Applications of Magnetic Resonance Imaging

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## MRI milestones

<table>
<thead>
<tr>
<th>Decade</th>
<th>Development</th>
<th>Year</th>
<th>Impact</th>
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<tbody>
<tr>
<td>1970–1980</td>
<td>Demonstration of imaging by nuclear magnetic resonance</td>
<td>1973</td>
<td>Lauterbur</td>
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<td></td>
<td>Slice selection</td>
<td>1974</td>
<td>Mansfield</td>
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<td></td>
<td>Cryogenic magnets</td>
<td>1977</td>
<td>Improved homogeneity, stability</td>
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<td>Increased static field strength</td>
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<td>Improved image quality</td>
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<td>Abandonment of line-scan and back-projection methods</td>
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<td>First commercial MRI available</td>
<td>1980</td>
<td>Optimized image uniformity</td>
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<td></td>
<td>Birdcage coils</td>
<td>1985</td>
<td>Improved stability and SNR</td>
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<td>Introduction of clinical cryogenic magnets</td>
<td>1985</td>
<td>Faster imaging</td>
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<td>Shielded gradient designs</td>
<td>1986</td>
<td>Improved image quality</td>
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<td>Gadolinium contrast agents</td>
<td>1988</td>
<td>Improved clinical contrast</td>
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<td>Turbo sequences</td>
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<td>Faster exam times, dynamic studies (cardiac)</td>
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<td></td>
<td>– FLASH</td>
<td>1985</td>
<td></td>
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<td></td>
<td>– TSE</td>
<td>1986</td>
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<tr>
<td>1990–2000</td>
<td>Phased array coils and multiple receivers</td>
<td>1990</td>
<td>Extended FOV imaging for spine</td>
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<td>Parallel imaging</td>
<td>1999</td>
<td>Paved the way for parallel imaging</td>
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<td>Actively shielded magnets</td>
<td>1999</td>
<td>Enhanced sensitivity and speed</td>
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<td>Clinical 3T systems become available</td>
<td>2000</td>
<td>Improved siting</td>
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<td>Commercial 7T magnets and above</td>
<td>2002</td>
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FLASH, fast low angle shot; TSE, turbo spin-echo; FOV, field of view; FDA, Food and Drug Association.

Numerous sequences
Playing with contrasts
From model to contrasts

Model derived from Bloch equations

Amplitude $M_T$ of transverse magnetization

$$M_T = M(\text{extrinsic parameters}; \text{intrinsic parameters})$$

- **Sequence parameters**
  - Flip angles
  - Delays
  - Trajectory
  - (...)

- **Tissue parameters**
  - Relaxation
  - Proton density
  - Diffusion
  - Susceptibility
  - (...)

Qu'est ce qu'une image?
Example of the Spoiled Gradient Recalled Echo (SPGR)

\[
M_T = M_0 \sin \alpha \left[ 1 - \cos \alpha \exp \left( - \frac{\text{TR}}{T_1} \right) \right]^{-1} \exp \left( - \frac{\text{TE}}{T_2^*} \right) \left[ 1 - \exp \left( - \frac{\text{TR}}{T_1} \right) \right]
\]
From model to contrasts

Model derived from Bloch equations

Amplitude \( M_T \) of transverse magnetization

\[
M_T = M(\text{ep}; \text{ip})
\]

Contrast parameterized by the sequence parameters \( \text{ep} \)

\[
\text{contrast}_i = \frac{\partial M_T}{\partial \text{ip}_i}(\text{ep}; \text{ip}) / M_T (\%)
\]

Sensitivity

\( \text{contrast}_i \) must be maximized

Specificity

\( \text{contrast}_j \) must be minimized \( j \neq i \)
Example of SPGR contrasts

Always proton density-weighted

**T1-contrast** depends on $\alpha$ and TR

**T2*-contrast** (linearly) increases with TE
SPGR T1-contrast

Fixed rat brain / 11.7 T

\[ \alpha = 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, 90° \]
SPGR T2*-contrast

Muscle tissue / 4.7 T

TE = 7.2 ms  15.1 ms  23 ms  30.9 ms
Imaging of the susceptibility differences
Susceptibility

Dimensionless susceptibility $\chi$

Magnetic response of a substance placed in an external magnetic field $H$

$$M = \chi H$$

Closely related to the permeability $\chi = \mu_r - 1$

$\chi$ depends on chemical composition and molecular arrangement
Susceptibility spectrum

\[
\chi < 0 \quad \chi > 0
\]

Ferro-, Para-, Dia- Magnetism

Diamagnetism  Paramagnetism  Ferromagnetism

\[ M \downarrow H \quad M \uparrow H \quad M \uparrow H \]

Ferromagnetism

\[ \chi \]
Field perturbations

Susceptibility differences

Difference of $\chi$ between compartments induces MF perturbations

Spheric inclusion

Geometry
Spatial arrangement
Orientation vs $B_0$
Effects of field perturbations on NMR signal

