

Quantum Physics and Medical Imaging - MRI

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Cavendish Laboratory

and

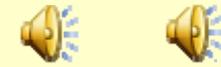
Fitzwilliam College



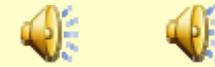
Magnetic Resonance Imaging - MRI

- Very Important
- Harmless
- Flexible
- Physics Experiment Using Magnetism
- First Clinical Scanner 1986
- Nobel Prizes for Medicine 2003
- Still rapidly developing
- Superconducting Magnets - CERN

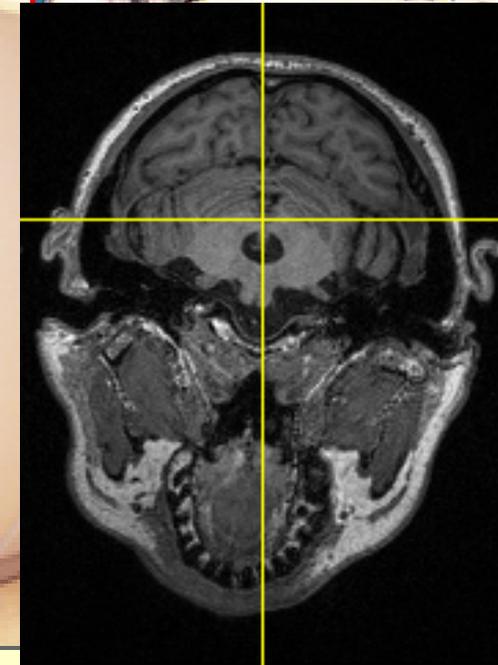
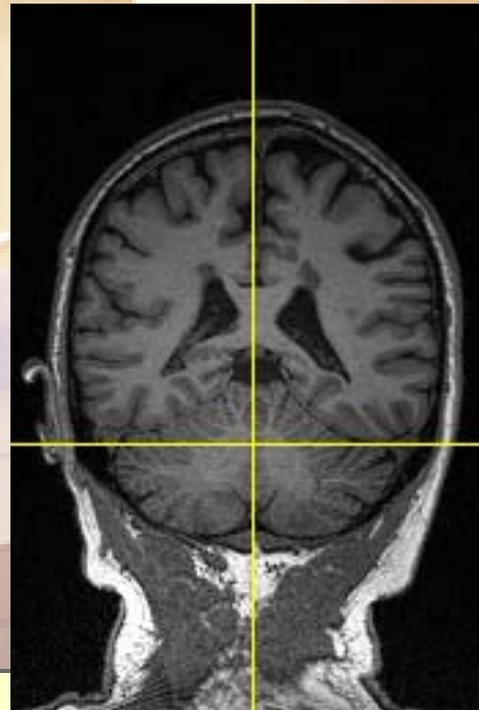
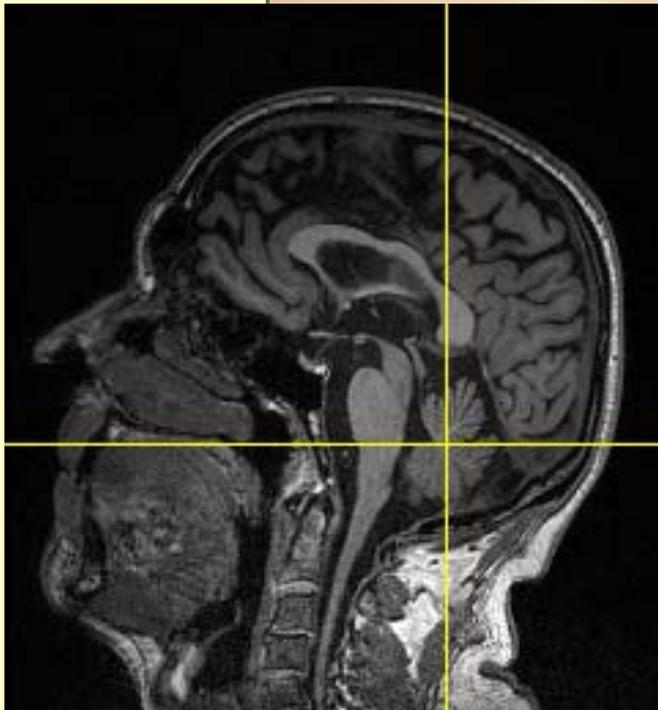
Clinical MRI Scan



Clinical MRI Scan

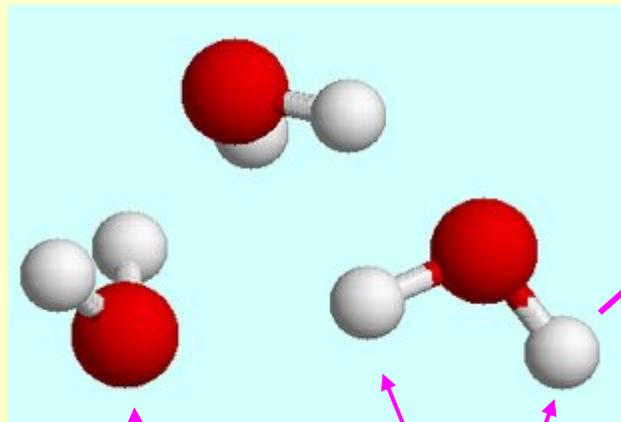


But how does it work?



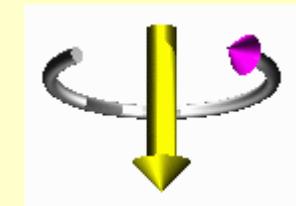
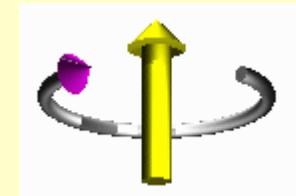
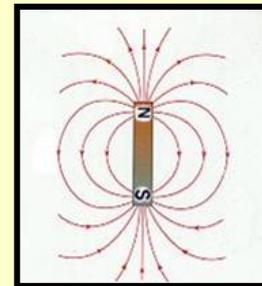
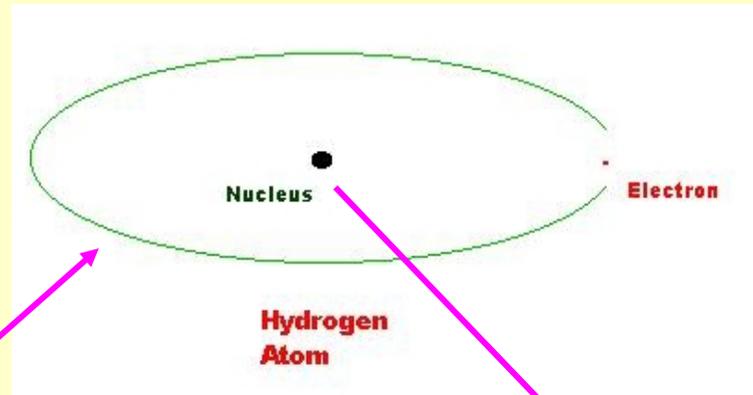
How it works (outreach version)

Water H_2O



O

H



Human body is
> 50% water!

Proton has spin
mini bar magnet

Outline

- Spin Physics
- MRI
- Clinical System
- Applications

Spin

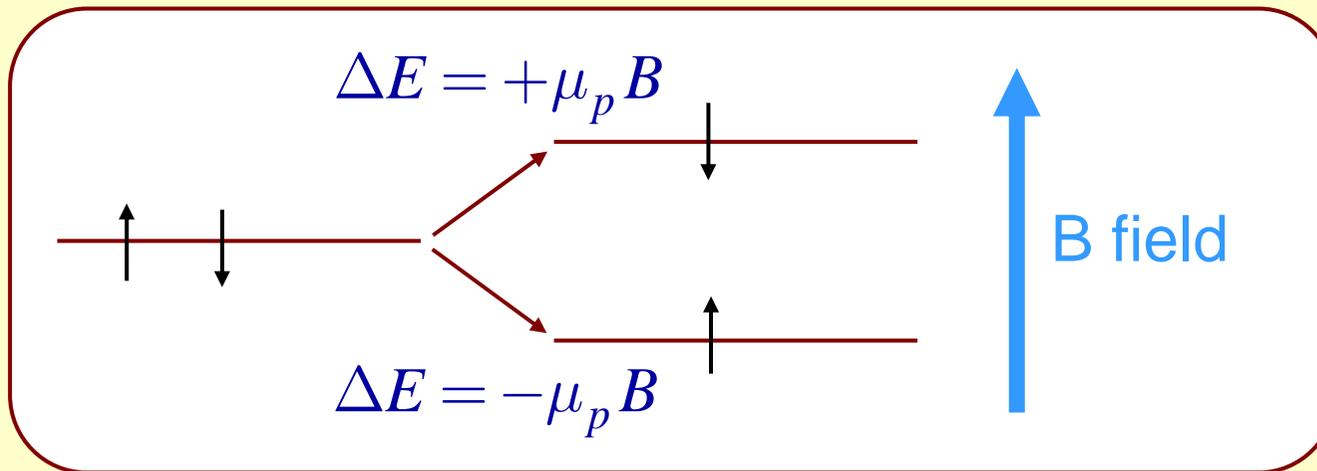
- Protons have spin $\frac{1}{2}$
- Quantized angular momentum $\pm \frac{1}{2} \hbar$
- Associated magnetic moment μ_p $\mu_p = 5.59 \frac{e\hbar}{2m_p}$
- Quantum states: $\uparrow_z, \downarrow_z, \uparrow_x = \frac{1}{\sqrt{2}} (\uparrow_z + \downarrow_z)$
- State in x-y plane precesses around z-axis in presence of B field along z-axis.

Spin

Energy in \underline{B} field

$$-\underline{\mu}_p \cdot \underline{B}$$

hence splitting:



$$2\Delta E = \hbar\omega_0, \quad \omega_0 = 2.675 \times 10^8 B \equiv \gamma B$$
$$\gamma / 2\pi = 42.58 \text{ MHz / tesla}$$

