Chapter 9
Medical Imaging

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Contents

- Principle and Applications of
  - MRI
  - PET
  - NIRS

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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.

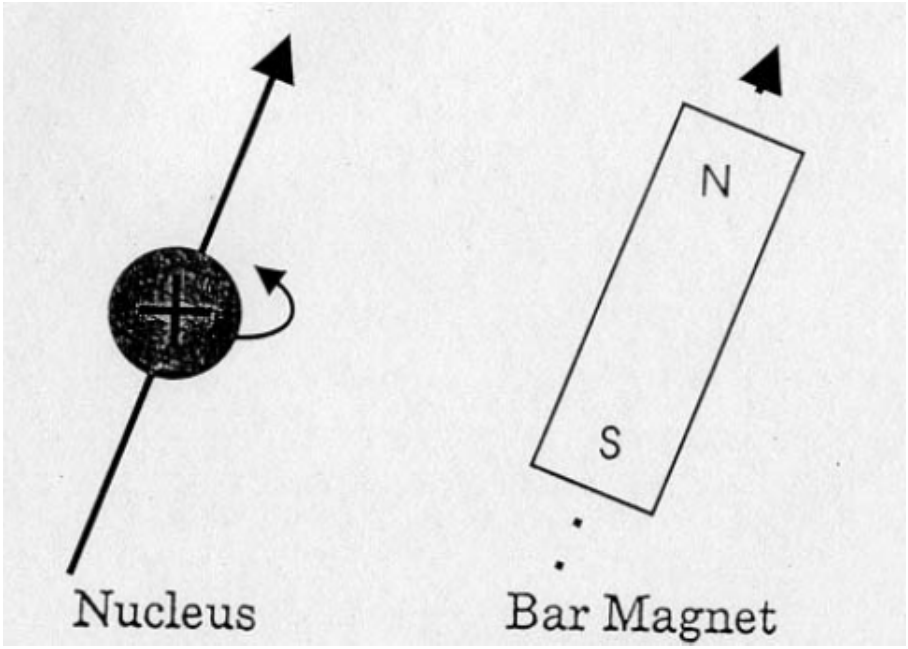
  (4) Apply RF pulses (electromagnetic waves) for exciting spins in the position of which resonant frequency is same to one of the applied pulses.

  (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.

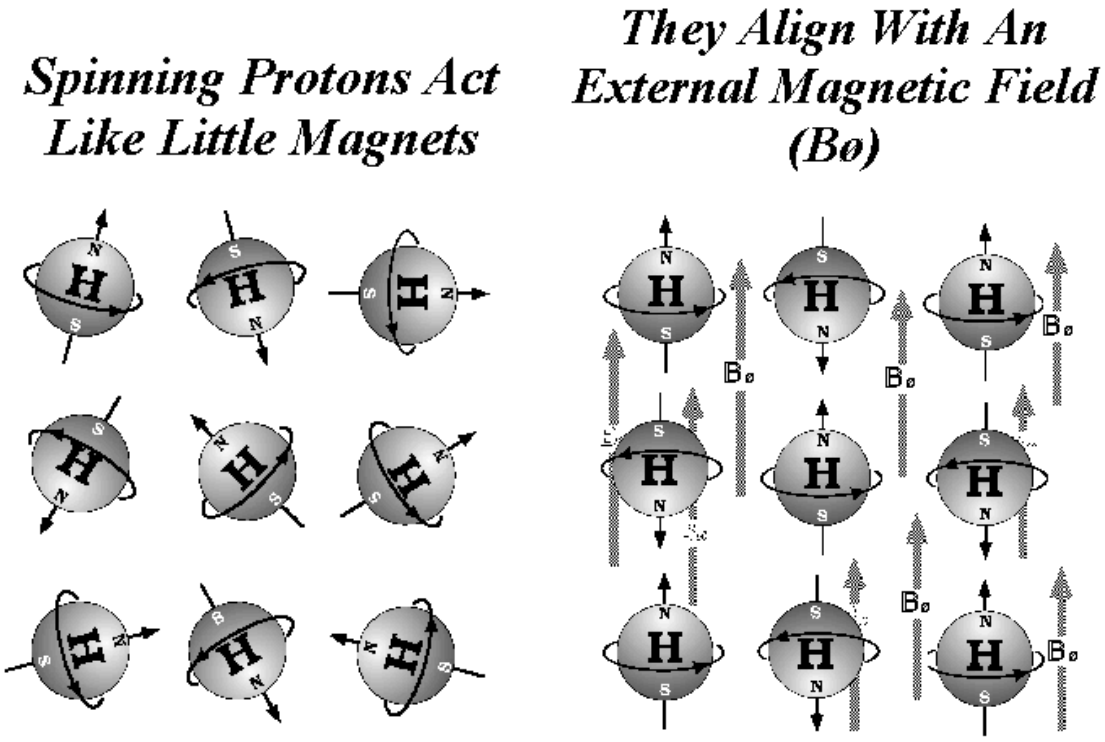
Spins of the Nucleus

- 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

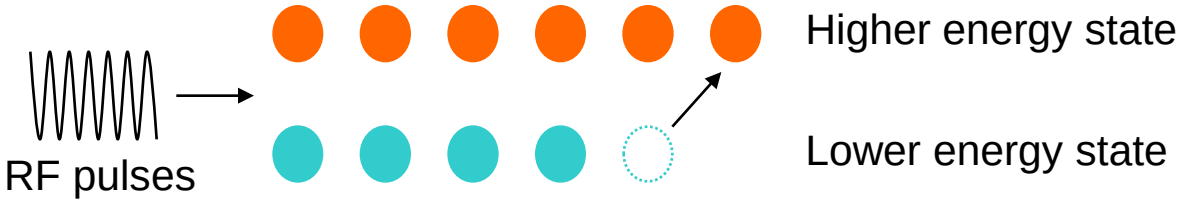
- Spins of protons align parallel to the field (low energy) or antiparallel to it (high energy).
- The population of two states follows Boltzmann distribution.



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 (proportional to magnetic field).



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

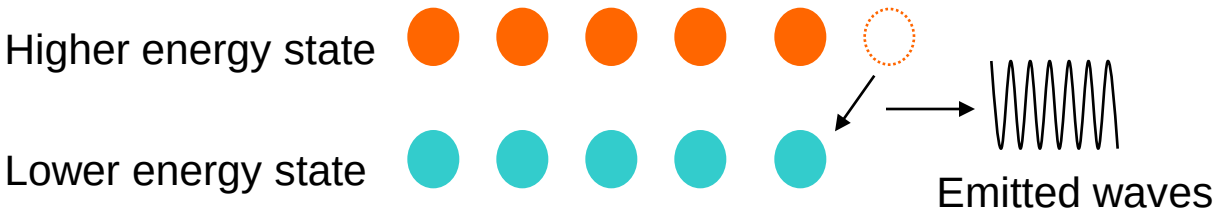
$$\nu = \frac{\gamma}{2\pi} B_o : \text{Larmor frequency}$$

γ : gyromagnetic ratio (nuclei - specific constant)

