Perfusion-Based fMRI

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May 7, 2006

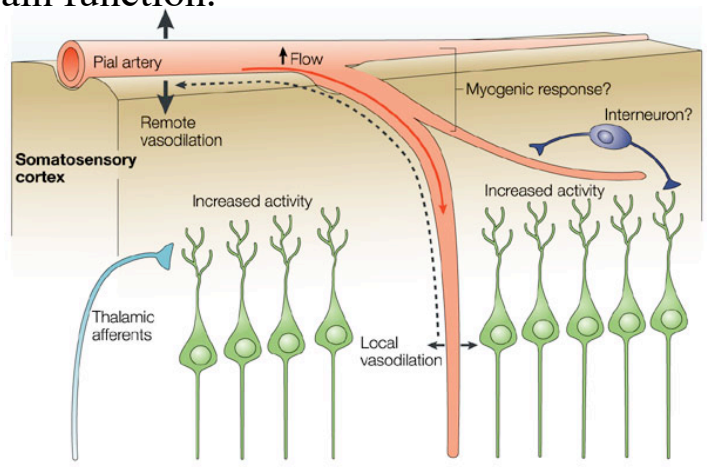
Goal

To provide a basic understanding of the theory and application of arterial spin labeling in functional MRI.

Topics

1. What is Cerebral Blood Flow?
2. Arterial Spin Labeling
3. Data Processing
4. Applications

Cerebral blood flow (CBF) is a fundamental physiological quantity. Closely related to brain function.



From C. Iadecola 2004

Cerebral Blood Flow (CBF)

CBF = Perfusion
= Rate of delivery of arterial blood to a capillary bed in tissue.

Units: $\frac{\text{(ml of Blood)}}{\text{(100 grams of tissue)(minute)}}$

Typical value is 60 ml/(100g-min) or 60 ml/(100 ml-min) = 0.01 s^{-1}, assuming average density of brain equals 1 gm/ml

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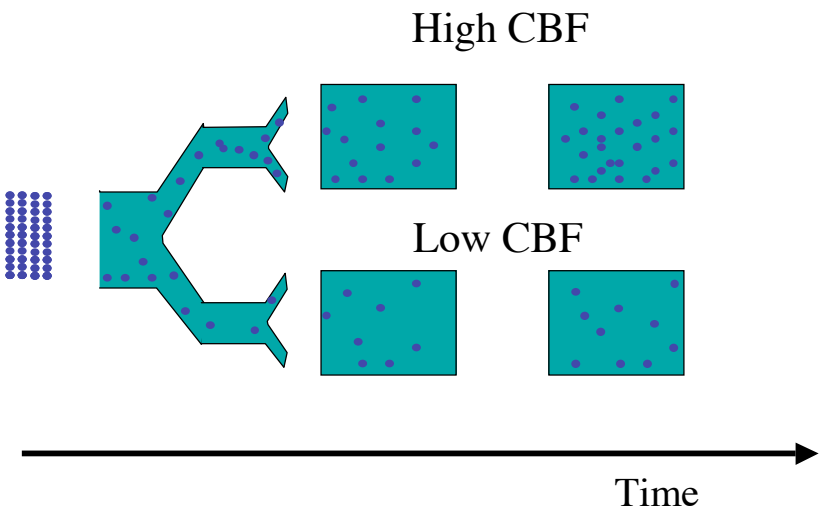

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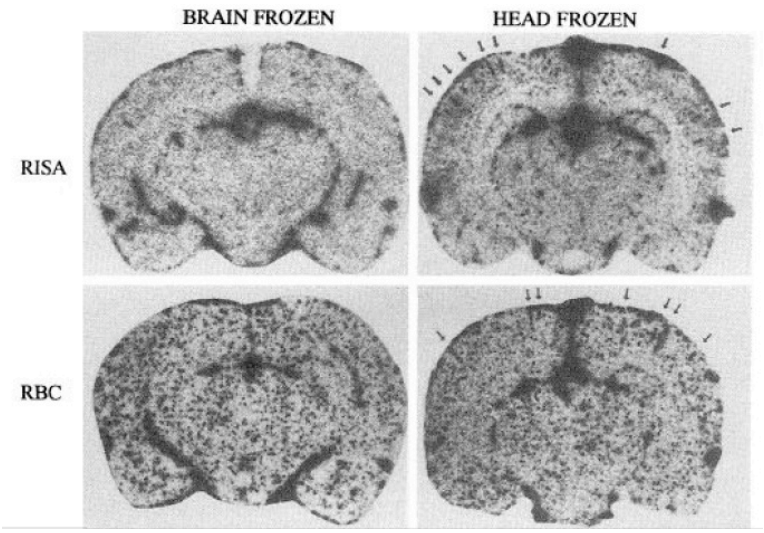

Bereczki et al 1992

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Methods for Measuring CBF

1. Quantitative Autoradiography
2. Laser Doppler
3. Diffusible and Radioactive Tracer Based Methods
4. PET and SPECT
5. Contrast-Based MRI
6. Arterial Spin Labeling

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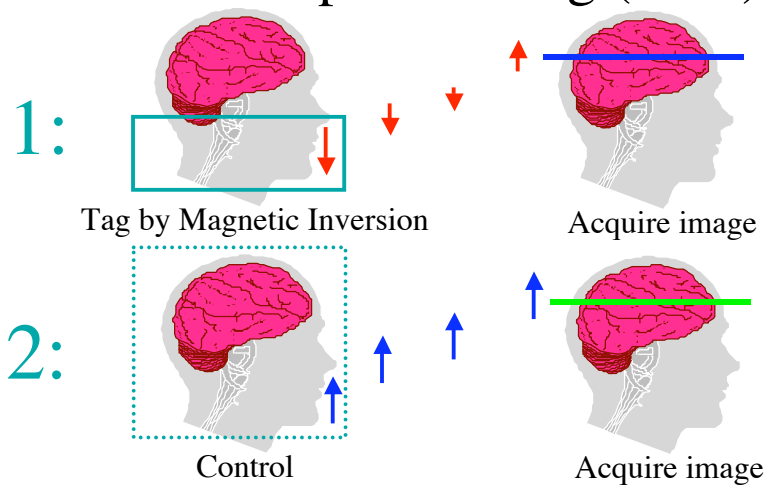
Arterial spin labeling (ASL)



Control - Tag = ΔM ∝ CBF

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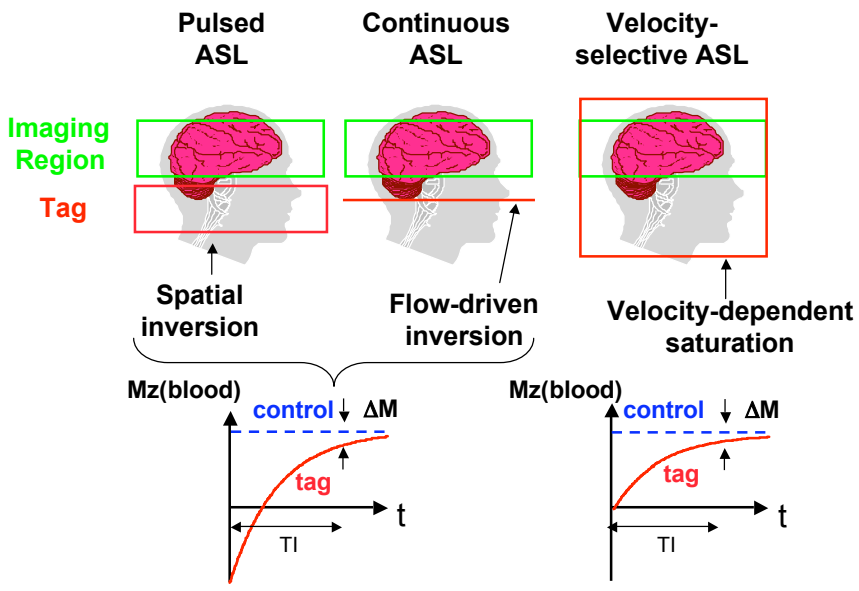

