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

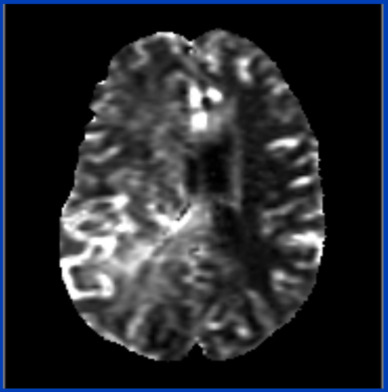
- blood flow – ml blood / min / 100 g of tissue
- blood volume – ml blood /100 g of tissue
- mean transit time – seconds

Normal values for brain

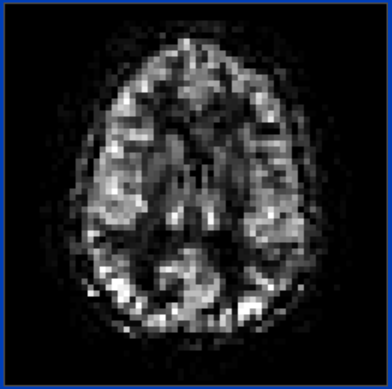
	Gray Matter	White Matter
CBF (ml /min/100 g)	60 - 80	20 - 30
CBV (ml / 100 g)	4 - 6	2 - 4
MTT (s)	4 - 5	5 - 6