Net Magnetization

- In B field get more magnetic moments in lower energy state

- Energy gap $2\mu_p B = \hbar\omega_0$

- Boltzmann distribution

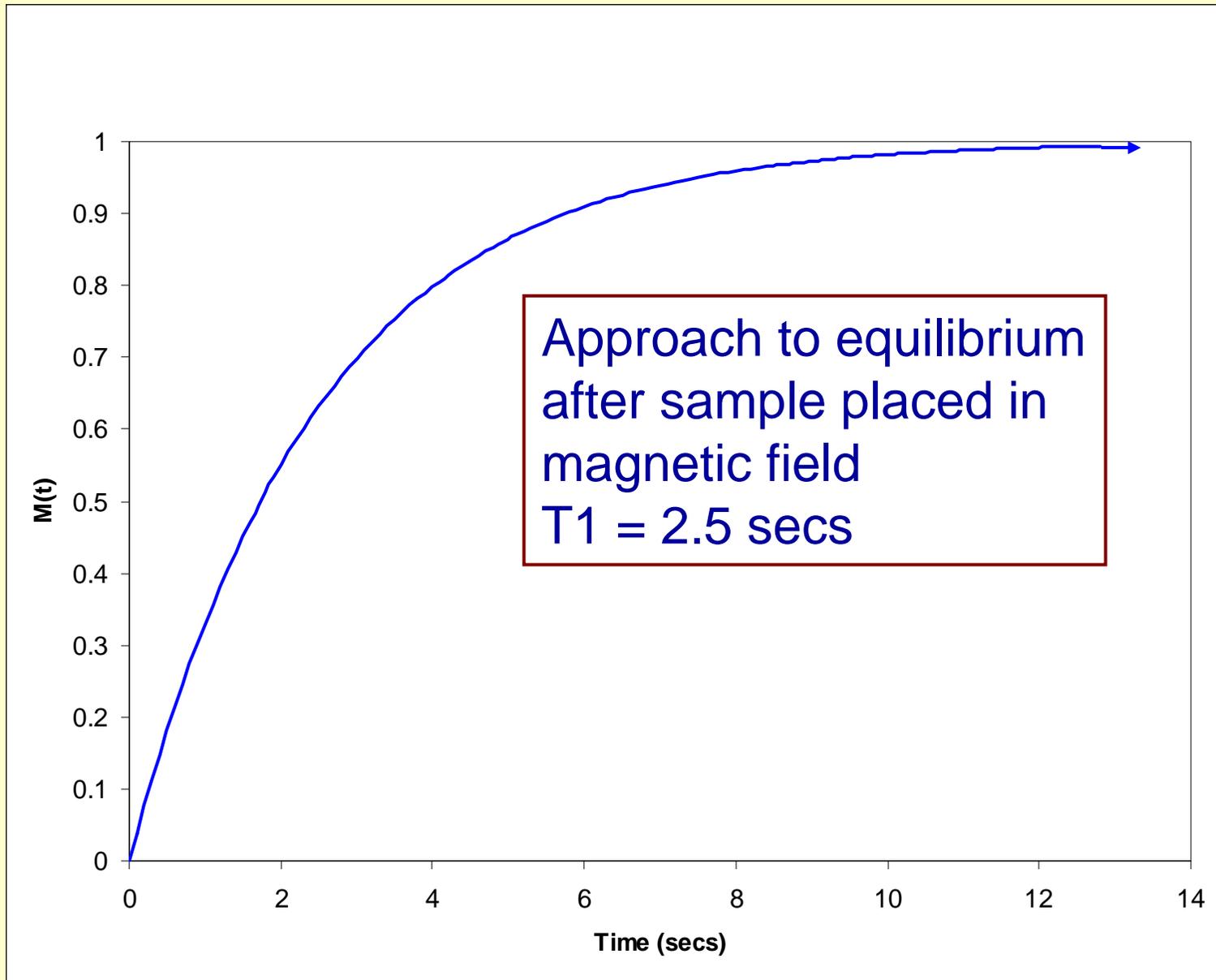
- Net magnetization

$$M_0 \approx N \frac{\mu_p^2 B}{k_B T}$$

T_1

- When protons placed in B field it takes time for equilibrium to be established.
- Basically each proton has a constant probability of being flipped into equilibrium configuration
- T1 due to “spin-lattice” interactions
- Leads to exponential approach to equilib

$$M(t) = M_0(1 - e^{-t/T_1})$$



Nuclear Magnetic Resonance (NMR)

- Once system in equilibrium can perturb using RF field at resonant frequency ω_0
- RF pulse rotates net magnetization from z-axis into x-y plane
- Spins precess in x-y plane and generate detectable RF signal

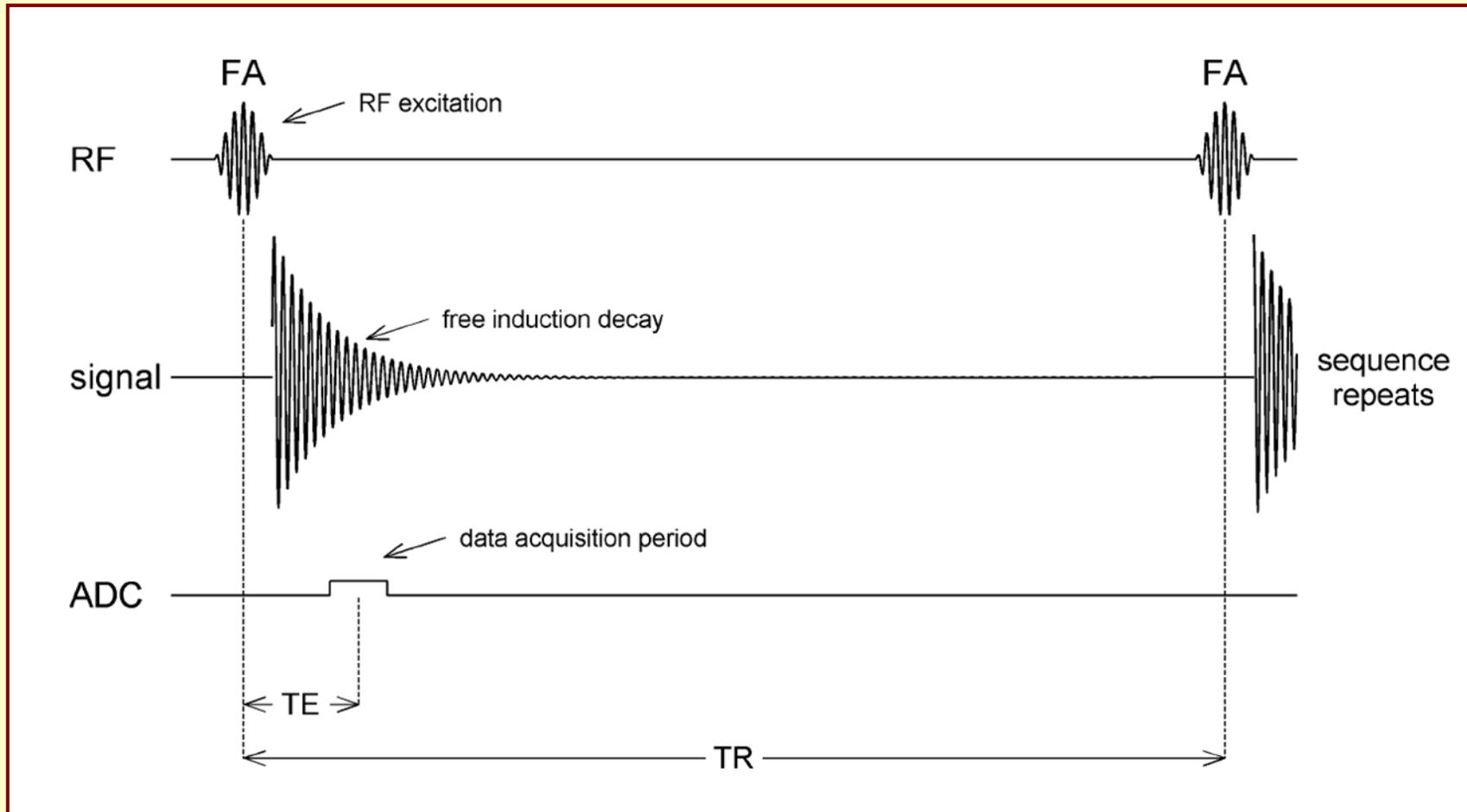
$$\nu_0 = 42 \text{ MHz / Tesla}$$

- NMR uses high fields up to ~21 T



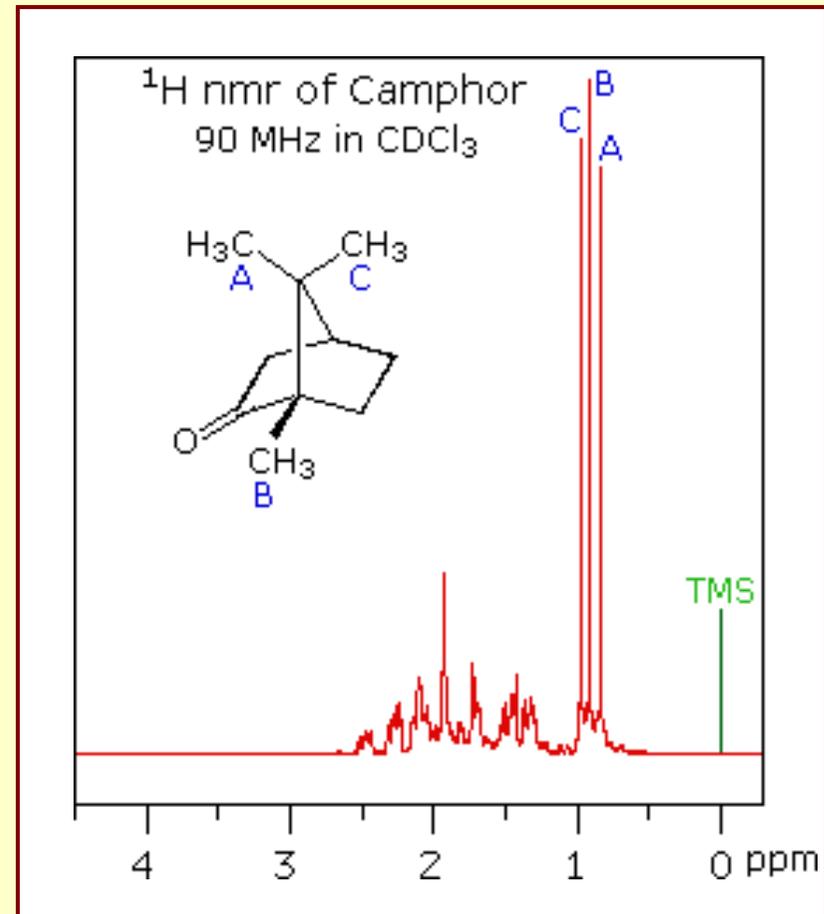
900 MHz NMR spectrometer for structural biology research in the Center for Biomolecular NMR jointly run by the Heinrich-Heine-Universität Düsseldorf und the Forschungszentrum Jülich.

Free Induction Decay (FID)



Typical NMR Spectrum

- NMR requires sample to be in very uniform B field (good few parts in 10^6 or better)
- Detected signal has range of frequencies from protons in different local molecular locations
- Needs FFT



Spin Precession is like a Gyroscope



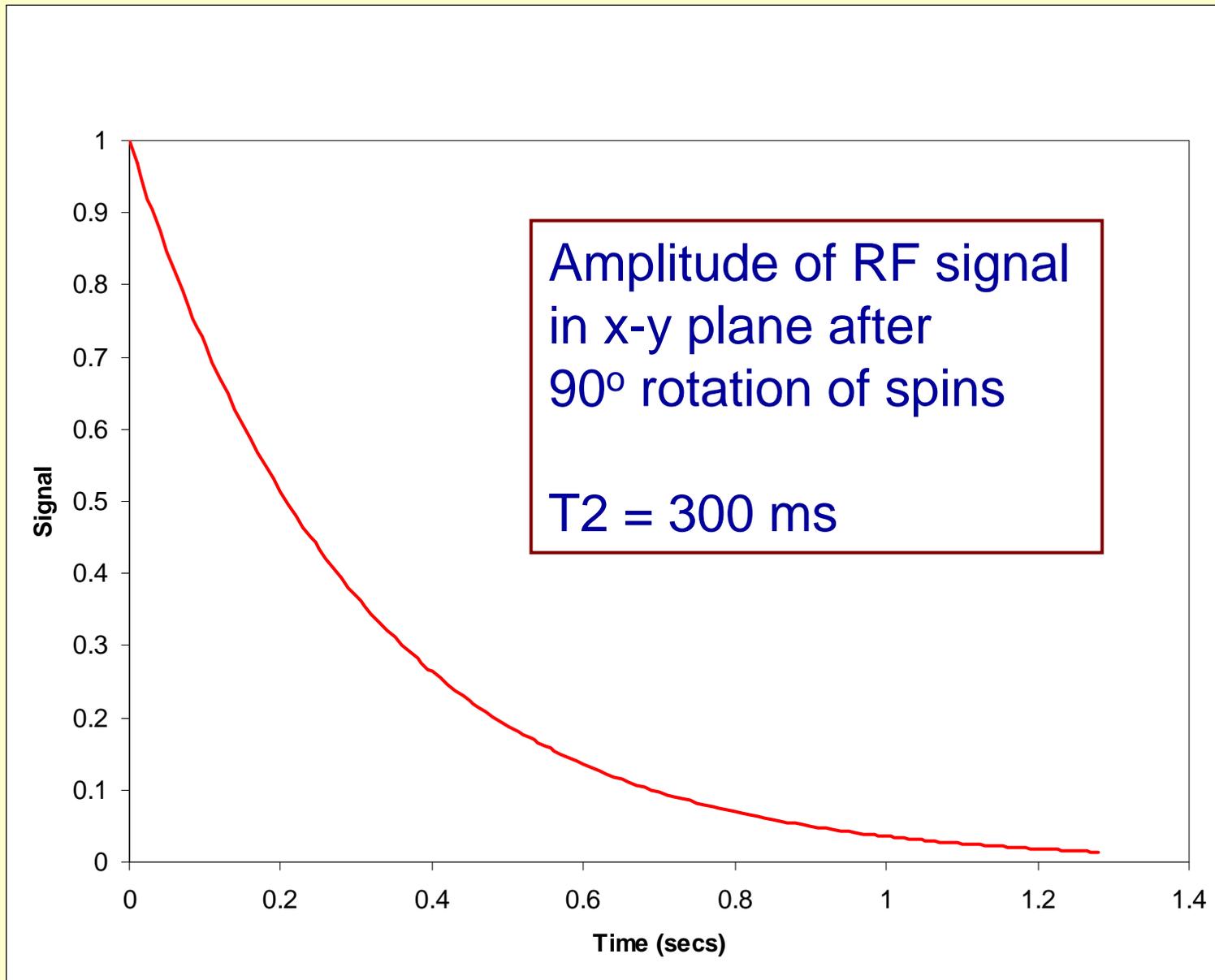
Gravity plays the role of the magnetic field for gyroscope.