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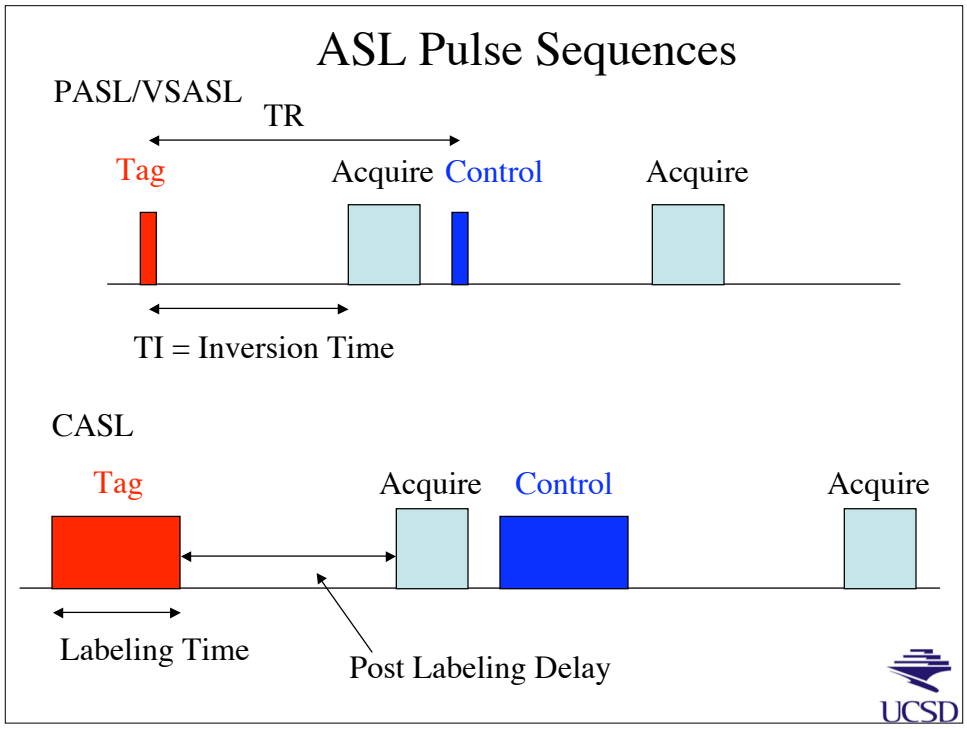
ASL Pulse Sequences
PASL/VSASL
TR
Tag
Acquire
Control
Acquire
TI = Inversion Time
CASL
Tag
Acquire
Control
Acquire
Labeling Time
Post Labeling Delay
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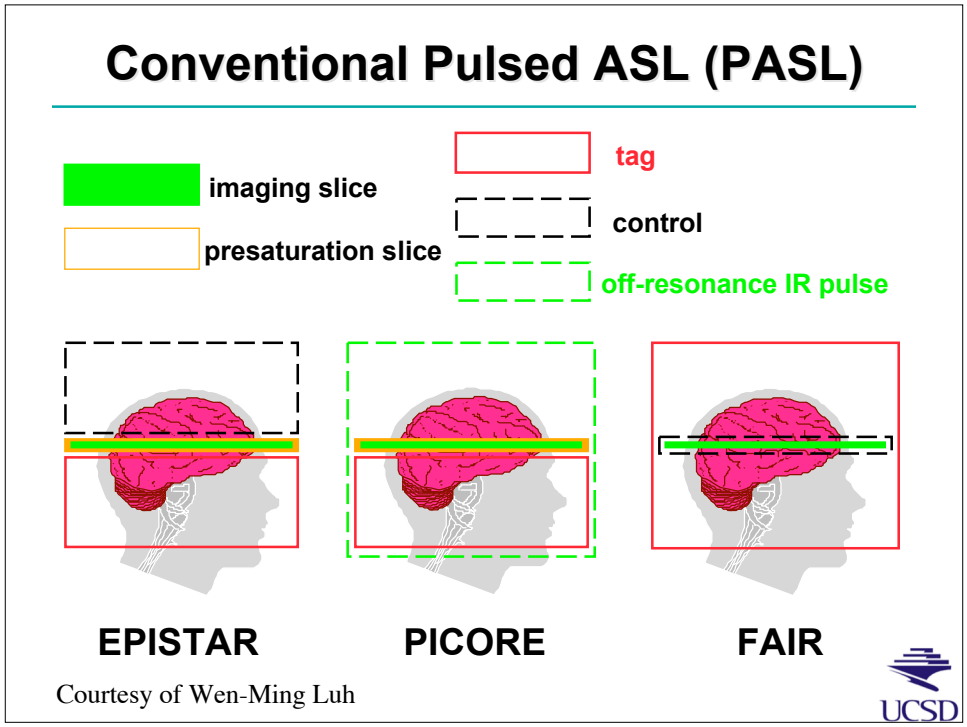
Conventional Pulsed ASL (PASL)
imaging slice
presaturation slice
tag
control
off-resonance IR pulse
EPISTAR
PICORE
FAIR
Courtesy of Wen-Ming Luh
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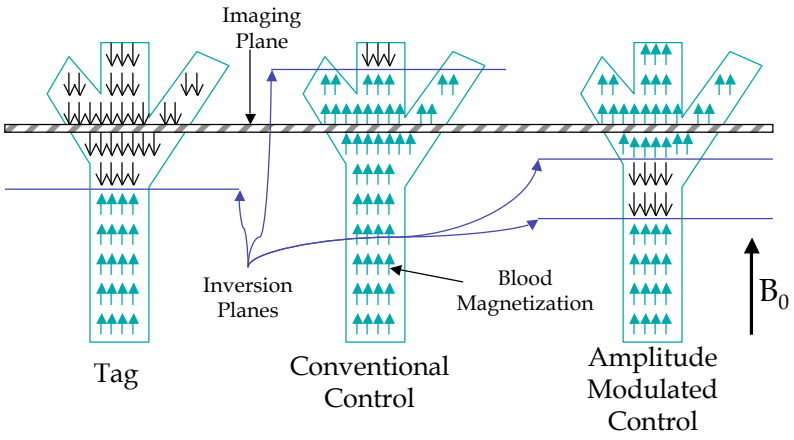
Continuous ASL (CASL)



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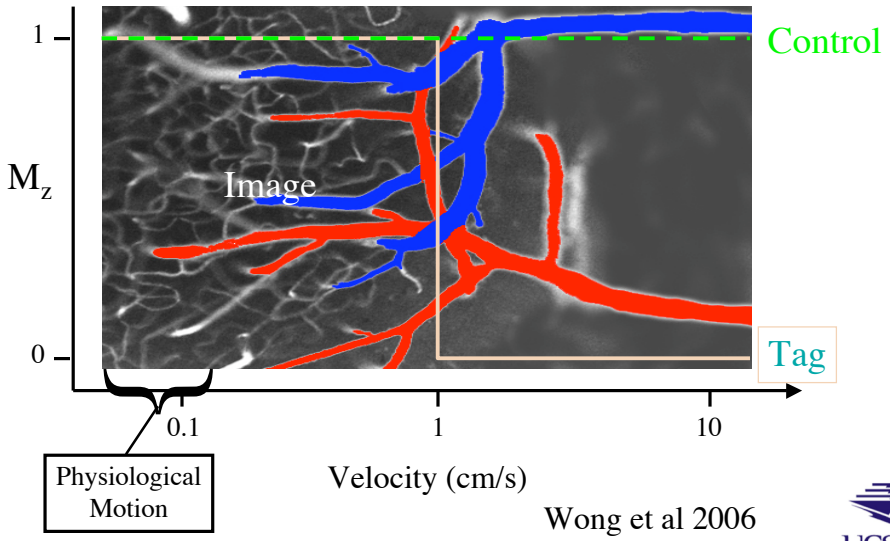
Velocity Selective ASL (VSASL)



