BME I5000: Biomedical Imaging

Lecture 8
Magnetic Resonance Imaging
(mostly NMR)

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Blackboard: **http://cityonline.ccny.cuny.edu/**

Schedul e

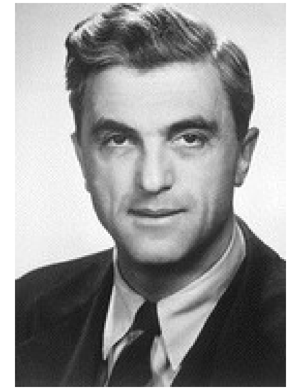
1. Introduction, Spatial Resolution, Intensity Resolution, Noise
2. X-Ray Imaging, Mammography, Angiography, Fluoroscopy
3. Intensity manipulations: Contrast Enhancement, Histogram Equalisation
4. Computed Tomography
5. Image Reconstruction, Radon & Fourier Transform, Filtered Back Projection
6. Nuclear Imaging, PET and SPECT
7. Maximum Likelihood Reconstruction
8. Magnetic Resonance Imaging
9. Fourier reconstruction, k-space, frequency and phase encoding
10. Optical imaging, Fluorescence, Microscopy, Confocal Imaging
11. Enhancement: Point Spread Function, Filtering, Sharpening, Wiener filter
12. Segmentation: Thresholding, Matched filter, Morphological operations
13. Pattern Recognition: Feature extraction, PCA, Wavelets
14. Pattern Recognition: Bayesian Inference, Linear classification

Biomedical Imaging

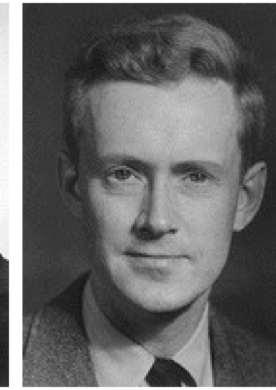
Imaging Modality	Year	Inventor	Wavelength Energy	Physical principle
X-Ray	1895	Röntgen (Nobel 191)	3-100 keV	Measures variable tissue absorption of X-Rays
Single Photon Emission Comp. Tomography (SPECT)	1963	Kuhl, Edwards	150 keV	Radioactive decay. Measures variable concentration of radioactive agent.
Positron Emission Tomography (PET)	1953	Brownell, Sweet	150 keV	SPECT with improved SNR due to increased number of useful events.
Computed Axial Tomography (CAT)	**1972**	**Hounsfield, Cormack (Nobel 1979)**	**keV**	**Multiple axial X-Ray views to obtain 3D volume of absorption.**
Magnetic Resonance Imaging (MRI)	1973	Lauterbur, Mansfield (Nobel 2003)	GHz	Space and tissue dependent resonance frequency of kern spin in variable magnetic field.
Ultrasound	1940-1955	many	MHz	Measures echo of sound at tissue boundaries.

MRI - History

Nuclear Magnetic Resonance (NMR)
Felix Block and Edward Purcell
1946: atomic nuclei absorb and re-emit radio frequency energy in an external magnetic field
1952: Nobel prize in physics
1971: NMR Tumor detection (Damadian)

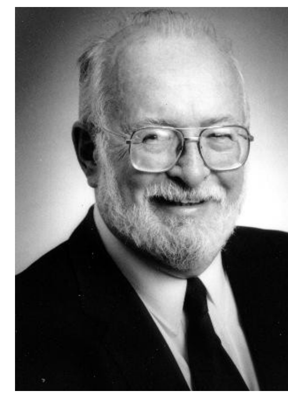


Bloch



Purcell

Magnetic Resonance Imaging (MRI)
1973: Lauterbur suggests NMR could be used to form images
1977: clinical MRI scanner patented
1977: Mansfield proposes echo-planar imaging (EPI) to acquire images faster
2003: Nobel Price in Medicine



Lauterbur

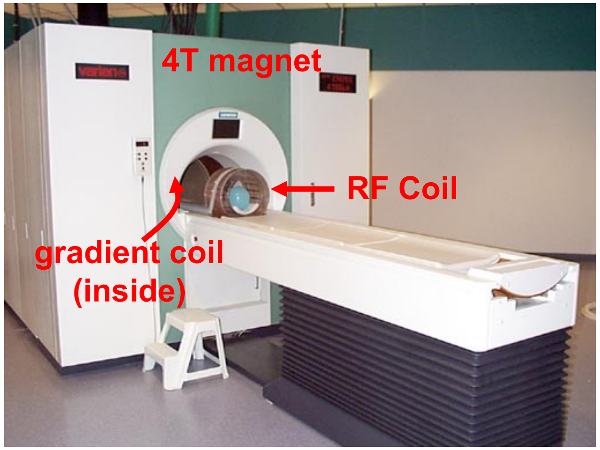
Mansfield

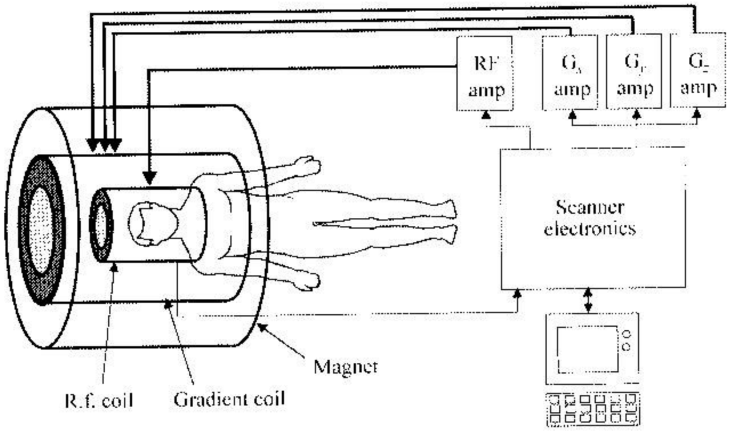
Functional MRI (fMRI)
1990: Ogawa observes BOLD effect with T2*: blood vessels became more visible as blood oxygen decreased
1991: Belliveau observes first functional images using a contrast agent
1992: Ogawa et al. and Kwong et al. publish first functional images using BOLD signal

