MAGNETIC RESONANCE IMAGING PRINCIPLES

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Overview

1) Magnetism
2) Radio Frequency Signal
3) Relaxation

} NMR Physics

4) Gradients
5) How to Make an Image
6) k-space

} MRI Principles

NUCLEAR MAGNETIC RESONANCE

Nuclear Magnetic Resonance

- NMR relies on two properties of atomic nuclei: the magnetic moment and the spin that were introduced by Wolfgang Pauli in 1924.

- We can think in terms of classical physic that atoms are like spinning tops. These tops can spin at only given frequencies and exert particular magnetic forces (since they are a discrete quantum quantities)

Nuclear Magnetic Resonance

- Isidor Rabi (1938, Phys Rev 53) showed that when a magnetic field oscillates at the same frequency as some atomic nuclei, these ones absorb the energy from the field. This is called magnetic resonance.

- The frequency of the field should thus match the spin frequency, and this match corresponds to the resonance frequency. (1944 Nobel Prize in physics)

Nuclear Magnetic Resonance

- NMR was discovered independently by Felix Bloch *(1946, Physiol Rev, 70)* and Edward Purcell *(1946, Physiol Rev, 69).*

- They showed that atomic nuclei of bulk matter placed in a magnetic field absorb and re-emit radio waves, a phenomenon called nuclear induction or nuclear magnetic resonance. (1952 Nobel Prize in physics)

This phenomenon turned out to be very useful for studying physical, chemical, and biological properties of matter

1. MAGNETISM

NMR: Magnetism

- We have seen that atomic nuclei (protons + neutrons) have spins and magnetic moments

  - Outside a magnetic field, spins of nuclei are randomly oriented whereas inside a magnetic field, spins of nuclei tend to be aligned with the magnetic field

    - *Magnetic field strengths are measured in units of gauss (G) and Tesla (T).*
    - *1T= 10 000G*
    - *Earth's magnetic field = 0.5G (0.000005T)*

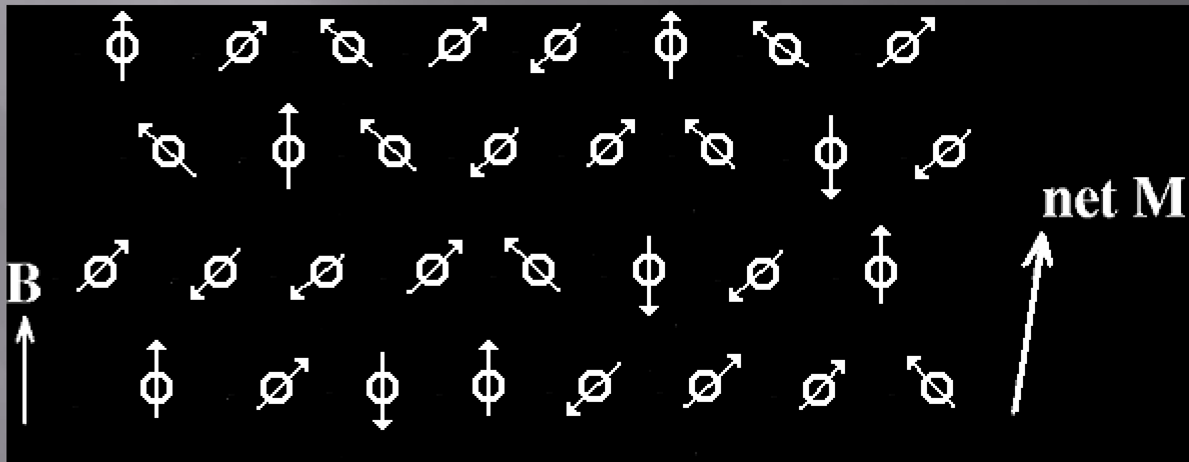
NMR: Magnetism

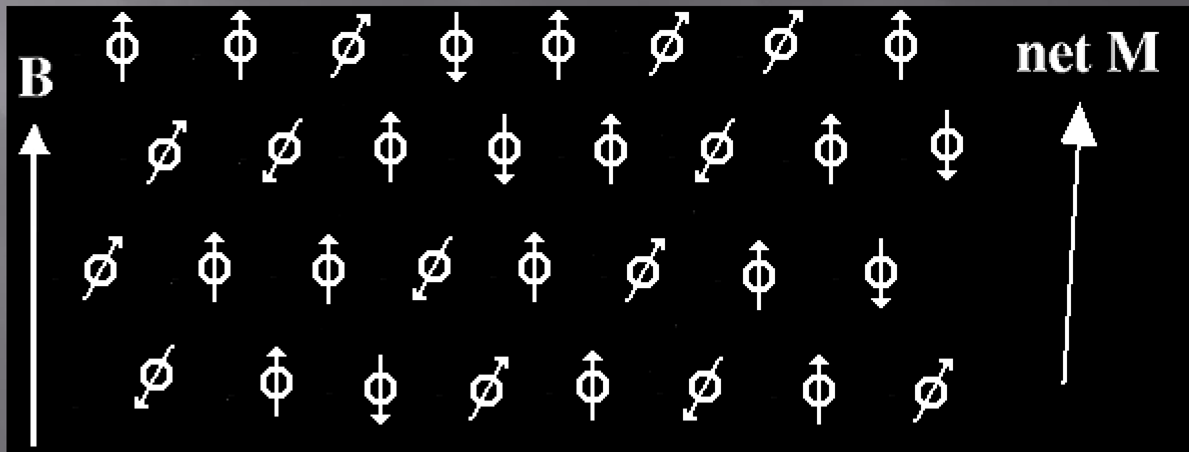
- For a magnetic field B_0, the alignment of spins corresponds to low and high energetic states of the nuclei (spins are said aligned or counter-aligned). If more nuclei are in the low energetic state than in the high one (or the other way round), it exists a net (macroscopic) magnetization M_0 for all the nuclei.

