Physics in Medical Imaging

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- Very Brief Overview
- Some Computational Challenges
- Future Prospects

UNIVERSITY OF CAMBRIDGE

Remote sensing of the human body using:

- Electromagnetic radiation
- Sound waves
- Radioactivity
- etc….

Physicists can make important contributions.

Part of a current trend for physicists to move into biology

"Biology is purely digital?"

Some Current Imaging Modalities

- X-Rays (2D projected “flat” Image)
- CT (Stack of 2D slices -> 3D)
- PET (3D Quite rare in UK)

Invasive using ionizing radiation

- Ultrasound (common 2D & 3D)
- MRI (3D Quite widespread)
- MEG (research 2D?)
- THz (just emerging 2D?)

Non Invasive

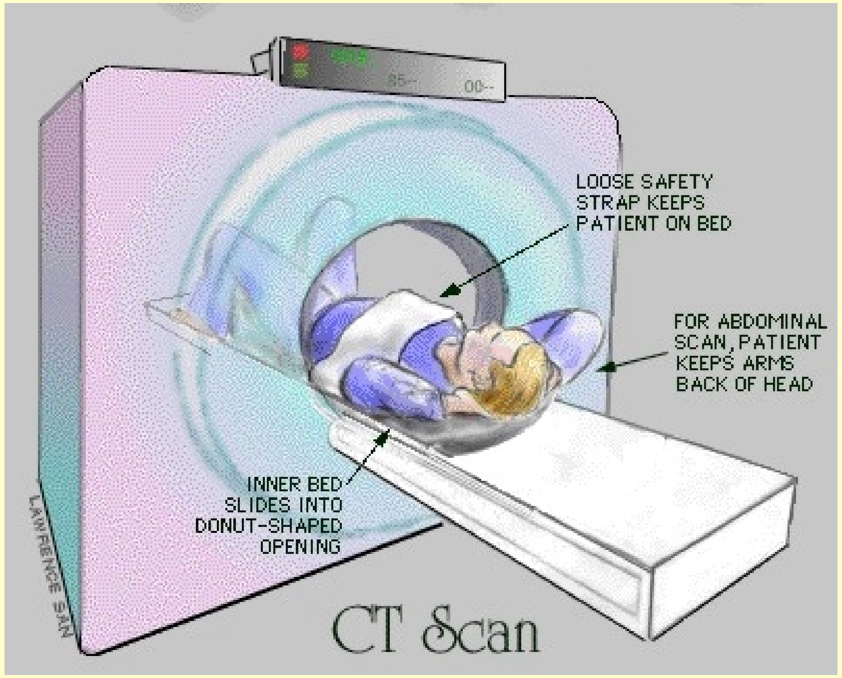
X-rays are well known

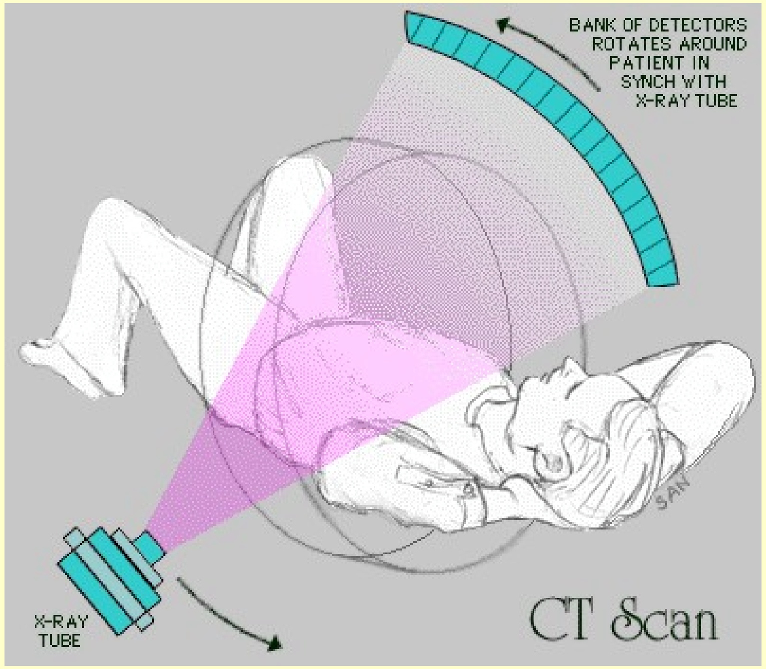
The famous radiograph made by Roentgen on 22 December 1895.

This is traditionally known as “the first X-ray picture” and “the radiograph of Mrs. Roentgen's hand”.

Poor for Soft Tissue!

CT scanners are a modern development





Still Poor for Soft Tissue!

CT Scan gives RADON Transform

- Let $f(x,y)$ denote the absorption coefficient of the object at a point (x,y). The intensity of the detected beam is given

$$I = I_0 \exp\left[-\int_L f(x,y)du\right]$$

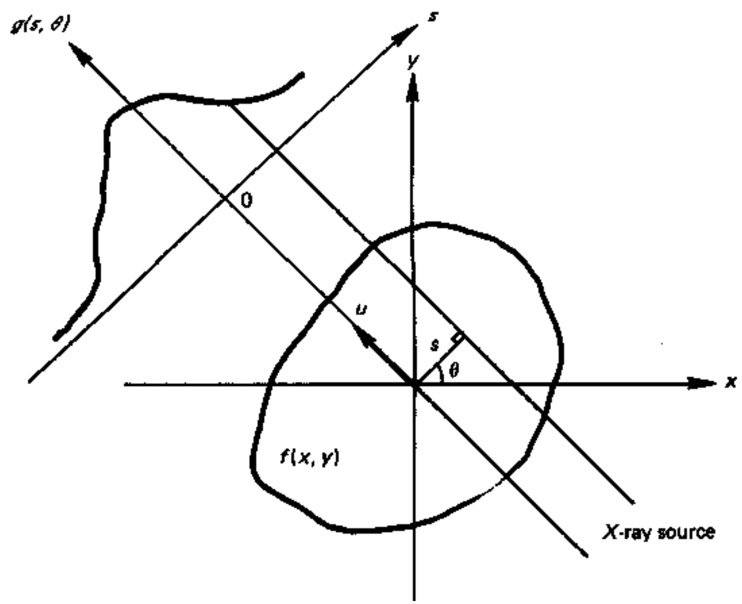
where I_0 is the intensity of the incident beam, L is the path of the ray, and u is the distance along L.

- The observed signal is defined by $g = \ln\left(\frac{I_0}{I}\right)$.
- Linear transform is obtained as

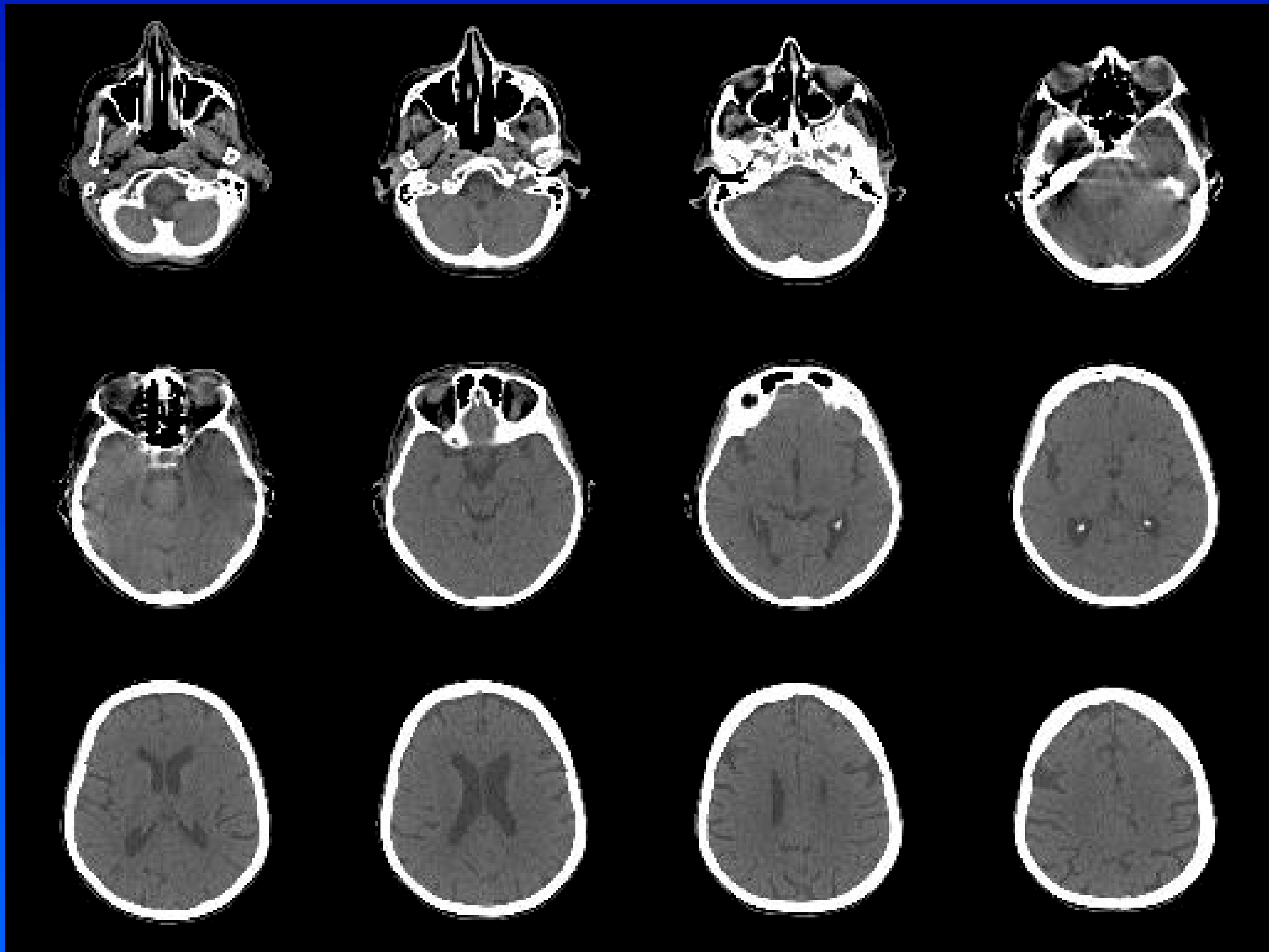
$$g = g(s,\theta) = \int_L f(x,y)du$$

$$-\infty < s < \infty, 0 \le \theta < \pi$$

- The image reconstruction problem is to determine $f(x,y)$ from $g(s,\theta)$.



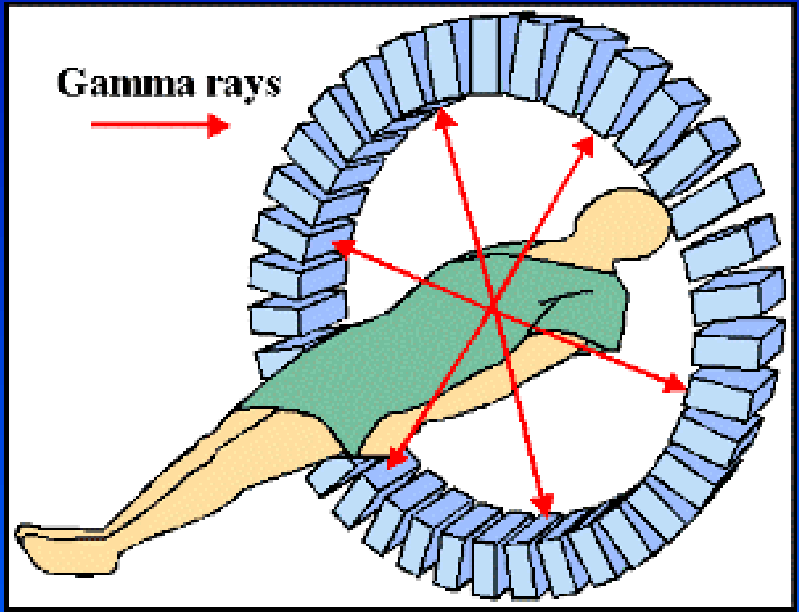
Typical CT Montage



Some soft tissue detail is visible on the best modern CT images

CT slices through torso

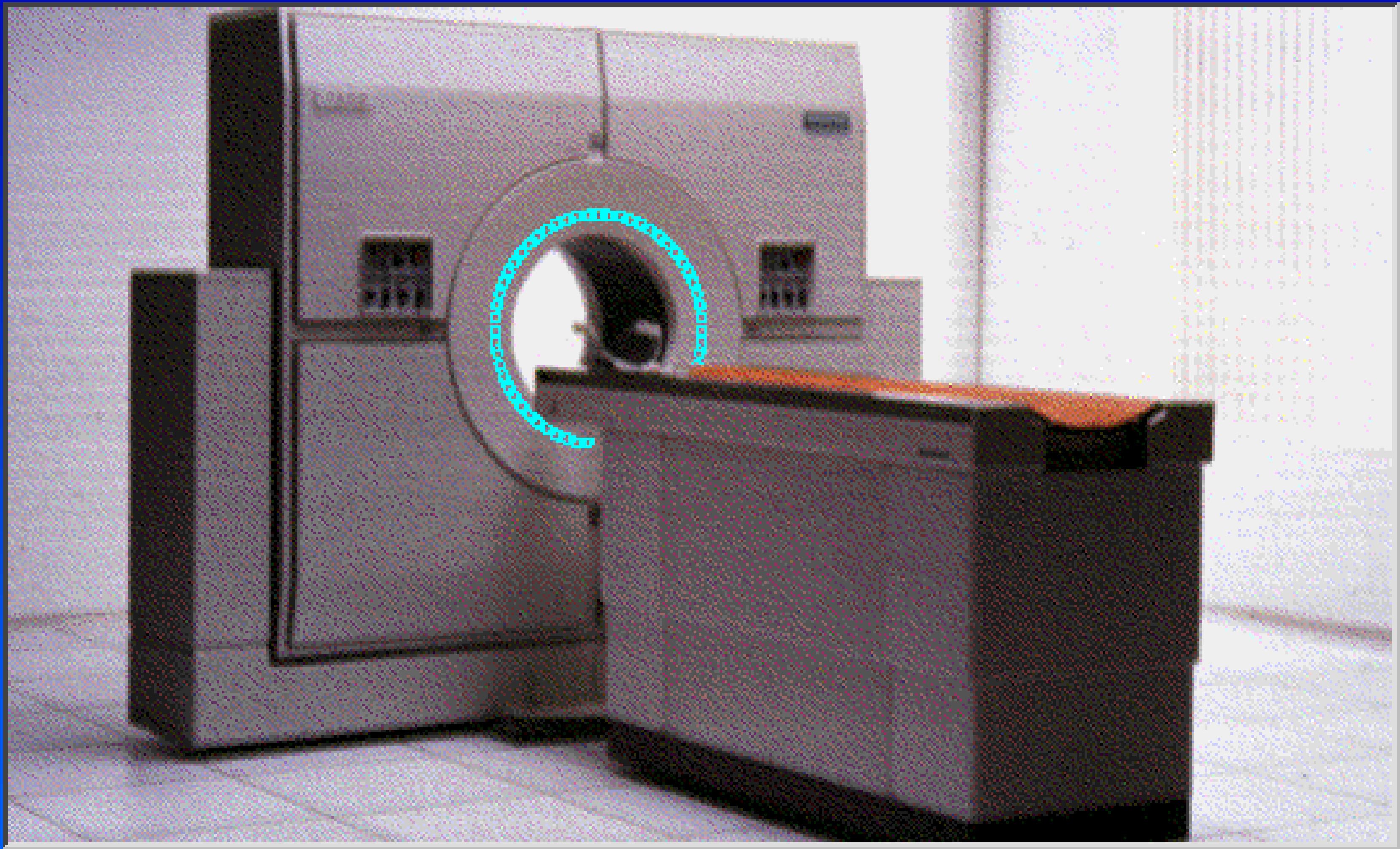
Positron Emission Tomography (PET)