Gyroscope wants to fall but is prevented by conservation of angular momentum.

Similarly quantized spin coupled magnetic moments precess.

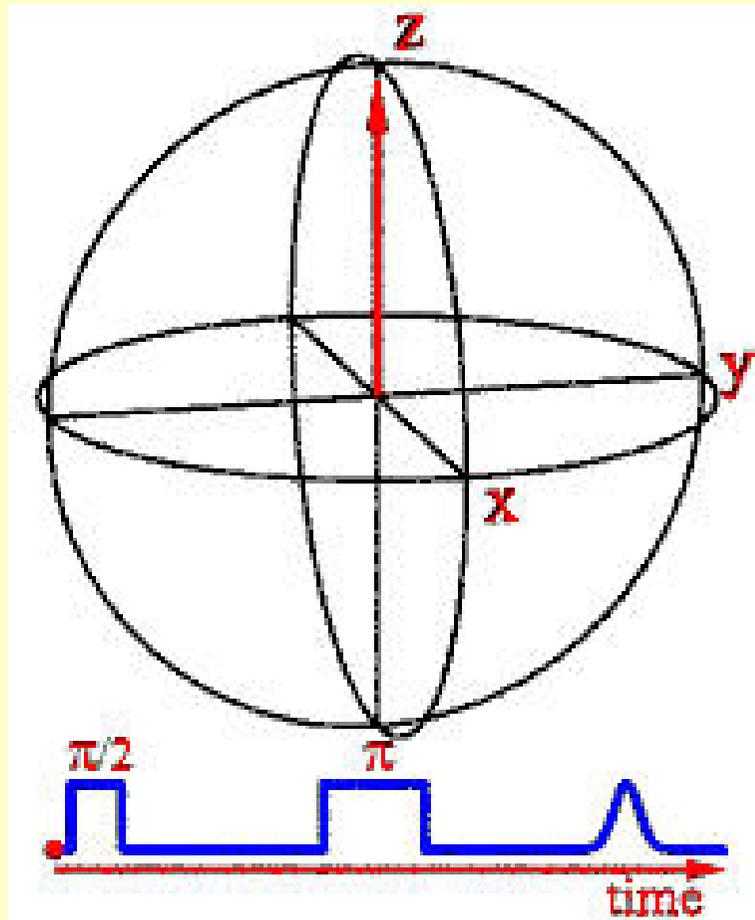
T2

- Magnetization in x-y plane relaxes back to equilibrium at with rate constant T2
- Usually $T2 < T1$ due to in plane dephasing of spins
- “Spin-Spin” interactions responsible for T2
- May observe additional dephasing if magnetic field not perfectly uniform.



Dephasing

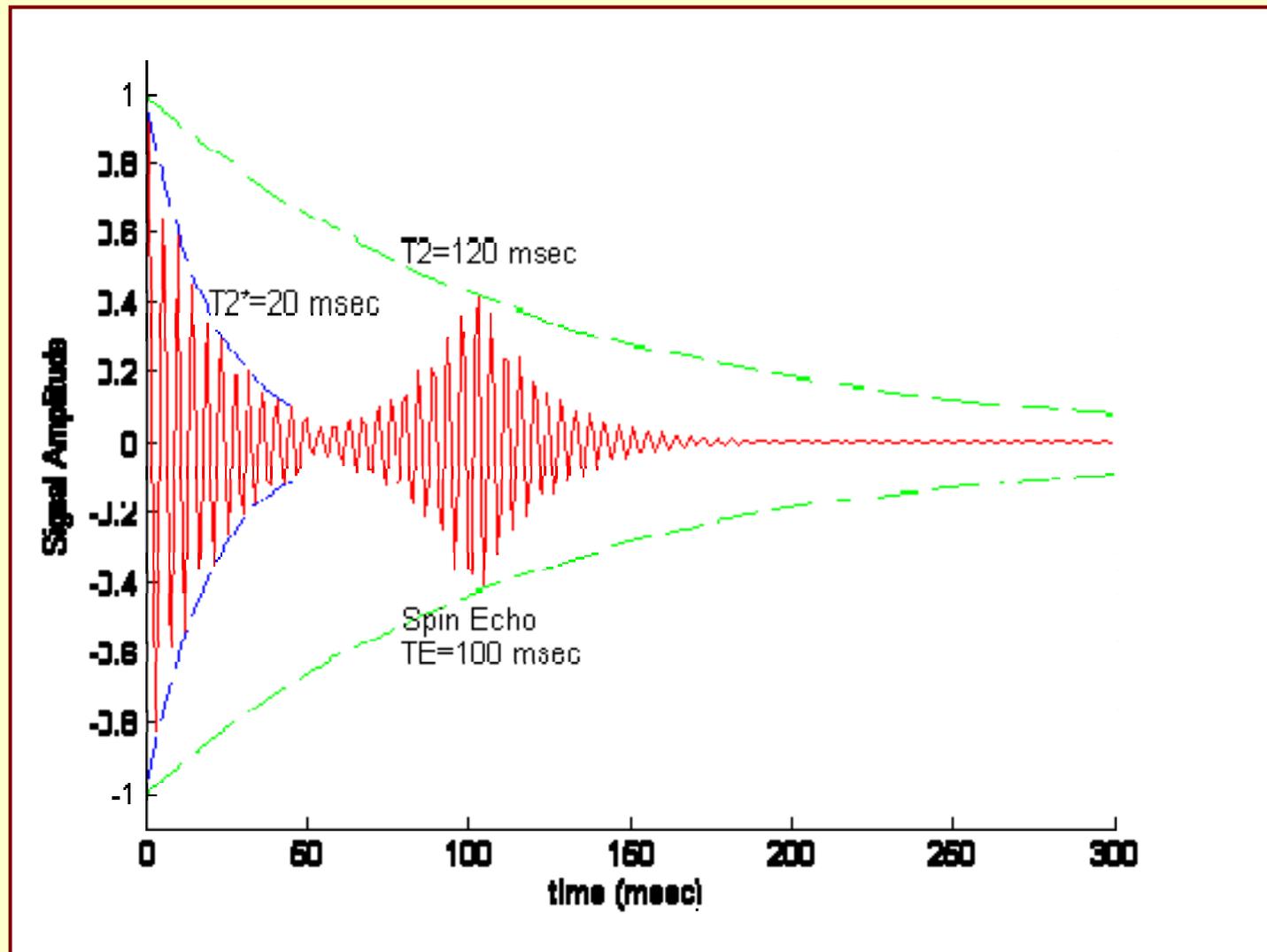
- In perfectly uniform B field decay rate T2
- T2 includes dephasing in x-y plane and relaxation back to equilibrium (at T1)
- If B-field not perfectly uniform there is additional dephasing so observe decay at $T2^* < T2$
- Can recover additional dephasing using 180° RF pulse – spin echo.



static

© <http://www.physics.monash.edu.au/~chrisn/espin.html>

Spin Echo



T_2

- Expect signal in x-y plane to decay at rate given by T_1
- In practice usually find faster decay at rate $T_2 < T_1$
- This is due to dephasing of spins as they rotate in x-y plane.
- T_1 and T_2 are intrinsic properties of matter and depend on *spin-lattice* and *spin-spin* interactions

Clinical Application - Imaging

T_1 and T_2 vary for different tissues. Hence may be possible to image soft tissues with better contrast than x-rays. Also no radiation dose!

Substance	T1 (ms)	T2 (ms)
Water	3000	1000
CSF	2000	250
White matter	680	90
Gray Matter	810	100
Liver	420	45
Fat	240	85
Mineral Oil	28	16