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 ~1.5- 2 s

TE = 30 -50 ms

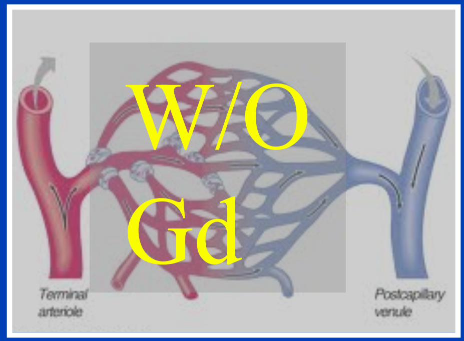
~1.5 min

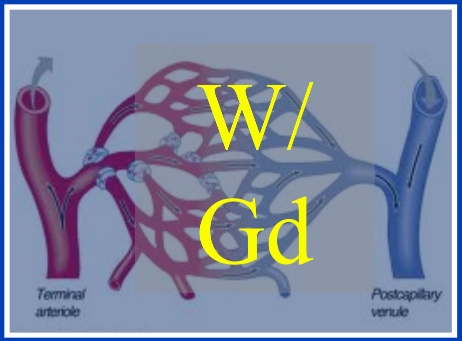
Bolus Injection

Gd 0.1 - 0.2 mmol/kg

DSC - Mechanism

Gd Chelates: Paramagnetic, Intravascular





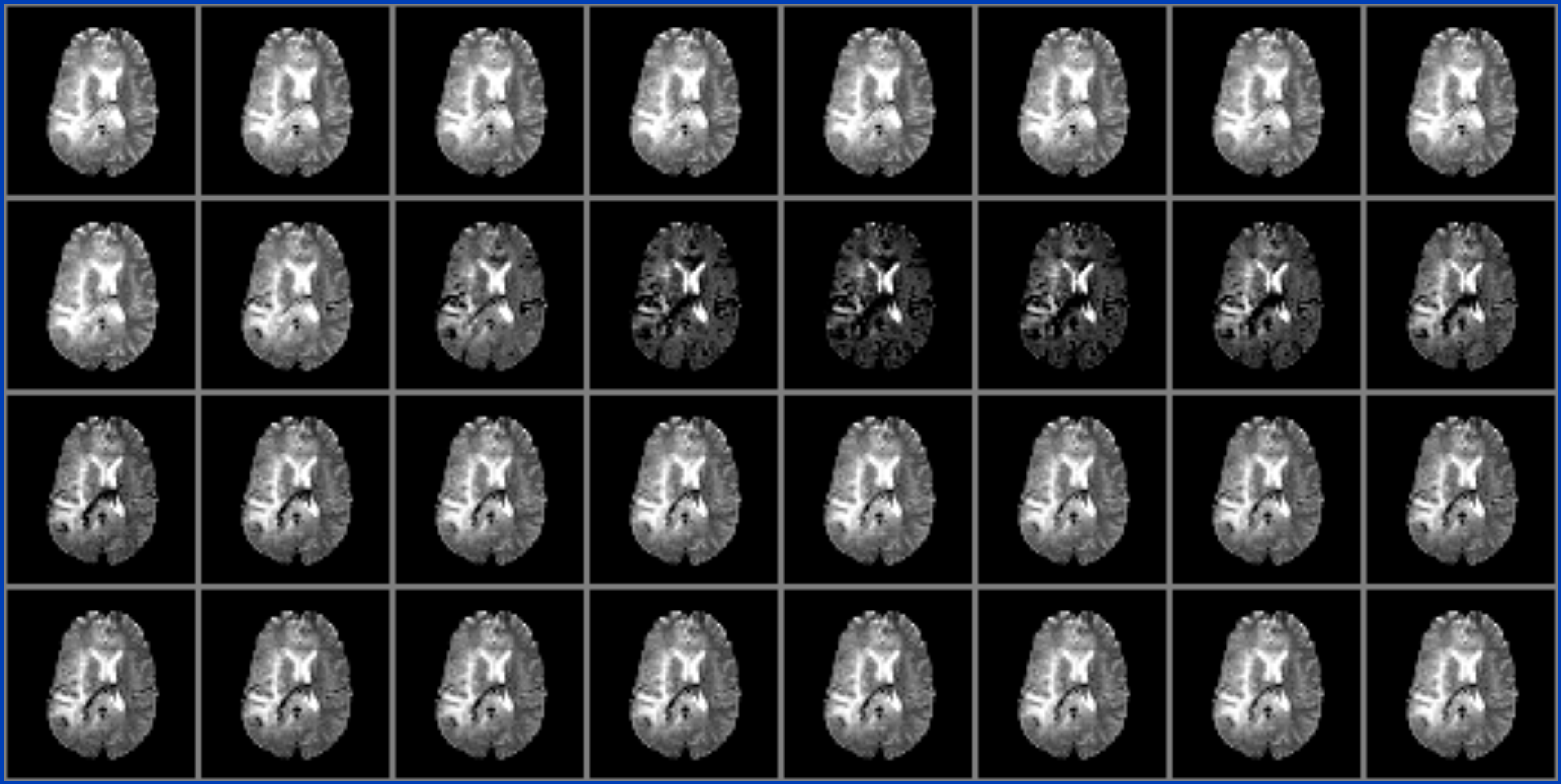
Tissue/ Blood $\Delta\chi$ ↑

Field Inhomogeneity ↑

R_2* (=1/T_2*) ↑

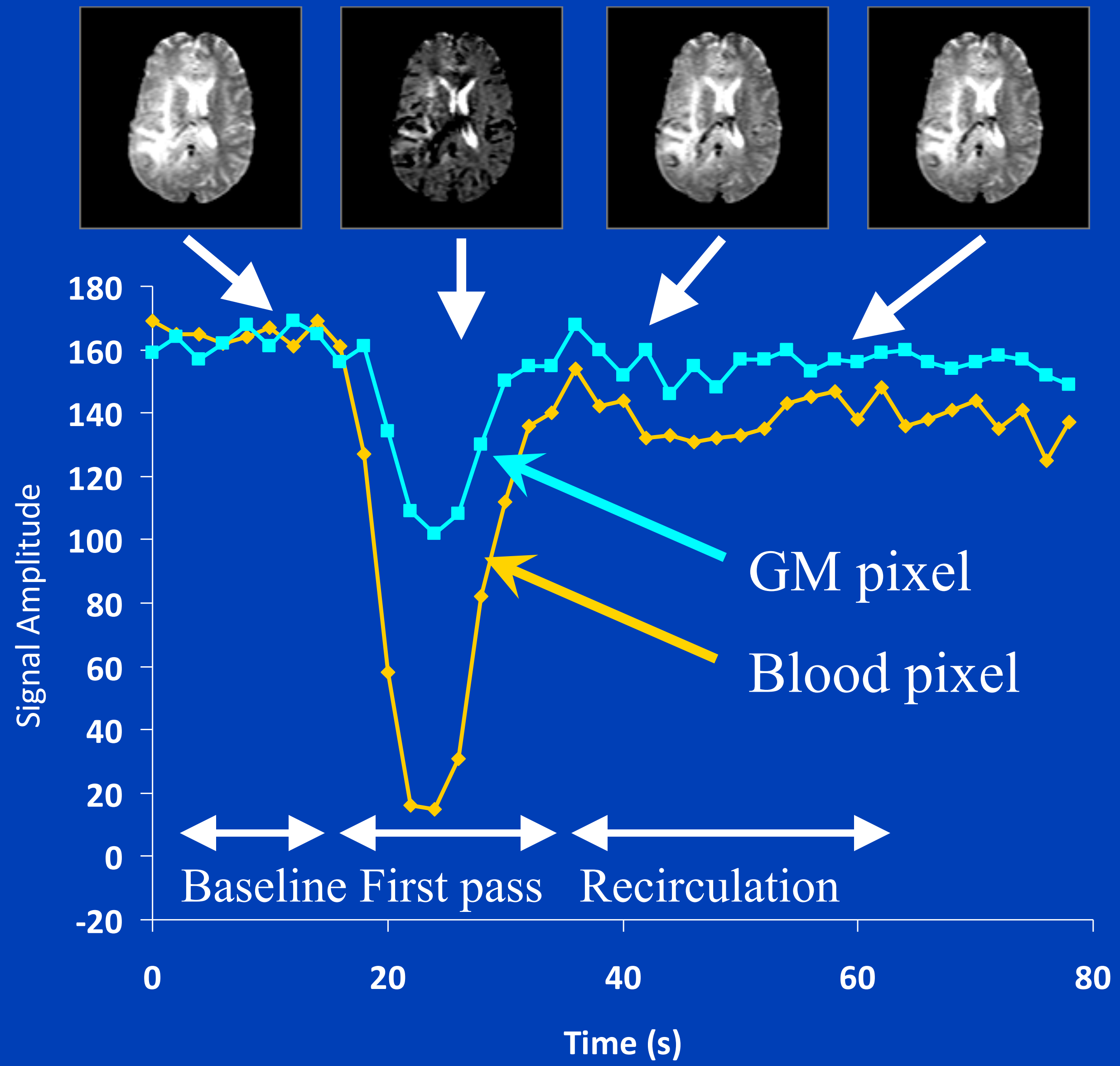
GE/SE MRI Signal ↓

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

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

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

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

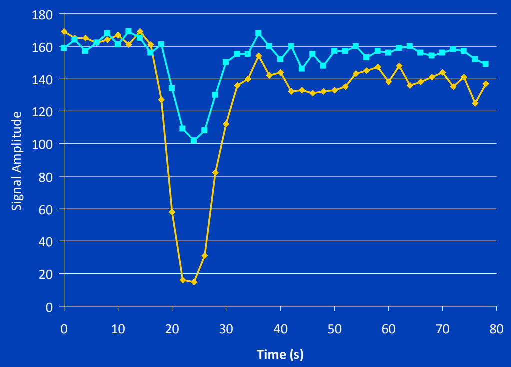
C – Gd concentration

S_c – Signal with Gd

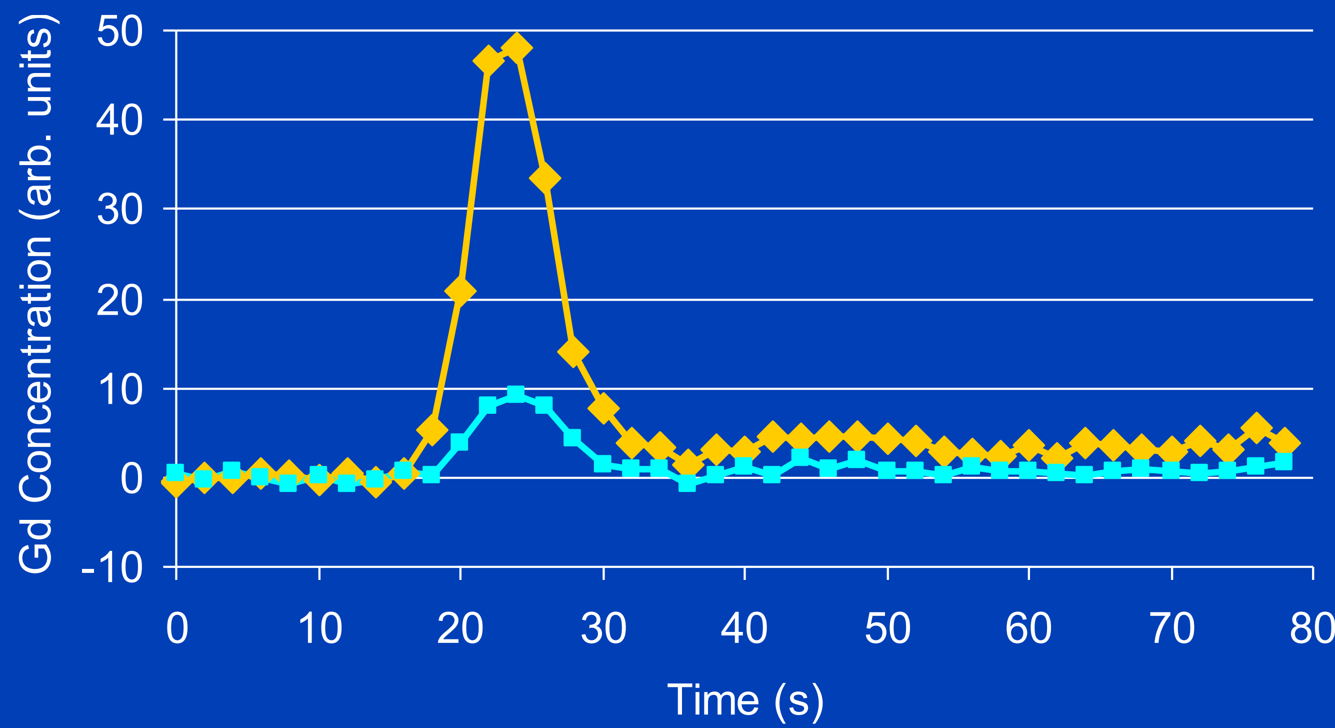
S_0 – Baseline signal without Gd

k – proportionality constant

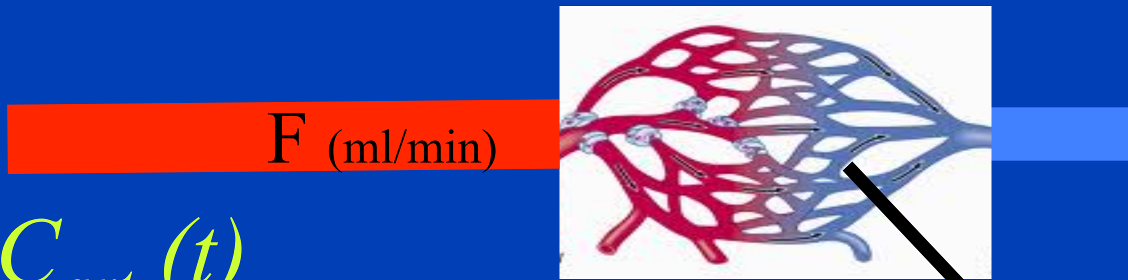
DSC: Concentration vs time



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



DSC – CBV, CBF, MTT ?



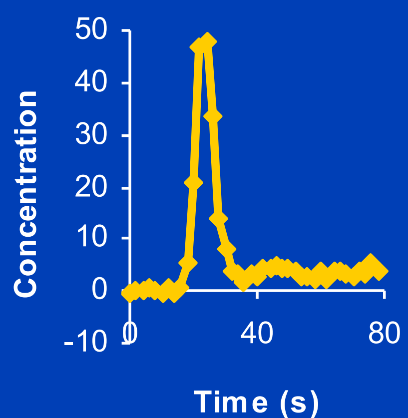
$C_{art}\,(t)$

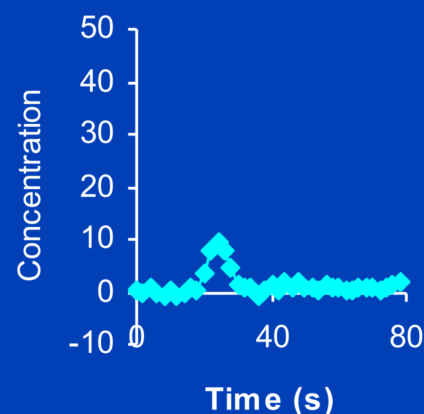
Arterial input function (AIF)

$C_{tis}\,(t)$

Tissue Response

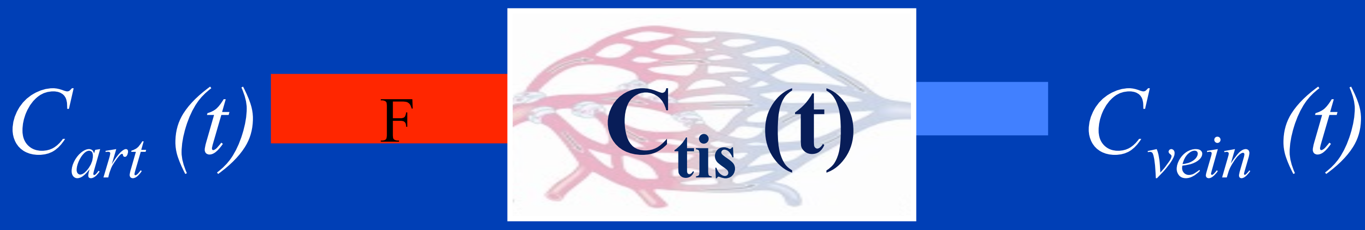
Tracer Kinetic Theory



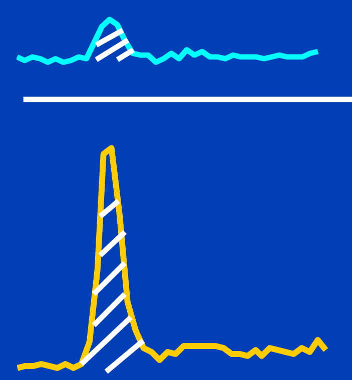


$$MTT = \frac{CBV}{CBF}$$

DSC- Calculation of CBV



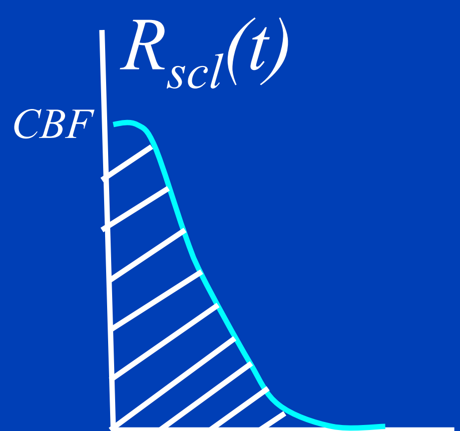
$$CBV = \frac{k_H}{\rho} \frac{\int C_{tis}(t) \cdot dt}{\int C_{art}(t) \cdot dt}$$



DSC- Calculation of CBF and MTT

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

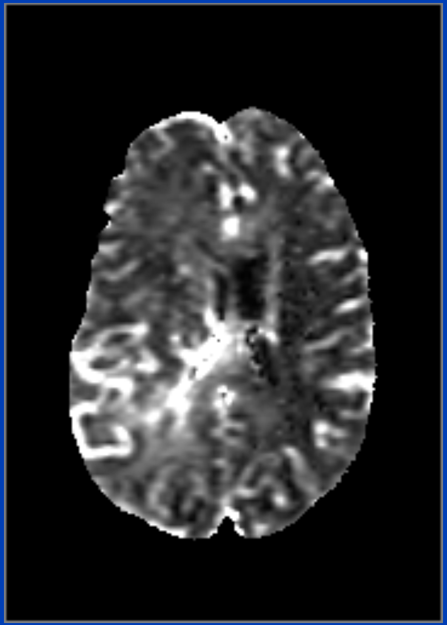
$$R_{scl}(t) = Deconvol\,(\,C_{tis}(t),\ C_{art}\,(\mathrm{t}))$$



