Magnetic Resonance Imaging: Techniques and Trends

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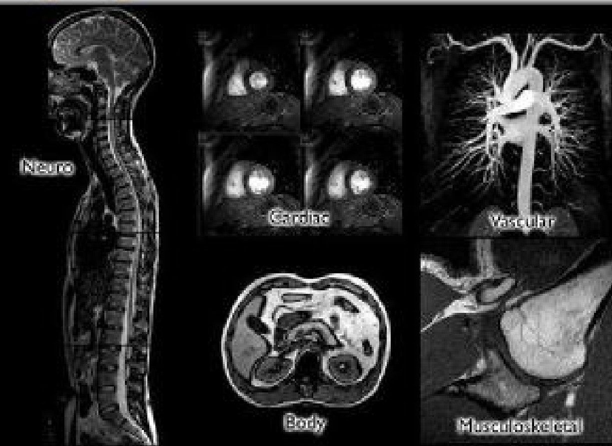
MR imaging



Extreme flexibility with respect to...
- body part, coverage and orientation
- contrast mechanisms
- duration and imaging methods

Trade-off: Compromise between speed, SNR and spatial resolution.

Overview

Basic NMR
- Magnetization
- Precession
- The basic NMR measurement

Contrast
- Quick overview
- Relaxation

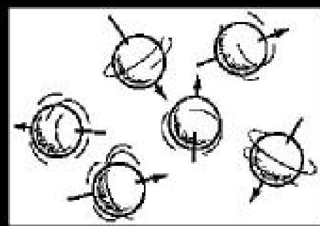
Imaging
- Gradients
- Slice selection
- Image formation
- k-space
- Artifacts

Overview(2)

Technological trends
- Fundamental limitations
- Emerging techniques:
  - Field strength
  - Detector arrays
  - Use of prior knowledge, undersampling
  - Real-time feedback

DTU collaborations

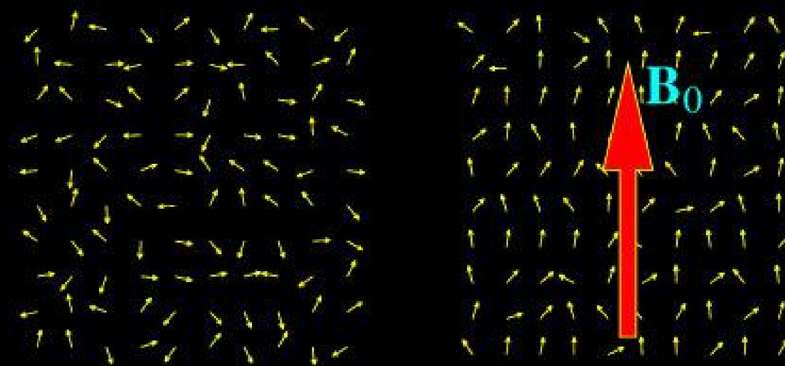
Nuclear spin



Proton spin gives rise to magnetic property:
Hydrogen nuclei behave like bar magnets

Influence of the magnetic field

Partial alignment of the magnetic moments:



A macroscopic magnetization is formed.
The equilibrium magnetization is along the magnetic field.

The equilibrium magnetization

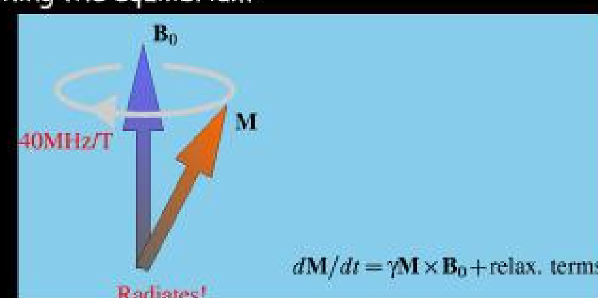
The net magnetization:

- Nearly nothing (a few ppm compared to full alignment).
- It is proportional to the applied magnetic field.
- It is impossible to detect in the equilibrium state.