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

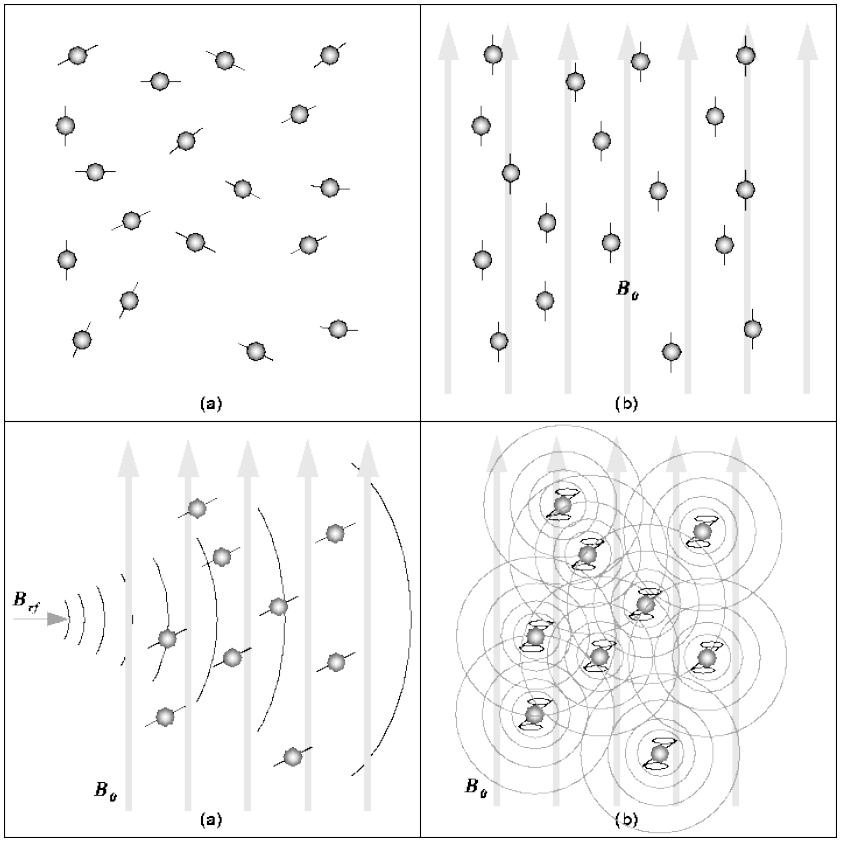
Relaxation

- 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.

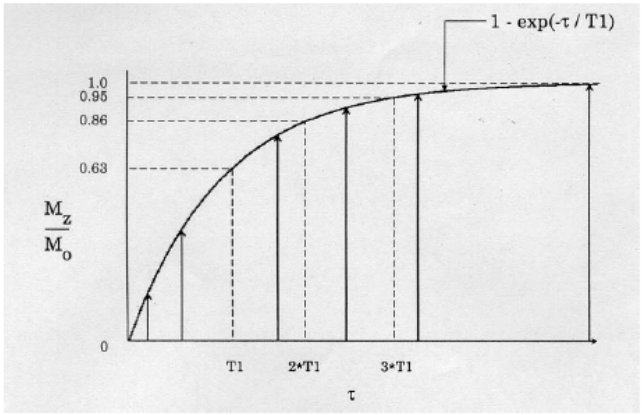
(3) Excitation. Apply RF pulses: *M* tilt away.

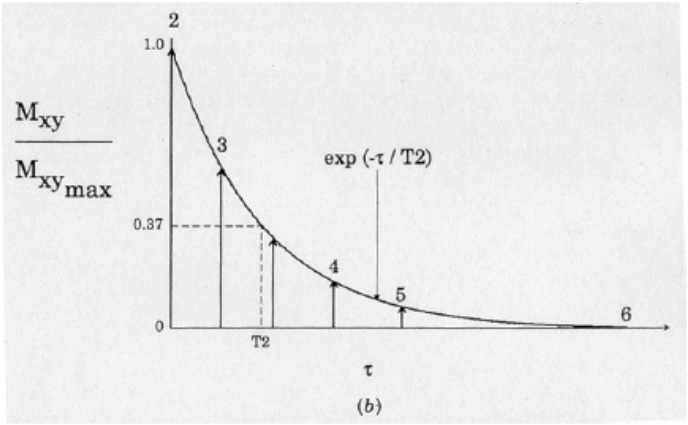
(4) Relaxation. Turn off RF pulses: *M* relax (realign) with emitting electromagnetic waves.

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*.





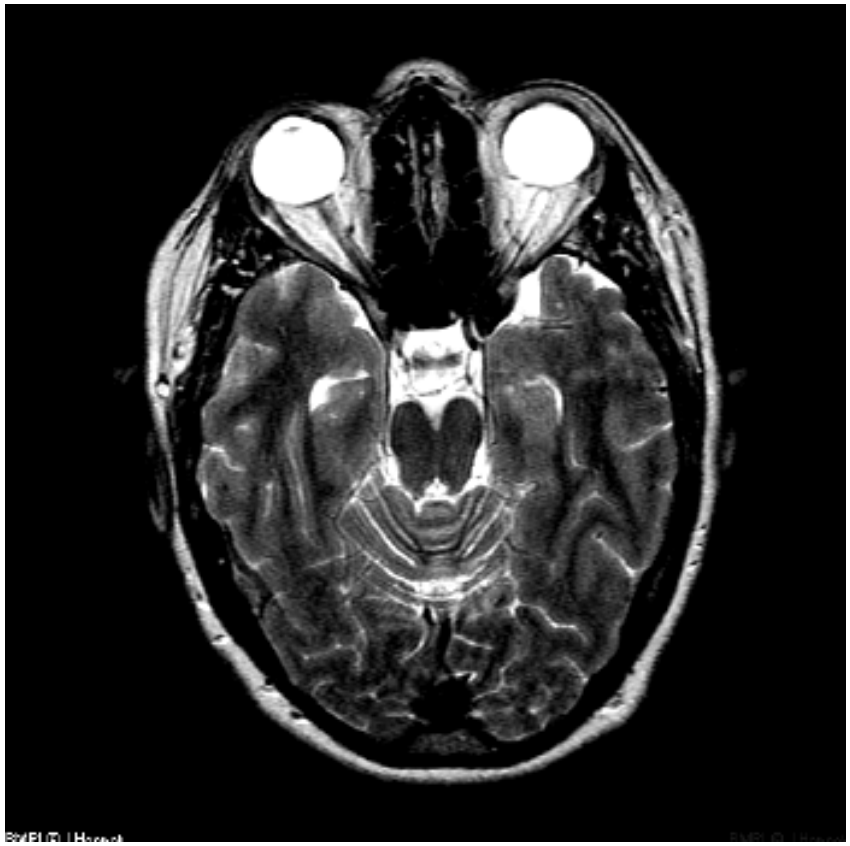
- Electromagnetic waves emitted during relaxation also have two types of decay time: free induction decay (FID) response signal.

