Chapter 9
Medical Imaging

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Motivation and Overview

- Question:

  "How can we measure the density of atoms of interest in a certain position from the subject, that is, make 3D image of atom densities?"

- Solution:

  (1) Choose a species of atom of interest.

  (2) Find an atom-specific physical quantity: the gyromagnetic ratio due to the spin of the nucleus.

  (3) Apply an external gradient magnetic field in order to make the magnetic resonant frequency of nuclei depend on its position.

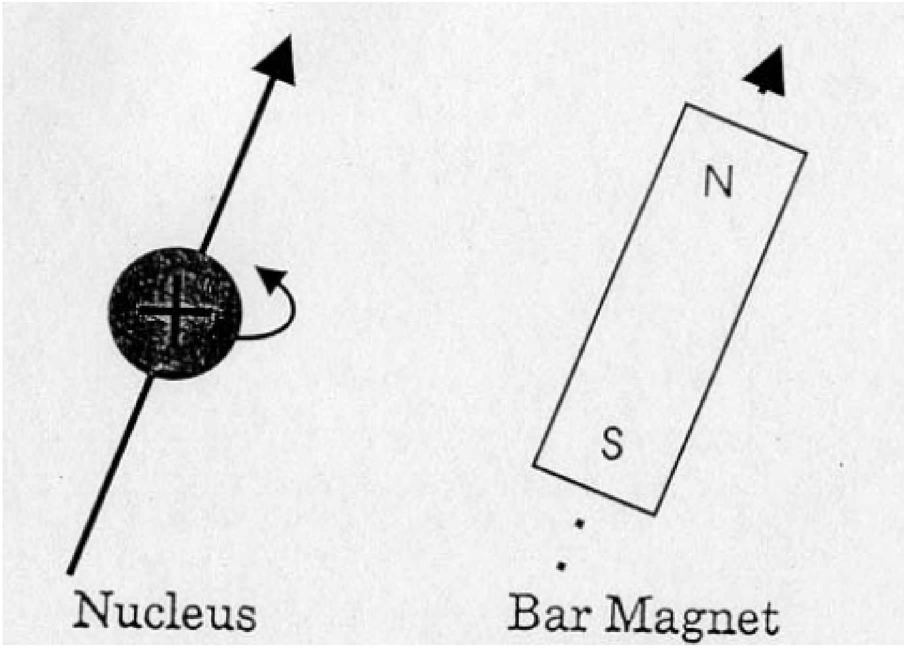
  (4) Apply RF pulses (electromagnetic waves) for exciting spins in the position of which resonant frequency is same to one of the applied pulses.

  (5) Turn off the pulses then spins are relaxed with emitting electromagnetic waves.

  (6) Detect the emitted waves and calculate the atom density in the position.

