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

<table>
<thead>
<tr>
<th></th>
<th>Gray Matter</th>
<th>White Matter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CBF</strong> (ml/min/100 g)</td>
<td>60 - 80</td>
<td>20 - 30</td>
</tr>
<tr>
<td><strong>CBV</strong> (ml/100 g)</td>
<td>4 - 6</td>
<td>2 - 4</td>
</tr>
<tr>
<td><strong>MTT</strong> (s)</td>
<td>4 - 5</td>
<td>5 - 6</td>
</tr>
</tbody>
</table>
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 $\approx 1.5$ - $2$ s
- TE = $30$ - $50$ ms
- $\approx 1.5$ min

**Bolus Injection**
- Gd $0.1$ - $0.2$ mmol/kg
DSC - Mechanism

Gd Chelates: Paramagnetic, Intravascular

W/O Gd 

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 vs Time

GM pixel
Blood pixel

Baseline First pass
Recirculation

Time (s)

Signal Amplitude

0 20 40 60 80 100 120 140 160 180

0 20

-20
DSC: Signal loss to Concentration

\[ \Delta R_2^* = k \cdot C \]

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

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

- \( C \) – 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?

Arterial input function (AIF)

C_{art}(t)

F (ml/min)

Tissue Response

C_{tis}(t)

Tracer Kinetic Theory

MTT = \frac{CBV}{CBF}
DSC- Calculation of CBV

\[ \text{CBV} = \frac{k_H}{\rho} \left( \frac{\int C_{\text{tis}}(t) \cdot dt}{\int C_{\text{art}}(t) \cdot dt} \right) \]
DSC- Calculation of CBF and MTT

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

\[ R_{scl}(t) = \text{Deconvol}(C_{tis}(t), C_{art}(t)) \]

\[ CBF = R_{scl}(0) \]

\[ MTT = \frac{CBV}{CBF} \quad \text{and} \quad \frac{\int R_{scl}(t)\,dt}{R_{scl}(0)} \]
DSC – CBV, CBF, MTT maps

CBV

CBF

MTT
DSC – CBV, CBF, MTT maps

CBV

CBF

MTT
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

2D/3D EPI/SPIRAL
TR ~ 2 - 5 s
TE = minimum
~ 4-5 minutes

**Perfusion Maps**

Control

Label

**LABELING**
0.5 – 2.5 s

**IMAGING**
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)

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

One compartment model: Labeled blood stays in the vasculature

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

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

- \( R_{1a} \) – relaxation rate of arterial blood
- \( \alpha_0 \) – labeling efficiency
- \( \tau \) – labeling time
- \( \Delta S \) – signal change
- \( S^{eqm} \) – steady state signal
- \( \lambda \) – brain/blood partition coefficient of water
ASL: Pulsed Labeling (QUIPSS II)

Proximal Inversion

Proximal Saturation

Image

RF/Signal

Gradient

Label $G_i \neq 0$

Voxel View Label
ASL: Pulsed Labeling (QUIPSS II)

Control

$G_i = 0$

Label

$G_i \neq 0$

Voxel View

Label

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)

RF/Signal ➜ Label ➜ Control ➜ Image

Gradient ➜ $G_1$ ➜...

Label $G_1 \neq 0$

Control RF = 0

Voxel View Label Control
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

3T, Head Coil, 3D-FSE, 3.7 x 3.7 x 5 mm³
8 shots, TR 5.9 s, Label dur 4.1 s, PL delay 1.64 s, Backgr supp
6 min 22 sec

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 mm^3
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 x 2 x 3 mm³
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

### %DS

### T1 (ms)

### CBF (ml/min 100g)

<table>
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<tr>
<th>Mean T1 (ms)</th>
<th>Gray Matter</th>
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<tr>
<td>ΔS/S (%)</td>
<td>1.43 +/- 0.25</td>
<td>0.3 +/- 0.04</td>
</tr>
<tr>
<td>CBF (ml/min 100g)</td>
<td>76 +/- 11</td>
<td>27 +/- 2.4</td>
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7T, 8Ch Rx, 2.1 x 2.1 x 3 mm³, 9 minutes, n=5
ASL: Pseudo Continuous labeling

\[ \phi = \gamma G_z t \]

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 x 3.6 x 5 mm³
Gradient-echo EPI
TE/TR = 20.8/5000 ms
τ/ν = 2500/1700 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 x 3.75 x 5 mm³
12 s per Cont/Label pair
SPM, Spatial normalization
smoothing (8 mm), N= 15

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

CBF
75 ± 11 ml/(min.100g)

ΔCBF
78 ± 7%

CBF
92 ± 16 ml/(min.100g)

ΔCBF
102 ± 10%
Functional Connectivity with ASL Perfusion

ASL (high pass)

BOLD

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

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