At 1.5T, for every one-million nuclei, there is about one extra spin aligned with the B_0 field!

NMR: Magnetism

Small B_0 produces small M_0 and large B_0 produces large M_0

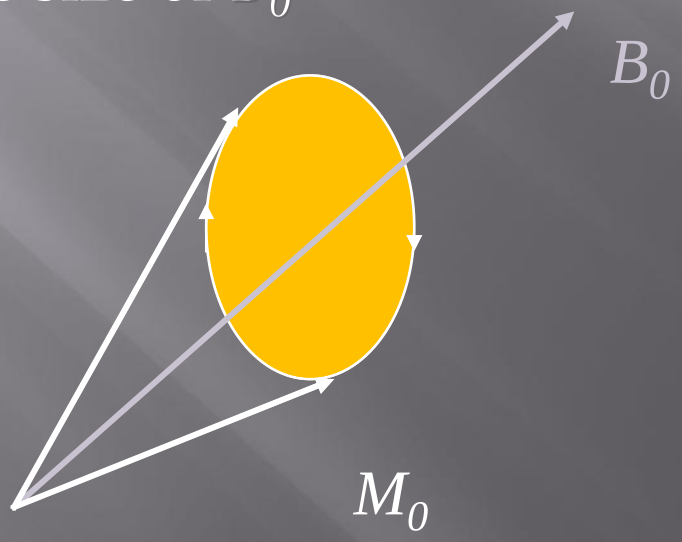




NMR: Magnetism

- In addition to the alignment of spins and the orientation of the magnetic moment, there also exists a rotation of M_0 around B_0 ,this is the precession

M_0 rotates (precesses) at a frequency ω, proportional to the size of B_0



$$\omega = \gamma . B_0$$

γ is the gyro-magnetic ratio which varies according to the type of nucleus (Larmor Frequency)

2. RADIO FREQUENCY SIGNAL

NMR: RF excitation

- Exposure of individual nuclei to RF radiation at the Larmor frequency ($\omega = \gamma . B_0$) causes:

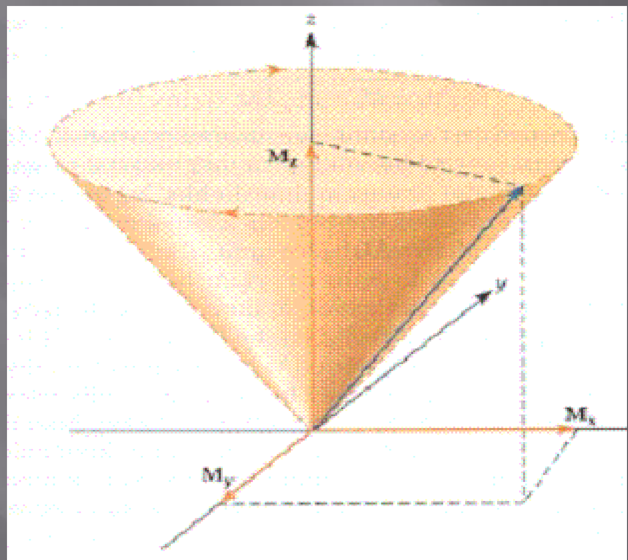
(i) some of the nuclei in the lower energy state to jump into the higher energy state and thus change their spins' alignment

(ii) precessions of the spins of excited nuclei to be in phase with each other

Note here that the state of the spins of the nuclei is a combination of the effects induced by the static magnetic field B_0 and the RF pulse.

NMR: RF excitation

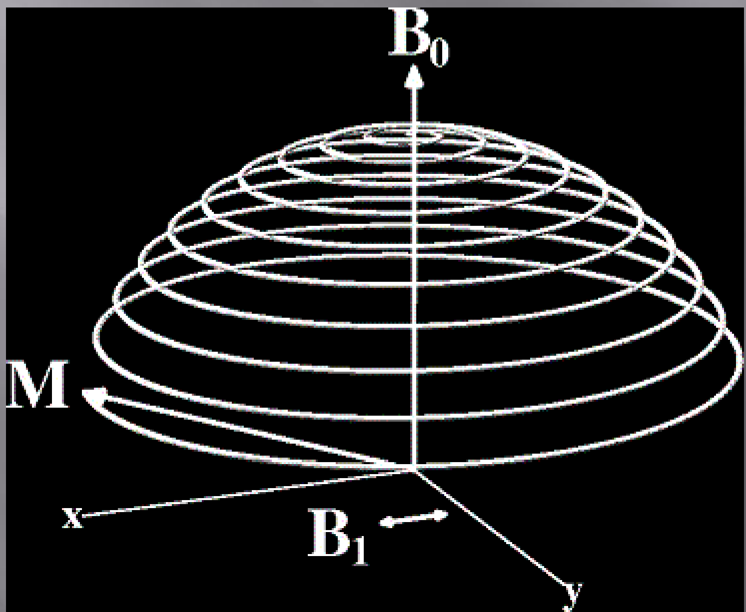
- To facilitates the description of *M*, it is usually characterized by a vector with *Mz*, the longitudinal component, aligned with B_0 and *Mxy*, the transversal component, that rotates around B_0



from Huettel et al. 2004 (p77)

NMR: RF excitation

- On a macroscopic level, RF exposure causes the net magnetization *M* to spiral away from the direction of the B_0 field.