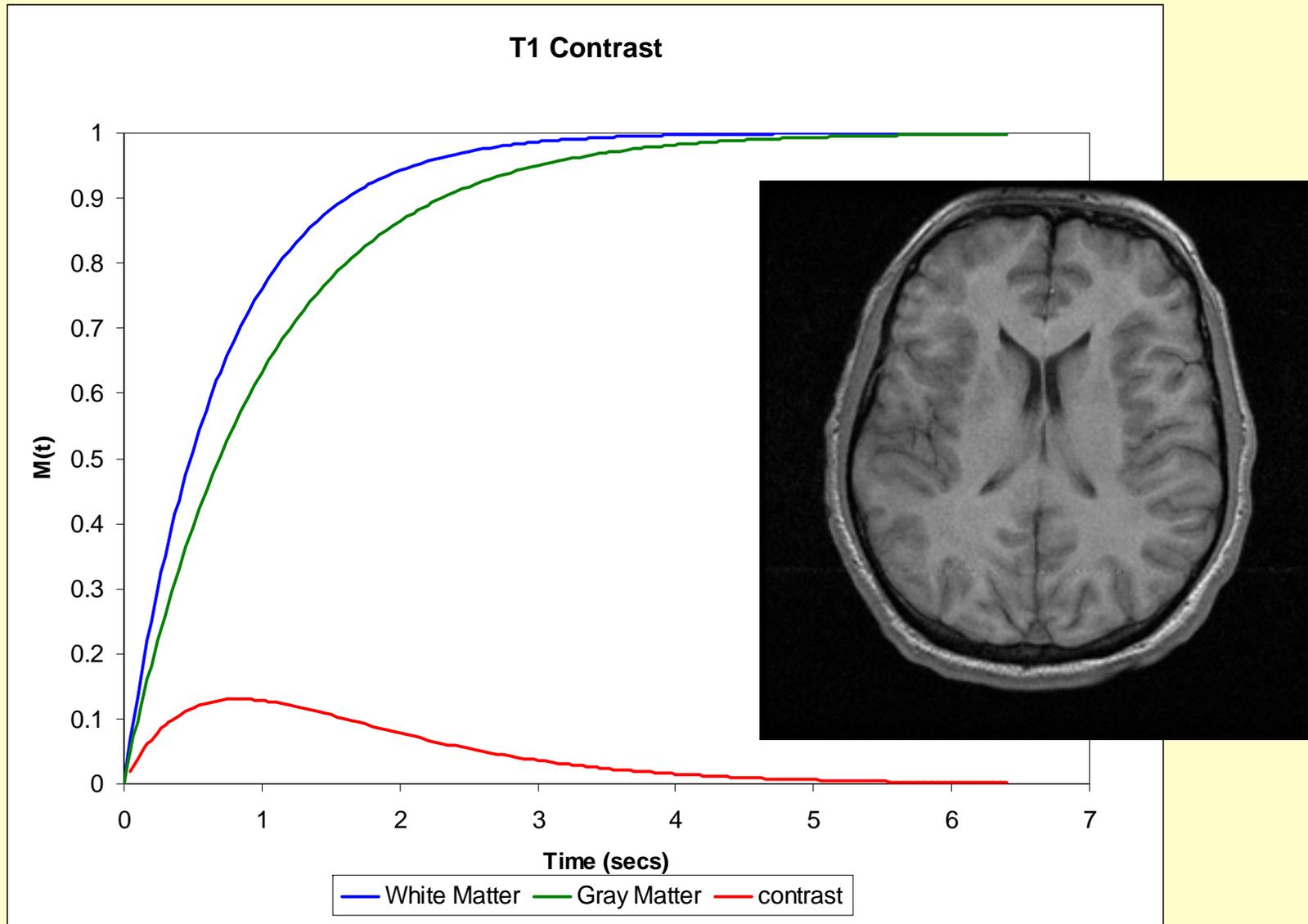
T_1 & T_2 at 1.5 T

Tissue	T_2 —1.5 T [ms]		T_1 —1.5 T [ms]	
	This study	Literature	This study	Literature
Liver	46 ± 6	$54 \pm 8^{(35)}$	576 ± 30	$\sim 600^{(23)}$
Skeletal muscle	44 ± 6	$35 \pm 4^{(25)}$	1008 ± 20	$1060 \pm 155^{(25)}$
Heart	40 ± 6	$44 \pm 6^{(36)}$	1030 ± 34	
Kidney	55 ± 3	$61 \pm 11^{(37)}$	690 ± 30	$709 \pm 60^{(37)}$
Cartilage 0°	30 ± 4	$42 \pm 7^{(25)}$	1024 ± 70	$\sim 1060^{(25)}$
Cartilage 55°	44 ± 5		1038 ± 67	
White matter	72 ± 4	$79 \pm 8^{(38)}$	884 ± 50	$778 \pm 84^{(38)}$
Gray matter	95 ± 8	$\sim 95^{(39)}$	1124 ± 50	$1086 \pm 228^{(38)}$
Optic nerve	77 ± 9		815 ± 30	
Spinal cord	74 ± 6		745 ± 37	
Blood	290 ± 30	$327 \pm 40^{(14)}$	1441 ± 120	$\sim 1200^{(30)}$

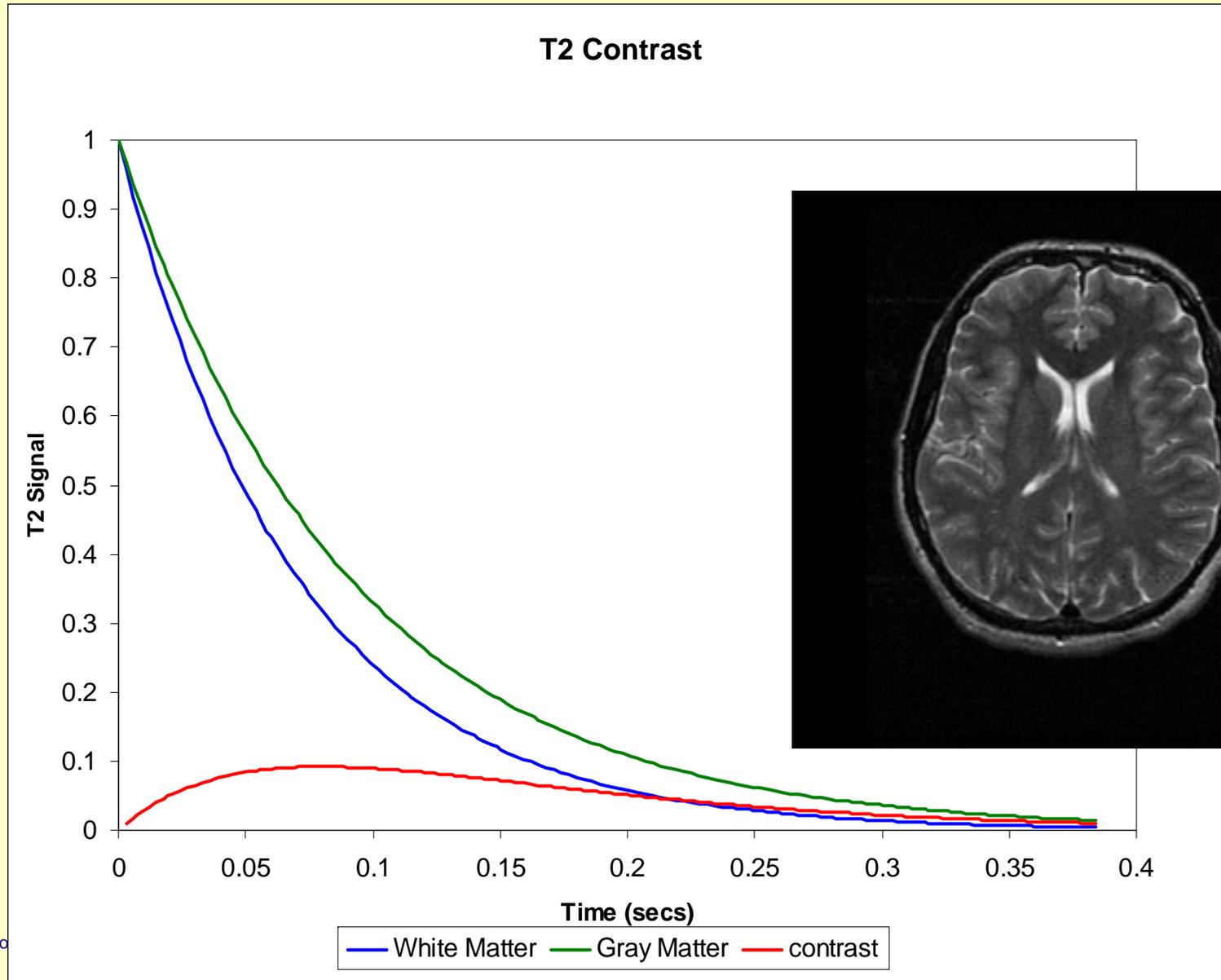
T_1 & T_2 at 3.0 T

Tissue	T_2 —3 T [ms]		T_1 —3 T [ms]	
	This study	Literature	This study	Literature
Liver	42 ± 3		812 ± 64	
Skeletal muscle	50 ± 4	$32 \pm 2^{(25)}$	1412 ± 13	$1420 \pm 38^{(25)}$
Heart	47 ± 11		1471 ± 31	
Kidney	56 ± 4		1194 ± 27	
Cartilage 0°	27 ± 3	$37 \pm 4^{(25)}$	1168 ± 18	$\sim 1240^{(25)}$
Cartilage 55°	43 ± 2	$45 \pm 67^{(26)}$	1156 ± 10	
White matter	69 ± 3	$56 \pm 4^{(27)}$	1084 ± 45	$1110 \pm 45^{(29)}$
Gray matter	99 ± 7	$71 \pm 10^{(27)}$	1820 ± 114	$1470 \pm 50^{(29)}$
Optic nerve	78 ± 5		1083 ± 39	
Spinal cord	78 ± 2		993 ± 47	
Blood	275 ± 50		1932 ± 85	$\sim 1550^{(30)}$

T1 contrast at 1.5 T



T2 contrast at 1.5 T



Magnetic Resonance Imaging (MRI)

- NMR is incredibly useful for molecular work
- But for images need to make signals position dependent
- Add gradients so that the B field (along z-axis) varies linearly as a function of position:

$$B = B_0 + G_x x + G_y y + G_z z$$

$$B = B_0 + \underline{\mathbf{G}} \cdot \underline{\mathbf{r}}$$

Signal

Without gradients: $S(t) = \int \rho(\underline{\mathbf{r}}) e^{i\omega_0 t} dV = e^{i\omega_0 t} \int \rho(\underline{\mathbf{r}}) dV$

Gradients give frequency change $\delta\nu(\underline{\mathbf{r}}, t) = \nu_0 \underline{\mathbf{G}} \cdot \underline{\mathbf{r}}$

Hence time dependent local phase change $\gamma \int_0^t \underline{\mathbf{G}}(t') \cdot \underline{\mathbf{r}} dt'$

Thus $S(t) = e^{i\omega_0 t} \int \rho(\underline{\mathbf{r}}) e^{i\underline{\mathbf{k}} \cdot \underline{\mathbf{r}}} dV$ $\underline{\mathbf{k}}(t) = \gamma \int_0^t \underline{\mathbf{G}}(t') dt'$

So $S(t) = e^{i\omega_0 t} \tilde{\rho}(\underline{\mathbf{k}})$ Fourier transform of ρ

Must drive gradients to span 2D or 3D k-space

Signal

Without gradients:

$$S(t) = e^{i\omega_0 t} \int \rho(\underline{\mathbf{r}}) dV$$

Gradients give frequency

$$\omega(\underline{\mathbf{r}}, t) = \nu_0 \underline{\mathbf{G}} \cdot \underline{\mathbf{r}}$$

Hence time dependence

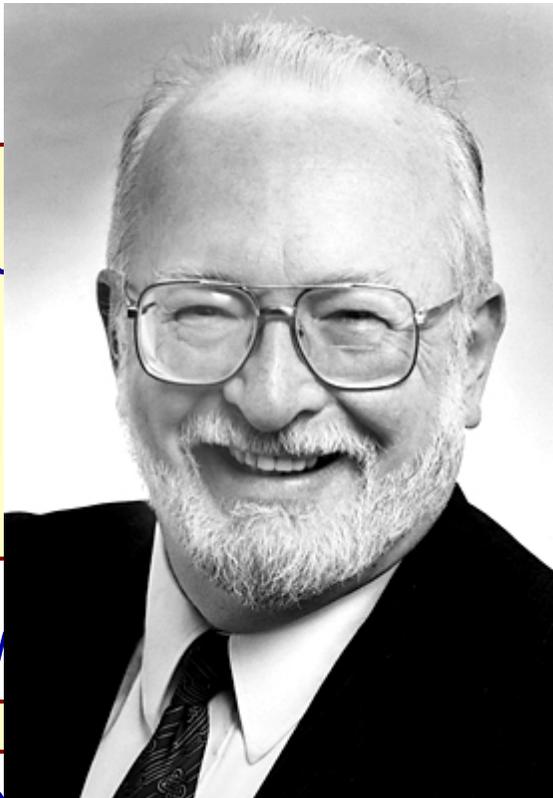
$$\text{Phase} = \gamma \int_0^t \underline{\mathbf{G}}(t') \cdot \underline{\mathbf{r}} dt'$$

Thus

$$S(t) = e^{i\omega_0 t} \int \rho(\underline{\mathbf{r}}) e^{i\gamma \int_0^t \underline{\mathbf{G}}(t') \cdot \underline{\mathbf{r}} dt'} dV = \gamma \int_0^t \underline{\mathbf{G}}(t') dt'$$