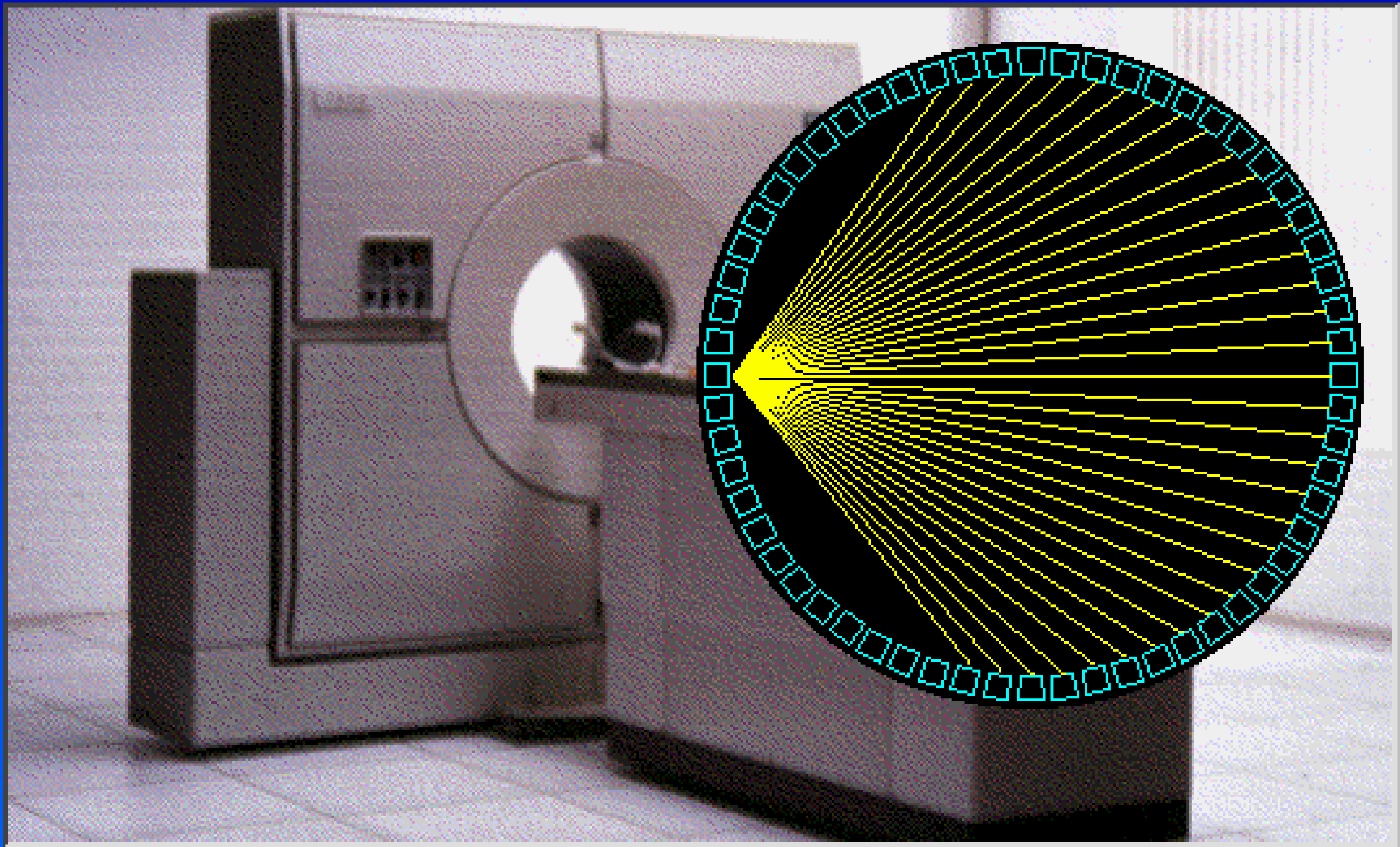
Inject (short-lived) positron emitting isotope.

Positron annihilates with electron giving pair of back to back 0.511 MeV gamma rays.

Detect both gammas using fast (5ns) coincidences, get "Line of Response" (LOR). Reconstruction of tracer distribution similar to CT – Radon Transform again.



(C) 1994 Crump Institute for Biological Imaging UCLA School of Medicine



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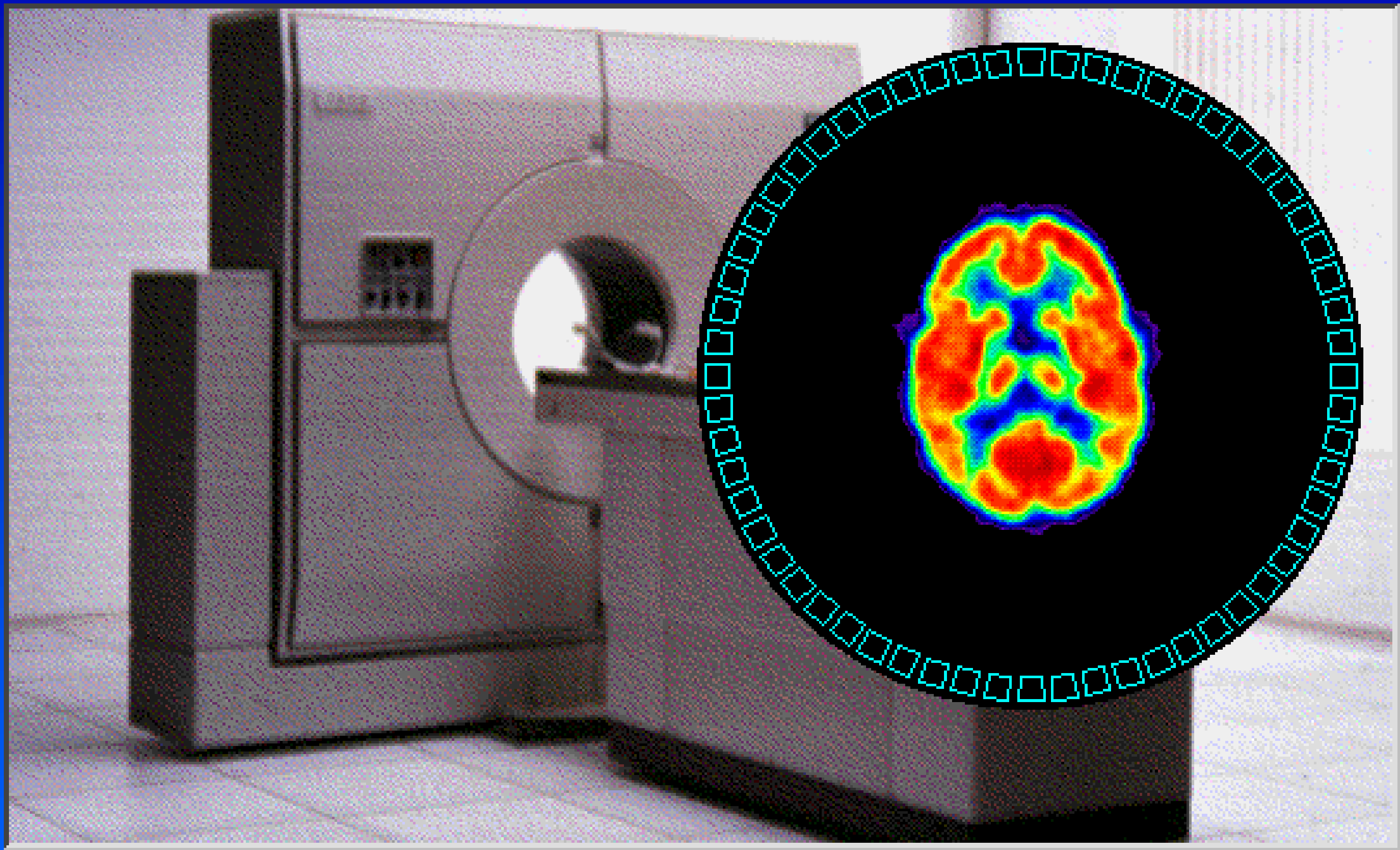

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Isotopes used in PET

	^{18}F	^{11}C	^{13}N	^{15}O	^{68}Ga
Maximum Energy (MeV)	0.63	0.96	1.20	1.74	1.90
Most Probable Energy (MeV)	0.20	0.33	0.43	0.70	0.78
Half-Life (mins)	110	20.4	9.96	2.07	68.3
Max Range in Water (mm)	2.4	5.0	5.4	8.2	9.1

Isotopes produced on Hospital Site

Tracers

^{15}O (Inhale, H_2O)

^{11}C (CO, CO_2)

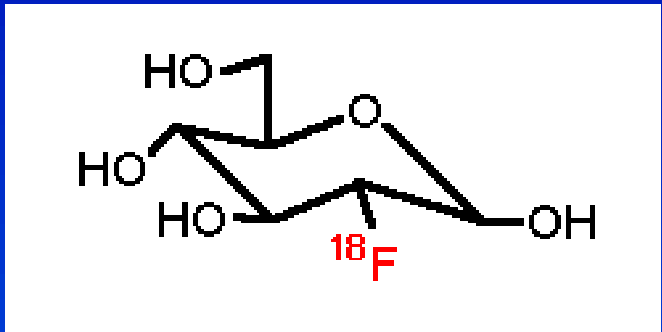
^{18}F (FDG)

…

Molecular imaging

GE Medical Systems PETtrace Cyclotron

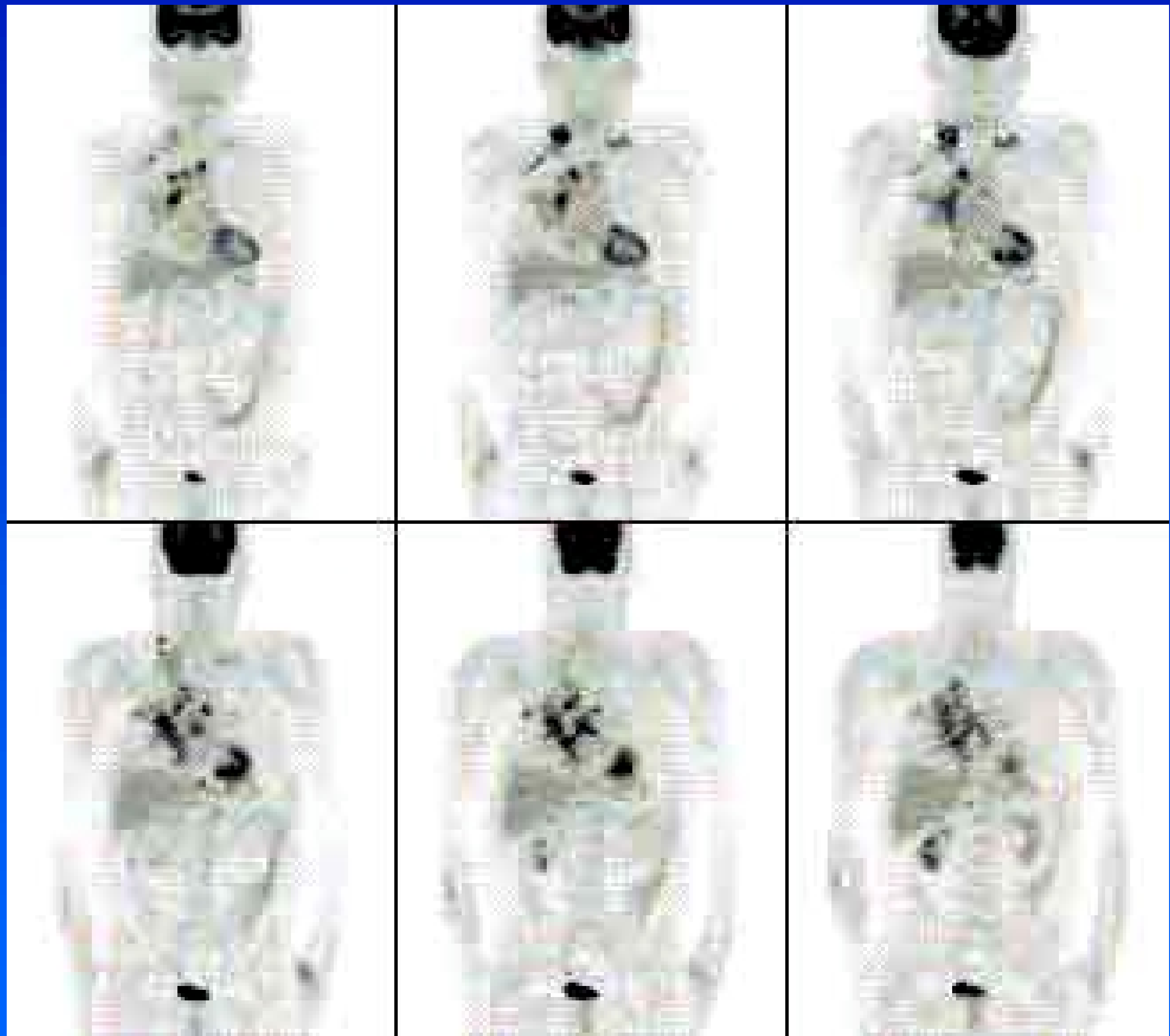
FDG or Fluorodeoxyglucose



The single most important PET tracer.