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

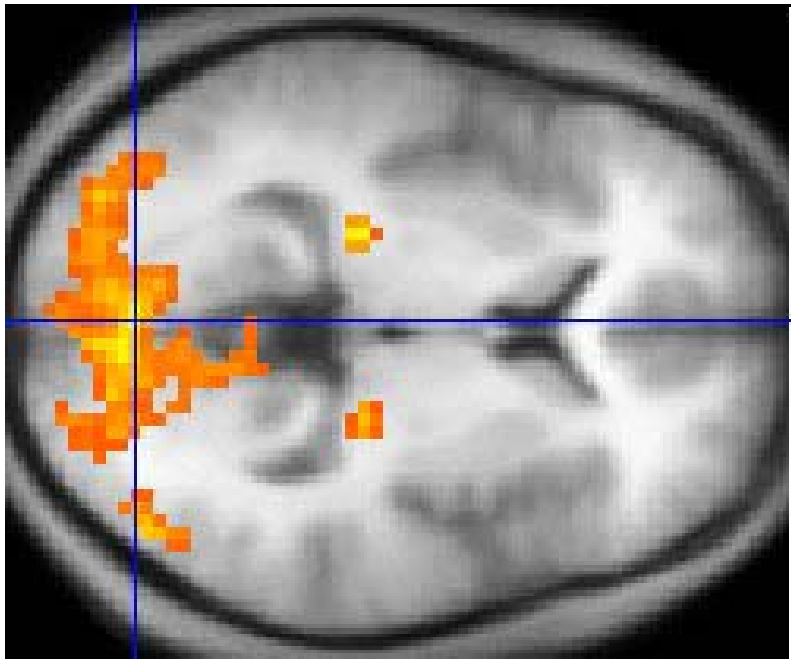
- T1-weighted imaging: gray / white matter
- T2-weighted imaging: tissue / cerebrospinal fluid



From Andrew Kucher

Functional MRI: Brain Activity

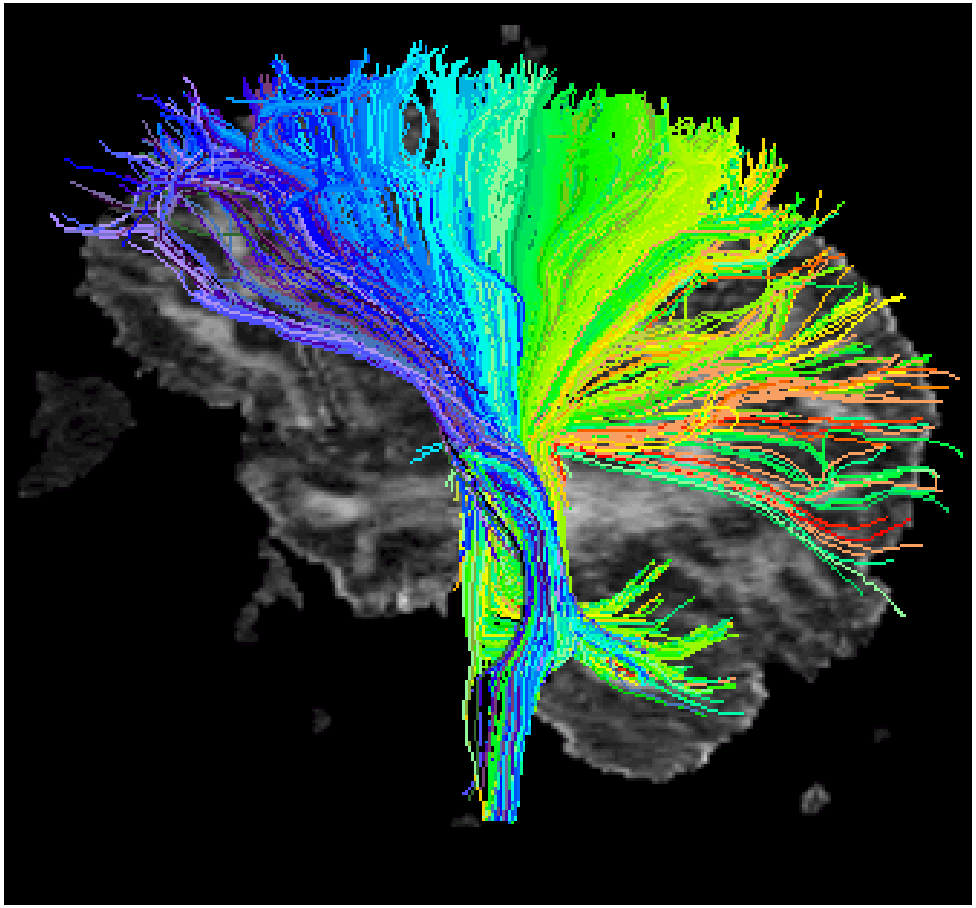
- T2* imaging: cerebral blood flow, cerebral blood volume and blood oxygenation
- Blood-oxygen-level dependent (BOLD) effect: increased neural activity causes an increased demand for oxygen, increasing the amount of oxygenated hemoglobin relative to deoxygenated hemoglobin.



From Washington Irving

Diffusion Tensor Imaging (DTI): Brain Connectivity

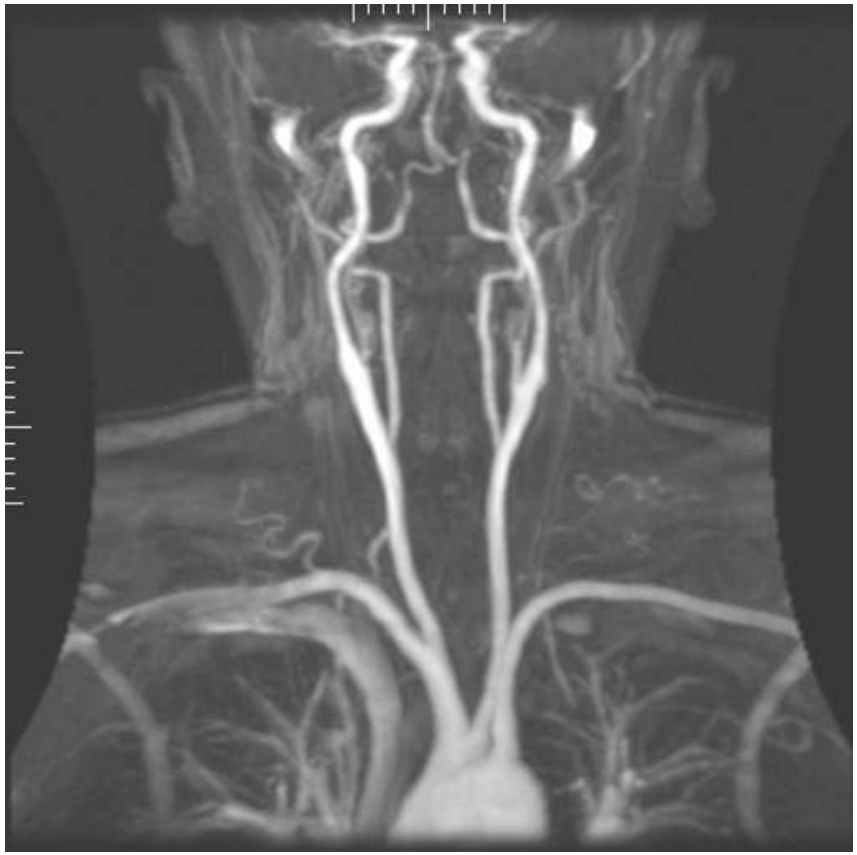
- The fractional anisotropy shows fiber directions: tractography.