Ogawa

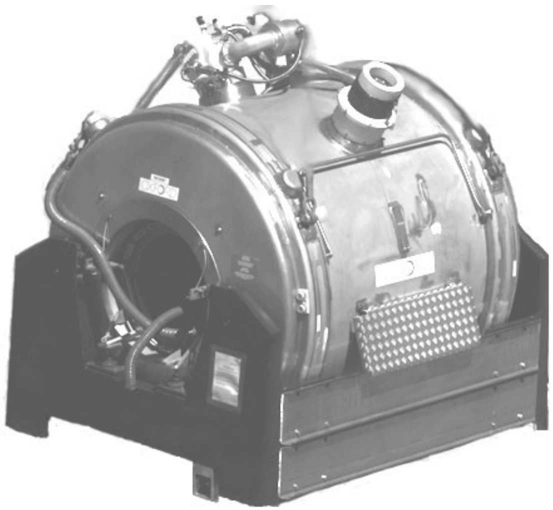
Adapted from Jody Culham, http://defiant.ssc.uwo.ca/Jody_web/fmri4dummies.htm

MRI - Equipment



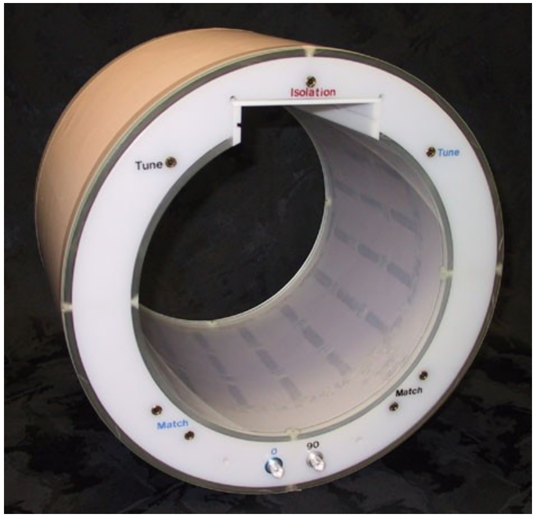


Magnet



Gradient Coil

RF Coil



Source: Joe Gati, photos

Adapted from Jody Culham, http://defiant.ssc.uwo.ca/Jody_web/fmri4dummies.htm

MRI – Basic Recipe

→ 1) Put subject in big magnetic field

When protons are placed in a constant magnetic field, they precess at a frequency proportional to the strength of the magnetic field (at typical radio frequencies). They also align somewhat to generate a bulk magnetization.

2) Transmit radio waves into subject [about 3 ms]

Exposure to radio frequency magnetic field will synchronize this precession.

3) Turn off radio wave transmitter

The coherent precession continues but decays slowly due to interactions with magnetic moments of surrounding atoms and molecules (tissue dependent!)

4) Receive radio waves re-transmitted by subject [10-110ms]

The coherent precession (oscillation) generates a current in an inductive coil. The detected signal is called magnetic nuclear resonance.

5) Store measured radio wave data vs. time

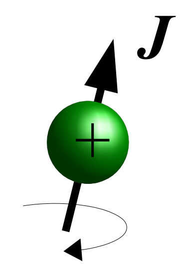
Now go back to 2) to get some more data with different magnetic fields and radio frequencies. (here lies the Art of MRI!)

6) Process raw data to reconstruct images

Source: Robert Cox's web site

MRI – Nuclear Spin

Nucleus has a quantum mechanical property called "spin" quantized by I. (I=1/2 for a proton in H_2O). Spin can be thought of as a spinning mass with an angular momentum $\boldsymbol{J}$.



$$|\boldsymbol{J}| = \frac{h}{2\pi}\sqrt{I^2 + I}$$

Since the particle is electrically charged this spinning will generate a magnetic moment $\boldsymbol{\mu}$:

$$\mu = \gamma \boldsymbol{J}$$

The gyromagnetic ratio γ is specific to each nucleus.

As we will see the magnetic fields and radio frequency (RF) are tuned to a specific value of γ, i.e. to a specific nucleus.

MRI – Nuclear Spin

Properties on nuclei found at high abundance in the body:

Nucleus	Atomic Number	Atomic Mass		$\gamma/2\pi$(MHz/T)	MRI Signal
Proton, ^{1}H	1	1	½	42.58	yes
Phosphorus, ^{31}P	15	31	½	17.24	yes
Carbon, ^{12}C	6	12	0		no
Oxygen, ^{16}O	8	16	0		no
Sodium, ^{23}Na	11	23	3/2	11.26	yes

MRI can be performed with odd odd atomic mass (non-zero spin)

^{1}H, ^{13}C, ^{19}F, ^{23}Na, ^{31}P

Most frequent medical imaging is performed with ^{1}H (proton)

abundant: high concentration in human body

high sensitivity: yields large signals

1.5T magnet uses RF at 3.87 MHz for proton imaging.