FDG follows the same metabolic pathway as Glucose, i.e. it is “burnt” in actively metabolizing cells. THEN the ^{18}F stays put. Thus ^{18}F accumulates at “hot-spots” of high metabolic activity.

Whole Body PET



PET Visualization

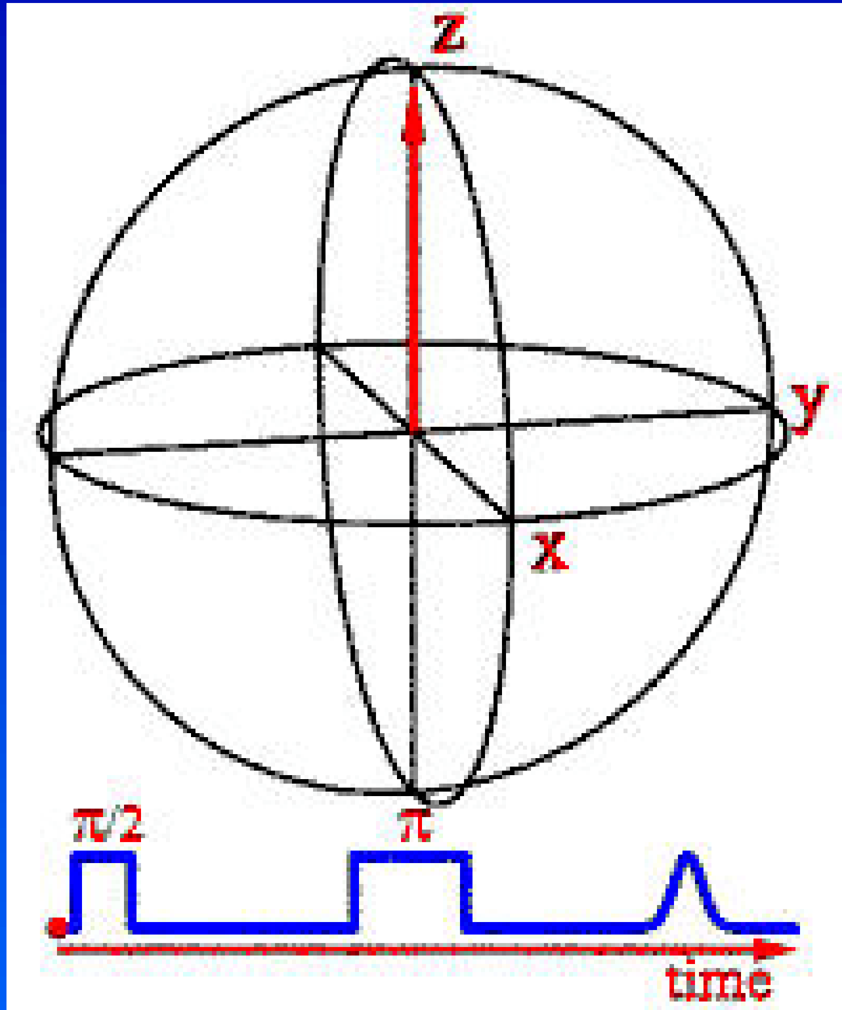
F-18 fluorodeoxyglucose (FDG). Patient with colorectal cancer. Image is maximum intensity projection through attenuation corrected whole body image, acquired in multiple axial fields-of-view and reconstructed with OSEM algorithm. High uptake is seen in the kidney, liver, bladder, and tumor.

Magnetic Resonance Imaging (MRI)

Magnetic Resonance Imaging (MRI)

- Protons are spin ½ and have a magnetic moment
- Line up spins with magnetic field
- Peturb – spins precess and emit em radiation
- Precession frequency is 42.6 MHz /Tesla for ^{1}H

Same method used in both NMR & MRI. MRI employs additional magnetic field gradients to obtain 3D image of proton density



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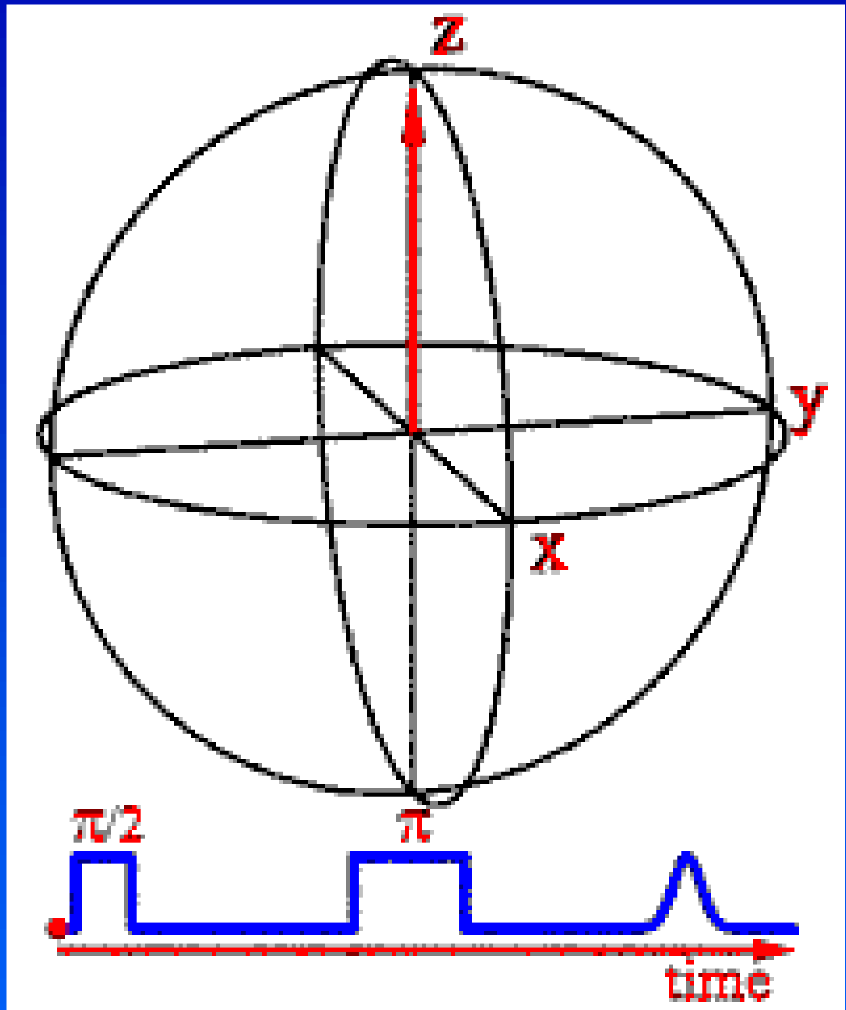

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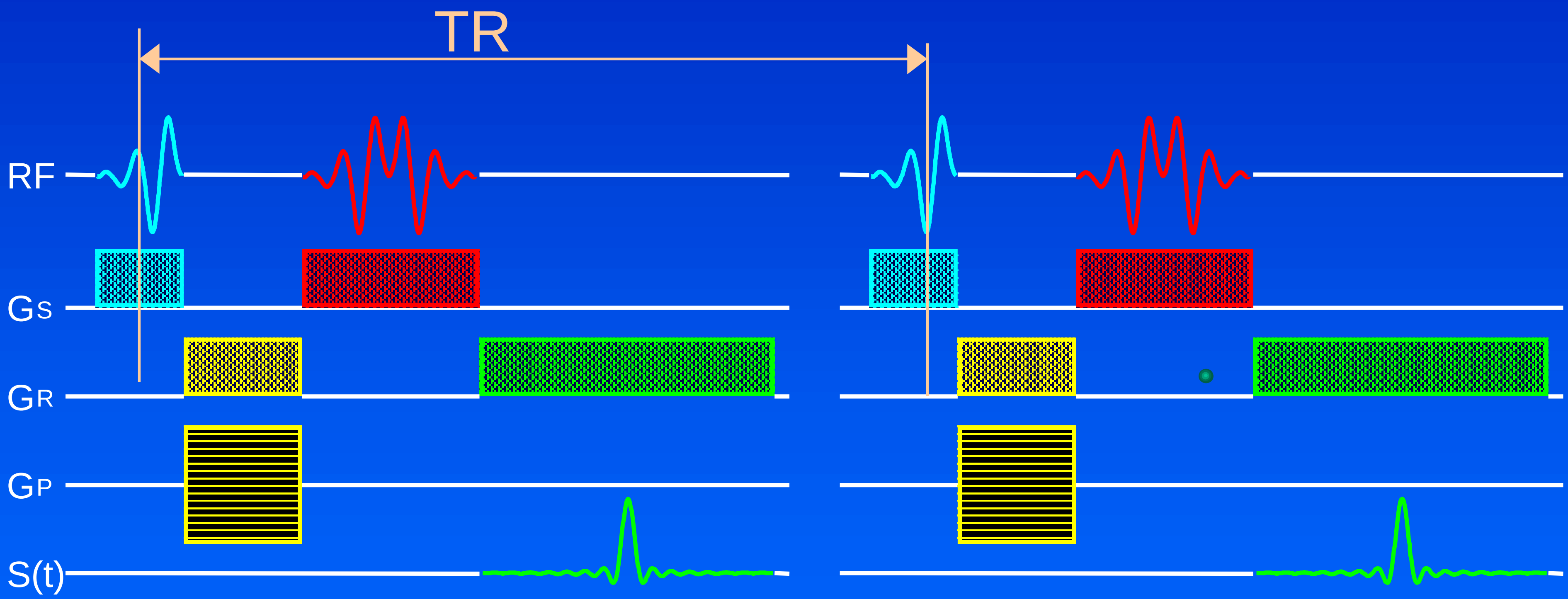
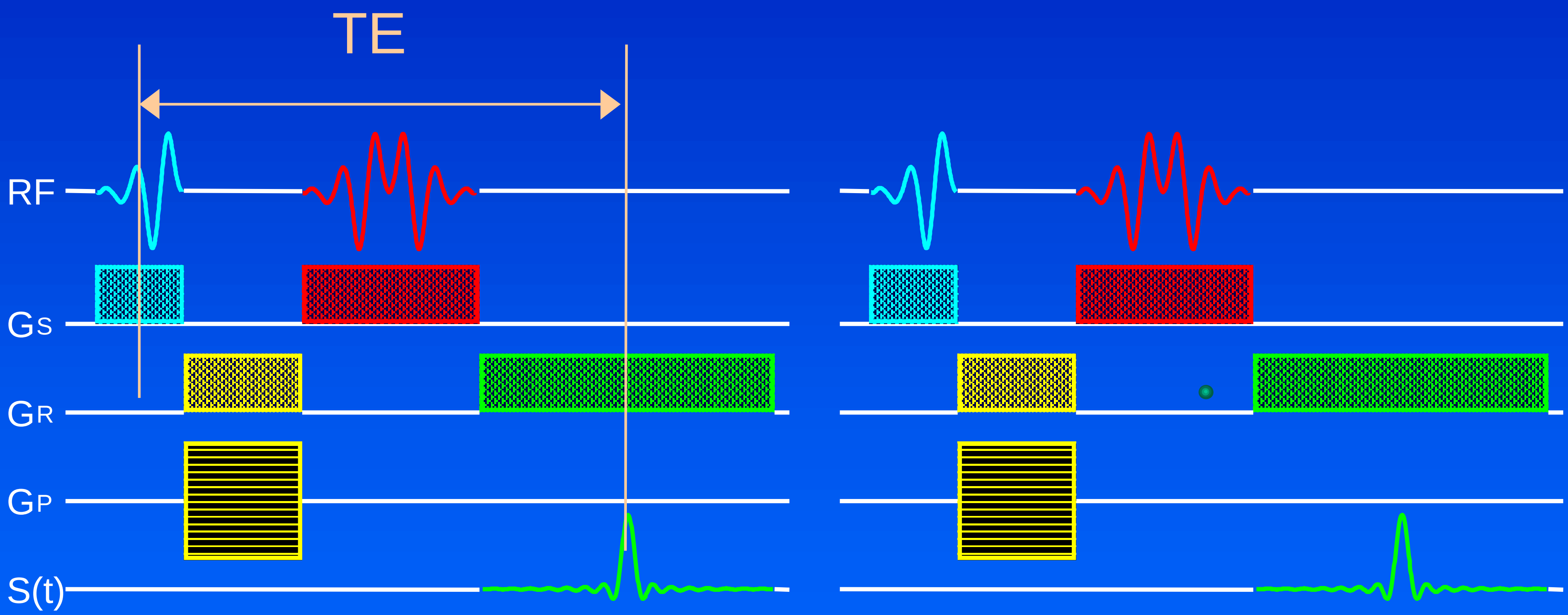
Typical MRI Sequence

