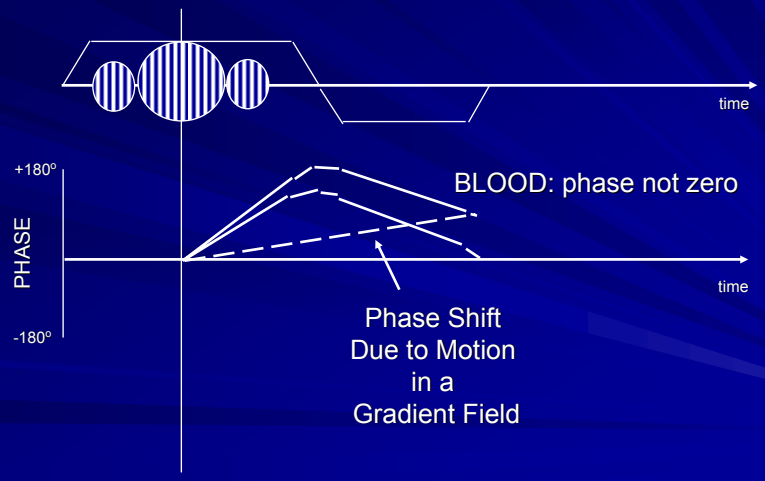
Phase Contrast Angiography

- By Moran 1982, Bryan et. Al. 1984 and Moran et. al. 1985
- It images moving spins by applying flow encoding gradients.
- Flow induced phase shift effects arise from the changes in phase of transverse magnetization as the blood moves along a magnetic field gradient.
- Although primary use is to image flow within blood it can also be used to image flow of CSF and also track motion.

Phase Contrast MRA (contd…)



Phase Contrast MRA (contd…)

- With a given gradient field, stationary spins precess at a constant rate
- Moving spins experience a change in precession frequency, depending on their velocity v, and the gradient strength, G.
- This causes a velocity-dependent phase shift, $\Delta\phi$

$$\Delta\phi = \gamma \int \Delta B dt$$

- For constant flow velocity,

$$x = x_0 + vt$$

- With an x-Gradient Gx, the field strength is

$$B = B_0 + \Delta B = B_0 + G_x x$$

- The phase shift is linear with velocity

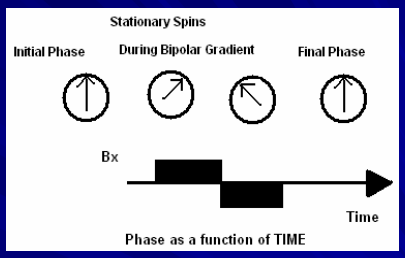
$$\Delta\phi = \gamma \int G_x v t dt$$
$$= \gamma v \int G_x t dt$$
$$= \gamma v M_1$$

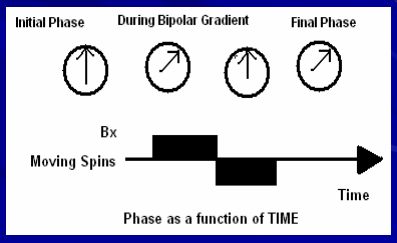
Phase Contrast MRA (contd…)

- For stationary spins all phase shifts will cancel out.
- The residual phase shift is directly proportional to the distance traveled and strength of pulses.
- For constant velocity induced phase shift is given by

$$\Phi(v) = \gamma v T A_g$$

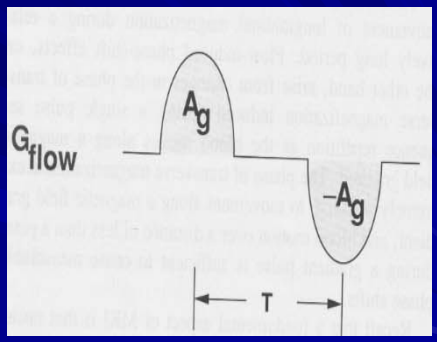
Where γ – gyromagnetic ratio, v – the velocity of moving blood, T – time interval and A_g – area of one gradient lobe.