Wong et al 2006

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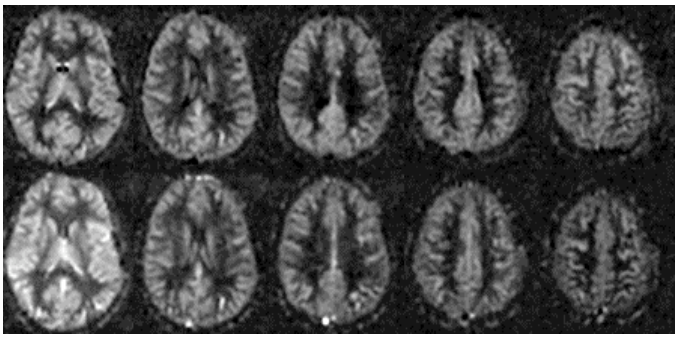
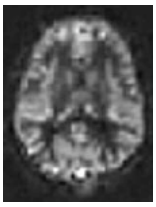
CASL

PASL





PASL VSASL

Credit: E. Wong

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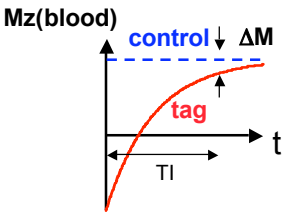
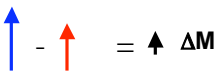
ASL Signal Equation





$$\Delta M = CBF \cdot A_{eff}$$

A_{eff} is the effective area of the arterial bolus. It depends on both physiology and pulse sequence parameters.

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Quantitative ASL

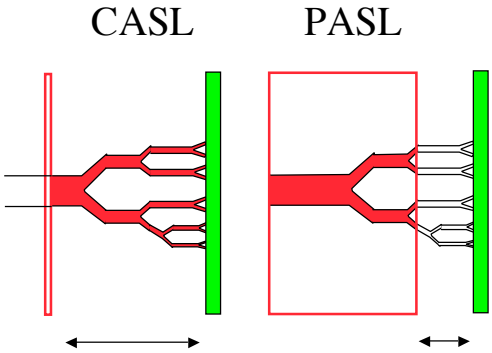
$\Delta M = CBF \cdot A_{eff}$

Goal: Make A_{eff} a well-controlled parameter that is robust to assumptions about physiological parameters.

Major Sources of Error for ASL

- Transit Delays
- Bolus Width in PASL
- Relaxation Effects - different relaxation rates for blood and tissue, time of exchange.
- Intravascular signal -- blood destined to perfuse more distal slices
- Offset bias to due imperfect subtraction of static tissue -- slice profiles, magnetization transfer effects

Transit Delays



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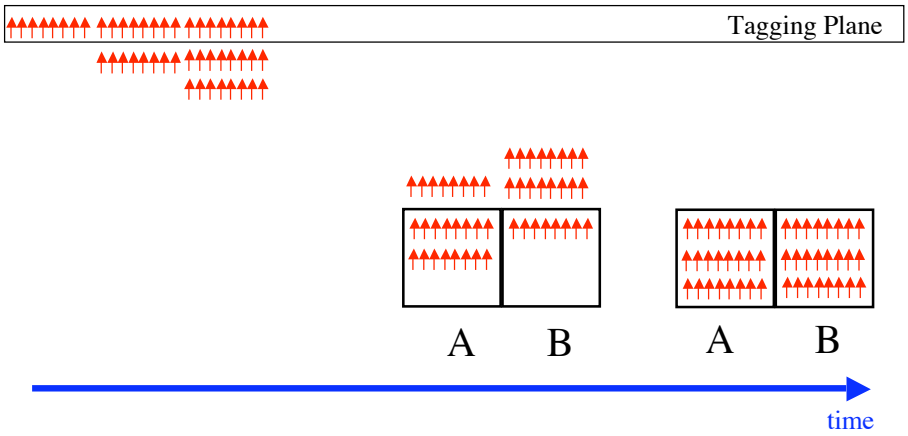
Controlling for Transit Delays in CASL



Voxels A and B have the same CBF, but voxel B will appear to have lower CBF if the measurement is made too early. Proper selection of post-labeling delay is key

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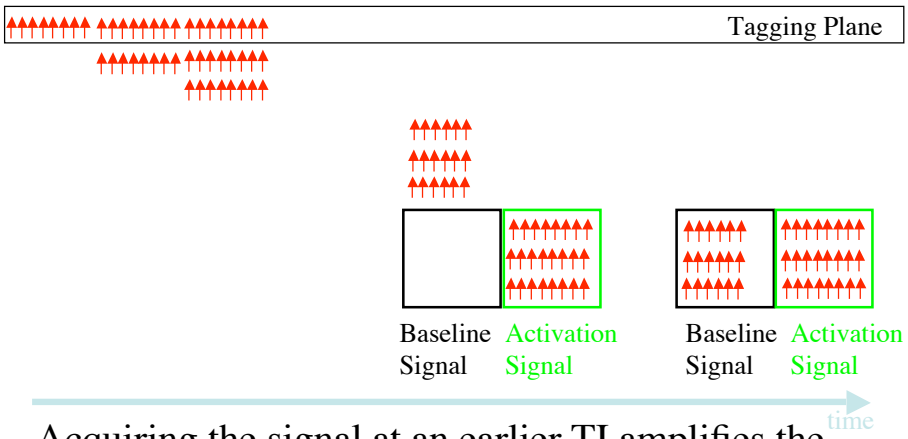
Amplifying Transit Delays Effects in CASL



Acquiring the signal at an earlier TI amplifies the difference between the activated state and the baseline state.

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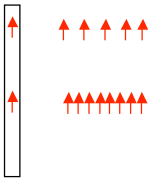
Arterial Bolus Width

CASL

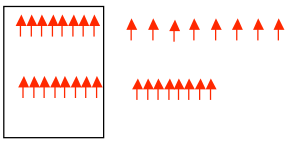


Baseline

Global flow increase

Temporal Width of bolus determined by the pulse sequence

PASL



Baseline

Global flow increase

time

Temporal Width of bolus determined by arterial velocity and size of tagging slab. Underestimates global flow changes.

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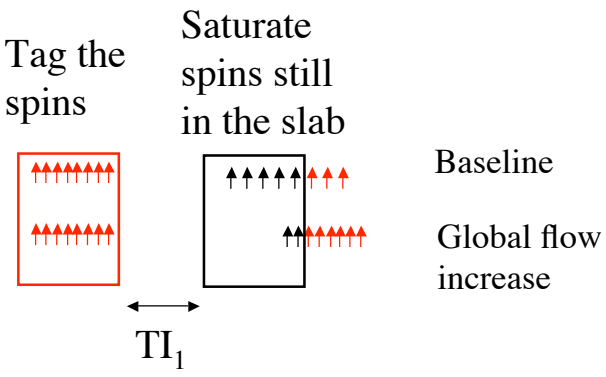
Defining Bolus Width in PASL (QUIPSS II)



Bolus temporal width = TI_1

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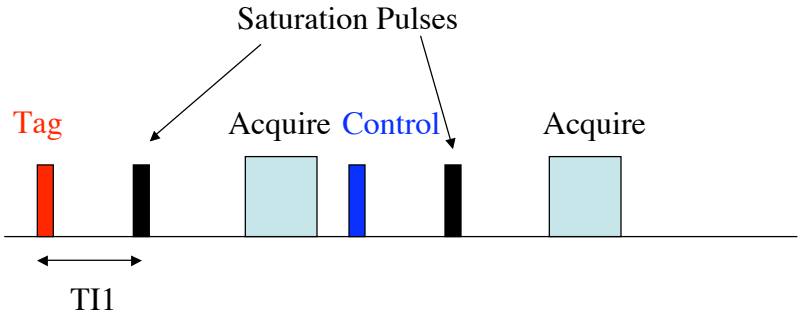
QUIPSS II Modification