- Large compartments
  - Small voxel size

- Small inclusions
  - Large voxel size

Modulation of phase and amplitude vs $TE$
  - e.g. $T2^*$ decrease
Detection of small inclusions

Bovine muscle at 9.4 T

With refocusing

Without refocusing

V(voxel) = 0.180 mm$^3$

T2* weighting

V(voxel) = 0.005 mm$^3$

MRI

Histological section

Detection of small inclusions

Human brain at 7 T

Duyn et al., PNAS (2007) DOI: 10.1016/j.mri.2010.02.007
Artifacts near interfaces

Human brain at 3T

**With refocusing**
T1-weighted SE
\[ V(\text{voxel}) = (0.5 \text{ mm})^3 \]

**Without refocusing**
T2*-weighted EPI
\[ V(\text{voxel}) = (3 \text{ mm})^3 \]
Fast imaging
Motion artifacts

\[ S(\mathbf{k}) \propto \int M_T(\mathbf{r}) \exp[i(\mathbf{r} + \Delta \mathbf{r}(t)) \cdot \mathbf{k}] \, d\mathbf{r} \]

\[ = \int M_T(\mathbf{r}) \exp[i(\mathbf{r}) \cdot \mathbf{k}] \exp[i\Delta \mathbf{r}(t) \cdot \mathbf{k}] \, d\mathbf{r} \]

Corrupted phase

Without motion

With motion
Going faster?

Keep the TR short!

Single short RF pulse

Fast gradient hardware
  - High slew rates
  - Compensation for the eddy currents

Fast electronics
  - Short dwell times

Efficient strategies for filling k-space
  - Echo planar imaging
  - No preparation gradient pulses
  - Undersampling
  - Acquisition during switching
Rapid motion … but periodic!

Synchronization between motion and acquisition

Cine MRI
Heart beating
1.5T
25 phases

Rapid motion and no periodicity

“Real time” MRI / 30 images per second

SPGR
Speaking
TR = 2.22 ms
V = 1.5 x 1.5 x 10 mm³
Radial filling

Susceptibility + Fast imaging = BOLD functional MRI (fMRI)
Effect of blood $O_2$ level on signal

The princeps observation, Ogawa (1990)

Rat brain
T2*-weighted SPGR
4.7 T

Effect of blood $O_2$ level on signal

Range of normal saturation
0.95 – 0.99

From the stimulus to the signal change

Task / Stimulus

Brain activation

Vascular coupling

Signal change

CMRO$_2$ Response

CBV Response

CBF Response

BOLD Response

~ 20 s

~ 1 %
BOLD fMRI experiment

**Short duration of BOLD overshoot**
- Stimulation in the magnet
- Signal returns to baseline
- Fast T2*-weighted imaging

**Low amplitude of BOLD overshoot**
- Repetition of the stimulation
- High field
- Signal filtering

**Detection of BOLD overshoot throughout the brain**
- Correlation analyses between stimulation paradigm and signal
- The result is a *statistical* activation map
Olfactory BOLD fMRI

Human olfactory/visual detection at 1.5T

- Olfaction: n = 51
- Vision: n = 25

Activation maps

Signal time course

Diffusion
Basics of diffusion

Random walk of molecules
Motion described by a statistical model $p(r;t)$
Gives the probability of finding the particle at $r$ at time $t$

The popular Gaussian model

$$p(r;t) = \frac{1}{\sqrt{4\pi Dt}} \exp\left( -\frac{r^2}{4Dt} \right)$$

Allows inferring the moments

$$\langle r \rangle = 0 \quad \langle r^2 \rangle = 2Dt$$

Diffusion coefficient
How to measure diffusion?

NMR signal dephasing

Relaxation / Static regime

\[ Rx(t) = \exp(-t/T2) \]

Off-resonance / Static regime

\[ Or(t) = \int \exp(-i\Delta \omega(r)t)dr \]

Diffusion / Non-static regime

\[ Df(t) \]
Ratios provide $D_f(TE)$
\[
\ln(Df(TE)) = -bD
\]

\(b = \) Diffusion weighting

Can be computed for any gradient pair

D is measured in the gradient direction

In the presence of barriers to free diffusion

\[D \rightarrow ADC (< D)\]
Mouse spinal cord *in vivo*

**Reference**

\[ b = 0 \text{ s/mm}^2 \]

**Diffusion weighted**

\[ b = 500 \text{ s/mm}^2 \]

**Map of the apparent diffusion coefficient**

3 \(10^{-3}\) mm\(^2\)/s

0 mm\(^2\)/s
Translational mobilities in muscle

1.2 $10^{-3}$ mm$^2$/s

0.4 $10^{-3}$ mm$^2$/s

Water

Fat

Attenuation

b-value

b-value

$0.01 10^{-3}$ mm$^2$/s
Diffusion anisotropies

Measurement of apparent diffusion coefficient in many directions

Weeden et al., Science (2012) DOI : 10.1126/science.1215280

Thank you !