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

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  - Positron emission and annihilation
  - Coincidence detection
  - Types of coincidence events
  - Radiotracers
  - Tracer for glucose dynamics
- Applications
  - FDG-PET for oncology
  - PET neuroimaging

Motivation and Overview

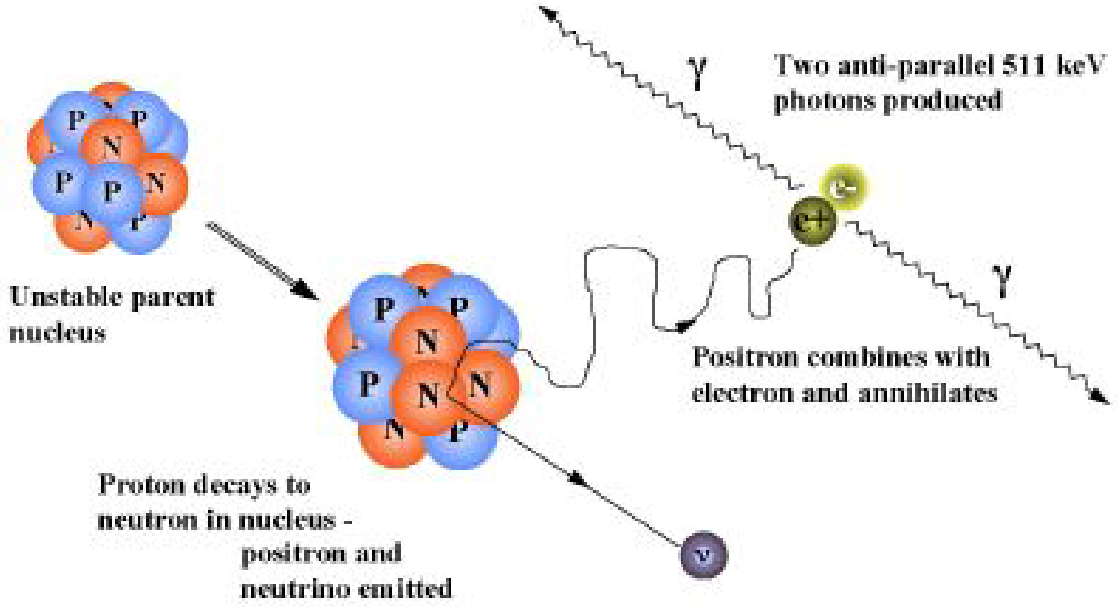
- Question:

  “How to find the position of chemical compounds that we want to trace?”

- Solution:
  - (1) Make the chemical compound contain a proton-rich unstable parent isotope: labeling.
  - (2) Inject labeled compounds into the subject.
  - (3) A proton in the isotope decays to a neutron with emitting a positron.
  - (4) The positron combines with a nearby electron and disappears with emitting two photons.
  - (5) Detect two emitted photons and calculate the position at which the positron disappeared.

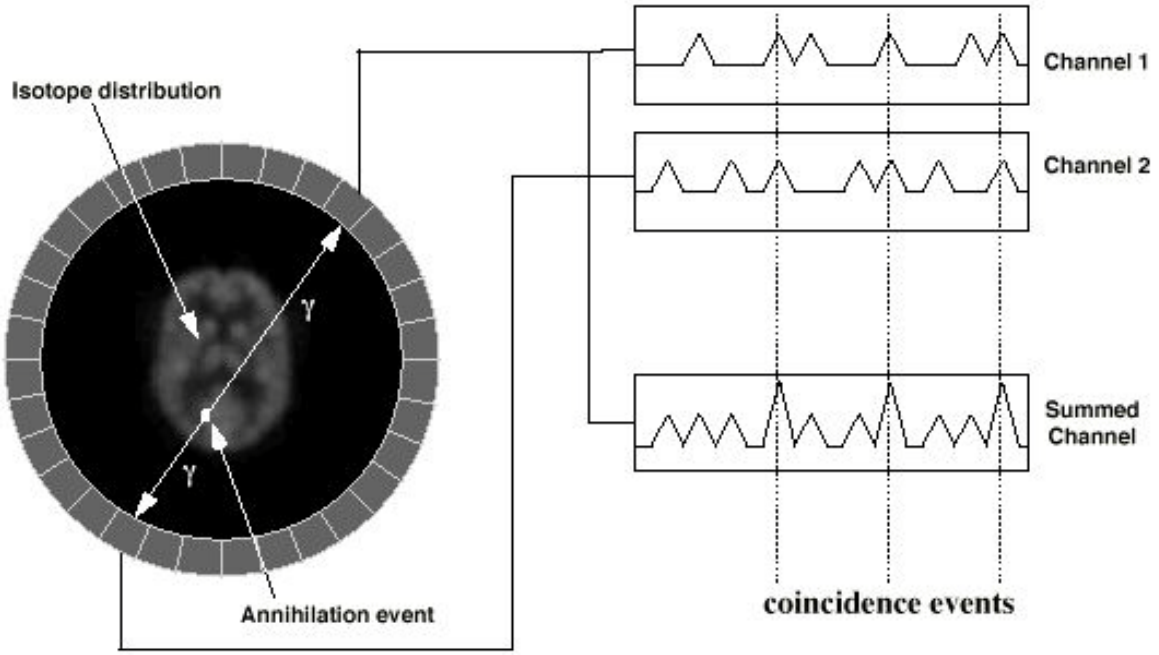
Positron emission and annihilation

- - A proton-rich unstable parent isotope decays to a daughter isotope through: Proton -> Neutron + Positron + Neutrino.
- - The emitted positron combines with a nearby electron and annihilates with emitting two photons.



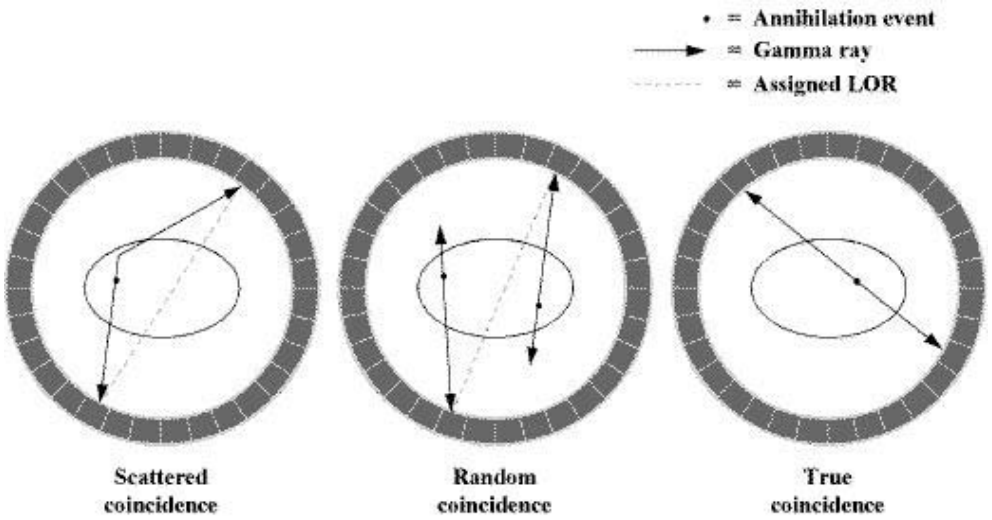
Coincidence detection

- When an annihilation event occurs at a certain position, a coincidence event is assigned to a line of response (LOR) joining the two relevant detectors.
- - In this way, positional information is gained from the detected radiation: an electronic collimation.