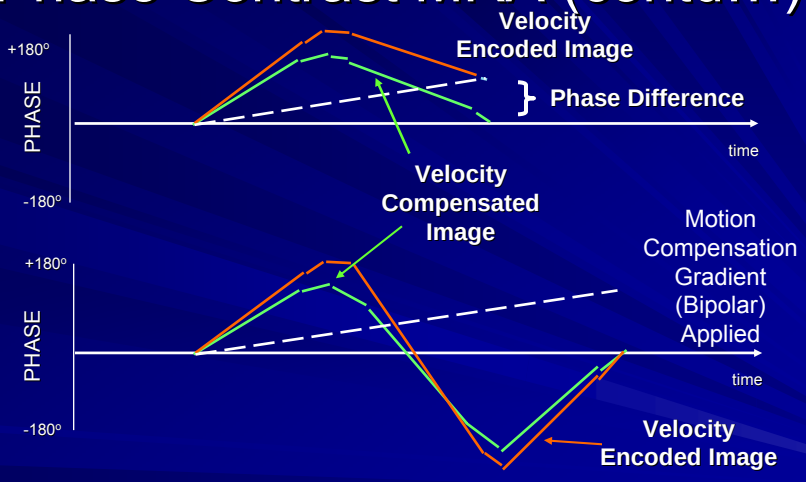


Phase Contrast MRA (contd…)

- It is not only velocity but the phase shift can be proportional to acceleration and higher order terms of motion.
- Gradient can be designed to make the phase shift proportional to any of these terms.
- The most simplest motion sensitizing gradient is the *Bipolar Gradient*.



Phase Contrast MRA (contd…)

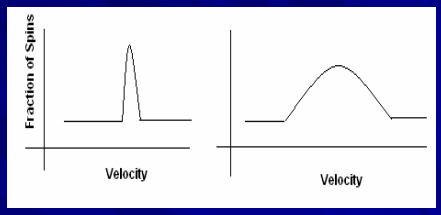


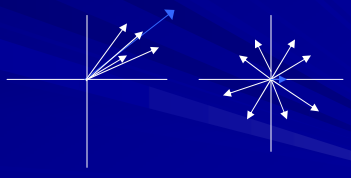
TISSUE: phase equals zero in <u>BOTH</u> images

BLOOD: phase is <u>DIFFERENT</u> in each image

Phase Contrast MRA (contd…)

- The Bipolar gradient gives phase shift independent of position (stationary) but proportional to velocity as shown before.
- Now velocities in a vessel are not always constant.
- This distribution of velocities induces distribution of phase shifts.
- Narrow distribution leads to the detected shift is due to average velocity effect, wider distribution leads to destructive interference leading to signal loss





Phase Contrast MRA (contd…)

- Methods:
  1. Incoherent phase sensitive method.
     - Signal loss caused by flow induced dephsaing.
  2. Coherent Phase sensitive method.
     - Velocity induced phase using the bipolar gradient is used to create an image.

Phase Contrast MRA (contd…)

- Incoherent Technique:
  - Two projection images acquired one during rapid flow (systole) and other during quiescent flow (diastole).
  - Systole image shows considerable signal loss from dephasing, while diastolic image is less affected.
  - Subtraction of the two images yields an angiogram.

Phase Contrast MRA (contd…)

- Incoherent Technique:
  - Two image are acquired one with flow compensation and the other without flow compensation.
  - Two images are subtracted to obtain an angiogram.
- Limitations of Incoherent technique:
  - Subject to a lot of patient motion artifacts.
  - Sufficient loss of signal in slow flow is achieved only if extremely strong bipolar pulses are used.