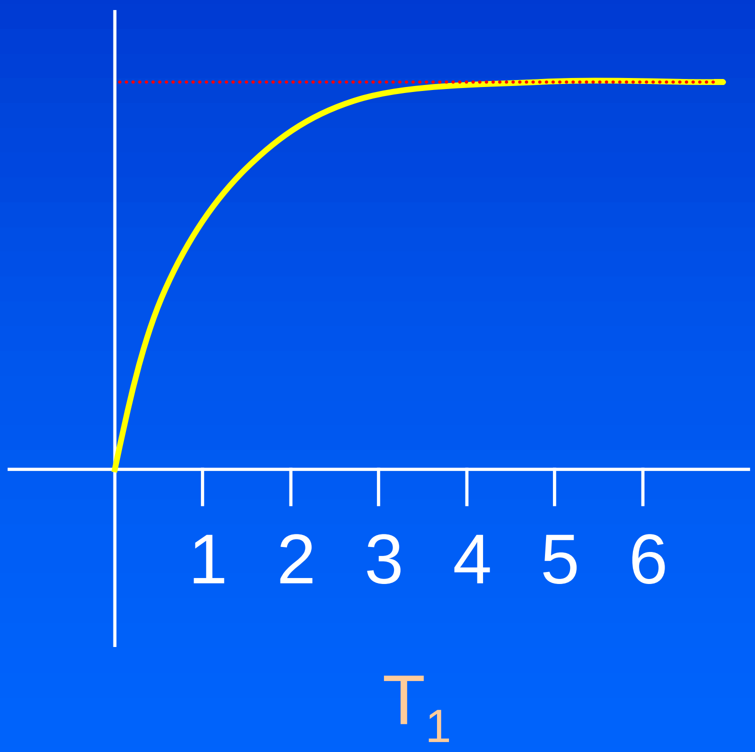


TE – Time to echo

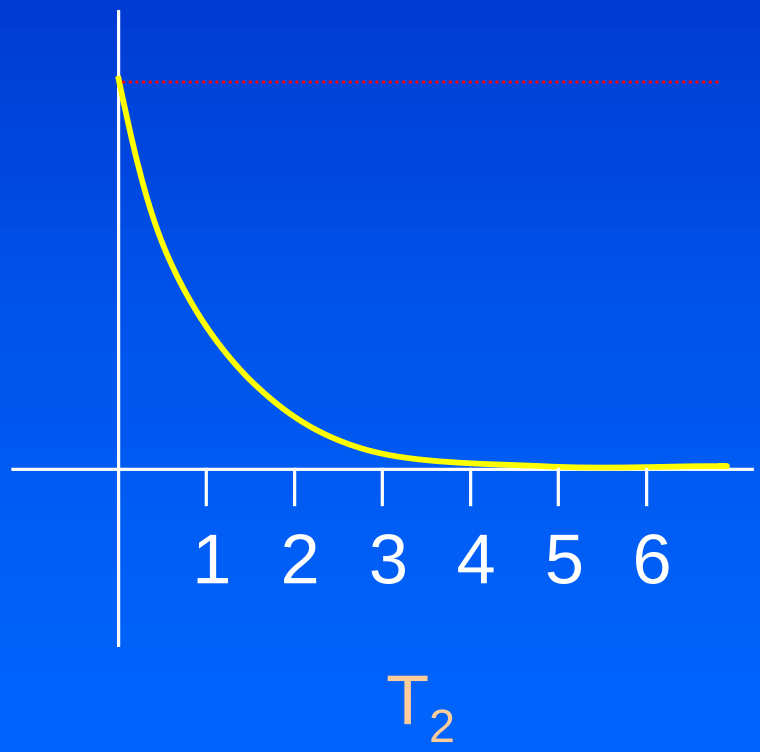


Controlling contrast

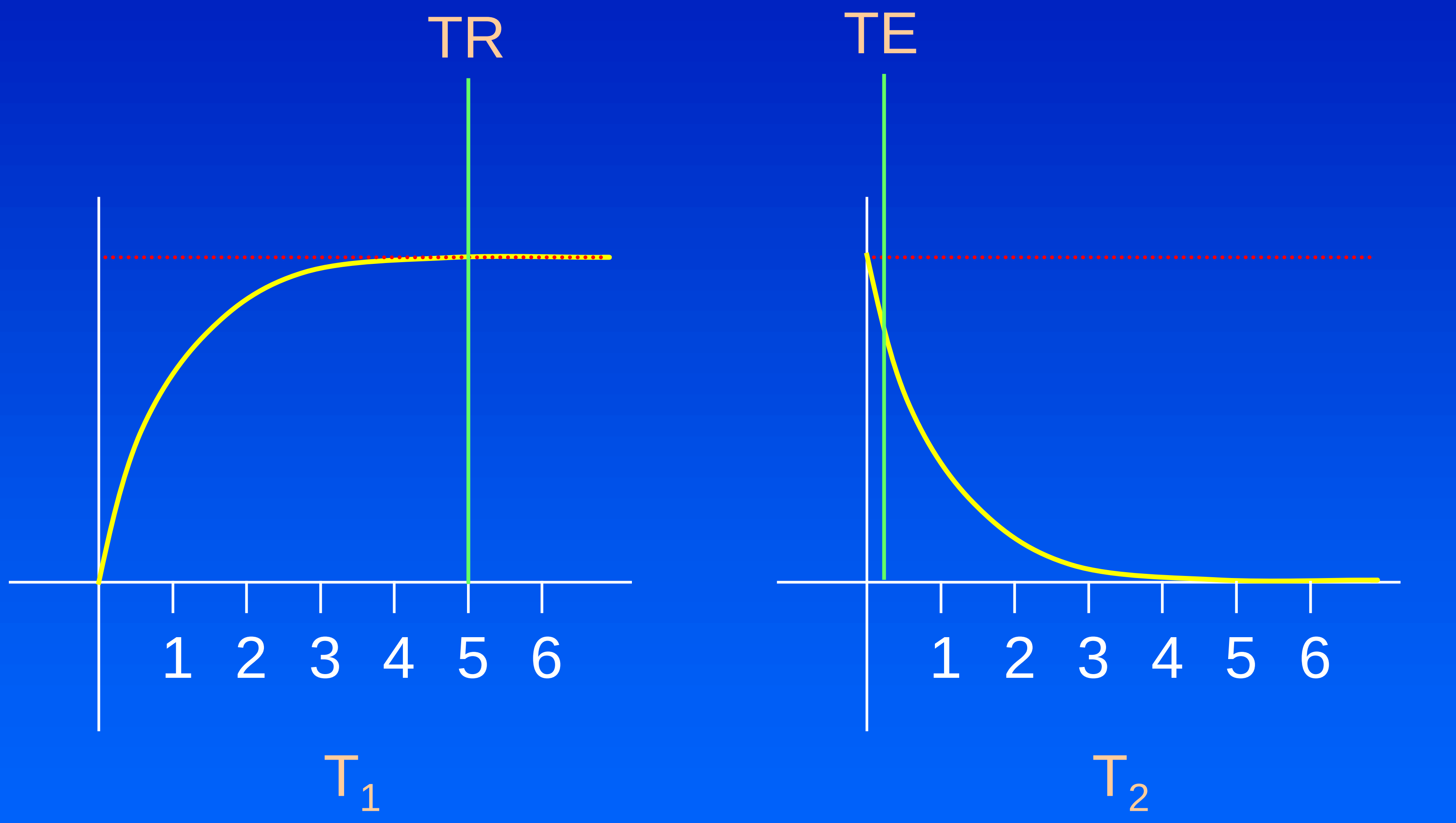
Spins in x-y plane relax back to z axis



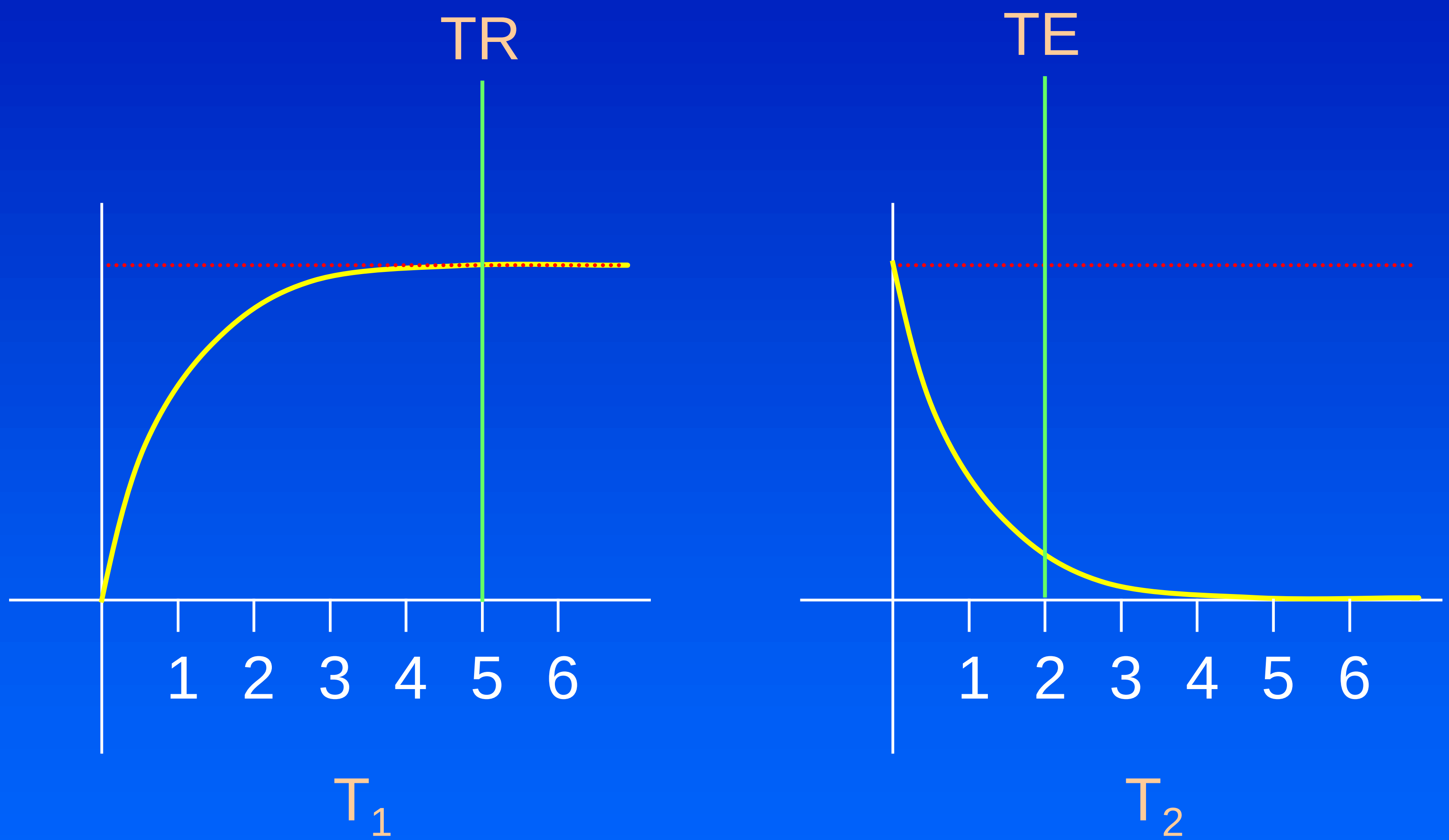
Spins in x-y plane dephase



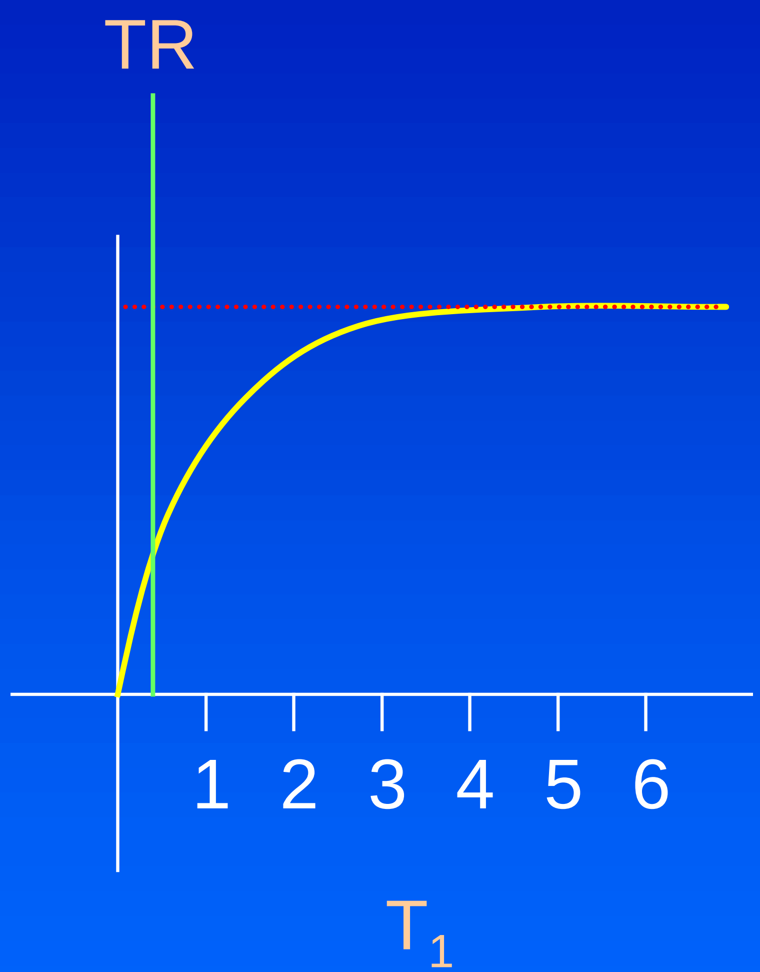
Proton Density Weighting

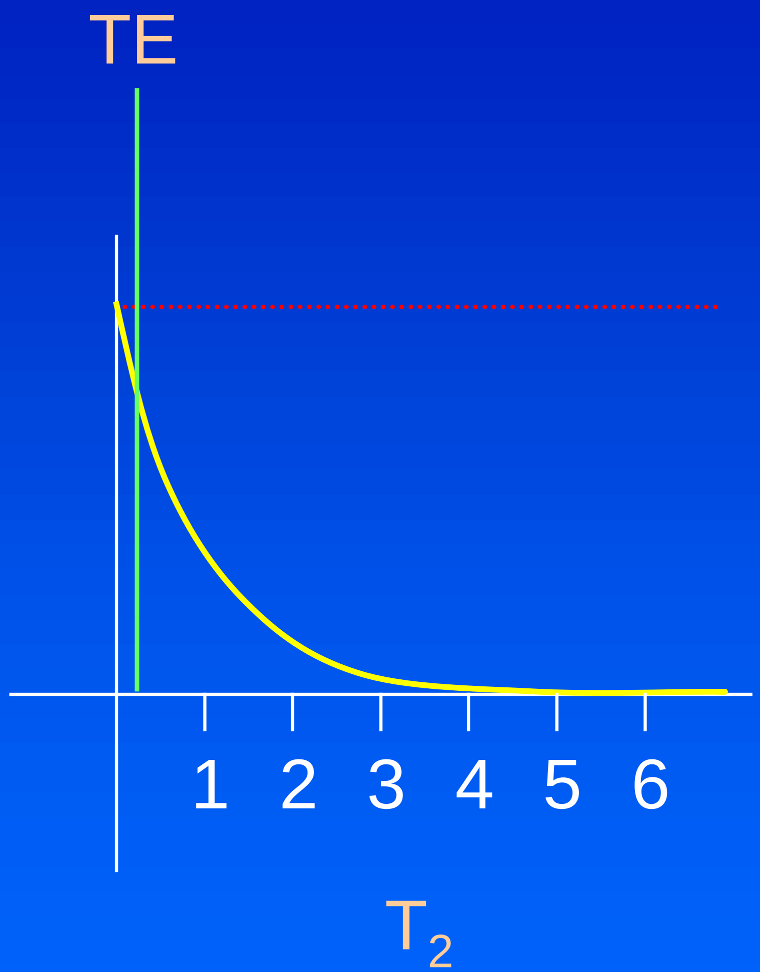


T_2 Contrast

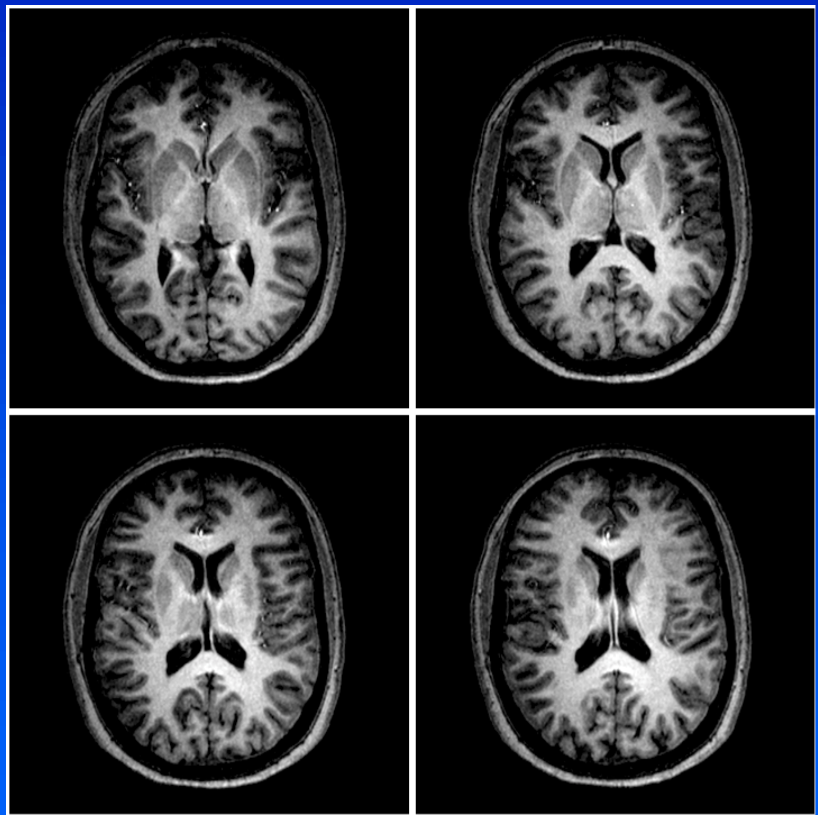


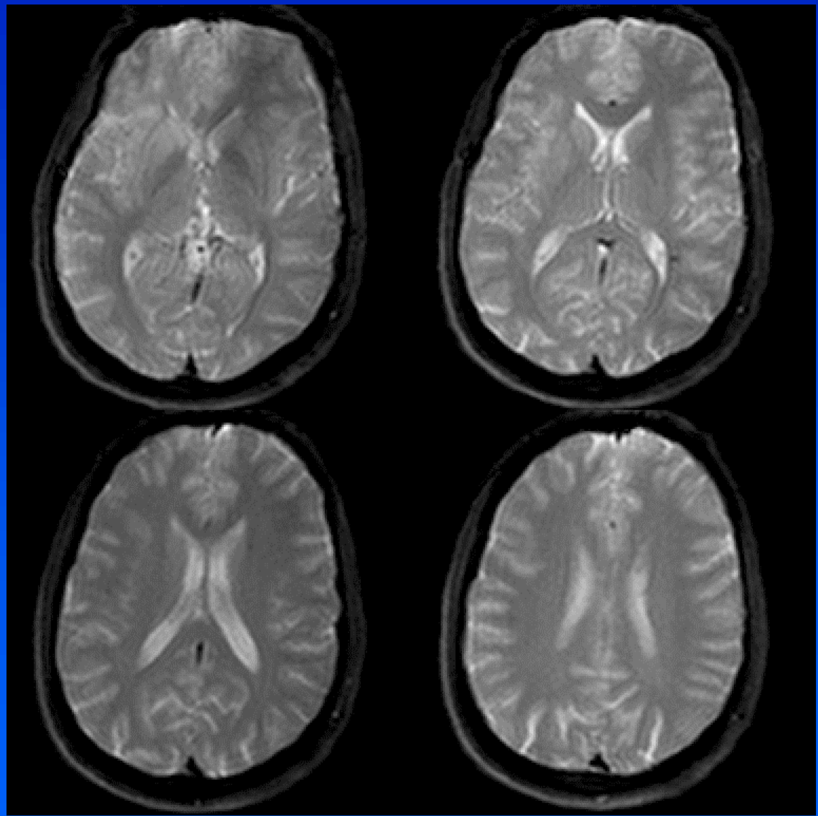
