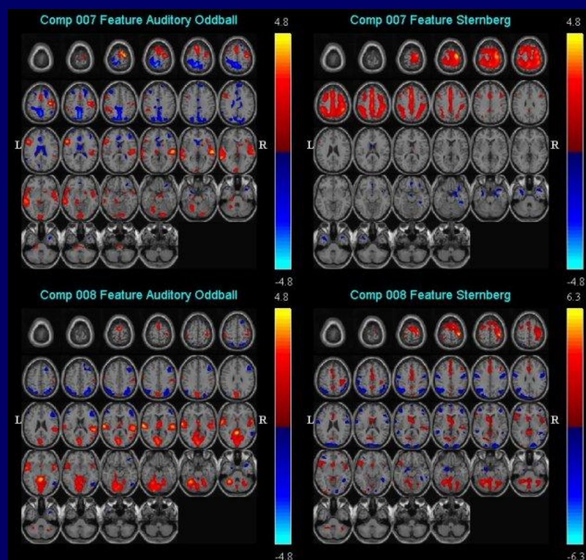
fMRI
Functional Magnetic Resonance Imaging



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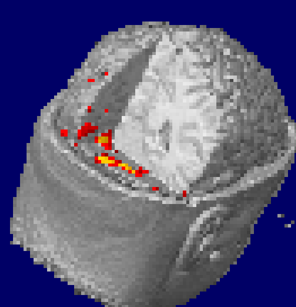
Functional Magnetic Resonance Imaging



Functional: investigate brain functions

Magnetic: source of signal (B0, RF pulses, …)

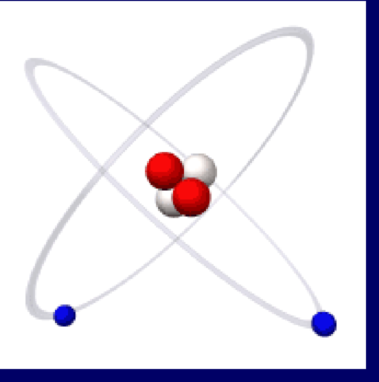
Resonance: excitation and detection

Imaging: turning signals into images

Advantages of MRI

- non invasive
- non ionizing radiations
- visualization of soft tissues
- flexibility of contrasts – broad applicability
- flexibility of protocols (targeted nuclei , DTI, …)
- high spatial resolution

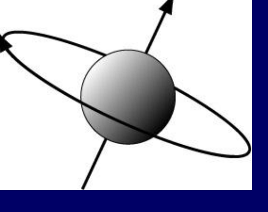
Main actors



Atoms are made of protons, neutrons and electrons.
Here: He

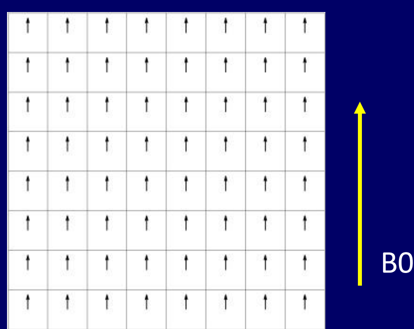
Main actors

- Hydrogen is the widespread and lightest element in the human body:
  - fat
  - water



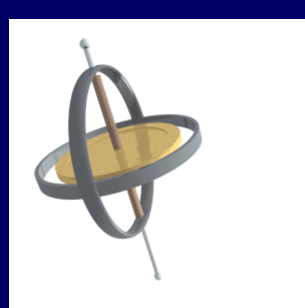
- Hydrogen nuclei are made of 1 p+
- Protons have an intrinsic physical property: spin.
- This vector is randomly oriented in space

Main actors



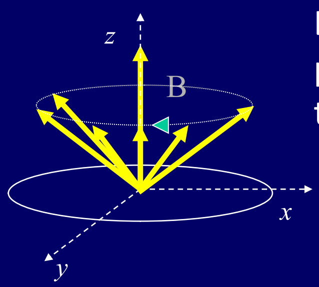
- Normally, the orientation of spins is random
- In a strong magnetic field (B0), spins like to align with this field, leading to a net magnetization, when averaging over a large number of nuclei.

Precession



Larmor frequency

It's the characteristic frequency in which spins are precessing



Larmor frequency =
physical properties of the nucleus (γ)
the local magnetic field (B0):

$$\omega=\gamma B_0$$

At 3T, free protons precess at ~120 MHz

Larmor frequency

Gyromagnetic ratio (MHz/T) = cst

$$\omega = \gamma\ B_0$$

Intensity (T)

Ex. For hydrogen
γ = 42 MHz/T, thus in a
3T magnetic field,
ω=120MHz

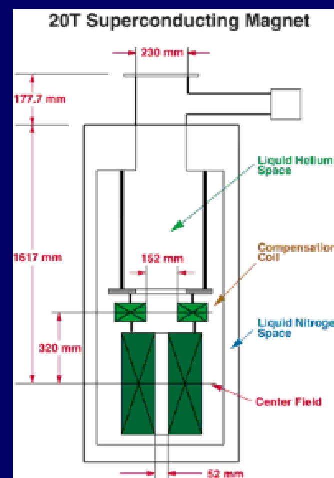
Magnets

• In RMN, B0 is about 1-11T

• Earth magnetic field: 10-6T

• Fridge magnet 0.01 T

• Research needs powerful (electro) magnets [superconductivity is required]



Magnets

A new electromagnet being built at Florida's National High Magnetic Field Laboratory will be the world's first reusable 100T magnet. Its pull will be about two million times stronger than the average refrigerator magnet.

Security and screening

- Very strong magnetic fields cause ferromagnetic objects to fly
- Intra-body (vital) materials:
  - pace makers
  - shrapnel
  - tatoos
- Check compatibility of material before entering the magnet room
- Intensity and gradients : can cause muscular and cardiac fibrillations
- Skin contacts !
- Loops in cables (ECG monitoring)

Security and screening

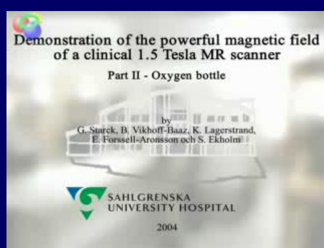
Specific Absorption Rate (SAR)

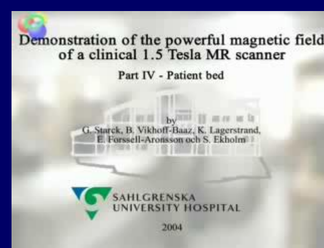
Defined as the RF power absorbed per unit of mass of an object, and is measured in watts per kilogram (W/kg).