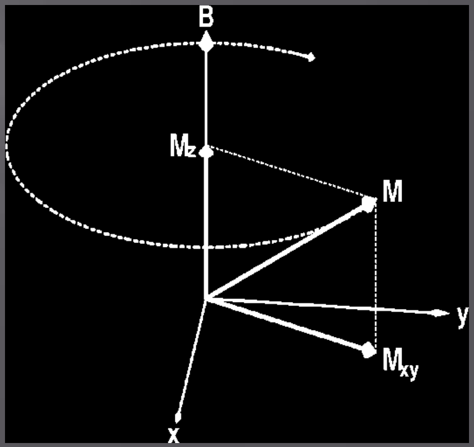


The RF pulse changes the number of nuclei at high and low energy states (*Mz* decreases) and puts spins in phase (*Mxy* increases).

NMR: RF excitation

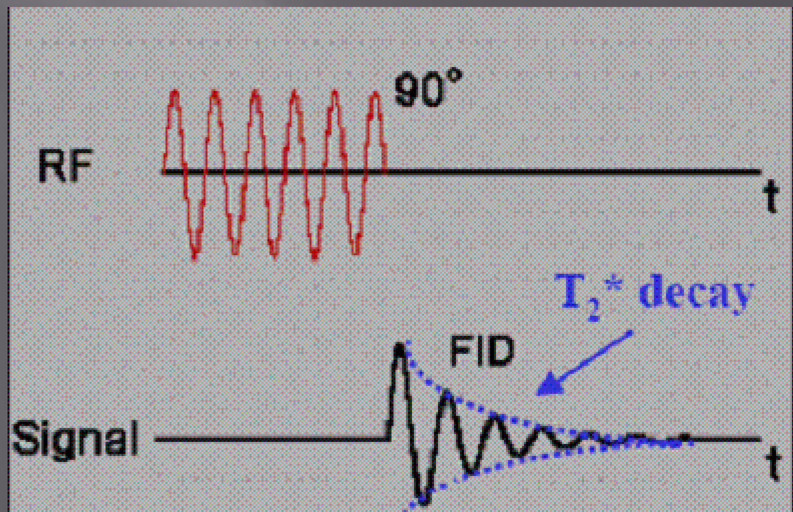
- In a rotating frame of reference (xyz), *M* rotates from a longitudinal position (*Mz* aligned with B_0) to an angle proportional to the length of time of the RF pulse. For example, after a certain length of time, *M* has rotated 90° and thus lies in the transverse or x-y plane.

- This angle of rotation is called the flip angle. Once flipped away from B_0, there is a component of the magnetization, *Mxy*, in the x-y plane which is detectable by an MRI receiver coil.



NMR: RF excitation

- After applying a RF pulse, *Mxy* is like a little magnet that rotates. It generates an oscillating voltage induced by magnetic field changes and is detected by a coil of wires placed around the subject, this is called magnetic *induction*. This voltage is the *RF signal* whose measurements form the raw data for MRI



Free induction decay

3. RELAXATION

NMR: Relaxation

- Relaxation is the process whereby nuclear magnetization returns to its initial state following a perturbation such as an RF pulse.

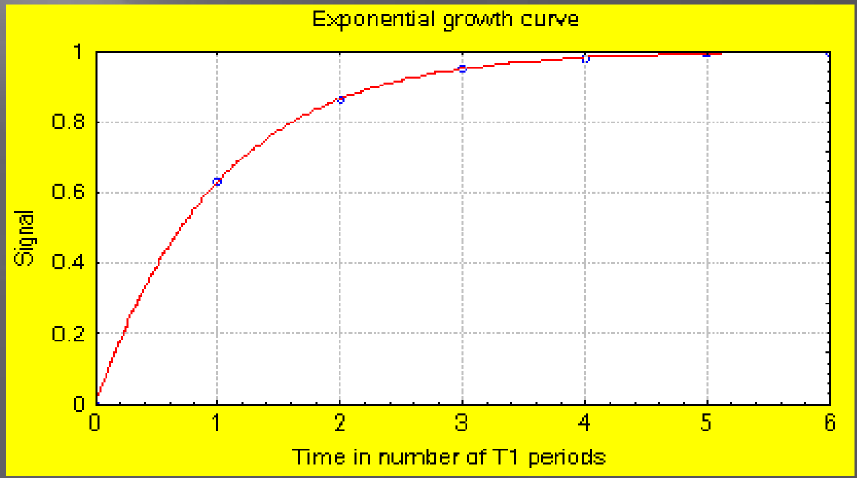
We distinguish:
T1 relaxation (Relaxation of M back to alignment with B_0 usually 500-1000 ms in the brain)

T2 relaxation (intrinsic decay of the transverse magnetization Mxy due to spins of nuclei getting out-of phase over a **microscopic** region (≈ 5-10 micron size - usually 50-100 ms in the brain)

NMR: Relaxation

- T1 relaxation: return of excited nuclei from the high energy state to the low energy state (*Mz* aligned with B_0). This loss of energy is spread to surrounding tissue (heating).

The T1 relaxation time is the time for the magnetization Mz to return to 63% of its original length. After two T1 times, the magnetization is at 86% of its original length. Three T1 times results in 95% recovery. Spins are considered completely relaxed after 3-5 T1 times.

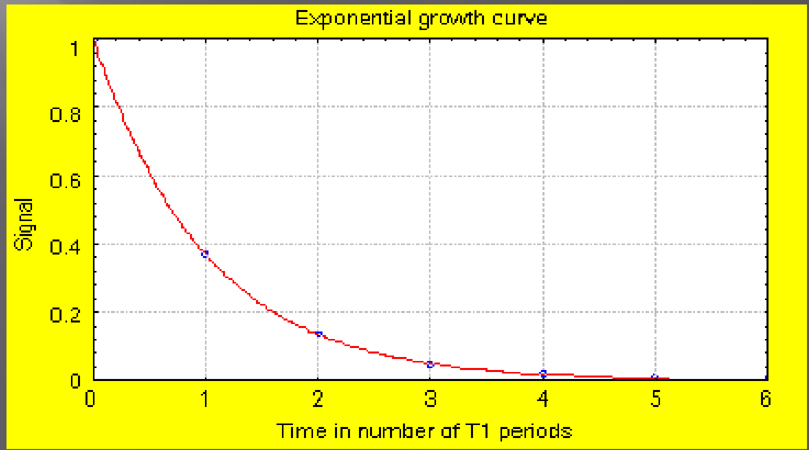


$$Mz = M_0\,(1 - e^{-t/T1})$$

NMR: Relaxation

- T2 relaxation: Microscopically, T2 relaxation occurs when spins of nuclei interact and thus get out-of phase. Macroscopically, this results in loss of the transverse magnetization *Mxy*.