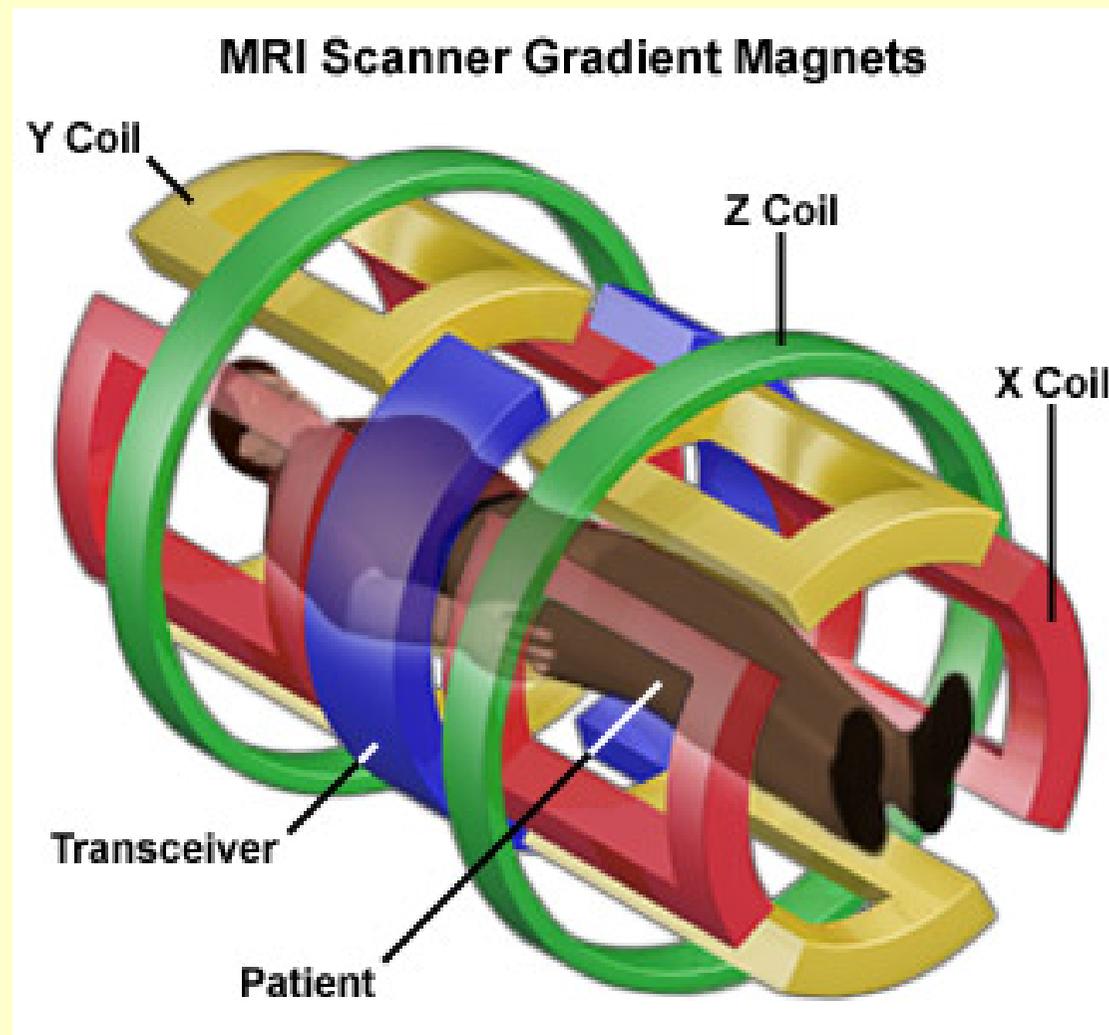
So

$$S(t) = e^{i\omega_0 t} \tilde{\rho}(\underline{\mathbf{k}}) \quad \text{Fourier transform of } \rho$$