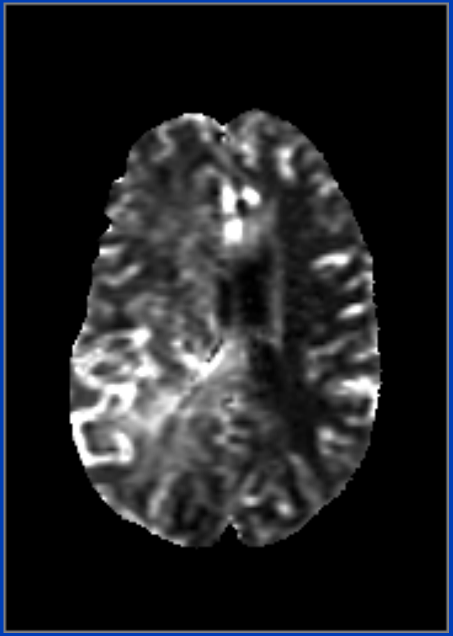
$$CBF = R_{scl}(0)$$

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

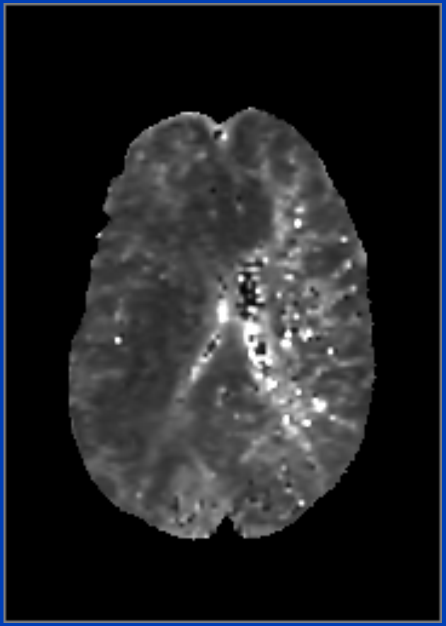
DSC – CBV, CBF, MTT maps



CBV

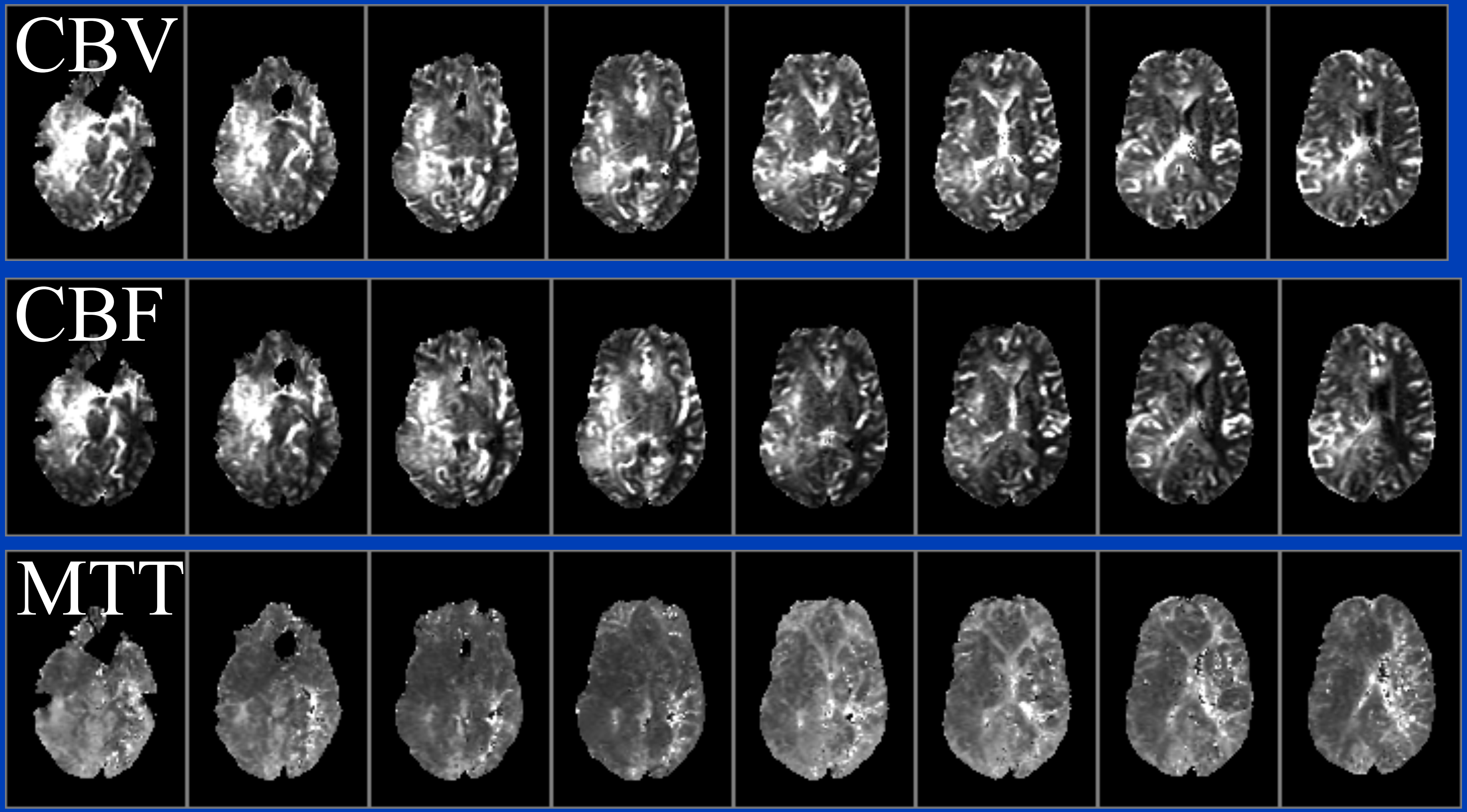


CBF

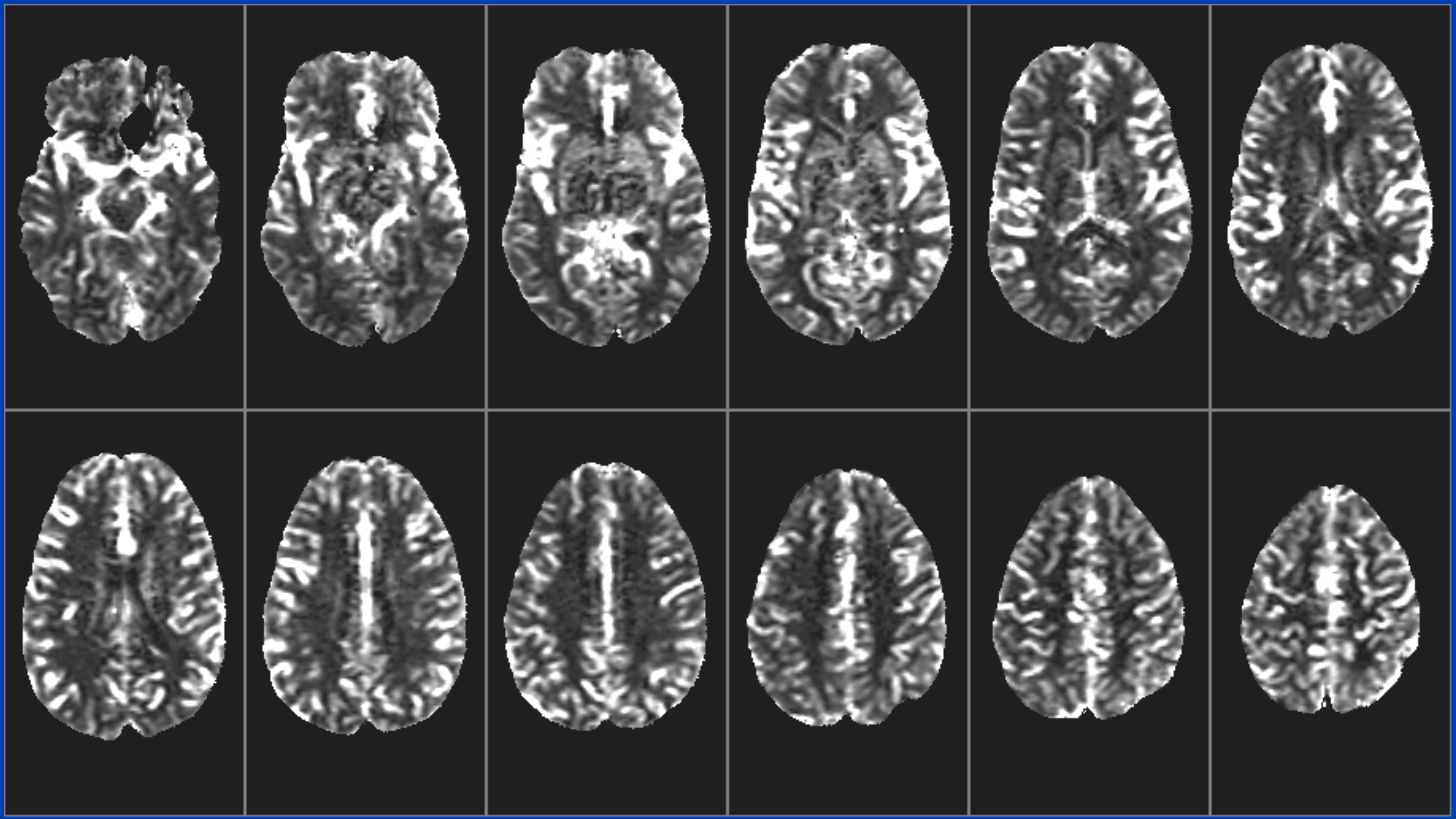


MTT

DSC – CBV, CBF, MTT maps



DSC – CBF maps



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

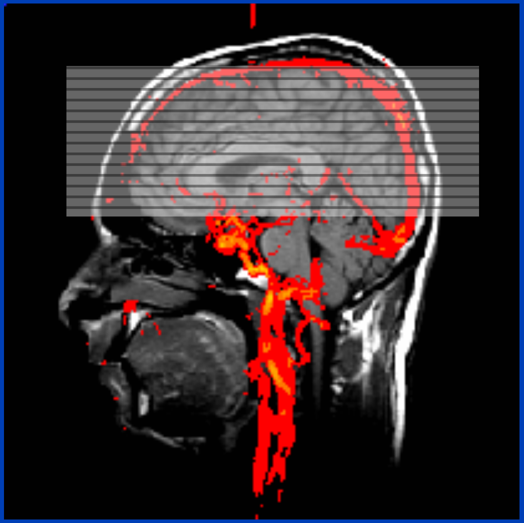
DSC: Quantification Issues

- 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



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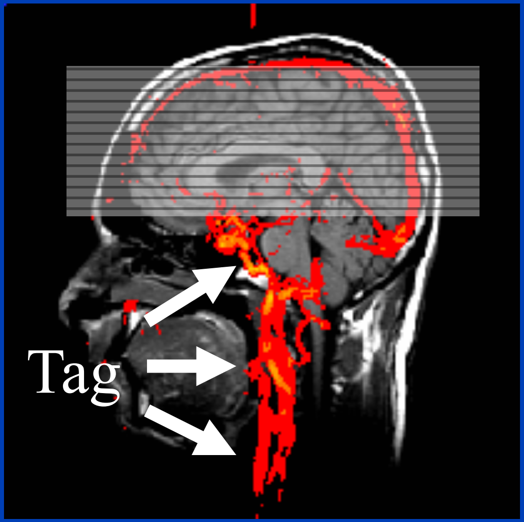


=> Perfusion Maps

Control

Label

2D/3D EPI/ SPIRAL

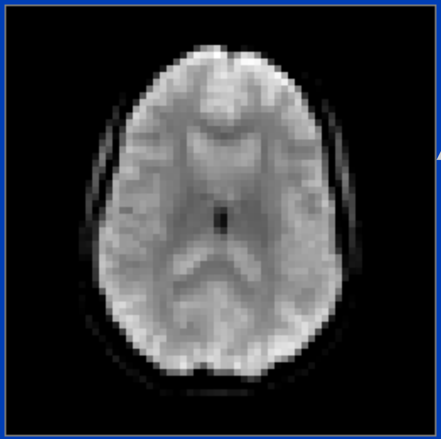
TR ~ 2 - 5 s

TE = minimum

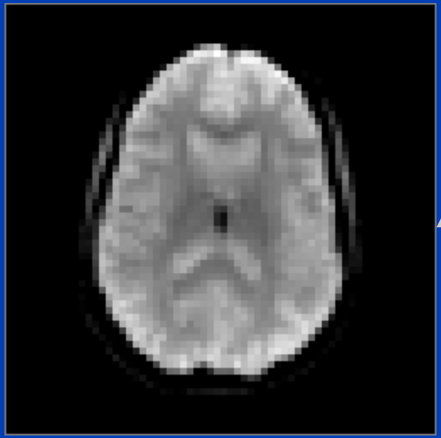
~ 4-5 minutes

LABELING		IMAGING
0.5 – 2.5 s	1- 2 s	0.3 - 0.7 s

ASL: Control/Label/Difference

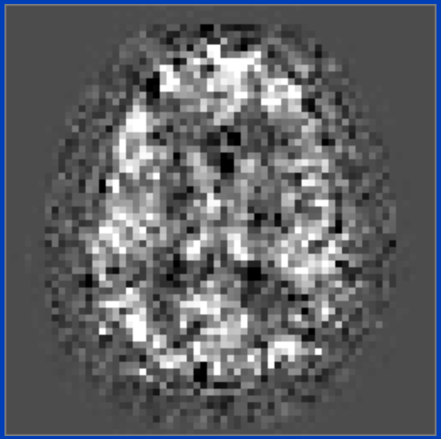


Control

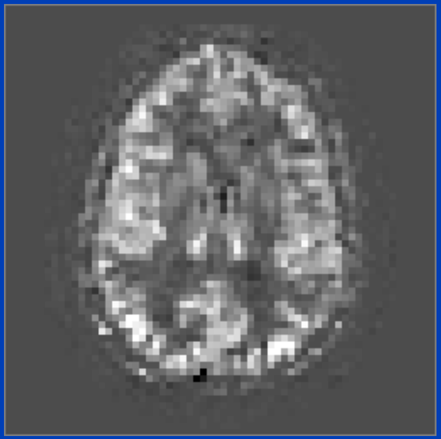


Label

Difference (ΔM) images



1 pair
(10 sec)



24 pairs
(4 min)

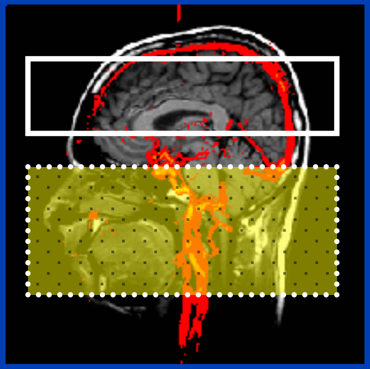
ΔM: GM – 0.9 %, WM – 0.15 %

ASL: Labeling Strategies

- Pulsed ASL (PASL)
  - Wide labeling slab
  - Created by a short pulse (milliseconds)
  - Input function – decaying exponential (T1 of blood)

PASL

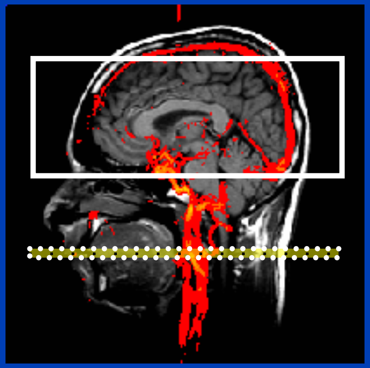
Labeling Slab



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

CASL

Labeling Plane



ASL- Quantification of CBF

One compartment model: Labeled blood stays in the vasculature

PASL

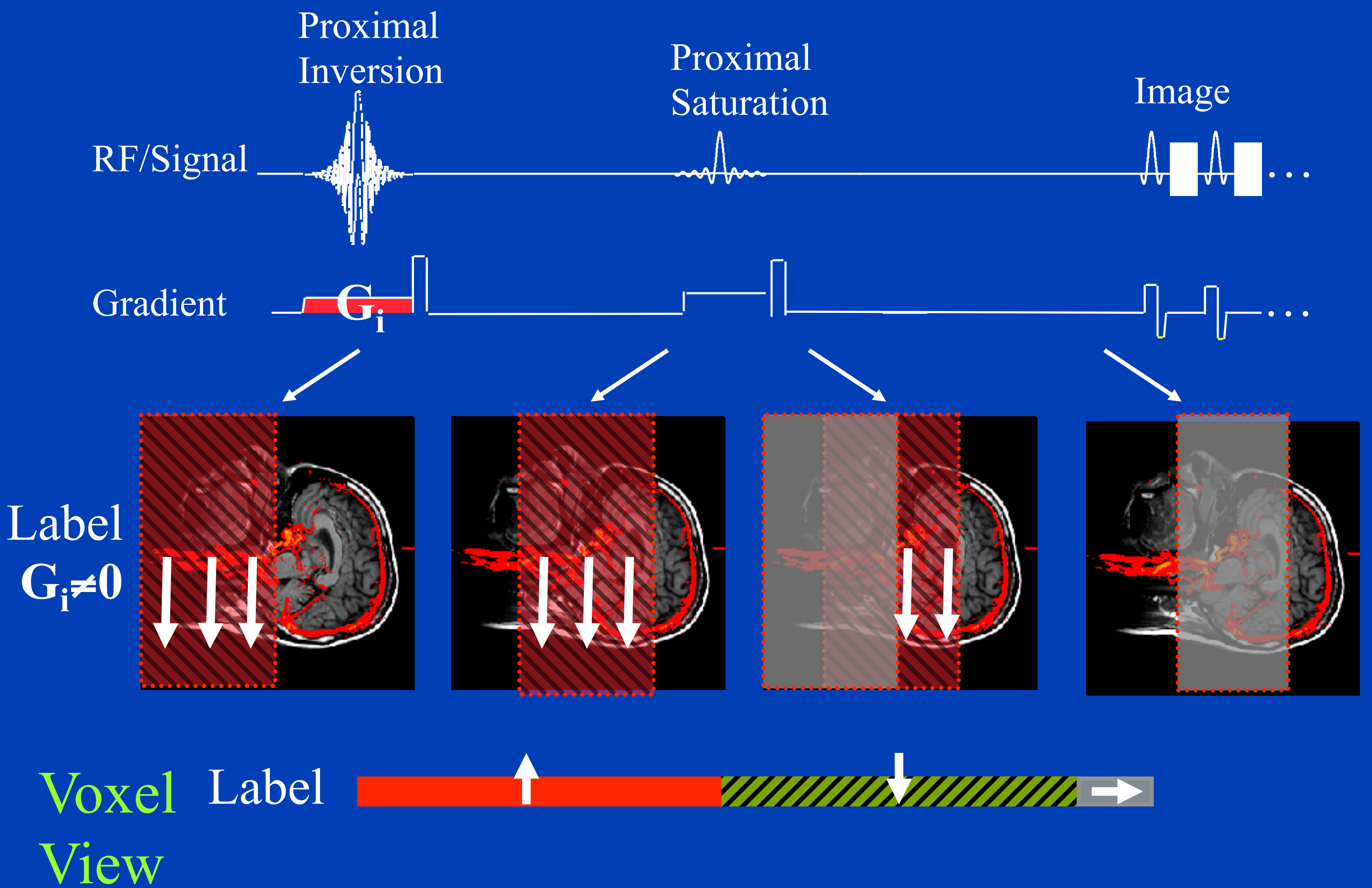
$$CBF_{PASL} = \frac{\lambda}{2\alpha_0} \cdot \frac{\exp(w \cdot R_{1a})}{\tau \cdot \exp(-\tau \cdot R_{1a})} \cdot \frac{\Delta S}{S^{eqm}}$$