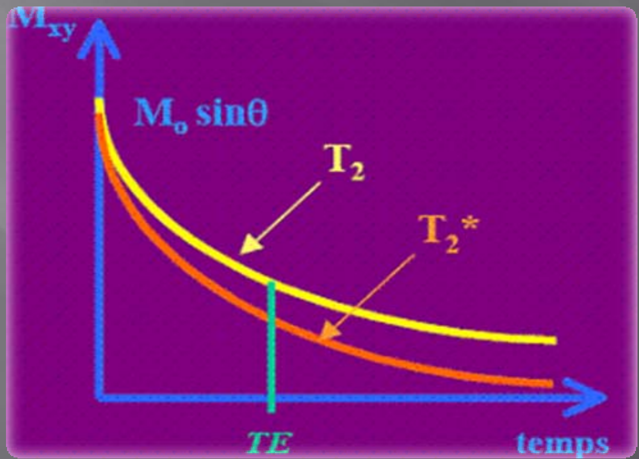
In pure water, the T2 and T1 times are approximately the same, 2-3 seconds. In biological materials (higher density than water = more interaction between spins), the T2 time is considerably shorter than the T1 time. For CSF, T1=1.9 sec and T2=0.25 sec. For white matter in the brain, T1=0.5 sec and T2=0.07 sec (70 msec).



$$Mxy = M_0 \, e^{-t/T2}$$

NMR: Relaxation

- T2* relaxation is the overall decay of the observable RF signal over a **macroscopic** region (millimeter size). It is related to the phase difference of the magnetizations between microscopic regions due to field inhomogeneity. Macroscopically, it is characterized by a loss of transverse magnetization at a rate greater than T2.

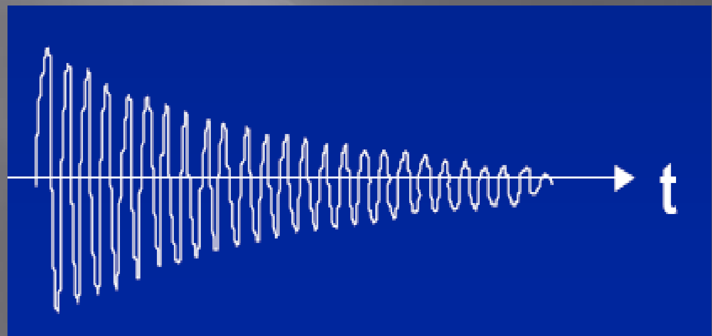


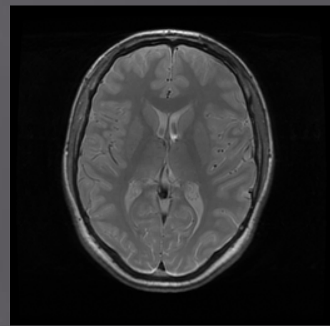
1. Because the parallel alignment of atoms' spin with B0 is energetically more favourable than the antiparallel state state, there is a net excess of spins aligned with B0 creating a net magnetization
2. The spins precess according to the Larmor frequency which depends on the gyromagnetic ratio of each type of atoms
3. When a RF pulse (B1) rotating synchronously with the processing spins is applied, the net magnetization rotates away from its equilibrium position (moves from aligned with B0 (z-axis) to perpendicular to B0 (xy-plane)) – this occurs for an RF equal to the Larmor frequency (magnetic resonance)
4. B1 equalizes the populations of spins in the two energy states (decrease of the magnetization along the z-axis) and also introduces phase coherences among spins.
5. The transverse magnetization (xy plane) decreases as magnetic moments move out of phase as a result of their mutual interaction. This is referred as relaxation. The different kind of relation processes (T1, T2, T2*) reflect different interactions of the spins with the environment or with other spins – the relaxation rates differ depending on the properties of the tissue which is the basis of image contrast.

MRI: MAKING IMAGES

MRI: making images

- We can only detect one dimensional signal, i.e. the total RF signal from the entire 3D volume inside the "RF coil" (the detecting antenna) .. How do we make an image from that?





  - 1st NMR experiment in 1945, 1st MRI Image in 1972
  - 2003 Physiology or Medicine Nobel prize: Lauterbur and Mansfield

MRI: making images

- 1. Put the subject into the magnet, within B0

  = alignment (parallel or anti-parallel) of protons' spins

- 2. Excite some protons (H+) in one part of the brain (RF pulse) = change in the alignment of a fraction of the protons' spins and creation of Mxy, i.e. smthg that can be measured