T_1 Contrast



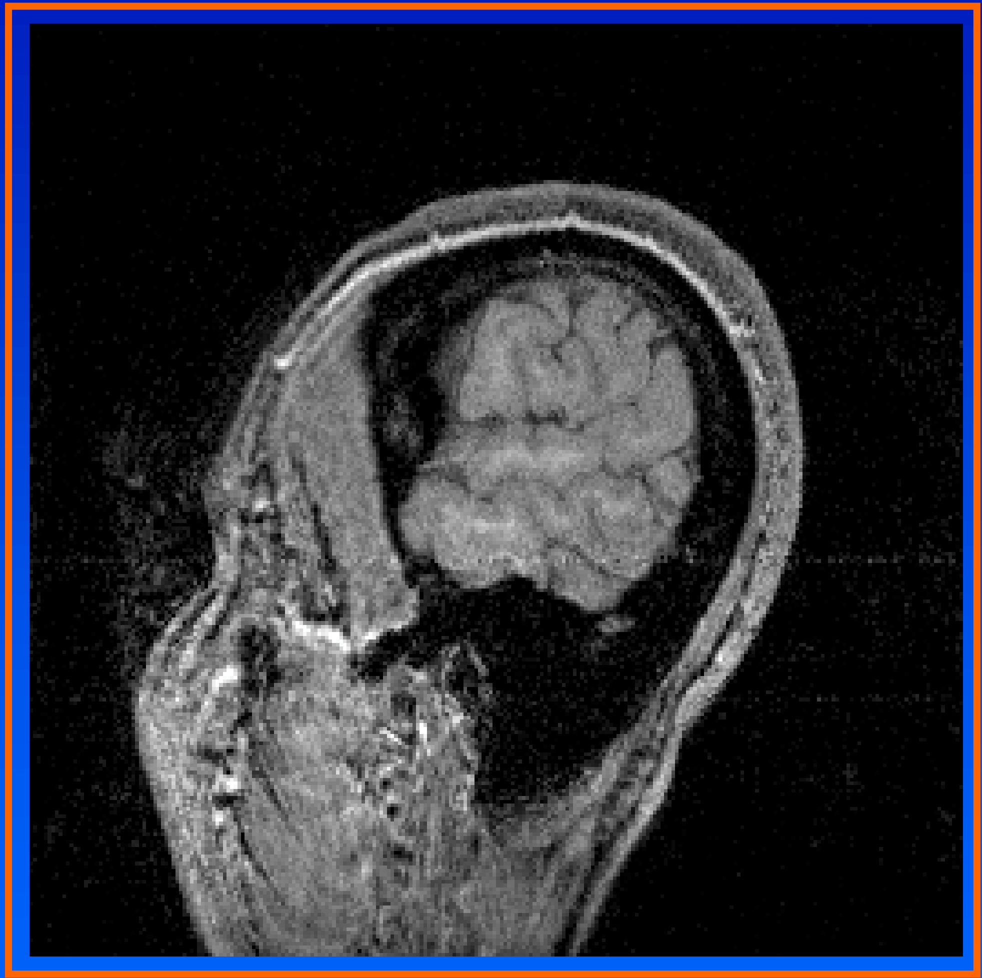


MRI Soft Tissue Contrast





Full 3D brain scan from 3T MRI at WBIC



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fMRI (functional MRI)

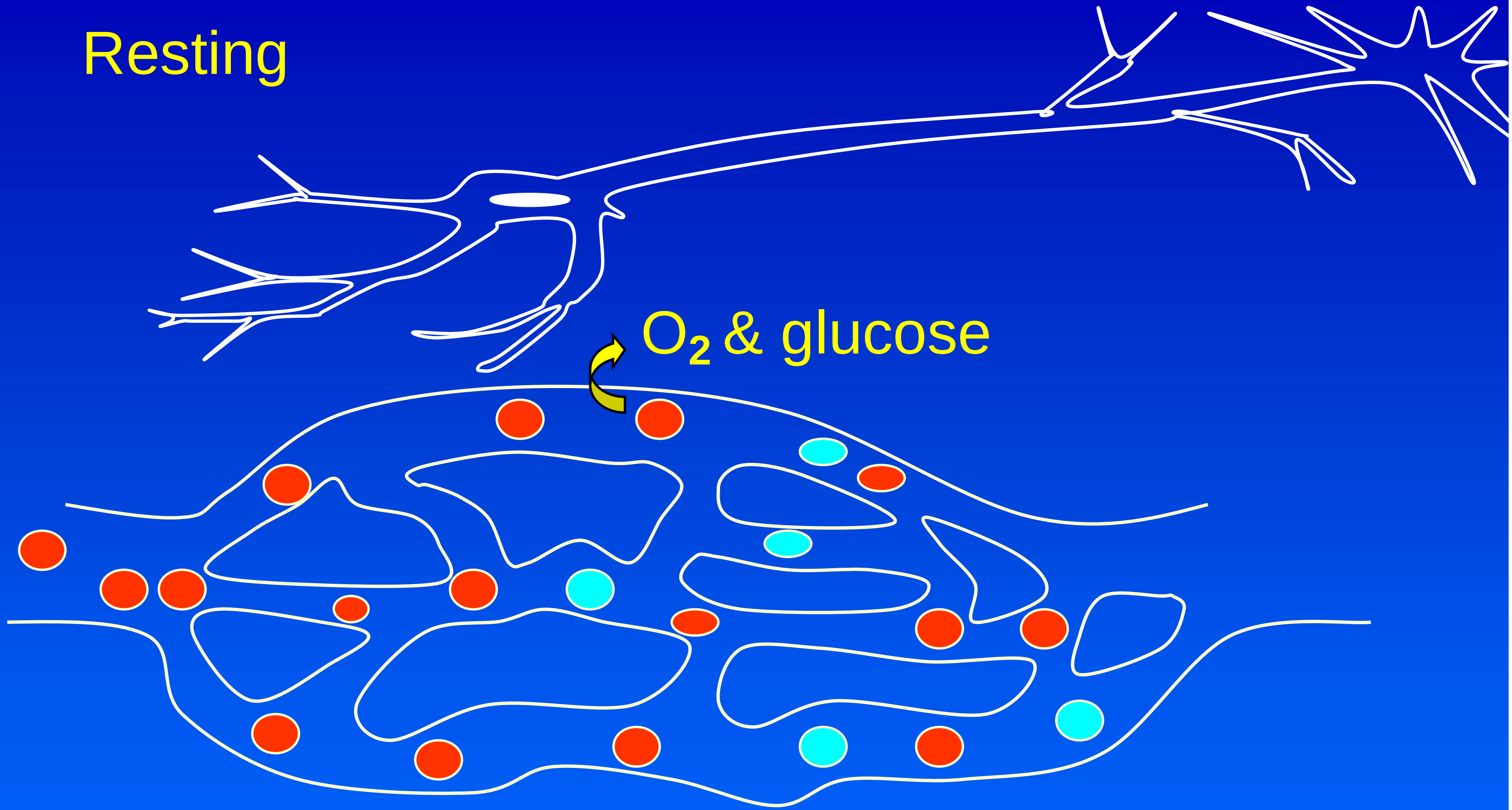
Monitor T2 or T2* contrast during cognitive task

eg acquire 20-30 slices every 4 seconds

Design experiment to have alternating blocks of task and control condition

Look for statistically significant signal intenisty changes correlated with task blocks