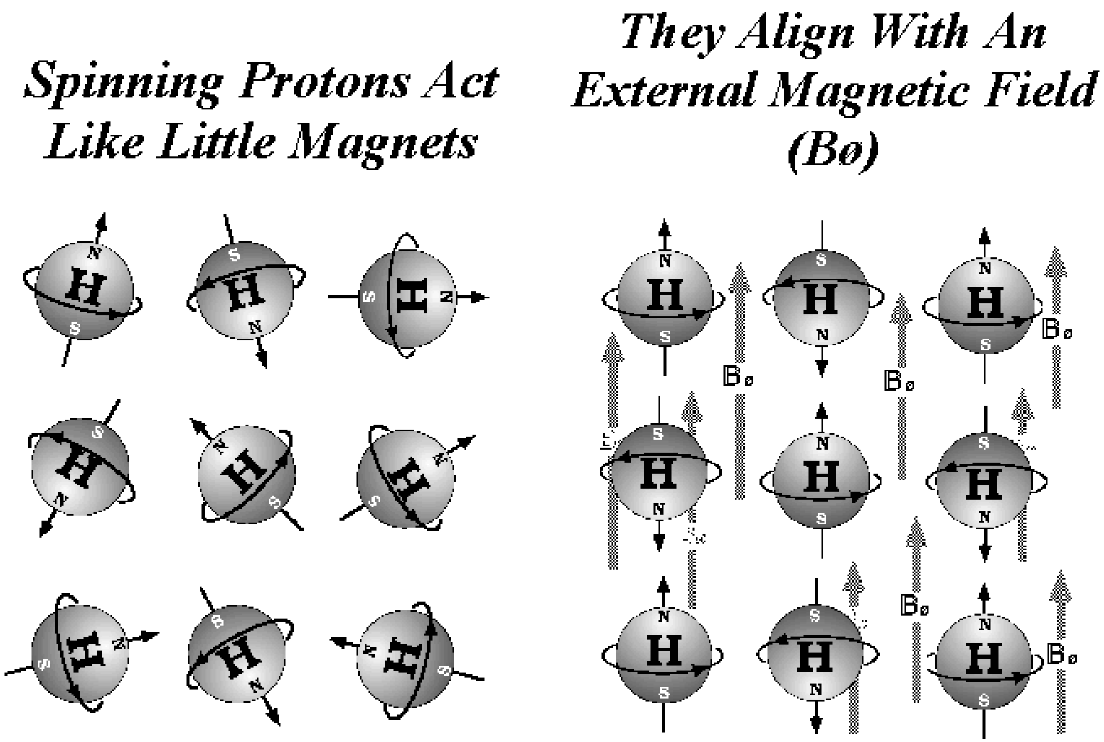
Spins of the Nucleus

- The intrinsic spin of the nucleus depends on how it is composed of protons and neutrons.
- The nucleus of ^{1}H atom (proton) is mostly employed in MRI.
- Z-axis spins of the proton (s_z) can have only two values: $\pm\frac{1}{2}\hbar$



Spins in an External Uniform Magnetic Field

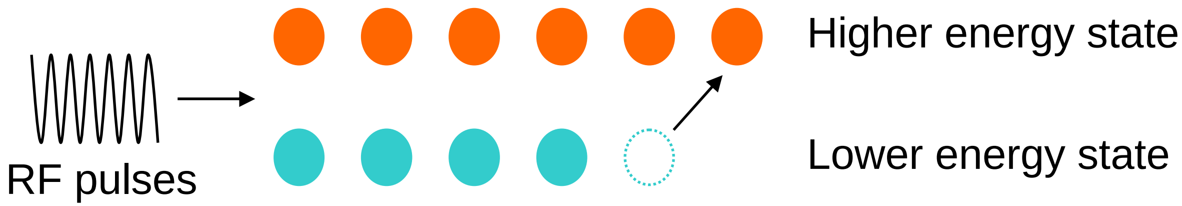
- Spins of protons align parallel to the field (low energy) or antiparallel to it (high energy).
- The population of two states follows Boltzmann distribution.



From James Voyvodic

Excitation by RF pulses

- RF pulses = electromagnetic waves
- Apply RF pulses of the resonant frequency to spins at equilibrium.
- Some spins at the lower state go up to the higher state by absorbing energy of the same energy.
- The resonant frequency is nuclei-specific: Larmor frequency.



$$\Delta E = 2\mu_z B_o = h\nu$$

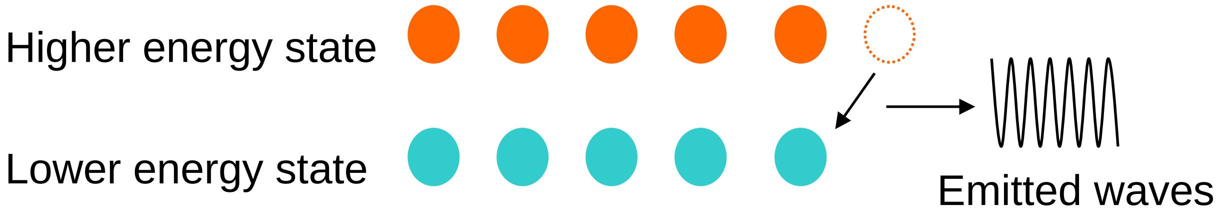
$$\nu = \frac{\gamma}{2\pi} B_o : \text{Larmor frequency}$$