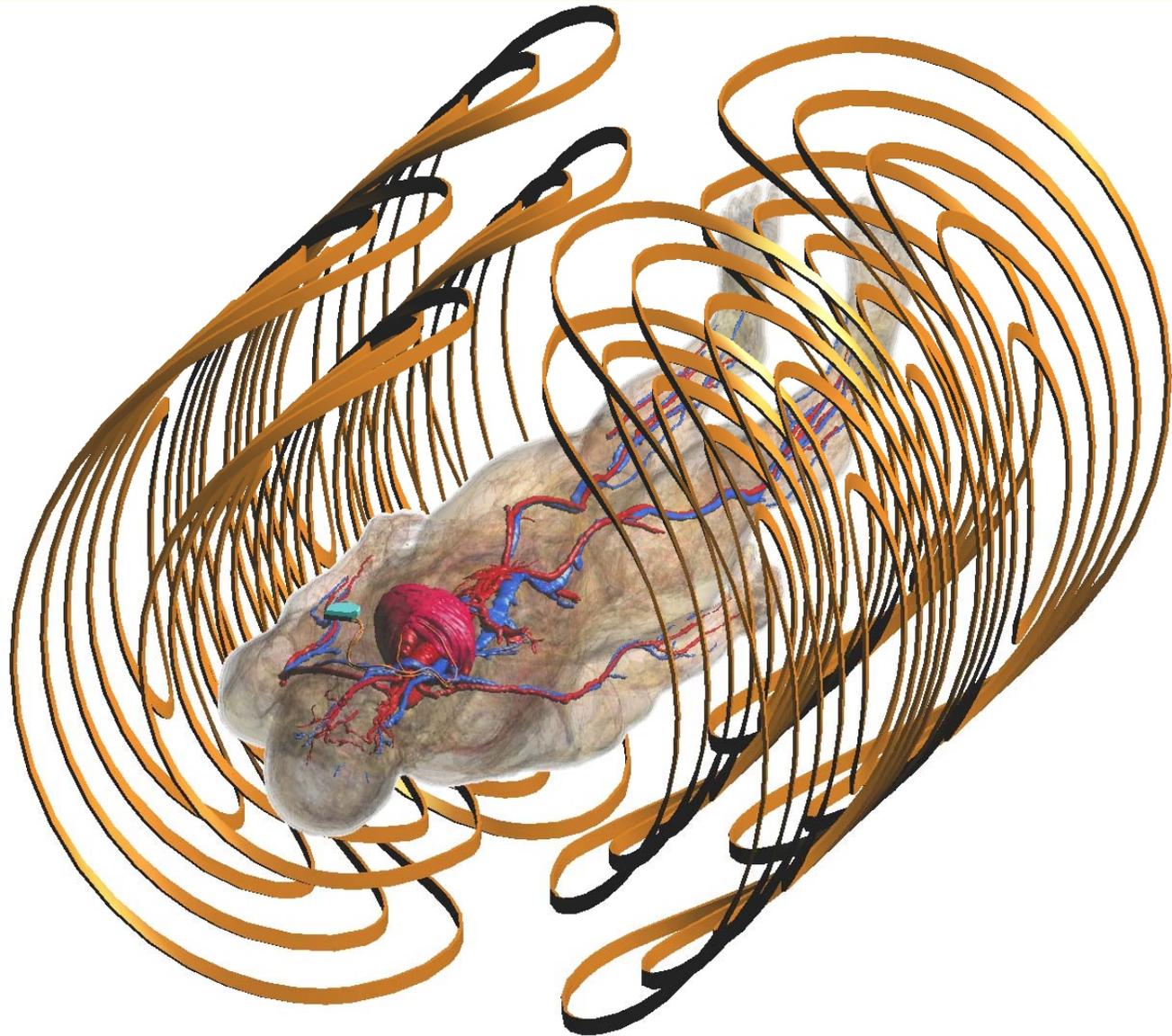


Paul Lauterbur Shared Nobel Prize for Medicine 2003

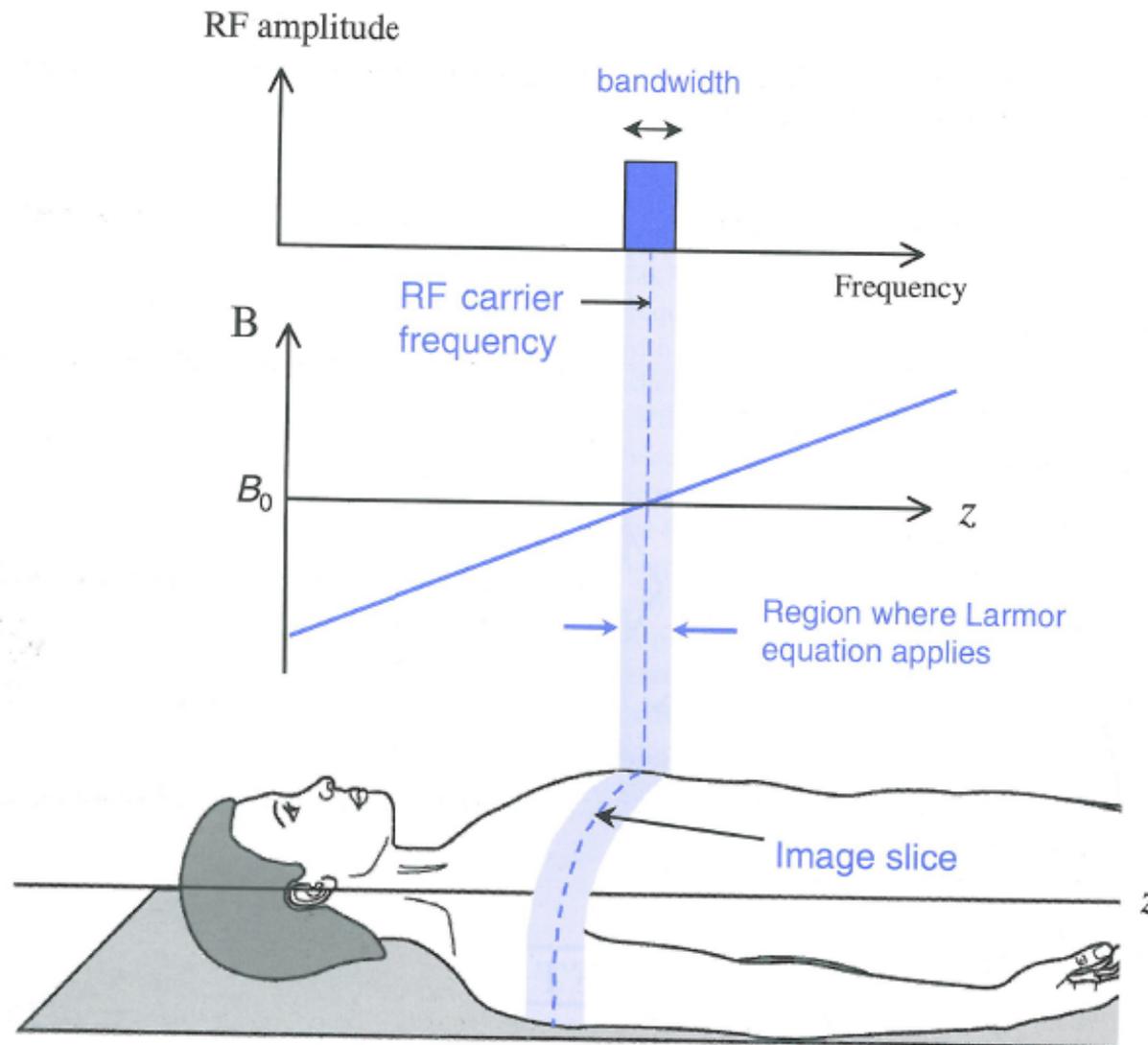
Gradient set



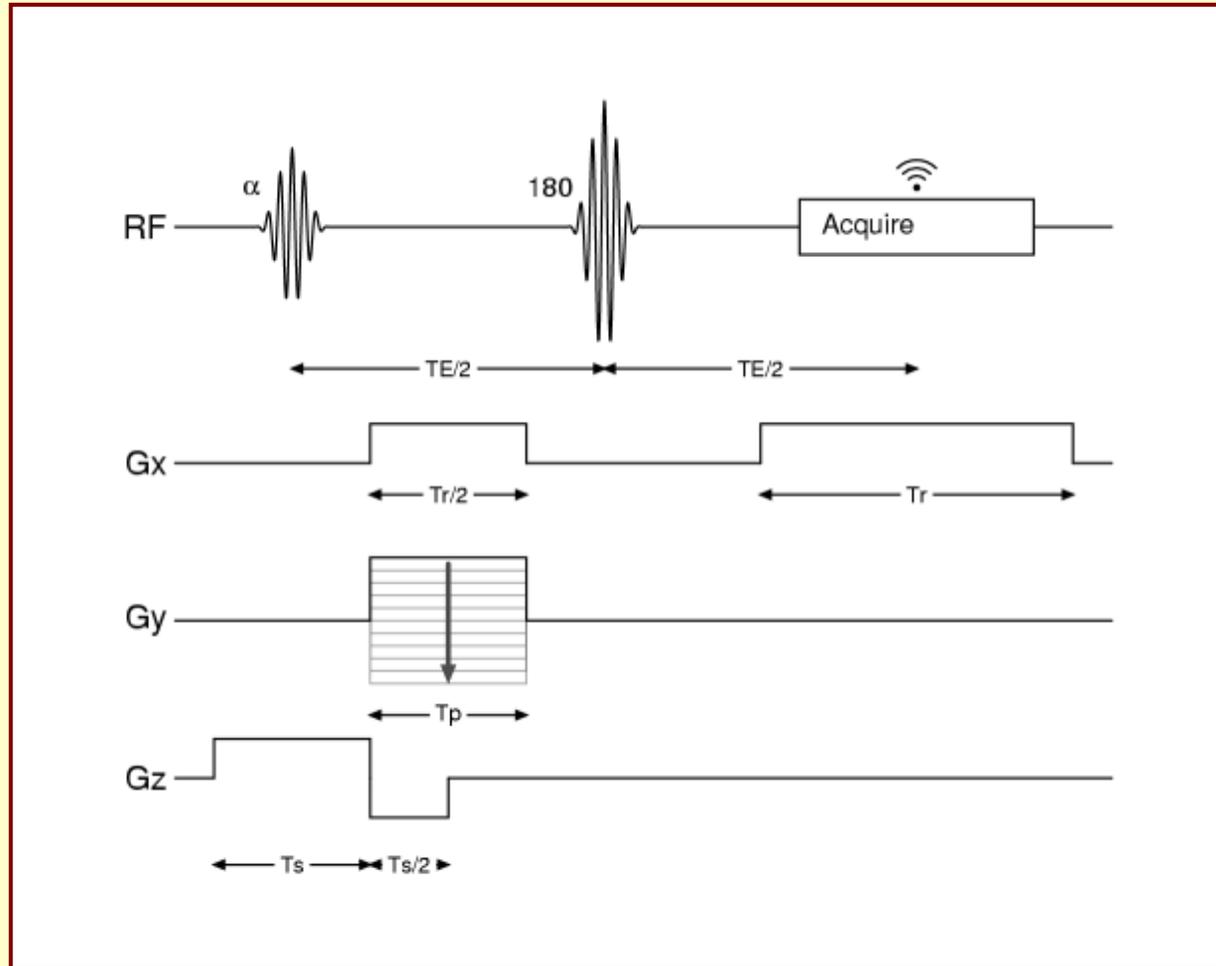
Gradient Coils 2



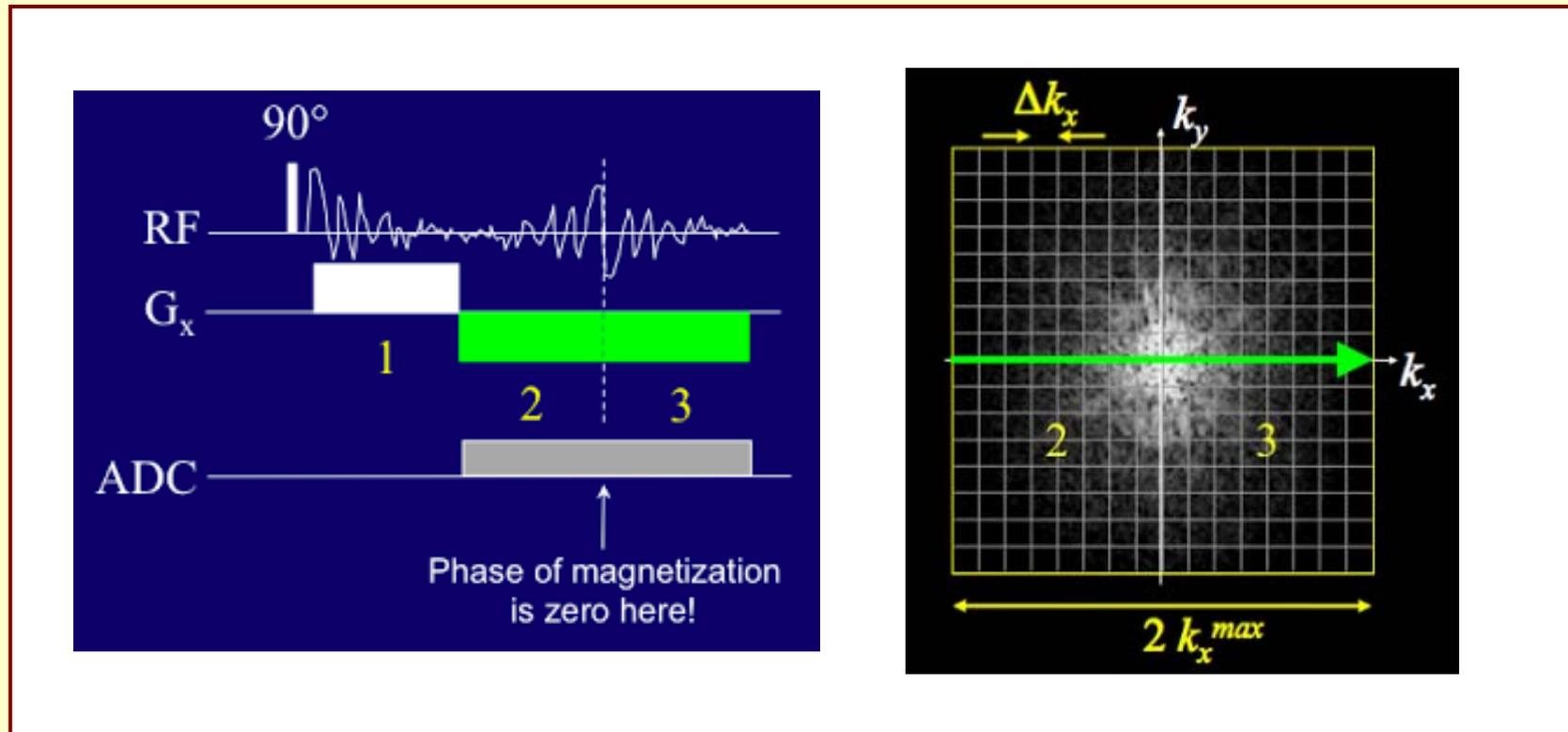
2D Slice Selection



Spin Echo - Sequence

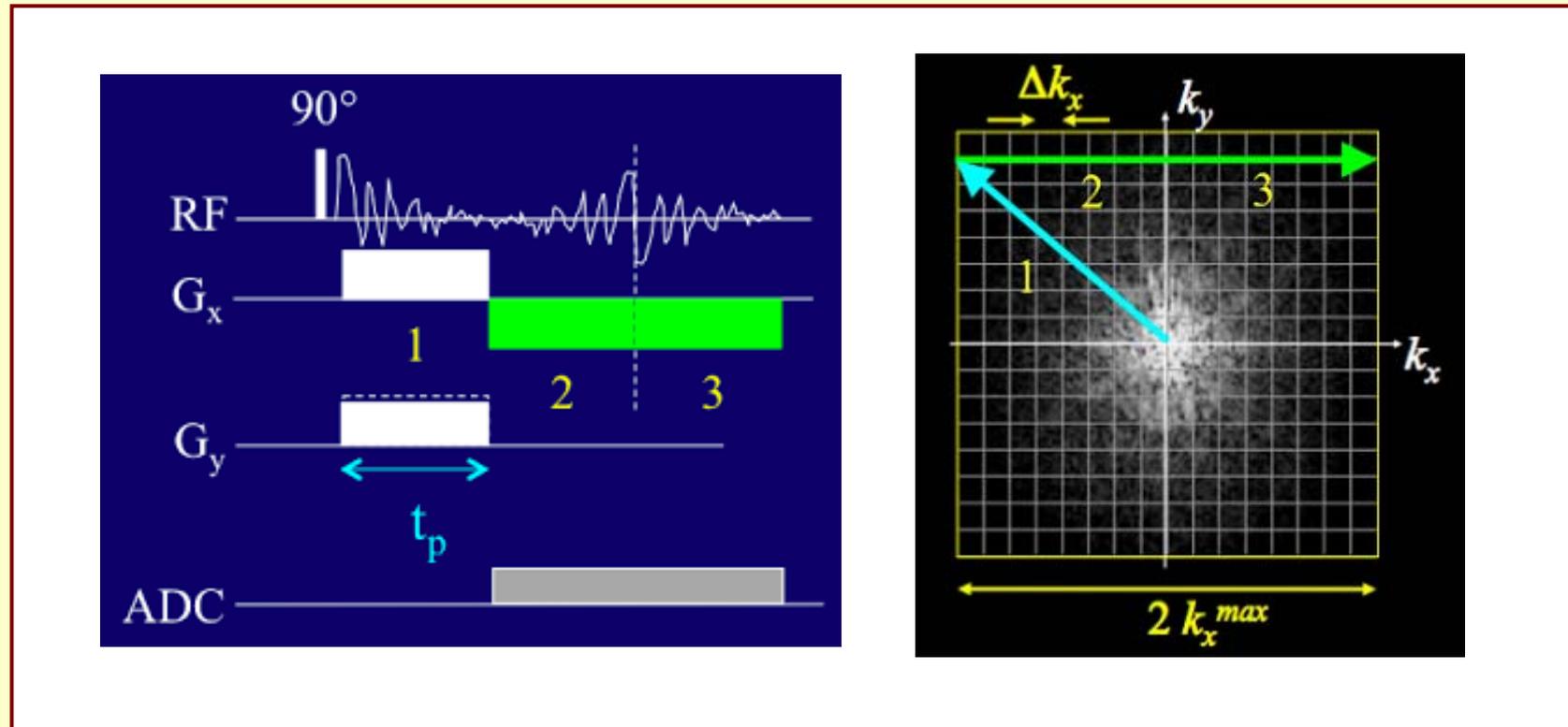


Can use gradient for spin echo



Single k_x line at $k_y = 0$

k-space

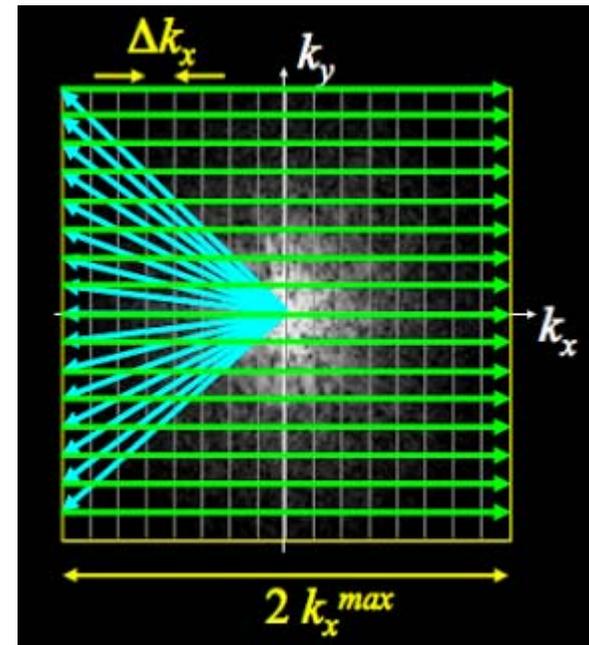


Single k_x line at variable k_y

k-space

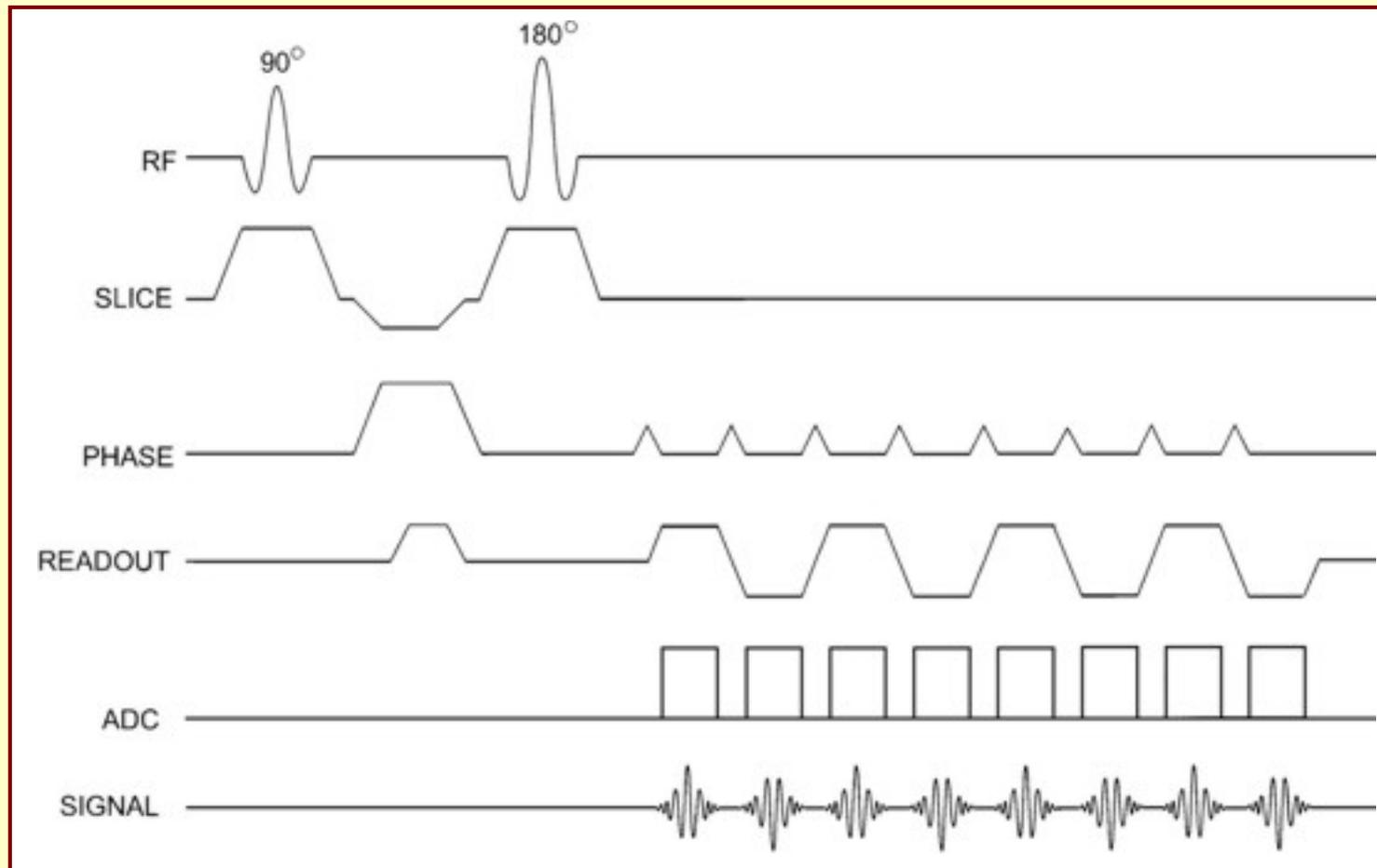
Either repeat above
for each k-line (slow)

Or use EPI faster,
but worse signal to