CASL

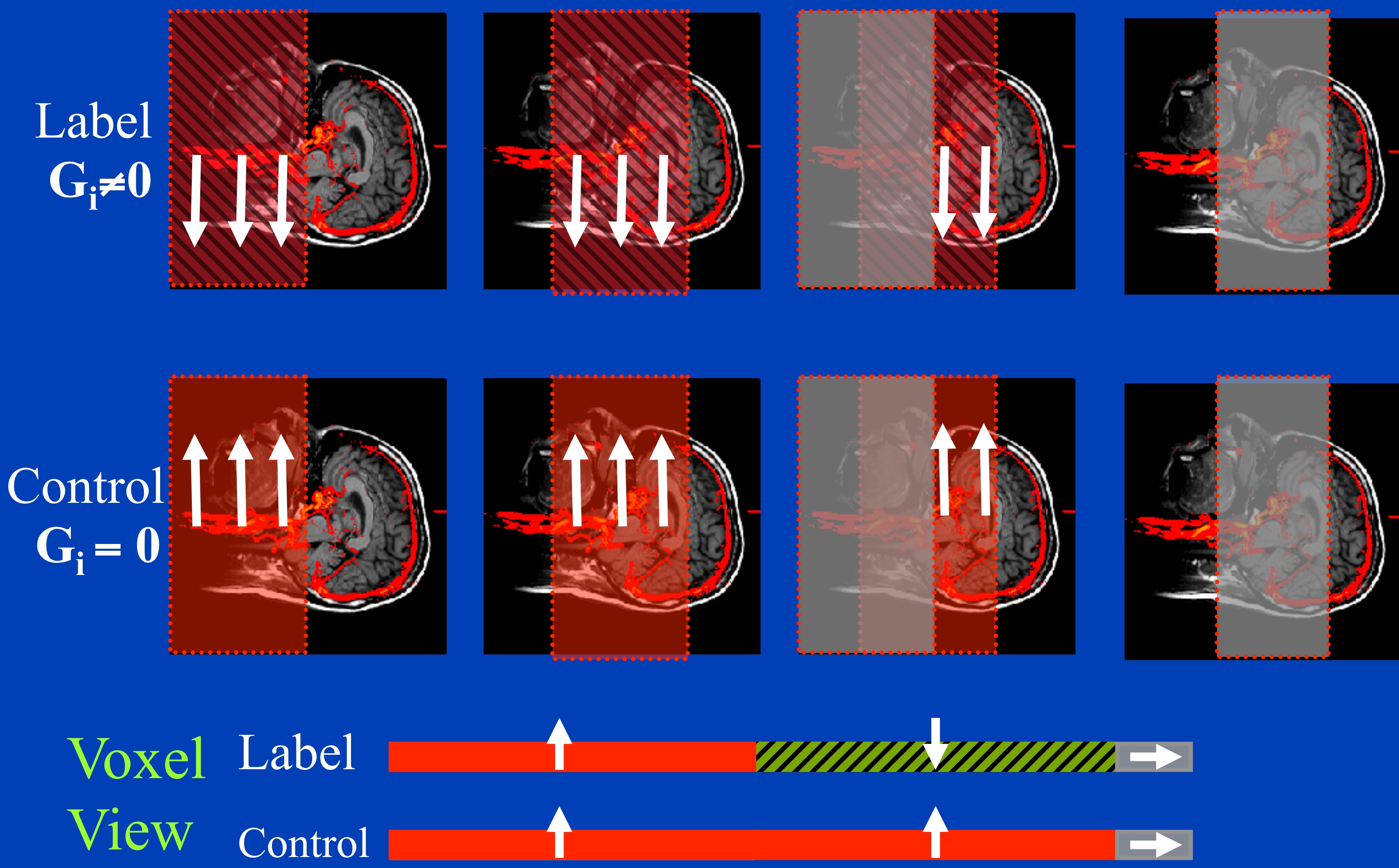
$$CBF_{CASL} = \frac{\lambda R_{1a}}{2\alpha_0} \cdot \frac{\exp(w \cdot R_{1a})}{[1 - \exp(-\tau \cdot R_{1a})]} \cdot \frac{\Delta S}{S^{eqm}}$$

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

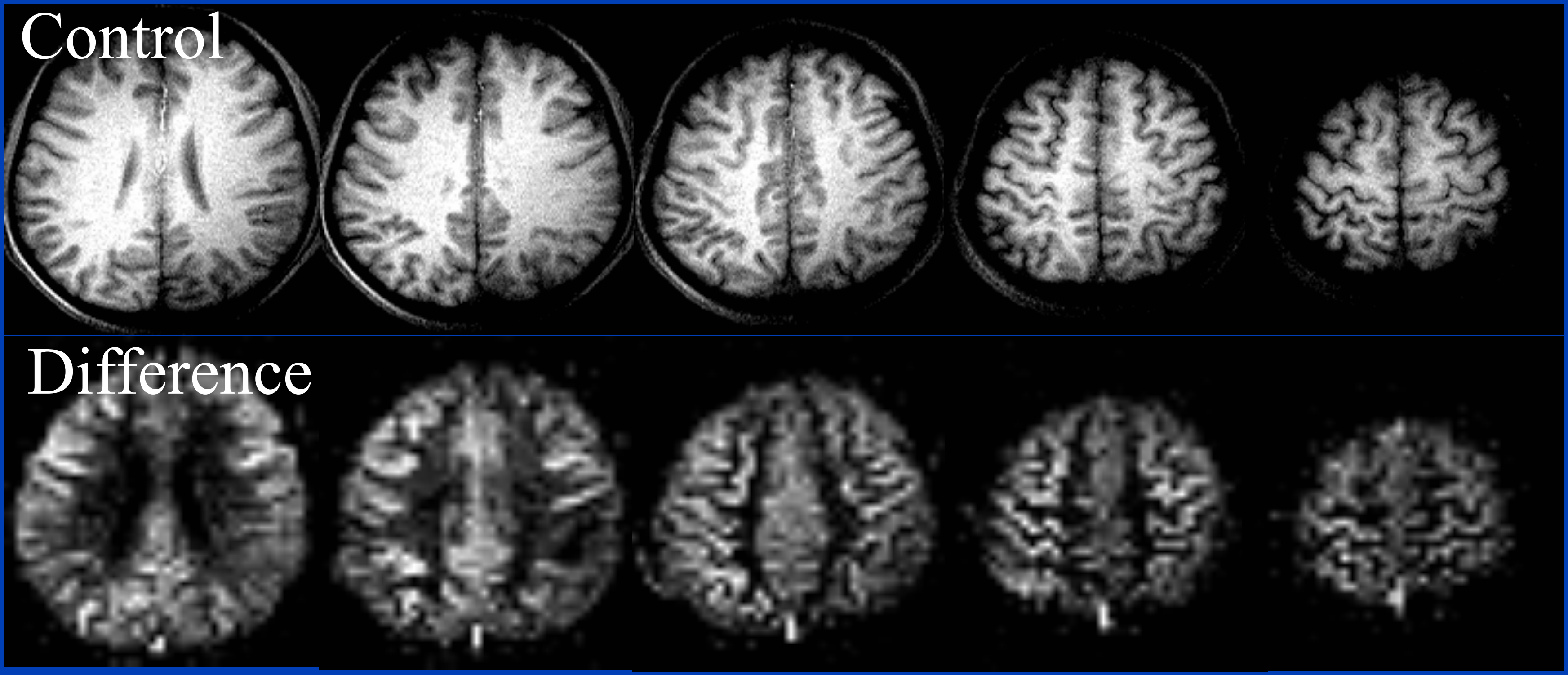
ASL: Pulsed Labeling (QUIPSS II)



ASL: Pulsed Labeling (QUIPSS II)



ASL: Pulsed Labeling (Q2TIPS)

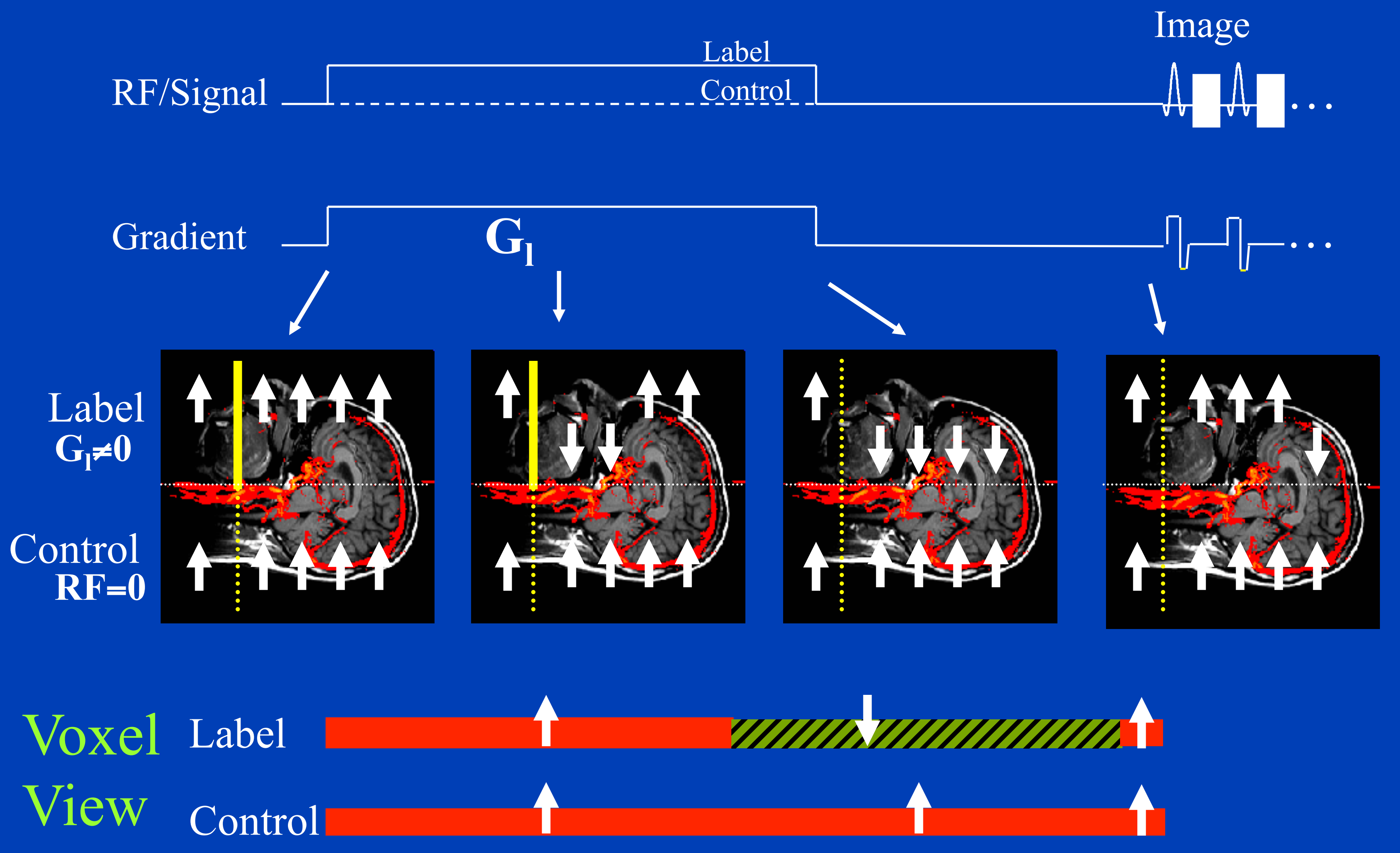


Advantages:
- High tagging efficiency
- Low SAR
- Ease of implementation

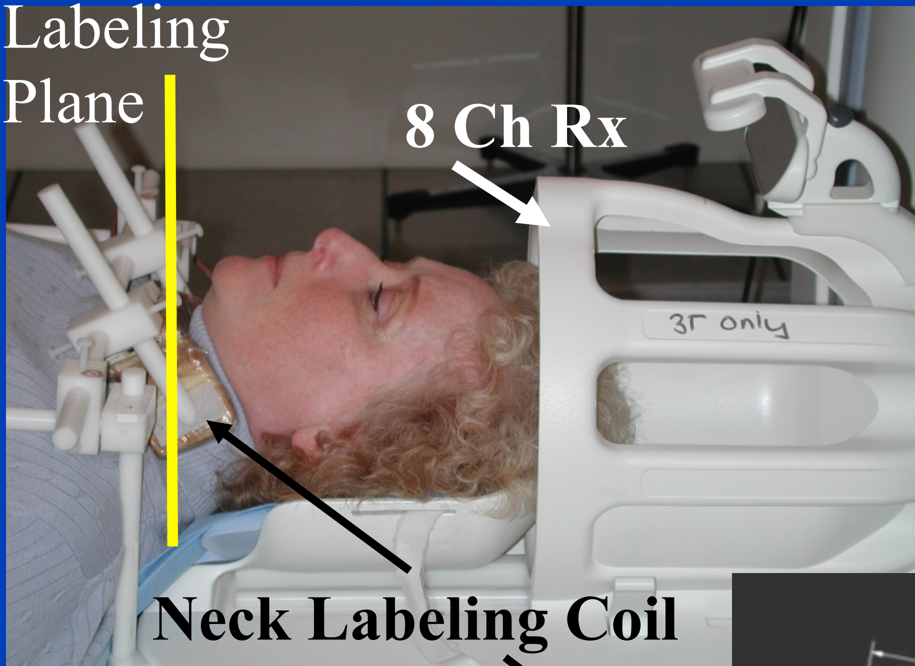
Disadvantage:
- Limited coverage

ASL: Continuous Labeling

(Flow-driven Adiabatic Fast Passage)

