

Perfusion Imaging

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Perfusion Imaging: Outline

- Introduction
- Dynamic Susceptibility Contrast (DSC)
 - Method, Quantification
 - Examples
- Arterial Spin Labeling (ASL)
 - Method, Labeling Techniques, Quantification
 - Examples
- Functional imaging with perfusion

Definitions

Perfusion – capillary blood flow delivered to tissue

MRI methods can assess

- blood flow – ml blood / min / 100 g of tissue
- blood volume – ml blood / 100 g of tissue
- mean transit time – seconds

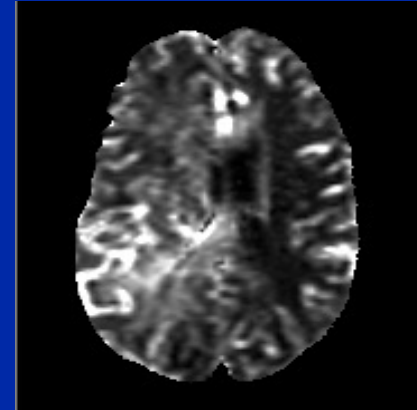
Normal values for brain

	Gray Matter	White Matter
CBF (ml / min / 100 g)	60 - 80	20 - 30
CBV (ml / 100 g)	4 - 6	2 - 4
MTT (s)	4 - 5	5 - 6

Perfusion MRI

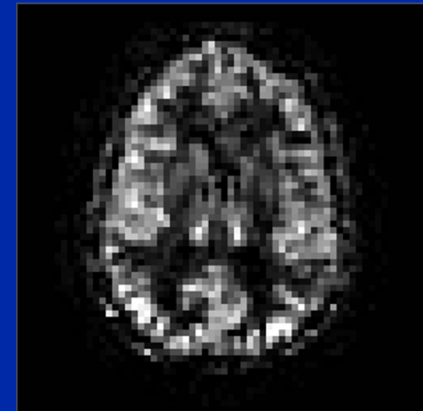
■ Dynamic Susceptibility Contrast (DSC)

- Requires contrast injection
- Large signal changes, Fast
- Single application (clinical)



■ Arterial Spin Labeling (ASL)

- No external contrast required
- Small signal change, Slow
- Multiple measurements (clinical and research)



Dynamic Susceptibility Contrast (DSC)

Monitor passage of Gadolinium contrast through tissue using rapid T2*/T2 weighted MRI