γ : gyromagnetic ratio (nuclei-specific constant)

e.g. $\gamma / 2\pi = 42.57 MHz / Tesla$ for 1H atom (proton)

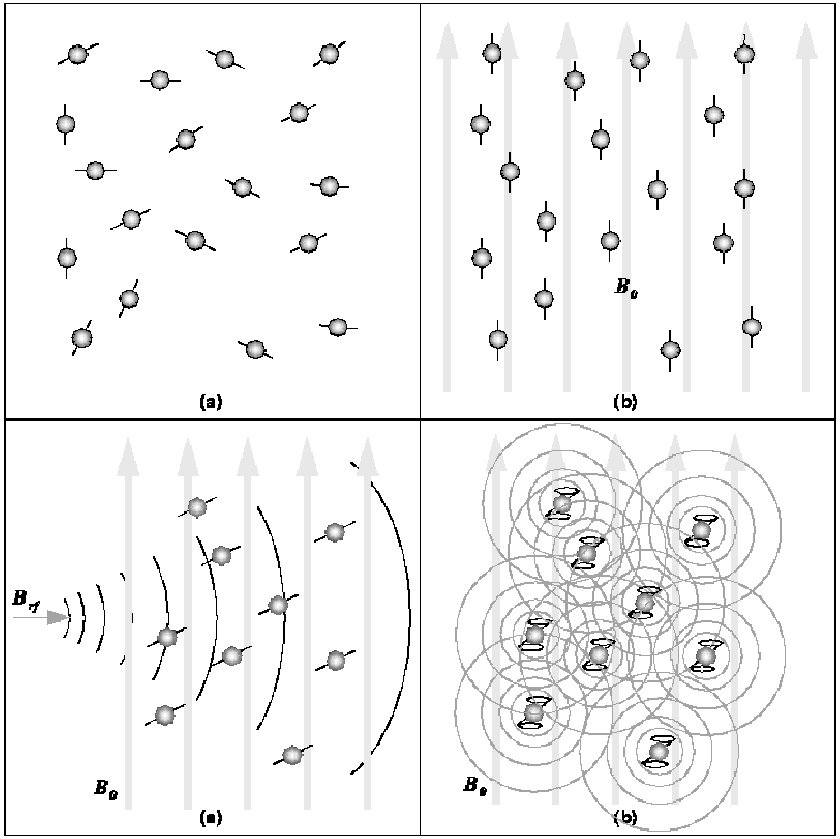
Relaxation

- Turn off the RF pulses.
- The spin population returns to its original equilibrium: relaxation.
- During relaxation, the nuclei lose energy by emitting electromagnetic waves of which frequency is same to the resonant one.



Net Magnetization *M*: Macroscopic View

- *M(r,t)*: sum of magnetic moments of all spins in a small volume (voxel)
- Changes in *M* during each process:



(1) Thermal equilibrium. Without B_o (external uniform magnetic field): the net magnetic moments (*M*) in random fashion

(2) Alignment. Apply B_o: *M* align parallel or antiparallel to B_o.

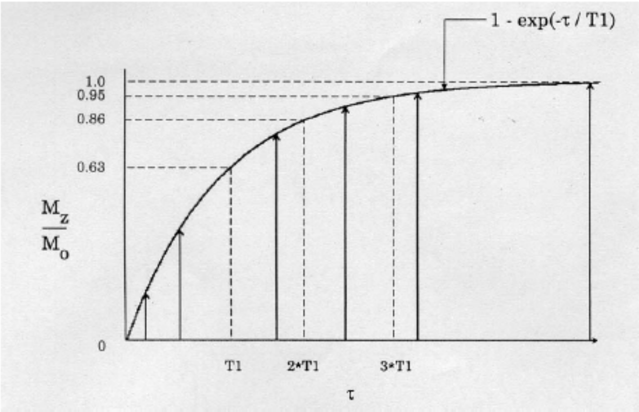
(3) Excitation. Apply RF pulses: *M* tilt away.