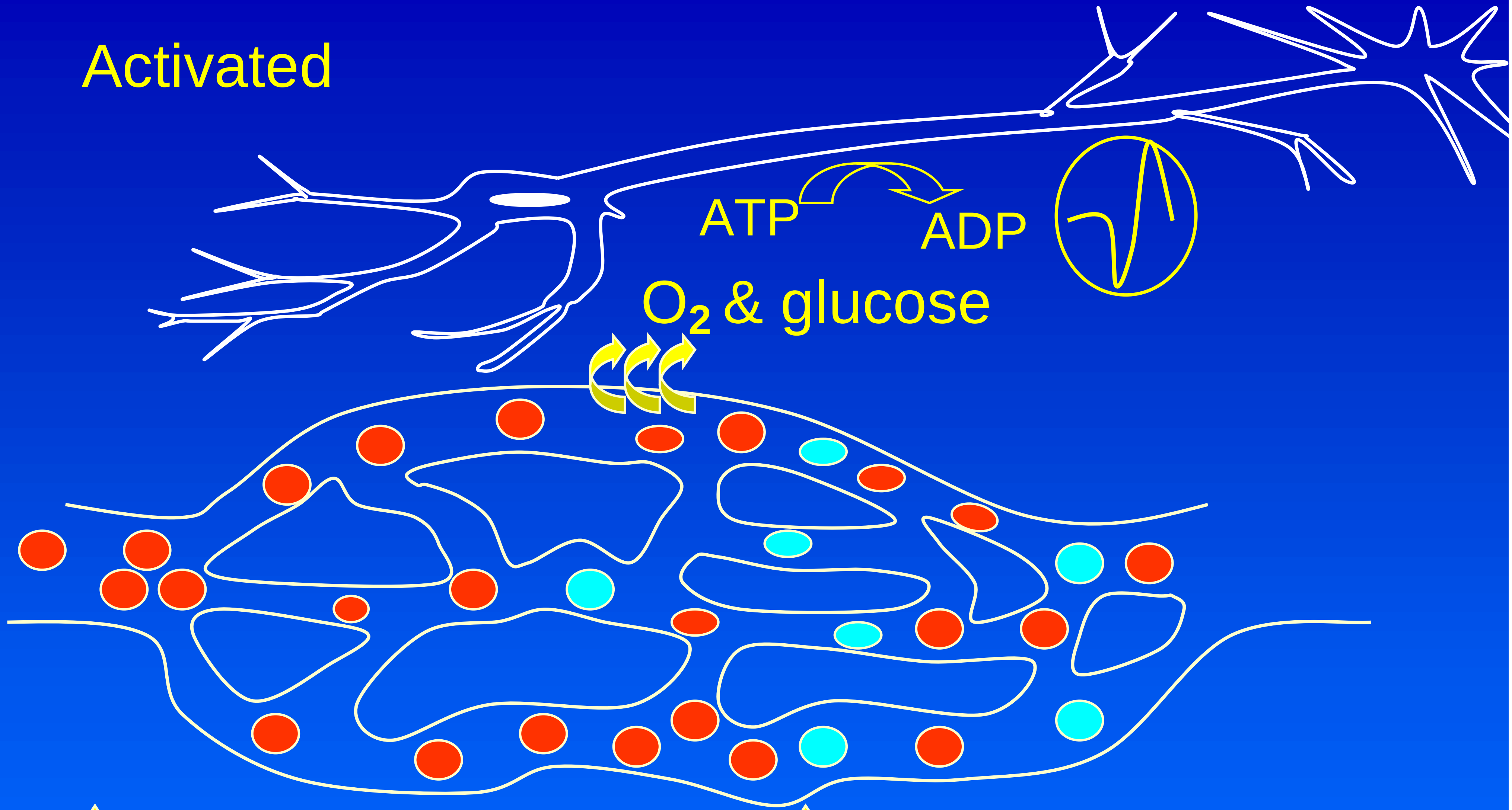
Resting



oxyhaemoglobin

deoxyhaemoglobin

Activated



↑ Blood flow
'over-compensation'

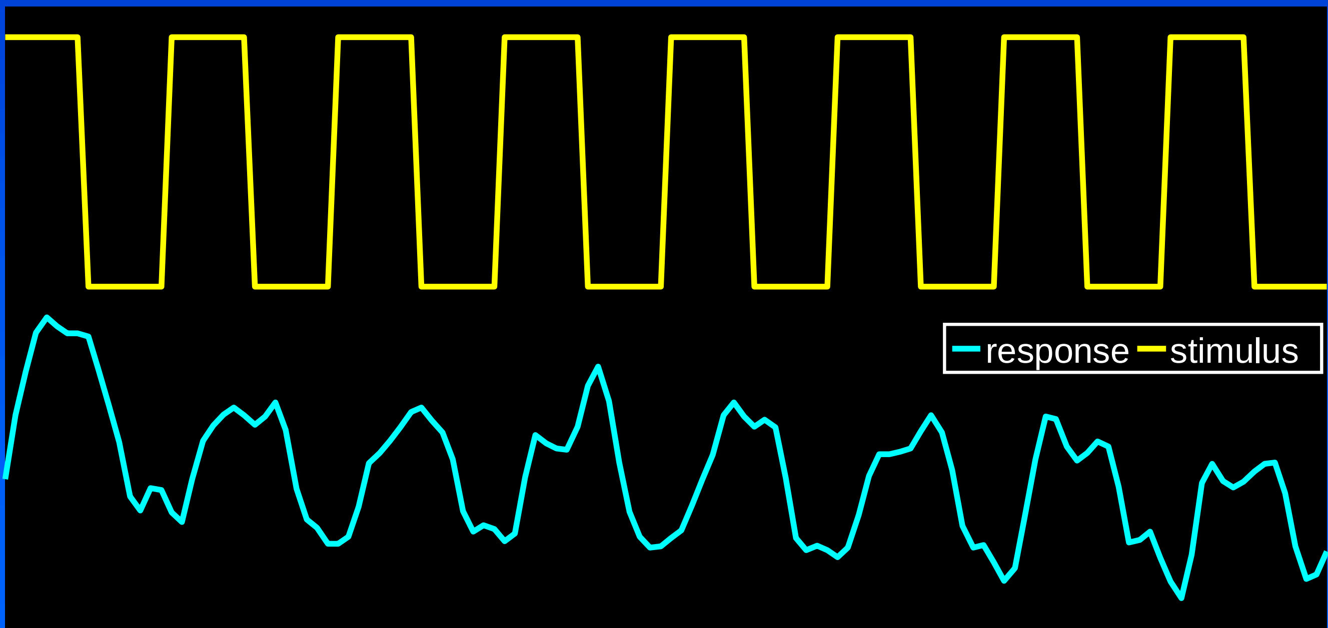
↑ $\%O_2$

↑ BOLD signal

Finger Tapping Experiment

Echo-Planar fMRI – Typical Data

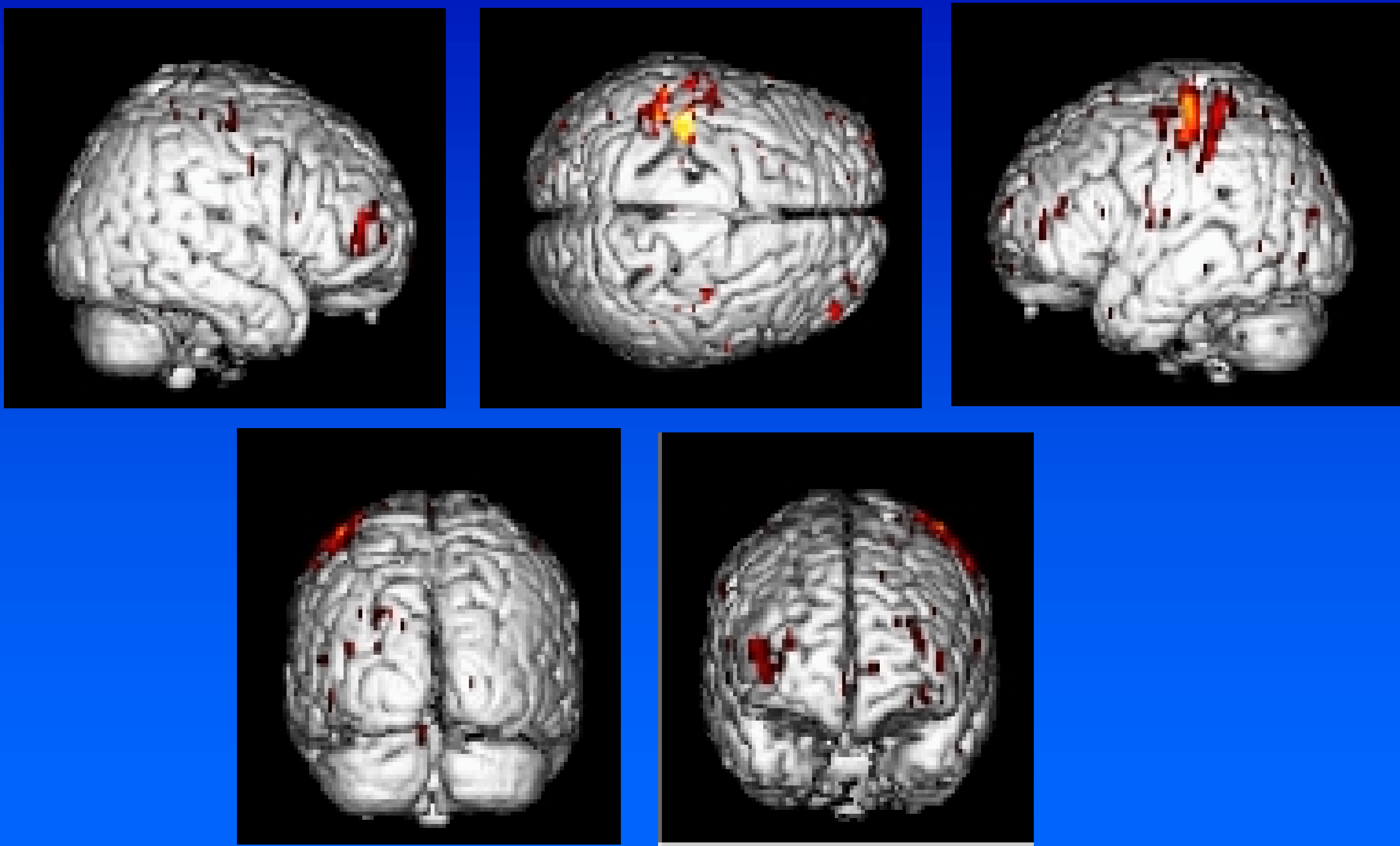
N.B. Signal/Noise ration is generally poor



GE-EPI images fMRI correlation maps

Signal response averaged over region

Finger Tapping Experiment



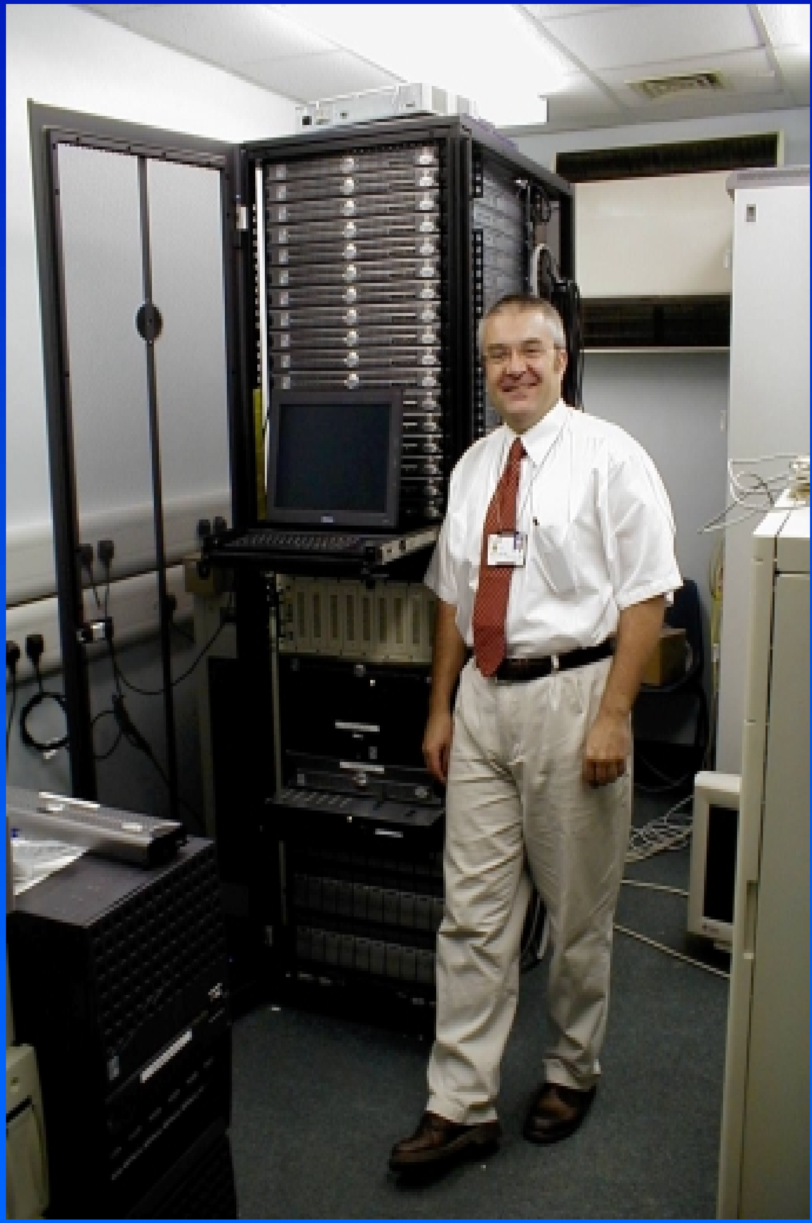
Computational Challenges

- Improved image reconstruction: eg 3D PET
- Simulation: eg BOLD response
- Visualization of 3D data sets
- Image registration, *inter* and *intra* modalities

