Magnetic Resonance Imaging: Basics, Techniques and Trends

31545 Medical Imaging Systems

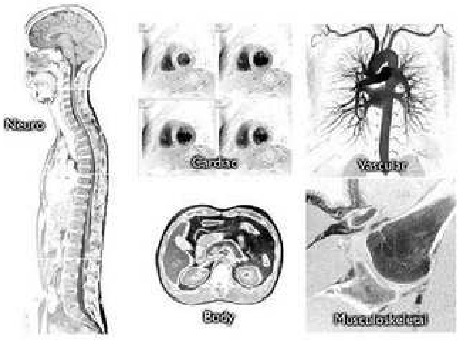
▸ Software and animations: http://www.drcmr.dk/bloch and http://www.drcmr.dk/MR

Lars G. Hanson, Bldg. 349, room 109

DTU Elektro
http://www.elektro.dtu.dk/

MR-afdelingen, Hvidovre Hosp.
http://www.drcmr.dk/

MR imaging



Extreme flexibility with respect to...
- body part, coverage and orientation
- contrast mechanisms: structure, flow, diffusion, thinking...

Overview, 1st lecture

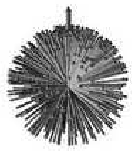
Basic NMR
- Equipment
- Nuclear spin and magnetization
- Precession
- Resonance and excitation
- Pulse sequences

Contrast
- Quick overview
- Relaxation
- Dephasing
- Spin-echoes

Supplementary material

Lecture notes:
- http://www.drcmr.dk/MRnotes
- 47 pages in English and Danish

Animations and software:
- http://www.drcmr.dk/MR
- http://www.drcmr.dk/bloch



Repetition: Java compass

http://www.drcmr.dk/MR

Equipment

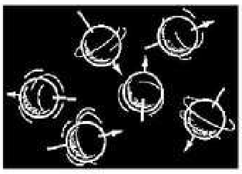
You need...

- Magnet, radio wave transmitter and receiver, patient

Nuclear spin

Certain nuclei possess "spin"
- H-1, P-31, C-13, F-19, Na-23, He-3,...

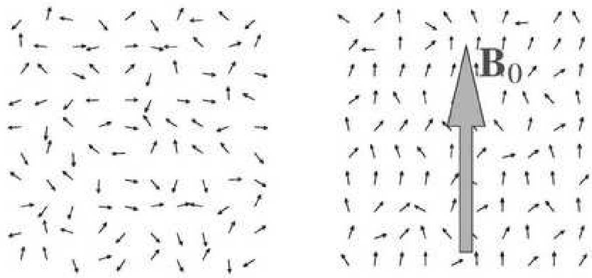
Protons (Hydrogen nuclei):



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

Influence of the magnetic field

Partial alignment of the magnetic moments:

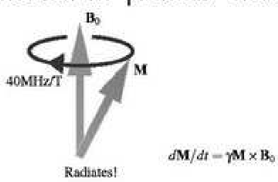


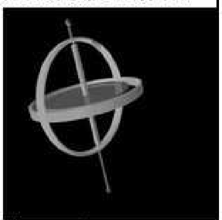
A macroscopic magnetization is formed.
The equilibrium magnetization is along the magnetic field.

Precession

When a compass needle is kicked...
...it oscillates in a plane through north.

When a proton is kicked...
...the magnetization "precess" in a cone around north:





The difference is due to the rotation of the protons.

Precession and the RF field

The magnetization precess at the Larmor frequency:

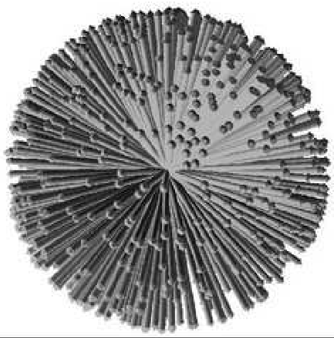
$$f = \gamma B_0 = 42\ \text{MHz/T} \cdot B_0$$

- The "gyromagnetic ratio" is 42 MHz/T for hydrogen.

Typically the RF field is also rotating around Bo.
- Magnetic field vector follows precession.
- This is most efficient.

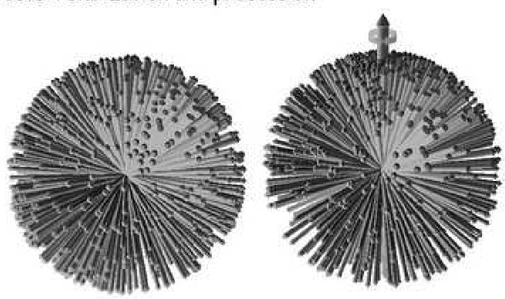
The spin distribution

Equilibrium spin distribution in absense of field is isotropic:



The spin distribution

Field effects: Polarization and precession



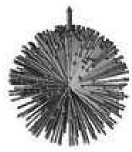
Reasons that nuclei don't align perfectly:
- Nuclear interactions and motion.
  - Think compasses in tumble dryer.

The equilibrium magnetization

The net magnetization:

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

The spin distribution

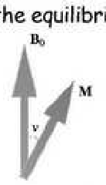


Radio waves can rotate the spin distribution as a whole.
- The magnetic component of the EM field is responsible.

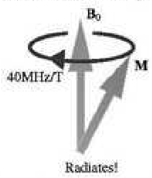
Relative orientations are preserved:
- Sufficient to keep track of net magnetization!

The MR signal

The basic MR experiment:
- Place patient in the strong magnetic field.
- Apply radio waves perturbing the equilibrium magnetization.
  - E.g. a 30 degree rotation.



- Switch off RF and measure the precession of the magnetic dipole:

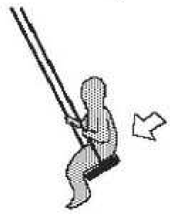


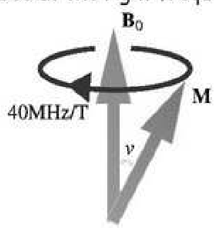
$dM/dt = \gamma M \times B_0$

- Analyze the weak emitted radio signal.

Excitation

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



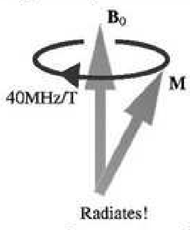


Pushing the swing at the eigen-frequency changes the amplitude.
Radio waves at the Larmor frequency changes the angle v.

Transfer of energy!