Precession

Assume some means of disturbing the magnetization.

Reestablishing the equilibrium:

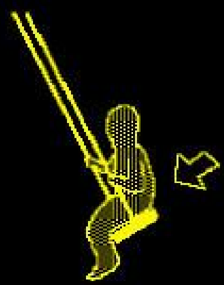


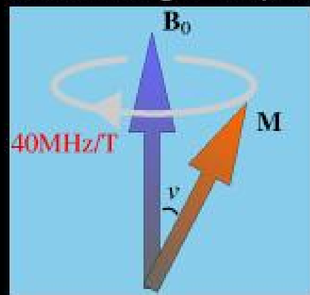
Precession of the magnetic dipole.

The system returns to thermal equilibrium.
Radio waves are emitted and detected.

Excitation

Resonance:
The pertubation is induced by radio waves (excitation).
Large effect if the system is perturbed at the right frequency.





Pushing the swing at the eigen frequency changes the amplitude.
Radio waves at the Larmor frequency changes the angle v.

Transfer of energy!

The MR signal

The basic MR experiment:

You need...

magnet

radio wave emitter and receiver

The MR signal

The basic MR experiment:

Place patient in the strong magnetic field.

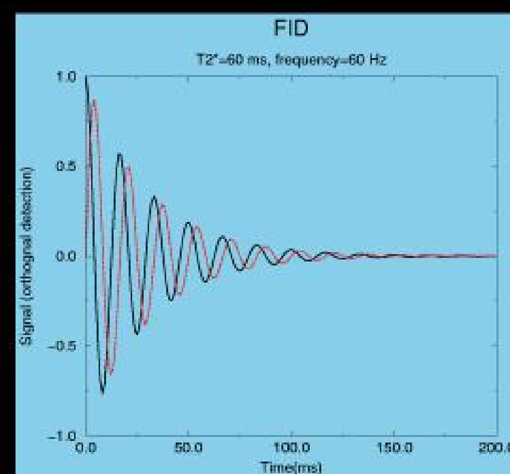
Apply resonant radio waves perturbing the equilibrium magnetization.
- E.g. a 90 degree rotation.

Step back and watch the system return to equilibrium.
Analyze the weak, sampled radio signal.

Vocabulary:
The free induction decay (FID) is the sampled signal.

The MR signal

FID with a single frequency component:



Orthogonal coils detect changes in Mx, My, respectively.

Image contrast

Many influences on the signal:

- Water content (proton density, PD).
- Relaxation (local nuclear environment).
- Dephasing.
- Flow, perfusion and diffusion.
- Neuronal activation.
- Metabolic properties.
- ...

Normally a mix is measured: Weightings.

- Example: Proton density weighting (water content, mostly)

Unwanted contrast:

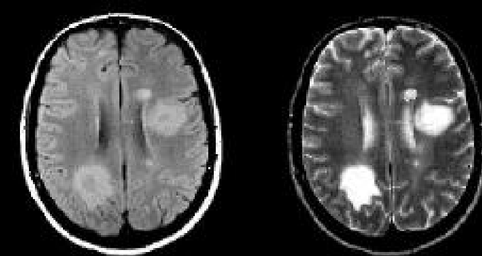
- Coil sensitivity variation.
- Field inhomogeneity.
- Motion artifacts.

Relaxation time contrast

T1- and T2-weighted imaging

The work horses of clinical imaging:

- Always available, reliable and require little post-processing



T1- and T2-weighted sequences.

Imaging

Gradients

Field gradients:

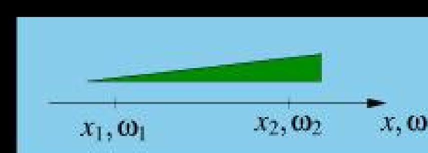
Linear variations in main field B0 induced by gradient coils.

