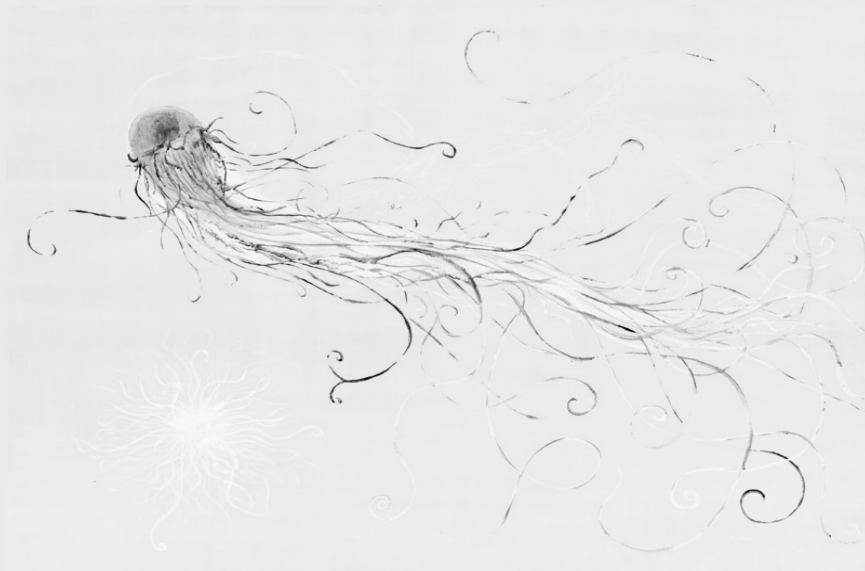


# **PERFUSION - MRI ARTERIAL SPIN TAGGING**

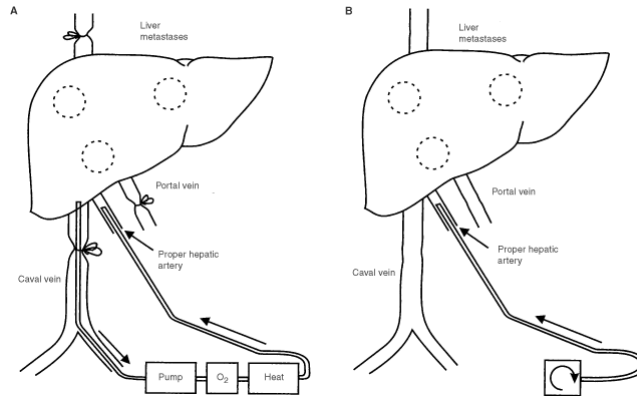
by  
**Kenny K Israni**

*Mar 30, 2006*

## **PERFUSION**



## PERFUSION



- ***Abnormalities in perfusion can have profound effects (cessation of blood flow to the brain can cause unconsciousness in only 5-10 seconds)***

## PERFUSION

### ➤ ***Measurements using MRI***

- ***Using Exogenous agents (bolus tracking of Gd-DTPA or steady-state techniques)***
- ***Using Endogenous label (water molecules in arterial blood are labeled – Arterial Spin Tagging)***

## PERFUSION

### ➤ *PARAMETERS*

- *Perfusion (P)*

$$P = F / W \quad [\text{mL}/(\text{min} \cdot 100\text{g})]$$

*F* – blood flow rate (mL/min)

*W* – mass of tissue in 100gm

## PERFUSION

### ➤ *PARAMETERS*

- *Perfusion Rate (f)*

$$f = \rho P \quad [\text{mL}/(\text{mL} \cdot \text{min})]$$

*ρ* – tissue density (100g/mL)

*P* – perfusion (mL/min . 100g)

## PERFUSION

### ➤ *PARAMETERS*

- *Blood Volume fraction (q)*

$$q = V/V_o$$

*V – volume of distribution of the tracer (blood) within the tissue*

*V<sub>o</sub> – volume of a voxel*

## PERFUSION

### ➤ *PARAMETERS*

- *Mean Transit Time (T<sub>mtt</sub>)*

$$T_{mtt} = V/F = qV_o/F$$

- *For non-diffusible tracers (exogenous agents), T<sub>mtt</sub> is typically a few seconds*
- *For freely diffusible tracers (labeled arterial water), T<sub>mtt</sub> is much longer*

## PERFUSION

### ➤ PARAMETERS

- *Tissue-Blood partition coefficient ( $\lambda$ )*

$$\lambda = C_t / C_b$$

$C_t$  – *concentration of tracer in tissue*

$C_b$  – *concentration of tracer in blood*

- *For freely diffusible tracers (labeled arterial water), the tracer diffuses into the tissue, as a result  $\lambda$  is close to 1.0*