Precession

Reestablishing the equilibrium after excitation:



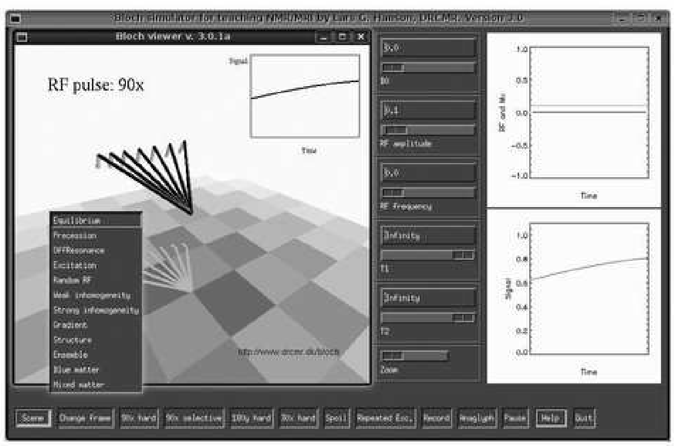
$dM/dt = \gamma M \times B_0 + \text{relax. terms}$

Precession of the magnetic dipole.

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

Upcoming....

Animated Bloch Dynamics



Animated Bloch Dynamics

$$dM/dt = \gamma M \times (B_0 + B_1(t)) + \text{relaxation terms}$$

Precession
Resonant excitation (soft pulses)
Non-selective excitation (hard pulses)
Transversal and longitudinal relaxation
The spin ensemble
The rotating frame of reference

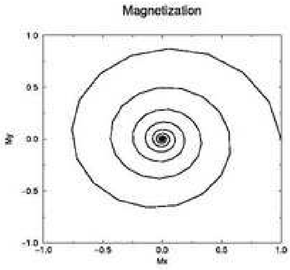
starring

B_0 : The main magnetic field along z
$\omega_0 = \gamma B_0$: The Larmor precession frequency
ω : The RF field frequency
B_1 : The amplitude of the transversal RF field (i.e. in the xy-plane)
T_2 : The transversal relaxation time (i.e. orthogonal to B_0)
T_1 : The longitudinal relaxation time (i.e. along B_0)

▸ Start Bloch....

The MR signal

The oscillating transversal magnetization:



- Representation as a complex number, Mxy = Mx + i My:

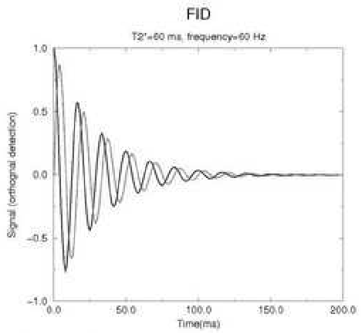
$$M_{xy}(t) = M_{xy}^{t=0} \exp(-i\omega_0 t) \exp(-t/T_2)$$

  - The transversal relaxation time T2 is time constant for signal loss.

The MR signal

A voltage is induced in the receiving coil (antenna).

MR signal with a single frequency component:

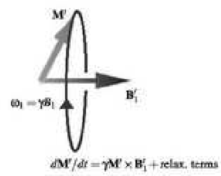


Orthogonal coils detect changes in Mx, My, respectively.
Signals are modulated down from the Larmor frequency to near zero.

The Bloch equation demonstration

The demonstration showed:

- Precession:
  - The magnetization oscillate in the xy-plane
  - Radio waves are emitted
- Resonant excitation (selective, soft pulse)
  - A weak resonant RF field will rotate the magnetization.
  - Only circularly component following precession contribute.
- Non-selective excitation
  - A short strong RF pulse excites non-selectively
- T2- and T1-relaxation
- Rotating frames of reference
  - Often chosen to match the RF frequency
  - MR measurements are described in this frame
  - Measurement data are demodulated by this frequency



Software and animations with soundtracks:

- http://www.drcmr.dk/bloch

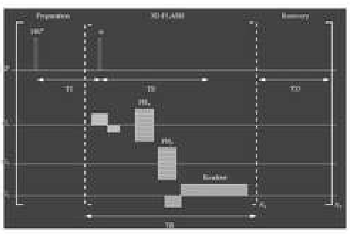
MR sequences

MR sequence definition:

- A succession of RF pulses, gradient pulses, waiting and sample periods.

MR sequences can be fairly complicated and have long acronyms.

- Example: MPRAGE (Magnetization Prepared Rapid Gradient Echo)
- Long coherence time leaves enormous room for creativity.



- Sequence and sequence parameters determine contrast.

Contrast

Image contrast

Many influences on the signal:

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

Unwanted contrast:

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

Relaxation time contrast

Typical radiologist statement after MRI exam:

"PD- and T1-weighted imaging were normal.
T2-weighted imaging revealed a subcortical lesion".

T1, T2 and proton density (PD) are parameters characterizing tissue:

- just like "temperature" or "water content".
- The "proton density" is, in fact, the water content.

T1 and T2 time-constants are somewhat special:

- Can only be determined by MRI (they are "MR contrast parameters")
- Reflect aspects of consistency (molecular mobility)

So what is "weighting" ??

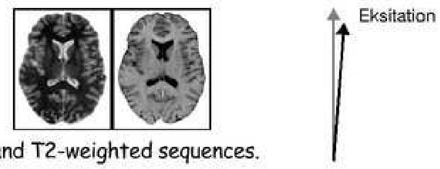
- The parameters above are seldom measured quantitatively...
- ...but their relative values may be apparent in the images.
- i.e: The contrast in a "T1-weighted" image comes mostly from T1-differences.

So why all this talk about T1 and T2?

Relaxation time contrast

T1- and T2-weighted imaging

- The work horses of clinical imaging:
  - Always available, reliable and require little post-processing
  - Sensitive to pathology

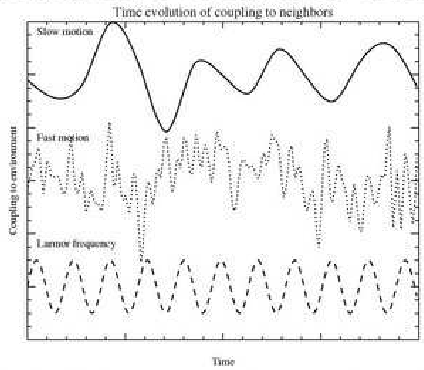


T1- and T2-weighted sequences.