Gradients are needed for

- localization during preparation
- imaging
- flow and diffusion encoding
- suppression of artifacts

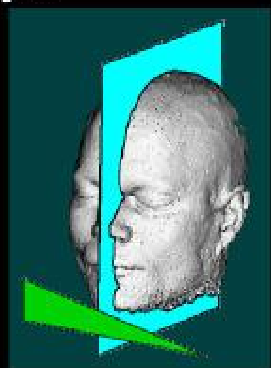
Field in presence of gradient: $B_z = B_0 + \mathbf{G} \cdot \mathbf{r}$

E.g. gradient along $\hat{x}$: $B_z(x) = B_0 + G_x \cdot x$



Gradients(2)

Example:
Gradient from left to right.



Gradients in a nut shell:
Gradients induce a correspondence between position and frequency.

Gradients(3)

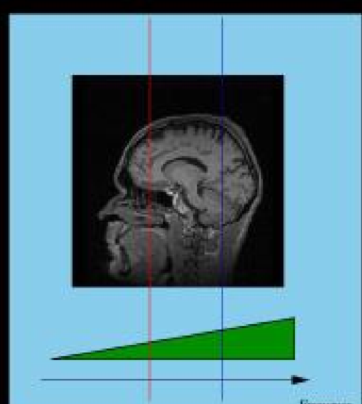
Slice selection:

Apply gradient from left to right.
All spins within the plane oscillate at the same frequency.

Only spins on resonance are affected by RF.

Gradients(4)

Frequency encoding for discrimination within the plane:
- Coding spatial information in the frequency content of the signal.



Imaging: Spectroscopy in the presence of gradients.

Gradients(5)

Spin orientation immediately after excitation:

"Phase roll" after application of a gradient:

- No net magnetization (no signal).

If only some spins are present:

- Net magnetization and signal!

Gradients(6)

Gradients can be used to probe regular structure.
- Only signal when the phase roll matches the structure.

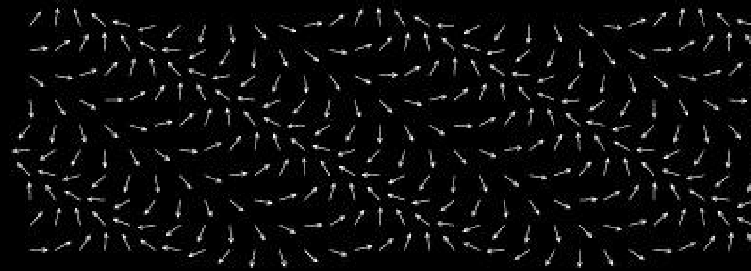
The frequency of the phase roll is...
- proportional to the duration and strength of the gradient

The direction of the phase roll is...
- along the direction of the applied gradient.

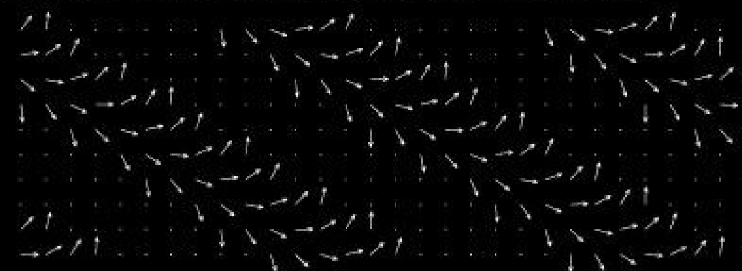
This idea can be extended to more dimensions...