High SAR can cause local heating in tissues.
Can be decreased:
- by using small volumes of emission
- By optimizing sequence parameters (↑ TR, ↓ nb slices, ↓echo trains)

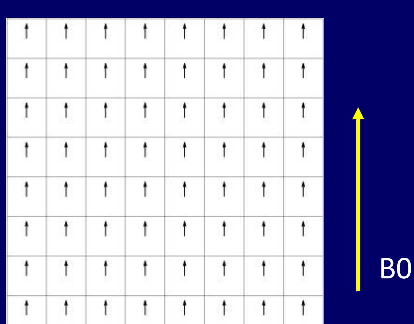
Security norms (IEC 601-2-33): no increase > 1 deg C
(induced by 1W/kg during an hour)

Security and screening



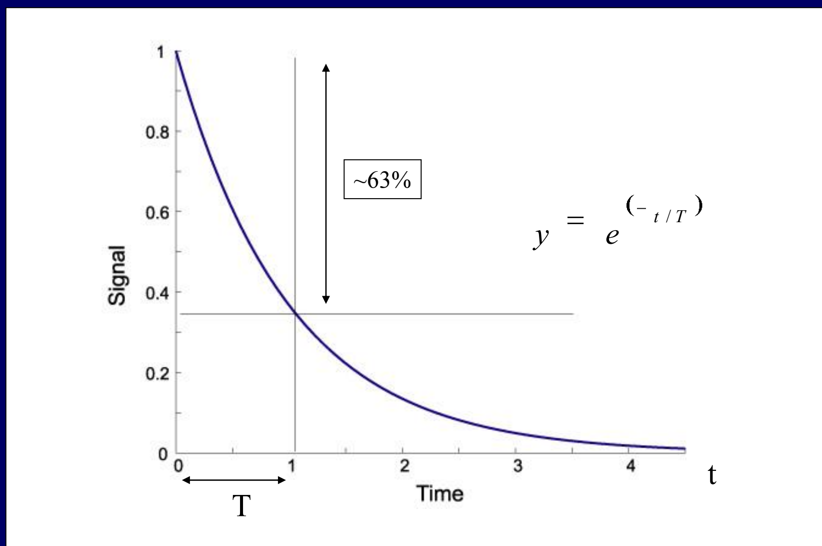


Magnetization

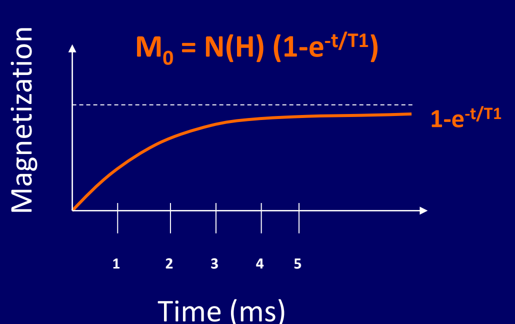


In B0, spins align with this field, leading to a net magnetization, when averaging over a large number of nuclei.

Alignment takes some time



Alignment takes some time

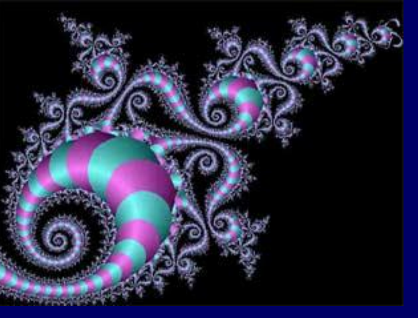


For a given B_0, the net magnetization M_0 depends on:

1. T1 (time constant of $1-e^{-t/T1}$) specific to the material
2. Spin density: N(H)

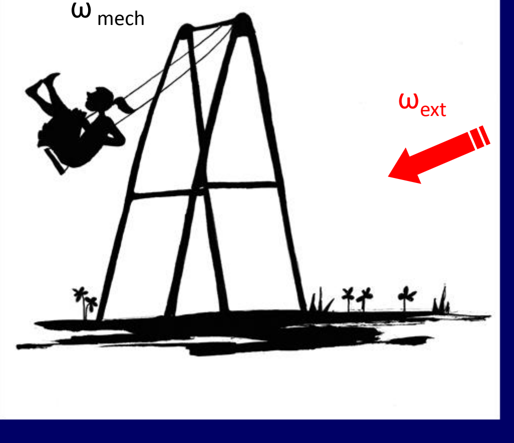
RF Pulse

- RF waves are electromagnetic waves for which the frequency is set by convention between 9 kHz and 3000 GHz
- An RF pulse can interact with a nuclei spin precessing at the same frequency as the pulse.
  This exchange of energy is resonance



- When frequency of excitation is performed at proper frequency, the exchange of energy between the system and the stimulation is optimal. In particular: stimulate spins at Larmor frequency.

Resonance



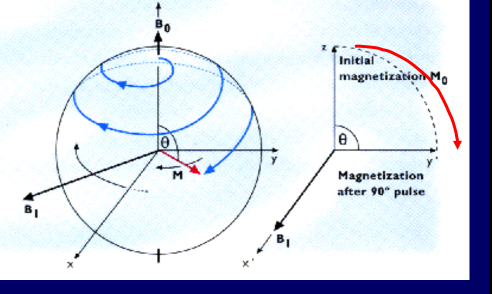
ω_{mech} depends on *length and gravity*

If $\omega_{ext} = \omega_{mech}$ ➡ System gains energy

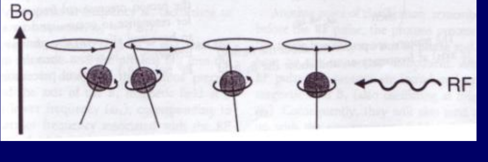
How to measure the magnetic field?

- Impossible to measure directly a MF // external MF (e.g. B_0)
- To be able to measure the longitudinal MF, we need to alter its orientation to induce a transverse component
- But only RF pulses at the Larmor frequency (precession) are not blind

RF Pulses

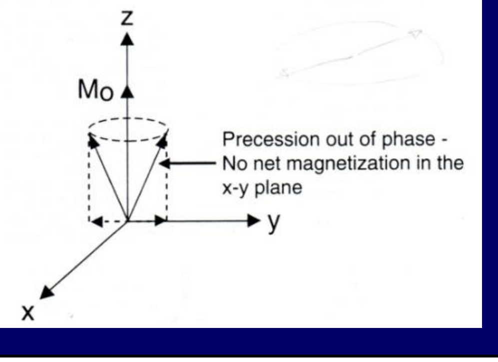


How to measure the magnetic field?



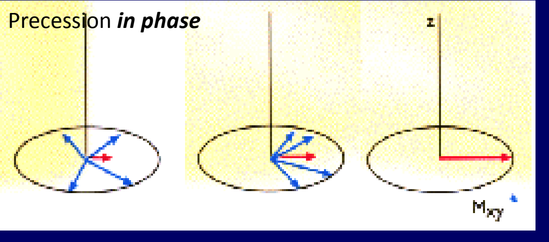
- Spins precessing about B_0 become out of phase

- This phase shift cancels the transverse component (x-y) of magnetization



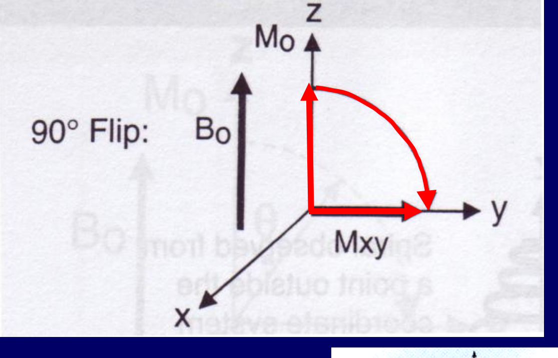
The RF Pulse reduces the longitudinal component

How to measure the magnetic field?