- Transversal T2-relaxation
  - Loss of signal due to dephasing of spins
  - Reversible loss caused by inhomogeneity
  - Irreversible loss caused by spin-spin interactions, elastic and inelastic
- Longitudinal T1-relaxation
  - Return of Mz to equilibrium
  - caused by inelastic spin-spin interactions only (so T2<T1)

Nuclear motion as a source of relaxation

Random motion of molecules: Random nuclear interactions

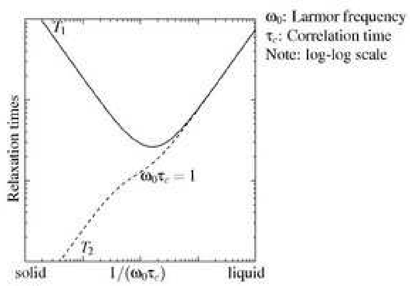


Changes matching the Larmor precession causes transitions.
Correlation time:

- Typical time between changes of environment.

Relaxation

Relaxation time dependence on motional frequency:



- Solids: Short T2, Long T1
- Liquids: Long T2=T1 (seconds)
- Intermediate: Intermediate

The Larmor frequency depends on the field strength

- High field shifts properties toward solid regime.

Animated Bloch Dynamics - Reloaded

T1 and T2 contrast

Field inhomogeneity

Reversible dephasing: T2*

Recovering lost signal: The spin echo

- **Start Bloch....**

Overview, 2nd lecture

Basics continued...

- Bloch equation, lab and rotating frames
- Equipment
- Gradients
- Relaxation time contrast

More contrast mechanisms

- Contrast agents and perfusion
- Flow and diffusion
- Spectroscopy
- Functional imaging

Imaging methodology

Technological trends

Recent DTU collaborations

The Bloch equations

Time evolution of a magnetic dipole in magnetic field:

$$\frac{d\mathbf{M}}{dt} = \gamma \mathbf{M} \times (\mathbf{B}_0 + \mathbf{B}_1(t)) + \text{relaxation terms}$$

M : The net magnetization

γ: The gyromagnetic ratio (40 MHz/T for protons)

B_0 : Static magnetic field, e.g., 3 tesla

$B_1(t)$: Radio frequency field. Oscillates near the Larmor frequency $\nu \simeq \gamma B_0$, i.e., the nuclear precession frequency

The Bloch equations(2)

Measurements of (Mx, My) are represented as complex numbers.

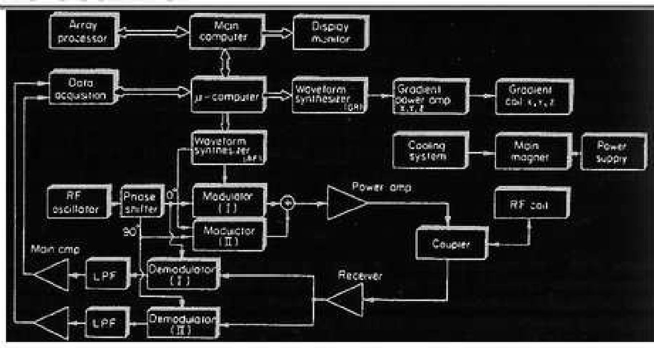
Complex representation. Definitions:

$$M_{xy} = M_x + iM_y = M'_{xy} e^{-i\omega t}$$

All quantities are slowly varying in the rotating frame of reference:

- The precession of the magnetization
- The oscillation of the radiofrequency field

The scanner



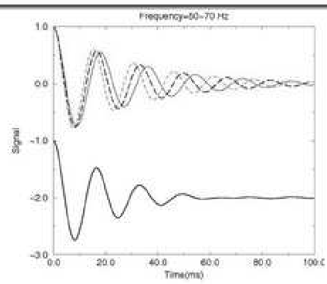
- Cho, Jones & Singh

- Measurements are performed in the rotating frame.
  - RF waveforms are modulated.
  - Complex samples, Sxy = Sx + i Sy, are demodulated.

Start IDL....

Relaxation time contrast revisited

T2* contrast



Signal decay time T2* < T2.

Field inhomogeneity result from...

- limited hardware capabilities.
- variations in magnetic properties of tissue/air/bone.
- variations in magnetic properties on a microscopic scale.

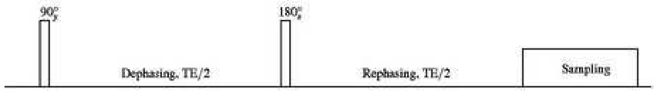
T2* contrast

Signal drop-out due to inhomogeneity
- here caused by dental fillings.

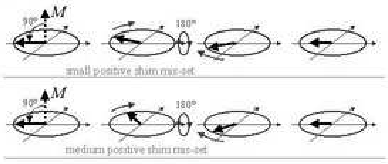
T2* contrast can be useful, e.g., for
- studies of neuronal activation.
- perfusion studies.
- detection of hemorrhage (bleeding).

The spin-echo

Signal loss due to inhomogeneity is reversible.



Phase coherence is recovered at echo time TE.
T2 contrast rather than T2*



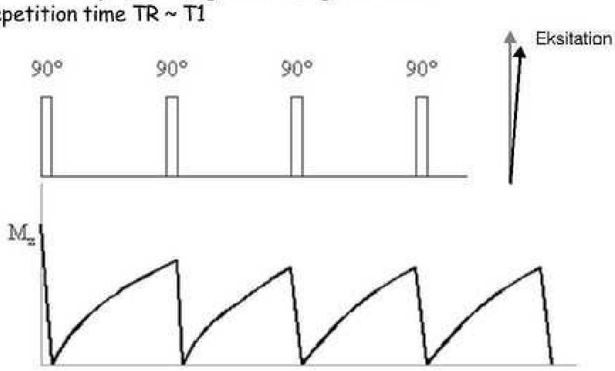
Spin echo contrast

Contrast from relaxation times and water content:

T1-, PD- and T2-weighted spin echo.

T1 contrast, saturation

Partial recovery of the longitudinal magnetization:
- Repetition time TR ~ T1



Conventional contrast

PD-weighting (proton density, water content):
- Long repetition time: TR >> T1
  - Full T1 relaxation.
- Short echo time: TE << T2
  - No T2 signal decay.

T2-weighting:
- Long repetition time: TR >> T1
  - Full T1 relaxation.
- Long echo time: TE ~ T2
  - Significant T2 signal decay.

T1-weighting:
- Short repetition time, TR ~ T1
  - No time for relaxation (saturated measurement).
- Short echo time, TE << T2
  - No T2 signal decay.