## ARTERIAL SPIN TAGGING (AST)



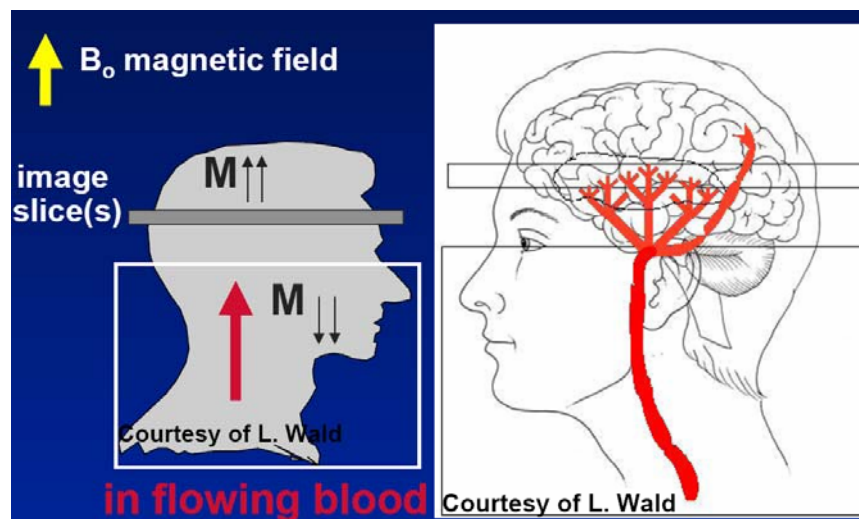
## ARTERIAL SPIN TAGGING (AST)

### ➤ OVERVIEW

- *Magnetization of water molecules in arterial blood is labeled, so that it causes an MR signal change as the arterial blood perfuses into the tissue*
- *AST labels magnetization by **Saturation or Inversion***
- *AST techniques*
  - *Pulsed AST (higher labeling efficiency)*
  - *Continuous AST (higher SNR, better perfusion quantification)*
- *Single-slice and multi-slice acquisitions*

## ARTERIAL SPIN TAGGING (AST)

### ➤ PRINCIPLE

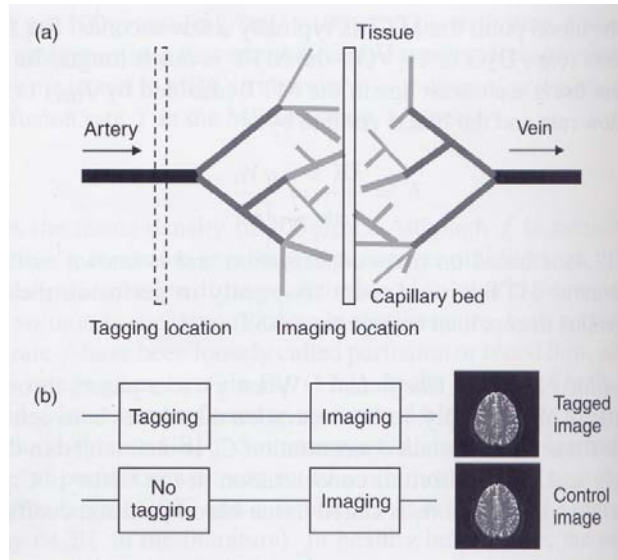


## ARTERIAL SPIN TAGGING (AST)

### ➤ PRINCIPLE

*(a) magnetization of arterial blood is labeled at a location proximal to the imaging plane*

*(b) Images acquired with and without AST are subtracted*



## ARTERIAL SPIN TAGGING (AST)

### ➤ PRINCIPLE

- *Magnetization of water protons in arterial blood is labeled for perfusion measurements*
- *RF inversion pulse is applied at a location proximal (upstream) to the tissue of interest*
- *After a time delay, a pulse sequence is played to acquire an image distal (downstream) to the tagging position*
- *Signal change is measured by subtracting the images acquired with and without labeling*

## ARTERIAL SPIN TAGGING (AST)

### ➤ *PRINCIPLE*

- $M_t$  – tagged image
- $M_c$  – control image
- $|M_c - M_t|$  - qualitative perfusion-weighted image
- Perfusion quantification relies on signal change between  $M_c$  and  $M_t$  (typically this signal change is only 1-2%) Thus, other factors causing signal variation must be avoided or compensated for.

## ARTERIAL SPIN TAGGING (AST)

### ➤ *PRACTICAL CONSIDERATIONS*

- *MT effect causes signal loss substantially larger than the perfusion-induced signal. Hence, its important to equalize the MT effect between the tagged ( $M_t$ ) and control images ( $M_c$ )*
- *Perfusion quantification is very sensitive to random noise. Hence, signal averaging is used to increase the SNR.*
- *Due to the need of signal averaging, imaging pulse sequences like EPI that offer fast acquisition are used in AST*



## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ PRINCIPLE

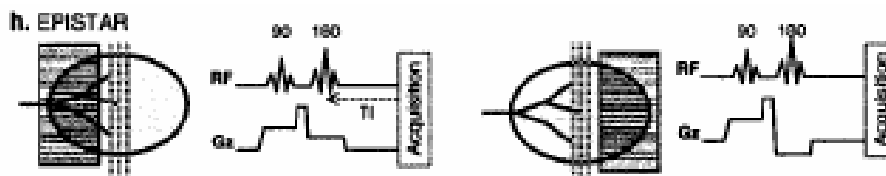
- *RF inversion pulse is applied to produce a **bolus of labeled magnetization***
- *The bolus travels from the artery to the capillary bed, exchanges with the unlabeled magnetization of the tissue water and experiences  $T_1$  relaxation*