Types of coincidence events

- True coincidence: Both photons do not undergo any form of interaction prior to detection, and no other event is detected at that moment.
- Scattered coincidence: One photon has undergone at least one Compton scattering event prior to detection. It adds statistical noise to the signal.
- Random coincidence: Two photons not arising from the same annihilation event are incident on the detectors at the same moment. It also adds statistical noise to the data..



Radiotracers

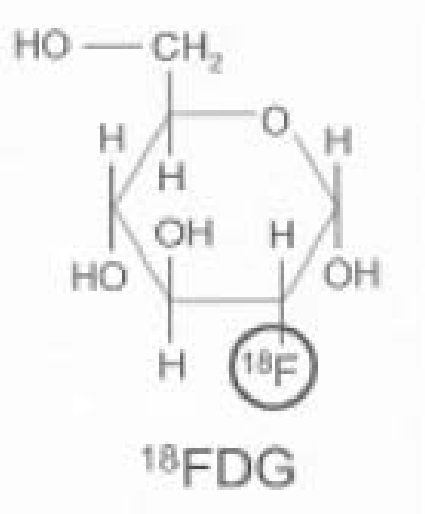
- Chemical compounds labeled with positron-emitting radionuclides
- These tracer compounds can be used to track biochemical and physiological processes.
- Radiotracers for various purposes have been developed.

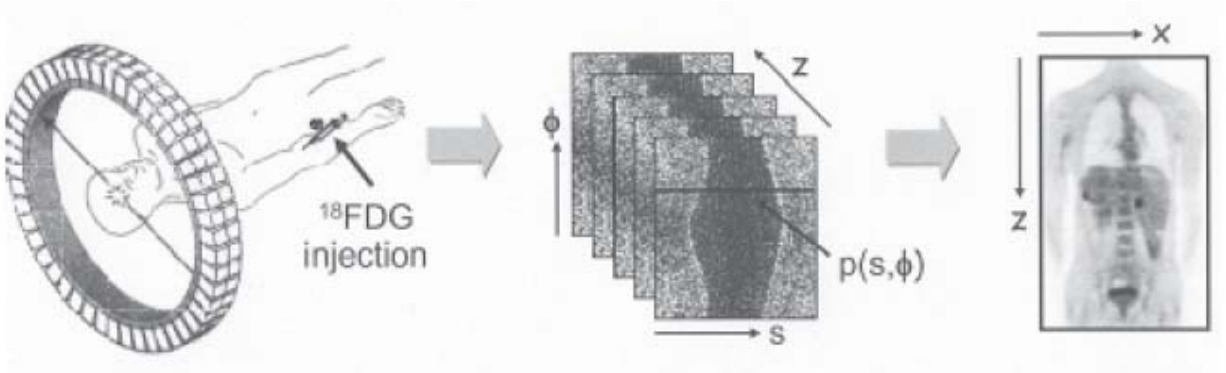
Radiotracers

Isotope	Tracer compound	Physiological process or function	Typical application	Example reference
^{11}C	methionine	protein synthesis	oncology	Hellman *et al* (1994)
^{11}C	flumazenil	benzodiazepine receptor antagonist	epilepsy	Burdette *et al* (1995)
^{11}C	raclopride	D2 receptor agonist	movement disorders	Antonini *et al* (1997)
^{13}N	ammonia	blood perfusion	myocardial perfusion	Kuhle *et al* (1992)
^{15}O	carbon dioxide	blood perfusion	brain activation studies	Kanno *et al* (1984)
^{15}O	water	blood perfusion	brain activation studies	Huang *et al* (1983)
^{18}F	Fluoro-deoxy-glucose	glucose metabolism	oncology, neurology, cardiology	Brock *et al*, 1997 (review)
^{18}F	Fluoride ion	bone metabolism	oncology	Hawkins *et al*(1992)
^{18}F	Fluoro-mizonidazole	hypoxia	oncology - response to radiotherapy	Koh *et al* (1995)

The tracer for glucose dynamics imaging: Fluorodeoxyglucose (FDG)

- A glucose analog that is taken up by glucose-using cells.
- The glucose metabolism imaging can be constructed by employing this tracer.

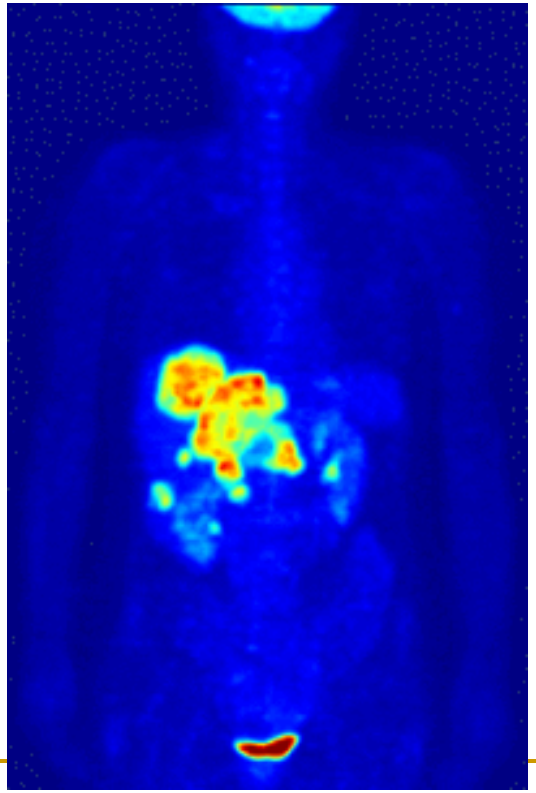




From Blair Mackiewich

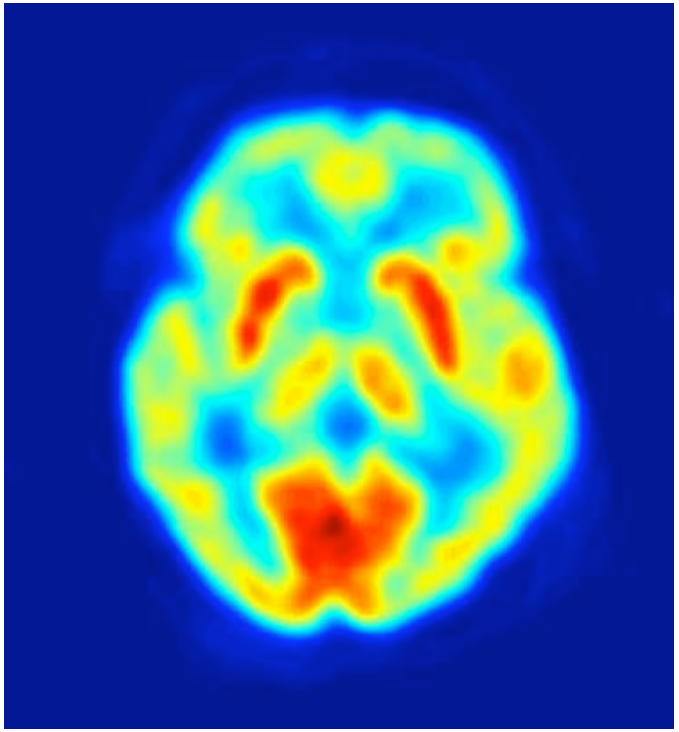
FDG-PET for oncology

- - Used for diagnosis, staging, and monitoring treatment of cancers, particularly in Hodgkin's disease, non Hodgkin's lymphoma, and lung cancer.
- - Oncology scans make up over 90% of all PET scans in current practice.