More contrast mechanisms

Contrast agents

Contrast agents:

Normally a paramagnetic substance (e.g. Gadolinium complex)
Used commonly to change relaxation rates

Before and after administration of agent shortening T1:
Only acute MS lesions are hyper intense (BBB opened in acute phase)

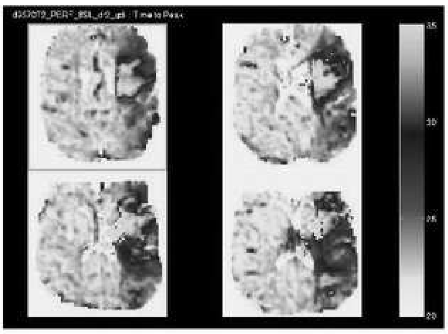
Contrast agents

Fast brain imaging during contrast injection (bolus):

One second interval between images.

Contrast agents

Measurement of blood supply:

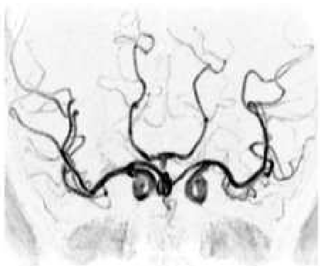


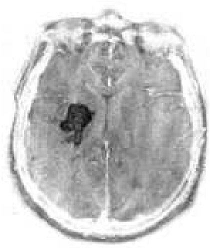
Duration before bolus arrives in tissue

- Quantitating the perfusion requires deconvolution or spin labelling.

Flow and diffusion weighting

Flow and diffusion weighting.

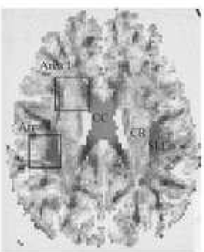


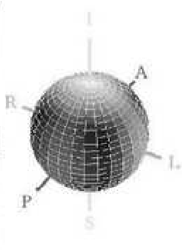


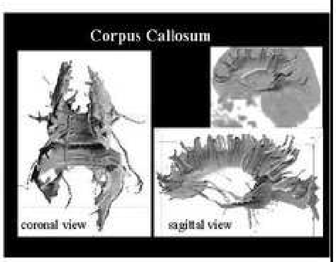
Fiber directionality

Measuring nerve-fiber directionality

- The diffusion is high along the nerve fibers.
- Diffusion tensor describes anisotropic diffusion
- Measured by repeated diffusion weighting
- Basis for tractography



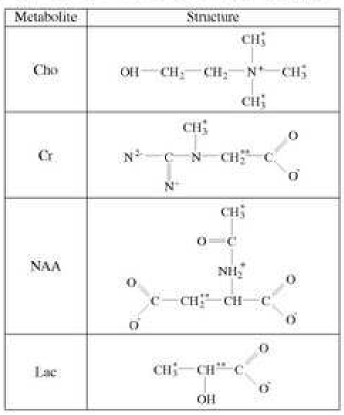




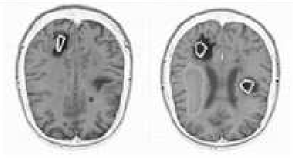
Spectroscopy

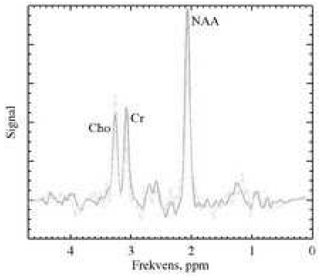
MR can distinguish chemical substances

Molecular structure influences local magnetic field



Sclerosis and spectroscopy





Marked regions:
- Normally appearing white matter(solid curve).
- Lesions(dashed curve).

Increased choline reflects turn-over of cell membranes.
Possibility of characterising normally appearing white matter.

Functional imaging, fMRI

Activation of brain:
- Increased oxygen consumption
- Increased blood supply.
- Increased oxygen conc.
- Changed relaxation times.
  - deoxy-haemoglobin is paramagnetic.
- Changed MR signal.
  - Activation: Signal increases.
  - Rest: Signal decreases.

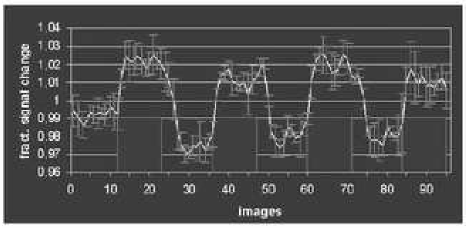
Examples:
visual stimulation
language lateralisation.

Language lateralisation, fMRI

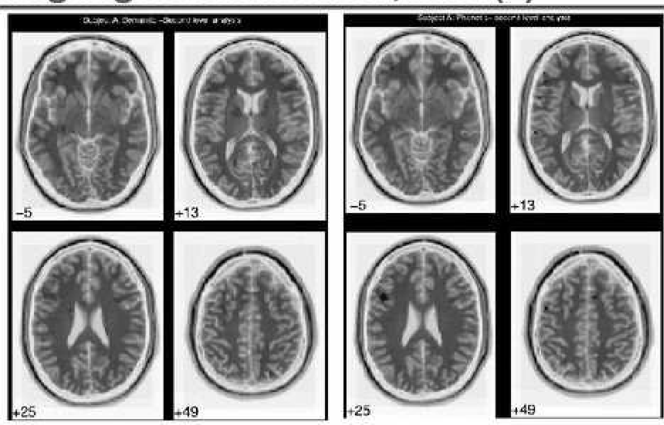
Hope: Localization of language areas ahead of surgery.

Semantic task:
- Patient switch between word generation and rest.
  - Categories "fruit", "month", "animal", "tree",...

Phonetic task:
- Patient switch between word generation and rest.
  - Initial letter "F", "R", "E", "T",...



Language lateralisation, fMRI(2)



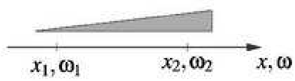
Regions activated by semantic and phonetic tasks.

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 $\hat{x}$: $B_z(x) = B_0 + G_x \cdot x$

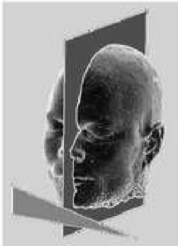


Gradients

Slice selection:

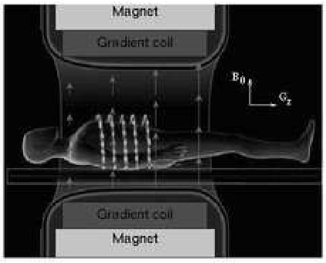
Apply gradient from left to right.
All spins within the plane oscillate at the same frequency.