Phase Contrast MRA (contd…)

- Coherent Technique:
  - Function of bipolar gradient is to create velocity induced phase shifts.
  - It can be applied along any principal or oblique axes.
  - Polarity if the bipolar gradient is varied so that the phase of the flowing blood will be altered.
  - Subtracting the acquired data from one another leaves only flow dependent signal.

Phase Contrast MRA (contd…)

- Two methods used for subtraction
  1. Phase Difference
  2. Complex Difference
  - Also toggle bipolar gradient is characterized by aliasing velocity VENC (Velocity Encoding).
  - By definition if velocity component along gradient is +/- VENC then the resulting phase difference is +/- π.
  - If change in 1st moment of bipolar velocity gradient is Δm_1 then:

$$VENC = \pi / |\Delta m_1| \gamma$$

Phase Contrast MRA (contd…)

- Phase Difference Reconstruction:
  - Two main applications quantifying the flow velocity and rate and determining flow direction.
  - The phase difference of a pixel is given by

$$\Delta\Phi = \gamma \Delta m1 v = \frac{v\pi}{VENC}$$

Where v is the flow velocity.

Phase Contrast MRA (contd…)

- Flow direction can be reliably determined when v <= VENC.
- As long as VENC is sufficiently high velocity can be quantitated by using the previous equation:

$$v = \left(\frac{\Delta\Phi}{\pi} \right) VENC$$

sign of phase difference tracks sign of v

- Sometimes in order to suppress noise the phase diff. images are multiplied by the corresponding magnitude images on a pixel-by-pixel basis.

Phase Contrast MRA (contd…)

- Flow Quantification:
  - The volume flow rate (ml/min) are given by the pixel area multiplied by the average velocity through a vessel.

$$Q_{pixel} = 60\ a\ v$$

60 converts seconds to minutes.

  - Acquisition for flow quantification is such that the scan plane cuts the vessel in cross section.
  - Bipolar gradient is along the flow direction.
  - It is also useful to obtain time resolved depiction of the flow when studying the pulsatile arterial flow.
  - This is done by retrospective or prospective cardiac gating.

Phase Contrast MRA (contd…)

- Exact determination of vessel boundary is difficult due to partial volume effects.
- ROI is selected in the Magnitude image.
- Other contributions to errors in flow quantification are concomitant field, but fortunately it can be corrected.
- Eddy current phase error have slow spatial variation, they can corrected during postprocessing.

Phase Contrast MRA (contd…)

- Complex Difference Reconstruction:
  - Accomplished by subtraction of complex data from two toggles of bipolar gradient.
  - Subtraction can be performed in any domain (IFT is linear)
  - Subtraction in k-space is simpler.
  - Advantage is that Partial Fourier can be used for reconstruction.
  - Where as in image domain it can be performed in a pixel-by-pixel basis.
  - In practice Phase Difference is sensitive to partial volume effects so Complex Difference is preferred.
  - Unless flow direction or quantification is required.

Phase Contrast MRA (contd…)

- Image Sensitive to Flow in Three Directions:
  - This type of PC image is called speed or Three direction image.
  - It is calculated by taking square root of the sum of the squares of three PC images.
  - The values of VENC along three directions need not be same.
  - CD method is used as three direction images are not used for flow detection and also the direction is lost due to sum of squares.

$$S = \sqrt{CD^2_{freq} + CD^2_{PE} + CD^2_{Slice}}$$

Phase Contrast MRA Advantages

- Variable velocity sensitivity
- Good background suppression
- Minimal saturation effects
- Short T1 tissues do not show up on images

Phase Contrast MRA Limitations

- Single thick section projection
- Vessel overlap artifact
- Sensitive to flow in only one direction
- Unstructured flow may cause problems