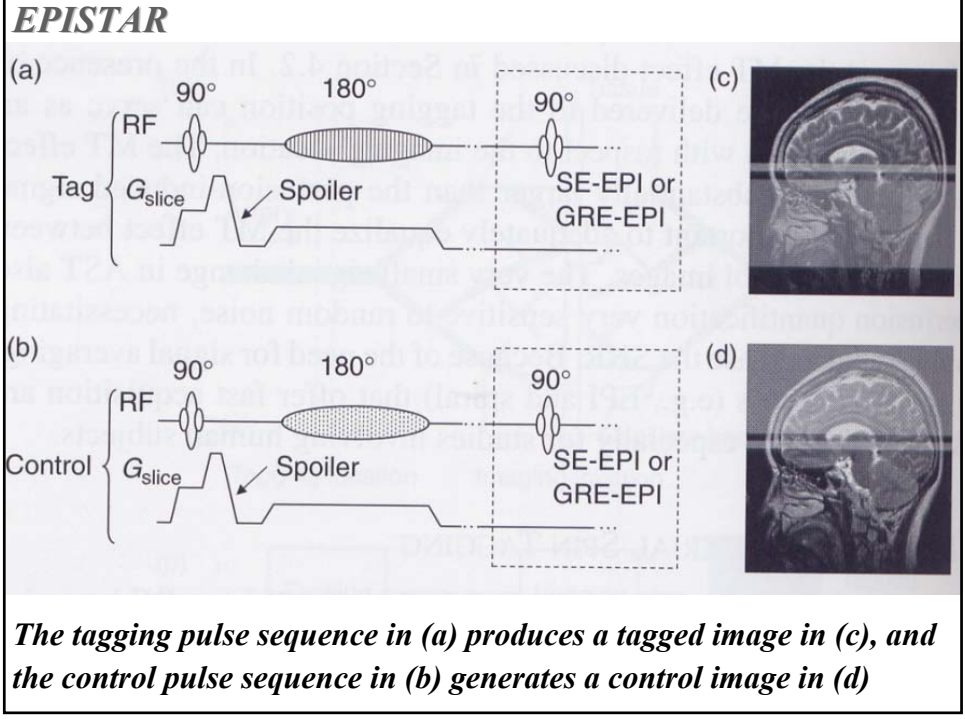
## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ EPISTAR

- *Echo-planar Imaging and Signal Targeting with Alternating Radiofrequency (EPISTAR)*
- *Alternates between acquiring a tagged image ( $M_t$ ) and a control image ( $M_c$ )*





## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ EPISTAR

- *The 90° pulses at the beginning of the sequences are slice-selective spatial saturation pulses applied at the imaging slice location*
- *Spoiler gradient can be played along any axis to dephase the magnetization*
- *The 180° pulses invert the spins in the boxed area proximal to the imaging slice*
- *To reduce the effect of the tagging pulse on the imaging slice, a gap (~ 1cm) is prescribed between the inverted slab and the imaging slice*

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *EPISTAR*

- *A long delay time (1 sec) is introduced to allow the inverted spins to travel to the imaging slice*
- *Tagged arterial blood causes a MR signal reduction in the imaging slice*
- *Spin echo (SE) or Gradient echo (GRE) EPI pulse sequence is used*

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *EPISTAR*

- *The tagging pulse results in MT effect in the tagged image*
- *To balance the MT effect, an inversion pulse identical to that in the tagging sequence is also played prior to the acquisition of control image*
- *The two tagged areas are symmetrically placed with respect to the imaging slice*

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *EPISTAR*

- $f_0$  – frequency offset of the imaging slice
  - $f_0 - f_{epistar}$  – carrier frequency for tagging pulse
  - $f_0 + f_{epistar}$  – carrier frequency for control pulse
- $$f_{epistar} = (\gamma / 2\pi) \cdot G\Delta r$$

$\gamma$  – gyromagnetic ratio

$G$  – tagging gradient

$\Delta r$  – center-to-center distance between the tagging slab and the imaging slice

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *EPISTAR*

- *The MT effect is symmetric and cancels after image subtraction*

$$\Delta M_{epistar} = M_c - M_t$$

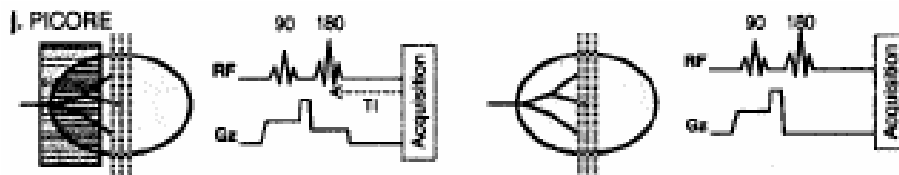
- $\Delta M_{epistar}$  is positive as  $M_t$  carries the inverted magnetization
- *Single-shot EPI is used*