- 3. Receive the signal from the precessing protons' spins

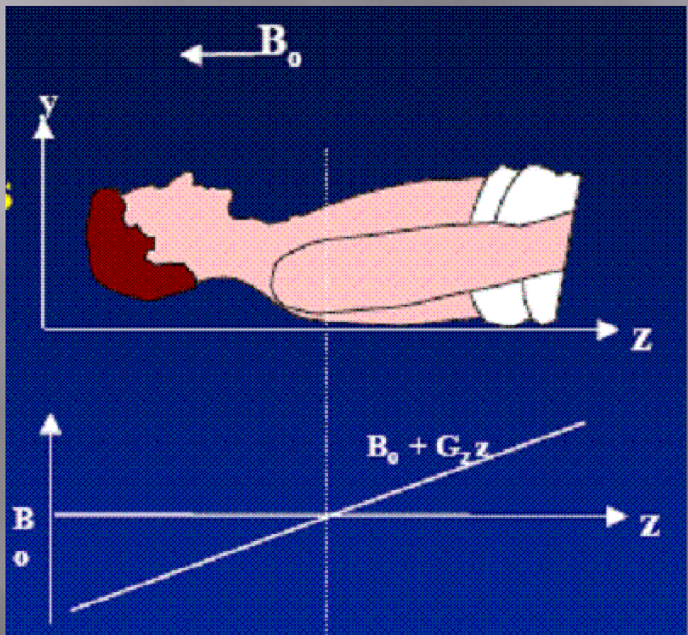
  = transform frequencies and phases into an image (and this is what all is about here!!)

  … but how since we have only 1 signal from the whole volume??

4. GRADIENTS

MRI: gradient fields

- The resonance frequency of protons at a given location depends on the value of the magnetic field applied at this location

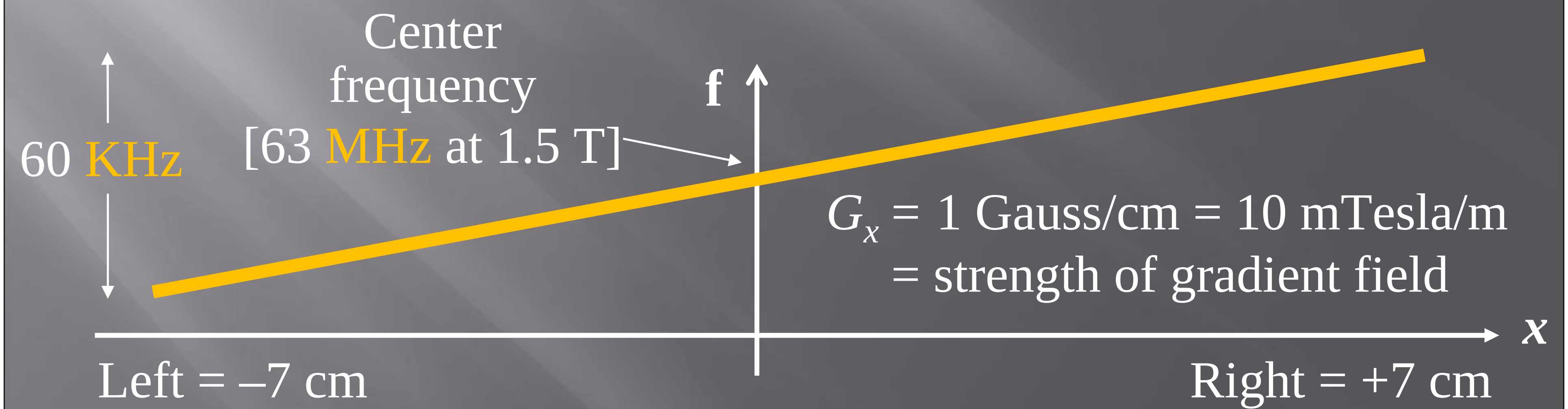


We can apply additional (very small) magnetic field changing over space to tune the frequency of protons

$\omega = \gamma.\ B_0 + G_z$

MRI: gradient fields

- Example of gradient field:
- The gradient field changes linearly its intensity across the subject space. Consequently, the precession frequency of protons varies across the space (= *frequency and phase encoding*).

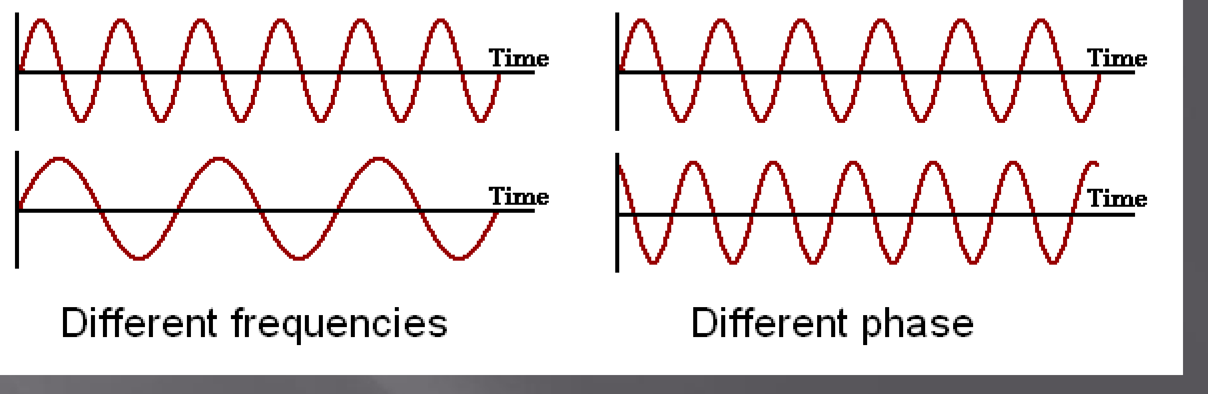


$$\omega = \gamma . B_0 + G_z$$

5. HOW TO MAKE AN IMAGE

MRI: encoding the signal

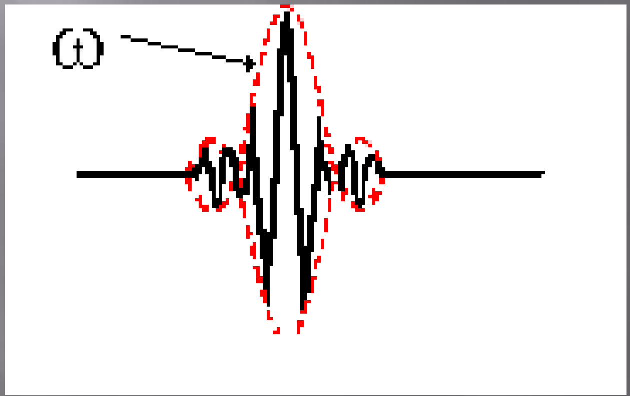
- ❶ Select one slice: modify *M* in only one thin (2D) slice using a gradient field Gz (perpendicular to the slice) and an RF pulse that corresponds to the resonance frequency of protons within that slice
  - ➔ The RF signal we detect must come from this slice
- ❷ Deliberately make magnetic field strength *B* depend on the (x,y) location within the slice (Gx & Gy)
  - ➔ Frequencies and phases in the measured signal will tell where it comes from