MRI – Big Magnet

Very strong

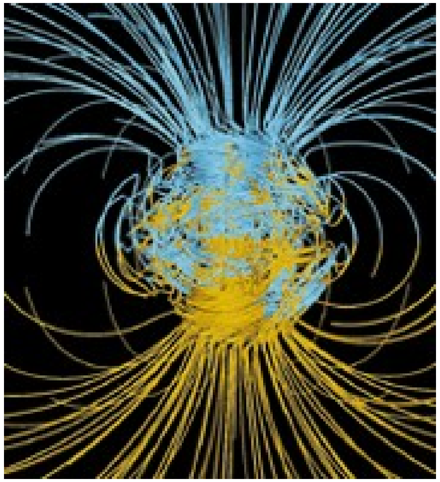
1 Tesla (T) = 10,000 Gauss

Earth's magnetic field = 0.5 Gauss

4 Tesla = 4 x 10,000 ÷ 0.5 = 80,000X Earth's magnetic field

Continuously on

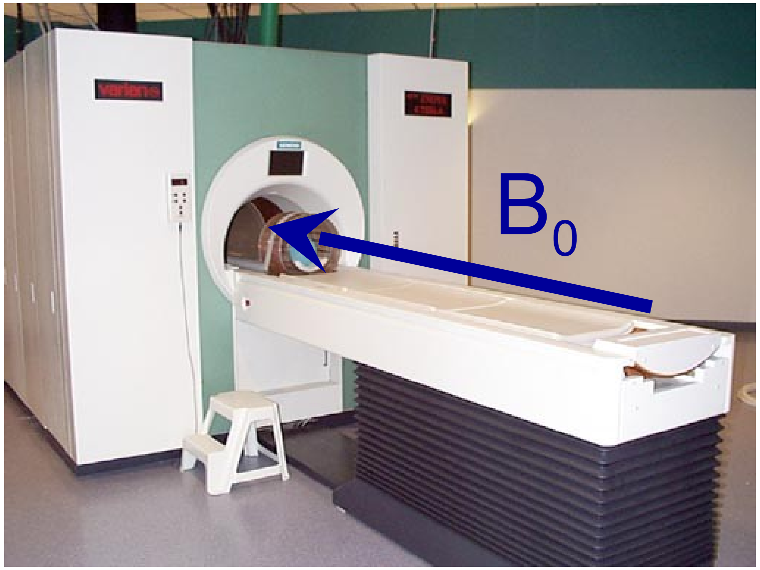
Main field = B_0



Source: www.spacedaily.com

x 80,000 =

Robarts Research Institute 4T

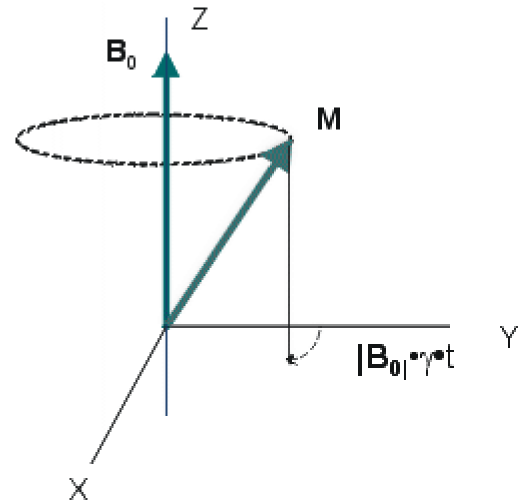


Adapted from Jody Culham, http://defiant.ssc.uwo.ca/Jody_web/fmri4dummies.htm

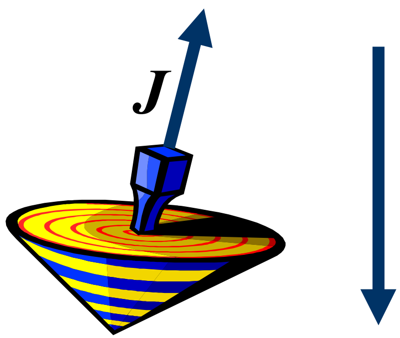
MRI – Nuclear Spin in Magnetic Field

When a spin is placed in a homogeneous external magnetic field B_0 it precesses at a frequency ω_0.

$$\omega_0 = \gamma B_0$$



The effect is analogous to a spinning mass in a gravitational field:



Quantum mechanics however dictates that the valued for the z-orientation of J (and μ) can only be:

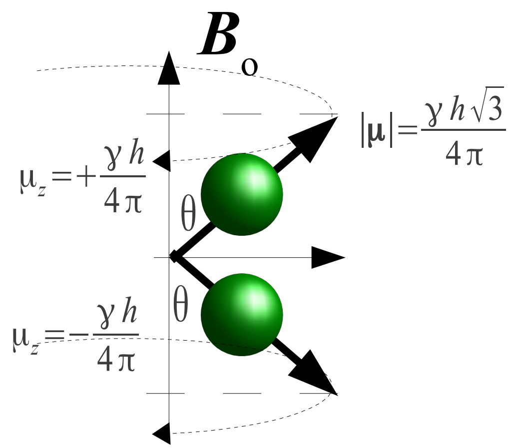
$$\mu_z = \gamma J_z = \frac{\gamma h}{2\pi} m_I$$

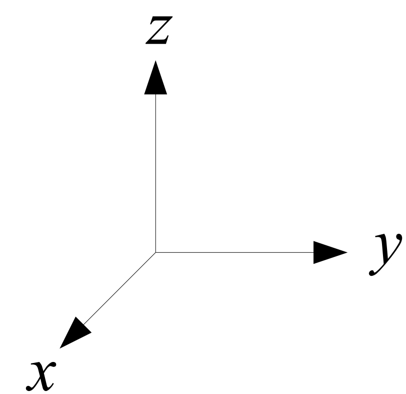
with m = ±½ for I = ½.

graphic from http://www.ecf.utoronto.ca/apsc/courses/bme595f/notes/

MRI – Nuclear Spin in Magnetic Field

Given the quantization of $|\mu|$ and μ_z the spin can only be at angles $\Theta = \pm 54.7^o$ with external field B_o:





These are called "parallel" and "anti-parallel" states. They have different energy levels.

$$E = \mp \mu_z B_o = \mp \frac{\gamma h B_0}{4\pi}$$

MRI – Bulk Magnetization

In a macroscopic sample with many nuclei the number of nuclei with “parallel” or “anti-parallel” spin configuration is given by the Boltzman distribution:

$$\frac{N_p}{N_a}=\exp\left(-\frac{\Delta E}{kT}\right)=\exp\left(+\frac{\gamma h B_0}{2\pi k T}\right)\approx 1+\frac{\gamma h B_0}{2\pi k T}$$

For a 1.5T field we find that in 1 million protons there are only 5 more parallel than anti-parallel spins.

This small difference however is enough to generate a macroscopic or “bulk” magnetization in the *z*-direction

$$M_0=\sum_{n=1}^{N}\mu_{z,n}=\frac{\gamma h}{2\pi}\left(N_p-N_a\right)=\frac{\gamma^2 h^2 N}{16\pi^2 k T}B_0 \quad \propto B_0$$

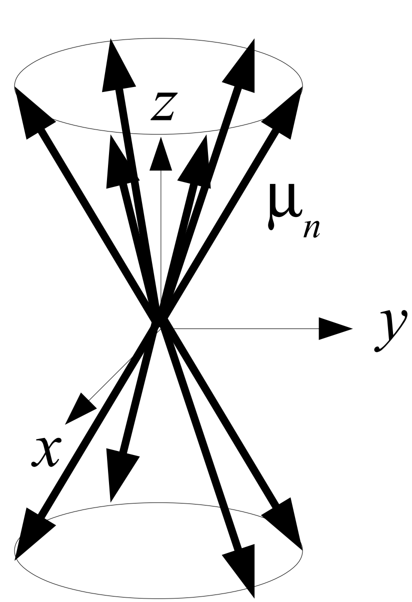
N is the total number of nuclei.