Only spins on resonance are affected by RF.



Gradients

Gradient along the body for vertical field:



- C-shaped open scanner with static vertical field and linearly polarized RF field.

Spatial encoding, 1D

Spin orientation immediately after excitation:

"Phase roll" after application of a gradient:

- No net magnetization (no signal).

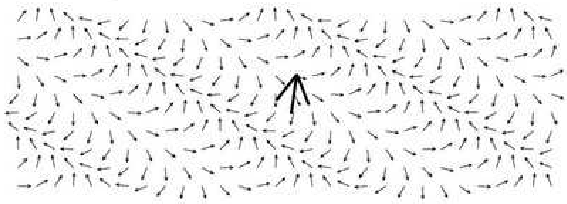
If only some spins are present:

- Net magnetization and signal!

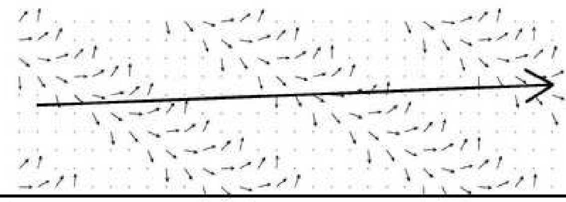
Start Bloch....

Spatial encoding, 2D

Hardly any net magnetization:

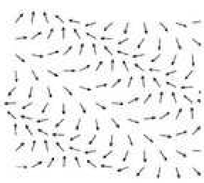


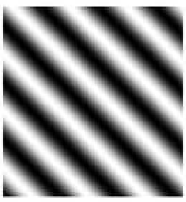
Large net magnetization and signal:



Imaging

Alternative visualization of phase roll (wave) patterns:





Lesson so far:

If the object has periodic variation in the water content,...

- ...then application of a matching gradient will give significant signal.

Turning it around...

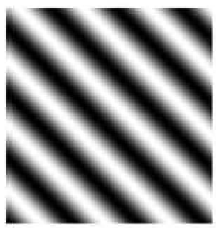
By application of gradients, we can measure how "striped" the patient is.

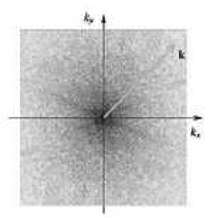
- This is imaging in a nut shell!

Imaging

To each wave pattern is assigned a wave vector k which is...

- pointing towards the direction of variation.
- having a length being the frequency of the variation.

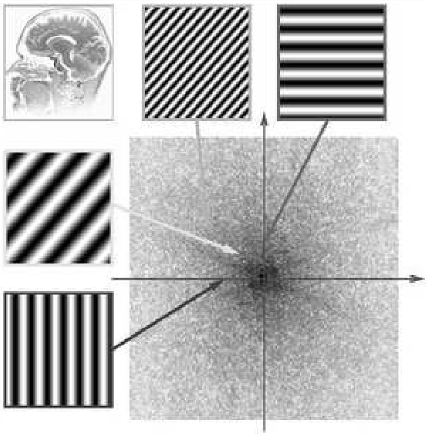




The similarity of the object to each wave pattern can be measured:

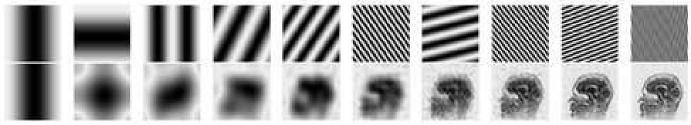
- Apply gradient to induce spatial phase roll pattern.
- The signal reflects the similarity of the object and the pattern.
- The signal is recorded in k-space
  - i.e. as a function of k.

The structure of k-space



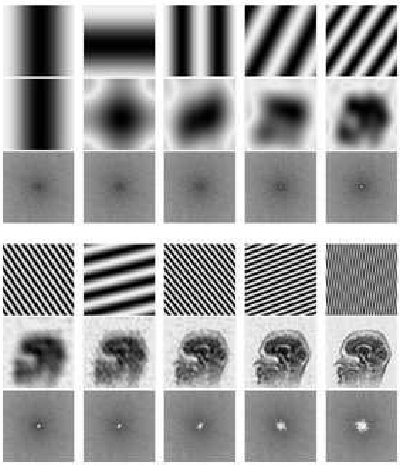
Reconstruction

Image reconstruction. Adding stripe patterns to form images:



- Number of contributing stripe patterns is doubled in each step.
- Bottom row is sum. Top is last pattern added.
- Last image consist of 1024 added patterns.

Reconstruction

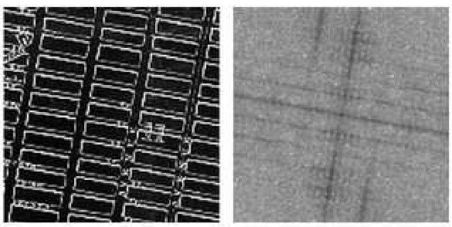


Manhattan

Manhattan

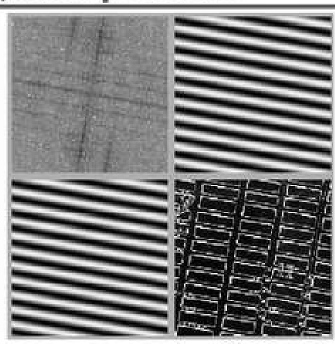
Manhatten and corresponding distribution of spatial frequencies

- i.e., the k-space representation.

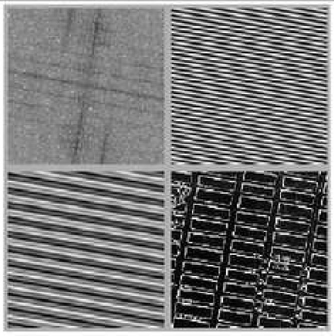


Bright regions in k-space signify regular patterns.