MRI: encoding the signal

➢ Slice selection

- We apply, in the same time, a Gradient along Z and an RF pulse. The slice selection results from their combination.
- Protons’ resonance frequencies vary along Z and thus an RF pulse at a given frequency will excite one part of the space along Z (= slice) only.



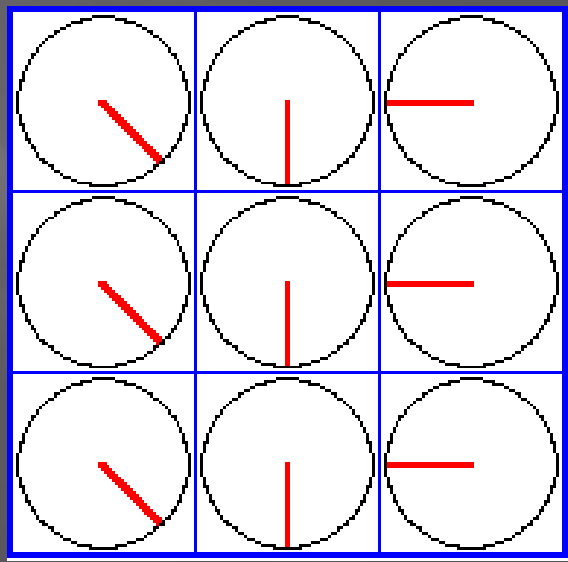
The width of the pulse (in frequency) will give the thickness of the slice (in space along Z)

MRI: encoding the signal

- *Phase encoding*

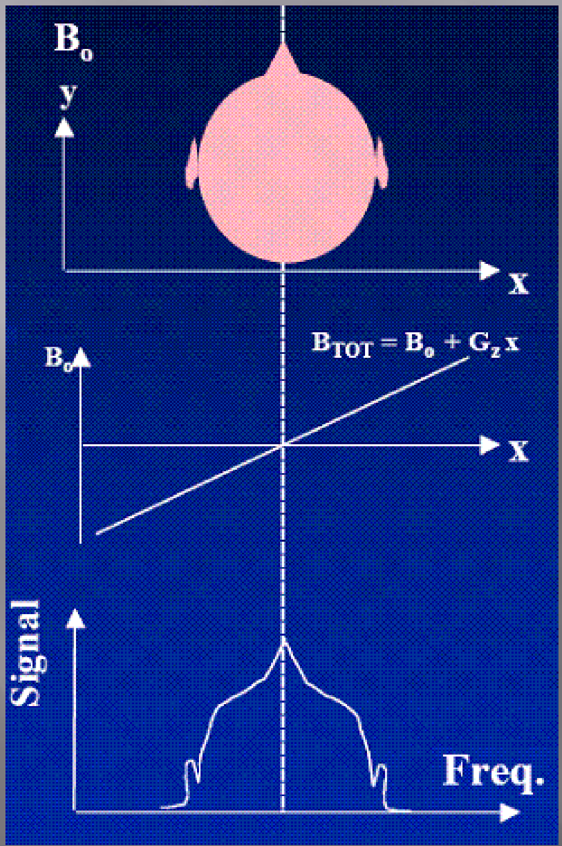
After the slice selection (RF pulse), we apply a gradient G along y for a short time.

This gradient, when on, modifies the precession frequency (Larmor frequency) along y. When Gy is switched off, the precession returns to the initial state (determined by B0 only). This creates phase difference along y that is used to code the location.



MRI: encoding the signal

➢ Frequency encoding



After the phase encoding, we record the signal.

During the recording, a gradient field Gx perpendicular to slice and phase gradients is turned on. Since frequency *f* varies across the space in a known way, we can assign each frequency to the location the signal comes from.

6. K-SPACE

MRI: receiving the signal

- What we receive is the sum of all the transverse magnetizations (Mxy) over a given volume.

$$S(t) = \iiint Mxy(x, y, z)\ dx\, dy\, dz$$

- Mxy precession depends on the gyromagnetic property of protons and B0 (Larmor frequency ω) and the gradients Gx Gy Gz. In addition, it depends on the T2 decay for the imaged material.

$$S(t) = \iiint Mxy(x, y, z) e^{-t/T2} e^{-i\omega 0t} e^{-i\gamma \int (Gx(t)x + Gy(t)y + Gz(t)z)dt}\ dx\, dy\, dz$$

(MR signal equation)

MRI: receiving the signal

- From this atrocious equation, we can remove:

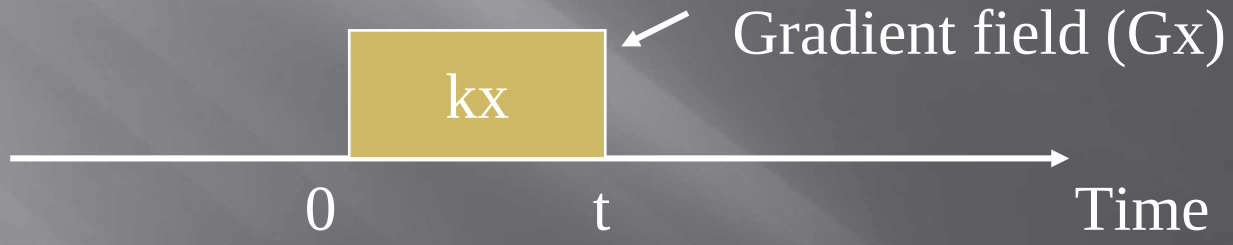
1) The components relative to Z as we decided to work only on a 2D slice (in this example)
2) The component relative to B0 as it is used for the initial alignment of spins 'only'. It is the gradients (that introduce phase and frequency differences) that code the location. Therefore the component relative to ω is removed
3) The T2 decay that affects signal amplitude but not location

$$S(t) = \int x \int y \, M(x, y) e^{-i\gamma \int (Gx(\tau)x + Gy(\tau)\ y) dt} \, dx \, dy$$

Effect of the gradient fields Gx and Gy

MRI: k-space

- The effect of gradient field can be simplified introducing the k-space; in this equation k is the time integral of the gradient field



  - The previous equation becomes

$$S(t)=\int x\int y\, M(x, y)e^{-i2\Pi kx(t)x}\, e^{-i2\Pi ky(t)y}\, dx\, dy$$

Time integral of the gradient in x and in y

MRI: k-space to image

$$S(t) = \int x \int y\, M(x, y) e^{-i2\Pi kx(t)x} e^{-i2\Pi ky(t)y}\, dx\, dy$$

- The equation is simplified by introducing the k-space because, at each pixel, the magnetisation M(x,y) can be solved easily (for a physicist) as it is a two dimensional Fourier transform.

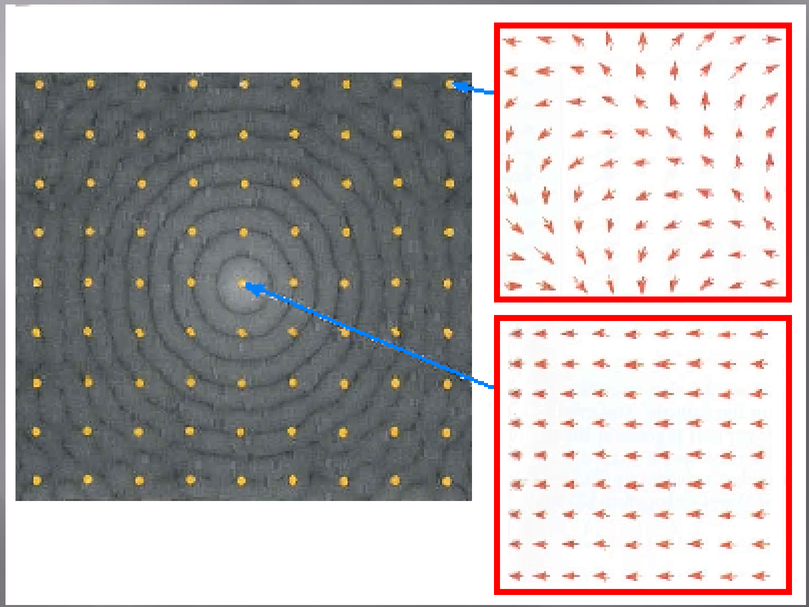
♦Fourier transform is a mathematical operation to move between time and frequency domains (1D) or between spatial (x,y) and spatial frequency domains (2D)

♦The recorded signal, S(t), is in the spatial frequency domain, and M(x,y) in the spatial domain

♦Therefore, a simple 2D inverse Fourier transform for S(t) will give us an MR image M(x,y)

MRI: Summary

- We use frequencies and phases for encoding the image and received S(t). Knowing the gradients we applied, we fill the k-space image (spatial frequency domain). The Fourier transform then gives us an image (spatial domain)

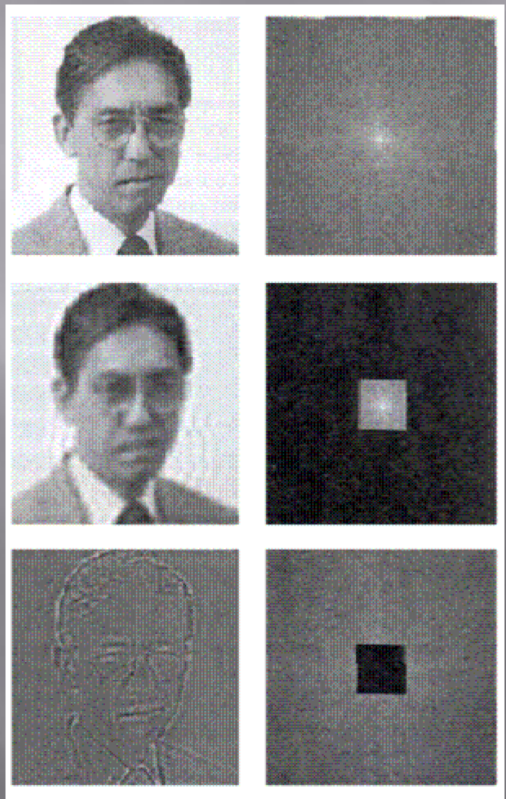


A k-space location (kx,ky) includes information from the whole image space. For instance, in the center of the k-space, magnetization vectors (= pixels) have the same orientation. Therefore, it gives the maximum signal.