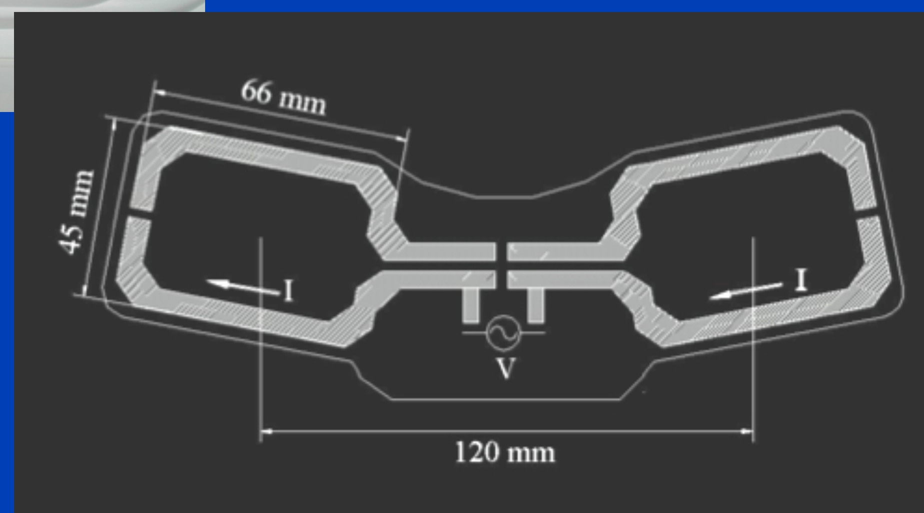


Continuous ASL: Neck Labeling Coil



Advantages:

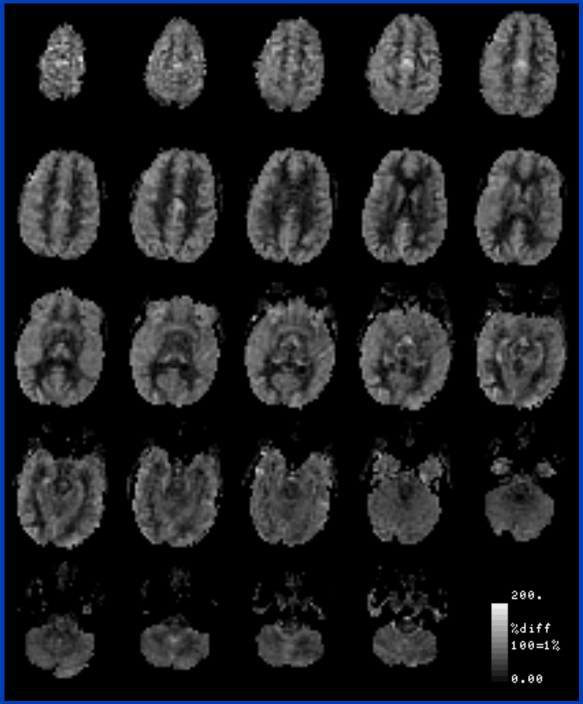
- Whole brain coverage
- High labeling efficiency
- Lower SAR



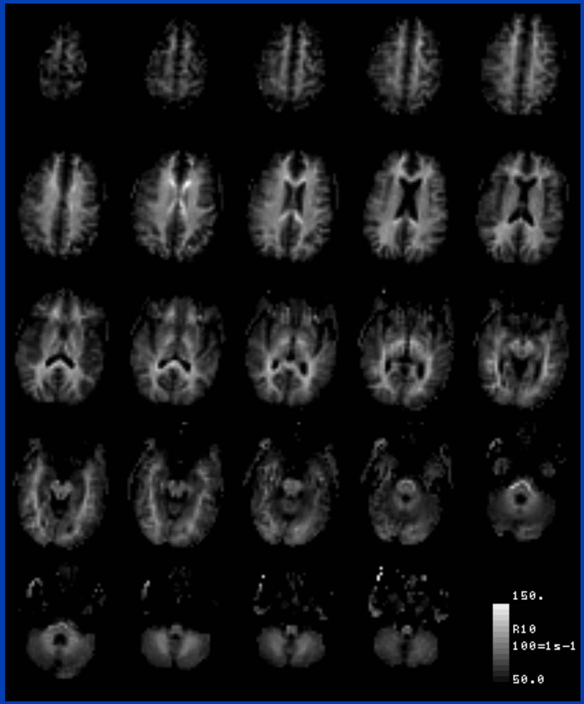
Disadvantage:

- Requires special hardware

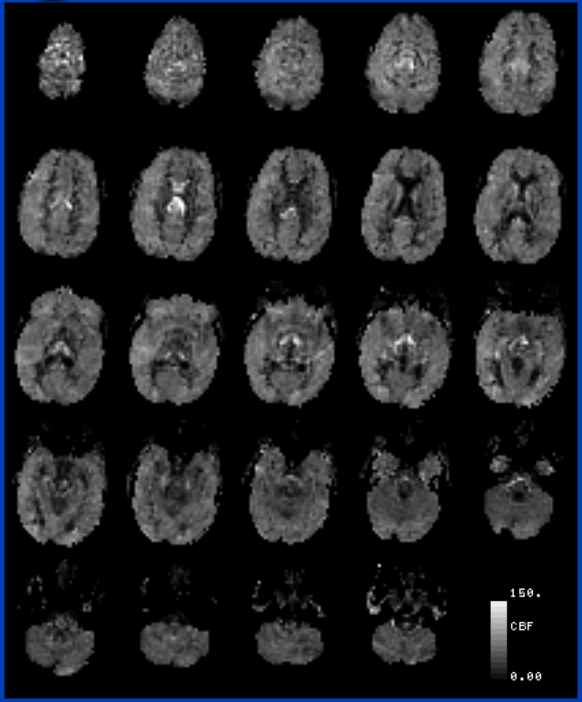
CASL with a Neck Labeling Coil: Multi-shot 3D-FSE Spiral



% ΔS



R1 map



CBF

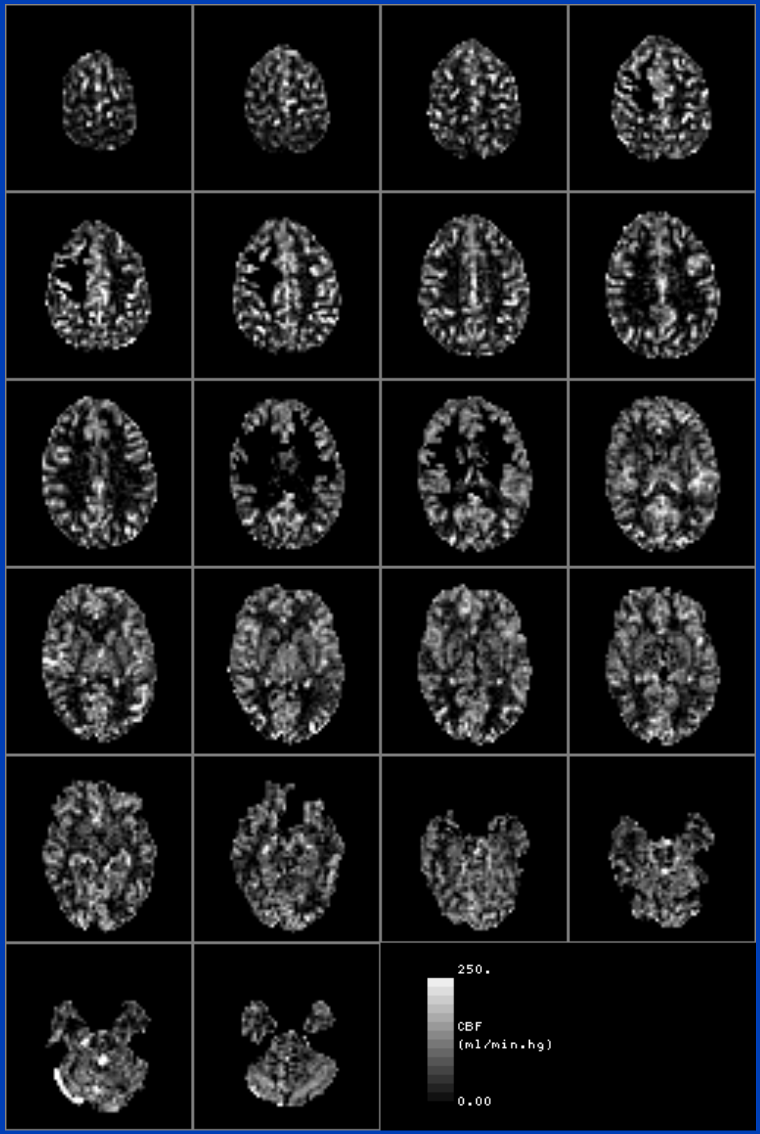
3T, Head Coil, 3D-FSE, 3.7 x 3.7 x 5 mm^3

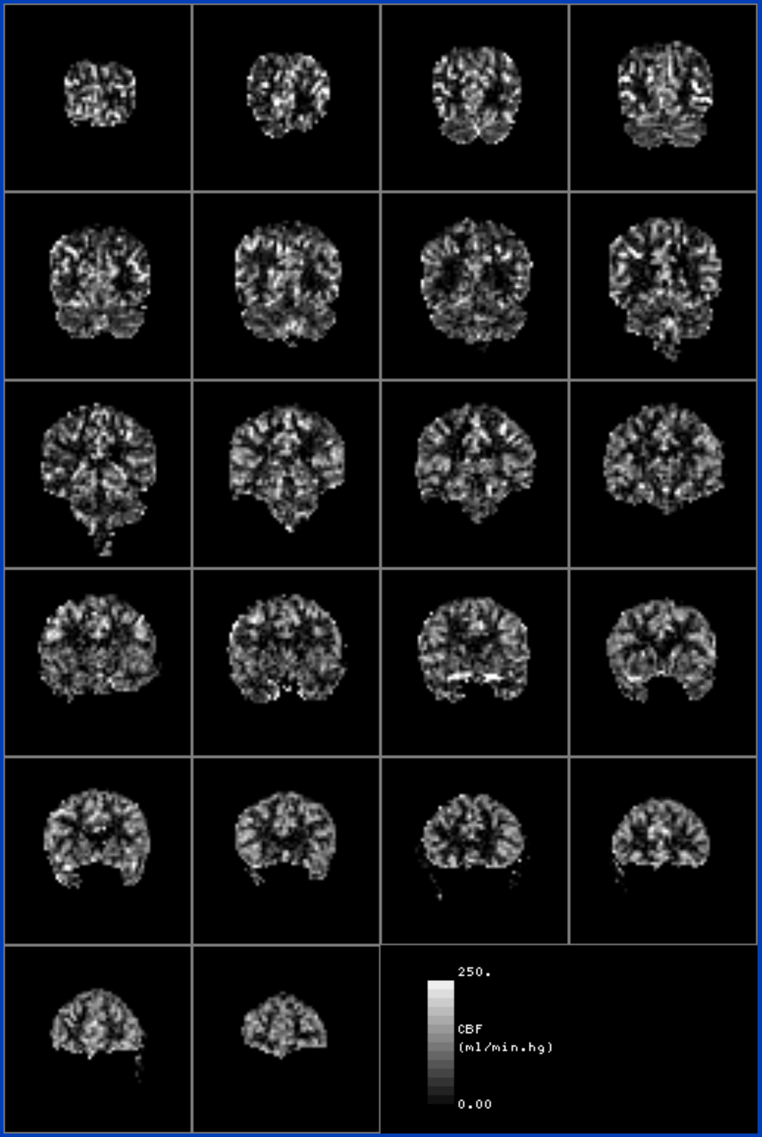
8 shots, TR 5.9 s, Label dur 4.1 s, PL delay 1.64 s, Backgr supp

