Perfusion MRI
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Blood Vessel
Component of circulatory system transporting blood throughout the body

- Artery: carry blood away from the heart
- Capillaries
  - Convey blood between artery and vein
  - Site of exchange of water and chemicals between blood and tissue
- Vein: carry blood back to the heart
**Perfusion**

- The delivery of blood to a capillary bed in tissue

- **Perfusion parameters**
  - Blood flow: the rate of blood supply to the brain in ml/100g/min
  - Blood volume: the volume of blood per unit tissue mass in ml/100g or unitless fraction
  - Mean transit time: the average time a tracer resides within the system in second
  - Vessel permeability: the volume of blood transferred from intravascular space to extravascular-extracellular space per unit time

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**Perfusion**

- **Clinical relevance**
  - hyper/hypo metabolism & ischemia: blood flow
  - abnormal vascularization (i.e. angiogenesis): blood volume, mean transit time
  - BBB breakdown in high grade tumor: vessel permeability
MRI Method

No ionizing radiation!

- Endogenous contrast (blood)
  - Freely diffusible including interior of cells
  - Arterial Spin Labeling (ASL) MRI

- Gd-based contrast agent (GBCA)
  - Gadolinium: paramagnetic element causing T2/T2*/T1 shortening
  - Extracellular tracer: passing through vessel walls but not in the brain due to blood brain barrier
  - Dynamic Susceptibility Contrast (DSC) MRI
  - Dynamic Contrast Enhanced (DCE) MRI

Arterial Spin Labeling (ASL)

- A method for measuring blood flow
- Blood signal inverted in tag but not in control
- ASL signal from subtraction of tag/control
Arterial Spin Labeling (ASL)

- **Pulsed ASL**
  - RF pulse
  - **8 saturation RF pulse**
  - Imaging
  - TI1 (0.6s) TI2 (1.6s)

- **Continuous ASL or Pseudo-continuous ASL**
  - RF pulse
  - **Cont. RF pulse**
  - Imaging
  - TI (1.6s) TI (2.6s)

**Lower SAR**

**Higher SNR**

**Quantification into Blood Flow**
- Assume the entire labeled signal delivered to tissue
- Estimate blood magnetization ($M_{blood}$) from a reference signal (tissue or CSF)

**PASL**

\[
\begin{align*}
\text{CBF} &= \frac{\Delta M \times 6000}{2\alpha M_{blood} T_1 e^{-T_1/T_1\text{blood}}} \\
& \quad \text{[ml/100g/min]}
\end{align*}
\]

**CASL or PCASL**

\[
\begin{align*}
\text{CBF} &= \frac{\Delta M \times 6000}{2\alpha M_{blood} T_1 T_1\text{blood} e^{-T_1/T_1\text{blood}} (e^{T_1/T_1\text{blood}} - 1)}
\end{align*}
\]

$\Delta M = \text{perfusion weighted signal (control – tag)}$, $\alpha = \text{tagging efficiency}$, $T_1\text{blood} = 1.66s$ @3T
Arterial Spin Labeling (ASL)

- How long to wait?

\[ M \] vs. \[ TI \]

\[ \delta t \] vs. \[ T \]

Transit delay effect!

Multi-TI acquisition

More accurate estimation of CBF

Clinically relevant information
A time from tagging plane to tissue
Arterial Spin Labeling (ASL)

- Renal ASL
  - GBCA contraindicated in patients with kidney dysfunction
  - can be only perfusion technique for kidney disease

Dynamic Susceptibility Contrast (DSC)

- Kinetic Model

\[ C_T(t) = R(t) \otimes C_A(t) \]

\[ \text{CBF} \propto \max(R(t)) \] (by deconvolution)

\[ \text{CBV} = \frac{\int_0^\infty C_T(t)dt}{\int_0^\infty C_A(t)dt} \]

\[ \text{MTT} = \frac{\text{CBV}}{\text{CBF}} = \int_0^\infty R(t)dt \]
Dynamic Susceptibility Contrast (DSC)