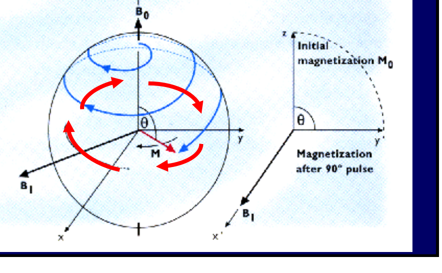


RF pulses put nuclei precessions back into phase (synchronize) and induce a transverse magnetization

How to measure the magnetic field?



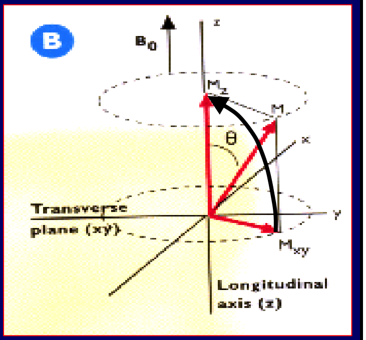
- The RF pulse cancels M_z and produces a M_{xy} of same magnitude
- M_{xy} rotates in the horizontal plane and can therefore be measured by a receptive antenna



Relaxation times

As soon as the RF pulse is off:

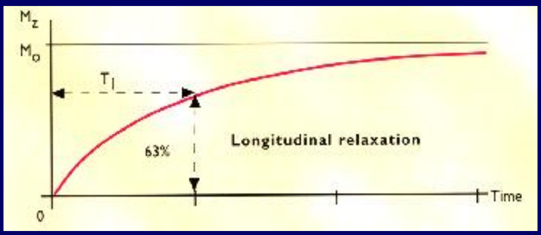
- spins converge back to their original phase shifts
- spins go back to their initial energy states



Therefore:

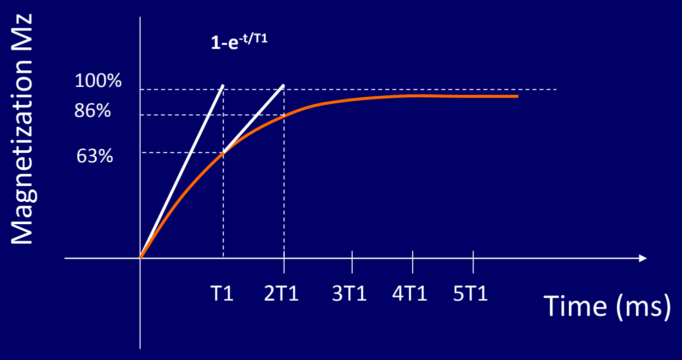
- M_{xy} decreases (transverse relaxation)
- M_z increases (longitudinal relaxation)

T1 Relaxation time



- T1 is the longitudinal relaxation time because related to the recovery of the Mz component
- T1 is a time constant of an <u>increasing</u> exponential function

T1 Relaxation time

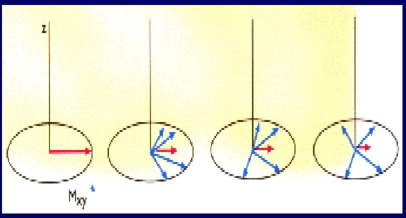


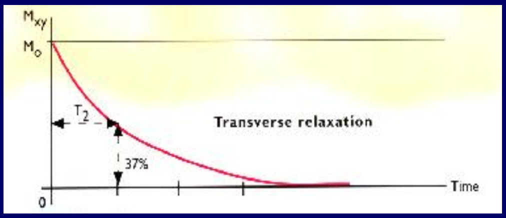
T1 is the amount of time necessary for the system to recover 63% of $M_{Z.}$

For t = T1 $\quad 1- e^{-t/T1} = 1- e^{-1} \approx 1- 1/2.72 = 1- 0.37 = 0.63$

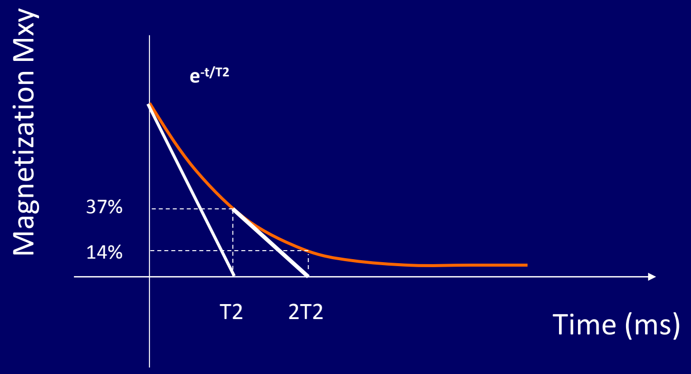
T2 Relaxation time

- As soon as the RF pulse is switched off, spins go back to their original phase shifts
- The transverse component M_{xy} decreases
- T2 is the transversal relaxation time
- T2 is a time constant of a <u>decreasing</u> exponential function





T2 Relaxation time

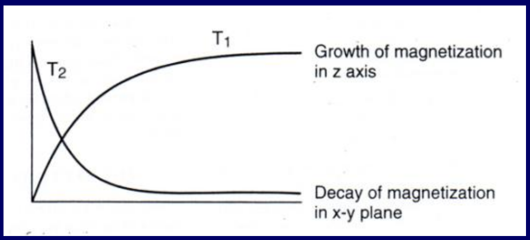


At time T2, only 37% of initial transverse magnetization remains (M_{xy}).

For t = T2, $e^{-t/T2} = e^{-1} \approx 1/2.72 = 0.37$

T1 and T2 reflect independent processes

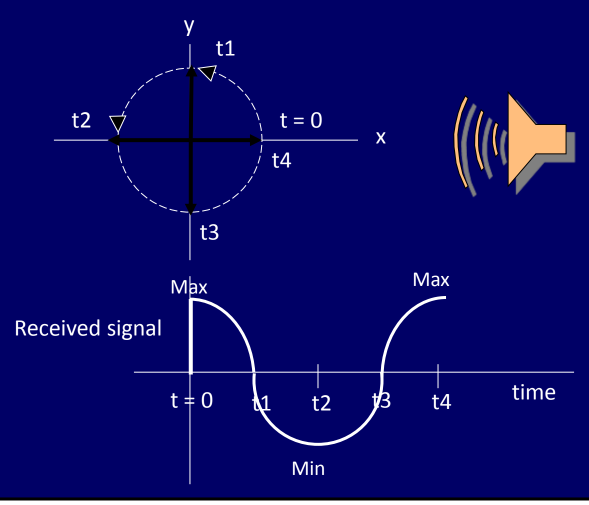
- The recovery of the longitudinal component and the decrease of the transverse component are two independent processes
- M_{xy} decreases 5 times faster than M_Z recovers



- T1 and T2 time constants depend material properties:
  T1: 200 to 8000 ms 5500 ms Water, 1200 ms Gray Matter, 860 ms White Matter
  T2: 30 to 150 ms

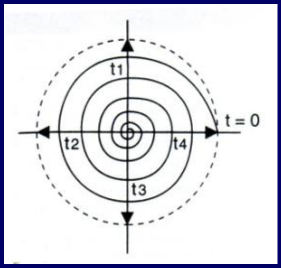
How to measure the signal?

