Magnetic Resonance Imaging: Basics and Techniques

31540 Introduction to medical imaging

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

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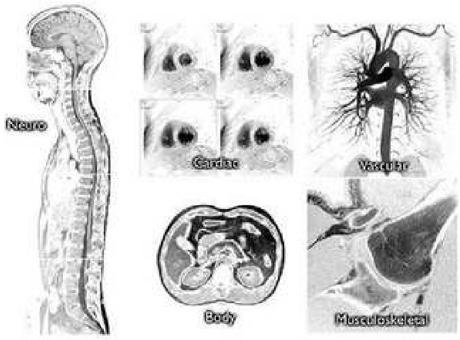
DTU Elektro
http://www.elektro.dtu.dk/

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

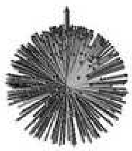
Basic NMR
- Equipment
- Nuclear spin and magnetization
- Precession
- Resonance and excitation
- Pulse sequences

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

Supplementary material

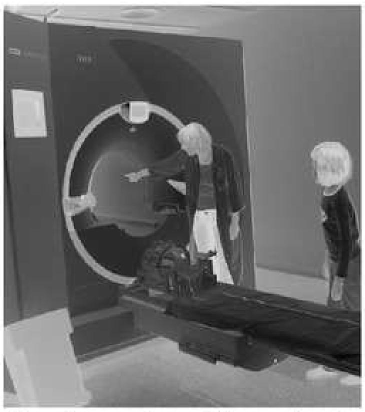
Lecture notes:
- http://www.drcmr.dk/MRnotes
- 47 pages in English and Danish

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



Equipment

You need...

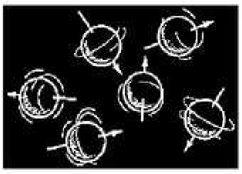


- Magnet, radio wave transmitter and receiver, patient

Nuclear spin

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

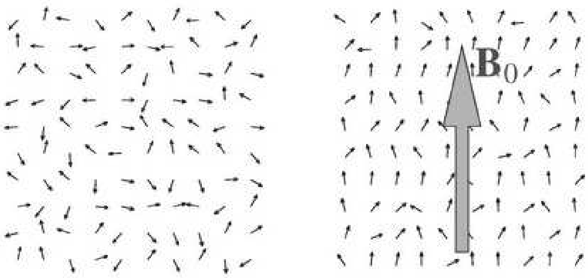
Protons (Hydrogen nuclei):



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.

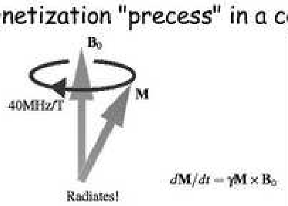
Repetition: Java compass

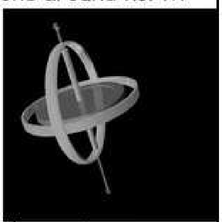
http://www.drcmr.dk/MR

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.

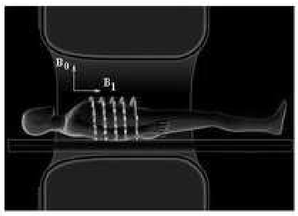
Precession and the RF field

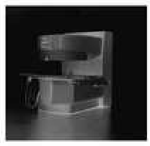
The magnetization precess at the Larmor frequency:

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

- 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.

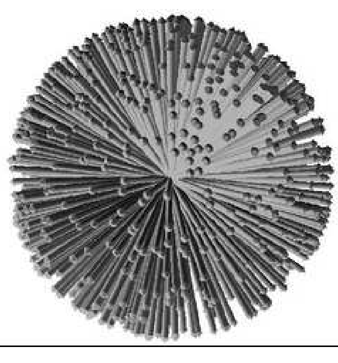




- C-shaped open scanner (right) with static vertical field and linearly polarized RF field.
  - Most scanners have horizontal field, however.

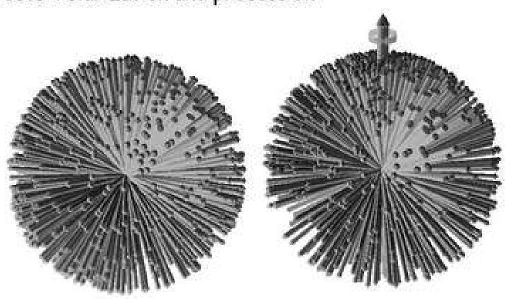
The spin distribution

Equilibrium spin distribution in absense of field is isotropic:



The spin distribution

Field effects: Polarization and precession



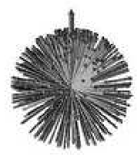
Reasons that nuclei don't align perfectly:
- Nuclear interactions and motion.
  - Think compasses in tumble dryer.