Imaging

Gradient Echo EPI

TR \sim 1.5- 2 s

TE = 30 -50 ms

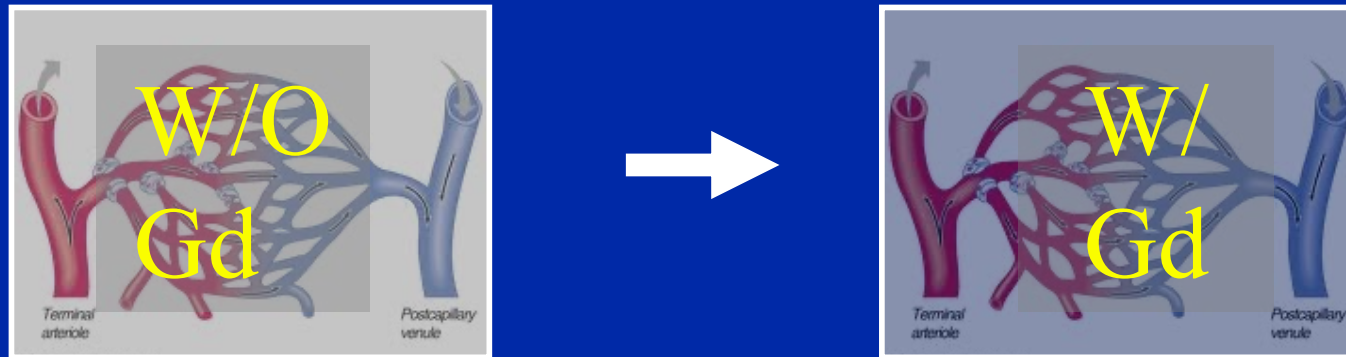
\sim 1.5 min

Bolus Injection

Gd 0.1 - 0.2 mmol/kg

DSC - Mechanism

Gd Chelates: Paramagnetic, Intravascular



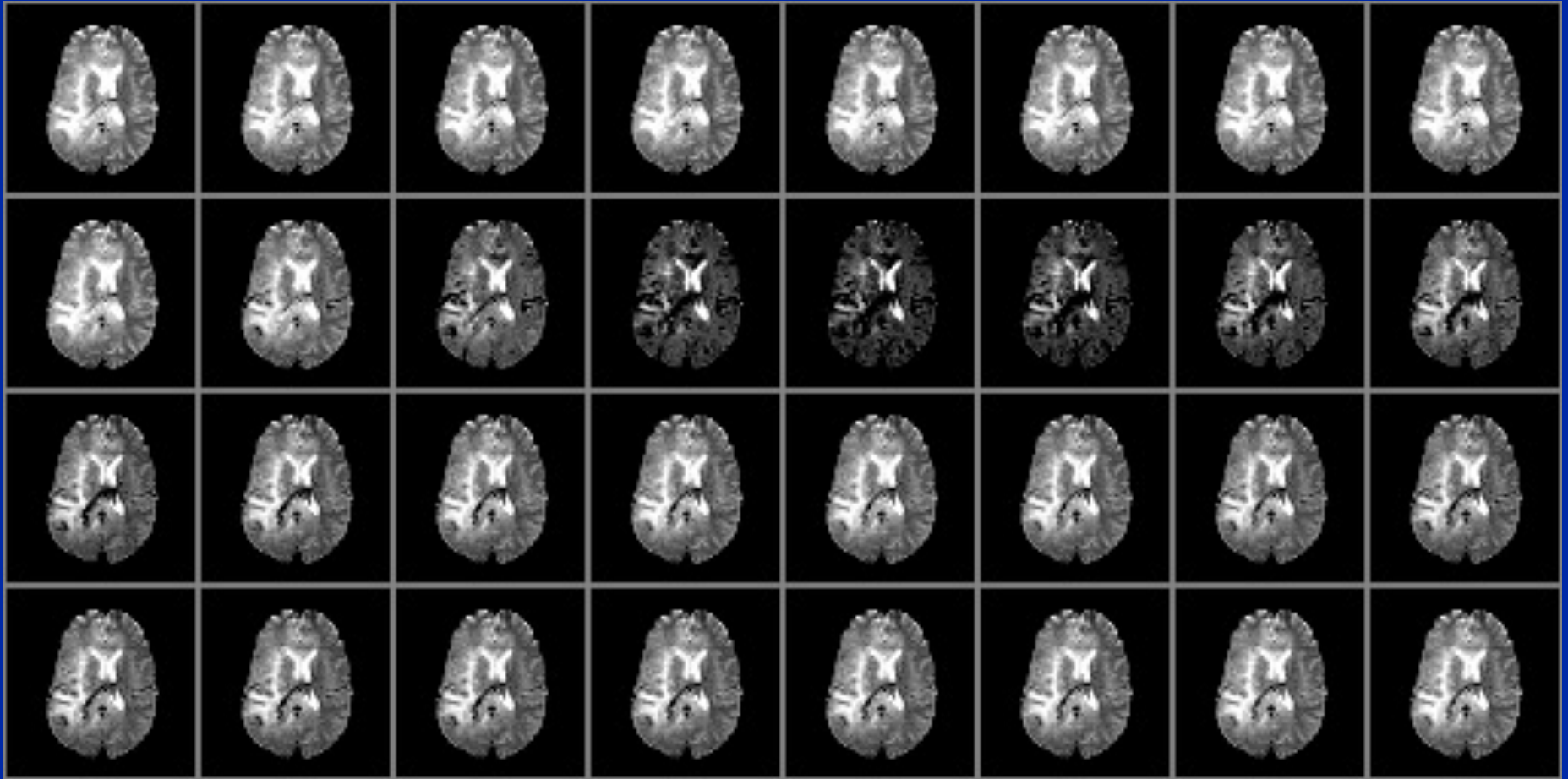
Tissue/ Blood $\Delta\chi$ ↑

Field Inhomogeneity ↑

R_2^* ($=1/T_2^*$) ↑

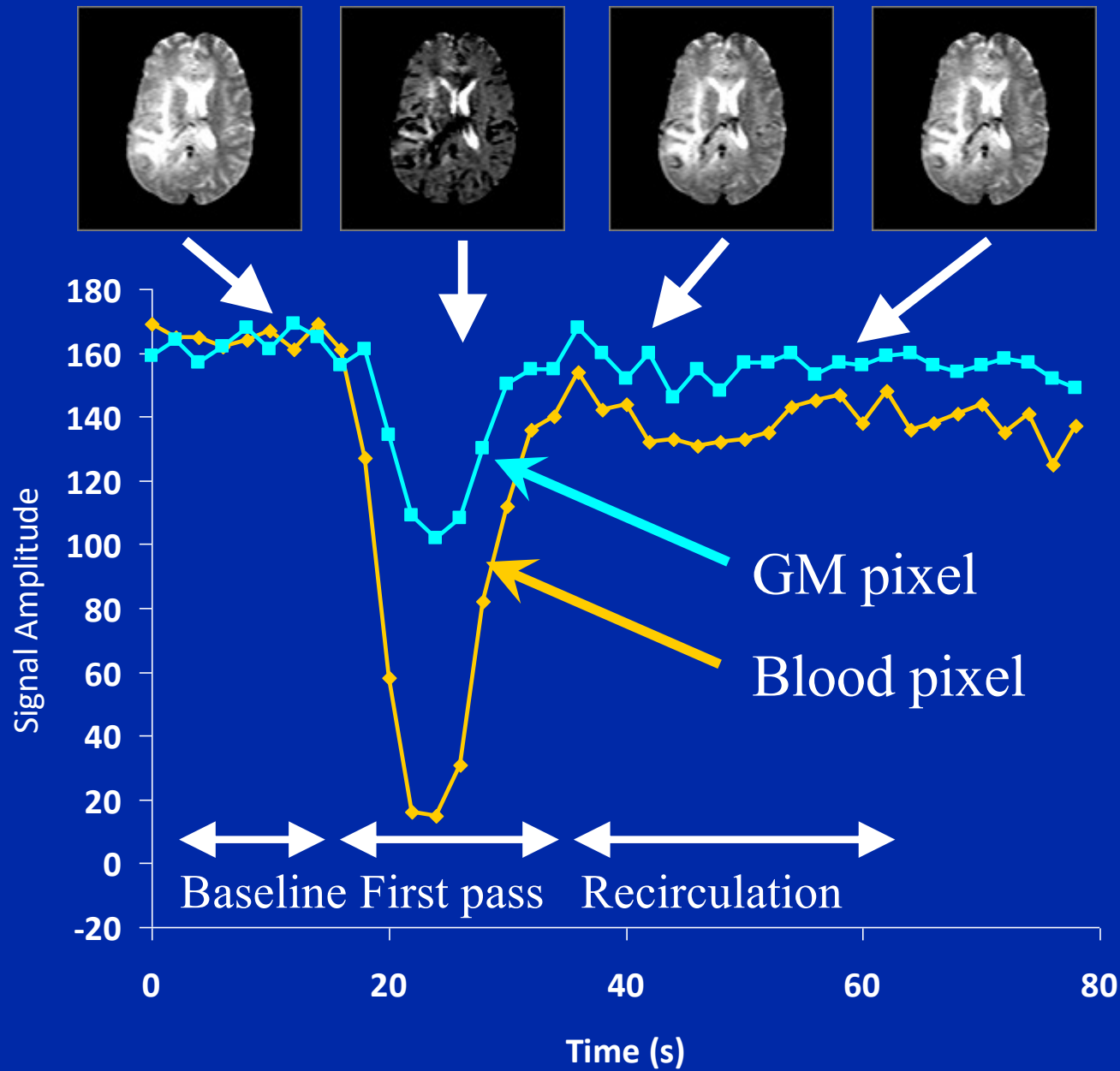
GE/SE MRI Signal ↓

DSC – Passage of Gd through tissue



1.5 T, 0.1 mmol/kg, GE- EPI, TE = 50 ms, TR = 2 s

DSC – Signal vs Time



DSC: Signal loss to Concentration

$$\Delta R_2^* = k \cdot C$$


$$S_c = S_0 \cdot \exp(-TE \cdot \Delta R_2^*)$$

C – Gd concentration

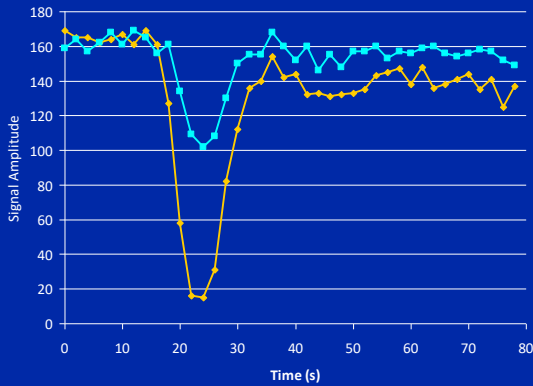
S_c – Signal with Gd

S_0 – Baseline signal without Gd

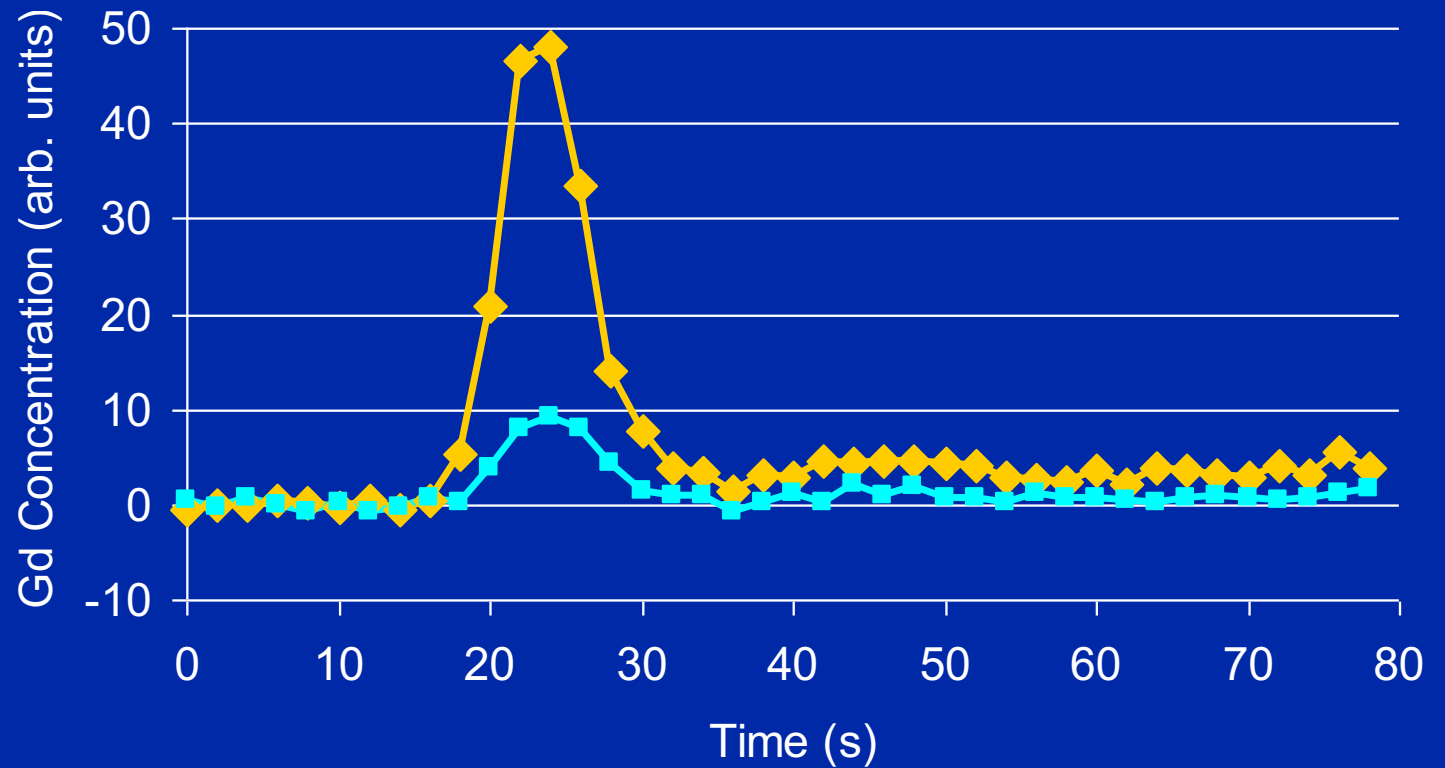
k – proportionality constant


$$C = -\frac{1}{k \cdot TE} \ln \frac{S_c}{S_0}$$

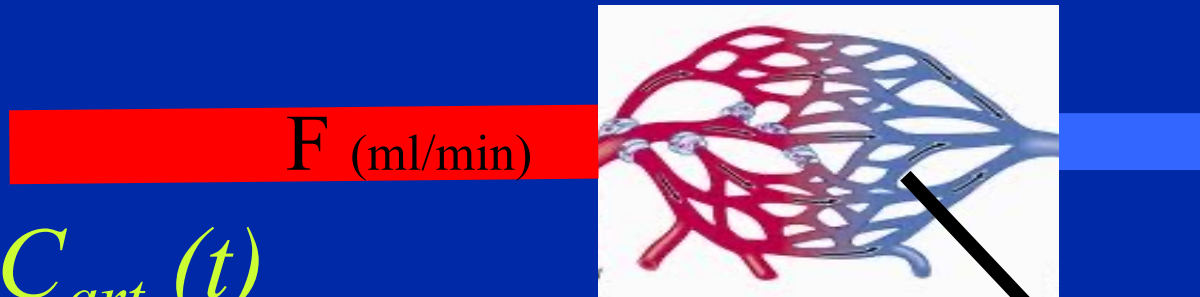
DSC: Concentration vs time



$$C = -\frac{1}{k \cdot TE} \ln \frac{S_c}{S_0}$$

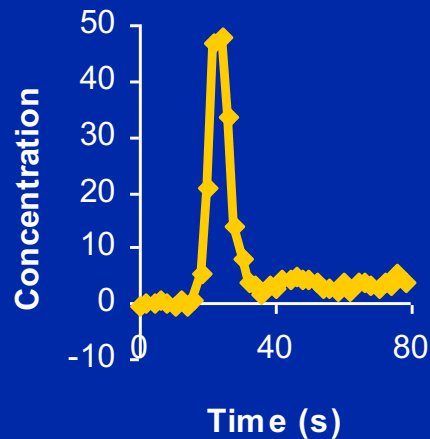


DSC – CBV, CBF, MTT ?



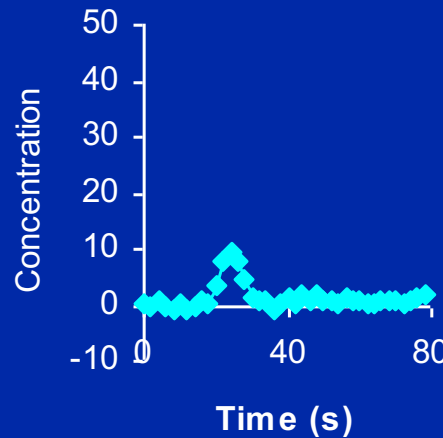
$$C_{art}(t)$$

Arterial
input
function
(AIF)



$$C_{tis}(t)$$

Tissue
Response



Tracer
Kinetic
Theory

$$MTT = \frac{CBV}{CBF}$$

DSC- Calculation of CBV



$$CBV = \frac{k_H \int C_{tis}(t) \cdot dt}{\rho \int C_{art}(t) \cdot dt}$$

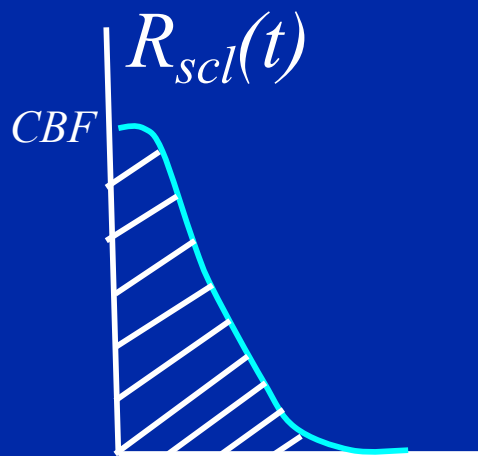
The equation is followed by a large white arrow pointing to two graphs. The top graph shows a cyan line representing tissue concentration $C_{tis}(t)$ over time, with a small peak shaded in blue and white. The bottom graph shows a yellow line representing arterial concentration $C_{art}(t)$ over time, with a sharp peak shaded in yellow and white.

DSC- Calculation of CBF and MTT



$$C_{tis}(t) = CBF \cdot \int_0^t C_{art}(\tau) R(t - \tau) d\tau$$

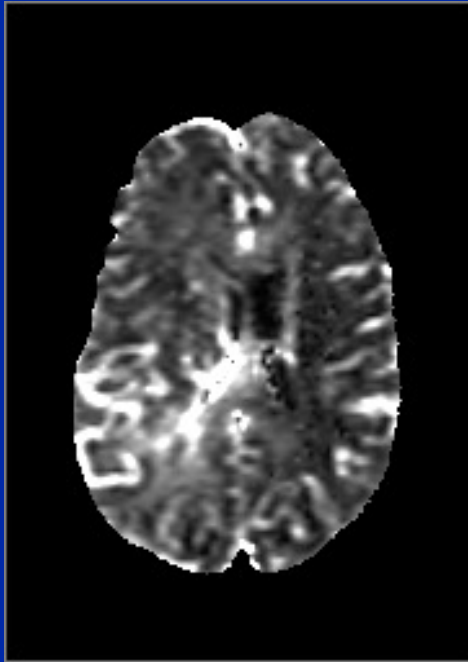
$$R_{scl}(t) = Deconvol(C_{tis}(t), C_{art}(t))$$



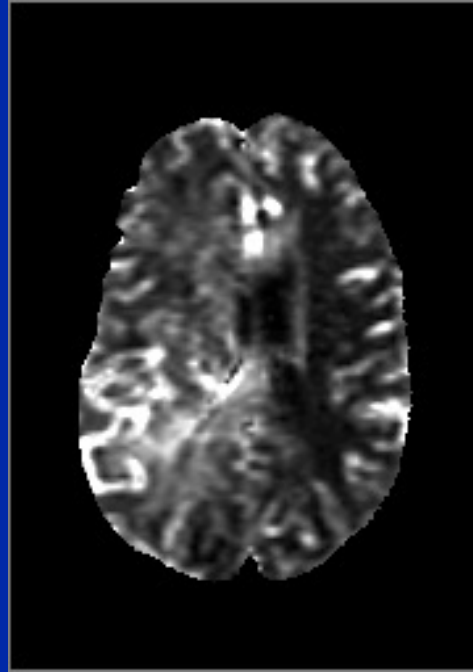
$$CBF = R_{scl}(0)$$

$$MTT = \frac{CBV}{CBF} \text{ and } \frac{\int R_{scl}(t) \cdot dt}{R_{scl}(0)}$$