Gradients(7)

Homogeneous spin distribution

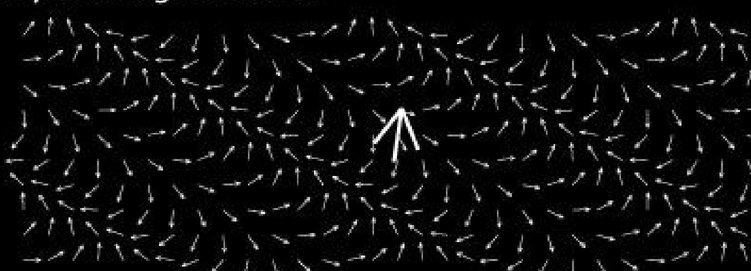


Variation in spin distribution matching the phase roll:

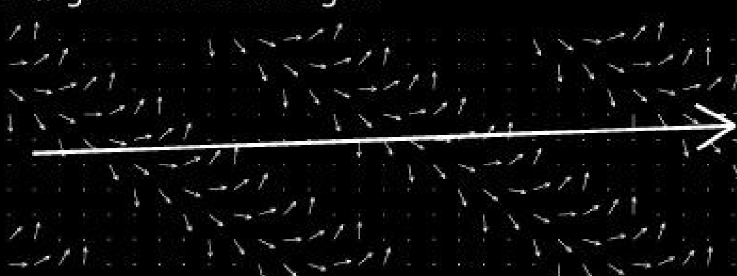


Gradients(8)

Hardly any net magnetization:



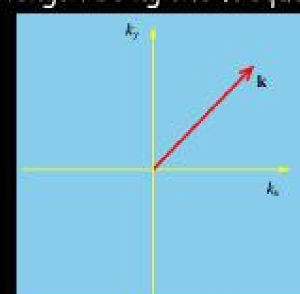
Large net magnetization and signal:

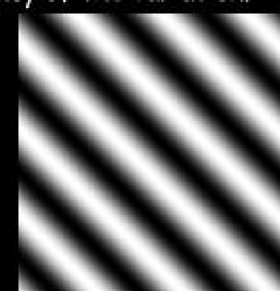


Fourier theory

The oscillatory functions are called "harmonics".

To each harmonic is assigned a vector k which is...
- pointing towards the direction of variation.
- having a length being the frequency of the variation.





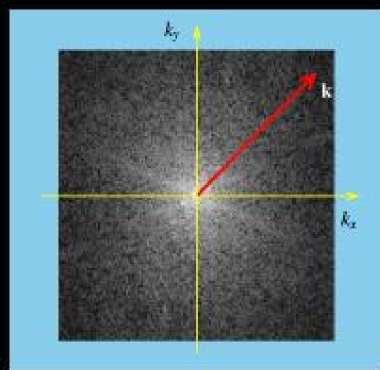
$$\mathbf{k}(t) = \gamma \int_0^t \mathbf{G}(t')\,dt'$$

Special case: $k = \gamma \cdot G \cdot t$ for gradient G, duration t.

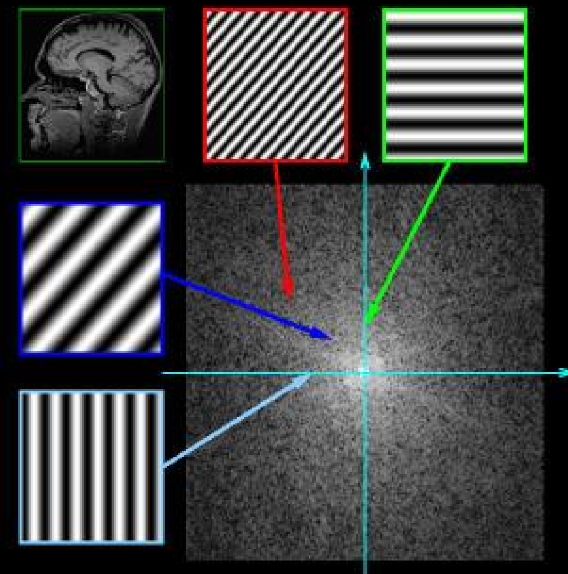
Fourier theory

The similarity of the object to each "harmonic" can be measured:

- Apply gradient to induce spin variation corresponding to a harmonic.
- The signal reflects the similarity of the object and the harmonic.
- The signal is recorded in k-space
  - i.e. as a function of k.