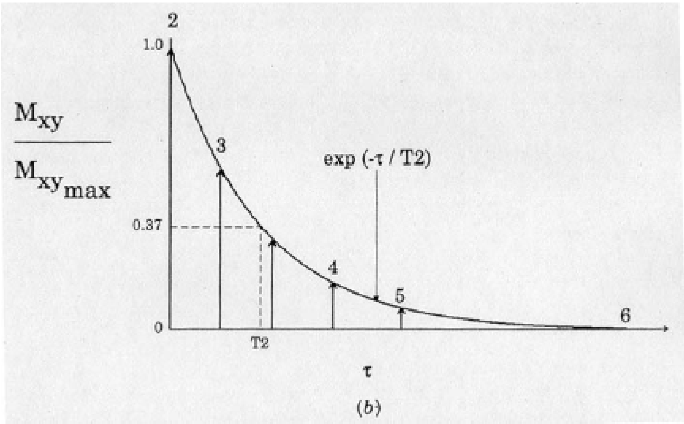
(4) Relaxation. Turn off RF pulses: *M* relax (realign) with emitting electromagnetic waves.

From Blair Mackiewich

Relaxation of *M*: FID Response Signal

- Relaxation of *M* has two types of decay time.
  - (1) Longitudinal relaxation(spin-lattice interaction) (M_z): spins return to its equilibrium at the decay time of *T1*.
  - (2) Transverse relaxation(spin-spin interaction) (M_{xy}): the coherence in M_{xy} disappears due to dephasing at *T2*.





- Electromagnetic waves emitted during relaxation also have two types of decay time: free induction decay (FID) response signal.

Image Contrast and 3D Imaging

- Image contrast
  - Without relaxation time: the intensity of the FID signal represents the proton density.
  - T1, T2, T2* imaging: the relaxation time represents various properties such as chemical environment, magnetic susceptibility, magnetic inhomogeneity, and so on.
  - Diffusion tensor imaging (DTI): diffusion can be measured in multiple directions and the fractional anisotropy in each direction is calculated for each voxel.
- 3D imaging
  - By applying the gradient magnetic field of which amplitudes depend on the position, each voxel can have different Larmor frequency.

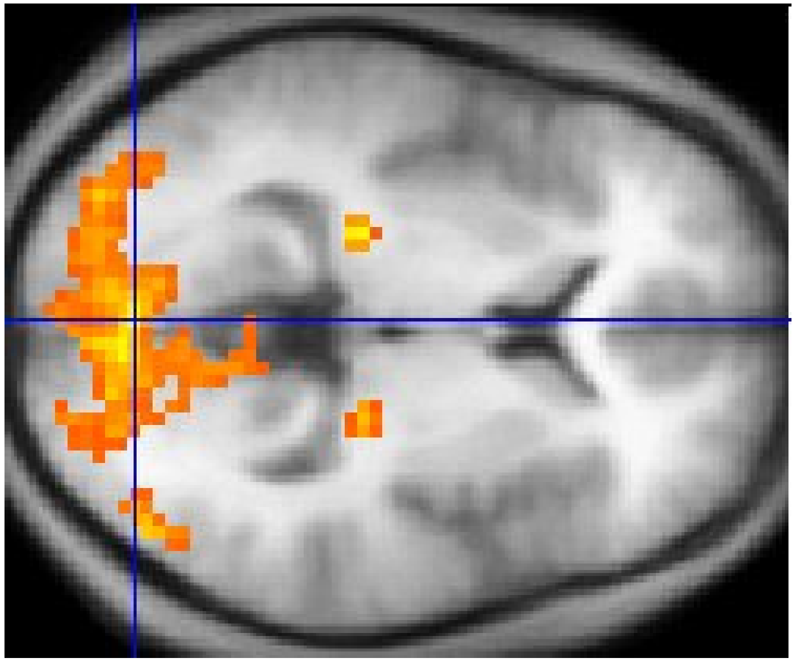
Conventional MRI: Brain Anatomy

- T1-weighted imaging: gray / white matter
- T2-weighted imaging: tissue / cerebrospinal fluid