noise

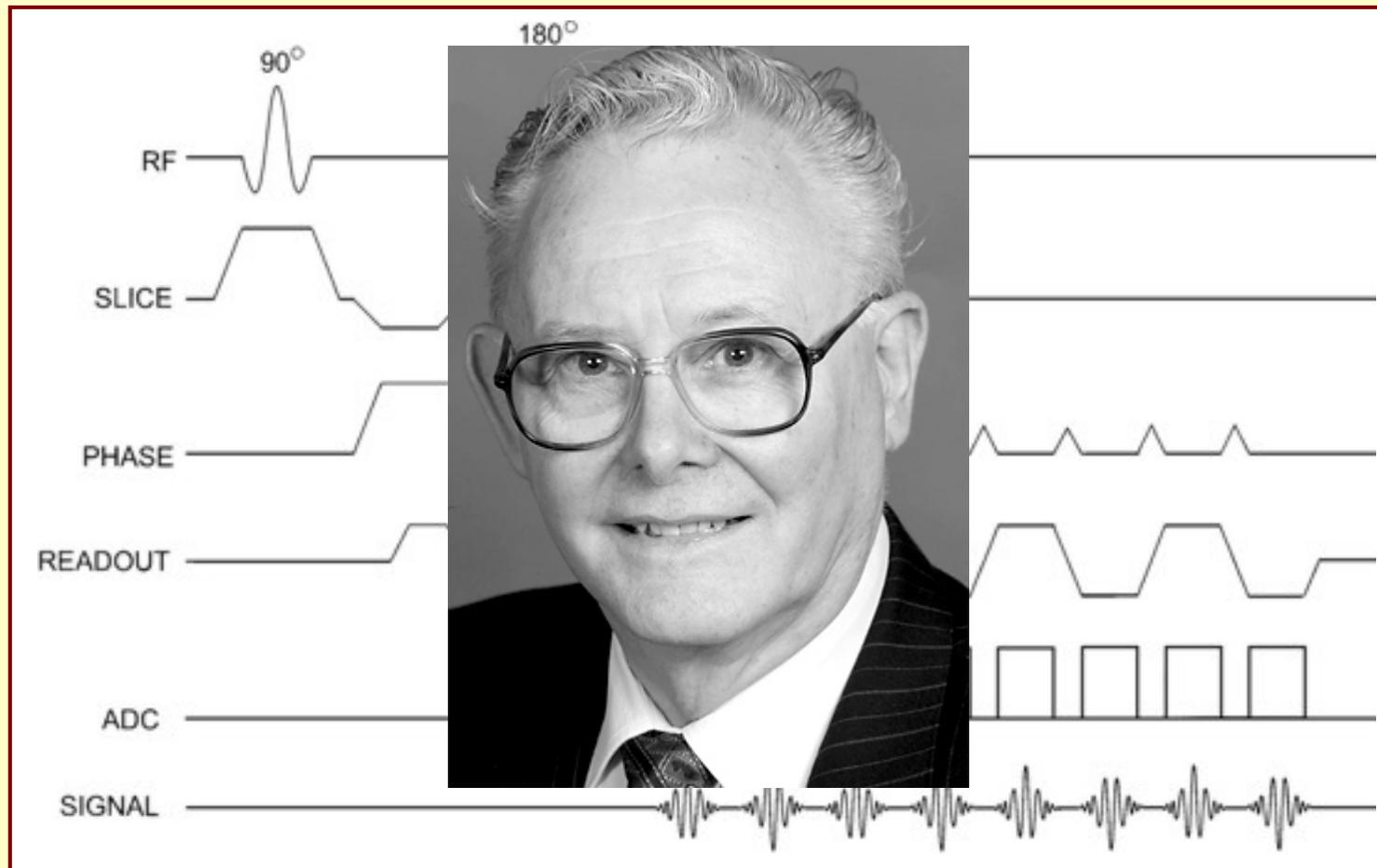


x-y plane in k-space

Echo Plane Imaging (EPI)



Echo Plane Imaging (EPI)



Peter Mansfield Shared Nobel Prize for Medicine 2003



Hospital MRI Scanner



RF (Birdcage) TX/RX

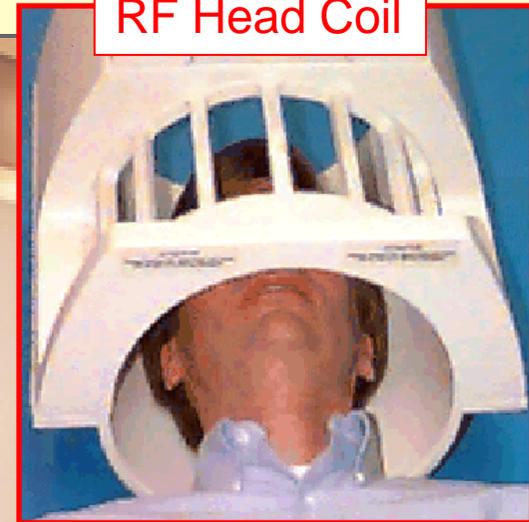


X, Y and Z Gradient Coils
inside magnet bore

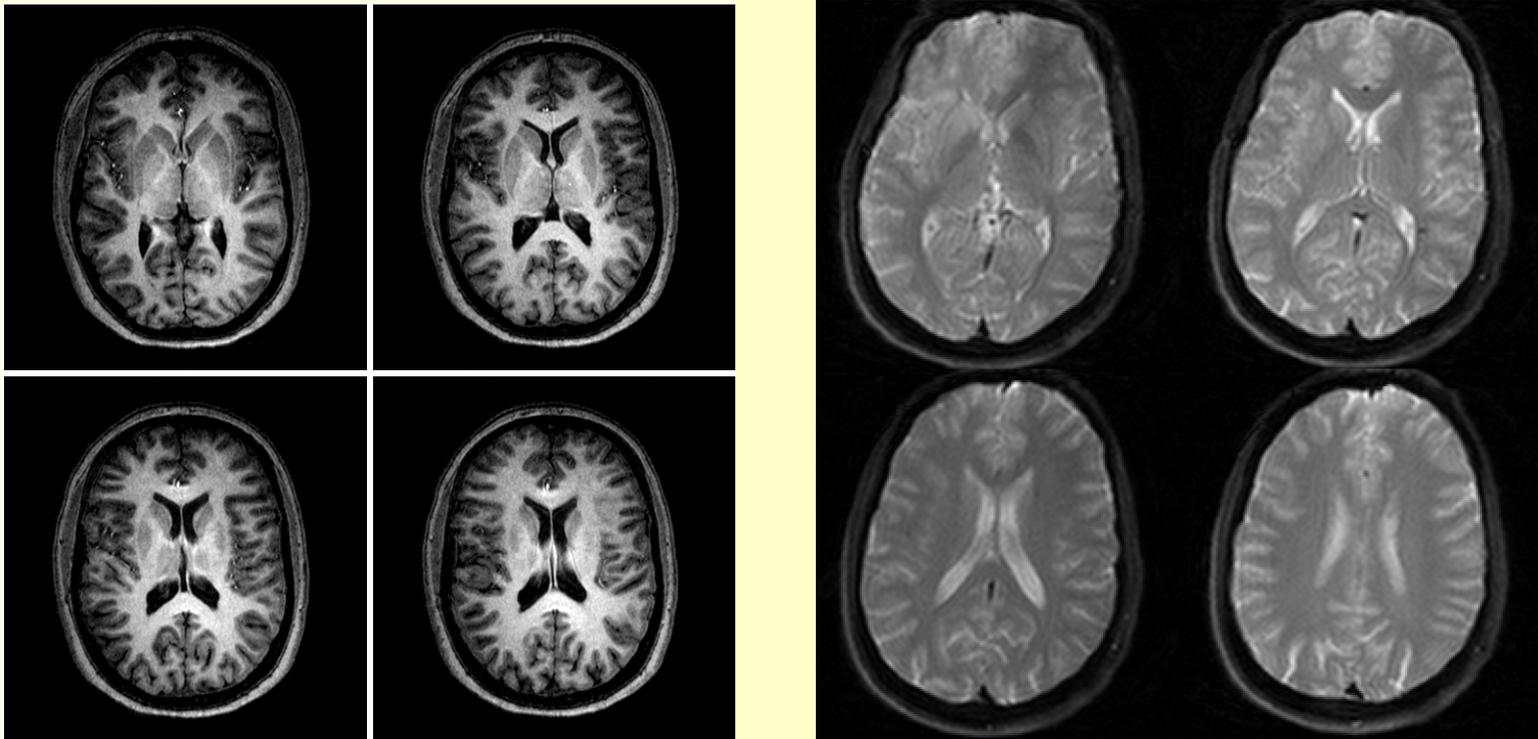


Superconducting
Solenoid, typically
1.5 or 3T

RF Head Coil



MRI Soft Tissue Contrast

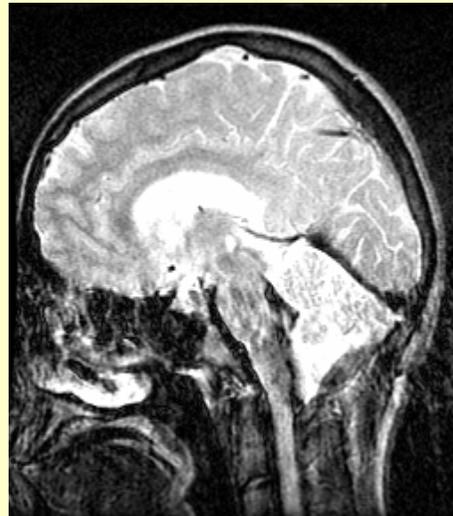


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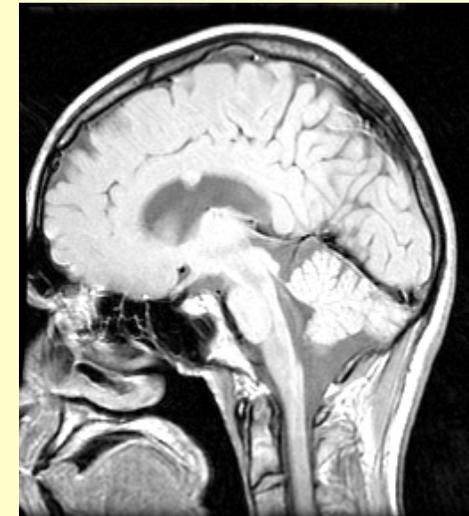
MRI of the Brain - Sagittal