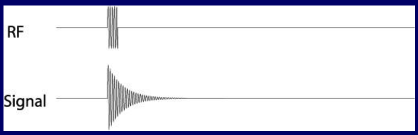
A coil positioned around the body detects variations of the transverse magnetic field M_{xy}



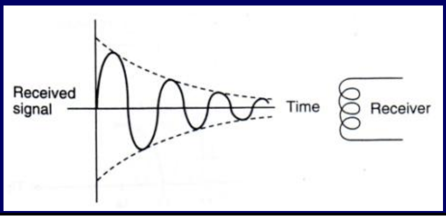
How to measure the signal?

When the RF pulse is switched off, the phase shifts of spins decrease the transverse component. The Mxy vector traces a spiral.





The signal captured by the antenna is a damped sinusoïd.



Free induction decay

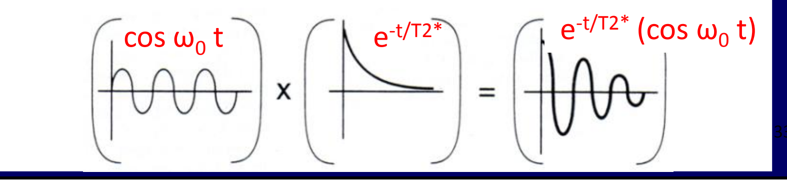
The signal received is called the Free Induction Decay signal.

When the RF pulse is off:

1. Spins precess freely ***(free)***
2. Norm of the transverse component (Mxy) decreases ***(decay)***
3. When Mxy rotates, it unduces an electric signal received by the antenna ***(induction)***

The signal is a sinusoid damped by an exp of time T2*:

$$M_{xy}(t) = M_0\, e^{-t/T2^*} (\cos \omega_0 t)$$



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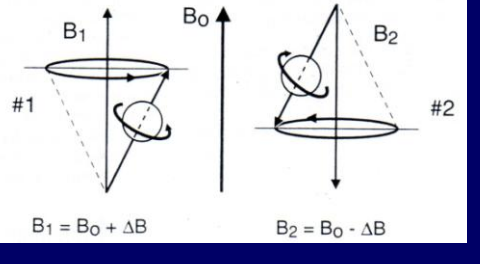
T2*??

T2 mainly depends on heterogeneity of the magnetic field. Slightly different local molecular environments induce different angular velocities ($<\omega_0$ or $><\omega_0$):



$\omega_1 = \gamma(B_0 + \Delta B)$ $\omega_2 = \gamma(B_0 - \Delta B)$

First cause of phase shift is linked to physical properties of the material. This is captured by T2.

T2*??

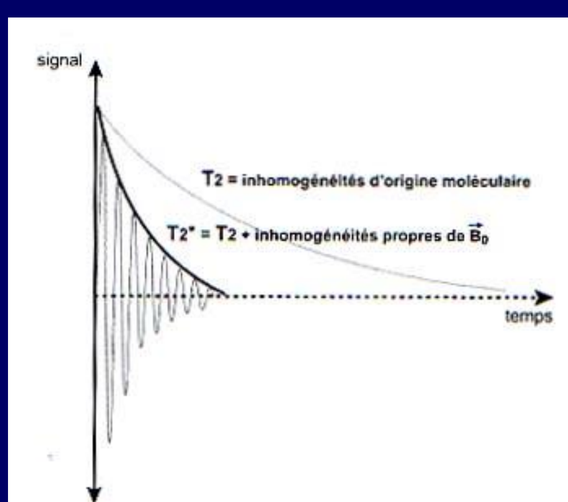
T2* depends on:

- Local heterogeneity of the magnetic field due to material properties (molecular origin) – T2
- Also heterogeneity of B_0 itself:

  - Protons are submitted to different magnetic fields according to their position
  - Consequently, the resonant frequency (precession) will be different and will put spins out of phase

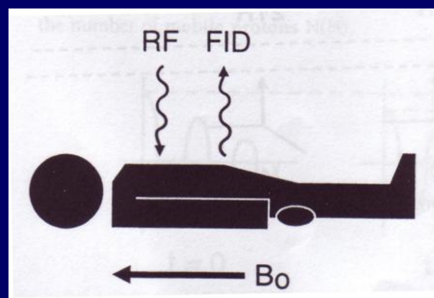
Second cause of phase shift is external and depends on the quality of B_0. This is captured by T2*. [T2* is T2 + TB_0]

T2* and T2



The FID signal decreases faster than expected, should we not have taken into account inhomogeneity of B0…

But how to create an image from spins?



• After the RF pulse has been transmitted, the antenna receives a FID signal coming from all protons of the body lying in the bore, without any spatial discrimination.

• To link spatial coordinates to the signal, we need to perturb the magnetic field smartly and iteratively.

• The image is build upon information from a sequence of FIDs

Scan timing

TR: time of repetition

TR corresponds to the interval between two 90-deg excitation RF pulses

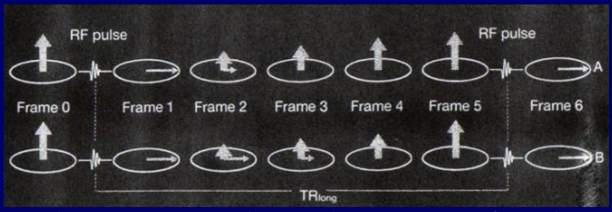
TE: time of echo

TE corresponds to the time elasped between the RF pulse and detection of the FID (spin echo).

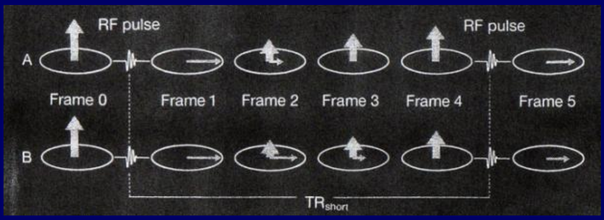
Both TE and TR can be adjusted by the operator and will modulate the signal. Flexibility!