6 min 22 sec

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

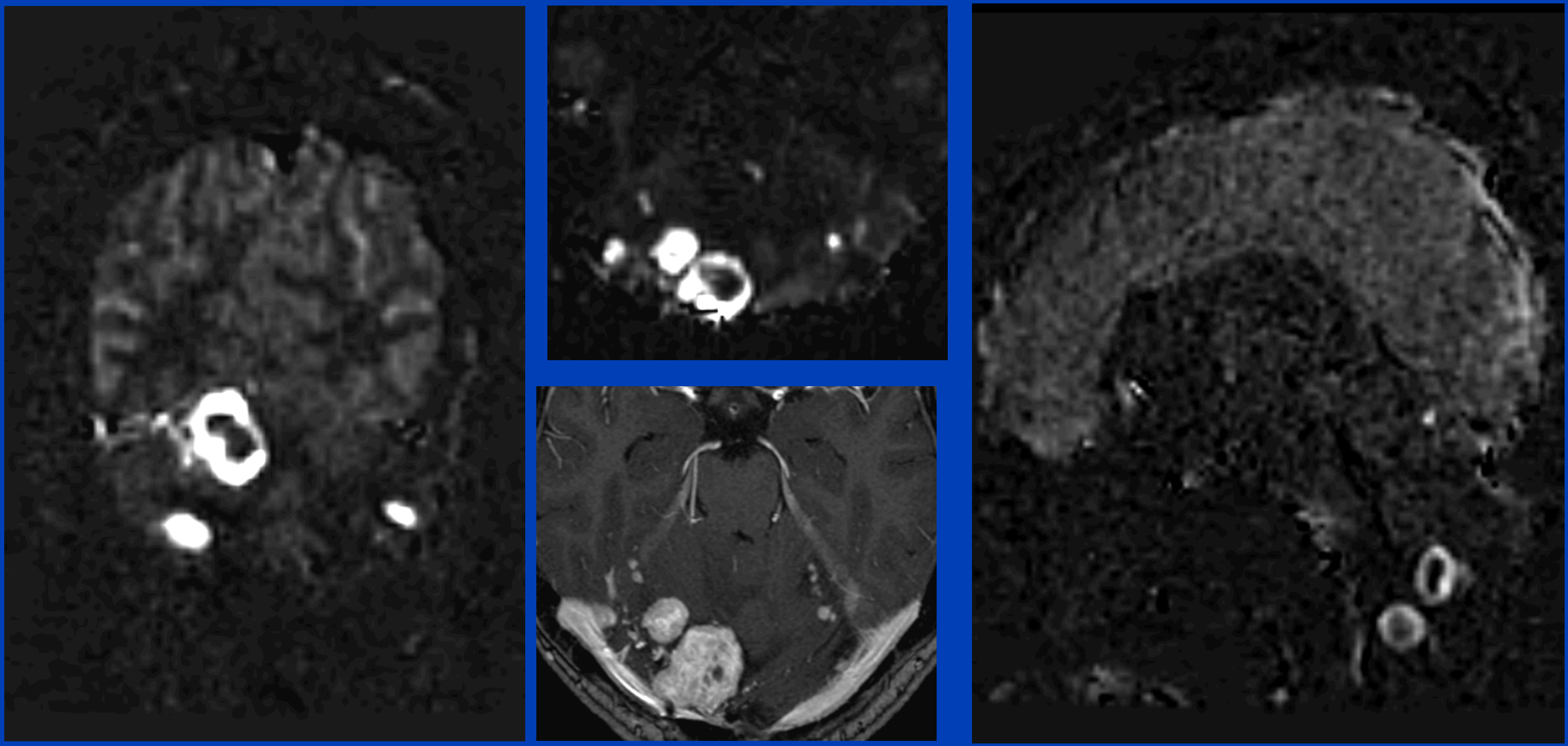
Continuous ASL: Neck Labeling Coil





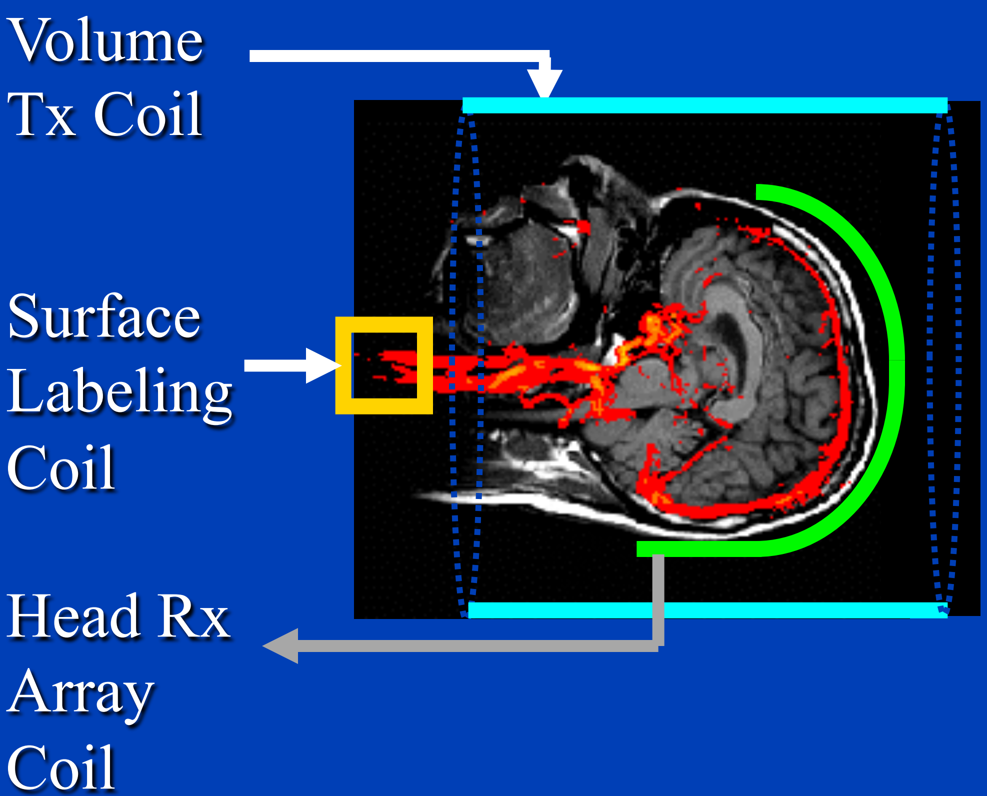
3T, 8 Ch Rx, 2D EPI, 3 x 3 x 3 mm^3, TE/TR 13 ms/5 s, 4.5 minutes

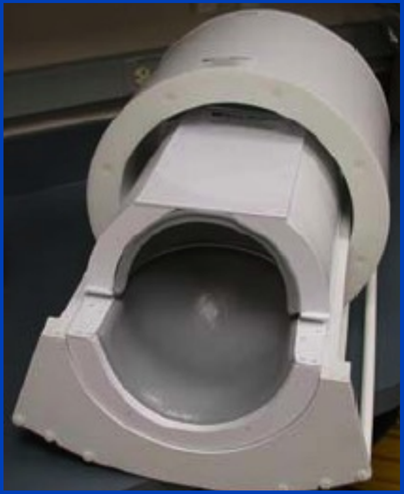
CASL with a Neck Labeling Coil: Hemangioblastomas



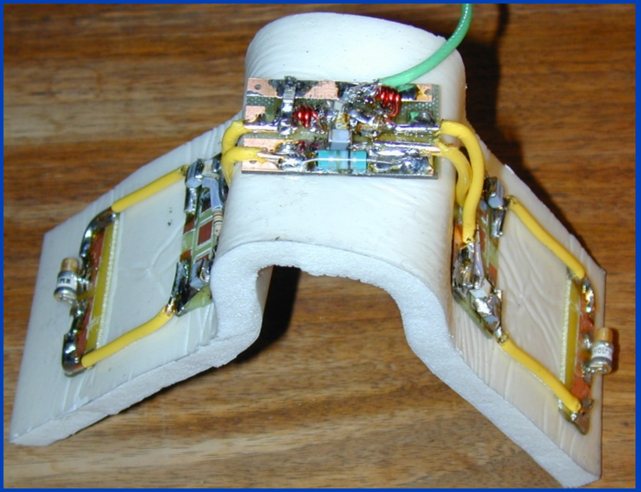
3T, 8 Ch Rx, 2D EPI, 1.5 x 1.5 x 3 mm^3
TE/TR 16 ms/5 s, LD/PLD 3 s/1.6 s
10 minutes

CASL Perfusion MRI at 7 T





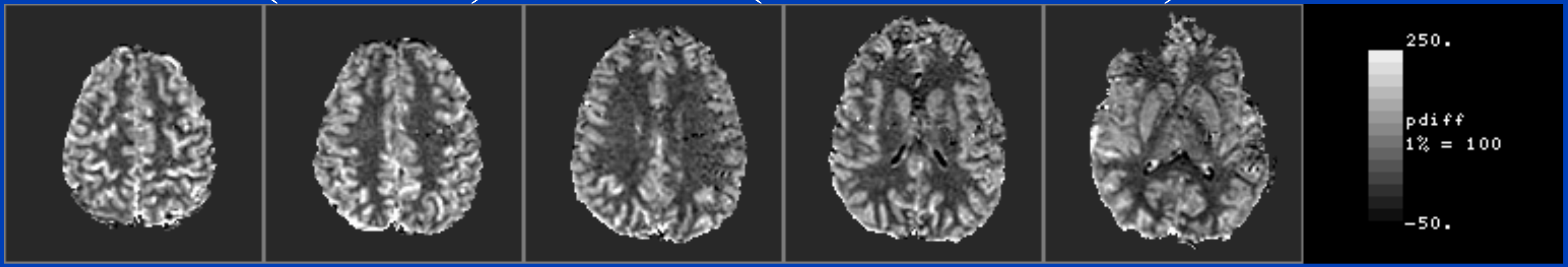
Tx Volume / 8 Ch Rx Array



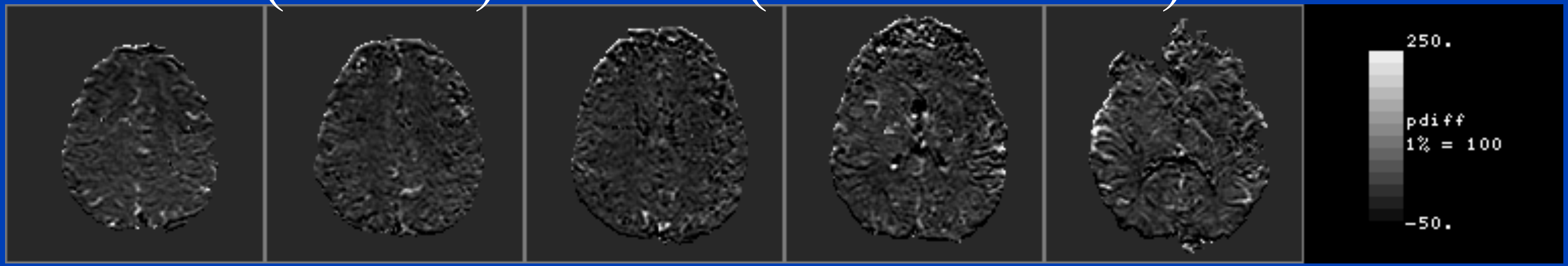
Neck Labeling Coil

7T CASL with a Neck Labeling Coil

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



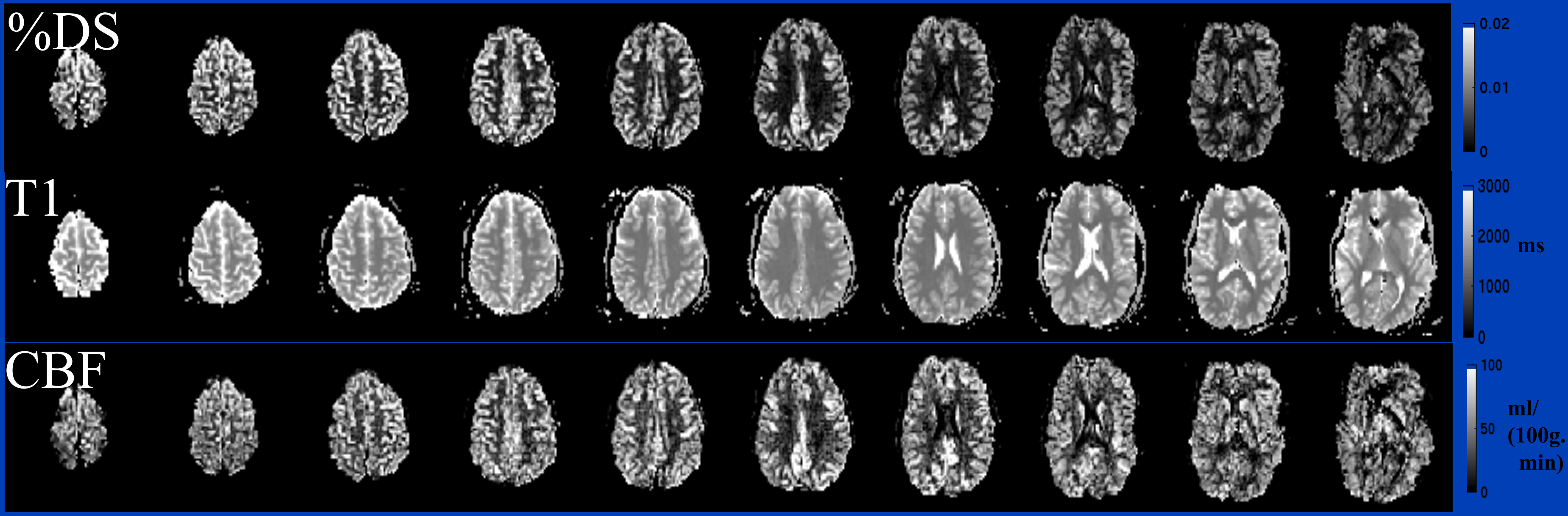
Control (RF off) - Label (RF –ve offset)



7T, 8 Ch Rx, 2D EPI, 2 x 2 x 3 mm^3
TE/TR 13 ms/5 s, ASSET X2, LD = 3 s, PLD 1.5 s
8 minutes