Summary

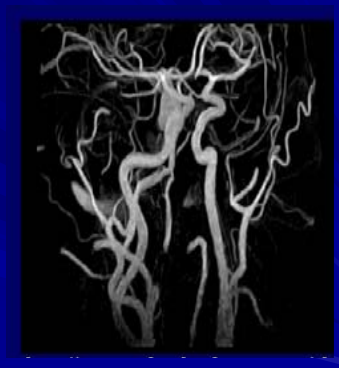
1. Two different approaches to MRA are commonly used: Time-of-Flight (TOF-MRA) & Phase Contrast (PC-MRA)
2. TOF-MRA is easy to implement and is robust but has difficulty with slow flow
3. 3D TOF can be combined with fast imaging methods and Gd contrast agents to obtain improved depiction of vascular structures

Summary

4. PC-MRA requires more time to acquire more images but can result in high resolution, fewer flow related artifacts, and quantitative measurement of flow
5. Phase-contrast MRI may provide the most accurate, noninvasive method for measuring blood flow *in vivo*

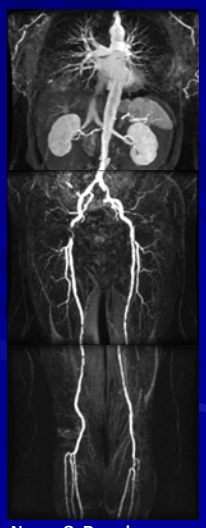
Contrast Enhanced MRA

- CEMTA by Prince et. Al 1999
- Relies on injected contrast agent changing the relaxation time of blood (T1).
- Gadolinium rare earth element Atomic no. 64 and weight 157.25 g/mol.
- Highly paramagnetic in its ionized state due to 7 unpaired electrons in 4f shell.
- Spins properties is what makes it an effective T1 shortening agent



Contrast Enhanced MRA (contd…)

- Gadolinium Chelate is injected intravenously as a bolus (5-10 s for 20 ml).
- Saline flush can be added to create a tighter bolus.
- Path is like from Vein to Right ventricle to pulmonary vessels and left ventricle after which the agent makes first pass in the arteries.
- If a concentration of 500 mM is injected by the time it reaches the arteries it becomes 1-10 mM.
- Main aim is to acquire 3D imaging when the agent is at (near) it peak during the first pass.



Contrast Enhanced MRA (contd…)

- T1 Reduction of Blood:
  - It can be expressed as a function of Gd concentration.

$$\frac{1}{T1} = \frac{1}{T_{lo}} + R_1 \times [Gd]$$

where R_1 – longitudinal relaxivity of the contrast agent.

T_{lo} – Longitudinal relaxation of blood in absence of agent

Relaxivity decreases as B_0 increases.

Contrast Enhanced MRA (contd…)

- SNR and TR considerations:
  - Most applications assume TR<<T1
  - Assuming spoiled GRE sequence with flip angle set to Ernst angle then

$\cos\phi_E = e^{-TR/T_1}$ = (1-TR/T_1)

S = $\frac{M_0 e^{-TE/T^*_2}\sqrt{\left(1-e^{-TR/T_1}\right)}}{\sqrt{1+e^{-TR/T_1}}}$ ~ M0 $\sqrt{\frac{TR}{2T_1}}$ e^{-TE/T^*_2}

  - Equation implies increasing TR increases the signal.
  - Long TR also means that data will be acquired when there is little or no contrast agent remaining.

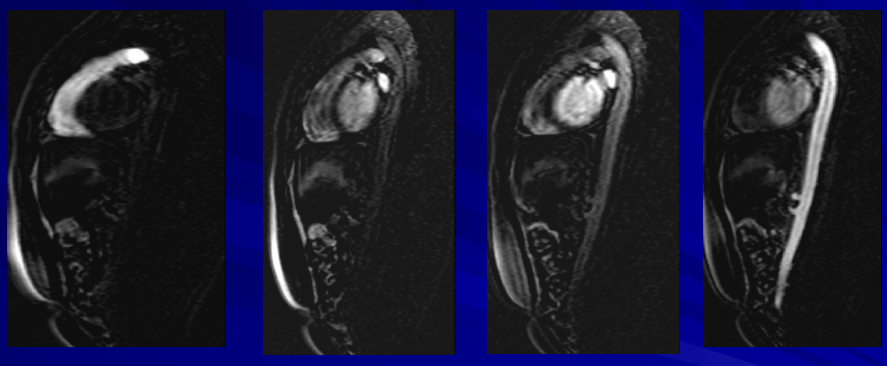
Contrast Enhanced MRA (contd…)