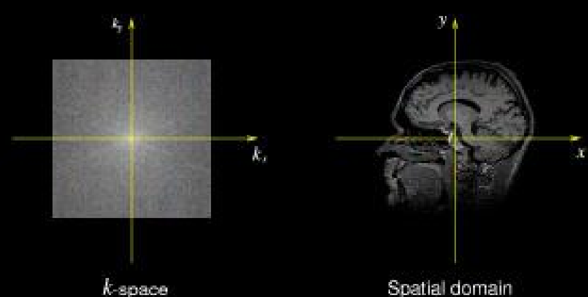


The structure of k-space



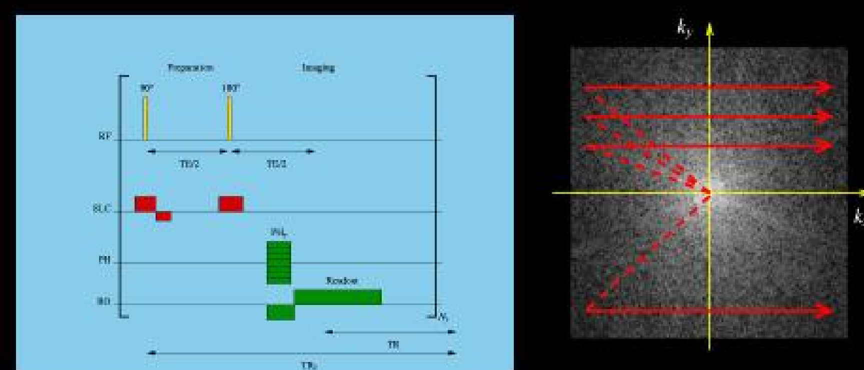
Fourier theory

- The spatial domain and k-space representations are equivalent.
- Tranformation between the two is performed with the "Fourier transform".



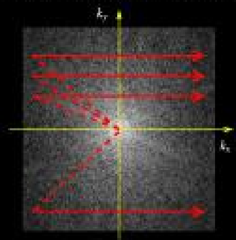
The spin-echo imaging sequence

Sequence and corresponding trajectory in k-space:



Resolution and field of view

K-space undersampling causes artifacts:
- Insufficient coverage: Partial volume effects.
- Insufficient sampling density: Aliasing.



Sampling k-space takes time.
- New technique: Detector arrays for avoiding aliasing

Technological trends

Technological trends in MRI

Fundamental limits:

Noise
- Thermal contributions, body dominated

Gradient oscillation causes nerve stimulation
- Remedy: Short dedicated gradient coils

RF causes body heating
- Increases with field
- Remedy: Special excitation schemes

Magnetic field may give biological effects above 10 Tesla
- 3 Tesla is current Danish maximum (DRCMR@Hvidovre)

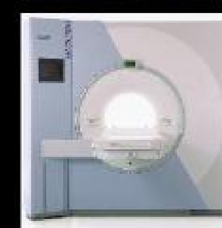
Patient
- Tends to leave after an hour

Leaves plenty of room for creativity....

Tech trends: High field

Conventional whole-body MRI: up to 1.5T

July 2002:
First Danish 3 Tesla system installed
Donation from the Simon Spies Foundation
Siemens Trio 3.0 Tesla whole-body scanner
- New product
- Body coil delivered May, 2003
- Gradient insert coil, ultimo 2003
- Best equipment available



Tech trends: Detector arrays

Increasing sensitivity or speed using detector arrays

Parallel imaging:

Redundancy used to speed up acquisition

- decreased sampling density
- special reconstruction avoid aliasing

Tech trends: Real time feed-back

Real-time feedback:

Acquired data used to guide data acquisition

Example:

- Imaging plane follows patient motion

Tech trends: Use of prior knowledge

Use of prior knowledge:

Good models decrease need for sampling

Example: Heart imaging

- Heart is moving rapidly (small region)
- Chest is moving slowly (large region)

Better use of prior knowledge will be increasingly important.