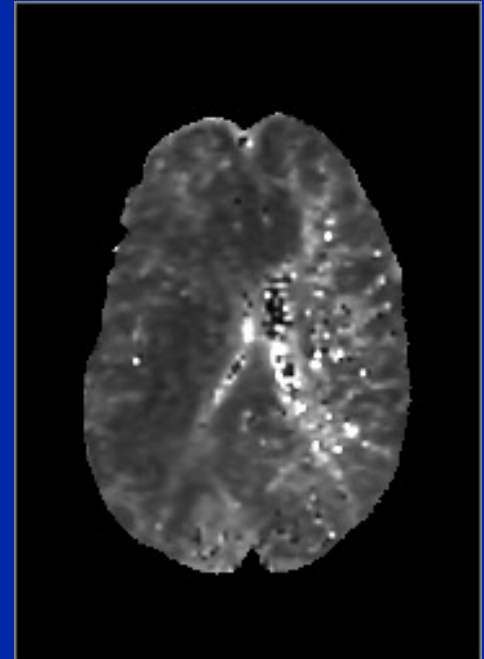
DSC – CBV, CBF, MTT maps



CBV

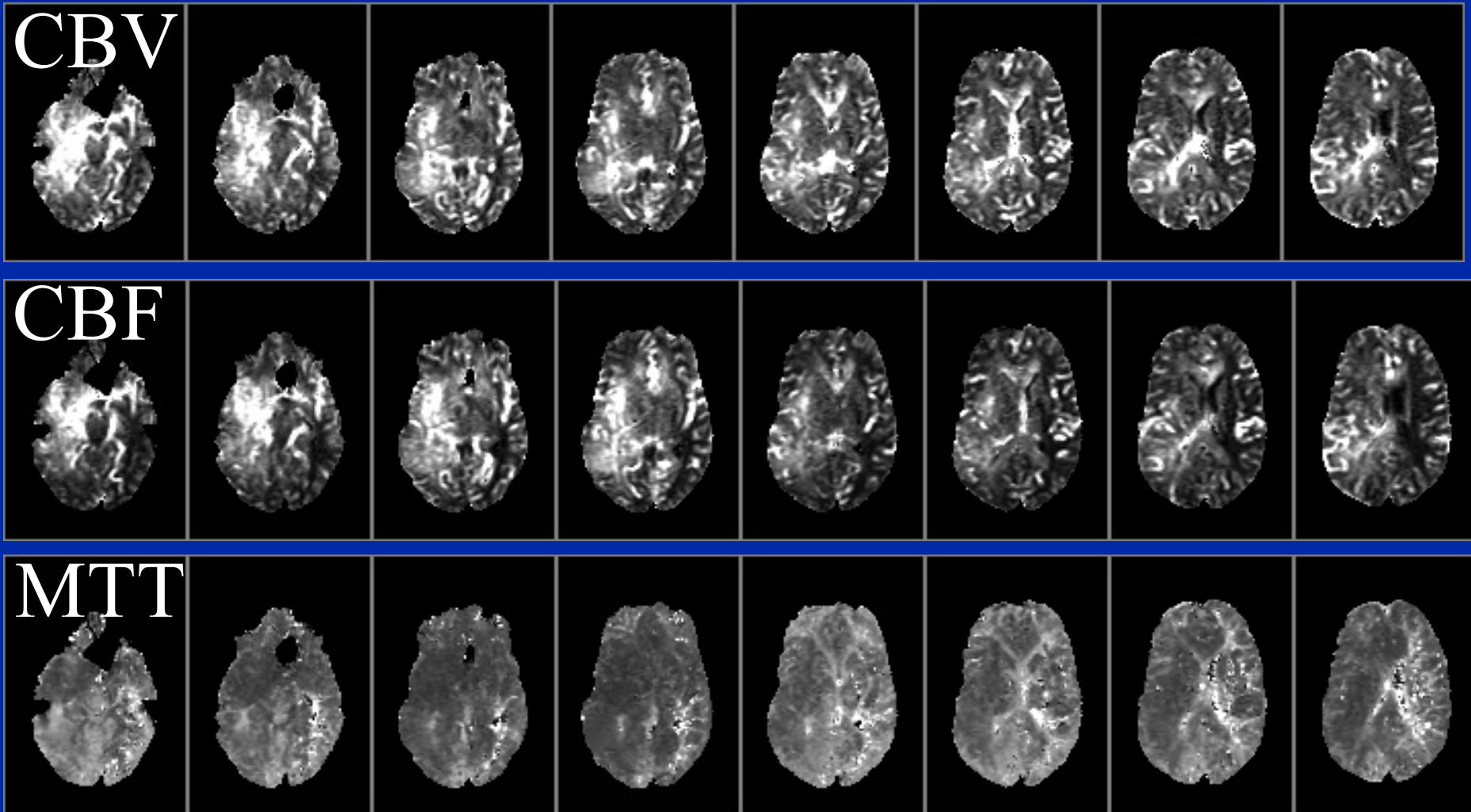


CBF

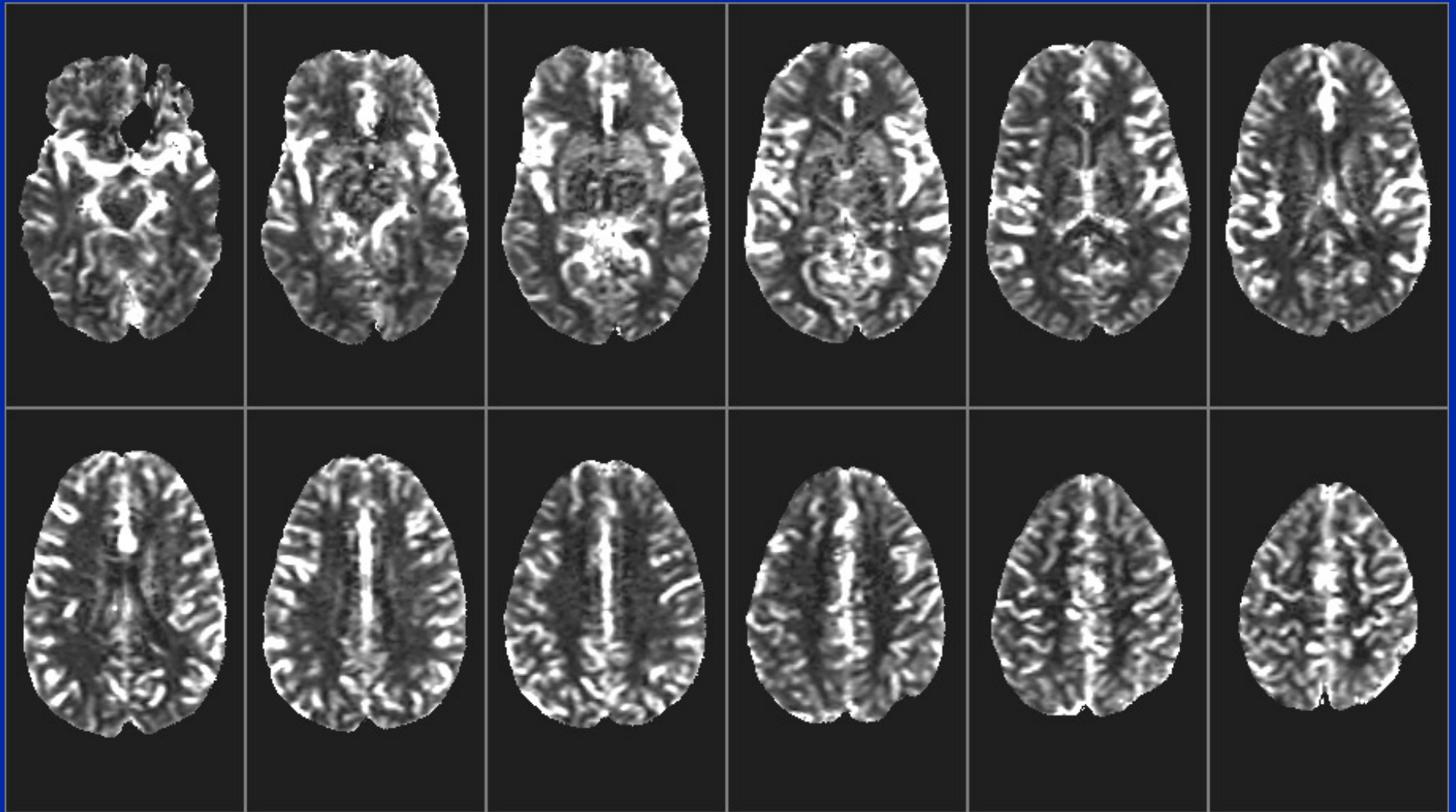


MTT

DSC – CBV, CBF, MTT maps



DSC – CBF maps



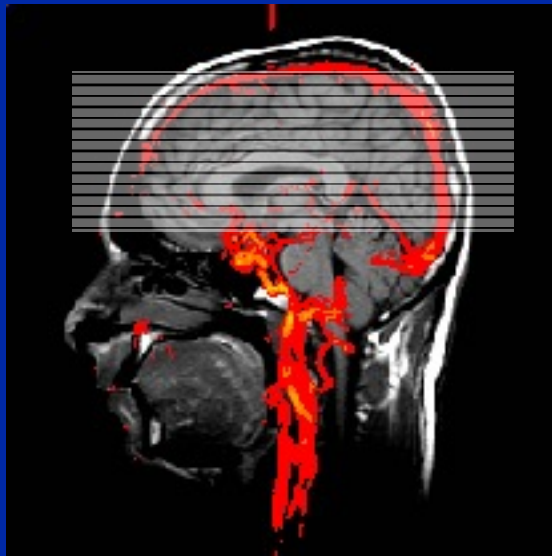
1.5 T, 0.1 mmol/kg, GE- EPI, TE = 50 ms, TR = 2 s

DSC: Quantification Issues

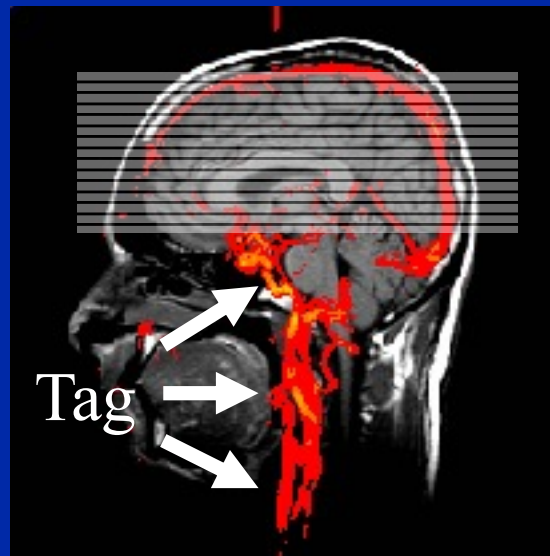
- Accuracy of $\Delta R_2^* \Leftrightarrow C$ relationship
 - Arteries (quadratic) and tissue (linear)
- Arterial input function (AIF) determination
 - Partial volume, vessel orientation effects
 - Truncation of the peak
 - Dispersion between measurement site and tissue (local AIF)
- Deconvolution errors
 - Sensitivity to noise
 - Sensitivity to bolus arrival times
- ◆ Absolute CBF/CBV require use of scaling factors determined separately

Arterial Spin Labeling (ASL)

Measure the change in MRI signal due to magnetic labeling (tagging) of inflowing blood



Control



Label

=> Perfusion
Maps

LABELING

0.5 – 2.5 s

1- 2 s

IMAGING

0.3 - 0.7 s

2D/3D

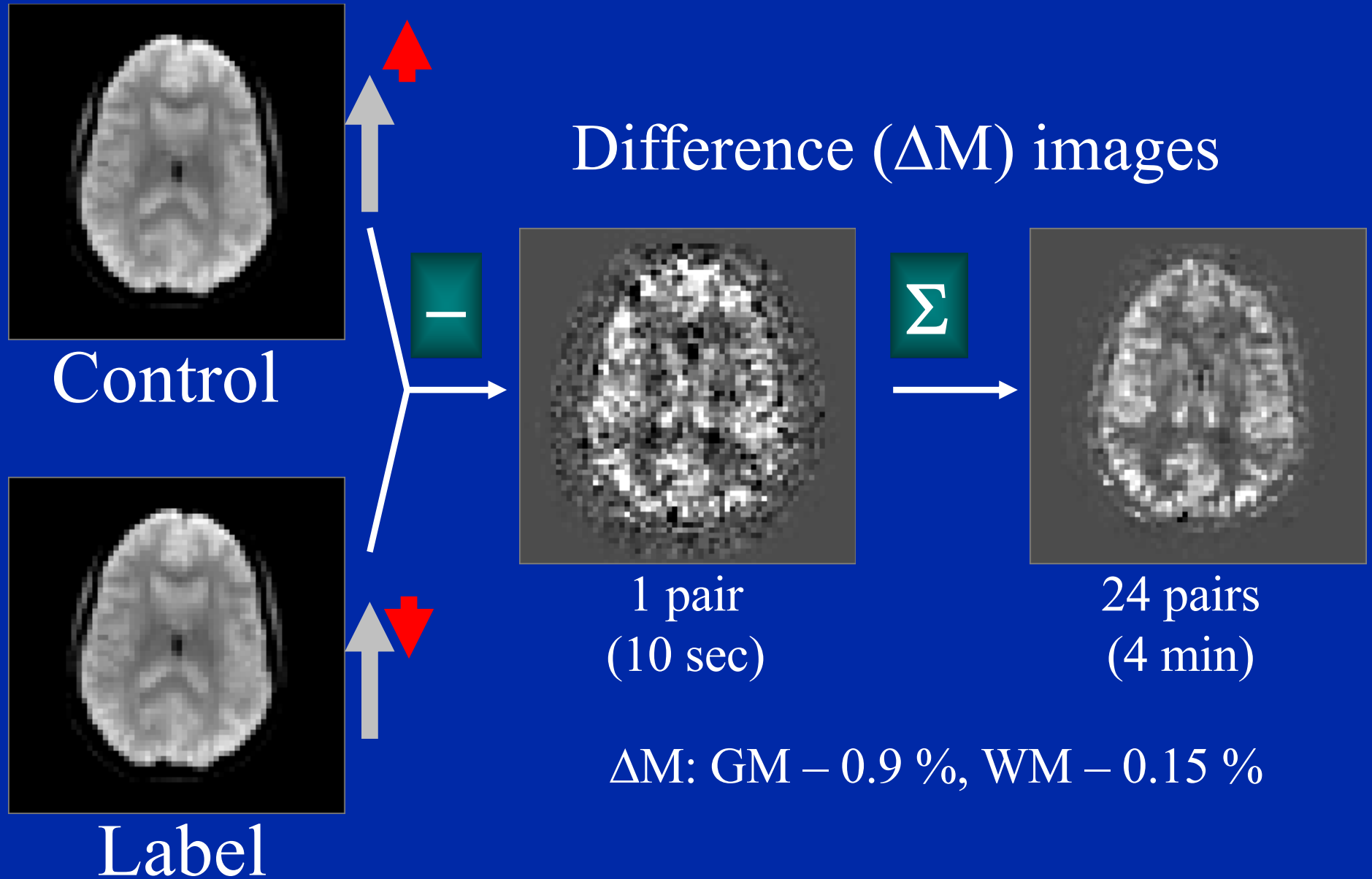
EPI/SPIRAL

TR ~ 2 - 5 s

TE = minimum

~ 4-5 minutes

ASL: Control/Label/Difference



ASL: Labeling Strategies

■ Pulsed ASL (PASL)

- Wide labeling slab
- Created by a short pulse (milliseconds)
- Input function – decaying exponential

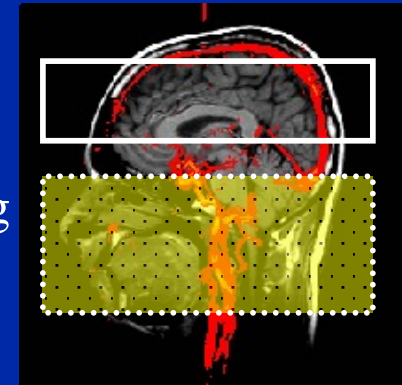
(T1 of blood)

■ Continuous ASL (CASL)

- Narrow labeling plane
- Long duration (seconds)
- Input function – constant

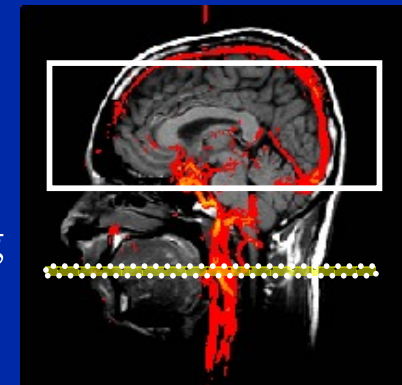
PASL

Labeling
Slab



CASL

Labeling
Plane



ASL- Quantification of CBF

One compartment model: Labeled blood stays in the vasculature

PASL

$$CBF_{PASL} = \frac{\lambda}{2\alpha_0} \cdot \frac{\exp(w \cdot R_{1a})}{\tau \cdot \exp(-\tau \cdot R_{1a})} \cdot \frac{\Delta S}{S^{eqm}}$$

CASL

$$CBF_{CASL} = \frac{\lambda R_{1a}}{2\alpha_0} \cdot \frac{\exp(w \cdot R_{1a})}{[1 - \exp(-\tau \cdot R_{1a})]} \cdot \frac{\Delta S}{S^{eqm}}$$