## ARTERIAL SPIN TAGGING (AST)

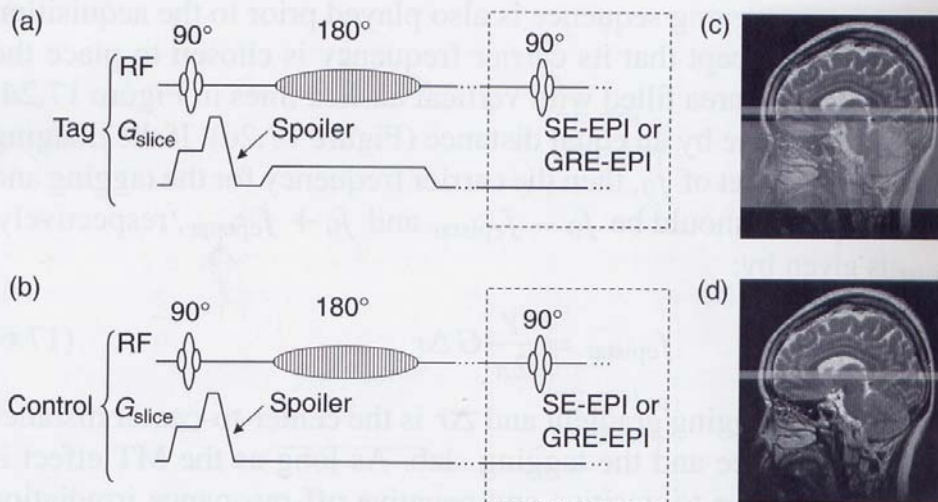
### ➤ PULSED AST

#### ❖ *PICORE*

- *Proximal Inversion with a Control for Off-resonance Effects (PICORE)*
- *Tagging sequence is same as EPISTAR, but the inversion pulse in control sequence is played without an accompanying slab-selection gradient*



#### *PICORE*



*The tagging sequence in (a) is identical to that in EPISTAR and produces tagged image (c). The control sequence (b) differs from (a) in that the slice-selection gradient during the inversion pulse is not played*

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *PICORE*

- *The MT effect is canceled out because the carrier frequency of the inversion pulse is same for the control and the tagging pulses*
- *The signal difference is given as*

$$\Delta M_{picore} = M_c - M_t$$

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *PICORE*

- *PICORE rejects the inflow from the distal side of the imaging slice, which causes a signal reduction in EPISTAR*
- *MT effects are better compensated in PICORE*
- *PICORE is less robust to eddy-current effects because the control sequence uses a different gradient waveform from the tagging sequence*

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *TILT*

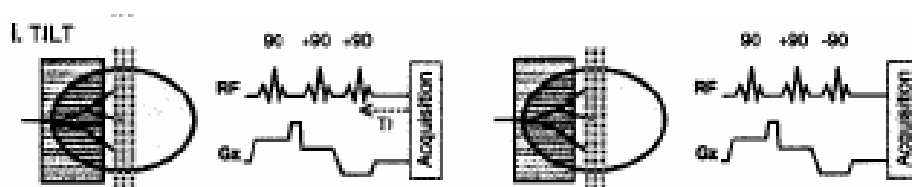
- *Transfer-insensitive Labeling Technique (TILT) replaces the inversion pulse in EPISTAR by two consecutive 90° pulses*
- *For tagged image, the two 90° pulses have the same phase, producing a net 180° magnetization inversion*
- *For control image, the 90° pulses have opposite phase, producing no change in magnetization*

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *TILT*

- *The MT effect is canceled out as the pulses for both the tagged and control image are applied at the same proximal location*
- *TILT is more robust against venous inflow than EPISTAR*

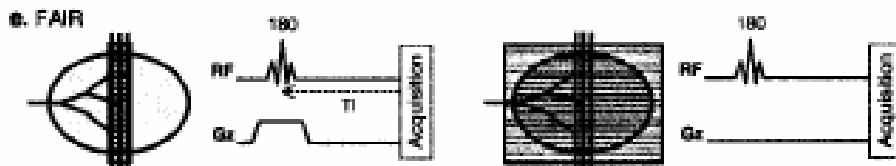


## ARTERIAL SPIN TAGGING (AST)

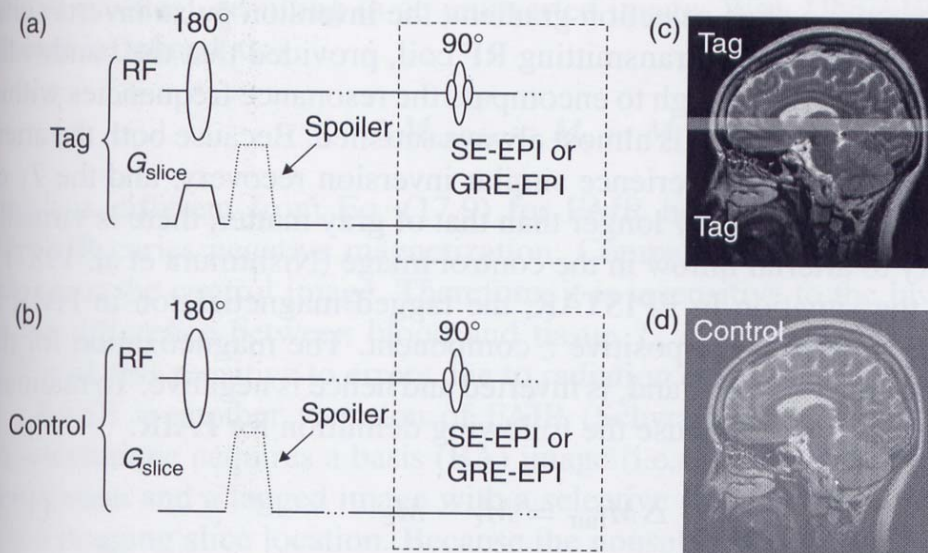
### ➤ PULSED AST

#### ❖ FAIR

- *Flow-sensitive Alternating Inversion Recovery (FAIR)*
- *Frequency-selective inversion pulse with and without slice-selection gradient is used to produce the tagged and control images respectively*



### FAIR



*The tagging pulse sequence in (a) produces a tagged image in (c), and the control pulse sequence in (b) generates a control image in (d)*



## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ FAIR

- *For the tagging sequence, the slice-selection gradient inverts spins in the imaging slice while leaving the spins elsewhere unaffected*
- *For the control sequence, the inversion pulse inverts spins in the entire volume*
- *The signal difference is given by*

$$\Delta M_{fair} = M_t - M_c$$

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ FAIR

- *FAIR is more robust against the MT effect because no off-resonance irradiation is applied with respect to the imaging slice*
- *Arterial blood from both sides of the imaging slice is tagged, hence when the flow direction is unknown, FAIR reduces errors in perfusion measurements*

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ UNFAIR

- *Uninverted FAIR (UNFAIR)*
- *Two consecutive inversion pulses are used in the pulse sequence*
- *For tagged image, one of the inversion pulses is played with the slice-selection gradient and the other is nonselective (to invert all spins)*
- *The magnetization of the imaging slice experiences a 360° rotation, rest of the volume experience a 180° rotation in magnetization*

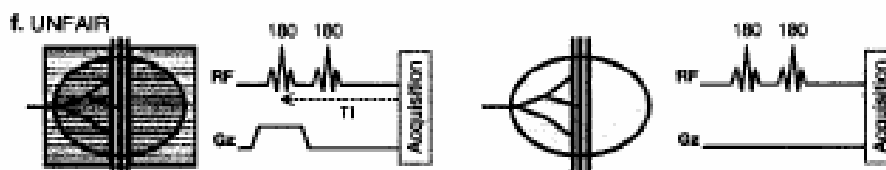
## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ UNFAIR

- *For the control image, both inversion pulses are nonselective resulting in an uninverted image*
- *The signal change is given by*

$$\Delta M_{unfair} = M_c - M_t$$

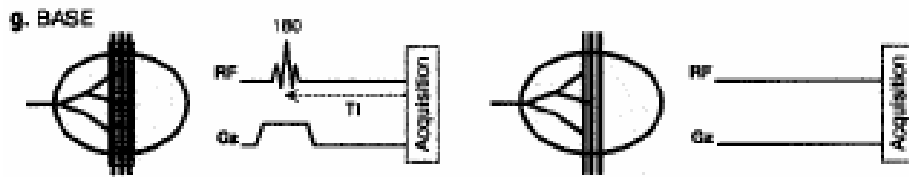


## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *BASE*

- *Basis image with a Selective inversion (BASE)*
- *For tagged image, a selective inversion pulse is applied at the imaging slice location*
- *Control image is acquired without any spin preparation*



## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *BASE*

- *BASE is more robust against mismatch, if the inversion profile doesn't entirely contain the imaging slice, the noninverted magnetization contributes to  $\Delta M$  in FAIR, but not in BASE*

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *FAIRER*

- *FAIR with an Extra Radiofrequency pulse (FAIRER)*
- *Slice-selective saturation pulse is delivered to the imaging location immediately after the inversion pulse of FAIR*
- *Reduces the TI (inversion time) sensitivity of the subtracted image*

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *Perfusion Quantification – Apparent T1*

- *Assumptions*
  - *MT effect is completely compensated for*
  - *T1 of blood is same as T1 of tissue*

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *Perfusion Quantification – Apparent T1*

- *Bloch equation in presence of perfusion,*

$$dM/dt = (M_0 - M)/T1 + fM_b - fM/\lambda$$

*M – longitudinal magnetization of the tissue*

*M<sub>0</sub> – magnetization at equilibrium*

*M<sub>b</sub> – magnetization of inflowing arterial blood*

*f – perfusion rate*

*λ – blood-tissue partition coefficient*

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *Perfusion Quantification by Image Subtraction*

- *Assumptions*

*- arterial blood flow is a **uniform plug flow** at both the leading and trailing edge of the tagged spins*

*- **thin slice** at the imaging location*

*- tagged water is **completely extracted** from the blood to the tissue under well-mixed condition*

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *Perfusion Quantification by Image Subtraction*

$$\begin{aligned} \Delta M(t) &= 0 & 0 \leq t < t_a \\ &= 2\alpha (M_0/\lambda) (t - t_a) f e^{-t/T1_b} & t_a \leq t < t_a + \delta \\ &= 2\alpha (M_0/\lambda) \delta f e^{-t/T1_b} & t_a + \delta \leq t \end{aligned}$$

$\alpha$  - fraction of achieved inversion over the max possible inversion

$M_0$  - magnetization at equilibrium

$\lambda$  - blood-tissue partition coefficient

$f$  - perfusion rate

$t_a$  - arrival time of the leading edge of the tagged spins

$\delta$  - duration when the tag remains in the imaging slice

$T1_b$  -  $T1$  relaxation of blood

## ARTERIAL SPIN TAGGING (AST)

### ➤ PULSED AST

#### ❖ *Perfusion Quantification by Image Subtraction*

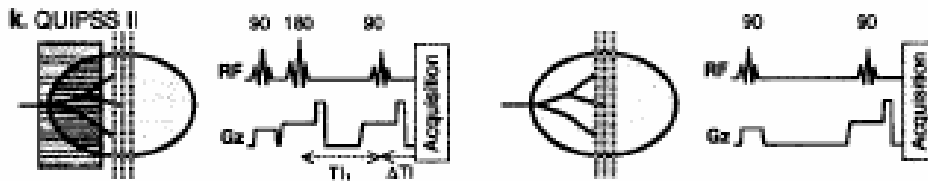
- *Since  $t_a$  and  $\delta$  are not known a priori, this method requires measurements at two time points (using two different TI values satisfying the condition,  $t_a \leq TI < t_a + \delta$ )*