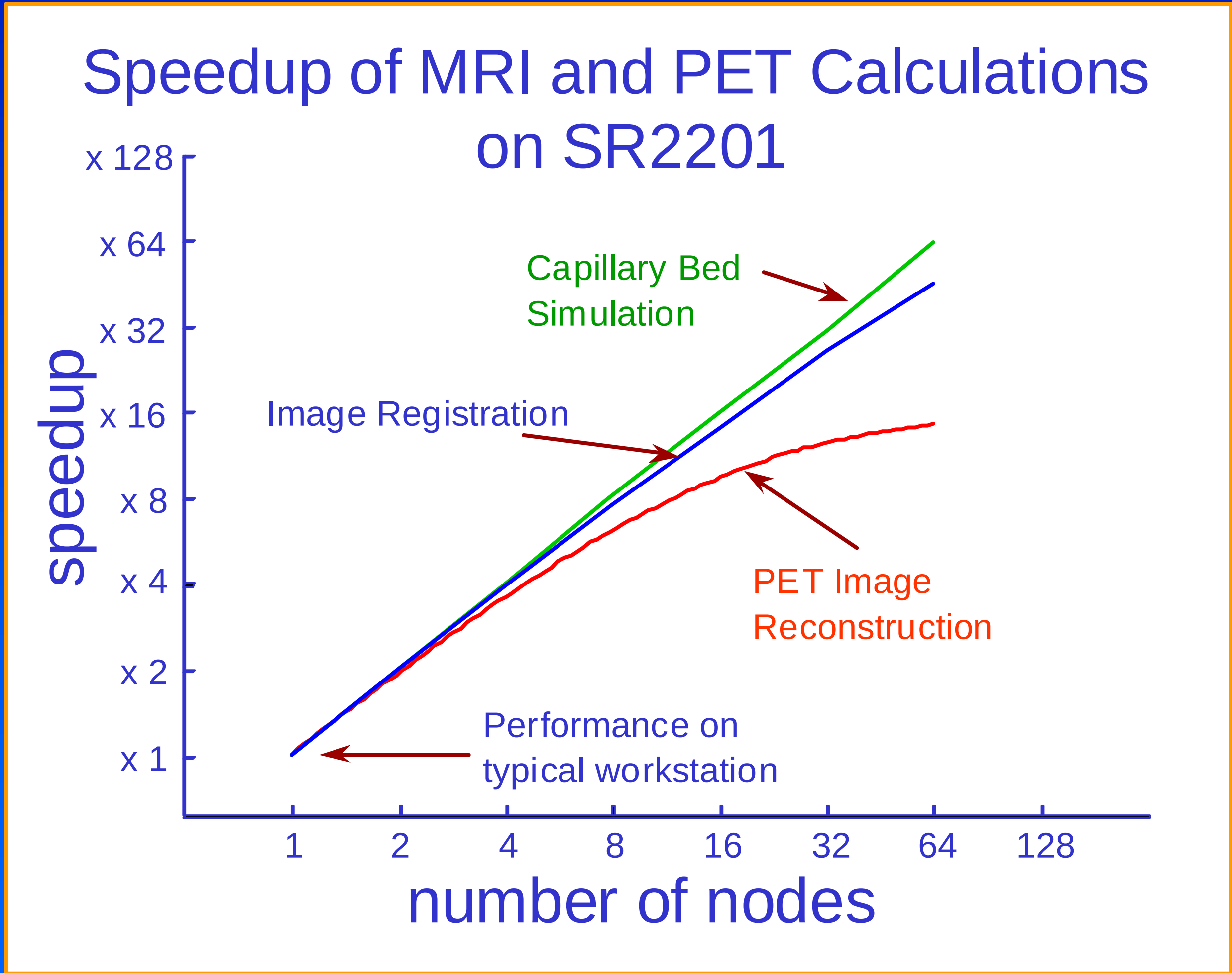
Commodity PC's have a role to play in the clinic

PC Cluster in Addenbrooke's Hospital

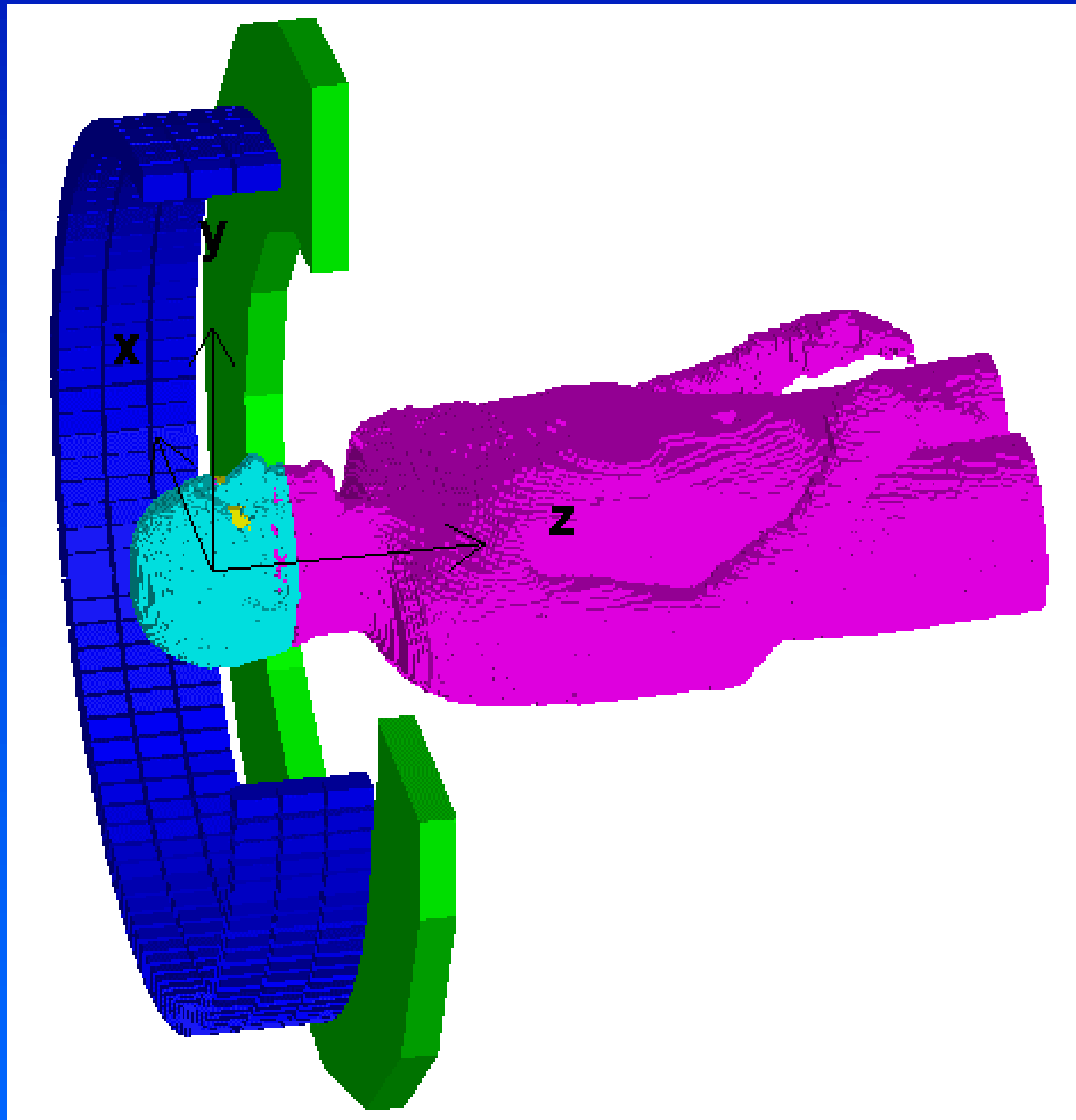
- 16 Dual 900 MHz (Dell 1550) 1Gb RAM
- Interconnect 100BaseT Extreme Networks Summit 48
- OS GNU/Debian Linux, LAM 6.3
- FORTRAN, C, C++ & MPI extensions
- Intel ICC compiler

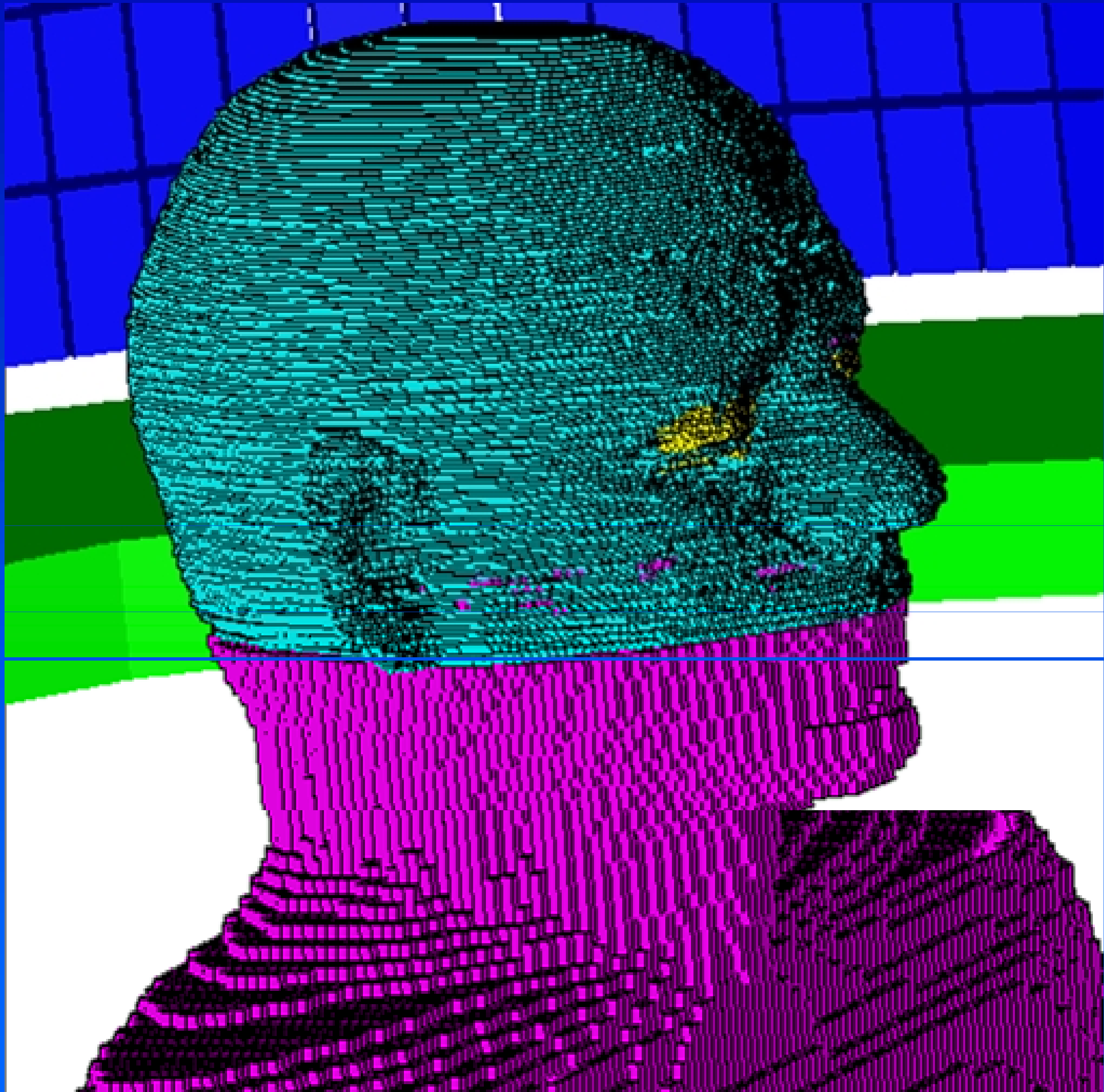


Speedup on Parallel Computer



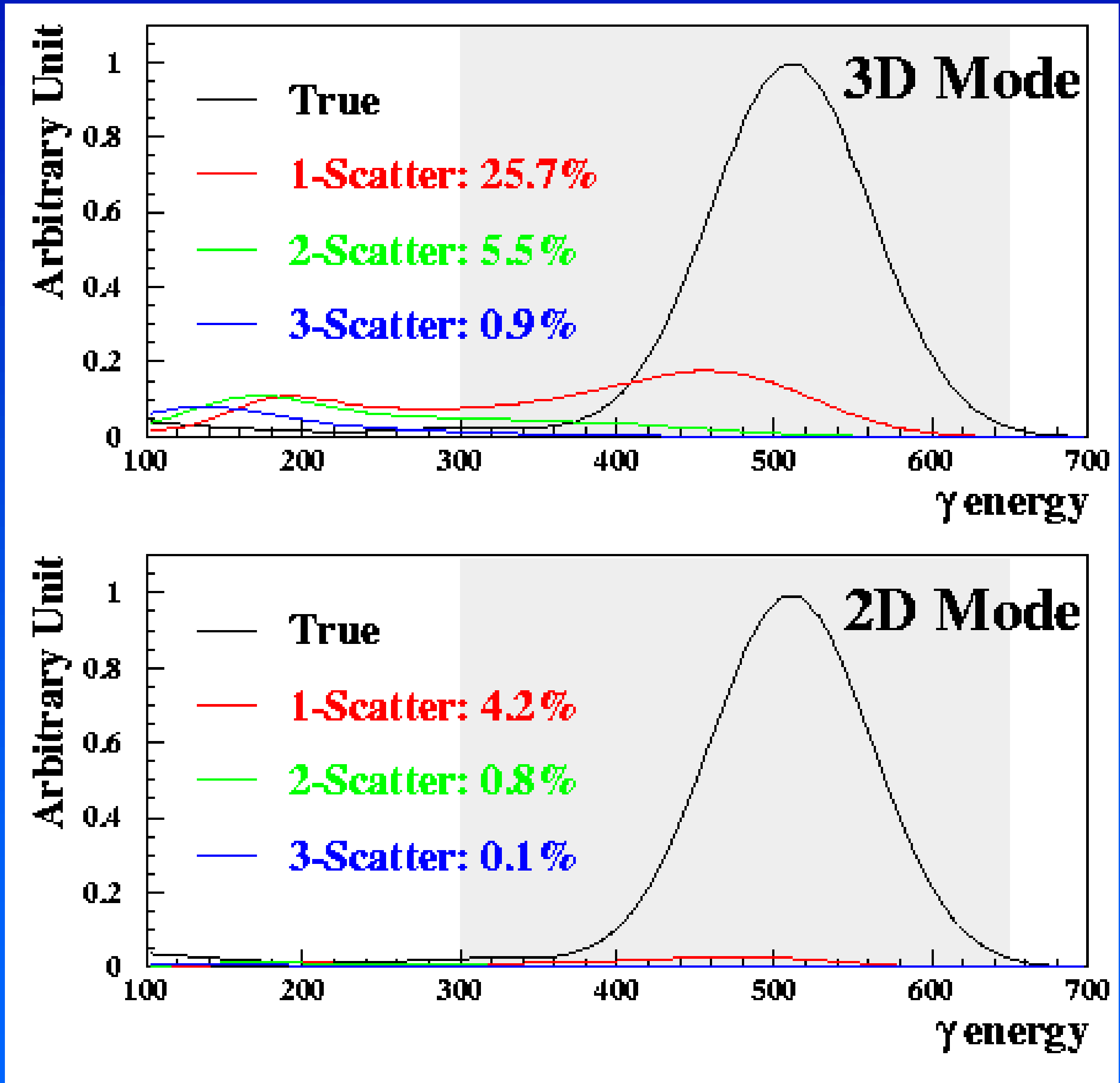
CERN GEANT used to simulate PET Scan





A High resolution anatomical phantom was used in the simulation

PET Simulation Results – CERN GEANT

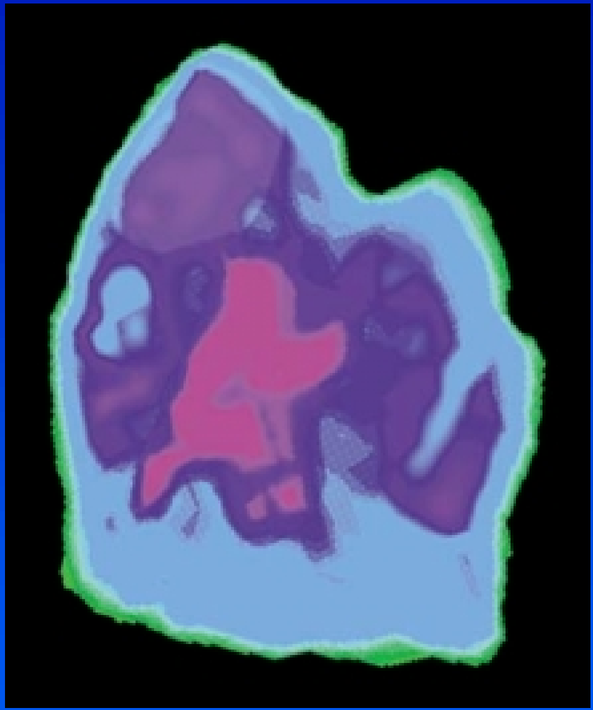


Contributions from direct and indirect gammas in both 2D and 3D modes.