R_{1a} – relaxation rate of arterial blood

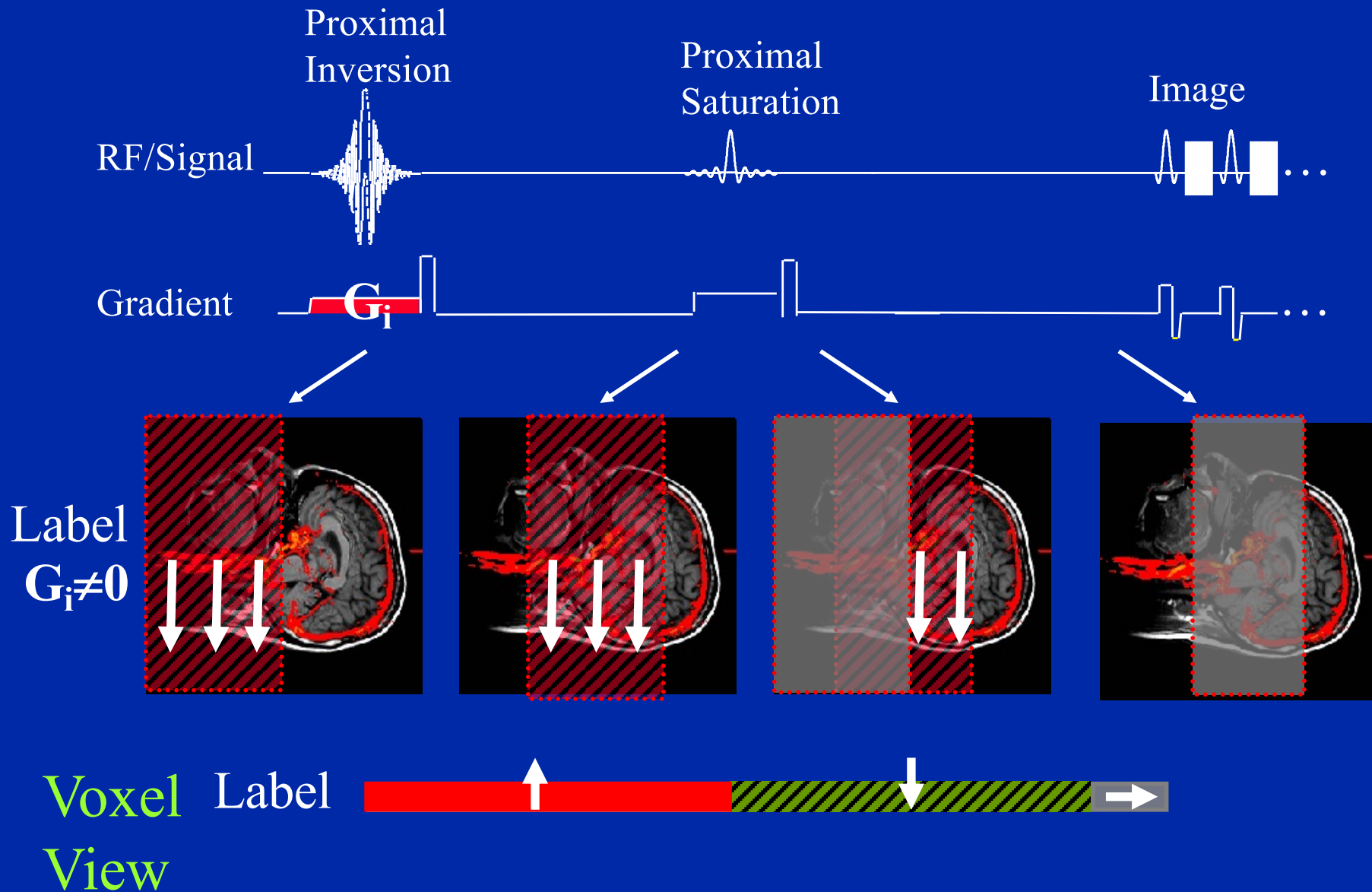
α_0 – labeling efficiency

τ – labeling time

w – post labeling delay

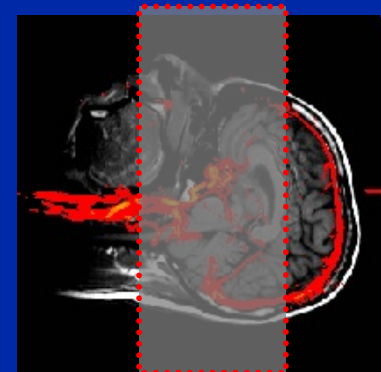
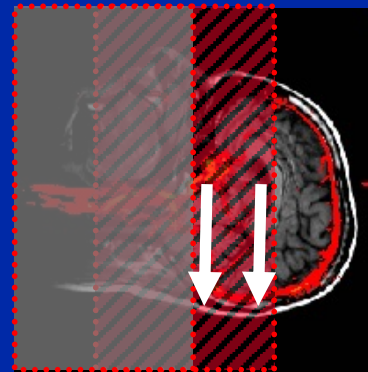
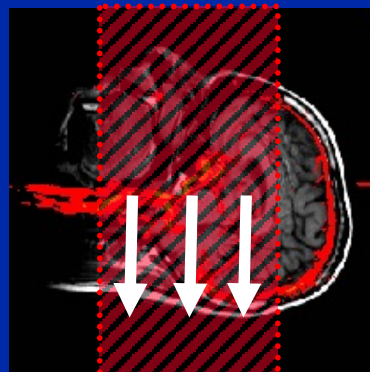
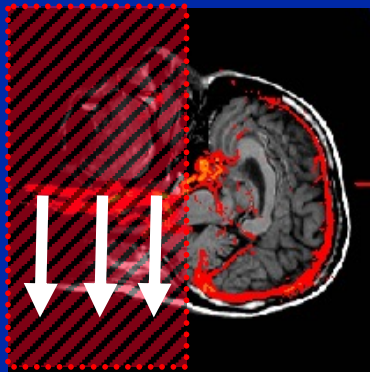
λ – brain/blood partition coefficient of water

ASL: Pulsed Labeling (QUIPSS II)

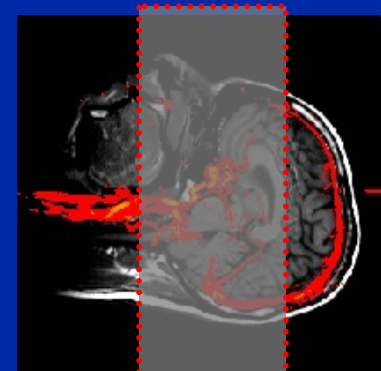
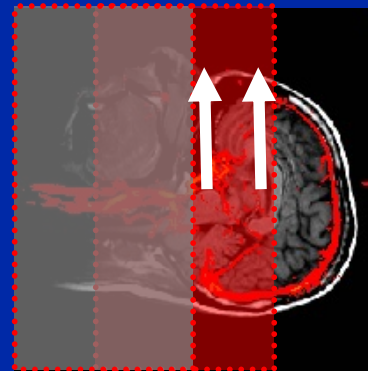
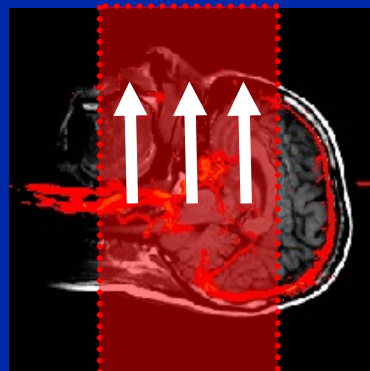
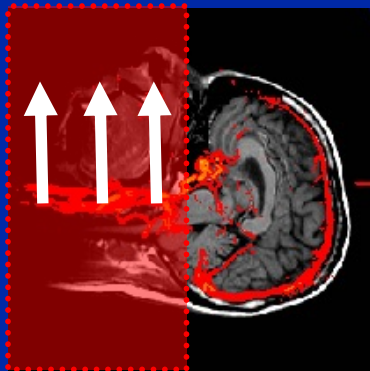


ASL: Pulsed Labeling (QUIPSS II)

Label
 $G_i \neq 0$



Control
 $G_i = 0$



Voxel

Label

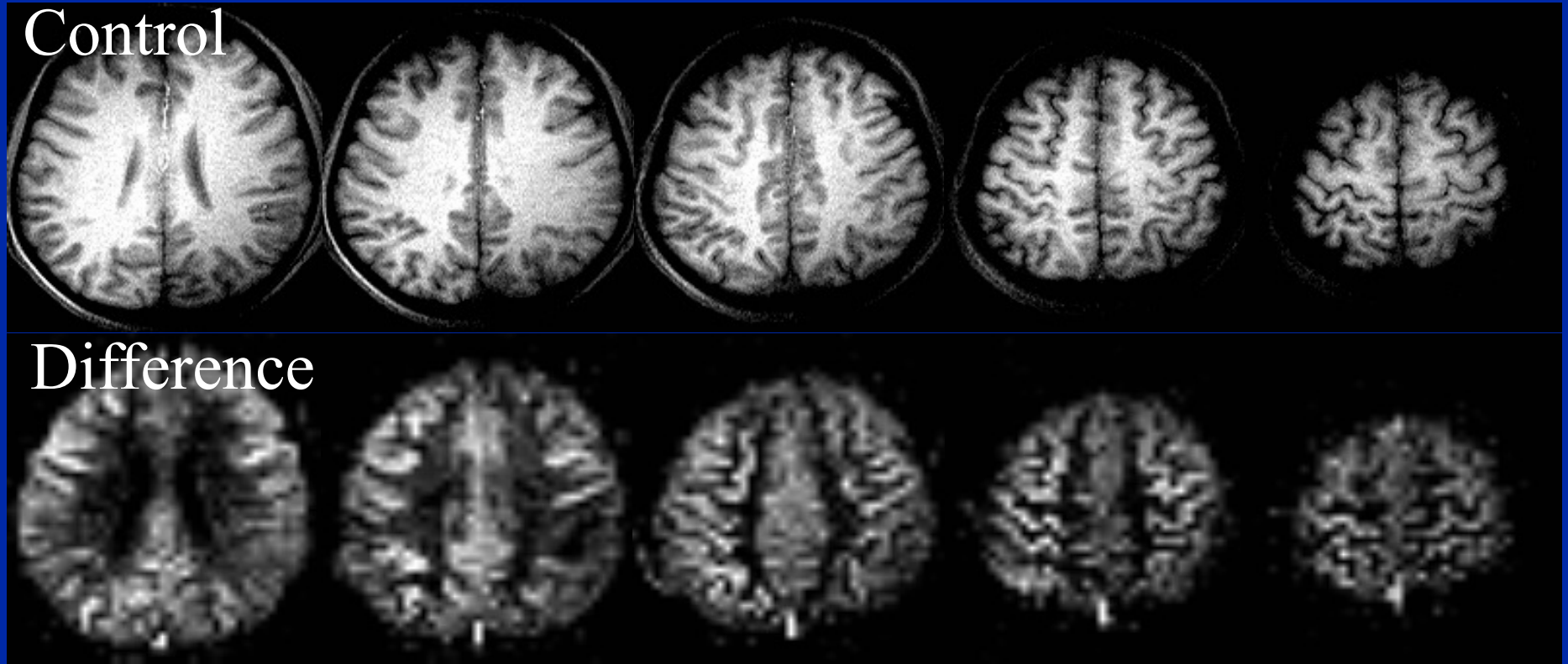


View

Control



ASL: Pulsed Labeling (Q2TIPS)



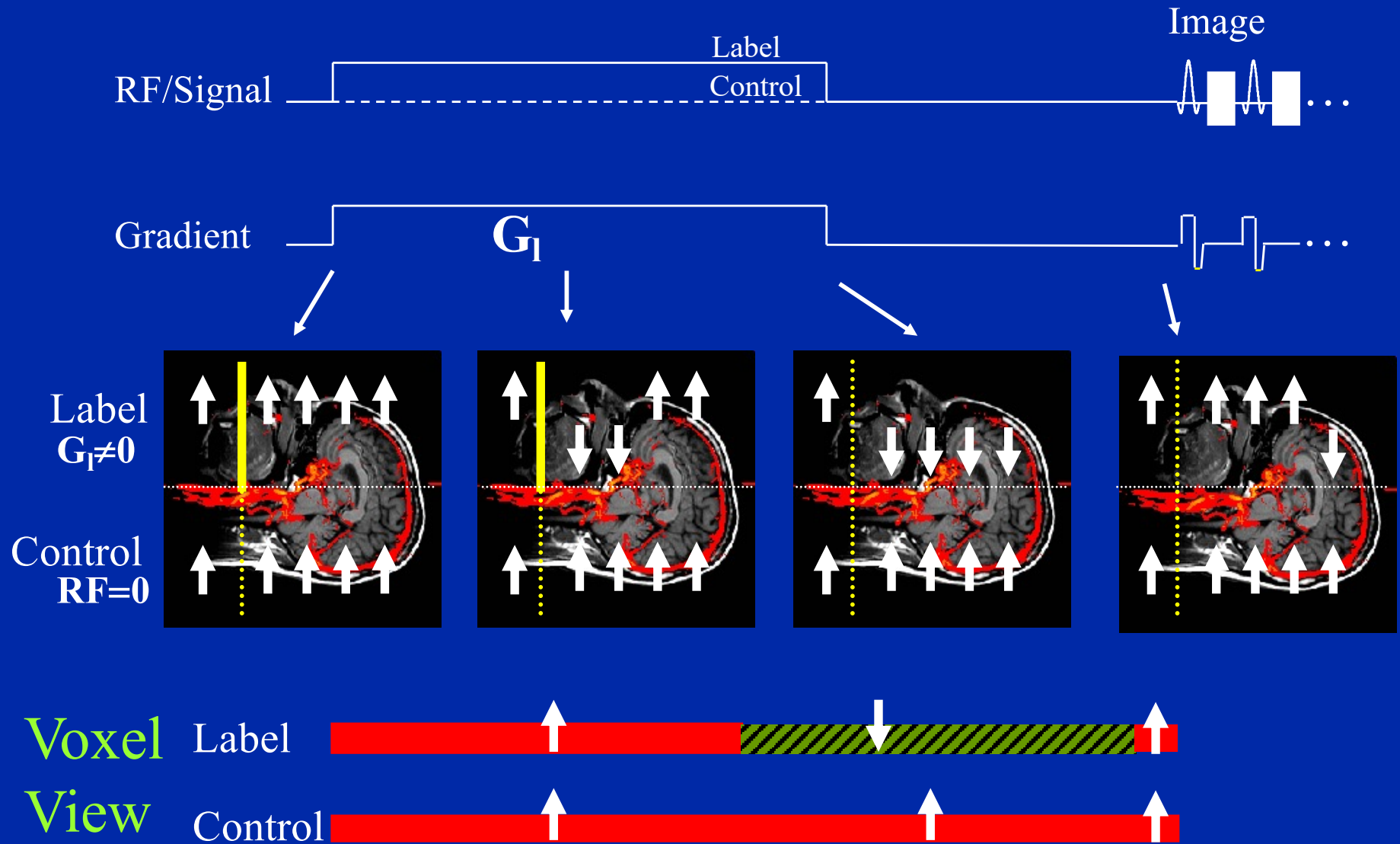
Advantages:

- High tagging efficiency
- Low SAR
- Ease of implementation

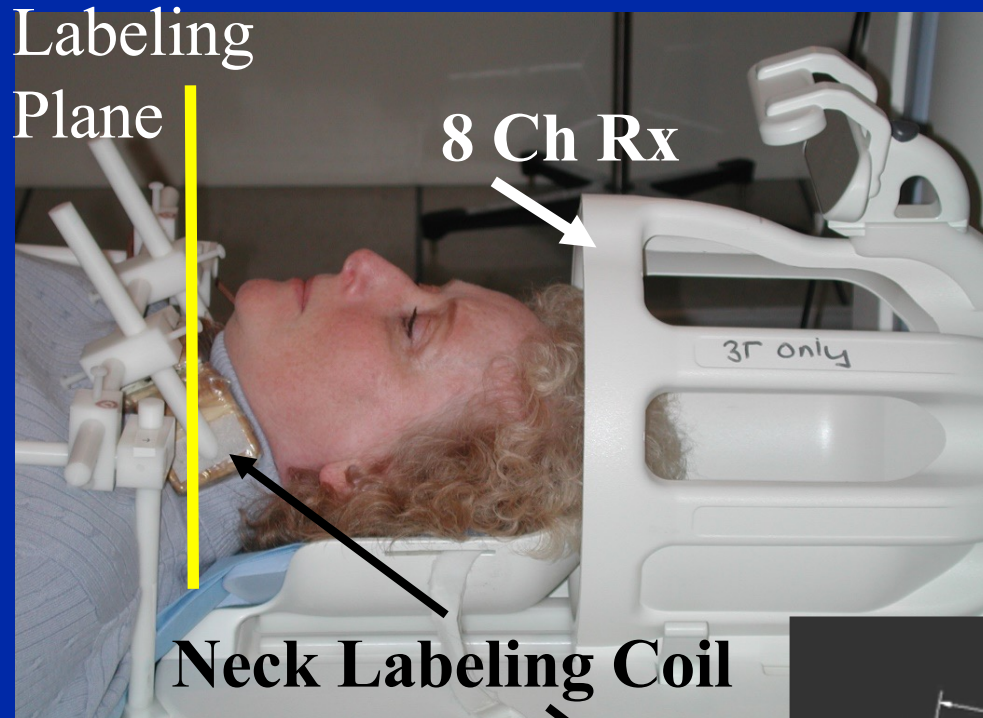
Disadvantage:

- Limited coverage

ASL: Continuous Labeling (Flow-driven Adiabatic Fast Passage)



Continuous ASL: Neck Labeling Coil

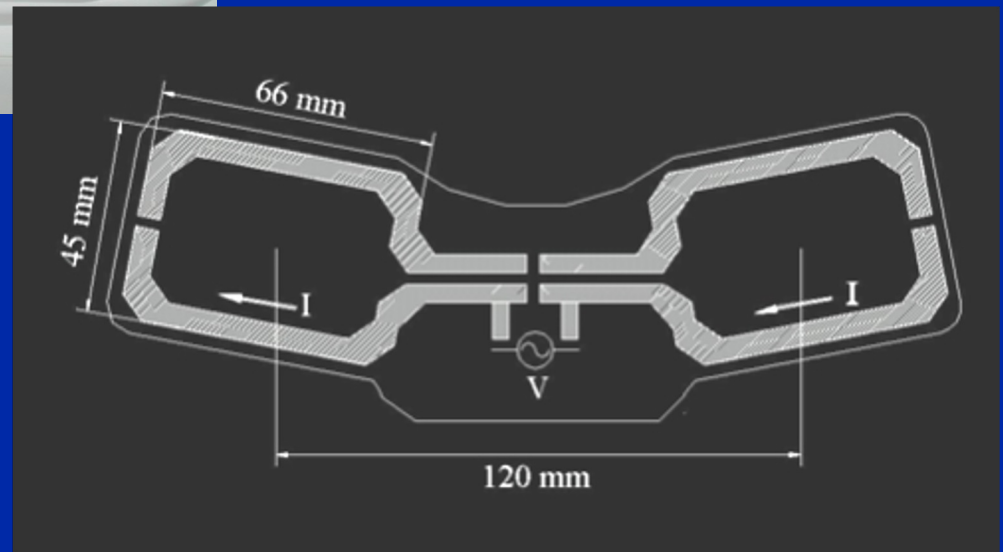


Advantages:

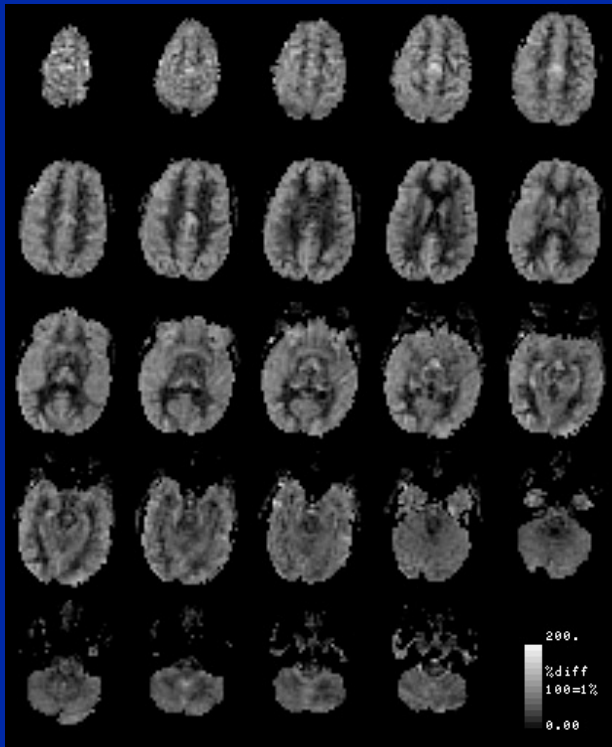
- Whole brain coverage
- High labeling efficiency
- Lower SAR

Disadvantage:

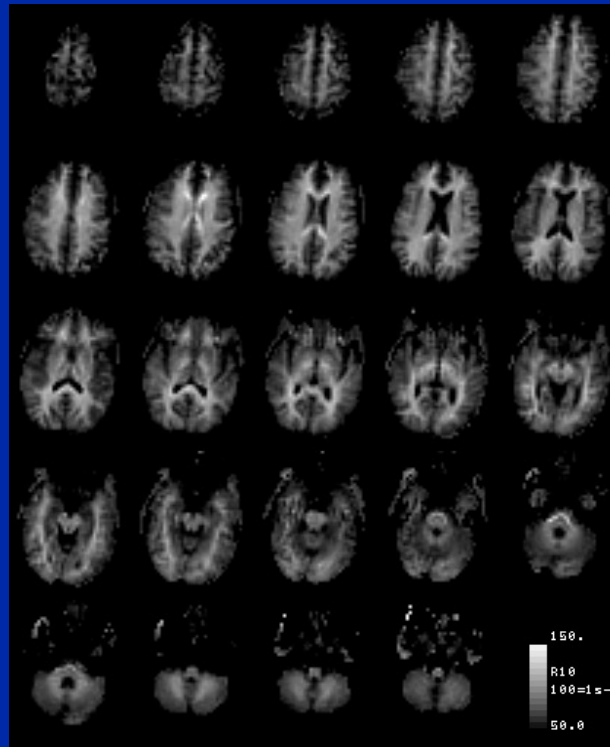
- Requires special hardware



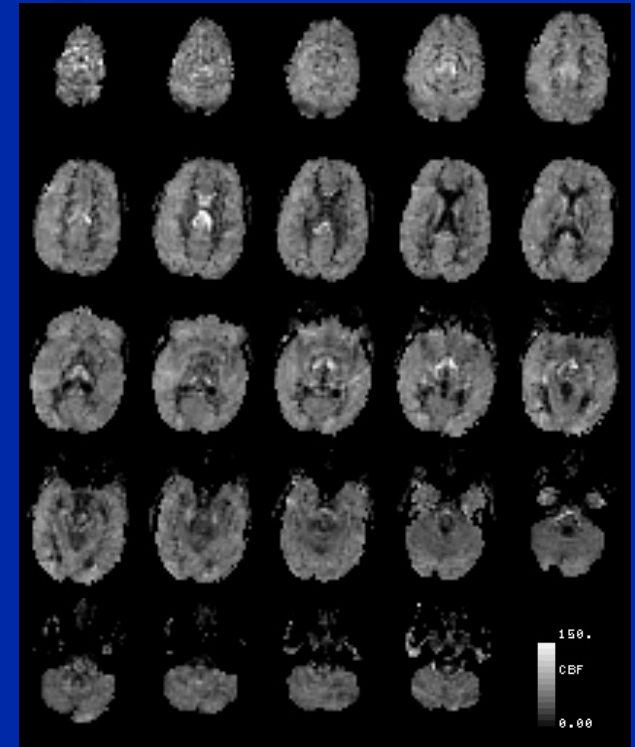
CASL with a Neck Labeling Coil: Multi-shot 3D-FSE Spiral



% ΔS



R1 map



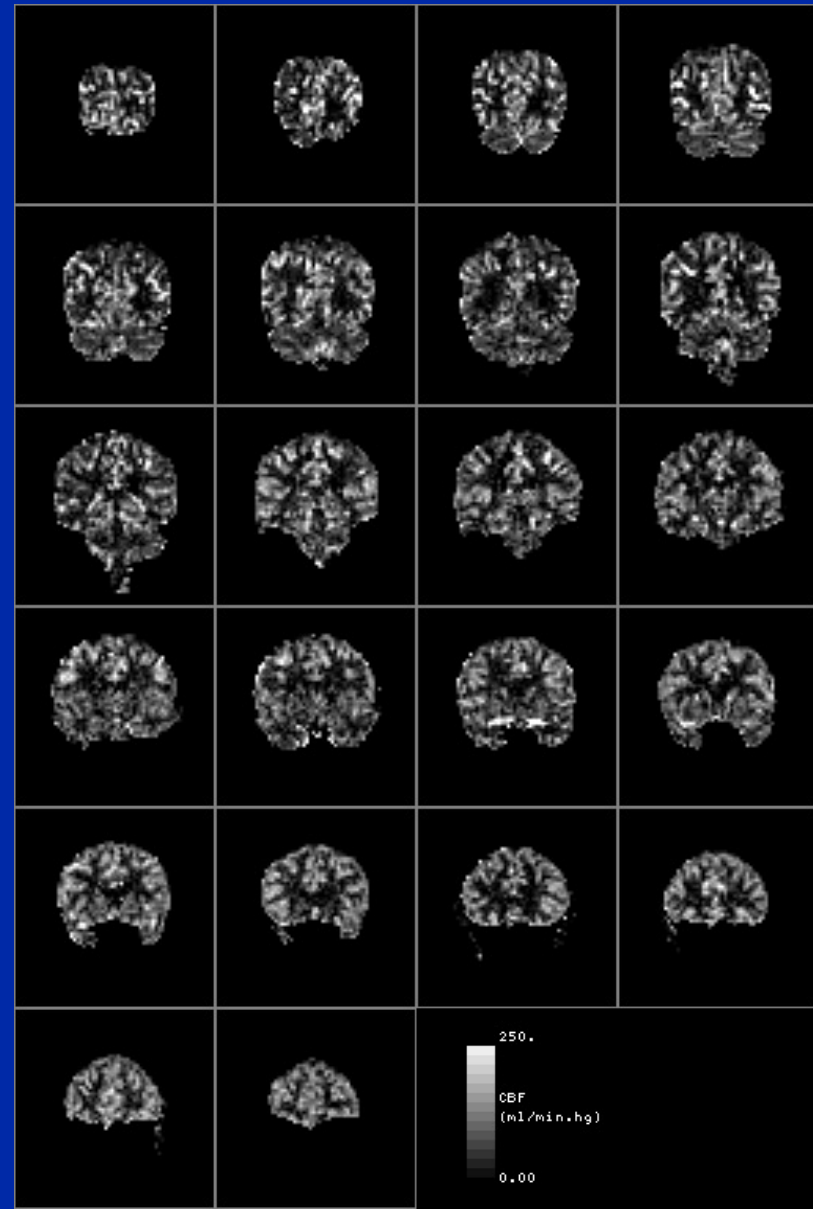
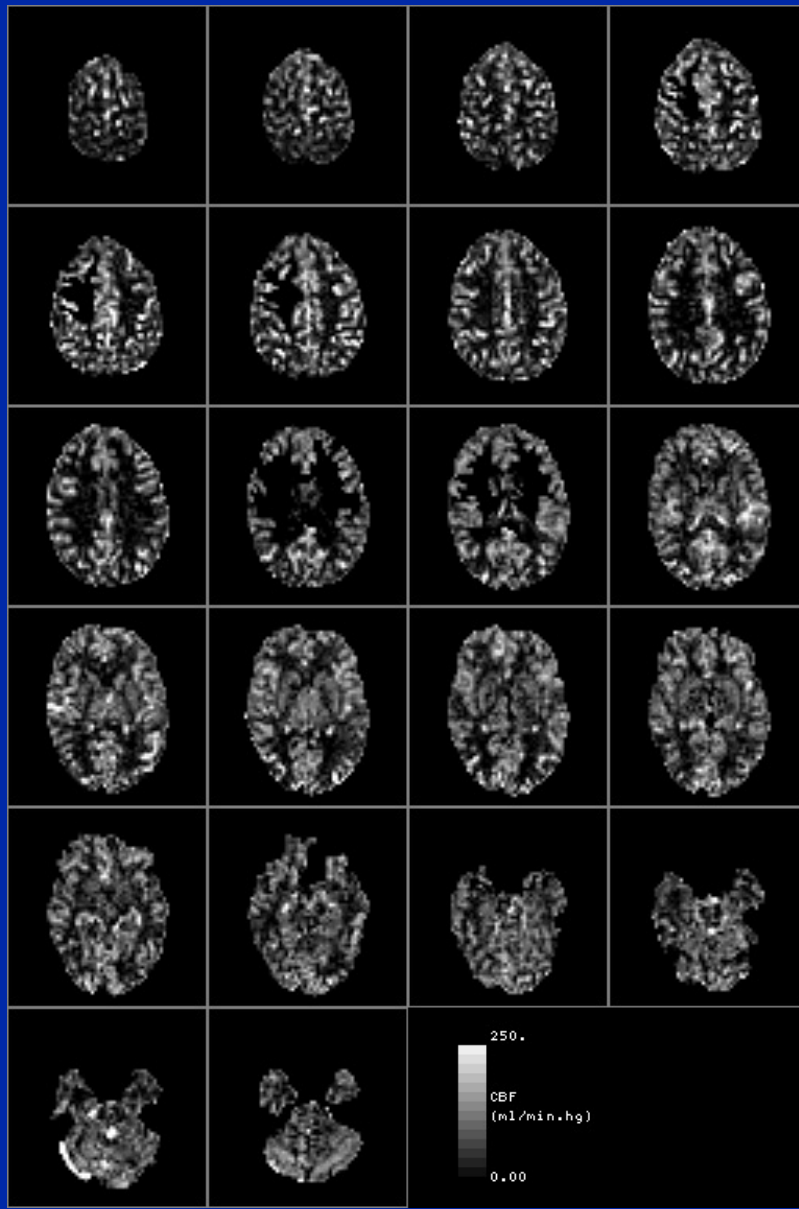
CBF