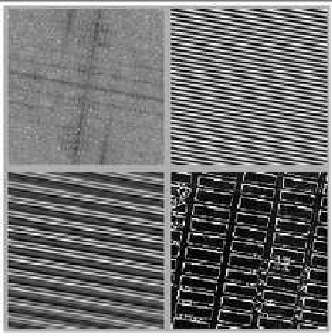
Manhattan, 0.01 percent



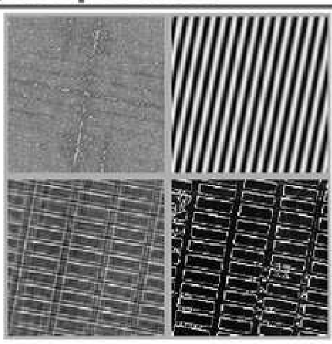
Manhattan, 0.02 percent



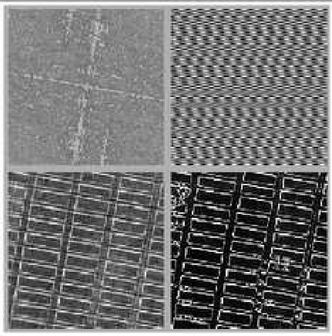
Manhattan, 0.05 percent



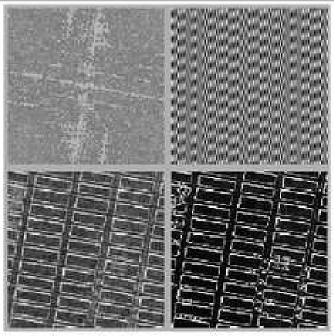
Manhattan, 1.6 percent



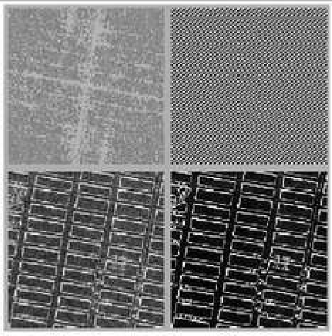
Manhattan, 6.3 percent



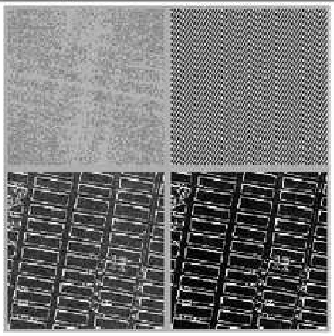
Manhattan, 13 percent



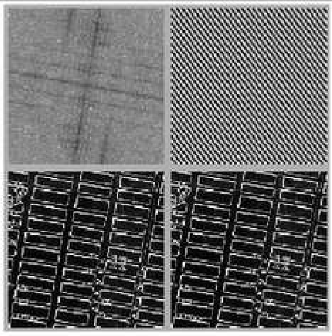
Manhattan, 25 percent



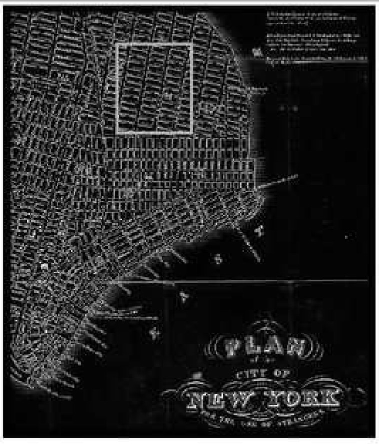
Manhattan, 50 percent



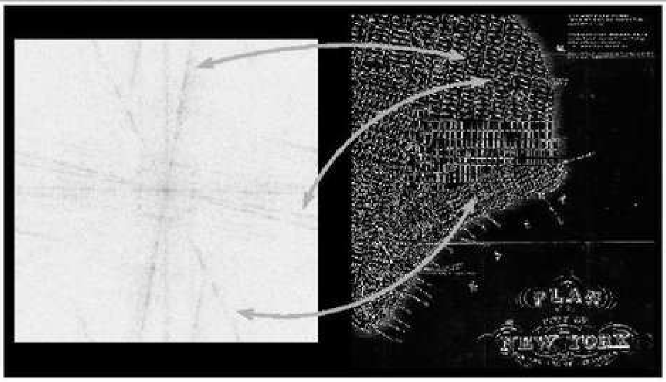
Manhattan, 100 percent



Manhattan

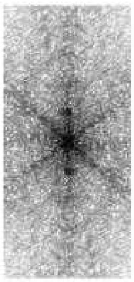


Manhattan



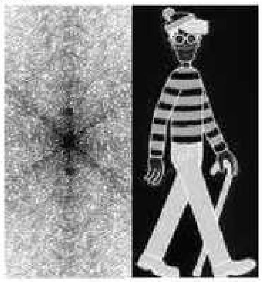
Find Waldo in k-space

"Find Holger i k-rummet":



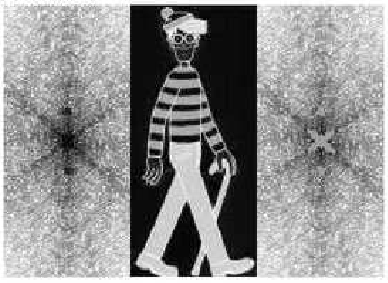
Find Waldo in k-space

"Find Holger i k-rummet":



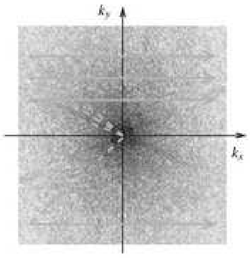
Find Waldo in k-space

"Find Holger i k-rummet":



Traversing k-space

Spin warp imaging:



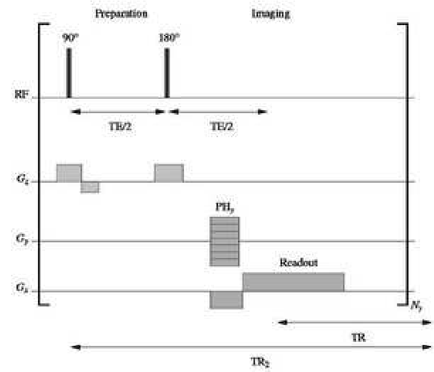
Moving in k-space:

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

So velocity in k-space equals gradient:

$$d\mathbf{k}(t)/dt = \gamma \mathbf{G}$$

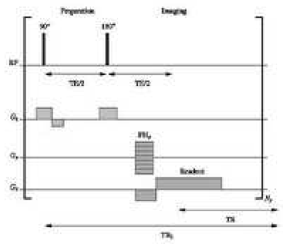
The spin-echo imaging sequence

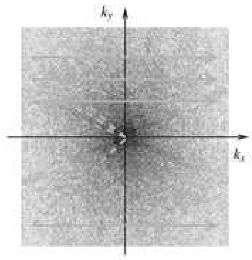


Sequence diagram: Time course of RF and gradient amplitudes.