Ultrasound

3D Ultrasound Imaging Group Departments of Radiology, Paediatrics and Reproductive Medicine, University of California, San Diego La Jolla, CA 92093-0610

Terahertz Imaging



Early days.

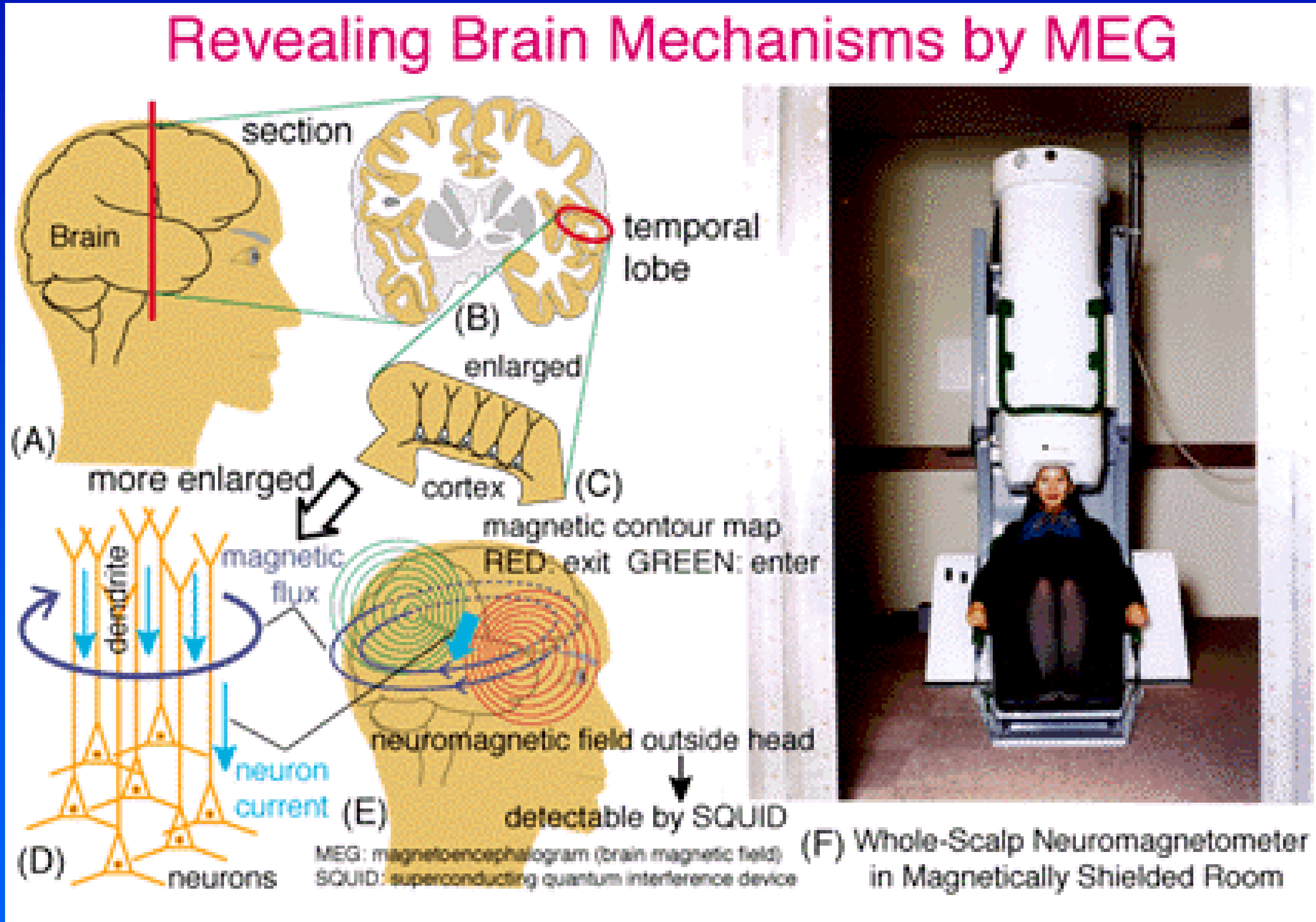
Limited depth of penetration.

Good for skin?

Image of Tooth

Physics World April 2000

MEG



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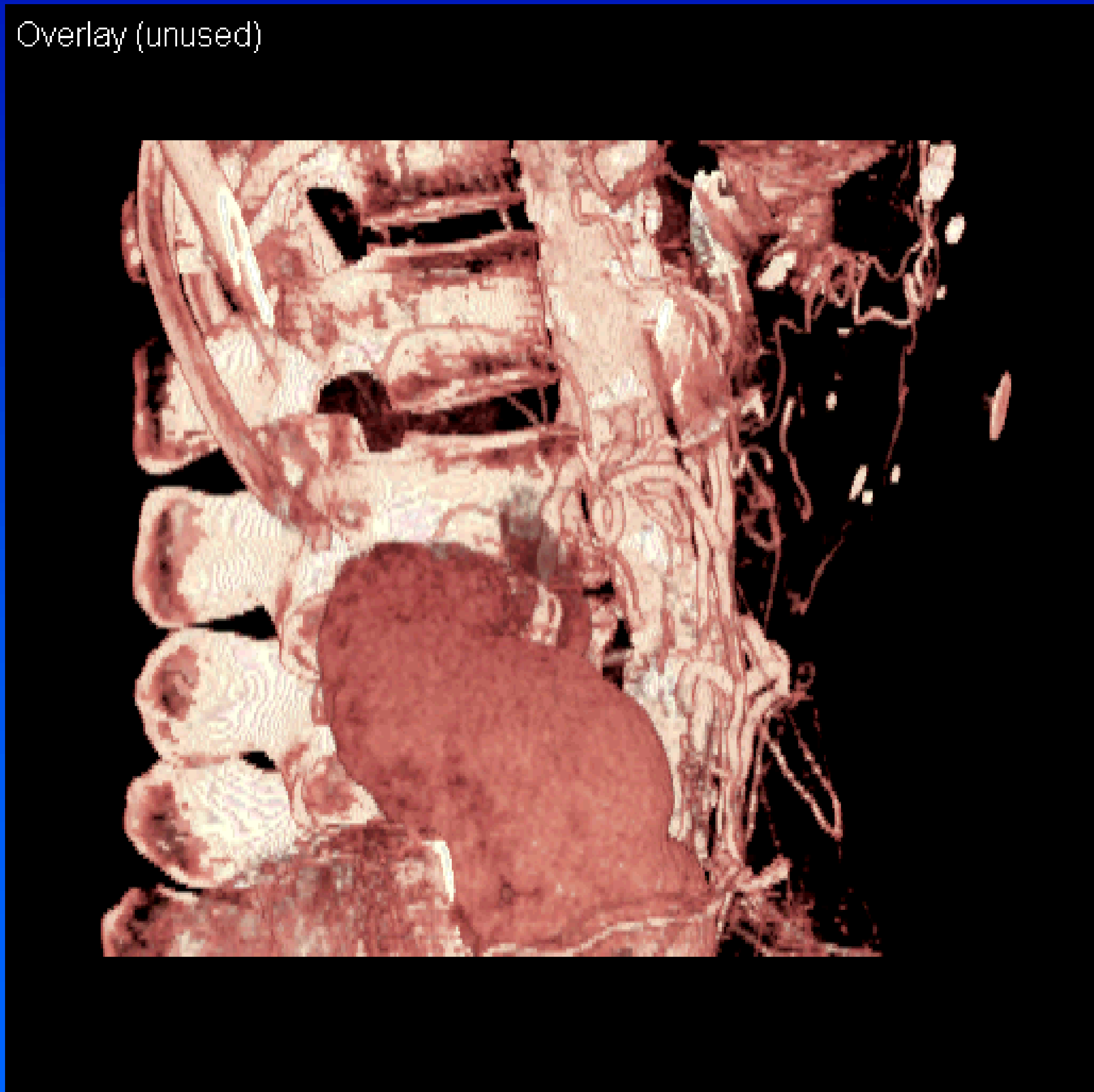
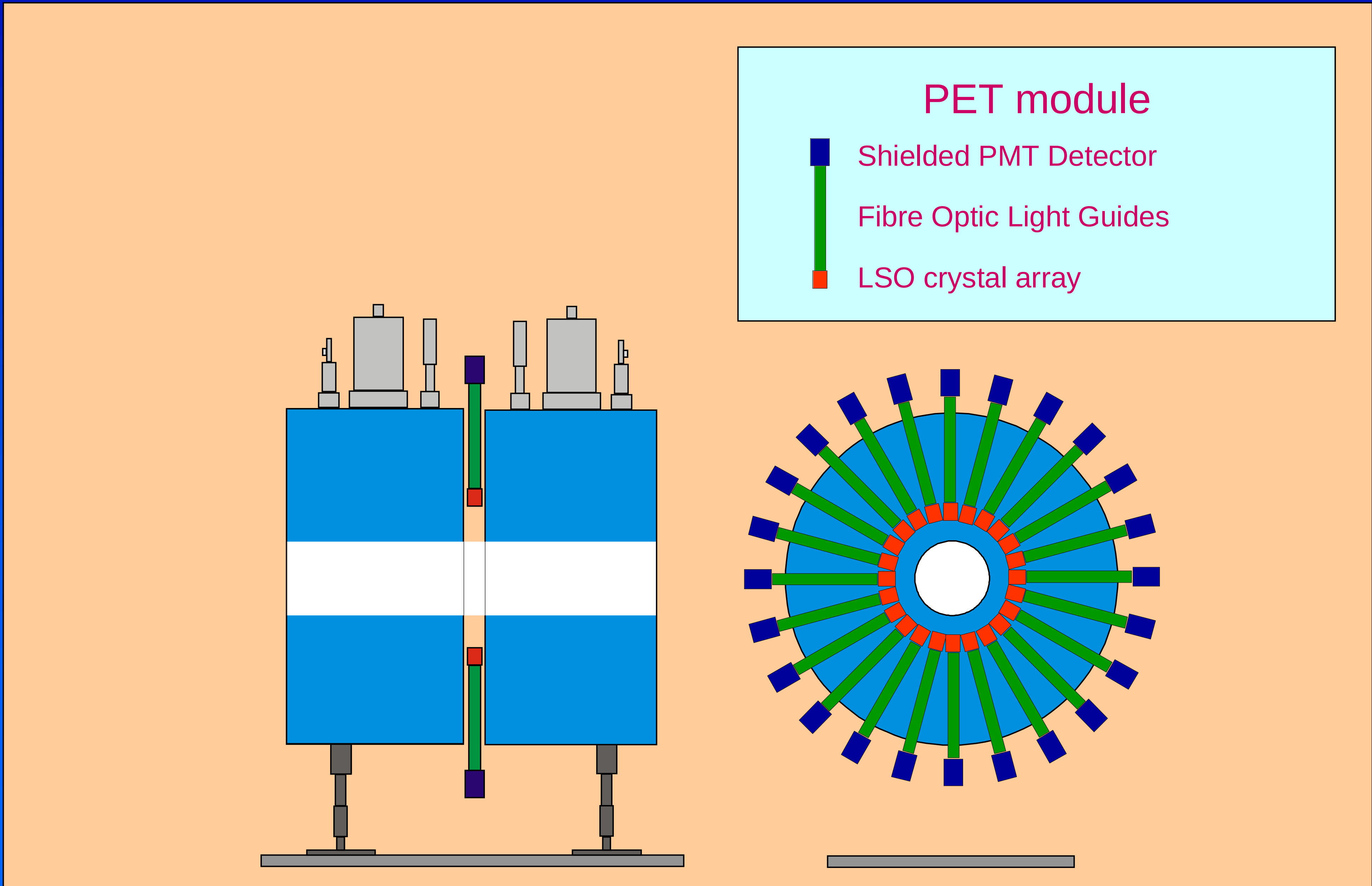
Visualization



Prototype PET/MRI System



References

MRI

“Principles of Magnetic Resonance Imaging”,
Zhi-Pei Liang & Paul Lauterbur, IEEE Press

http://www.cis.rit.edu/htbooks/mri/

http://www.brainmapping.org

PET

http://www.crump.ucla.edu/software/lpp/

General

http://www.wbic.cam.ac.uk