PET neuroimaging

- The brain is normally a rapid user of glucose but brain pathologies such as Alzheimer's disease greatly decrease brain metabolism.



Contents

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  - NIR spectra of hemoglobin
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  - Imaging brain activity
- Applications
  - Medical diagnostics
  - Brain Machine Interface

Motivation and Overview

- Question:

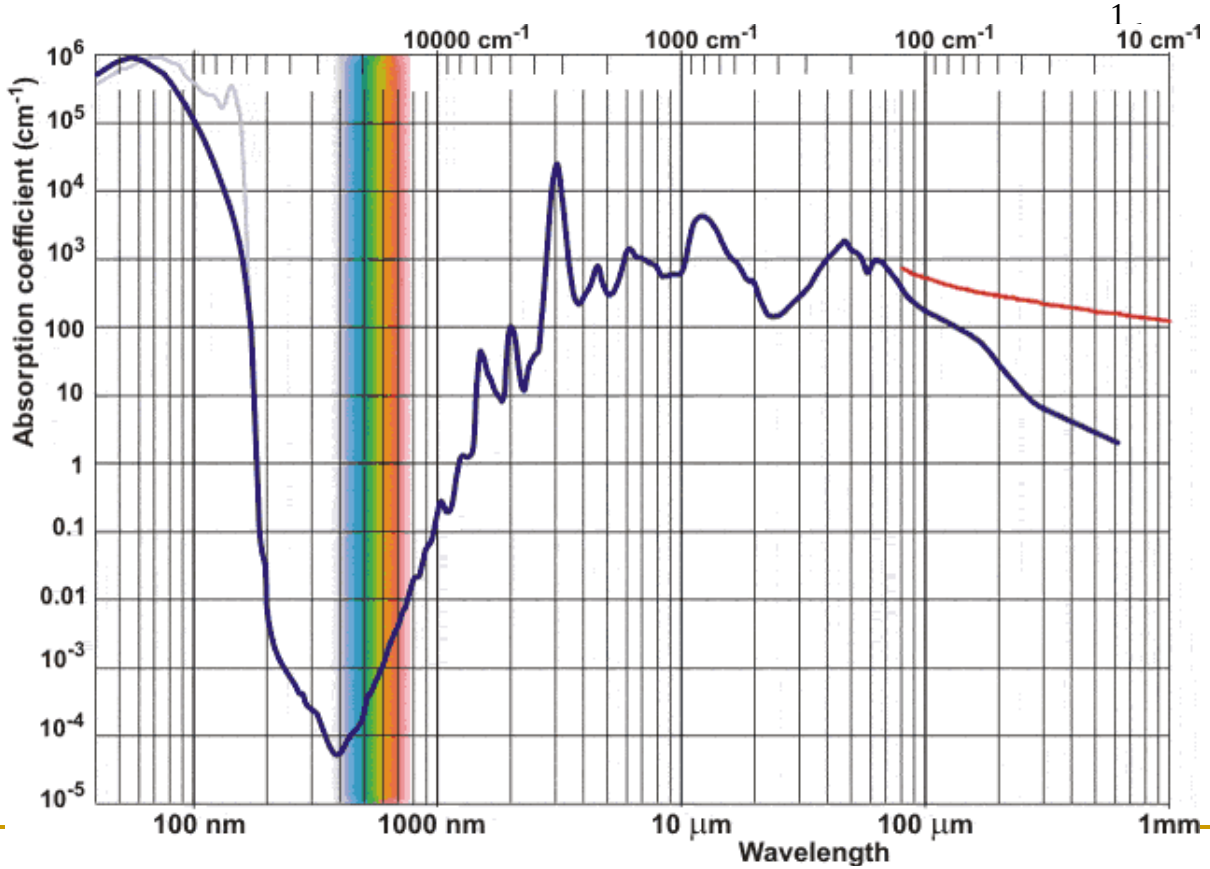
  How to image brain activity more conveniently

Solution:

- (1) Find the wavelength of light which can reach the cortex of brain with penetrating the scalp and skull: Near infrared (NIR) light.
- (2) Find physical and physiological quantities varied by brain activity: Increased neural activity causes an increased demand for oxygen, increasing the amount of oxygenated hemoglobin (HbR) relative to deoxygenated hemoglobin (HbO2), so called, blood-oxygen-level dependent (BOLD) effect.
- (3) NIR absorption spectra of HbR and HbO2 are different from each other.
- (4) Detect light intensities transmitting through the brain and calculate the blood-oxygen-level which represents brain activity.
- Choose a species of atom of interest.

Near infrared light

- - Near infrared light is rarely absorbed by the skull, skin and water that is the most abundant molecules in human body.
- - The light absorption of matter depends on the wavelength of light.



Spectrum of water

(red: sea water)

Penetration of NIR light

- light can penetrate the human head because it is rarely absorbed by the skin, skull and water.