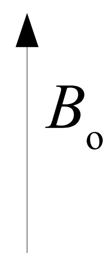
MRI – Bulk Magnetization

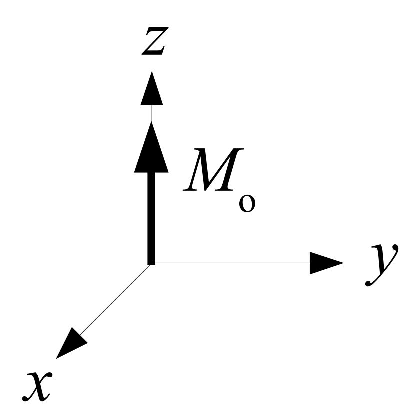
The small excess number of "parallel" spins generates bulk magnetization M_o in the z-direction.

The strength is proportional to the external magnetic field B_0.

The spins in transverse direction (x and y axis) do not add coherently as the spins precess out of phase.







$$M_z = M_o$$
$$M_x = 0$$
$$M_y = 0$$

$$\boldsymbol{M} = [M_x, M_y, M_z]$$

The effect of bulk magnetization $\boldsymbol{M}$ is equivalent to that of summed effect of individual spins. (but often easier to think about)

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Now go back to 2) to get some more data with different magnetic fields and radio frequencies. (here lies the Art of MRI!)

6) Process raw data to reconstruct images

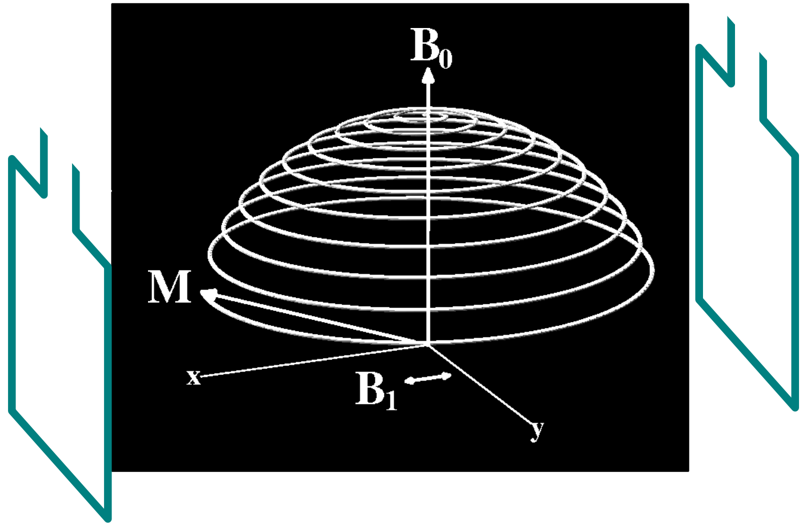
Source: Robert Cox's web site

MRI – RF pulse

If we apply in addition to B_0 a field component B_1 (<<B_0) in the x-direction ***oscillating at frequency ω_0*** the trajectory for ***M*** will be:

$$B_x(t) = B_1 \sin(\omega_0 t)$$

emitting RF coil

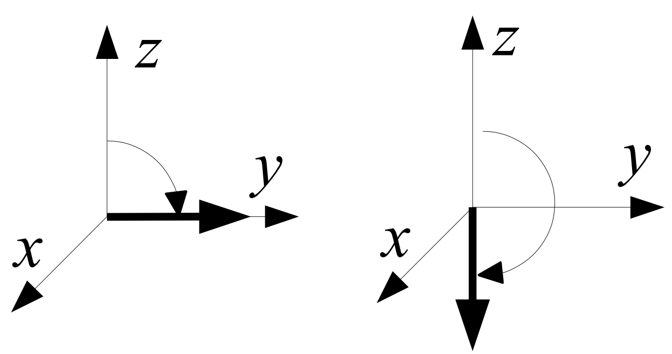


This time varying B_1 field is applied for a short time (few ms) with an RF coil at the x-axis. The final "flip" angle depends on the length of this RF pulse and the strength of B_1.

Useful flip angles are:

$\alpha = 90^o$ M_z is converted into M_y

$\alpha = 180^o$ M_z is converted into $-M_z$



MRI – RF pulse

The Swing Analogy:

Oscillating spins generate bulk magnetization M_z lined up with B_0:
A bunch of kids are swinging at different swings, all with the same frequency but out of phase. The average weight of the kids is straight down from the pole – it is "aligned" with external gravity.

RF pulse (oscillating B_1) generates transverse M_x, M_y oscillation:
If parents push a little bit on every swing , in synchrony, and at the natural frequency of the swings, soon all kids are swinging together in phase. The average weight of the kids is now oscillating back and forth, i.e. there is now a oscillating transverse component.

How well they are lined up at the end depends on how often and how strong they were pushed.
Note that if the parents pushed at a frequency other than the natural frequency of the swings their effort would not amount to much.

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Source: Robert Cox's web site

MRI – RF pulse

Now a oscillating B1 field perpendicular to B0 will be applied at resonant (precession) frequency ω_0