3T, Head Coil, 3D-FSE, $3.7 \times 3.7 \times 5 \text{ mm}^3$

8 shots, TR 5.9 s, Label dur 4.1 s, PL delay 1.64 s, Backgr supp
6 min 22 sec

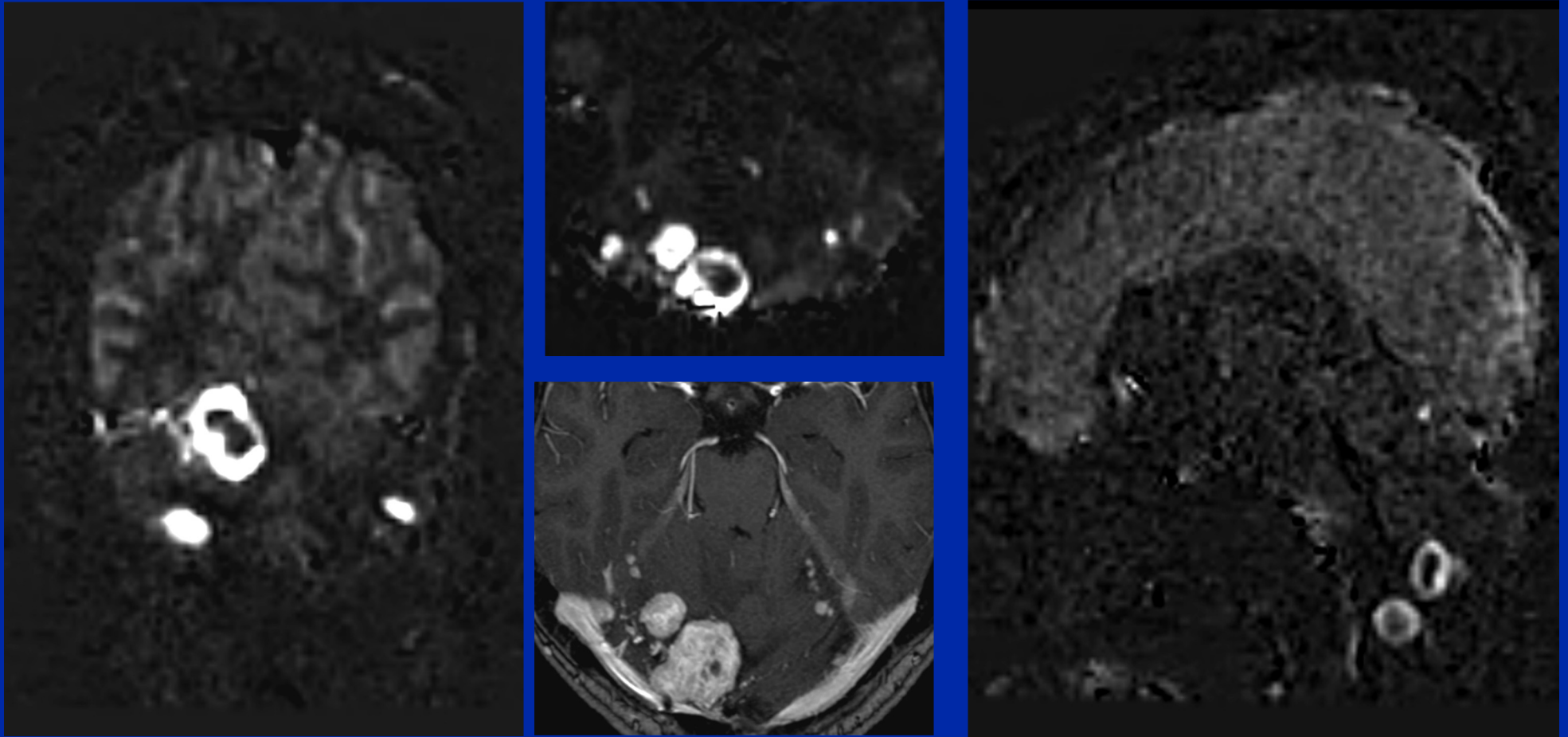
Talagala et al, *MRM* 52: 131-140 (2004)

Continuous ASL: Neck Labeling Coil



3T, 8 Ch Rx, 2D EPI, 3 x 3 x 3 mm³, TE/TR 13 ms/5 s, 4.5 minutes

CASL with a Neck Labeling Coil: Hemangioblastomas



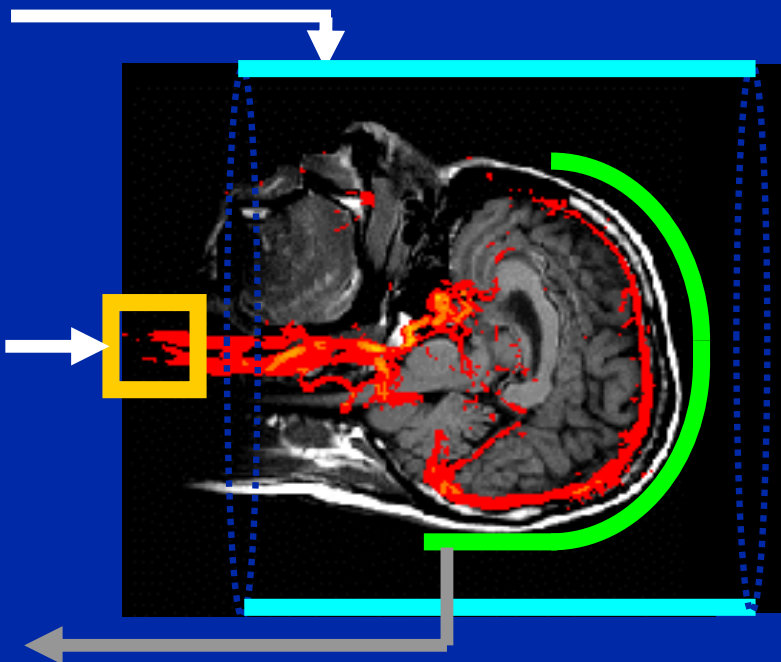
3T, 8 Ch Rx, 2D EPI, 1.5 x 1.5 x 3 mm³
TE/TR 16 ms/5 s, LD/PLD 3 s/1.6 s
10 minutes

CASL Perfusion MRI at 7 T

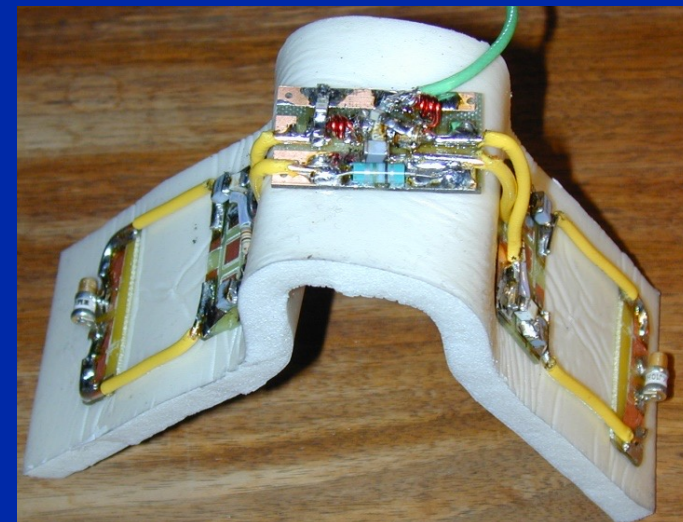
Volume
Tx Coil

Surface
Labeling
Coil

Head Rx
Array
Coil



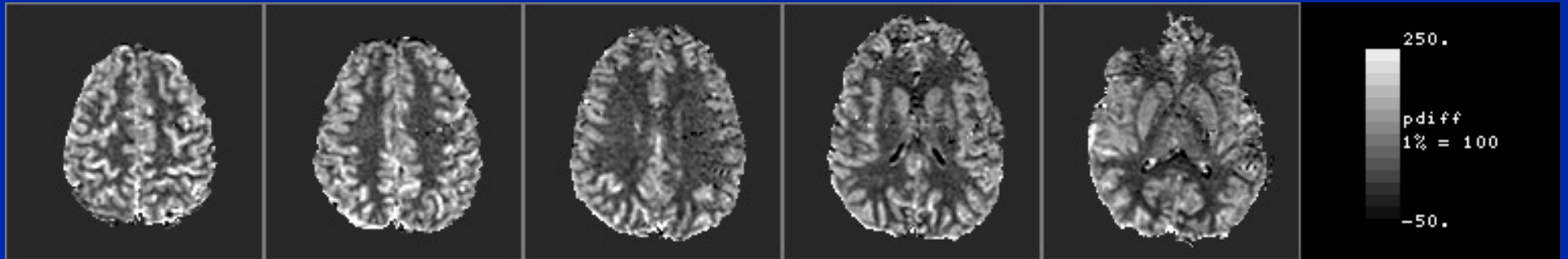
Tx Volume / 8 Ch Rx Array



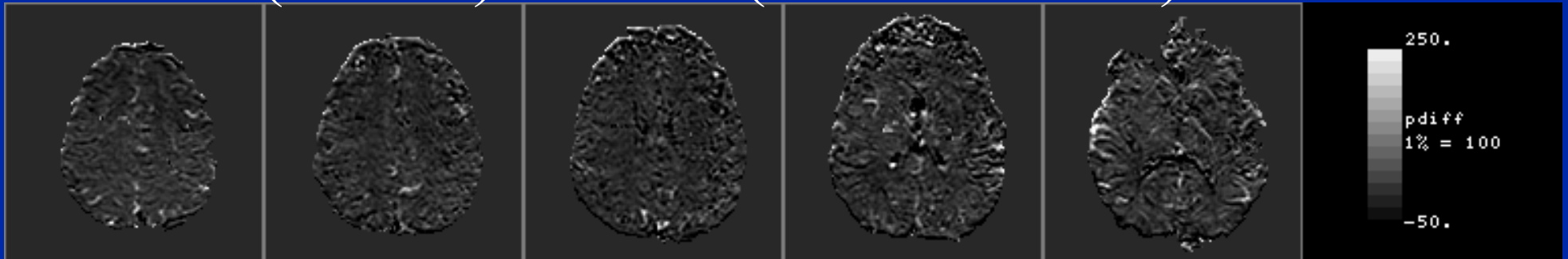
Neck Labeling Coil

7T CASL with a Neck Labeling Coil

Control (RF off) - Label (RF +ve offset)

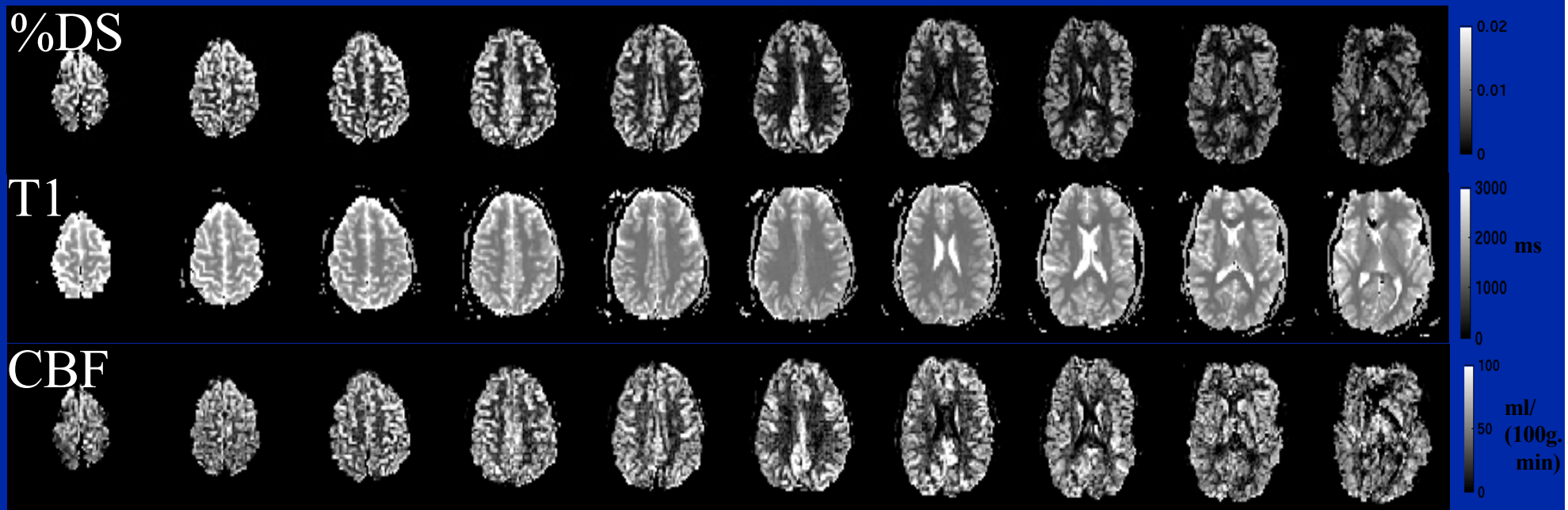


Control (RF off) - Label (RF -ve offset)



7T, 8 Ch Rx, 2D EPI, $2 \times 2 \times 3 \text{ mm}^3$
TE/TR 13 ms/5 s, ASSET X2, LD = 3 s, PLD 1.5 s
8 minutes

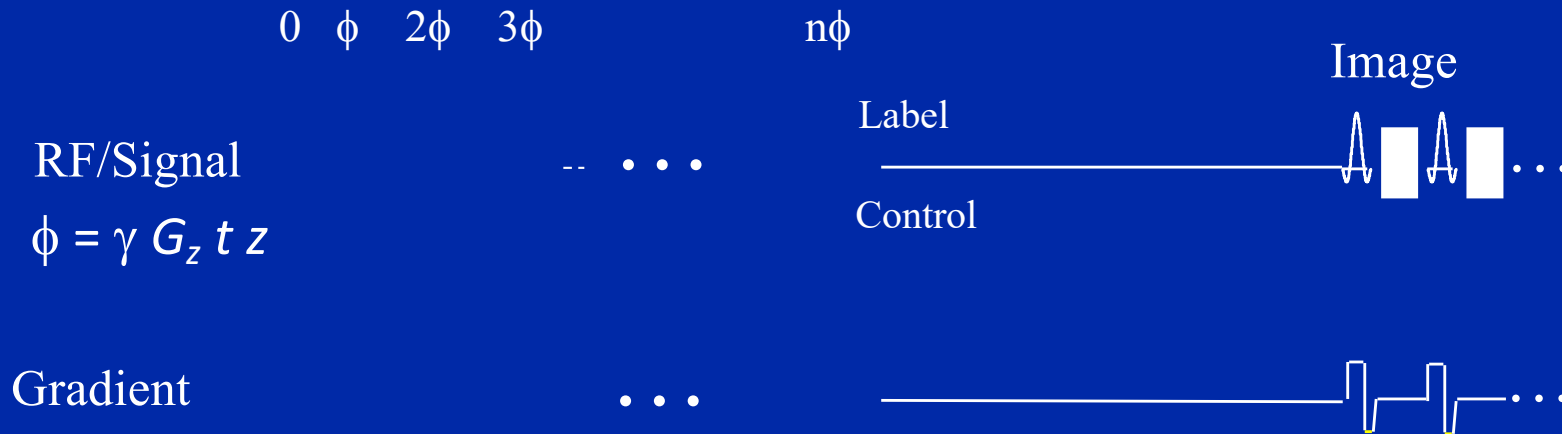
CASL Perfusion MRI at 7 T



	Gray Matter	White Matter
Mean T1 (ms)	1940	1363
$\Delta S/S$ (%)	1.43 +/- 0.25	0.3 +/- 0.04
CBF (ml/min.100g)	76 +/- 11	27 +/- 2.4