Adapted from Huettel et al. 2004 (p87)

MRI: k-space to image, example

- Here Dr Ogawa in spatial domain vs spatial frequency domain (k-space)

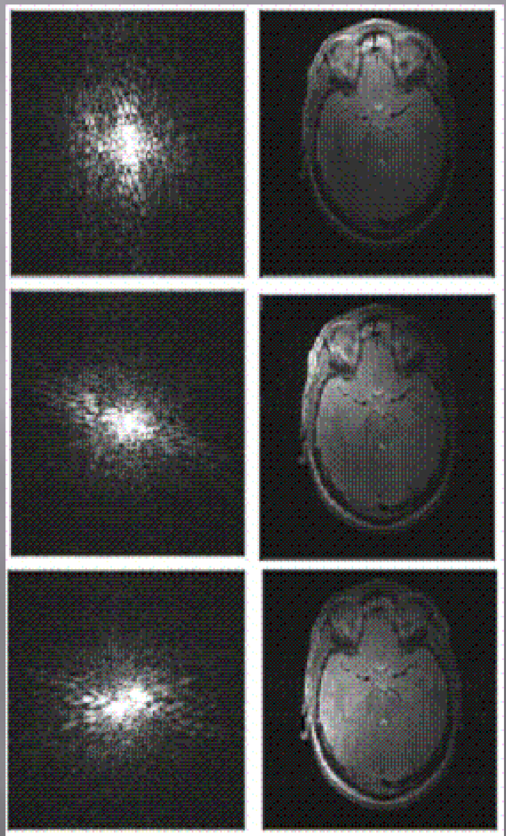


From Huettel et al. 2004 (p86)

- The center of the k-space provides low spatial frequency information (and we can see almost every thing) vs high spatial frequency encoded in periphery of the k-space

MRI: k-space to image, example

- Look at the brain in the K-space !!

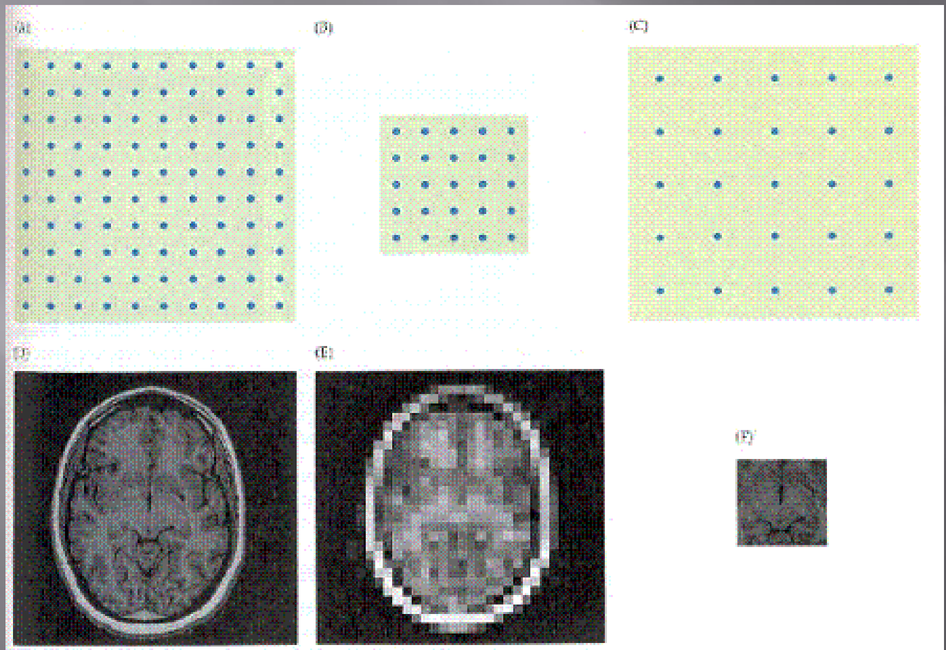


Data from AMI center (GE 3T), Low Temperature Lab, Helsinki

- Example from a multichannel head coil: Each channel samples the whole spatial domain but shows a higher SNR for the parts of the brain closest to the coil. The orientation in the image space is perpendicular to the orientation in k-space

MRI: k-space to image, example

- In MRI, the sampling and FOV of the k-space affects the quality of your images:

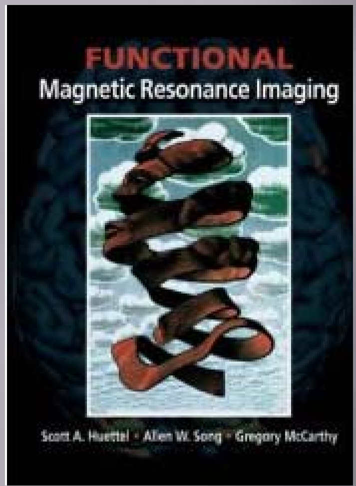


From Huettel et al. 2004 (p93)

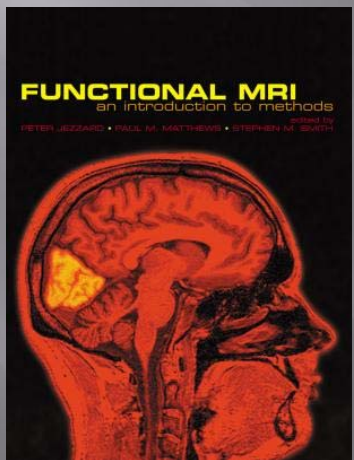
- ♦Small FOV in k-space = poor image resolution
- ♦Sparse sampling of k-space = small FOV in image space

References

Books



Huettel, Song and McCarthy. Functional Magnetic Resonance Imaging, Sinauer Associates



Jezzard, Matthews and Smith. Oxford University Press

- *Recommended Websites*

- *MRI physic*
  - http://www.cis.rit.edu/htbooks/mri/
  - http://www.mritutor.org/mritutor/
  - http://www.simplyphysics.com/
  - http://www.hull.ac.uk/mri/lectures/gpl_page.html
  - http://www.revisemri.com/

- *MRI safety issues*
  - http://www.mrisafety.com/