From Andrew Kucher

Functional MRI: Brain Activity

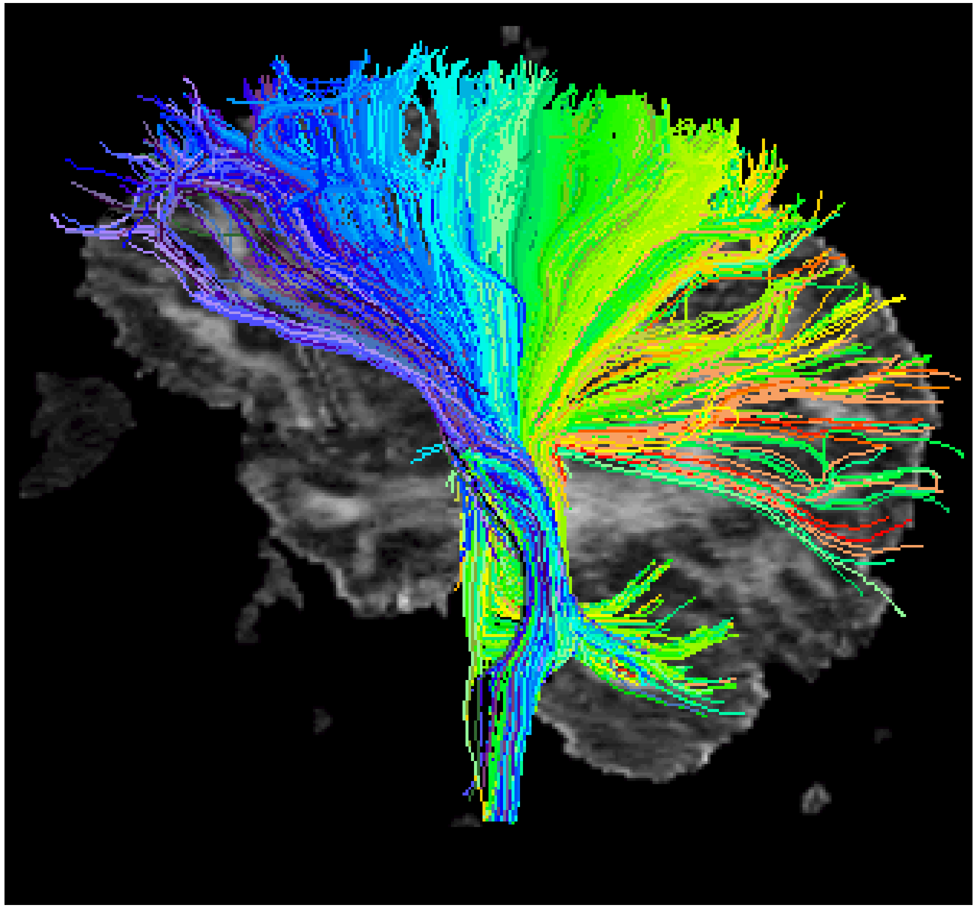
- T2* imaging: cerebral blood flow, cerebral blood volume and blood oxygenation
- Blood-oxygen-level dependent (BOLD) effect: increased neural activity causes an increased demand for oxygen, increasing the amount of oxygenated hemoglobin relative to deoxygenated hemoglobin.



From Washington Irving

Diffusion Tensor Imaging (DTI): Brain Connectivity

- The fractional anisotropy shows fiber directions: tractography.



From Mariana Lazar

Magnetic Resonance Angiography (MRA)

- Image of the arteries in order to evaluate them for stenosis (abnormal narrowing) or aneurysms (vessel wall dilatations)

From Ofir Glazer