## ARTERIAL SPIN TAGGING (AST)

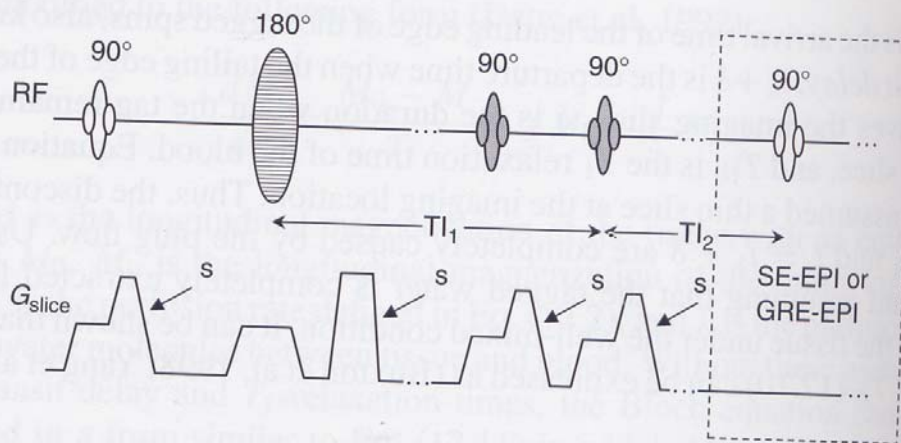
### ➤ PULSED AST

#### ❖ QUIPSS II

- *Quantitative Imaging of Perfusion using a Single Subtraction (QUIPSS)*
- *In this technique, the unknown transit delay time ( $t_d$ ) can be replaced with a known pulse sequence timing parameter ( $TI_1$ )*



### QUIPSS II



*The first 90° saturation pulse is applied to the imaging slice. The 180° pulse can be played as in EPISTAR, FAIR or PICORE. The following two 90° saturation pulses are applied to the tagging slab or the imaging slice. More or fewer saturation pulses can be employed*

## ARTERIAL SPIN TAGGING (AST)

### ➤ CONTINUOUS AST

#### ❖ PRINCIPLE

- *Flow-induced adiabatic inversion is used to produce a continuous supply of inverted arterial spins to the imaging location*
- *Consider an arbitrary RF pulse that has neither amplitude nor frequency modulation*
- *This pulse can produce adiabatic inversion if a magnetic field gradient  $G$  along the direction of motion is applied concurrently with the RF pulse*

## ARTERIAL SPIN TAGGING (AST)

### ➤ CONTINUOUS AST

#### ❖ PRINCIPLE

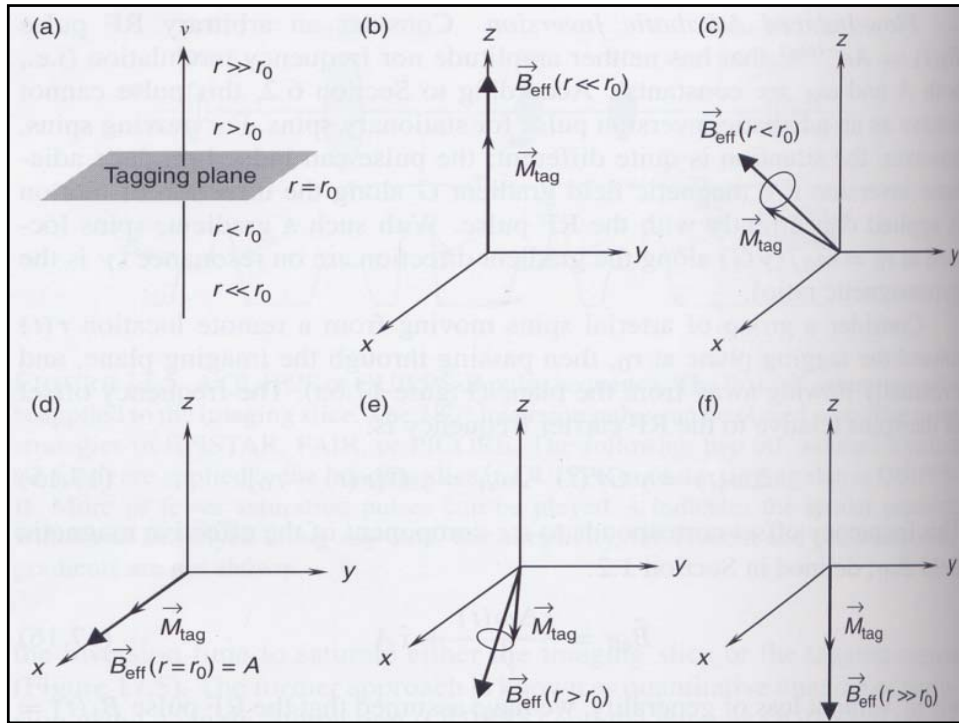
- *Consider a group of arterial spins moving from a location  $r(t)$  toward the tagging plane at  $r_0$ , then passing through the imaging plane and eventually flowing away from the plane*
- *The frequency offset of the spins is given by,*

$$\Delta\omega(t) = \gamma G r(t) - \omega_{rf} = \gamma G [r(t) - r_0]$$

*$\omega_{rf}$  - RF carrier frequency*

*$\Delta\omega(t)$  corresponds to a z component of the effective magnetic field ( $B_{eff}$ )*