7T, 8Ch Rx, 2.1 x 2.1 x 3 mm³, 9 minutes, n=5

ASL: Pseudo Continuous labeling

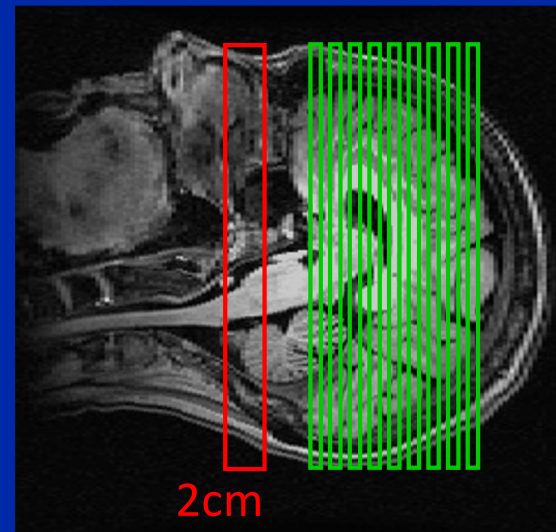


Advantages:

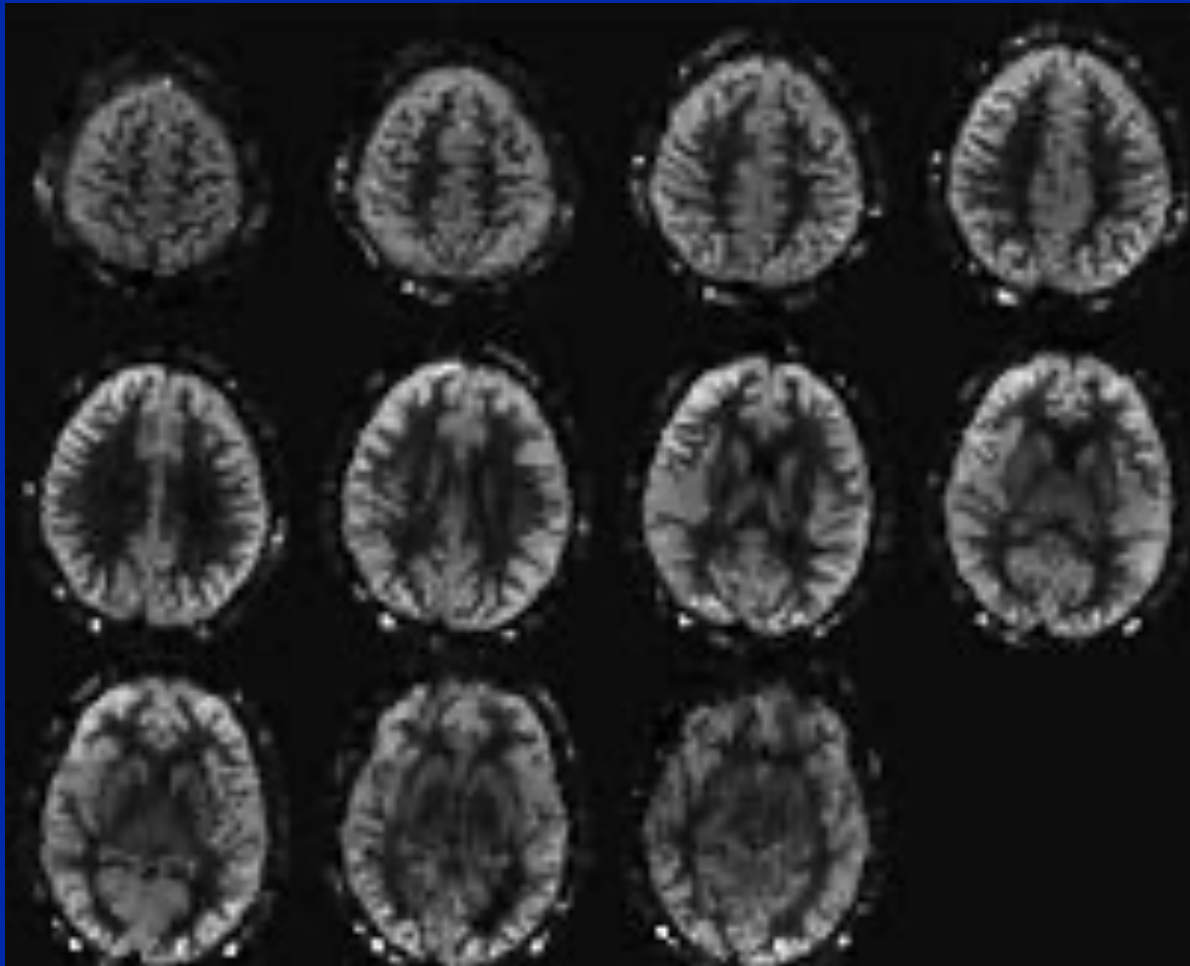
- Whole brain coverage
- High labeling efficiency
- Use standard hardware

Disadvantages:

- Higher SAR
- Sensitivity to off-resonance effects



Pseudo Continuous ASL: 3T data



3T

$3.6 \times 3.6 \times 5 \text{ mm}^3$

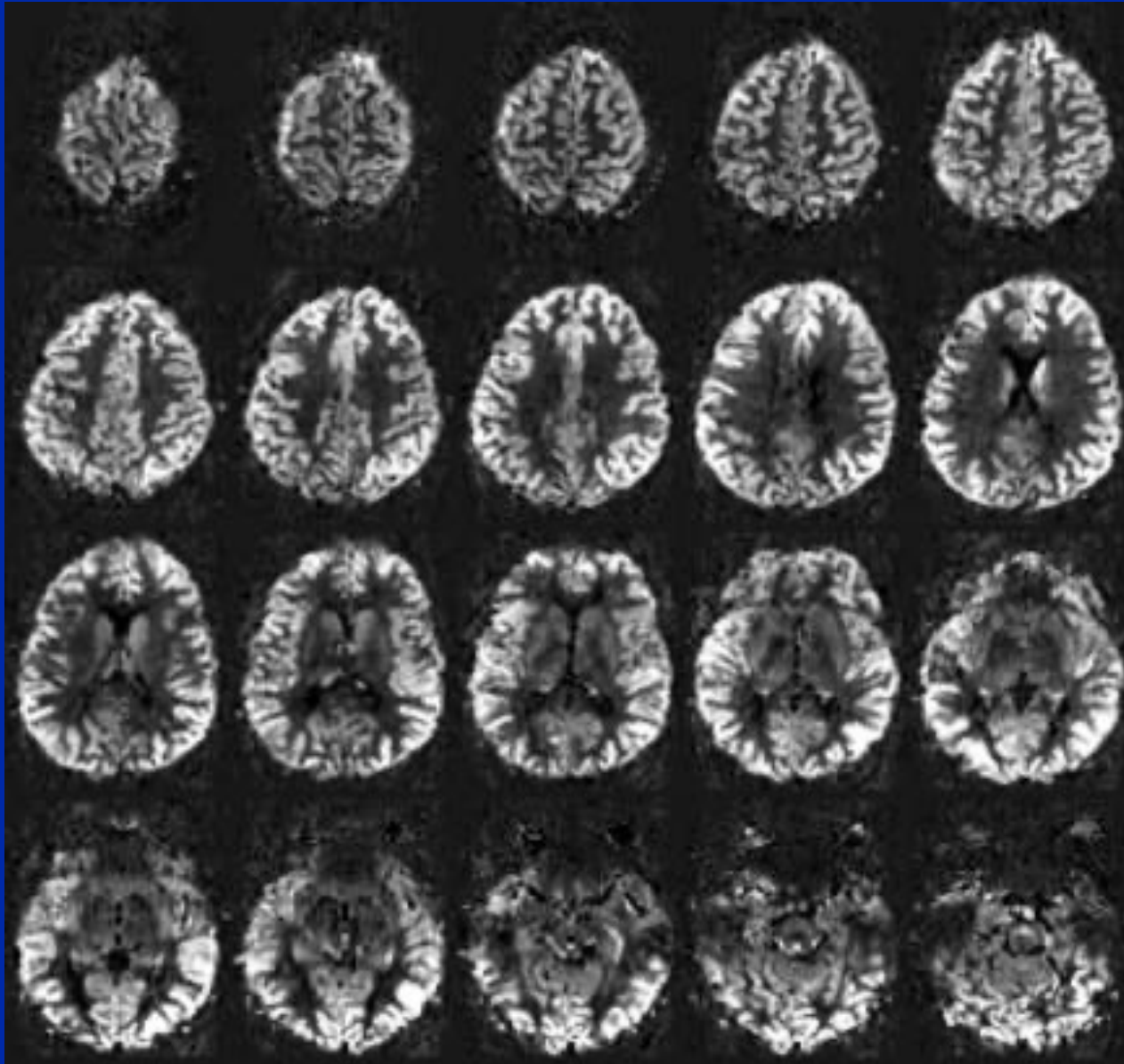
Gradient-echo EPI

$\text{TE/TR} = 20.8/5000 \text{ ms}$

$\tau/w = 2500/1700 \text{ ms}$

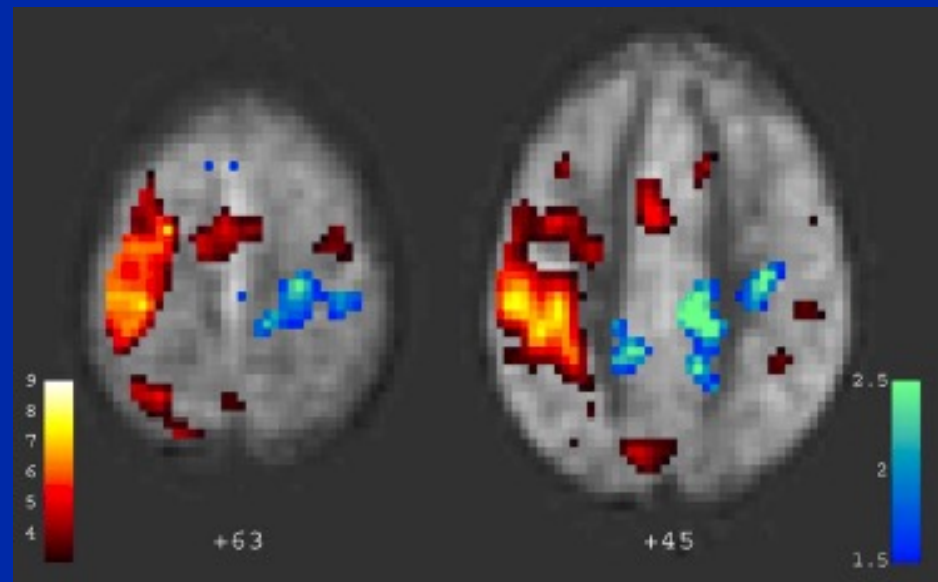
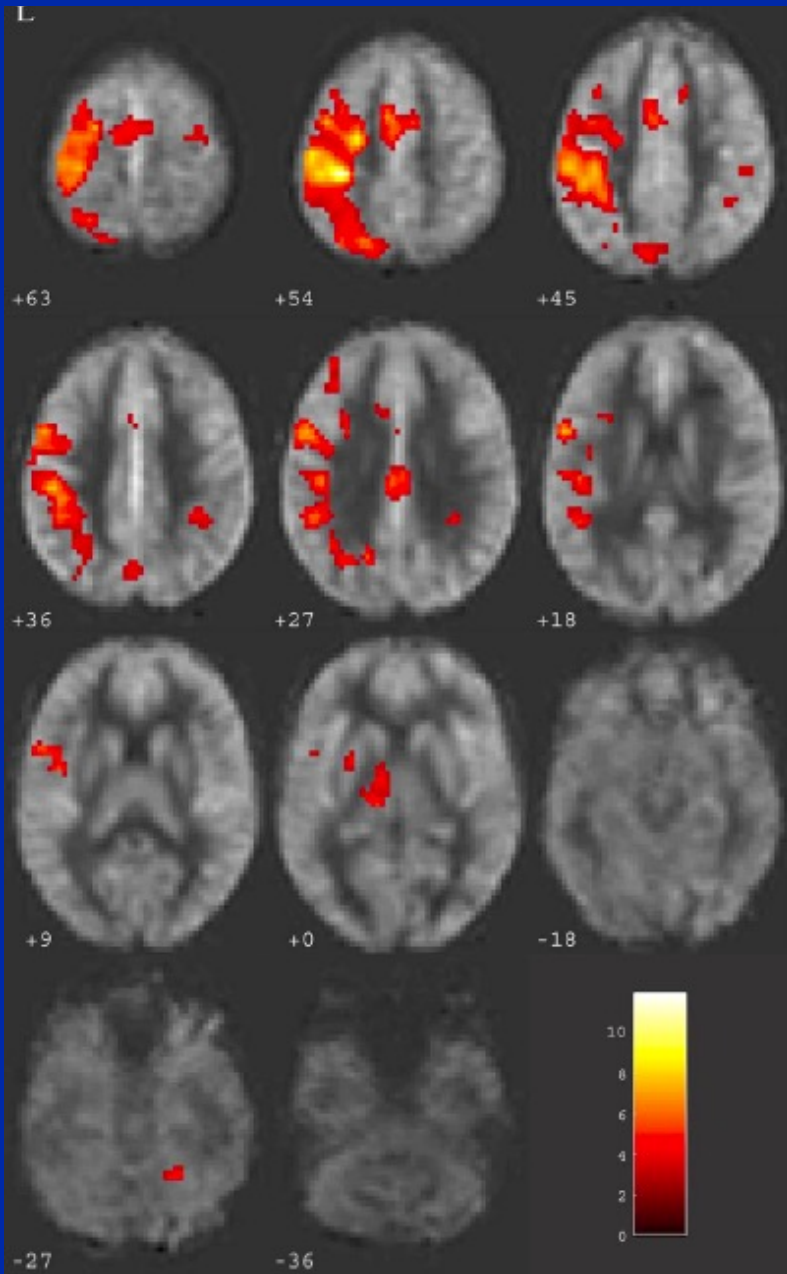
Scan time 5:00