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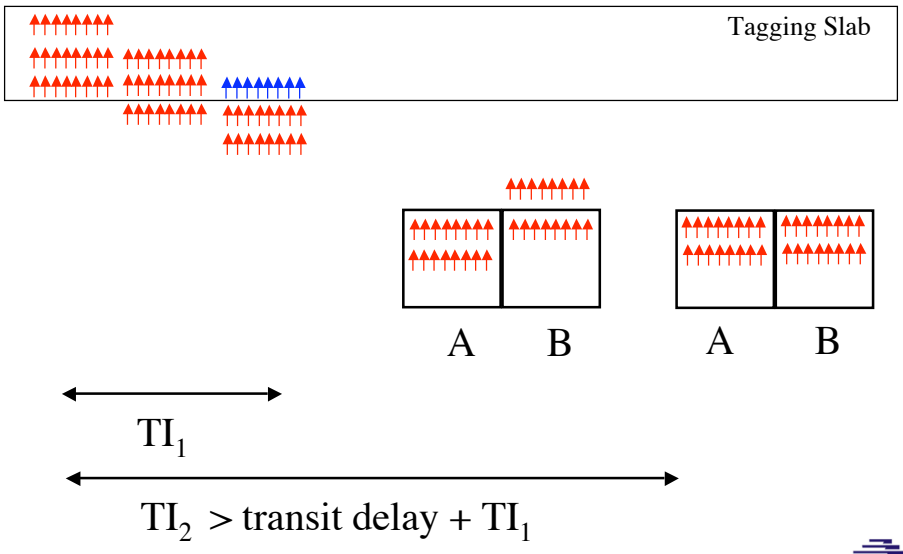
Controlling for Transit Delays in PASL



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Topics

1. What is Cerebral Blood Flow?
2. Arterial Spin Labeling
3. Data Processing
4. Applications

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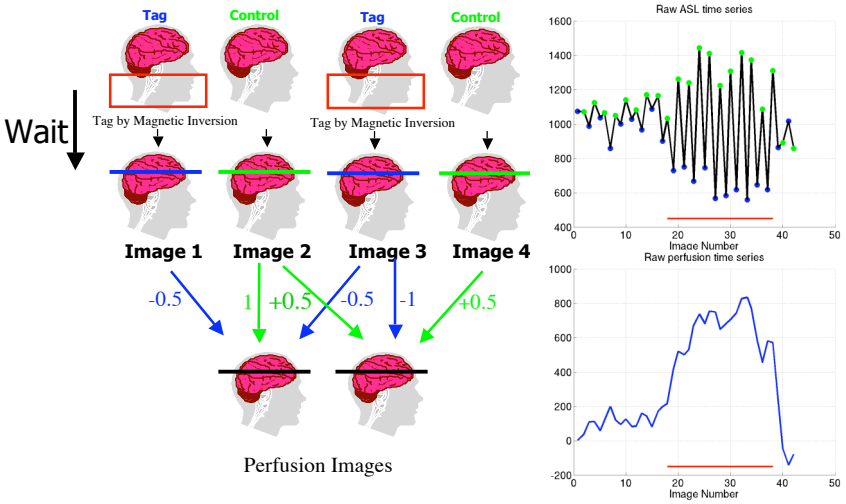
ASL Time Series



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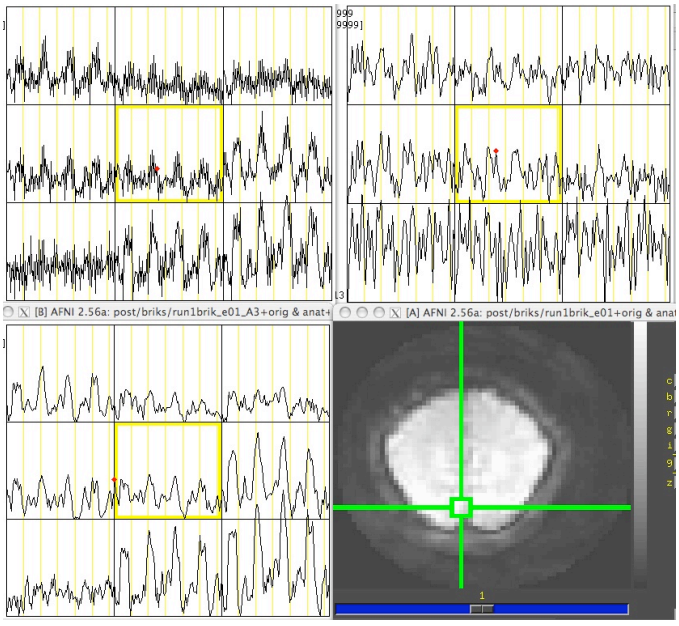
CBF and BOLD Time Series



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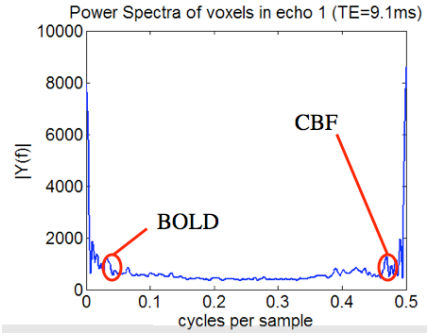
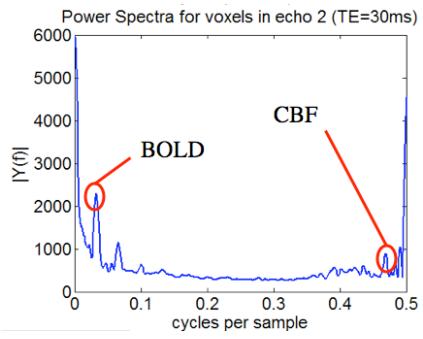

Power Spectra of voxels in echo 1 (TE=9.1ms)
|Y(f)|
cycles per sample
BOLD
CBF


Power Spectra for voxels in echo 2 (TE=30ms)
|Y(f)|
cycles per sample
BOLD
CBF

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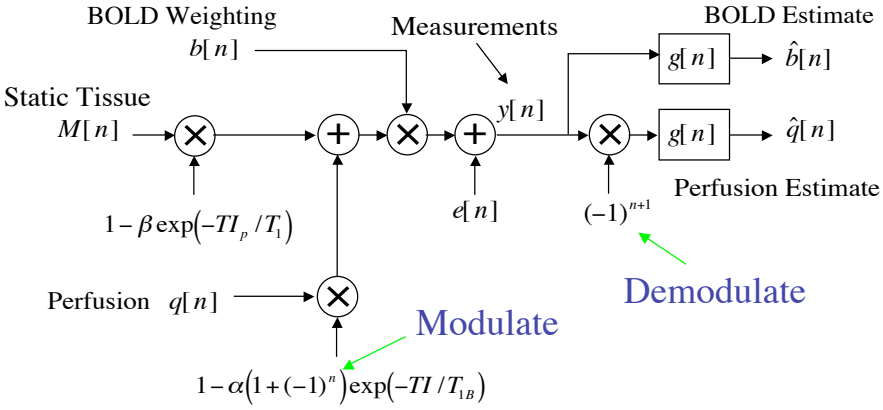
BOLD Weighting
b[n]
Measurements
BOLD Estimate
Static Tissue
M[n]
y[n]
g[n]
b̂[n]
g[n]
q̂[n]
Perfusion Estimate
1 − β exp(−TI_p / T_1)
e[n]
(−1)^{n+1}
Demodulate
Perfusion q[n]
Modulate
1 − α(1 + (−1)^n) exp(−TI / T_1B)