The spin-echo imaging sequence

Sequence and corresponding trajectory in k-space:





Traversing k-space

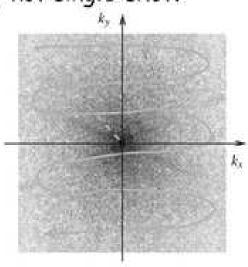
The complex signal:

$$\begin{aligned}
S_{xy}(t) &= \int \rho(\mathrm{r}) \exp(-i\phi(\mathbf{r},t))\,d\mathbf{r} \\
\phi(\mathbf{r},t) &= \int_0^t \gamma B_z(\mathbf{r},t')\,dt' \\
B_z(\mathbf{r},t) &= B_0 + \mathbf{r}\cdot\mathbf{G}(t) \\
\phi(\mathbf{r},t) &= \int_0^t \gamma(B_0 + \mathbf{r}\cdot\mathbf{G}(t'))\,dt' \\
&= \gamma B_0 t + \gamma \mathbf{r}\cdot \int_0^t \mathbf{G}(t')dt' \\
&= \gamma B_0 t + \mathbf{r}\cdot\mathbf{k}(t) \quad \text{with} \quad \mathbf{k}(t) \equiv \gamma \int_0^t \mathbf{G}(t')dt' \\
S_{xy}(t) &= \exp(-i\gamma B_0 t) \int \rho(\mathrm{r}) \exp(-i\mathbf{k}(t)\cdot\mathbf{r})\,d\mathrm{r} \\
S'_{xy}(t) &= \int \rho(\mathrm{r}) \exp(-i\,\mathbf{k}(t)\cdot\mathbf{r})\,d\mathrm{r}
\end{aligned}$$

- So Sxy(k) is the Fourier transform of the magnetization density.

Alternative sequences

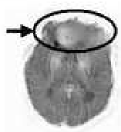
Why line-by-line? Why not single-shot?



Echo planar imaging (dogma EPI). TA ~ 100 ms.

High temporal resolution, but no magic:

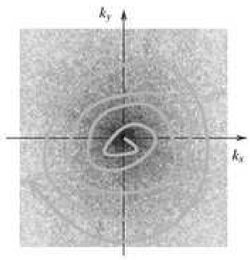
- Short duration is reflected in SNR.
- Demanding for hardware.
- Prone to artifacts.



Alternative sequences(2)

Any trajectory goes:

- Spiral EPI by gradient oscillation in two directions.



Even more hardware demanding, but has better flow properties.

Alternative sequences(3)

More possibilities:

Intermediate sequences,

- e.g., 3 lines per excitaion.

180 degree pulses does k-space reflection.

- affects contrast too.
- e.g., fast spin-echo.

Multi-slice imaging:

- Interleaved imaging.
- One slice is imaged, while others relax.
  - provides long TR.

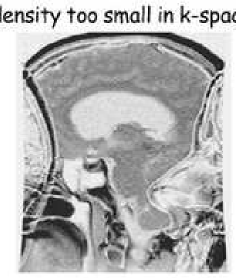
Extension to 3D imaging

- 3D k-space.

Artifacts

Most artifacts are best understood in k-space:

- Aliasing: Sampling density too small in k-space:

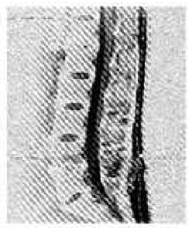


- Ghosting: Left/right asymmetry in k-space sampling.
  - Shadow displaced by FOV/2.
- Motion during k-space traversal.
  - e.g., flow artifacts.

Artifacts from k-space

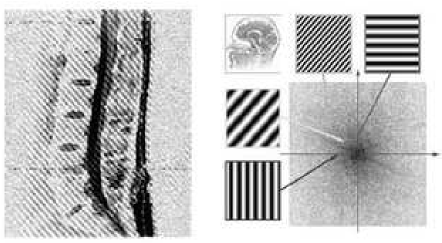
Image acquisition is done in k-space.

- Artifacts reflect this. Example:



Striped spine image. Why?

Artifacts from k-space

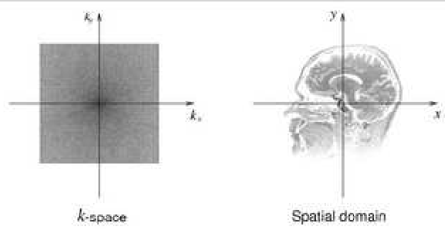


There is too much of a particular stripe pattern in the image,...
...because the measurement of that component went wrong.

"Raw data spikes"

- are often caused by small discharges during measurement.
- Likely sources: Low air humidity or loose connection (e.g. in light bulb)

Resolution and field of view



$$\text{Spatial Resolution: } \Delta x = 1/k_{\text{FOV}}$$
$$\text{Field of view: FOV} = 1/\Delta k$$

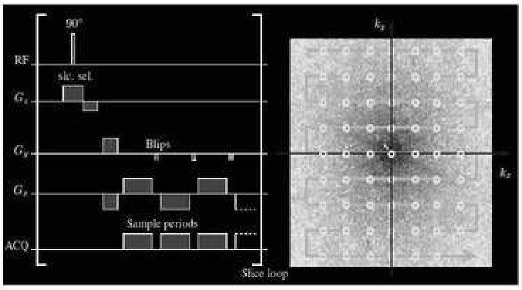
Violations cause artifacts

- Insufficient coverage: Partial volume effects.
- Insufficient sampling density: Aliasing.

It takes time to sample k-space: Choose region with care.

Echo planar imaging exercise

EPI sequence diagram and corresponding k-space trajectory:



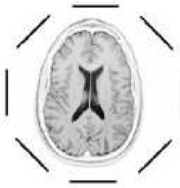
Tech trends: Detector arrays

Increasing sensitivity or speed using detector arrays

Parallel imaging:

Redundancy used to speed up acquisition

- decreased sampling density
- special reconstruction avoid aliasing



l d

MR sikkerhed

Potentielt skadelig indvirkning på organismen:

- Statiske magnetfelter
  - Deformerer molekyler med ændret kemi til følge.
  - Afbøjer ladede partikler hvorved spændinger dannes.
  - Formodentlig nær-ubetydelige under cirka 11T.
  - FDA vurderer felter op til 8T uden signifikant risiko for voksne (4T for børn).
  - IEC: Brug af felter over 4T kræver etisk godkendelse.
- Tidsligt varierende magnetfelter
  - Gradientanvendelse og bevægelse i randfelt.
  - Kan give nervestimulation, svimmelhed, metalsmag, fosfener,...
  - Ydre regioner mest udsat, f.eks. hjerte ved hovedskan.
  - Grænser for tilladelig gradient-ydelse er nået.
- Radiobølger i MHz området
  - Langtfra ioniserende. Giver opvarmning.
  - Grænser baseres på maks. 1 grad opvarmning.
  - "1st level controlled mode": Normal modus. Alle kan skannes.
  - "2nd level controlled mode": Skanner kræver aktiv accept fra operatør. Patientens egen temperaturregulering skal vurderes.