TR: Time of Repetition

Example :

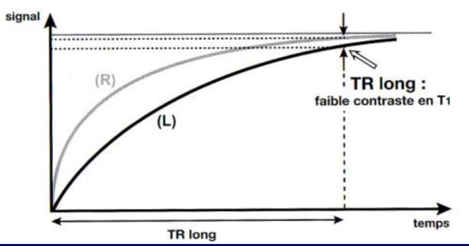


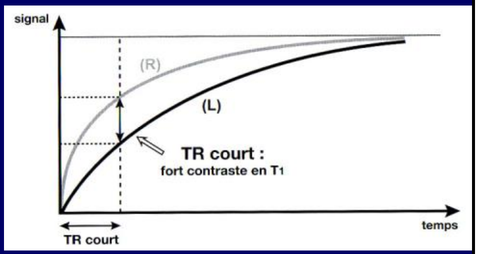
Tissue A has a relaxation time T1 shorter than tissue B. After a long TR, both A and B will have fully recovered their initial longitudinal component.



However, after a short TR only tissue A will have recovered its initial longitudinal component. At the second RF pulse, the transverse component of will be larger. Therefore, the signal received by the antenna will be different for A and B

TR: T1-weighted images





A long TR decreases the effect of T1:

TR_{long} : both the R and L tissues have nearly recovered their longitudinal component (steady state)

TR_{long} > 2000 ms (if TR=5 T1, the effect becomes negligible)

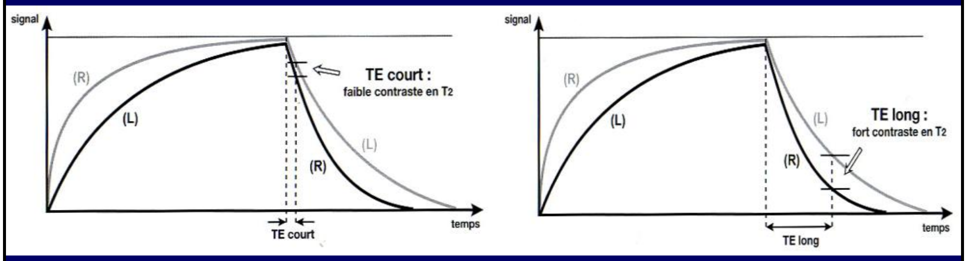
A short TR increases the effect of T1:

TR_{court} : signal of tissue R will have a higher signal (brighter) than L (darker)

TR_{court} < 500 ms

! Contrast !

TE: T2-weighted images



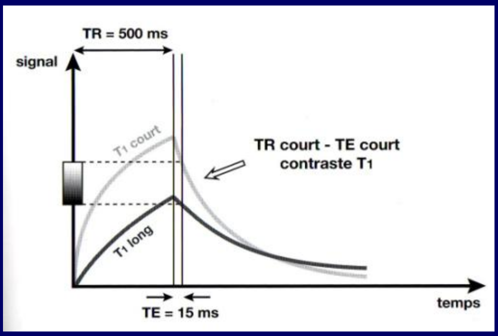
A short TE (<20-30 ms) decreases the T2 effect:

TE_{court} : differences in decreasing rates after the RF pulse are too tiny to be measurable

A long TE (>80-100 ms) increases the T2 effect:

TE_{long} : signal of tissu L (longer T2 constant) will be brighter than tissue R (darker).

T1-weighted short sequence



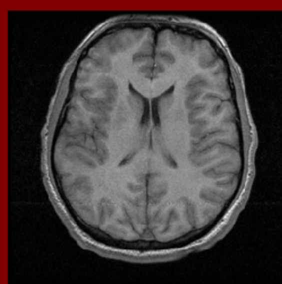
A medium TR (400-500 ms) to <u>enhance</u> the contrast in T1

A short TE (15 ms) to <u>minimize</u> the contrast in T2

Tissue with the shortest T1 yields the brighter signal

T1-weighted short sequence

T_1 Weighted Image

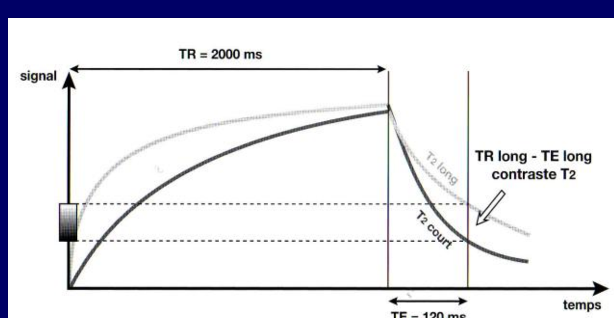


	T_1/s	R_1/s^{-1}
white matter	0.7	1.43
grey matter	1	1
CSF	4	0.25

1.5T

SPGR, TR=14ms, TE=5ms, flip=20°

T2-weighted long sequence



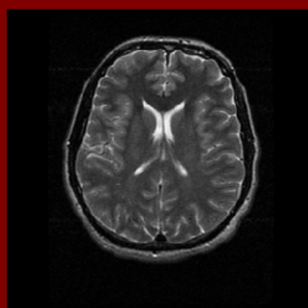
A long TR (2000 ms) to minimize the contrast in T1

A medium TE (120 ms) to enhance the contrast in T2

Tissue with the longest T2 yields the brighter signal

T2-weighted long sequence

T_2 Weighted Image

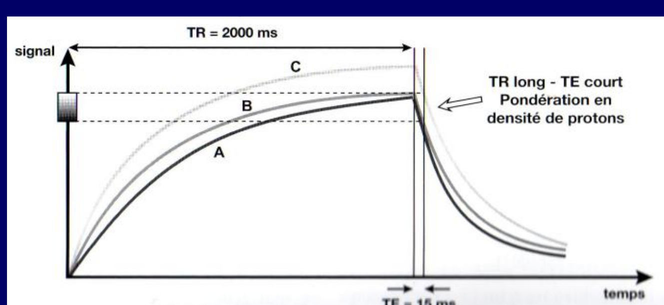


SE, TR=4000ms, TE=100ms

	T_2/ms
CSF	500
grey matter	80–90
white matter	70–80

1.5T

Proton density



A long TR (2000 ms) to minimize the contrast in T1

A super short TE (15 ms) to minimize the contrast in T2

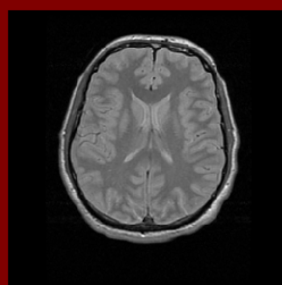
No T1-dependance (Mz recovered) not T2-dependence (no dephasing of Mxy)