- CEMRA Pulse Sequences:
  - Mainly uses spoiled GRE.
  - Since Speed is primary requirement wider bandwidth and partial echo acquisition is typically used.
  - No gradient moment nulling used.
  - To reduce scan time partial acquisition is used in 2 or even 3 directions.
  - CEMRA acquisitions can be divided into two:
    - Single Phase Methods.
    - Time Resolved Methods.

Contrast Enhanced MRA (contd…)

- Single Phase Methods:
  - Entire acquisition time devoted to obtain one 3D data set.
  - Increased spatial resolution and coverage.
  - It requires the bolus timing method:
    - Circulation of the bolus is tracked using 1) test bolus timing and 2) Fluoroscopic triggering.
  - Elliptical centric view order is used.
  - One minor drawback of the elliptical method is that there is no natural break points to apply chemical saturation pulses.

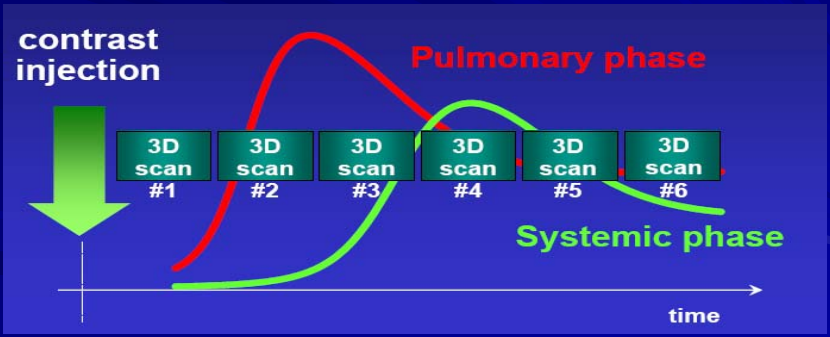
Contrast Enhanced MRA (contd…)



6sec 11sec 14sec 15sec

Contrast Enhanced MRA (contd…)

- Time Resolved:
  - Various 3D acquisitions are taken during the entire circulation of the contrast agent.



Contrast Enhanced MRA (contd…)

- Time-Resolved :
  - Allows visualization of stages of arterial enhancements: early, peak and late arterial phases.
  - Acquisition speeds at even higher premium.
  - Particularly used for Bilateral imaging of vessels in leg where arterial enhancement of different vessels occur at different times.
  - Unless breadth holding is required, operator is not needed.
  - They automatically provide several sets of precontrast mask.
  - To optimze the trade off of time, resolution and coverage, Keyhole and TRICKS can be used.

Contrast Enhanced MRA (contd…)

- Moving Table Methods:
  - Chase propagation of single bolus.
  - The table on which patient is lying is moved along so that the imaging volume follows the course of the first pass after injection.
  - Application are imaging arteries of pelvis, legs and feet.
  - Alternatively the entire volume can be covered by moving the table and acquiring one single volume.

Contrast Enhanced MRA (contd…)

1. CE-MRA has matured in the last five years and is clinically reliable in many applications including carotid and renal arteries.
2. Areas of development are improved spatial resolution, reduced acquisition time, and improved peripheral runoff studies.
3. Current projects which address these include alternative k-space trajectories and multi-coil (SENSE) imaging.

References

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2. *Magnetic Resonance Angiography: Concepts and Application*
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3. *3D Contrast MR Angiography*
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4. http://www.acmp.org/meetings/lakegeorge_2003/presentations/mr_angiography.ppt