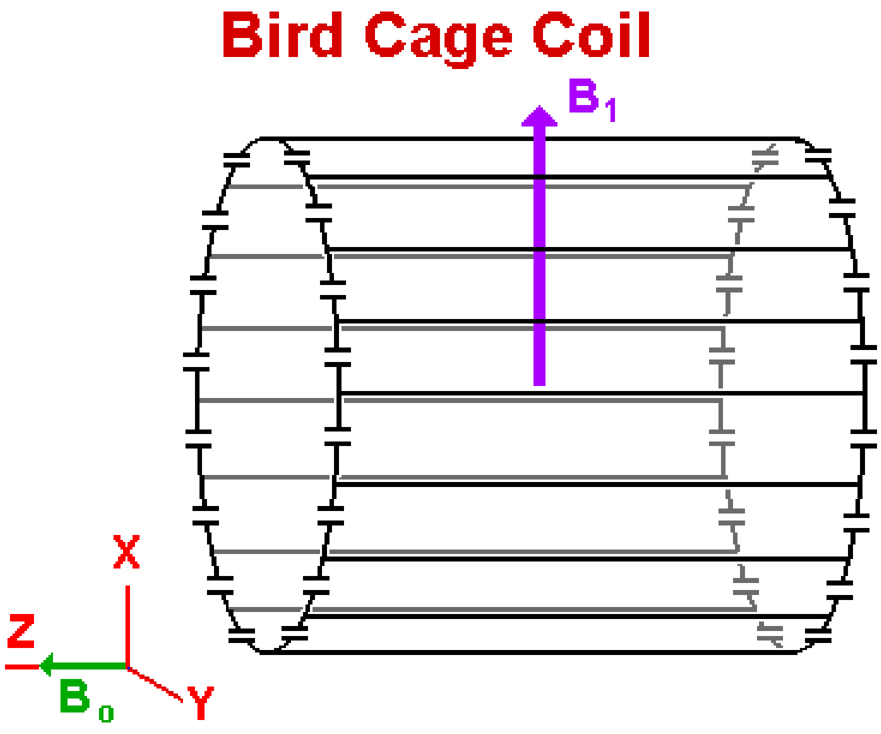


Image courtesy: Jeff Hornak

MRI – Bulk Magnetization, Bloch Equation

The bulk magnetization $\boldsymbol{M} = [M_x, M_y, M_z]$ in an external magnetic field $\boldsymbol{B} = [B_x, B_y, B_z]$ is governed by the Bloch equations

$$\frac{d\boldsymbol{M}}{dt} = \boldsymbol{M} \times \boldsymbol{B} - \frac{1}{T_2}\begin{bmatrix} M_x \\ M_y \\ 0 \end{bmatrix} - \frac{1}{T_1}\begin{bmatrix} 0 \\ 0 \\ M_z - M_0 \end{bmatrix}$$

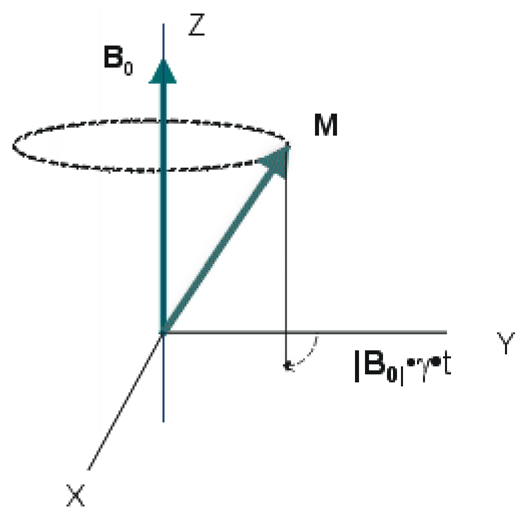
- The fist term is the same as the equation of motion for a single spin and leads again to a precession.
- The second term governs the transverse magnetization M_x and M_y. It leads to an exponential decay with time constant T_2.
- The third term governs the longitudinal magnetization M_z. It leads to a exponential relaxation towards the equilibrium magnetization M_o with time constant T_1.

MRI – Bloch Equation

If we consider time t much shorter than T_1 and T_2 we can just look at the first term.

$$\frac{d\boldsymbol{M}}{dt} = \boldsymbol{M} \times \boldsymbol{B} - \frac{1}{T_2}\begin{bmatrix} M_x \\ M_y \\ 0 \end{bmatrix} - \frac{1}{T_1}\begin{bmatrix} 0 \\ 0 \\ M_z - M_0 \end{bmatrix}$$

This is the same equation of motion as for a single spin. It describes a precession at frequency $\omega = \gamma|\boldsymbol{B}|$ around the orientation of vector $\boldsymbol{B}$. For a constant field $B_z = B_0$ the precession of the $\boldsymbol{M}$ vector is at $\boldsymbol{\omega}_0$.



Note however that the $\boldsymbol{M}$ vector can now take on any angle.

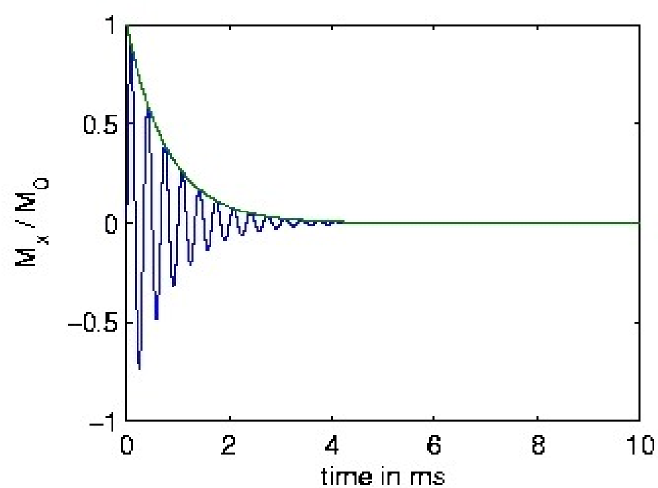
MRI – Free Precession - T_2 decay

After the RF pulse the system is left only with B_0. Any contribution in the transverse direction will precess around B_0 at ω_0. Lets now consider the second term:

$$\frac{d\boldsymbol{M}}{dt} = \boldsymbol{M} \times \boldsymbol{B} - \frac{1}{T_2}\begin{bmatrix} M_x \\ M_y \\ 0 \end{bmatrix} - \frac{1}{T_1}\begin{bmatrix} 0 \\ 0 \\ M_z - M_0 \end{bmatrix}$$

This term indicates that M_x, M_y will decay exponentially with a time constant T_2. Together with the precession this gives a damped oscillation, e.g. after a 90° pulse:

$$\begin{bmatrix} M_x \\ M_y \end{bmatrix}(t) = M_0 e^{-\frac{t}{T_2}} \begin{bmatrix} \sin(-\omega_0 t) \\ \cos(-\omega_0 t) \end{bmatrix}$$

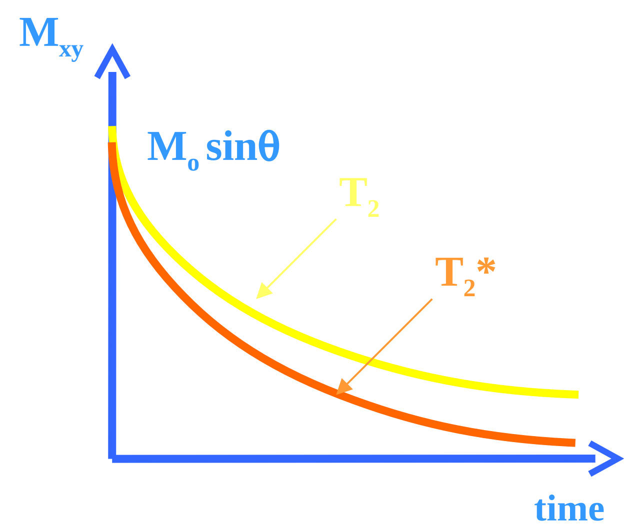


MRI – Free Precession - T_2 decay

The reason for this decay process is that each spins each see a slightly different local field around them. Each then oscillates at a slightly different frequency. The spins will be therefore quickly out of step, and the bulk transverse magnetization will disappear.