Image Acquisition
- T2/T2* changes at first passage
- A series of T2/T2* weighted images
- High temporal resolution (≤1.5 sec) is desired to sample contrast dynamics
- Long TR is desired to minimize T1 effect
- Single-shot Echo Planar Imaging is preferred
  - T2*: 2D GRE EPI w/ ~50ms TE @ 1.5T & ~1.5sec TR)
  - T2: 2D SE EPI w/ ~70ms TE @ 1.5T & ~1.5sec TR)
- Acceleration methods (Parallel or Multiband imaging) are used for a broader coverage or a higher spatial resolution

Dynamic Susceptibility Contrast (DSC)

- An example of DSC time series
Dynamic Susceptibility Contrast (DSC)

- Analysis of the dynamic curve per voxel
  - Conversion into $\Delta R_2^*$ or $\Delta R_2$ signal ($[\text{Gd}] \propto \Delta R_2^*$ or $\Delta R_2$)
  - Finding AIF
  - Calculation of CBF, MTT, & CBV

GRE vs. SE

- Change in GRE relaxivity ($\Delta R_2^*$) higher than change in spin-echo relaxivity ($\Delta R_2$)
  → GRE DSC-MRI has higher SNR and sensitivity than SE DSC-MRI

- $R_2^*$ is linear with respect to [Gd] over a broader range of vessel sizes than $R_2$
  → GRE DSC-MRI inherently more accurate than SE DSC-MRI.
  → GRE DSC-MRI more large vessel dominant.

- GRE is more prone to magnetic susceptibility artifacts (signal dropouts and/or geometric distortions) arising from the skull base, paranasal sinuses, or resection cavities.

*GRE DSC-MRI generally preferred for tumor imaging while SE DSC-MRI immune to susceptibility artifacts.
Dynamic Susceptibility Contrast (DSC)

- Contrast leakage

Leakage correction or A preload (1/3 or 1/4 dose) is required!

Dynamic Contrast Enhanced (DCE)

- Contrast Agent Leakage

\[ \text{CBV} \approx 0 \]
\[ C_f(t) = R(t) \otimes C_A(t) \]
\[ R(t) = K_{trans}e^{-k_{ep}t}, \quad k_{ep} = \frac{K_{trans}}{V_e} \]

Tofts model
Dynamic Contrast Enhanced (DCE)

- **Contrast Agent Leakage**

\[ R(t) = K_{\text{trans}} e^{-kep t}, \quad kep = \frac{K_{\text{trans}}}{ve} \]

Extended Tofts model

**Image Acquisition**
- A series of T1 weighted images
- Longer scan time for relatively slower response
- Minimum TE to minimize T2* shortening effect
- Short TR for T1 weighting and acquisition speed
- 3D SPGR w/ short TE (~5ms), short TR (~12ms), 15~30° flip angle, ~5 sec temporal resolution, ~5 min scan time

- Acceleration method (Parallel imaging in phase encoding and slice encoding directions) is widely used to improve temporal resolution but SNR penalty
Dynamic Contrast Enhanced (DCE)

• An example of DCE time series

![Dynamic Contrast Enhanced (DCE)](image)

Dynamic Contrast Enhanced (DCE)

• Analysis of the dynamic curve per voxel
  - Conversion of signal into [Gd]
    \[
    ([\text{Gd}] \propto \Delta R1, \text{T1w Signal} = M0 e^{\frac{sina (1-e^{-TR R1})}{\cos (1-e^{-TR R1})}} \rightarrow \text{tissue T1 map or assumed value}
    \]
  - Finding AIF
  - Calculation of \( K_{\text{trans}} \), \( V_e \), \( V_p \), \( k_{\text{ep}} \) (\( K_{\text{trans}} / V_e \))
  - \( K_{\text{trans}} \) related to permeability, surface area & flow

![Dynamic Contrast Enhanced (DCE)](image)
Dynamic Contrast Enhanced (DCE)

- Breast imaging
  - High spatial resolution (1~2mm isotropic), 1~3 min temporal resolution

![Graph showing persistent, plateau, and washout phases with high chance of tumor malignancy.]

### Summary

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