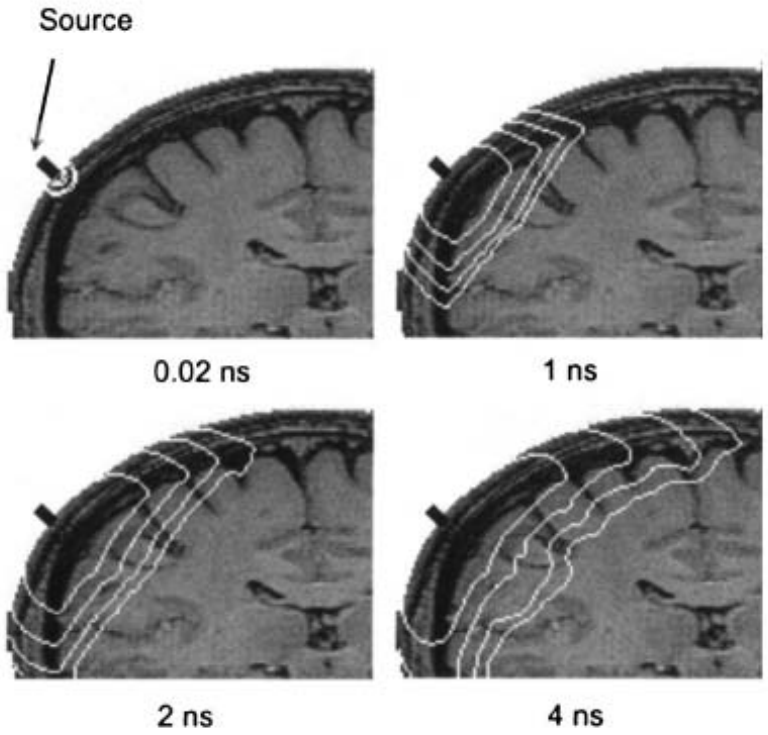
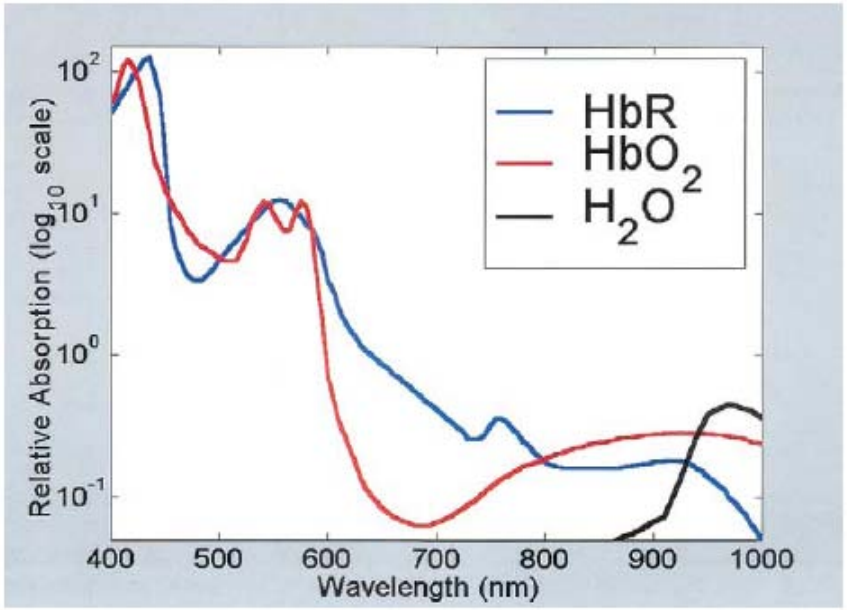


Fig. 2. FEM solution to the diffusion equation at four consecutive times superimposed on the coronal MRI slice of the head used for the optical model. White lines represent places where the photon density is 10%, 1%, 0.1%, and 0.01% of the maximum.

From Bruno Montcel

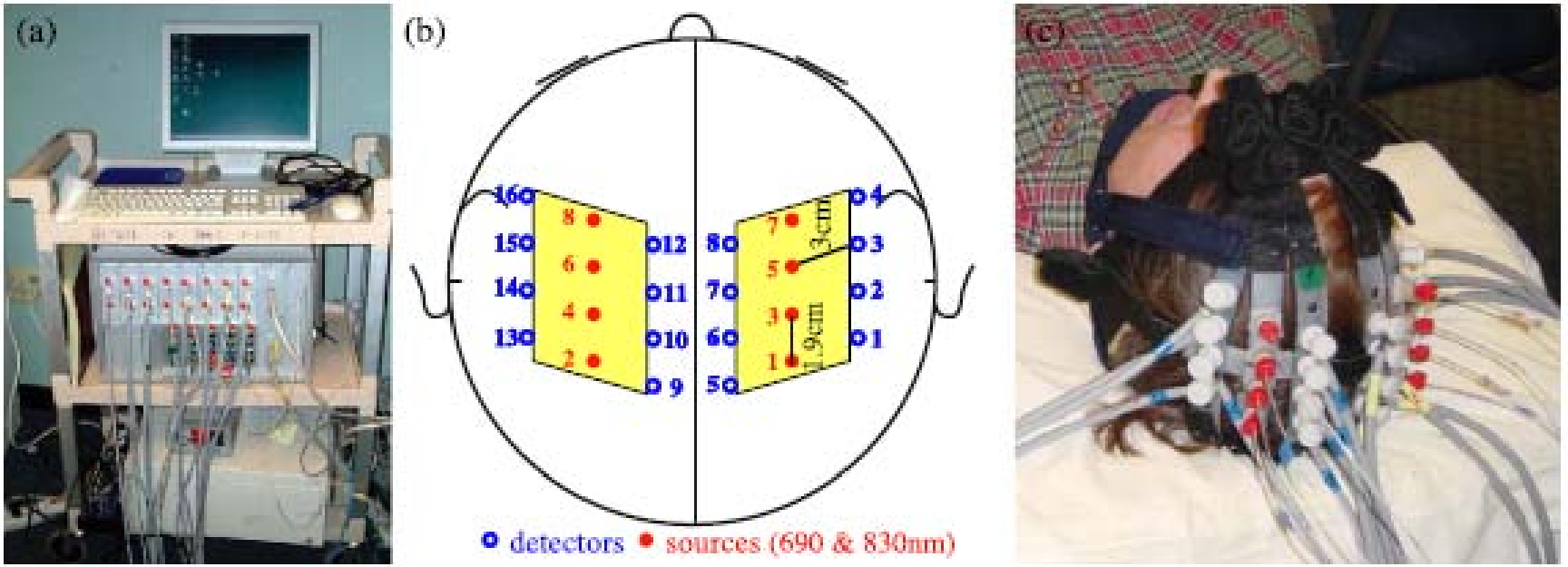
NIR spectra of hemoglobin

- - If we employed two wavelengths at which light absorption of HbR and HbO2 are different, we can detect relative changes in HbR and HbO2 concentrations ([HbR], [HbO2]).
- e.g. 690 and 830 nm



Instruments

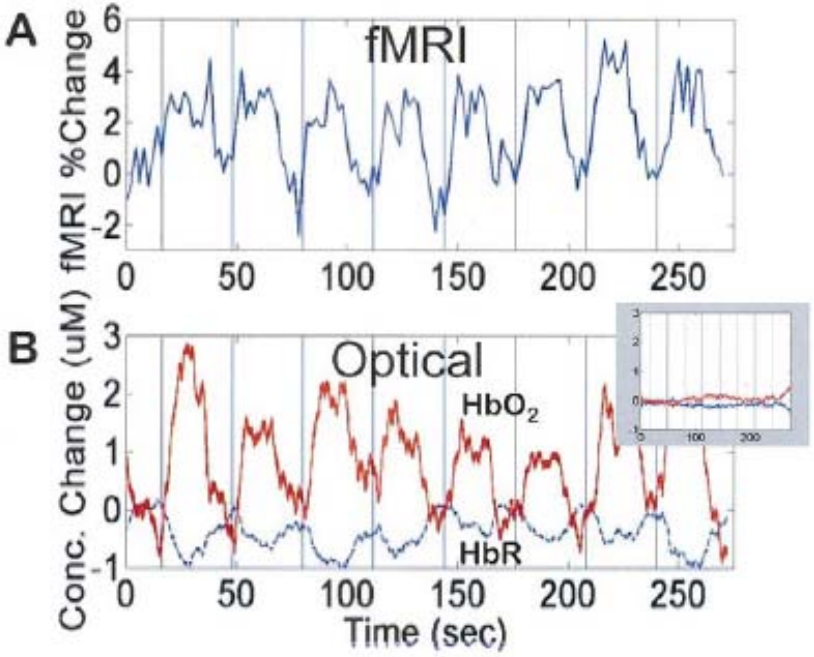
- - Many sources and detectors connected to optical fibers for conducting light to and from the head.