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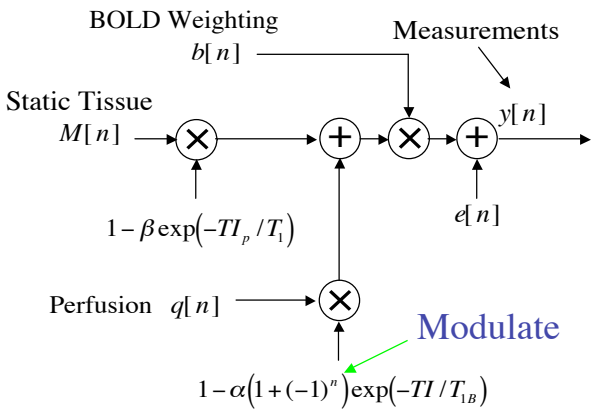

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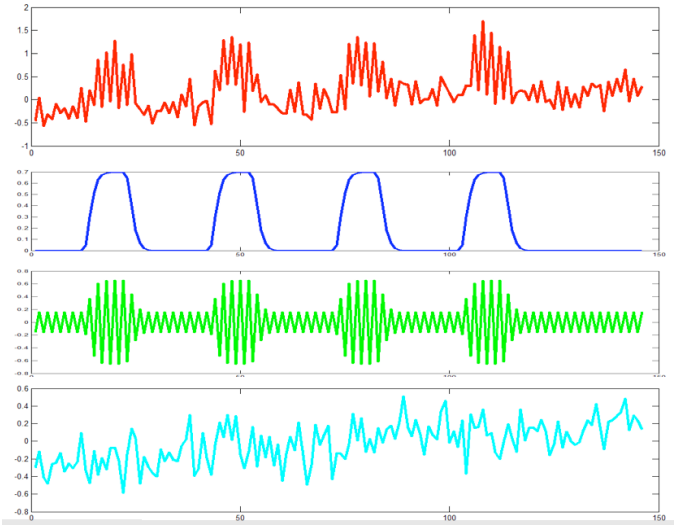
$$y = Xh_{BOLD} + MXh_{perf} + Sa + Pc + e$$



Hernandez-Garcia et al 2005; Roller et al 2006, Abstract 540

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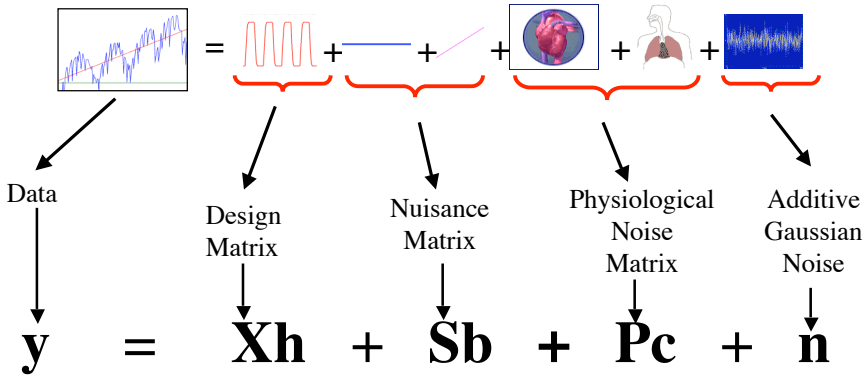
Removing Physiological Noise

Modeling a fMRI signal using a General Linear Model (GLM)



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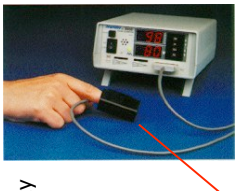
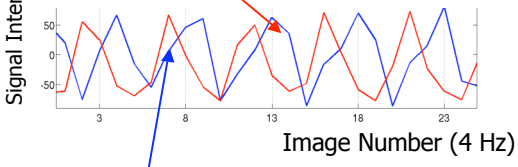
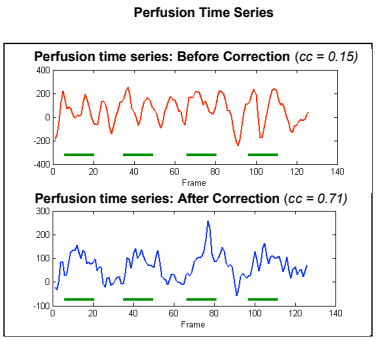
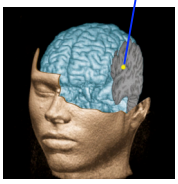
Removing Physiological Noise









Pulse Ox (finger)

Cardiac component estimated in brain

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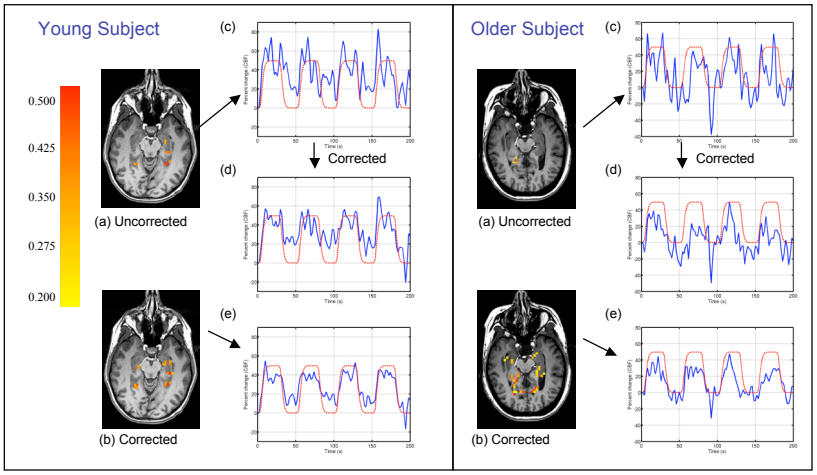
Removing Physiological Noise



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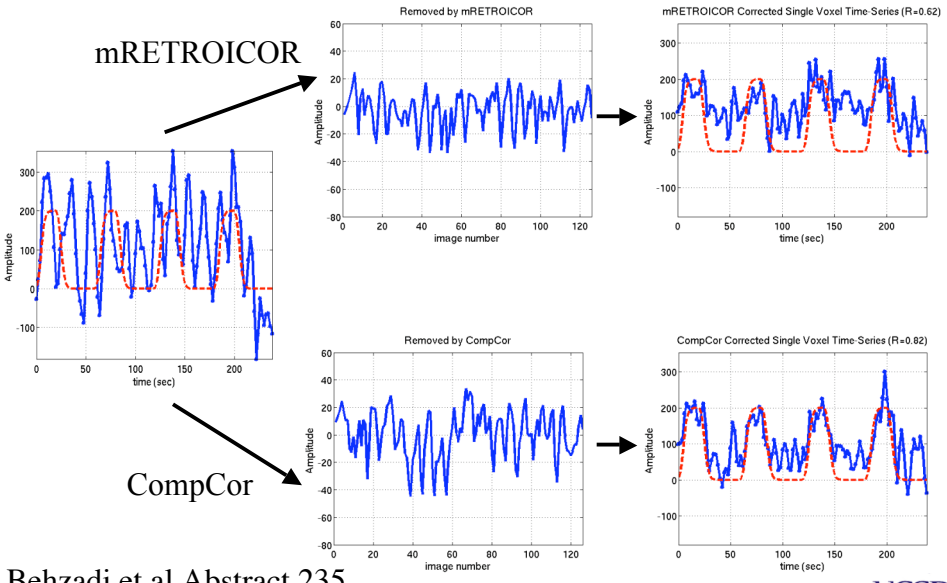
Principal Components Based Correction