Talagala et al ISMRM 2008

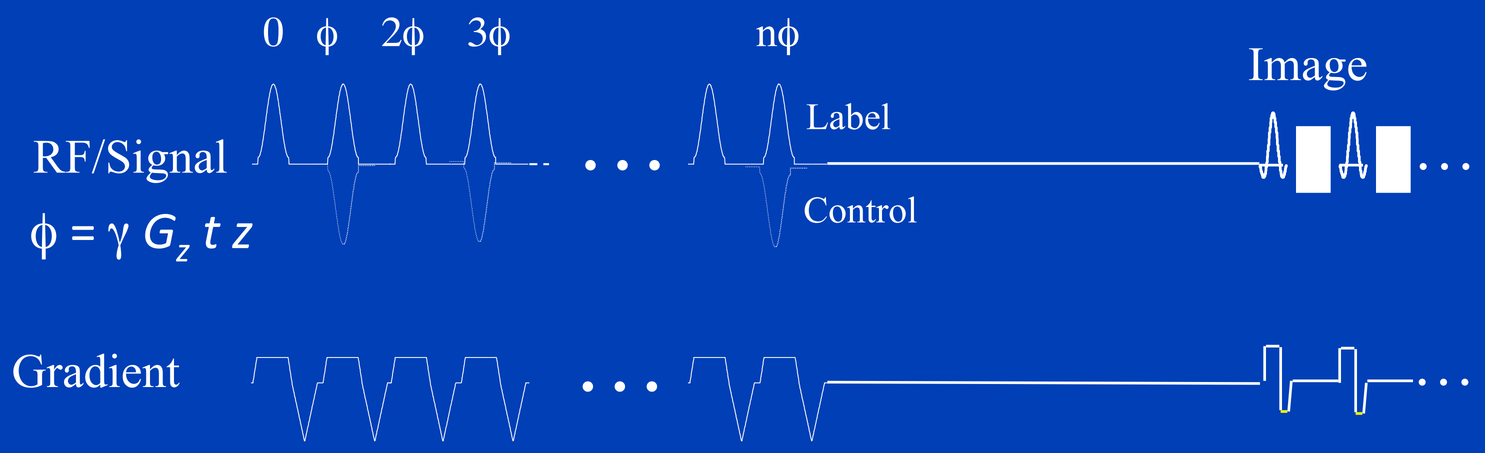
CASL Perfusion MRI at 7 T

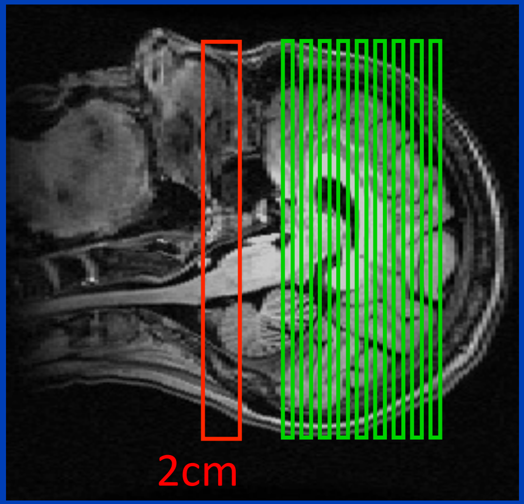


	Gray Matter	White Matter
Mean T1 (ms)	1940	1363
ΔS/S (%)	1.43 +/− 0.25	0.3 +/- 0.04
CBF (ml/min. 100g)	76 +/- 11	27 +/- 2.4

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

ASL: Pseudo Continuous labeling





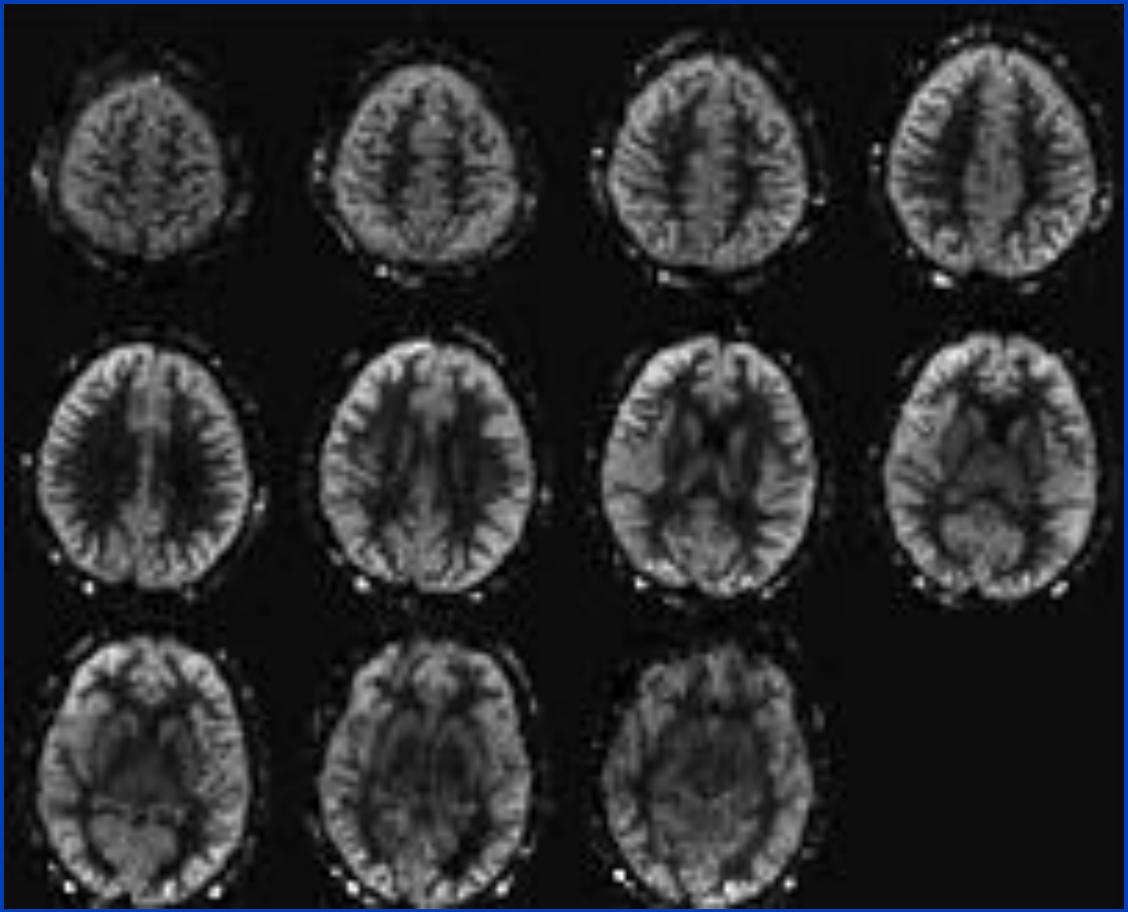
Advantages:

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

Disadvantages:

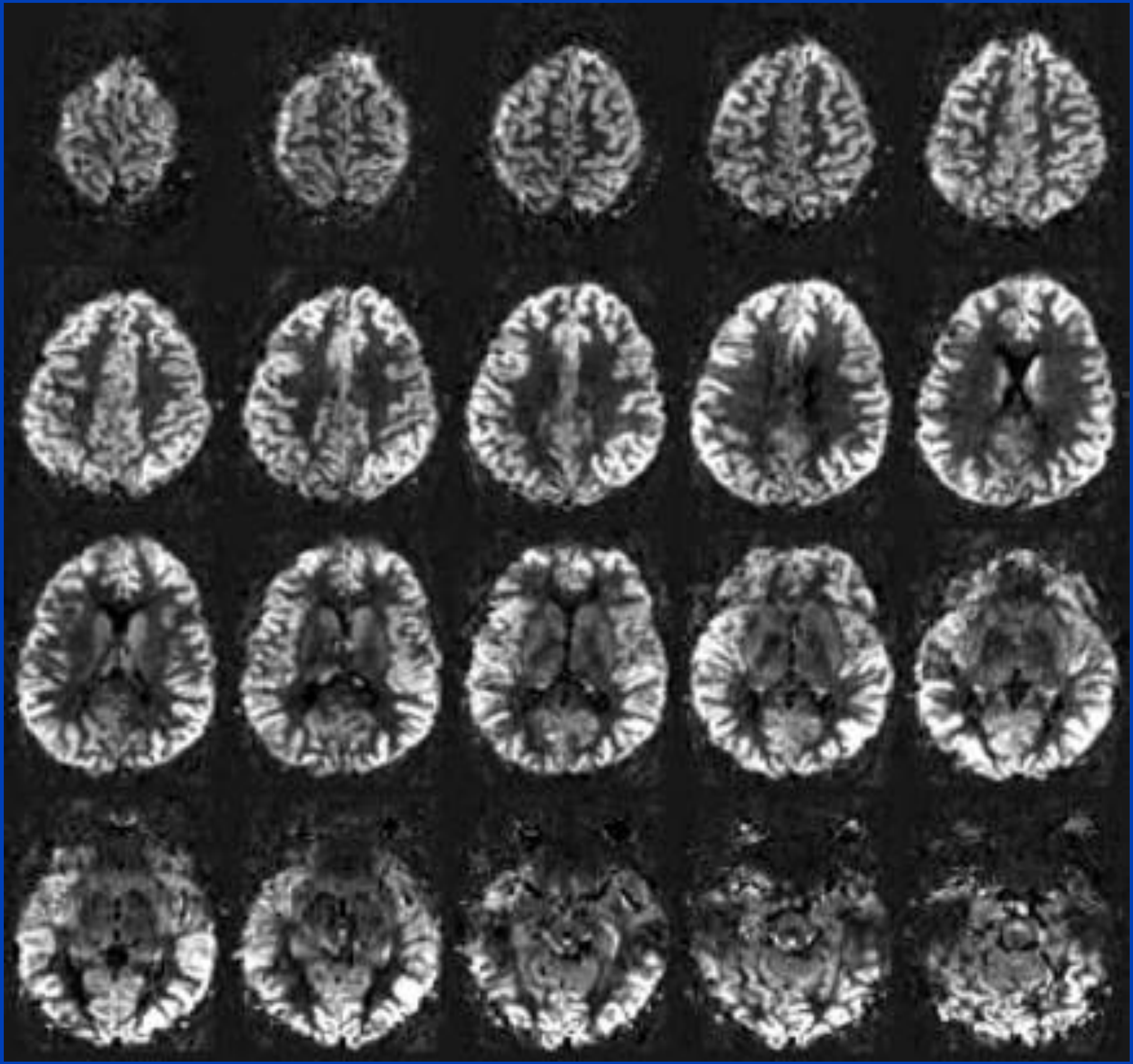
- Higher SAR
- Sensitivity to off-resonance effects

Pseudo Continuous ASL: 3T data



3T
$3.6 \times 3.6 \times 5\ mm^3$
Gradient-echo EPI
TE/TR = 20.8/5000 ms
τ/w = 2500/1700 ms
Scan time 5:00

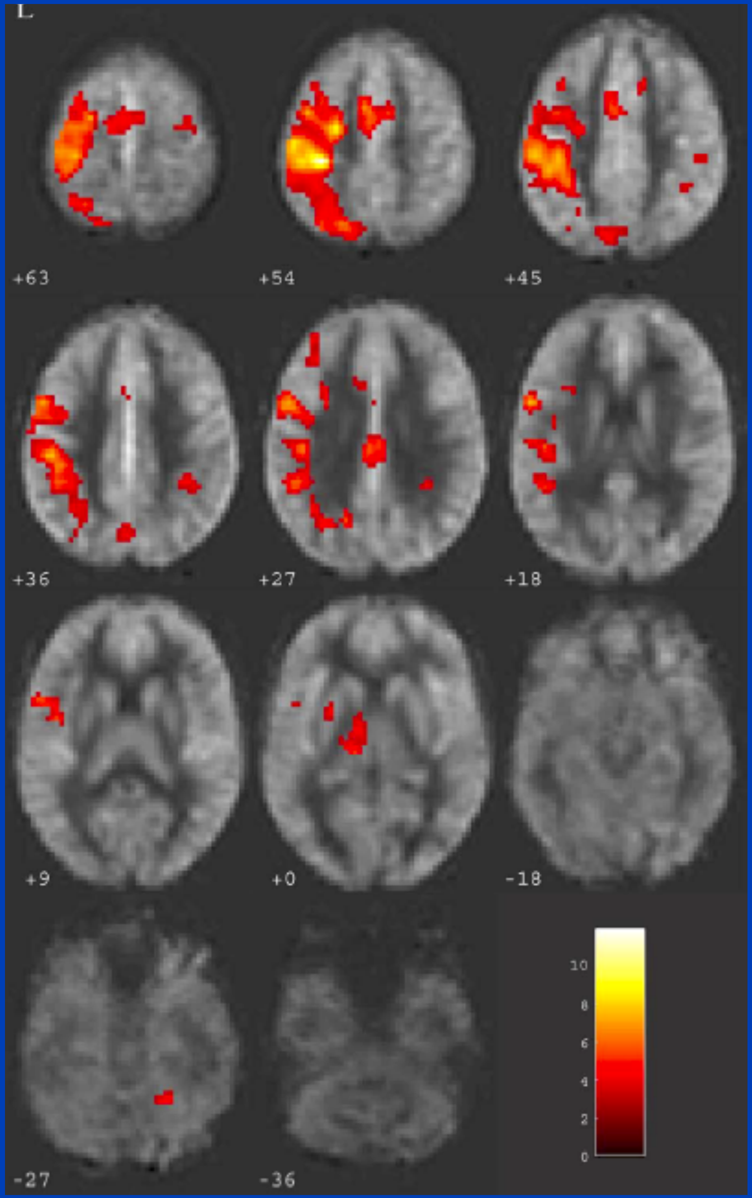
Pseudo Continuous ASL: 7T data

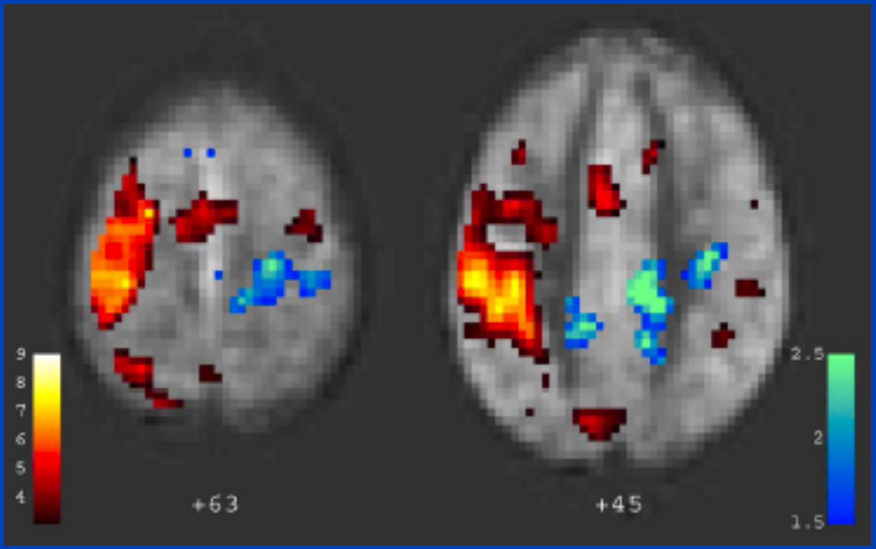


7T
2.3 x 2.3 x 3 mm^3
Gradient-echo EPI
TE/TR = 20.8/5100 ms
t/*w* = 3000/1200 ms
SENSE 3x
Scan time 4:15