More protons => larger Mz… but weak contrast for brain tissues

Proton density

Proton Density Contrast

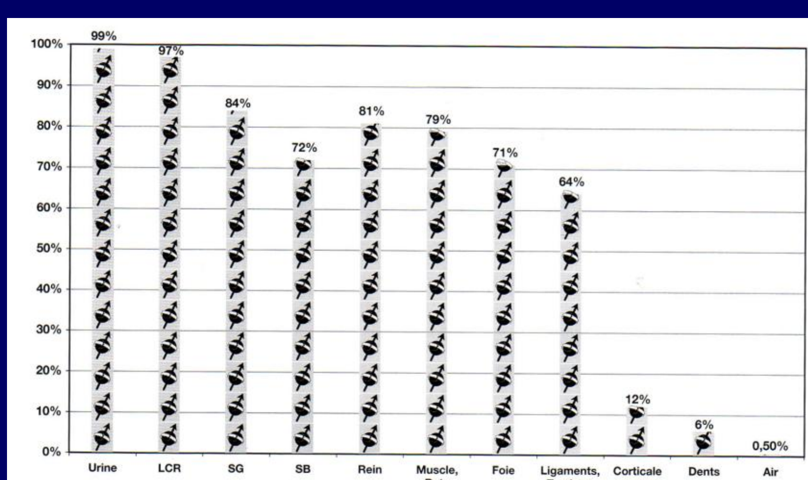
long TR (no T_1 weighting), short TE (no T_2 weighting)



SE, TR=4000ms, TE=15ms

	Proton Density
CSF	1
grey matter	0.92
white matter	0.79

Water in biological tissues



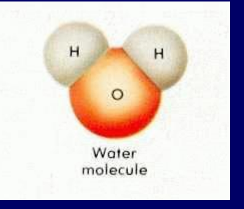
No protons => no signal whatever the sequence (bones, air)

Similar p+ density => low contrast (with proton density)

Physical properties of substances

H_2O : most important molecule because

- present in the body
- MRI is based on H^+



In the water molecule , H^+ has a precession rate >> its Larmor frequency => T1 is long. Thermal agitation prevents release of energy to the environment.

$$\omega (H_2O) > \omega_0$$

Consequently, these rapid movements tend to cancel out inhomogeneities of the magnetic field => T2 is long.

Water appears as low signal (dark) on a T1-weighted scan and as high signal (bright) on a T2-weighted scan.

Physical properties of substances

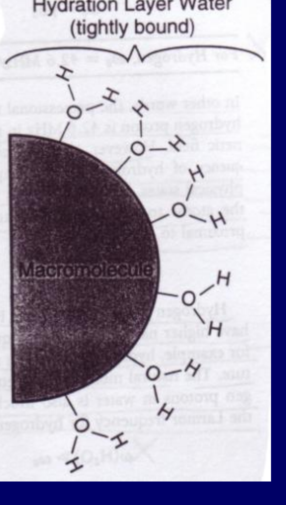
<u>Proteins + water</u> : calm down movement of water molecules.

Hydrophile macromolecules capture free H_2O.

Therefore, precession of H^+ will decrease and approach its Larmor frequency ω_0.

$\Rightarrow$ T1 and T2 decrease

Signal level will be intermediate.



Physical properties of substances

Fat:

H^+ in fat have a precession frequency close to its Larmor frequency.

$$\omega\ (\text{fat}) \approx \omega_0$$

$\Rightarrow$ T1 is short.

The structure of these molecules is such that dephasing is faster wrt H_2O.

$\Rightarrow$ T2 is short.

Physical properties of substances

Solids :

H^+ in solids have a precession frequency shorter to its Larmor frequency.

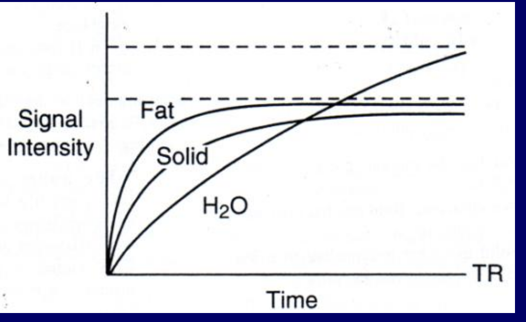
$$\omega\ (\text{solid}) < \omega_0$$

$\Rightarrow$ T1 is intermediate.

Compact structure having a lot of interactions between protons. Dephasing is fast.

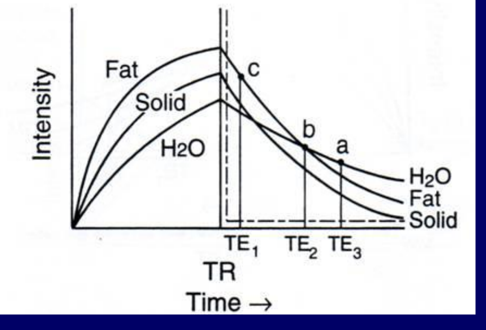
$\Rightarrow$ T2 is short.

Comparison of T1 across materials



- Fat and proteins + water: short T1 court
- Water : T1 very long => slow recovery
- Solids : T1 intermediate

Comparison of T2 across materials



- Water: very long => slow decrease of M_{xy}
- Solids : short T2 => rapid decrease of M_{xy}
- Fat: intermediate T2
- Proteins: short/intermediate T2 f(protein)

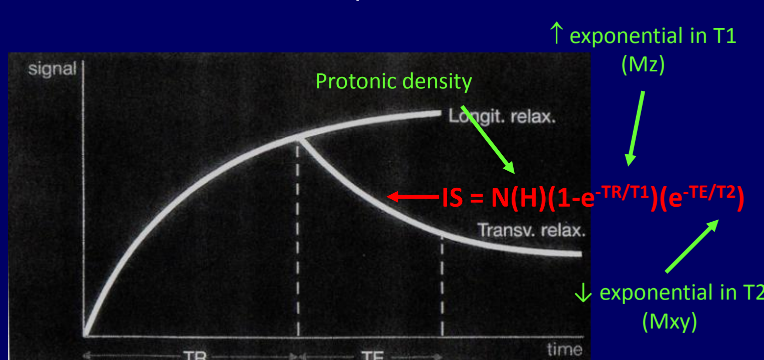
To give ideas

	T_1 en ms	T_2 en ms
Eau	3000	3000
Substance grise	810	100
Substance blanche	680	90
Foie	420	45
Graisse	240	85

- TE < TR (always?)
- TR is short if comparable to the shortest T1 (<500 ms)
- TR is long if 3 times a short T1 (> 1500 ms)
- Short TE if < 30 ms
- Long TE if 3 times a short T2 (> 90 ms)

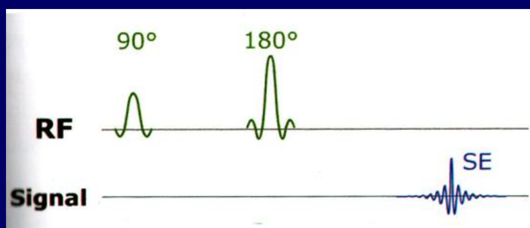
How to interpret the received signal?

To interpret the signal received at the antenna after a RF pulse, we need to combine the T1 and T2 phenomenon.