Behzadi et al Abstract 235

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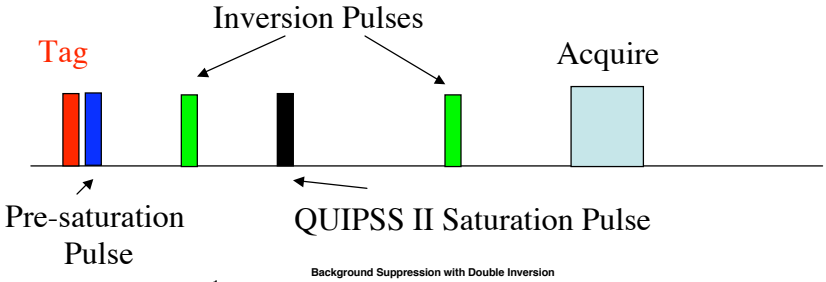
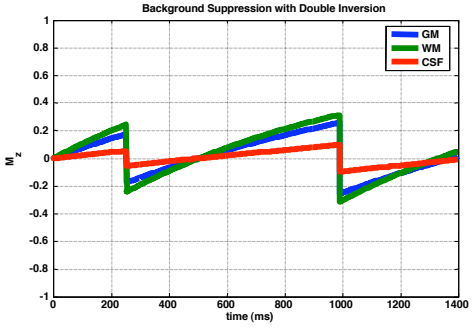
Background Suppression





Nulling of static tissue element

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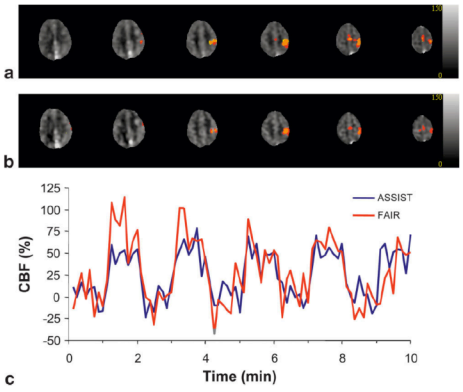
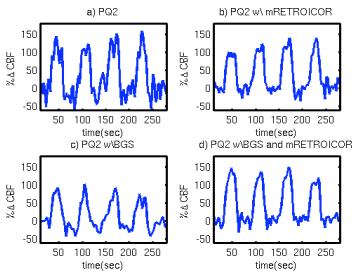
Background Suppression



St. Lawrence et al 2005

Visual Study Results



Behzadi et al Abstract 3295

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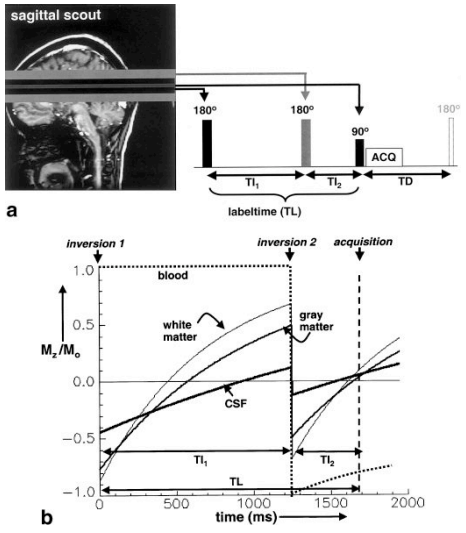
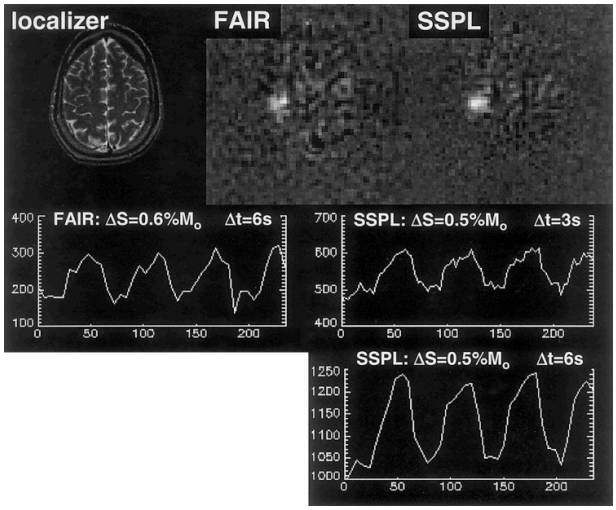
Single Shot Perfusion Labeling (SSPL)



From JA Duyn et al, MRM 2001

Single Shot Perfusion Labeling (SSPL)



From JA Duyn et al, MRM 2001

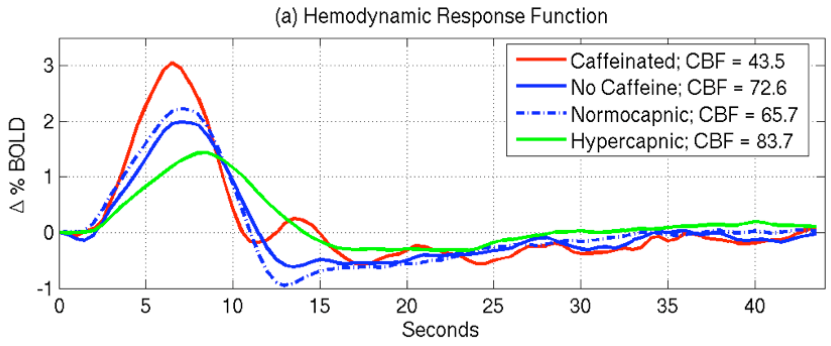
Topics

1. What is Cerebral Blood Flow?
2. Arterial Spin Labeling
3. Data Processing
4. Applications

Applications of ASL

1. Quantitative Measures of both baseline and functional CBF
2. Multimodal measures of CBF, BOLD, (and CBV) to estimate functional changes in oxygen metabolism.
3. Experiments with long task periods
4. Mapping of functional activity.

Baseline CBF Modulates the BOLD Response



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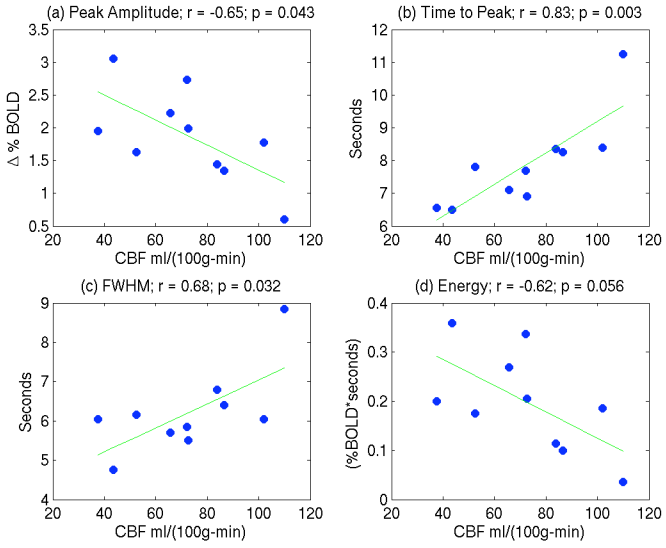
Effect of Baseline CBF on BOLD Response



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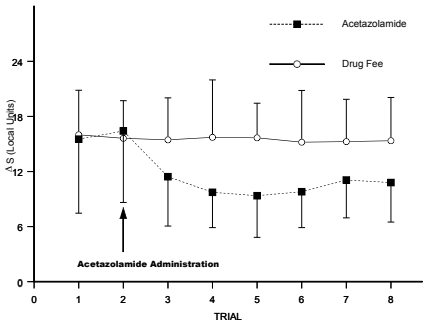
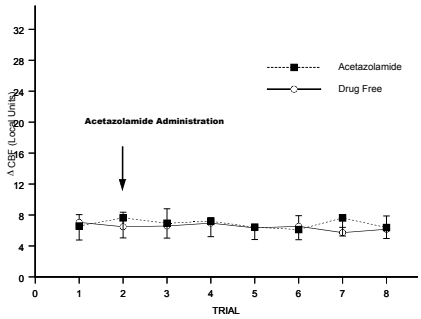
Effect of Acetazolamide on BOLD and CBF

Percent BOLD Changes



CBF Changes



Brown et al 2003

Effect of Hypercapnia on BOLD and CBF

Table 2
Across-subject average activation-induced changes in BOLD and CBF signals in VC and MC cortices during normocapnia, NC (column 2) and during the maximal HC-induced vasodilation condition, MAXHC (column 3)

	ΔS^{act}_{NC} (%)	ΔS^{act}_{MAXHC} (%)	Change (%)
$BOLD_{MC}$	0.99 ± 0.01	0.42 ± 0.01	−57.0 ± 1.1
$BOLD_{VC}$	1.15 ± 0.01	0.51 ± 0.01	−55.4 ± 1.1
CBF_{MC}	45.6 ± 0.57	39.3 ± 0.8	−13.9 ± 2.0
CBF_{VC}	40.0 ± 0.43	39.2 ± 0.6	−2.0 ± 1.9

For reference, the percent changes between these two conditions are listed in column 4.