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.

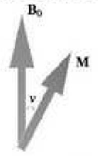
Relative orientations are preserved:

- Sufficient to keep track of net magnetization!

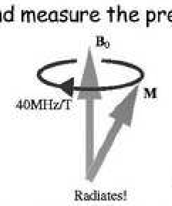
The MR signal

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:



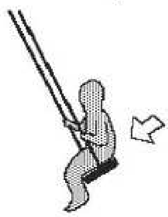
$dM/dt = \gamma M \times B_0$

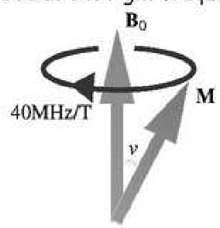
- Analyze the weak emitted radio signal.

Excitation

Resonance:

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



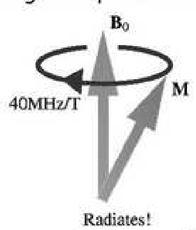


Pushing the swing at the eigen-frequency changes the amplitude.
Radio waves at the Larmor frequency changes the angle v.

Transfer of energy!

Precession

Reestablishing the equilibrium after excitation:



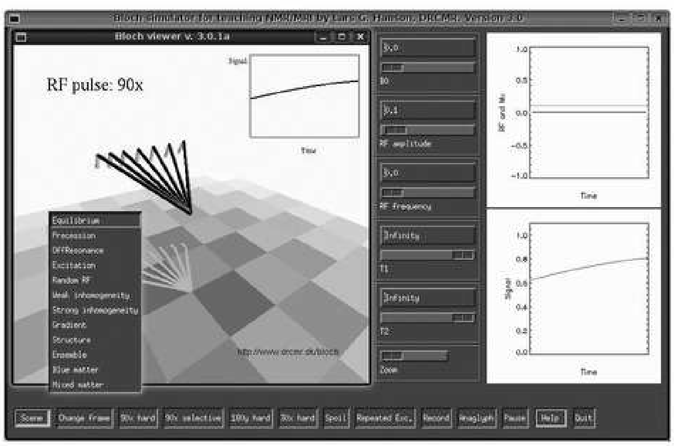
$dM/dt = \gamma M \times B_0 + \text{relax. terms}$

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

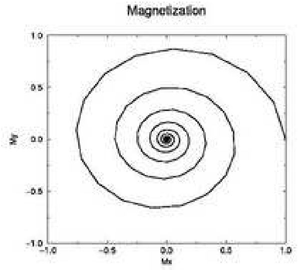
starring

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:

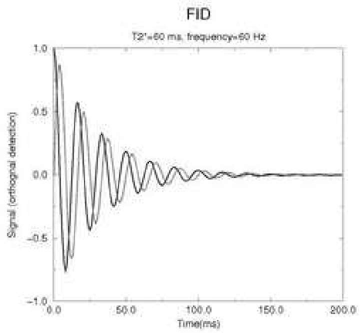


- The transversal relaxation time T2 is a time constant for loss of magnetization.

The MR signal

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

MR signal with a single frequency component:

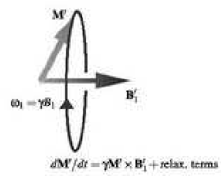


Orthogonal coils detect changes in Mx, My, respectively.
Signals are modulated down from the Larmor frequency to near zero.

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

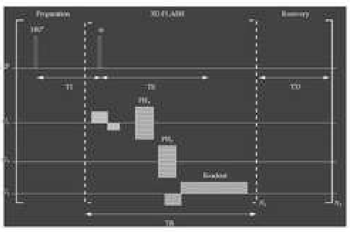
MR sequences

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" ??

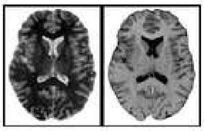
- The parameters above are seldom measured quantitatively...
- ...but their relative values may be apparent in the images.
- i.e: The contrast in a "T1-weighted" image comes mostly from T1-differences.

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



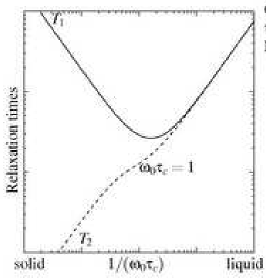
T1- and T2-weighted sequences.

Eksitation

- 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)

Relaxation

Relaxation time dependence on nuclear mobility:



ω_0: Larmor frequency
τ_c: Correlation time
Note: log-log scale

- The correlation time is typical time between changes in nuclear environment.
- 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.