Pseudo Continuous ASL: 7T data



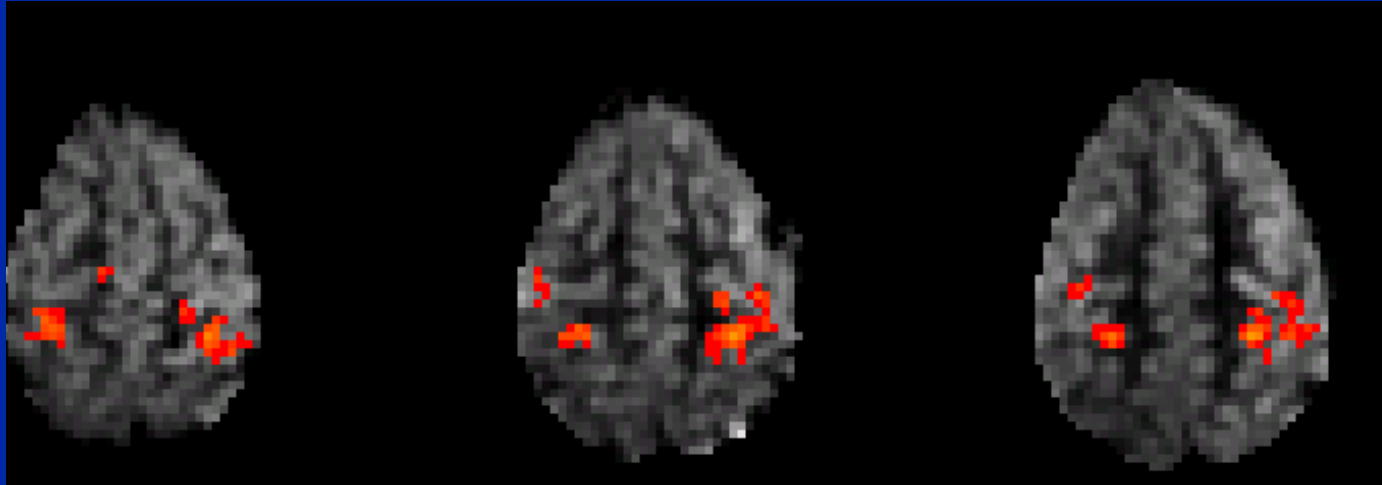
7T
2.3 x 2.3 x 3 mm³
Gradient-echo EPI
TE/TR = 20.8/5100 ms
 $t/w = 3000/1200$ ms
SENSE 3x
Scan time 4:15

CASL fMRI with a Neck Labeling Coil



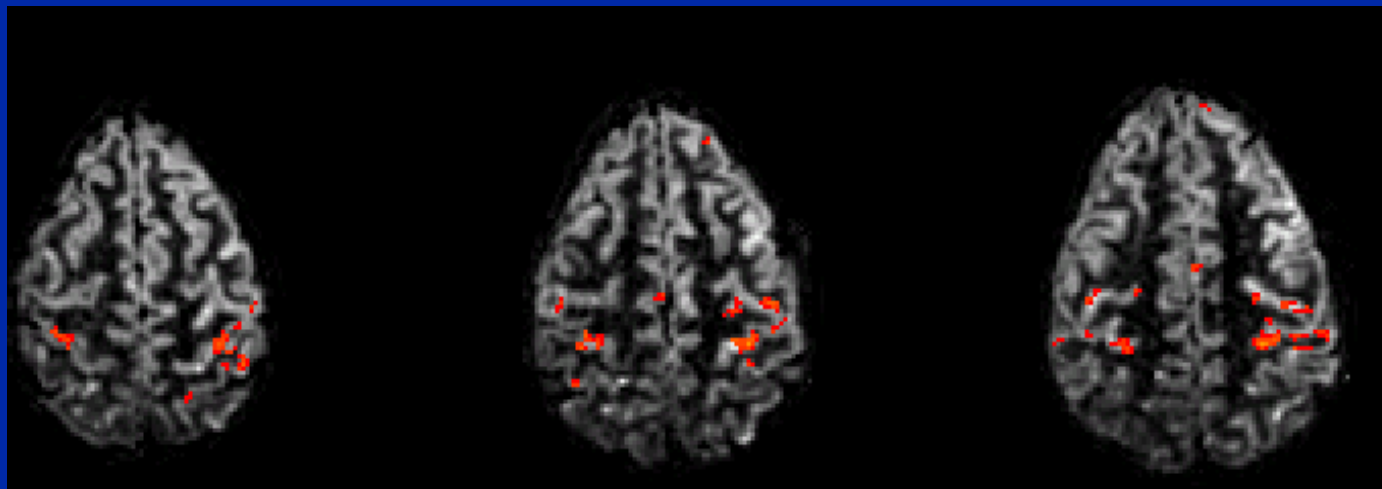
3T, Head Coil
Finger movement (0.5 Hz),
{48 s Task / 48 Rest} X 6, 10 min
GE EPI, $3.75 \times 3.75 \times 5 \text{ mm}^3$
12 s per Cont/Label pair
SPM, Spatial normalization
smoothing (8 mm), N= 15

3T CASL Perfusion fMRI with 16 Rx



CBF
 75 ± 11
ml/(min.100g)

Δ CBF
 $78 \pm 7\%$



CBF
 92 ± 16
ml/(min.100g)

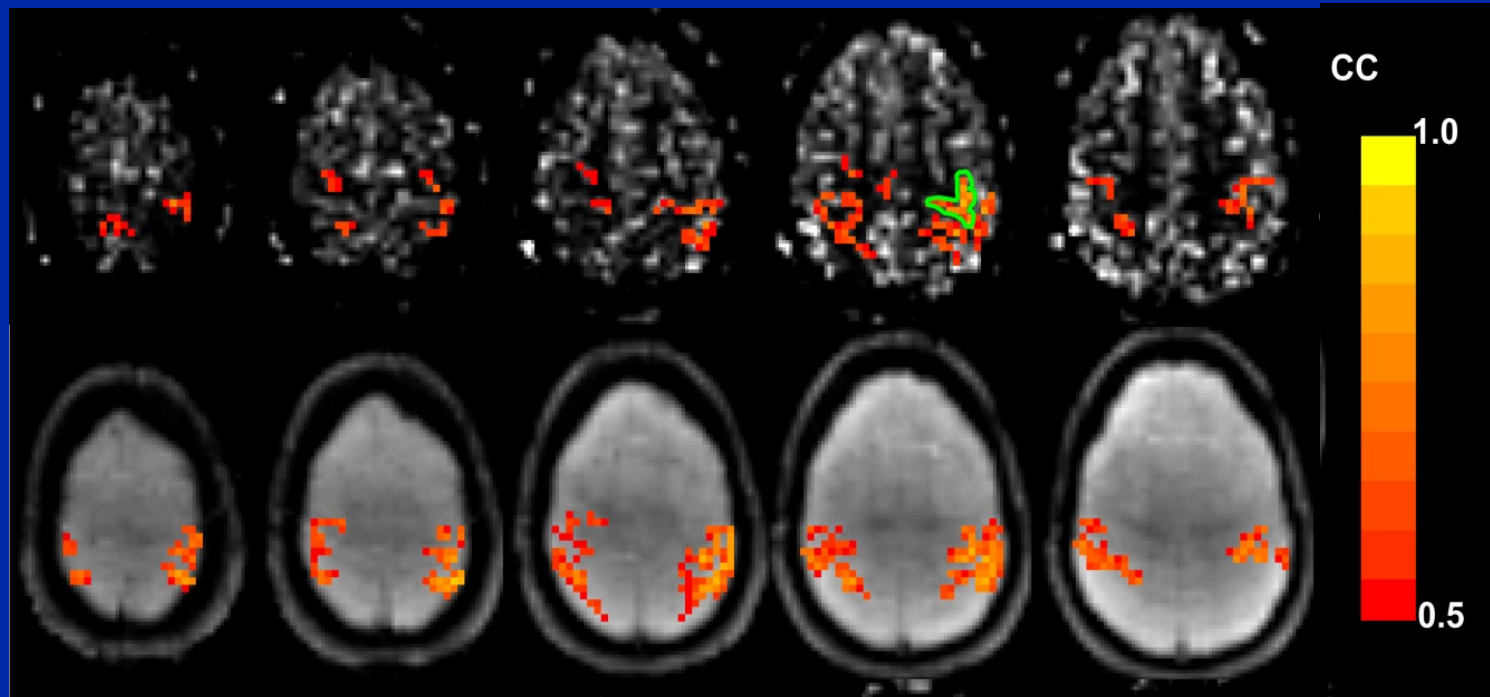
Δ CBF
 $102 \pm 10\%$

Finger movement (2 Hz), {40 s Rest / 40 Task} X 8, N = 6
GE EPI, TE 26 ms, 10 s per Control/Label pair, 10 min 40 sec

Functional Connectivity with ASL Perfusion

ASL
(high pass)

BOLD



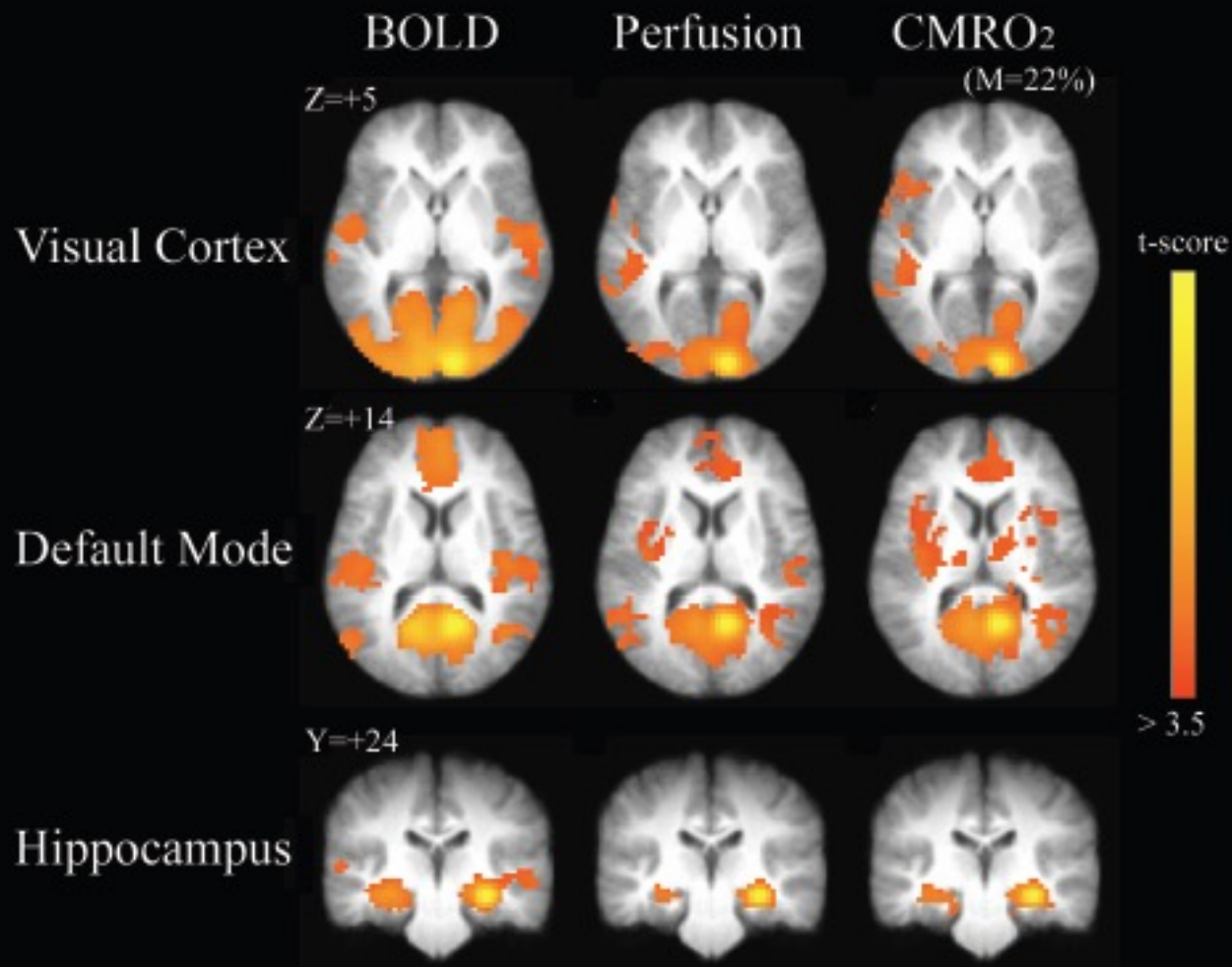
$\Delta\text{CBF} = 29 \pm 19\%$ $\Delta\text{BOLD} = 0.26 \pm 0.14\%$ (N=13)

3T, GE EPI, 16 Ch Rx, $3.75 \times 3.75 \times 3 \text{ mm}^3$

TE/TR 12.5/3200 ms, 10 min 40 sec

Functional Connectivity: BOLD, Perfusion, CMRO₂

b) Resting State:



Perfusion MRI: Summary

- Dynamic Susceptibility Contrast (DSC)
 - Requires contrast administration
 - Fast acquisition (< 2 min), whole brain coverage
 - Absolute quantification is difficult
- Arterial Spin Labeling (ASL)
 - No contrast required
 - 4-5 min acquisition, whole brain coverage
 - Absolute quantification is possible
 - Robust sequences are available
 - Useful for clinical and research work