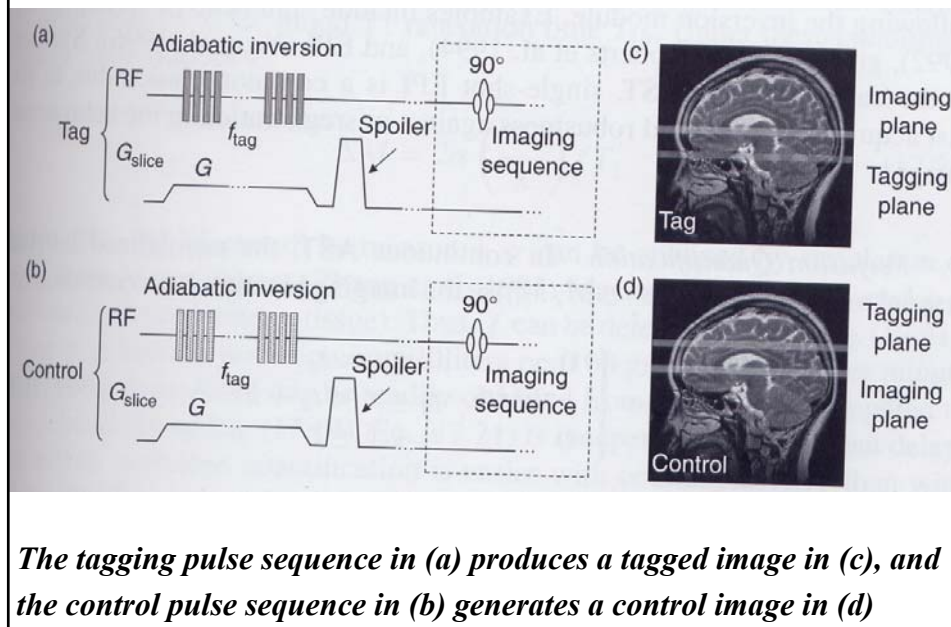


**(a)** Arterial blood flowing from a location remote from the tagging plane ( $r \ll r_0$ ), passing through the tagging plane ( $r = r_0$ ), and eventually moving away from the tagging plane toward the imaging location ( $r \gg r_0$ ).

**(b) – (f)** Change in direction of the effective magnetic field  $B_{\text{eff}}$  together with the magnetization vector  $M_{\text{tag}}$  during the course of the arterial blood flow in (a).

*Under the adiabatic condition, the magnetization of arterial spins  $M_{\text{tag}}$  follows  $B_{\text{eff}}$*

## CONTINUOUS AST PULSE SEQUENCE



## ARTERIAL SPIN TAGGING (AST)

### ➤ CONTINUOUS AST

#### ❖ Pulse Sequence

- For *tagged image*, the adiabatic inversion pulse has a *frequency offset  $f_{\text{tag}}$*  relative to the excitation pulse, so that the tagging plane *proximal to the imaging plane* is selected.
- For *control image*, the adiabatic inversion pulse has a *frequency offset  $-f_{\text{tag}}$*  relative to the excitation pulse, which moves the tagging plane *distal to the imaging plane*.
- $f_{\text{tag}}$  is adjusted so that the tagging location is a few centimeters proximal to the imaging slice.

## ARTERIAL SPIN TAGGING (AST)

### ➤ CONTINUOUS AST

#### ❖ *Perfusion Quantification*

- *The magnetization difference is given by,*

$$\Delta M = 2\alpha (M_0/\lambda) f T1'$$
$$(1/T1') = (1/T1) + (f/\lambda)$$

*T1 – tissue relaxation rate*

## ARTERIAL SPIN TAGGING (AST)

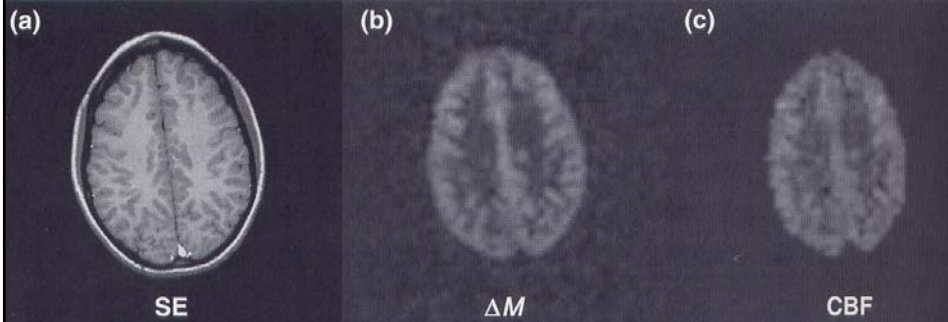
### ➤ CONTINUOUS AST

#### ❖ *Perfusion Quantification in 6 steps*

- *measuring the image intensity difference between  $M_t$  &  $M_c$*
- *normalizing the intensity to  $M_0$*
- *obtaining a T1 map*
- *determining  $\alpha$  through calibration or simulation*
- *calculating  $f$*
- *converting it to  $P$  if necessary*

## ARTERIAL SPIN TAGGING (AST)

### ➤ CONTINUOUS AST



*(a) A T1-weighted spin echo image, (b) the corresponding perfusion weighted image  $\Delta M$  and (c) the CBF map obtained at 1.5 T*