Stefanovic et al 2006

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1. Quantitative Measures of both baseline and functional CBF
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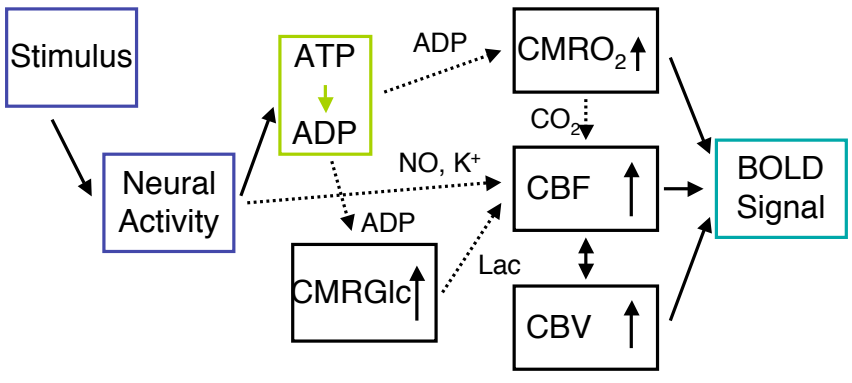
BOLD Dynamics



Credit: Rick Buxton

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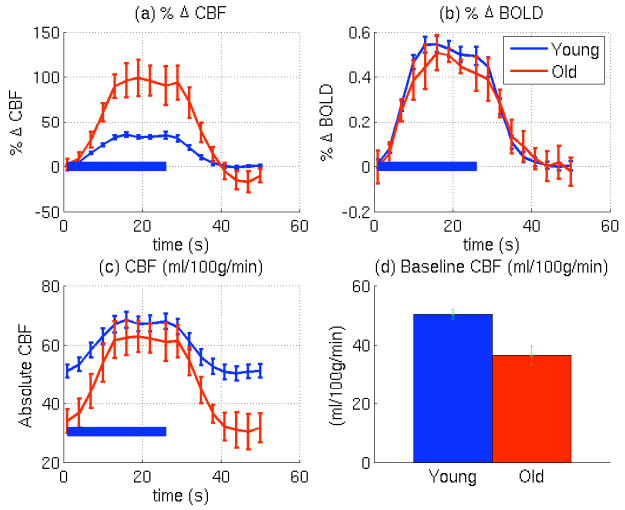
Effect of Age on CBF and BOLD Responses in the Hippocampus



Restom et al, Abstract 377

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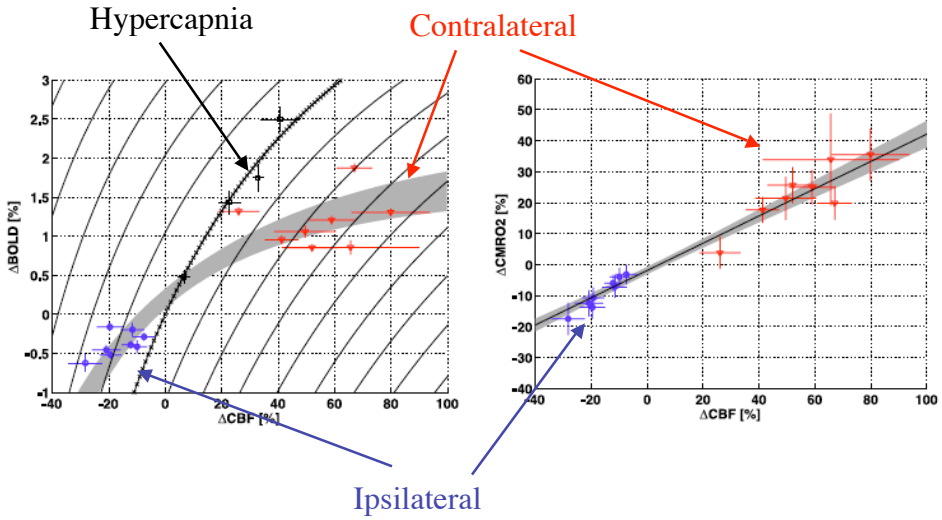
Estimation of $CMRO_2$ Changes with Combined CBF and BOLD measures



Stefanovic et al 2004

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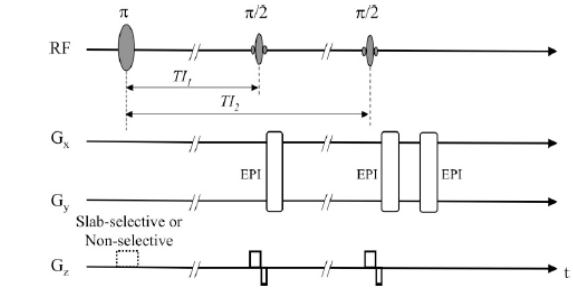
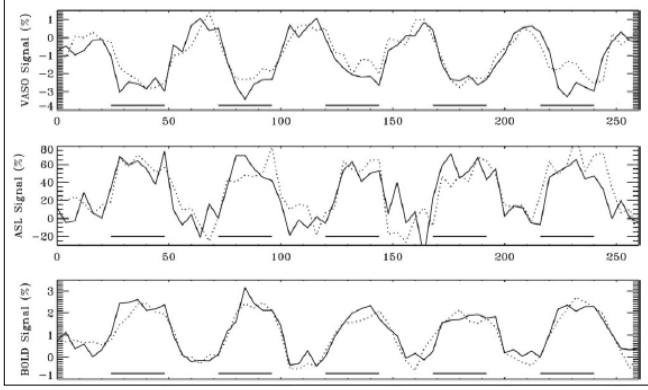


Simultaneous measure of CBF, BOLD, and VASO (CBV)

Yang et al 2004



VASO

CBF

BOLD

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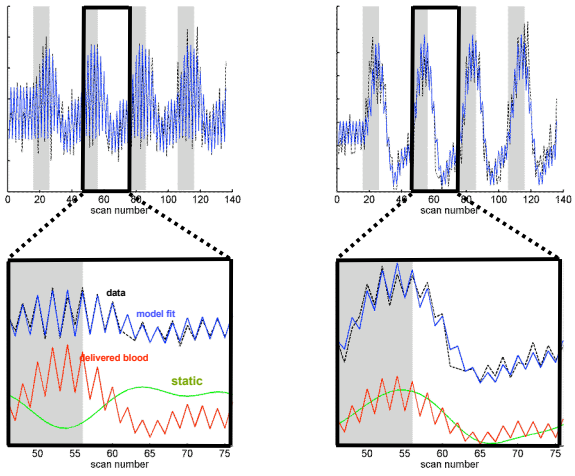
Bayesian Analysis of dual -echo ASL data
(Woolrich et al. Abstract 538)

TE=9 msecs

TE=30 msecs



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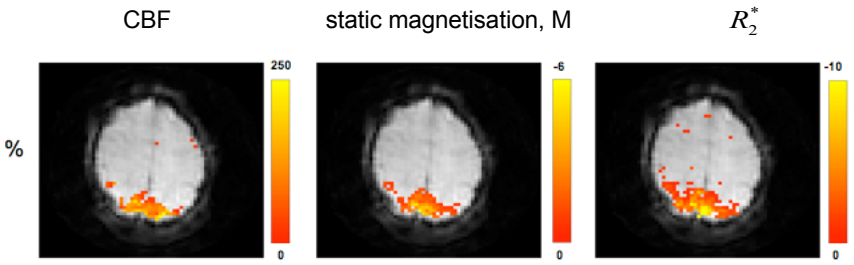
Bayesian Analysis of ASL data (Woolrich et al. Abstract 538)



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Applications of ASL

1. Quantitative Measures of both baseline and functional CBF
2. Multimodal measures of CBF, BOLD, (and CBV) to estimate functional changes in oxygen metabolism.
3. Experiments with long task periods
4. Mapping of functional activity.