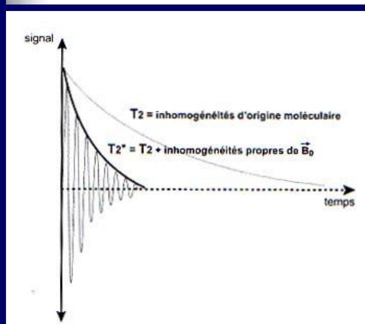


From time constants T1 and T2 of a given tissue, and values of TE and TR of the sequence, one can calculate the characteristic signal of a tissue.

Basic sequence: spin echo

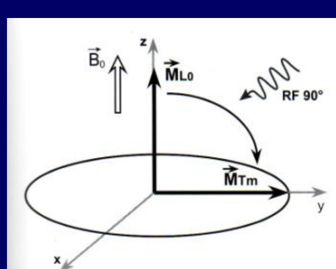


The spin echo sequence is a train of RF pulses.

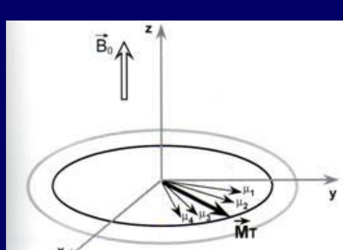


It allows to tackle the true T2 and avoid the problem due to $\underline{B_0}$ inhomogeneities that damp the signal much faster..

How does spin echo work?

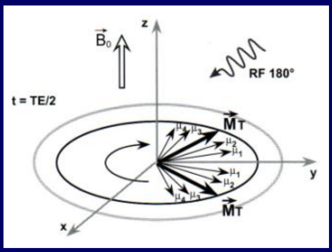


1. At t = 0
- impulsion RF 90 deg
- spins are in phase,
- vector M_{xy} is maximal

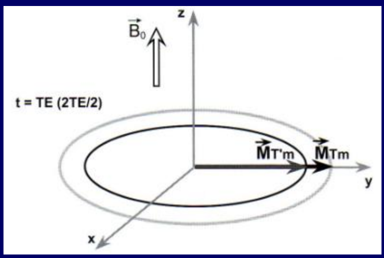


2.
- spins start dephasing
- faster spins (μ3 μ4) lead slower spins (μ1 μ2) that stay behind
- M_{xy} decreases in T2*

How does spin echo work?

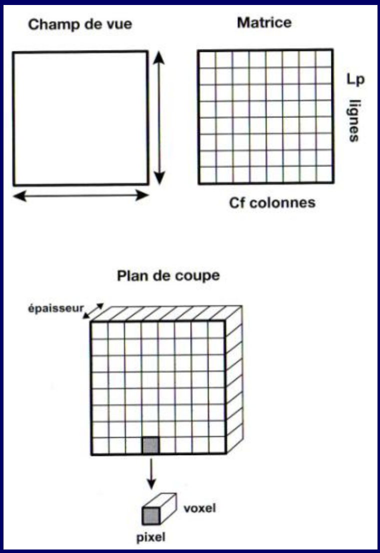


3. At t = TE/2
- impulsion RF 180 deg invert phase shifts
- slower spins (μ3 μ4) now lead faster spins (μ1 μ2)



4. At t = TE
- All spins are nearly in phase:
- $M_{xy'}$ is maximal and generates a measurable spin echo signal
- spin-spin dephasing is not corrected: $M_{xy}' < M_{xy}$
- M_{xy}' decreases in T2

Image reconstruction



Field of view (FOV): dimensions (height and width) in cm of the cutting plane.

Matrix size (MS): number of lines (freq encoding) and columns (phase encoding).

Third dimension is slice thickness.

Spatial resolution (pixel dimension): depends on FOV and MS
Ex.: if FOV=25cm, and a 128x128 matrix, a pixel will cover 5 mm²

Image reconstruction

Spatial localization of the signal needs small gradients of the magnetic field that superimposed to B_0

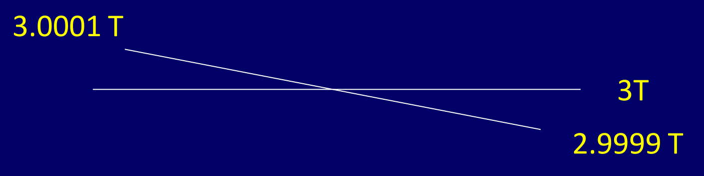
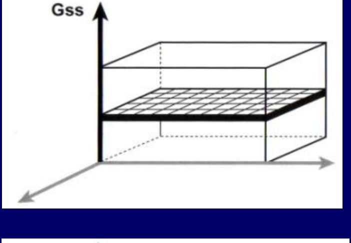
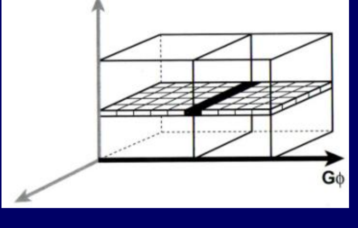


Image reconstruction

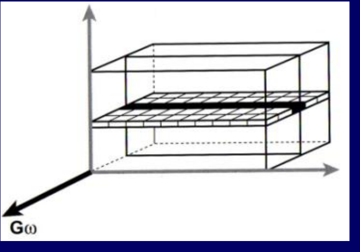


Slice selection gradient (Gss): selects a cutting plane inside a volume



Phase encoding gradient (Gϕ): selects rows inside the cutting plane

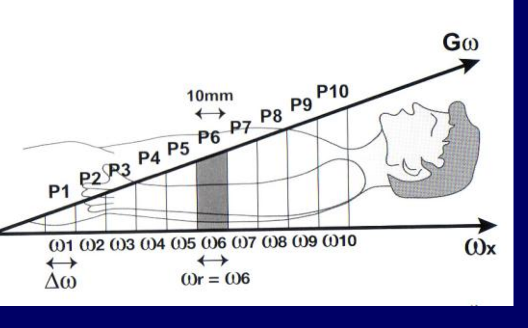
Image reconstruction



Frequency gradients (Gω):

Select columns within the cutting plane

1. Slice selection

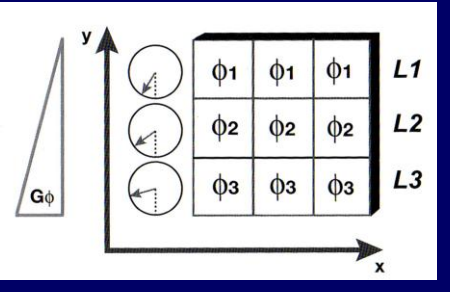


When exciting with a GSS, frequency will grow linearly in space.

If $\omega_r = \omega_6$, only P6 protons will flip by 90 deg (selectivity – notch).

By increasing the frequency of the RF pulse, one can successively select all the cutting plane in turn (P1, P2, P3 …)

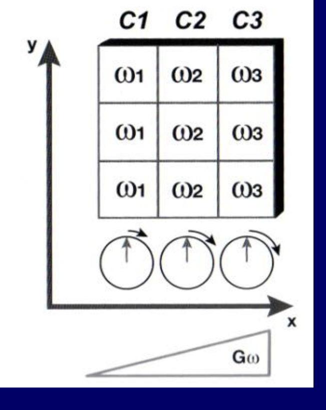
1. Phase coding



Excitation with Gϕ along Y-axis will increase the precession frequency of protons and induce the same phase shift ϕ1, ϕ2, ϕ3 in each row (L1, L2, L3).