The local magnetic fields are not the same because:

1. Each spin sees the magnetic field generated by other spins in the molecule. Quantified with T_2. ("spin-spin relaxation")
2. The field B_0 is not perfectly homogeneous. Quantified with T_2^+ and about 100 shorter than T_2.



Total effect is T_2^*:

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_2^+}$$

T_2^* dominated by T_2^+ and is just a few ms.

MRI – Free Precession - T_1 relaxation

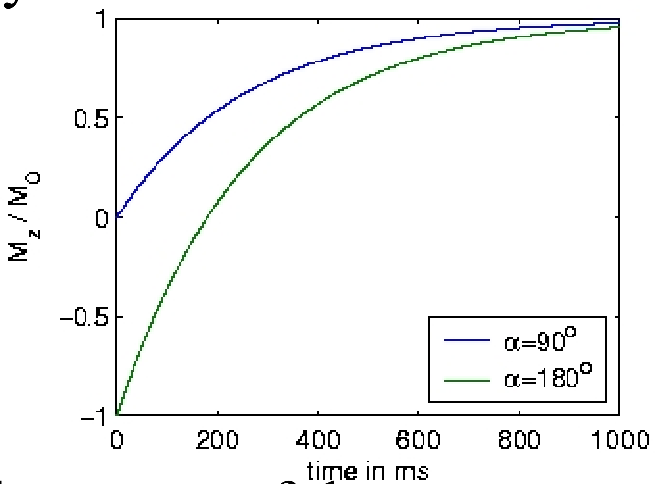
The third term in the Block equation describes the relaxation of the longitudinal magnetization M_z:

$$\frac{d\boldsymbol{M}}{dt} = \boldsymbol{M} \times \boldsymbol{B} - \frac{1}{T_2}\begin{bmatrix} M_x \\ M_y \\ 0 \end{bmatrix} - \frac{1}{T_1}\begin{bmatrix} 0 \\ 0 \\ M_z - M_0 \end{bmatrix}$$

This is a exponential relaxation back to the equilibrium value M_0, e.g. after a 90° pulse and a 180° respectively:

$$M_z(t) = M_0\left(1 - e^{-\frac{t}{T_1}}\right)$$

$$M_z(t) = M_0\left(2 - e^{-\frac{t}{T_1}}\right)$$



This exponential recovery represents the return of the system to its equilibrium condition M_z=M_0, whereby the spins loosing energy to the surrounding latice (“spin-latice relaxation”)

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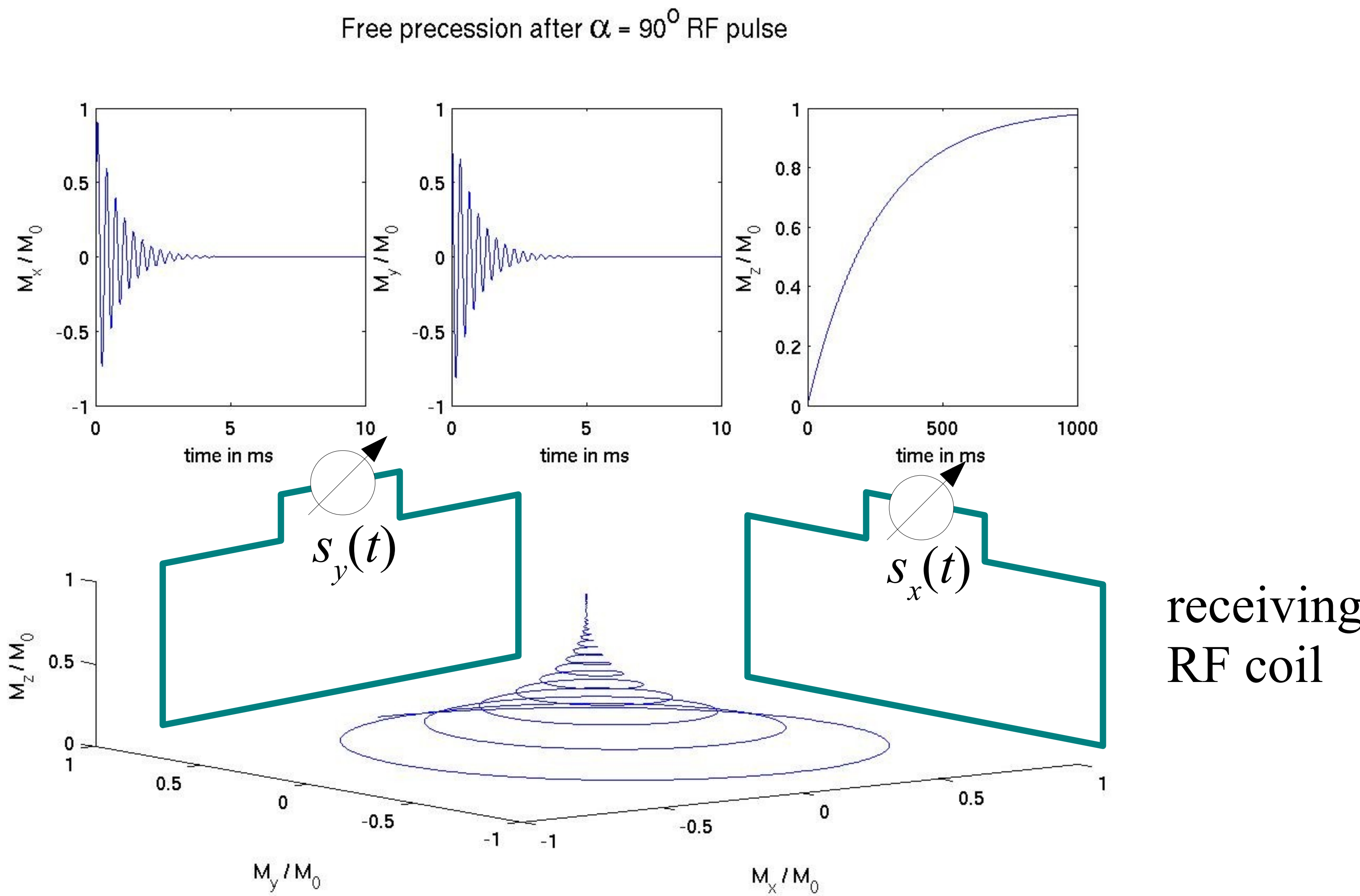
Source: Robert Cox's web site