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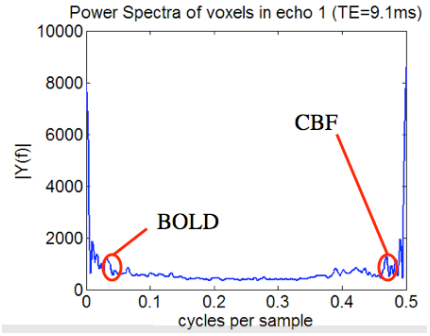

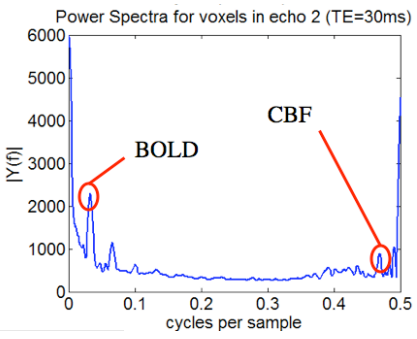

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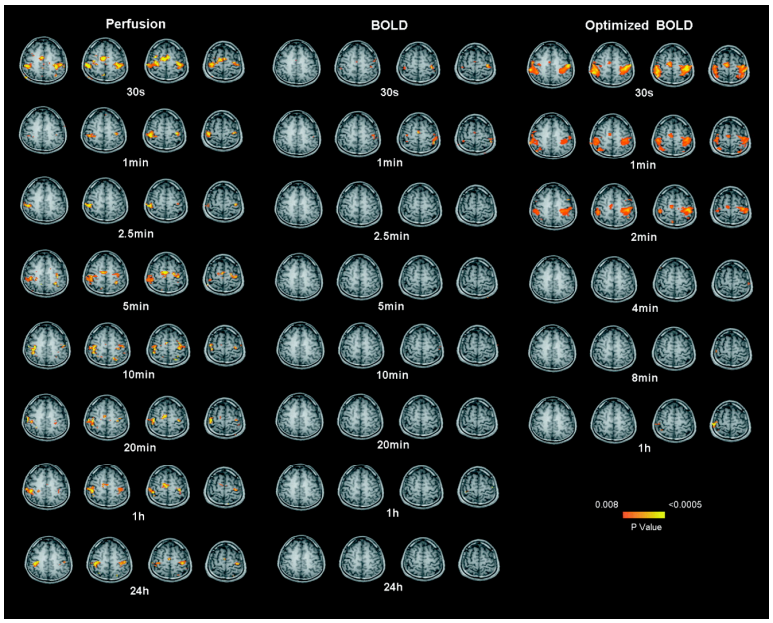
ASL with very low task frequencies - Wang et al., MRM 2003



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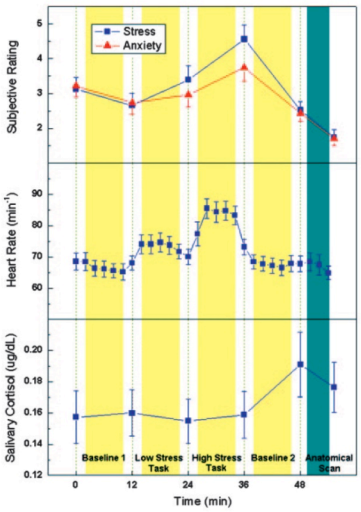
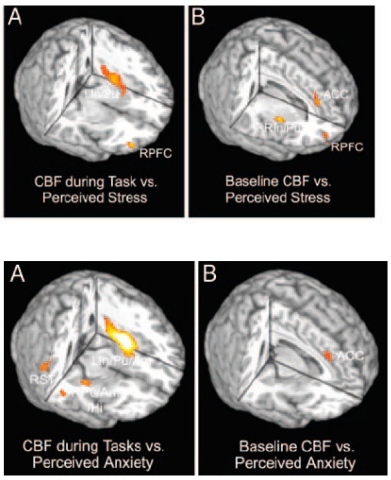
ASL Imaging of Stress- Wang et al., PNAS 2005





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ASL Imaging of Natural Vision; Rao et al, Abstract 167

CBF and BOLD activations during viewing of Road Runner "Gee W-h-I-z-z-z-z-z-z" Cartoon

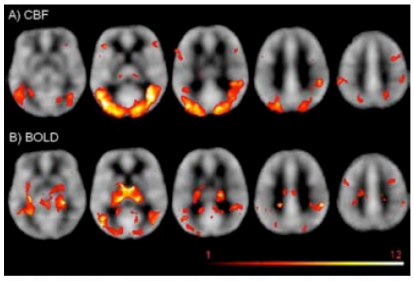

Fig.2. CBF and BOLD activations during freely viewing movie compared to baselines.

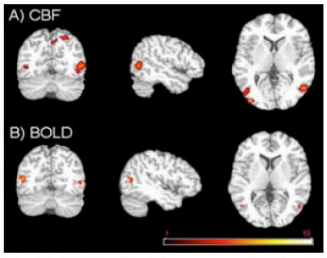

Fig.3. MT activations associated with motion perception.

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Applications of ASL

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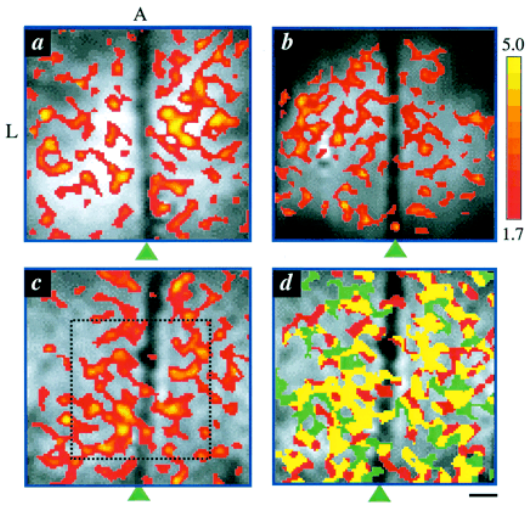

ASL Mapping of Cortical Columns in Cat Visual Cortex
Duong et al, PNAS, 2001.
FAIR sequence, TI = 1500 ms, TR 3000 ms

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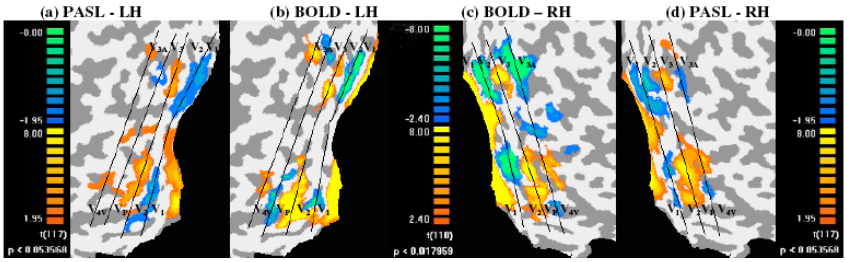

Z. Liu and X. Hu, Abstract 891

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Summary

1. Arterial spin labeling can provide non-invasive quantitative measures of baseline and functional CBF.

2. Since CBF is a well-defined physiological quantity, measures of CBF can be used to improve the interpretation of fMRI studies, especially for clinical populations.

3. The combination of CBF measures with BOLD (and CBV) measures can be used to estimate changes in oxygen metabolism.

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Acknowledgements

Yashar Behzadi
Rick Buxton
Wen-Ming Luh
Joanna Perthen
Khaled Restom
Eric Roller
Mark Woolrich
Eric Wong

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