Luh et al, *MRM* 69:402 (2013)

CASL fMRI with a Neck Labeling Coil

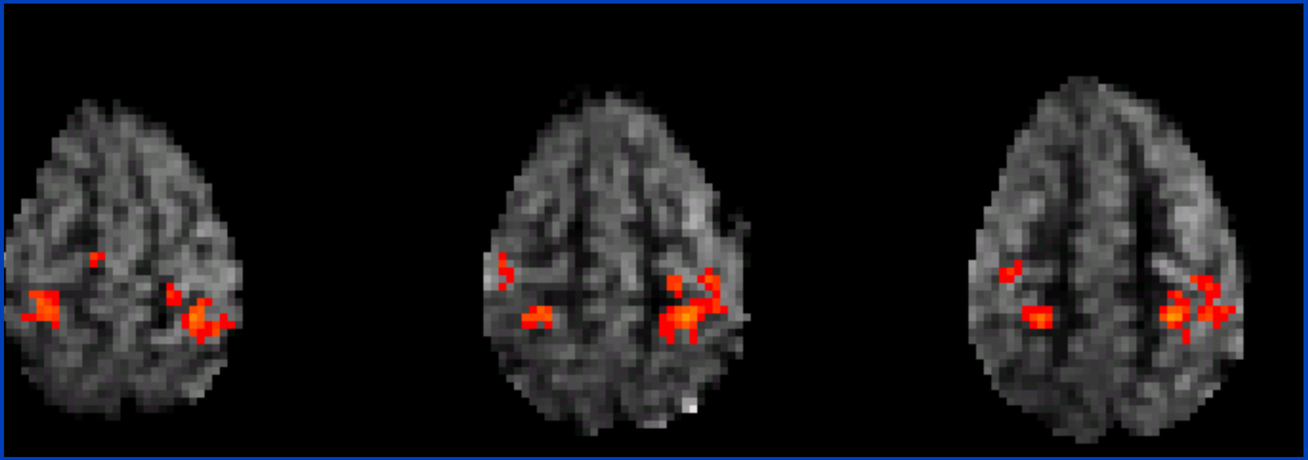




3T, Head Coil
Finger movement (0.5 Hz),
{48 s Task / 48 Rest} X 6, 10 min
GE EPI, 3.75 x 3.75 x 5 mm^3
12 s per Cont/Label pair
SPM, Spatial normalization
smoothing (8 mm), N= 15

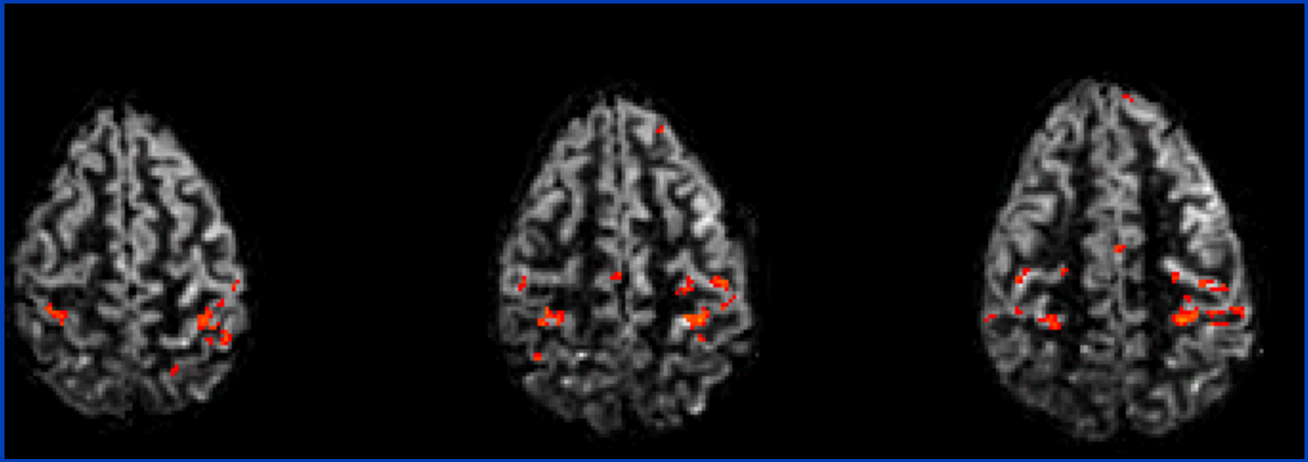
Garraux et al, *NeuroImage* 25:122-132 (2005)

3T CASL Perfusion fMRI with 16 Rx



CBF
75 ± 11
ml/(min.100g)

ΔCBF
78 ± 7%



CBF
92 ± 16
ml/(min.100g)

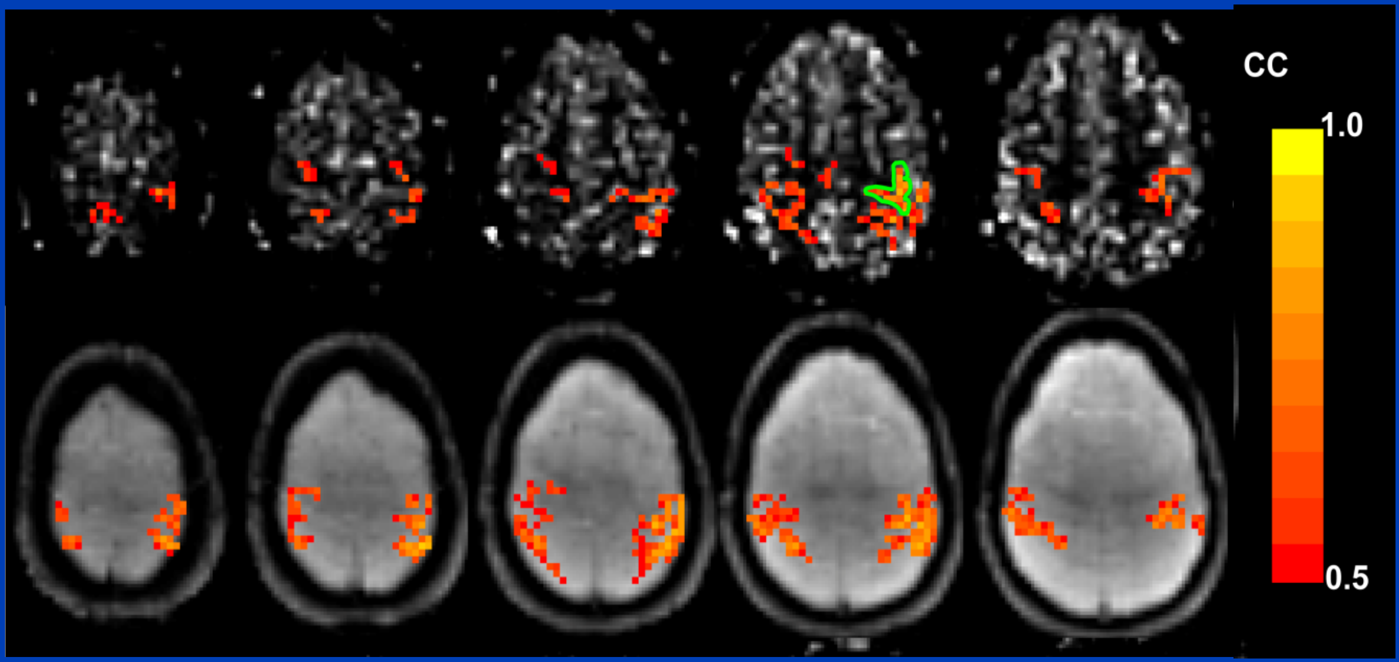
ΔCBF
102 ± 10%

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



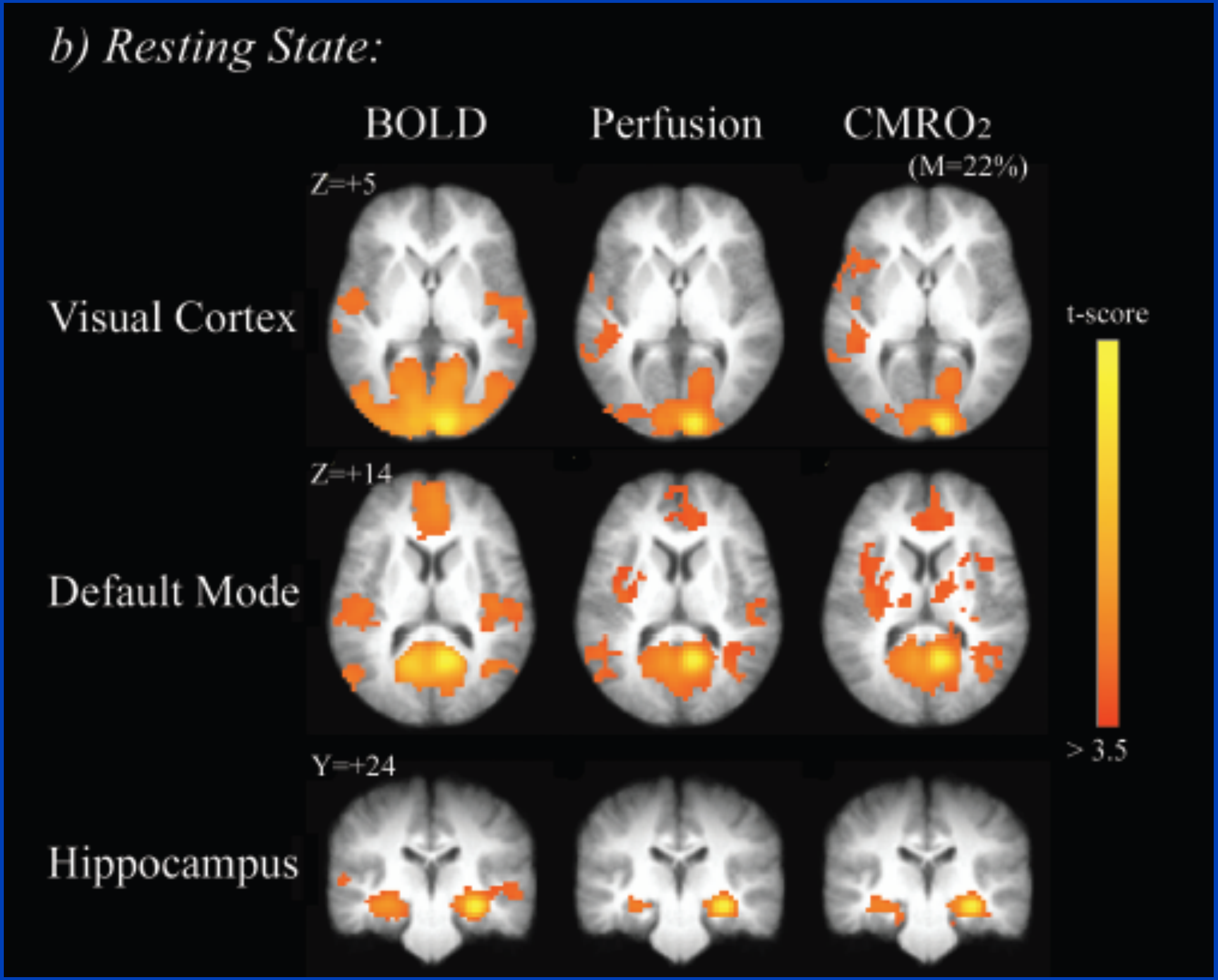
$\Delta CBF = 29 \pm 19\%$ $\Delta BOLD = 0.26 \pm 0.14\%$ (N=13)

3T, GE EPI, 16 Ch Rx, 3.75 X 3.75 X 3 mm^3

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

Chuang et al., *NeuroImage* 40, 1595 (2008)

Functional Connectivity: BOLD, Perfusion, CMRO2



Wu et al., *NeuroImage* 45, 694 (2009)

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