DTU collaborations

Recent DTU/DRCMR collaborations

Rapidly progressing field:
Several fruiful collaborations with DTU

Recent projects:

Lars Kai Hansen, Finn Årup Nielsen and co-workers:
- Analysis of functional imaging data, perfusion methodology, automatic tissue classification

Per Skafte Hansen, Stefan Wolff:
- 3D visualisation for epilepsy

Rasmus Larsen, Mikkel Stegmann:
- Cardiac imaging analysis

Hans Henrik Thodberg, Morten Mørup
- Snakes for rheumatology

Rodney Cotterill and co-workers:
- Brain function

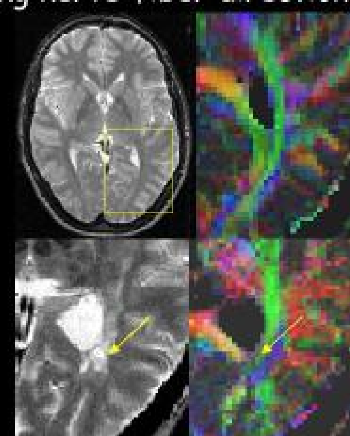
Contrast examples

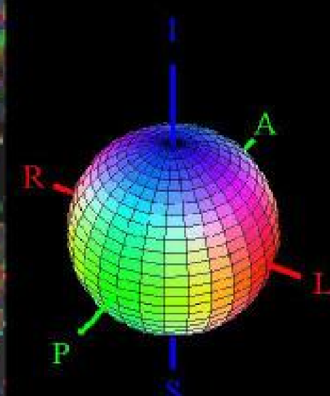
Contrast examples: Flow and diffusion

Angiography and diffusion weighting.

Contrast examples: Fiber directionality

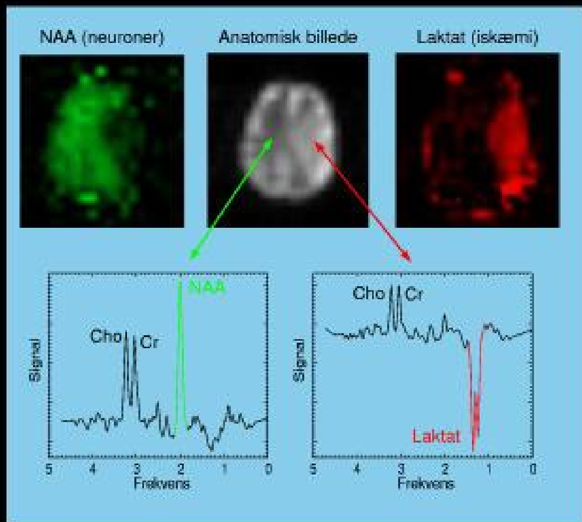
Measuring nerve-fiber directionality:





The diffusion is high along the nerve fibers.

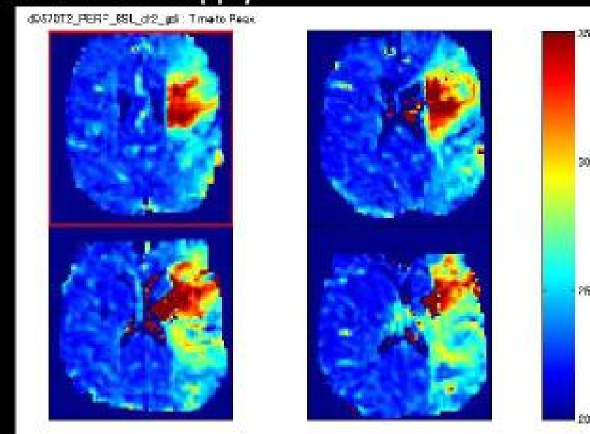
Contrast examples: spectroscopy



Metabolic images from stoke patient

Contrast examples: Perfusion

Measurement of blood supply:



Duration before bolus arrives in tissue

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