MR sikkerhed (2)

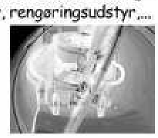
Skanner sikrer ALTID og KUN at grænser overholdes, hvis....

- ...patient-oplysninger er korrekt indtastet:
  - Vægt og egen temperaturregulering er som angivet.
- ...apparatur anvendes iflg. brugsanvisning:
  - Overhold angivne afstande til spoler
  - Implantater/elektroder/smykker påvirker lokal opvarmning!

MR sikkerhed (3)

Reelle farer (udover fejldiagnoser):

- Respekter kontraindikationer
  - Pacemakere, visse implantater,...
  - Udfyld og underskriv altid kontrolskema.
- Tænk når skanner foreslår "2nd level controlled mode"
- Brug MR-kompatibelt udstyr i skannerrum
  - Udstyr kan påvirkes af felt (f.eks. saturationsmåler eller respirator)
  - Elektroder/kabler kan give forbrændinger.
- Høj-effekt elektronik kan gå i brand.
  - Kend nødstop, brandslukningsudstyr, ilthaner,...
- Vær MEGET forsigtig med hvad der medbringes i skannerrum.
  - defibrillator, lejer, værktøj, iltbomber, rengøringsudstyr,...



Chair stuck in MRI....

- totem /home/larsh/mgp/images/safety/Chairgetsstuckinan MRImachine.flv

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
- Patient
  - Tends to leave after an hour

Limits must be acknowledged. Leaves plenty of room for creativity....

Technological trends

Technological trends:

- Use of higher fields
- Detector arrays for parallel imaging
- Real-time feed-back
- Use of prior knowledge
- Multi-modality MRI
- Real-time metabolic imaging

Tech trends: High field

Typical whole-body MRI: Up to 1.5T

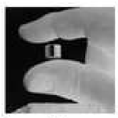
Current Danish high-field limit:

- 3 Tesla for human imaging (pictures: 3T@Hvidovre)

Efforts to go higher (7T, 9T). Challenges:

- Expensive equipment and siting is problematic
- Relaxation times are less favorable
  - shorter T2s, longer T1s
- RF field inhomogeneity increases
  - wavelength below body dimensions gives travelling waves
  - Remedy: Multiple receive and transmit channels/coils.
- B0 field inhomogeneity increases
  - Remedy: Faster imaging, dynamic shimming
- Mechanical forces increase
- List continues: Safety, acoustic noise, gradient linearity, shifts,,..

Diamagnetic levitation



$$B\frac{dB}{dz} = \mu_0 \rho \frac{g}{\chi}$$

- totem /home/larsh/mgp/images/safety/Levitatingfrog.flv

Tech trends: Detector arrays

Increasing sensitivity or speed using detector arrays

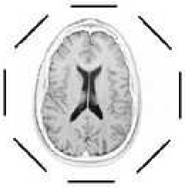
Parallel imaging:

Redundancy used to speed up acquisition

- decreased sampling density
- special reconstruction avoid aliasing

Technological trend

- Many channel systems, e.g., 32-96



Tech trends: Real-time feed-back

Real-time feedback:

Exciting new possibility

Acquired data is used to guide further data acquisition

Example:

- PACE: Imaging plane follows patient motion

Tech trends: Use of prior knowledge

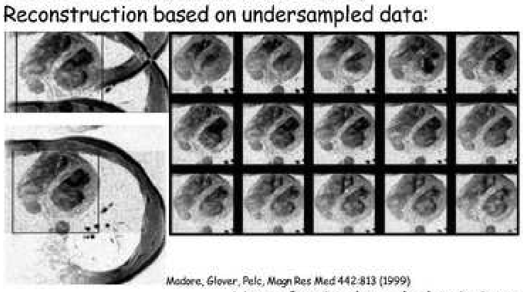
Use of prior knowledge:

Good models decrease need for sampling

Example: Heart imaging

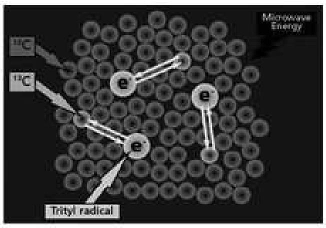
- Heart is moving rapidly (small region)
- Chest is moving slowly (large region)

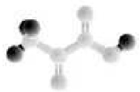
Reconstruction based on undersampled data:

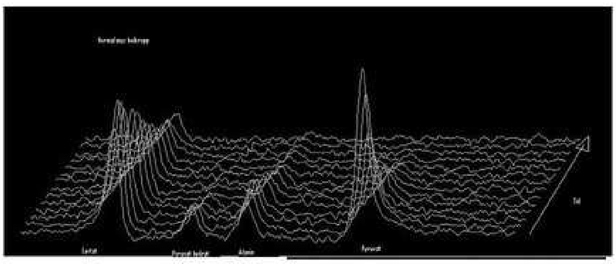


Madore, Glover, Pelc, Magn Res Med 442:813 (1999)

Use of prior knowledge is increasingly important.







Multi-modality: PET-MRI, EEG-MRI,...

Want to know more?

DTU courses involving MRI

Other DTU courses involving MRI

Medical Imaging
- Jens Wilhjelm and Markus Nowak Lonsdale

Medical Image Analysis
- Rasmus Larsen

Neurophysics
- Henrik Bohr

Upcoming MR course
- Lars G. Hanson and others

Acknowledgment

Image material from:

Egill Rostrup, Minna Nørgaard, Torben Lund
Elizabeth Kalowska, Sverre Rosenbaum
Mette Wiegell, Katja Krabbe
Annika Langkilde, Henrik Mathiesen

Internet: Belliveau, Jezzard and more

Scanners from the Simon Spies Foundation.