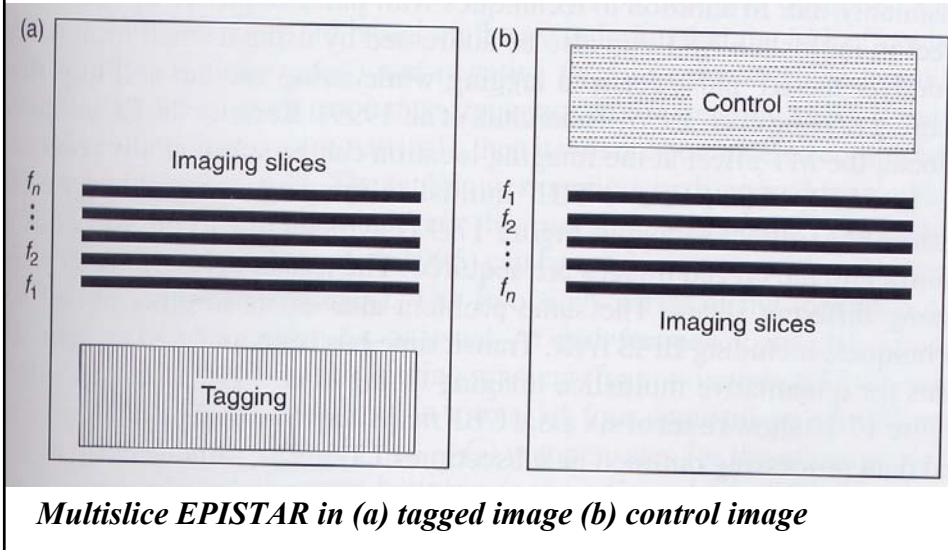
## ARTERIAL SPIN TAGGING (AST)

### ➤ MULTISLICE AST

- *AST experiments require a long inversion time and hence a long TR*
- *Even with single-shot EPI, large number of signal averages to increase SNR increases the total acquisition times considerably*
- *T1-mapping scan is required, which further adds on to the already long imaging time*
- *In multislice acquisitions, a single tagging pulse is played for a group of slices*

## ARTERIAL SPIN TAGGING (AST)

### ➤ MULTISLICE AST



## ARTERIAL SPIN TAGGING (AST)

### ➤ MULTISLICE AST

- *For tagged image, each slice receives a different off-resonance frequency*
- *For control image, the order of off-resonance frequency reverses*
- *MT effect does not cancel out, except for the slice located at the center of the group*

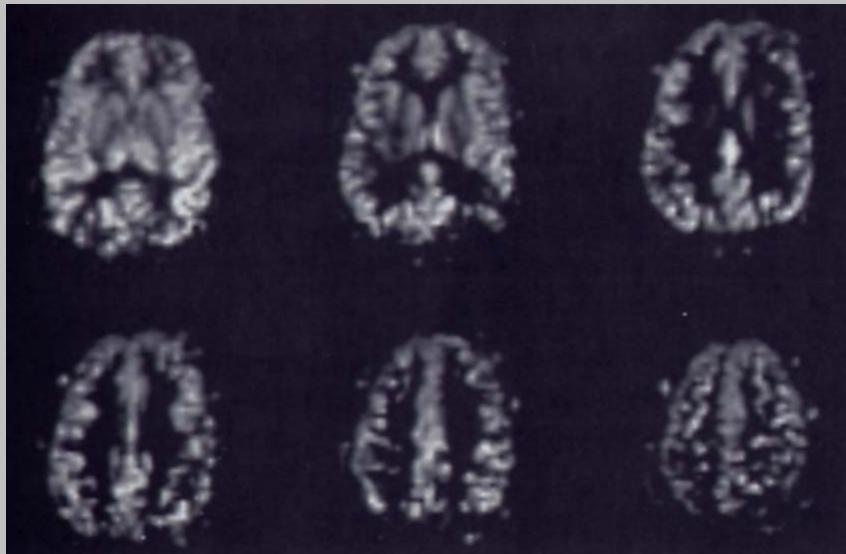
## ARTERIAL SPIN TAGGING (AST)

### ➤ MULTISLICE AST

- *In Multislice EPISTAR, the inversion pulse for the control image is applied at the same location as in the tagged image (proximal to the imaging slices). The MT effect is thus compensated to a large extent*
- *In Multislice Continuous AST, the inversion pulse for the control image is amplitude-modulated with a cosine function. If the frequency of the cosine function is  $f_m$  then the original tagging position  $r_c$  is split into two locations  $r_c \pm 2\pi f_m / (\gamma G)$*

## ARTERIAL SPIN TAGGING (AST)

### ➤ MULTISLICE AST



## ARTERIAL SPIN TAGGING (AST)

### ➤ *LIMITATIONS*

- *Asymmetric MT effects*
- *Arterial Signal elimination*
- *Specific Absorption Rate (SAR)*
- *Slice Profile*

## REFERENCES

- Matt A. Bernstein, Kevin F. King, Xiaohong Joe Zhou, *Handbook of MRI Pulse Sequences*, 2004
- Emmanuel L. Barbier, Laurent Lamalle and Michel De´corps, *Methodology of Brain Perfusion Imaging*
- Jingyi Xie, *Perfusion Pulse Sequence*