From M. A. Franceschini

Validation by comparing with fMRI

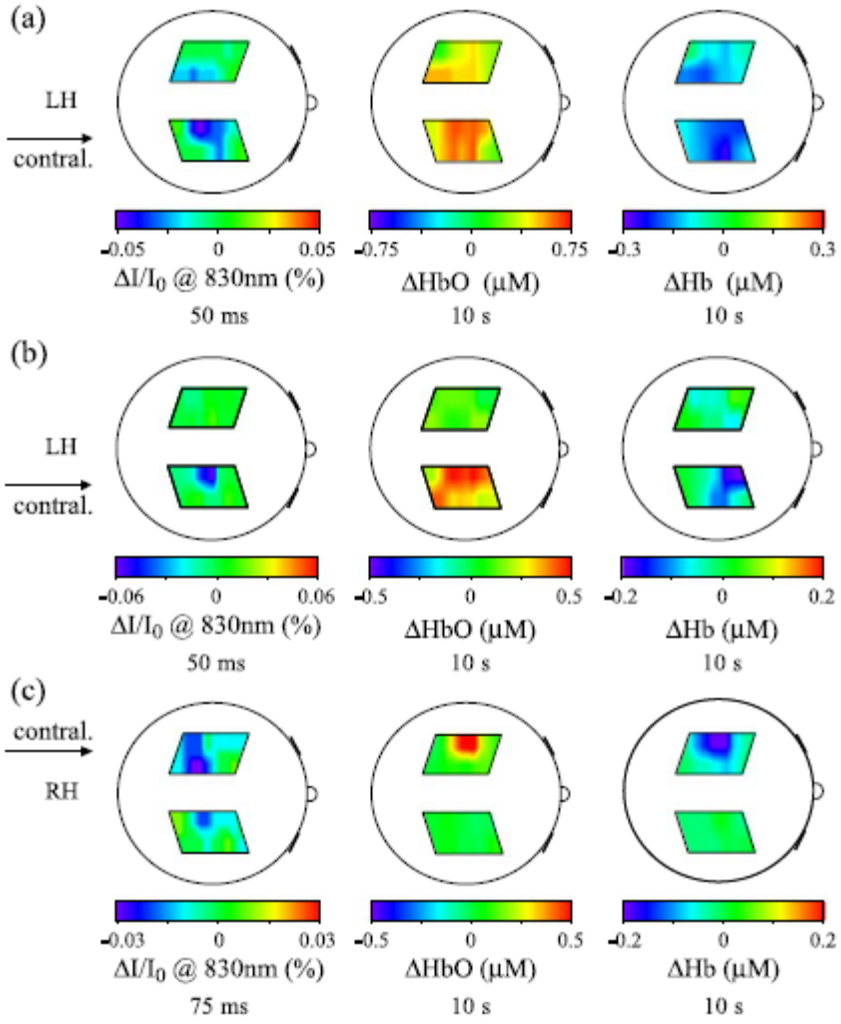
- Raw time courses when left finger tapping performed.
- (A) fMRI signal for left primary motor cortex.
- (B) Changes in [HbO2] and [HbR] determined from the single detector located closest to one monitored by fMRI. Inset shows control HbR and HbO2 time courses from the detector several centimeters away from the activated region.



From Gray Strangman

Imaging brain activity

- - Finger tapping / tactile experiment: Brain activity in the contralateral hemisphere is expected to occur.
- - Left: changes in the intensity after 50 ms. Center: changes in HbO2 after 10 s. Right: changes in HbR after 10 s.
- - (a) Left hand finger-tapping task; (b) left hand finger-tactile stimulation; (c) right hand finger-tactile stimulation



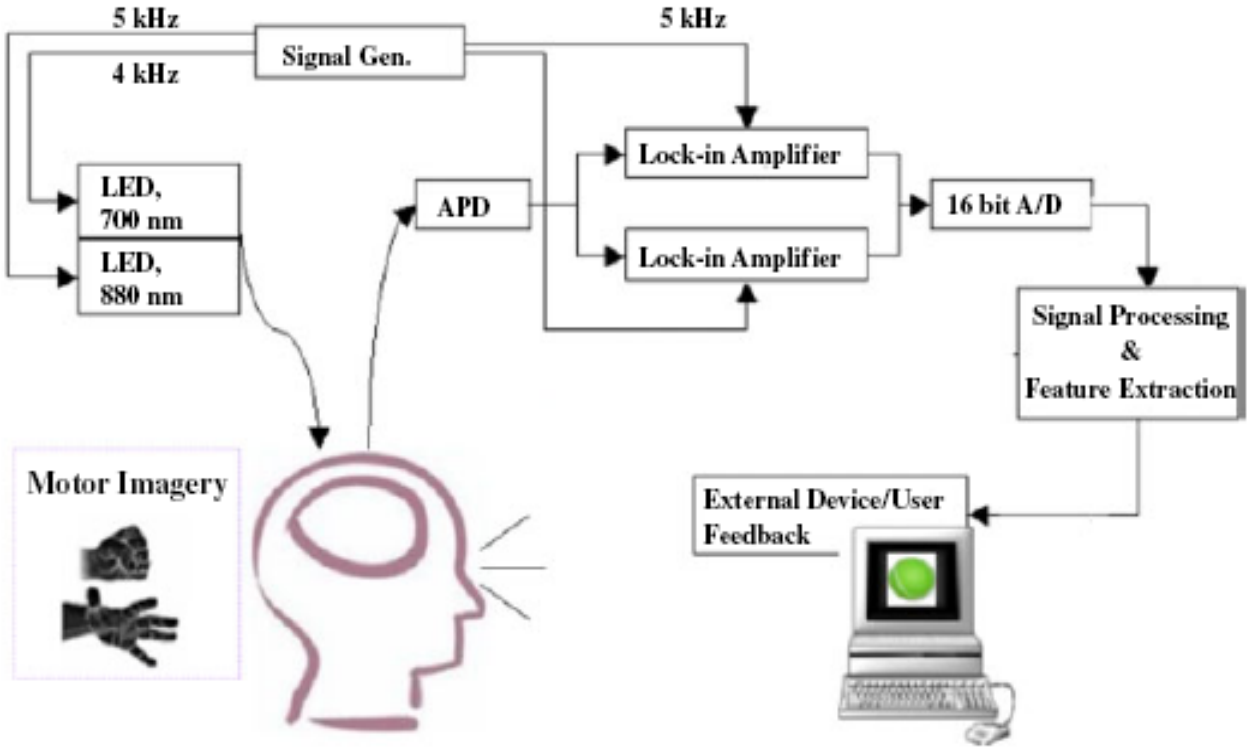
II. Applications

1. Medical diagnostics

- - The measurement of oxygen levels in the blood for blood sugar determination: Oximetry.
- - NIRS can be accompanied by other modalities such as magnetic resonance imaging (MRI) or computerized tomography (CT): Multimodal imaging.
- - NIRS can be used on infants, where fMRI cannot, and it is much more portable than fMRI machines.

2. Brain-machine interface (BMI)

- - By monitoring brain activity, we can have persons to control external devices by their thought only.
- - NIRS seems to be used only in the ‘slow decision’ BMI because significant hemoglobin concentration changes usually follow brain activity with the temporal latency of about 5 seconds.



From Shirley Coyle

Figure 1. Optical BMI architecture.