MRI – Free Precession

The overall free precession of the bulk magnetization ***M*** after RF pulse of $\alpha=90^o$ is then



MRI – Free Induction Decay

This precessing magnetization can be measured inductively with an receiver coil tuned to the resonant frequency ($\boldsymbol{\omega}_0$=3.87 MHz for ^{1}H). The detected signal is called the **Free Induction Decay** (FID). If we detect it in with a coil in *x* and *y* axis we can construct a complex variable

$$s(t) = s_x(t) + i s_y(t) \propto M_x(t) + i M_y(t) = M_{xy}(0) e^{-t/T_2^*} e^{-i\omega_0 t}$$

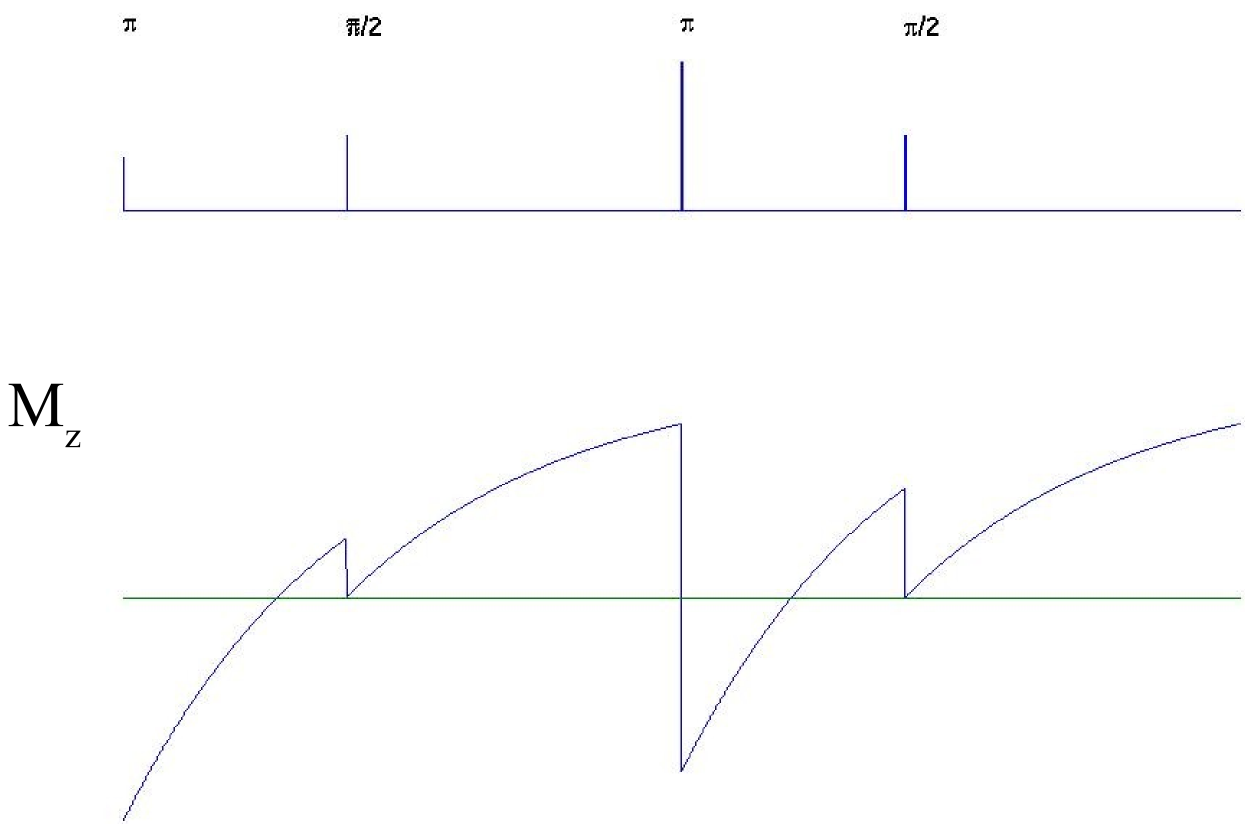
$M_{xy}(0)$ denotes here the magnitude of the M_x, M_y at the end of the RF pulse, i.e. at t=0 of the free precession. Its value is dependent of the specific pulse sequence and is affected typically by the decay times T_1 and T_2.

By modifying the RF pulses and measuring the magnitude of $s(t)$ one can make estimate the decay times T_1 and T_2.

