PERFUSION – MRI
CONTRAST BASED TECHNIQUES

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Mar 28, 2006

PERFUSION - MRI

➤ BOLUS TRACKING TECHNIQUES
  • Dynamic Susceptibility contrast
  • Dynamic Relaxivity contrast

➤ STEADY-STATE TECHNIQUES
  • Steady-state Susceptibility contrast
  • Steady-state Relaxivity contrast

➤ USING DIFFUSIBLE TRACERS
BOLUS TRACKING TECHNIQUES

➢ PRINCIPLE

Gd-DTPA
0.1-0.2 mmol/kg
3-5 ml/sec

Courtesy of L. Wald
Contrast agent in brain vessels produce changes in MR signal intensity

Susceptibility effects $\rightarrow T_2^*$ decreases $\rightarrow$ signal drop

Relaxivity effects $\rightarrow$ changes in blood-water longitudinal relaxation rates ($T_1$)

Signal vs time curve $\rightarrow$ concentration vs time curve

Integral of concentration time curve proportional to Cerebral Blood Volume (CBV)
BOLUS TRACKING TECHNIQUES

PRINCIPLE

Signal time course in perfused voxel

MR Signal intensity

Time

baseline 1st passage re-circulation

BOLUS TRACKING TECHNIQUES

PRINCIPLE

Concentration time curve in perfused voxel

Tracer Concentration

Area under curve Proportional to CBV

Arrival time

Time
BOLUS TRACKING TECHNIQUES

➢ PRINCIPLE

Quantification of perfusion is done using Central volume theorem

\[ CBF = \frac{CBV}{T_{mtt}} \]

- \( CBF \) – Cerebral Blood Flow
- \( CBV \) – Cerebral Blood Volume
- \( T_{mtt} \) – Mean Transit time
When a bolus of contrast agent is injected, the concentration $C_{voi}(t)$ of the tracer in a voxel (VOI) can be described as

$$C_{voi}(t) = \left(\frac{\rho}{k_h}\right) \cdot CBF_{voi} \cdot \int C_a(\tau) \cdot R(t-\tau) d\tau$$

$\rho$ – density of the tissue

$k_h$ – constant correcting for differences in hematocrit in capillaries and large vessels
BOLUS TRACKING TECHNIQUES

➢ TRACER KINETICS

• The CBV is expressed as

\[ CBV = \left( \frac{k_h}{\rho} \right) \cdot \left( \frac{\int C_{\text{voi}}(t) \, dt}{\int C_a(t) \, dt} \right) \]

• Relative CBV can be estimated without knowledge of \( C_a(t) \), assuming it the same for all parts of the tissue

BOLUS TRACKING TECHNIQUES

➢ CONCENTRATION DEPENDENCY

• \( C_{\text{voi}} \) used in the calculation of hemodynamics is related to the change in T2* relaxation

\[ C_{\text{voi}}(t) = k \cdot \Delta R2^* = k \cdot \Delta (1 / T2^*) = -(k / T_E) \cdot \ln(S(t) / S_0(t)) \]

\( k \) – proportionality constant

\( T_E \) – echo time

\( S(t) \) – signal intensity in VOI at time \( t \)

\( S_0(t) \) – baseline signal intensity

\( \Delta R2^* \) - relaxation rate
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BOLUS TRACKING TECHNIQUES

➢ DYNAMIC SUSCEPTIBILITY CONTRAST
  ❖ PRINCIPLE

  • $T2^*$-weighted imaging sequence
  • Signal vs time curve for each voxel
  • Contrast agent concentration $C_{voi}$
  • Concentration vs time curve for each voxel
  • Arterial input function $C_a$ is estimated from the signal of voxels containing or surrounding a large artery
  • $CBV$ and $CBF$ are then calculated using tracer kinetics
**BOLUS TRACKING TECHNIQUES**

- **DYNAMIC SUSCEPTIBILITY CONTRAST**
  - **PRACTICAL CONSIDERATIONS**

  - Difficult to measure $C_a$
  - In brain tissue, changes in $R2^*$ are due to extravascular spins
  - In blood, changes in $R2^*$ are due to magnetic field gradients arising between RBC and plasma
  - $C_{vol}(t)$ estimation is based on the assumption of absence of any $T1$ weighting $\rightarrow$ long $TR$ $\rightarrow$ low temporal resolution

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**BOLUS TRACKING TECHNIQUES**

- **DYNAMIC SUSCEPTIBILITY CONTRAST**
  - **METHODS**

  \[
  \text{rCBV}_{\text{index}} = \int_{0}^{t} \Delta R_2^*(\tau) d\tau. \\
  \text{rMTT}_{\text{index}} = \frac{\int_{0}^{t} \tau \Delta R_2^*(\tau) d\tau}{\int_{0}^{t} \Delta R_2^*(\tau) d\tau}. \\
  \text{rCBF}_{\text{index}} = \frac{\text{rCBV}_{\text{index}}}{\text{rMTT}_{\text{index}}}. 
  \]
BOLUS TRACKING TECHNIQUES

➤ DYNAMIC SUSCEPTIBILITY CONTRAST

T2-weighted image of an ischemic edema-bearing patient
Mean Transit time ($T_{mtt}$) index

relative CBV index
relative CBF index
BOLUS TRACKING TECHNIQUES

➤ DYNAMIC SUSCEPTIBILITY CONTRAST

Susceptibility bolus tracking curves obtained from the regions (1-4) pointed by arrows in (a) (rCBV index)