Relaxation - quantitative

Relaxation changes the transversal and longitudinal magnetization M_{xy} and M_z as follows (subst. T_2 with T_2^* if inhomogeneity matters):

$$|M_{xy}(t)| = |M_{xy}(t=0)|e^{-t/T_2}$$
$$M_z(t) = M_z(t=0)e^{-t/T_1} + M_0(1-e^{-t/T_1})$$

Example: Starting from equilibrium $M_z = M_0$ and after a 90° excitation at time $t = 0$, converting all longitudinal magn. to transversal:

$$|M_{xy}(t)| = M_0 e^{-t/T_2}$$
$$M_z(t) = M_0(1-e^{-t/T_1})$$

More generally, a short resonant RF pulse at time $t = 0$ with tip angle α rotates longitudinal magnetization as follows:

$$|M_{xy}(t=0_+)| = |M_z(t=0_-)\sin(\alpha)|$$
$$M_z(t=0_+) = M_z(t=0_-)\cos(\alpha)$$

The equations are combined to find effect of a series of pulses (for each: Redefine $t = 0$ and make sure that $M_{xy} \simeq 0$ before the pulse).

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...

- Relaxation time contrast revisited

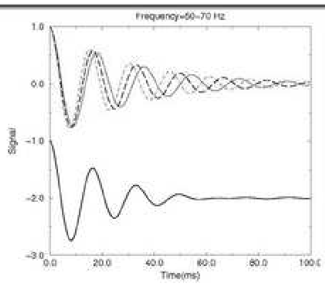
More contrast mechanisms

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

Imaging methodology

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.

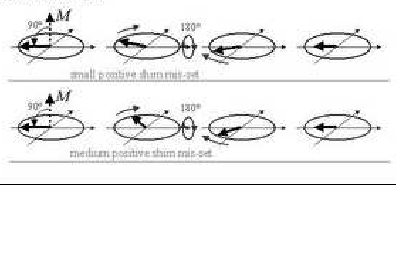
T2* contrast can be useful, e.g., for

- 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*



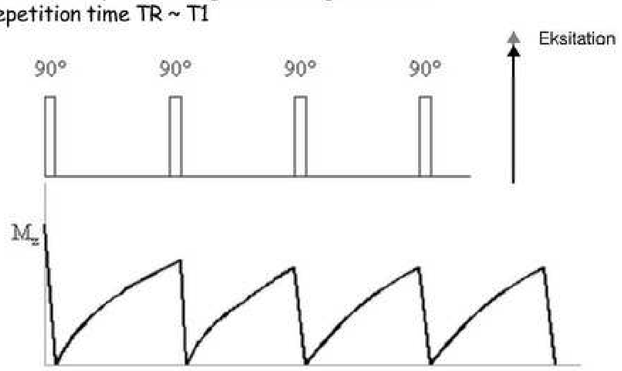
Spin echo contrast

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.

Imaging - an appetizer

Gradients

Field gradients:

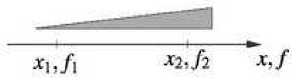
Linear variations in main field B0 induced by gradient coils.

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

Resonance frequency: $f = \gamma B_z$



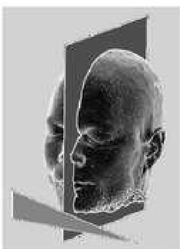
Spatial axis are converted into freq. axis by gradients.

Gradients

Slice selection:

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

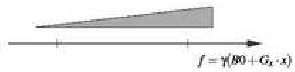
Only spins on resonance are affected by RF.



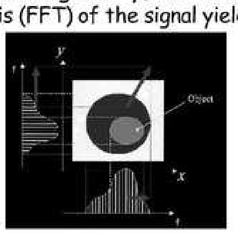
Reduces 3D imaging problem to 2D.

Gradients for recording projections

Gradient gives linear relation between position and frequency:



If a gradient is applied along x or y, for example,...
- ...a frequency analysis (FFT) of the signal yields a spatial projection.



When done for all directions, projection reconstruction can be used...
- ...but actually this is seldom done. A smarter variant exist.

▸ Story continues in 31545...

More contrast mechanisms

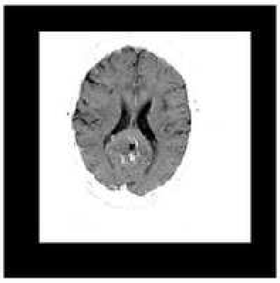
Contrast agents

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

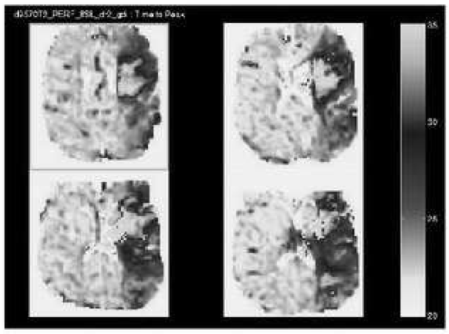
Fast brain imaging during contrast injection (bolus):



One second interval between images.