MRI – Pulse sequences to estimate T1, T2

T1 - Inversion recovery sequence

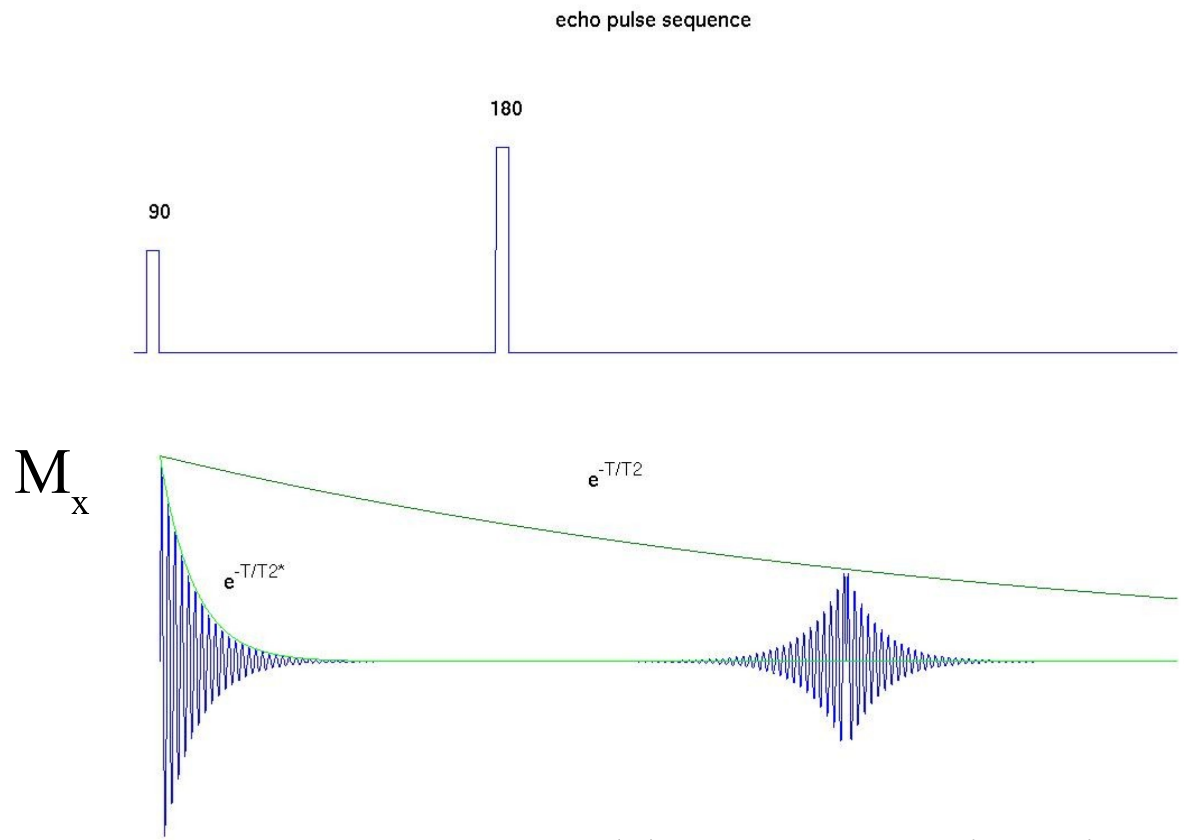
$180^o - \tau - 90^o$: the detected signal magnitude is $\propto 2 - \exp\left(-\frac{\tau}{T_1}\right)$



MRI – Pulse sequences to estimate T1, T2

T2 – Echo pulse sequence

90^o – τ – 180^o: the detected signal magnitude is $\propto \exp\left(-\frac{\tau}{T_2}\right)$



Assignment 8: Generate graphics representing the pulse sequence and FID for inversion recovery and echo pulse.

MRI – Nuclear Magnetic Resonance (NMR)

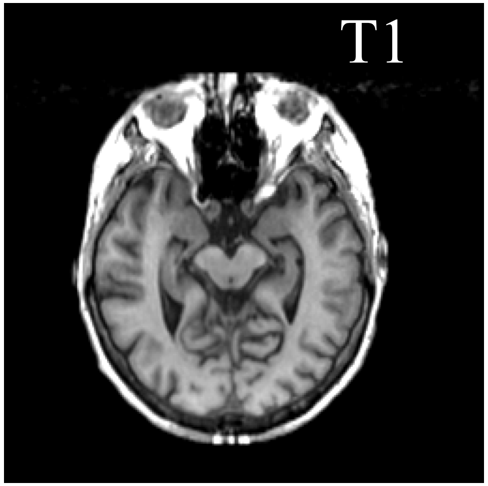
The decay constants T_1 and T_2 depend on physical properties of the resonating sample. By measuring the decay constants one can therefore deduce what is in the sample.

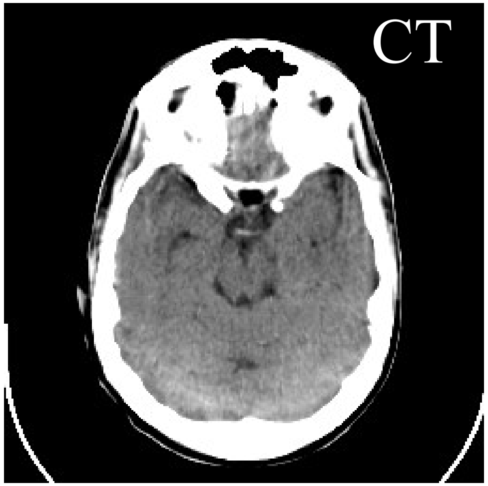
In the 70' is was realized that this may used for medical applications (Damadian)

Tissue	T1 (ms)	T2 (ms)
Fat	260	80
Muscle	870	45
Brain (gray matter)	900	100
Brain (white matter)	780	90
Liver	500	40
Cerebrospinal fluid	2400	160

MRI – T1 and T2 images

Tissue	MR-T1	MR-T2	CT
Bone	dark	dark	bright
Air	dark	dark	dark
Fat	bright	bright	dark
Water	dark	bright	dark
Brain	anatomic	intermediate	intermediate





Adapted from http://www.ecf.utoronto.ca/apsc/courses/bme595f/notes/

MRI – How to convert NMR into imaging?

But wait!

How can one generate images?

So far NMR only gives information on the entire sample which is resonating at one frequency ω_0 within the B_0 field.

Answer (Lauterbur 1973): Change the B_0 field with space and the resonance frequency will change with space. Resonating signal contains multiple frequency components each giving information about a different portion of space!

MRI – Basic Recipe

1) Put subject in big magnetic field

When protons are placed in a constant magnetic field, they precess at a frequency proportional to the strength of the magnetic field (at typical radio frequencies). They also align somewhat to generate a bulk magnetization.

2) Transmit radio waves into subject [about 3 ms]

Exposure to radio frequency magnetic field will synchronize this precession.

3) Turn off radio wave transmitter

The coherent precession continues but decays slowly due to interactions with magnetic moments of surrounding atoms and molecules (tissue dependent!)

4) Receive radio waves re-transmitted by subject [10-110ms]

The coherent precession (oscillation) generates a current in an inductive coil. The detected signal is called magnetic nuclear resonance.

5) Store measured radio wave data vs. time

Now go back to 2) to get some more data with different magnetic fields and radio frequencies. (here lies the Art of MRI!)

6) Process raw data to reconstruct images

Source: Robert Cox's web site