**Note the different vertical scales**
PERFUSION - MRI

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BOLUS TRACKING TECHNIQUES

➢ DYNAMIC RELAXIVITY CONTRAST
  ❖ PRINCIPLE

  • \textit{T1-weighted} imaging sequence
  • Assuming \textit{water exchange} between the intra and extra-vascular compartments \textit{is negligible} thus the MR signal can be written as

  \[ \Delta S(t) = S_{\text{intra}}(t) - S_{\text{intra}}(0) \]

  and originates from blood only

  • Like with Dynamic Susceptibility Contrast, this \textit{signal intensity is converted to a relative concentration of contrast agent}
BOLUS TRACKING TECHNIQUES

DYNAMIC RELAXIVITY CONTRAST

PRINCIPLE

- Change in relaxation rate $\Delta R1$ is linearly related to the blood concentration in the contrast agent.
- Using Inversion recovery or Saturation recovery fast imaging techniques, $S(t)$ is linearly related to $R1$.
- At low $T1$ values, signal vs concentration relationship decreases.

(A) Contrast-enhanced axial view T1-weighted image (B) Axial view T2-weighted image (C) Gradient-echo axial view perfusion MR image and rCBV color overlay map.
BOLUS TRACKING TECHNIQUES

➢ APPLICATIONS

- Characterization of tumor vascularity
- Follow-up of cancer treatments
- Study of vasodilatory capacity of brain
- Study of ischemia-reperfusion injuries and stroke

BOLUS TRACKING TECHNIQUES

➢ LIMITATIONS

- High temporal resolution required to determine rCBV and rCBF is obtained at the expense of spatial resolution and SNR
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STEADY-STATE TECHNIQUES

➢ PRINCIPLE

• Uses contrast agents with a long half-life in the vascular pool (like SPIO, AMI-227)
• Standard gradient-echo or spin-echo imaging sequences are used
• Offers high spatial resolution but does not allow rCBF and $T_{mn}$ to be measured

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STEADY-STATE TECHNIQUES

STEADY-STATE SUSCEPTIBILITY

PRINCIPLE

• Linear relationship between rCBV and R2* is exploited
• T2*-weighted imaging sequence

METHODS

SINGLE GRADIENT ECHO

• R2* changes due to contrast agent are obtained from the ratio of signal intensities before & after contrast injection

\[ \Delta R2^* = \left( \frac{1}{T_E} \right) \cdot \left( \frac{S_{\text{post}}}{S_{\text{pre}}} \right) \]

\( T_E \) – echo time
\( S_{\text{post}} \) – signal intensity after contrast injection
\( S_{\text{pre}} \) – signal intensity before contrast injection
STEADY-STATE TECHNIQUES

STEADY-STATE SUSCEPTIBILITY

METHODS

- SINGLE GRADIENT ECHO
  - *T*1-weighting of the signal may introduce *T*E-dependent errors
  - *T*1 effects cause underestimation of Δ*R*2*

- MULTIPLE GRADIENT ECHO
  - Insensitive to *T*1-weighting

\[ \Delta R^* = \left( \frac{1}{T^*_\text{post}} \right) - \left( \frac{1}{T^*_\text{pre}} \right) \]

*T*2* post - post injection relaxation time
*T*2* pre - pre injection relaxation time
STEADY-STATE TECHNIQUES

STEADY-STATE SUSCEPTIBILITY

Axial view T2-weighted image
Gradient-echo axial view perfusion MR image and rCBV color overlay map

LIMITATIONS

- Prior knowledge of the proportionality constant (k) between $\Delta R^2*$ and rCBV ($rCBV = k \cdot \Delta R^2*$)
- Vessel-size dependent
- Blood-Brain Barrier (BBB) should not be disrupted
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STEADY-STATE TECHNIQUES

➢ STEADY-STATE RELAXIVITY
  ❖ PRINCIPLE

  • *T1-weighted* imaging sequence
  • Assuming *water exchange* between the intra and extra-vascular compartments is negligible thus the MR signal can be written as
    \[ \Delta S(t)_{\text{intraV}} = S_{\text{intraV}}(t) - S_{\text{intraV}}(0) \]
    and originates from blood only
This increase in signal is related by

\[ rCBV(\%) = 100 \times \left( \frac{\Delta S(t)_{\text{intra}}}{\Delta S(t)_{\text{ref}}} \right) \]

\[ \Delta S(t)_{\text{ref}} \] - signal increase in a voxel that contains blood only

This T1-weighted MRI scan shows a mass in the left thalamus of the brain. The rCBV map of the same brain shows regions of red signals (arrow) that indicate high CBV, revealing that the mass is probably a tumor.
STEADY-STATE TECHNIQUES

STEADY-STATE RELAXIVITY

LIMITATIONS

• Partial volume effects
• Hematocrit differences in capillaries and large draining veins

A short echo time ($T_E$) is used

STEADY-STATE TECHNIQUES

APPLICATIONS

• Understanding BOLD contrast in situations where changes in CBV and oxygenation occur simultaneously
• measuring CBV in tumor studies
• Study of vasodilatory capacity of brain
• Study of ischemia-reperfusion injuries and stroke
REFERENCES

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