Contrast agents

Measurement of blood supply:

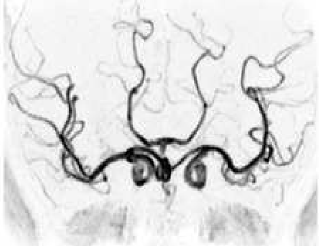


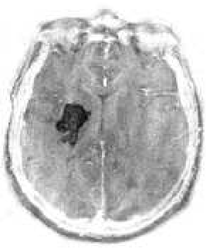
Duration before bolus arrives in tissue

- Quantitating the perfusion requires deconvolution or spin labelling.

Flow and diffusion weighting

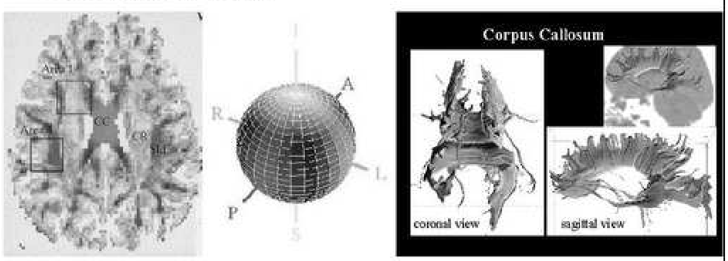
Flow and diffusion weighting.





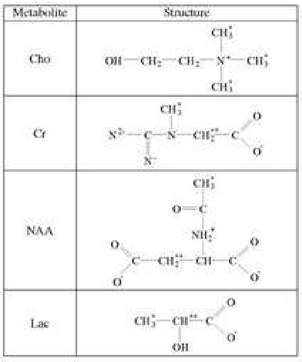
Fiber directionality

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

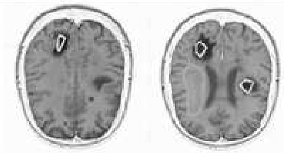


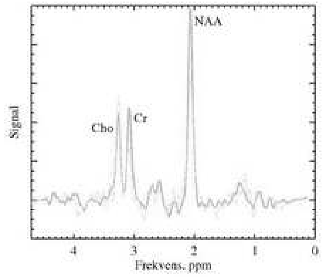
Spectroscopy

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.

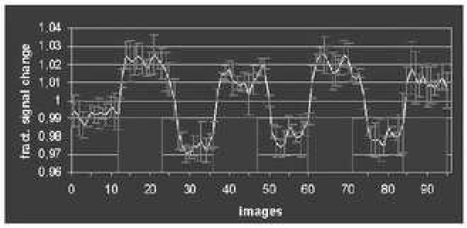
Examples:
- visual stimulation
- language lateralisation.

Language lateralisation, fMRI

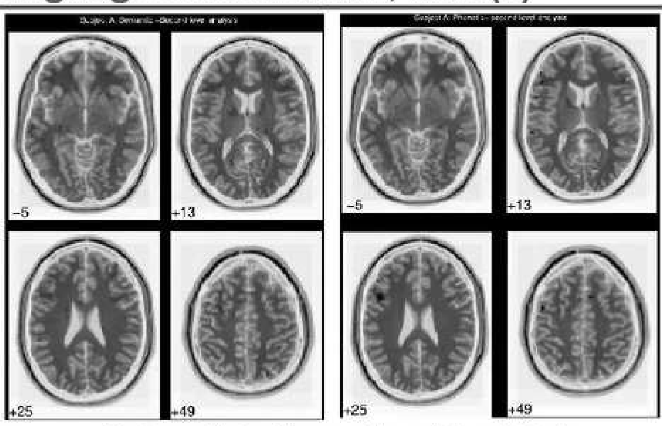
Hope: Localization of language areas ahead of surgery.

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.

Take-home messages

MRI is...
- not one, but many different exams:
  - Structural imaging: T1-, T2-, PD-weighting,...
  - Flow and diffusion imaging,...
  - Functional imaging,...
  - Metabolic imaging and more.
- provides excellent soft-tissue contrast
- now present at basically all larger hospitals
- completely safe, if conducted right.
  - Not relying on ionizing radiation, for example.
- Not always first choice:
  - Time consuming...
    - ...since many parameters are typically measured.
  - Relatively expensive. Running costs are high,...
    - ...but independent of #scans.
  - Contraindications exist:
    - Pacemaker, claustrophobia,...

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