When Gϕ is shut down, protons will recover their initial precession frequency BUT will keep their phase shift.

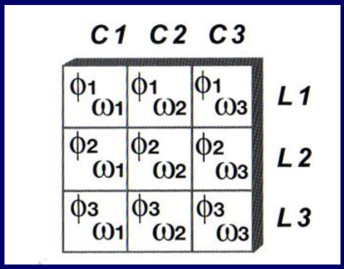
2. Frequency coding



Excitation with Gω along the X-axis will increase the precession frequency ω1, ω2, ω3 of protons in each column (C1, C2, C3)

Frequency coding is done when Gω is shut down: protons precess again at the same frequency.

Hence…



Proton identified by the ($\phi 1$, $\omega 1$) coding is easy in the frequency domain.

Then, inverse Fourier Transform to get space coordinates.

Temps d'acquisition d'une séquence « Tac »

Le Tac est un élément primordial car il conditionne:

- la durée de l'immobilité du patient
- la qualité de l'exploration

Tac = TR x NL (nombre de lignes de la matrice)

Tac = TR x NL x Nex (nombre d'excitations)

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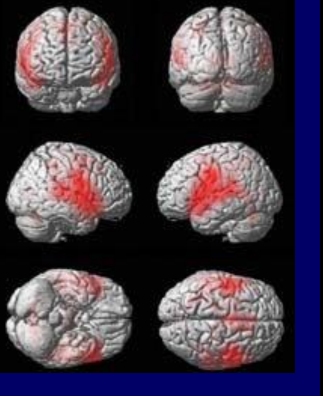
IRM fonctionnelle cérébrale (IRMf)

L'IRMf visualise sur une image IRM les aires cérébrales qui sont activées lors de la réalisation d'une tâche : on peut faire appel à des fonctions motrices, sensitives, sensorielles ou cognitives.



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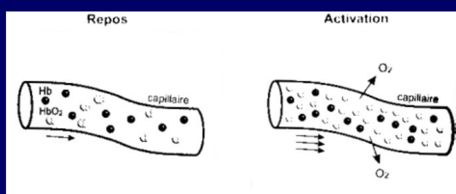
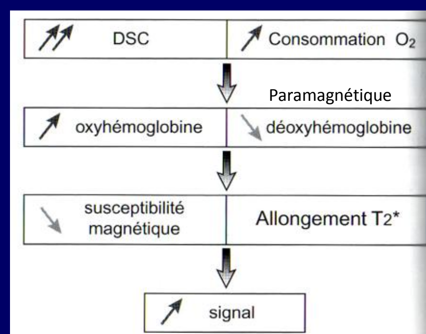
IRM fonctionnelle cérébrale

Méthode BOLD (Blood Oxygenation Level Dependent)

Cette méthode ne permet pas de mesurer directement l'activité neuronale, mais elle visualise les variations de perfusion pendant l'activation cérébrale.



Excès d'oxyhémoglobine dans les capillaires de l'aire activée



IRM fonctionnelle cérébrale

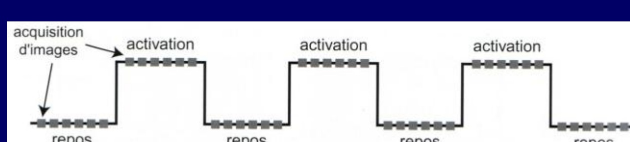
↑ du signal faible dans la zone activée très faible (2-3%)

✓ multiplication des mesures

✓ Bo élevé (1,5 T)

Déroulement d'un examen :

PARADIGME : Alternance de périodes de repos et de périodes d'activation



Acquisition EPI (écho-planar) : effectuée durant l'ensemble du paradigme, plus sensible au susceptibilités magnétiques, ultra rapide, permet de couvrir tout le cerveau.

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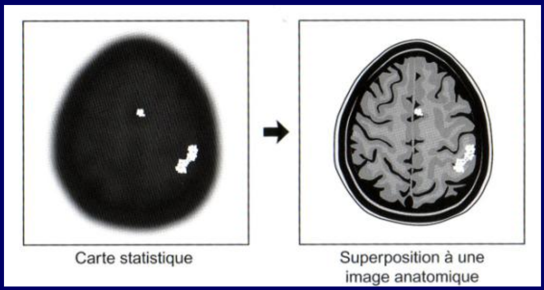
IRM fonctionnelle cérébrale

Le traitement des données :

Traitement statistique pour évaluer (pour chaque voxel) la différance de signal entre période d'activation et repos

Les résultats sont présentés sous forme de carte statistique, superposées à une image anatomique



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IRM fonctionnelle cérébrale

Domaines d'applications

En recherche

Études neurophysiologiques

Etudes cognitives

En pratique clinique

Localisation des régions de la motricité et du langage du cortex visuel et auditif à visée préopératoire

Détermination de la dominance hémisphérique du langage

Evaluation des possibilités de récupération fonctionnelle

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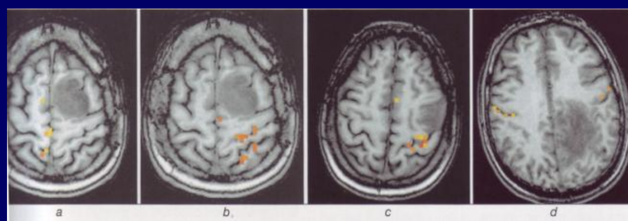
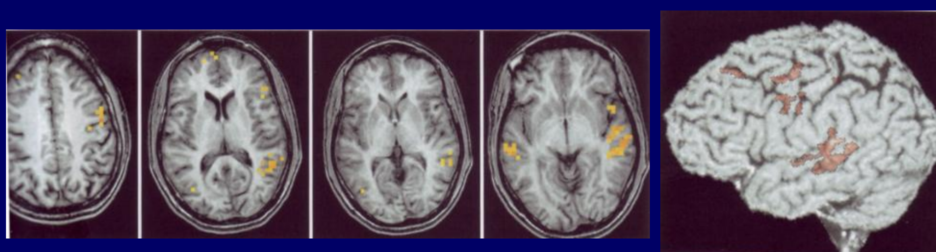
IRM fonctionnelle cérébrale



Cartographie d'activation des aires motrices primaires avant intervention chirurgicale: a) pied, b) épaule, c) main, d) face



Aires du langage

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INDICATIONS

Eléments anatomiques étudiés par l'IRM

Le cerveau et la moelle épinière : maladies neurologiques inflammatoires

Le rachis : hernie discale, lésions traumatiques du rachis et de la moelle…

Les viscères, les muscles, les articulations et les structures adjacentes

Les gros vaisseaux : sont étudiés pour le bilan de maladie athéromateuse, sténoses …

Les malformations artério-veineuse et cardiaques congénitales

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