T1 Contrast
 $T_E = 14 \text{ ms}$
 $T_R = 400 \text{ ms}$

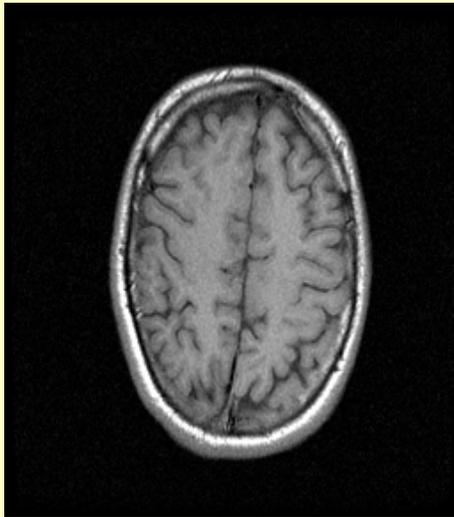


T2 Contrast
 $T_E = 100 \text{ ms}$
 $T_R = 1500 \text{ ms}$

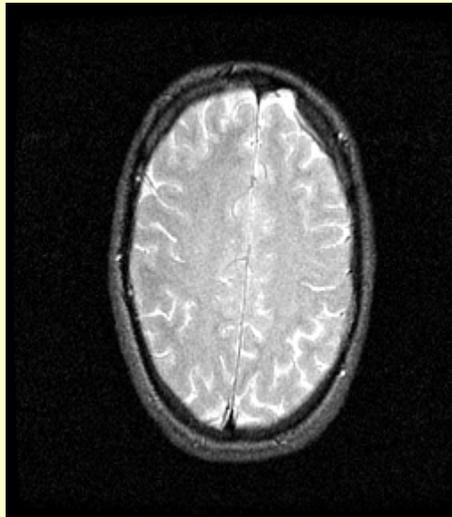


Proton Density
 $T_E = 14 \text{ ms}$
 $T_R = 1500 \text{ ms}$

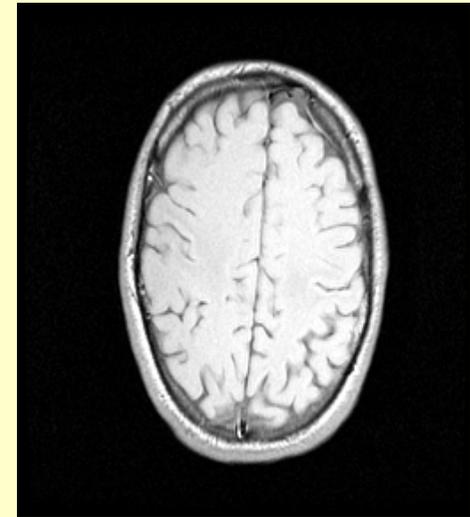
MRI of the Brain - Axial



T1 Contrast
 $T_E = 14 \text{ ms}$
 $T_R = 400 \text{ ms}$

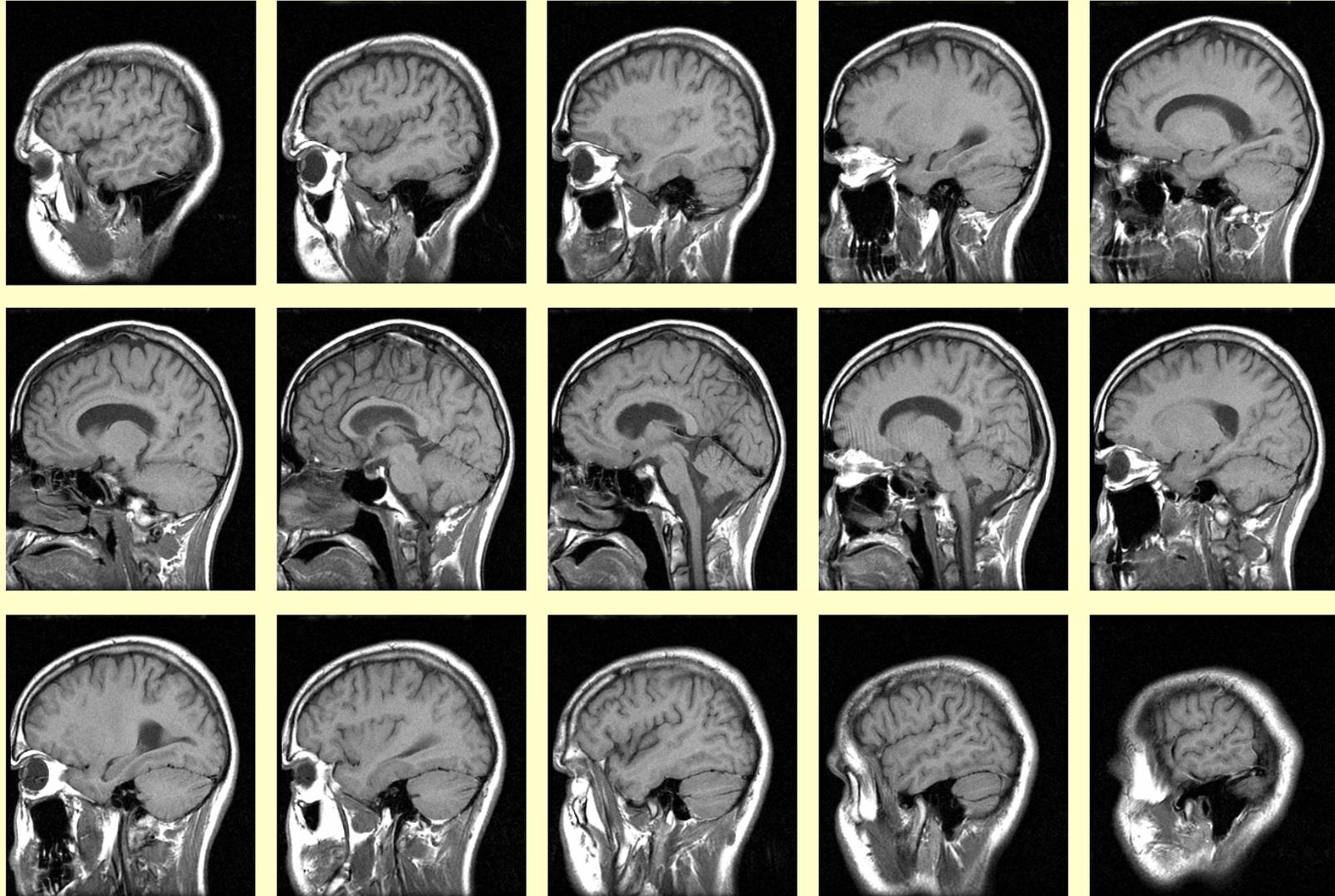


T2 Contrast
 $T_E = 100 \text{ ms}$
 $T_R = 1500 \text{ ms}$



Proton Density
 $T_E = 14 \text{ ms}$
 $T_R = 1500 \text{ ms}$

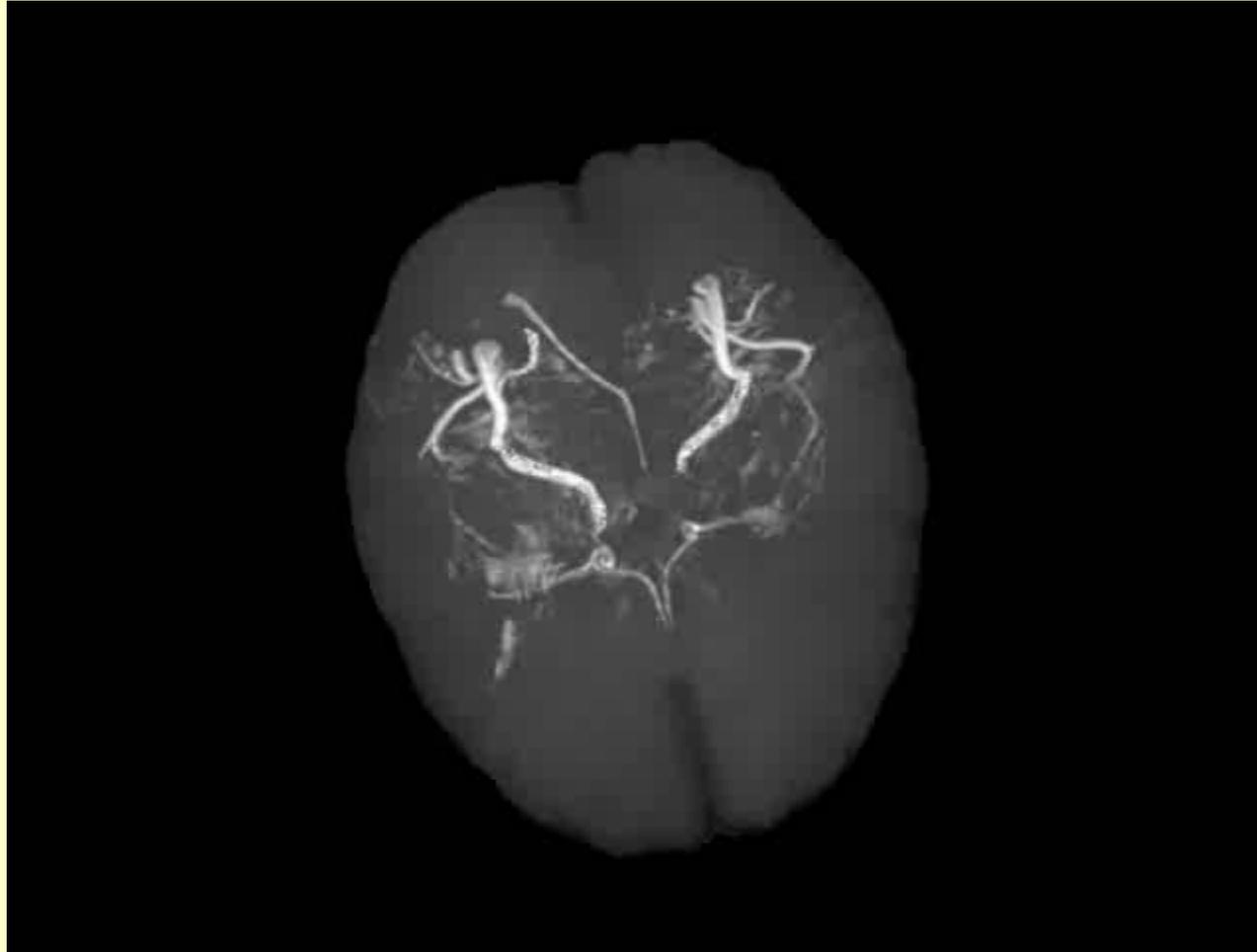
Brain - Sagittal Multislice T1



3D Volume Data Sets



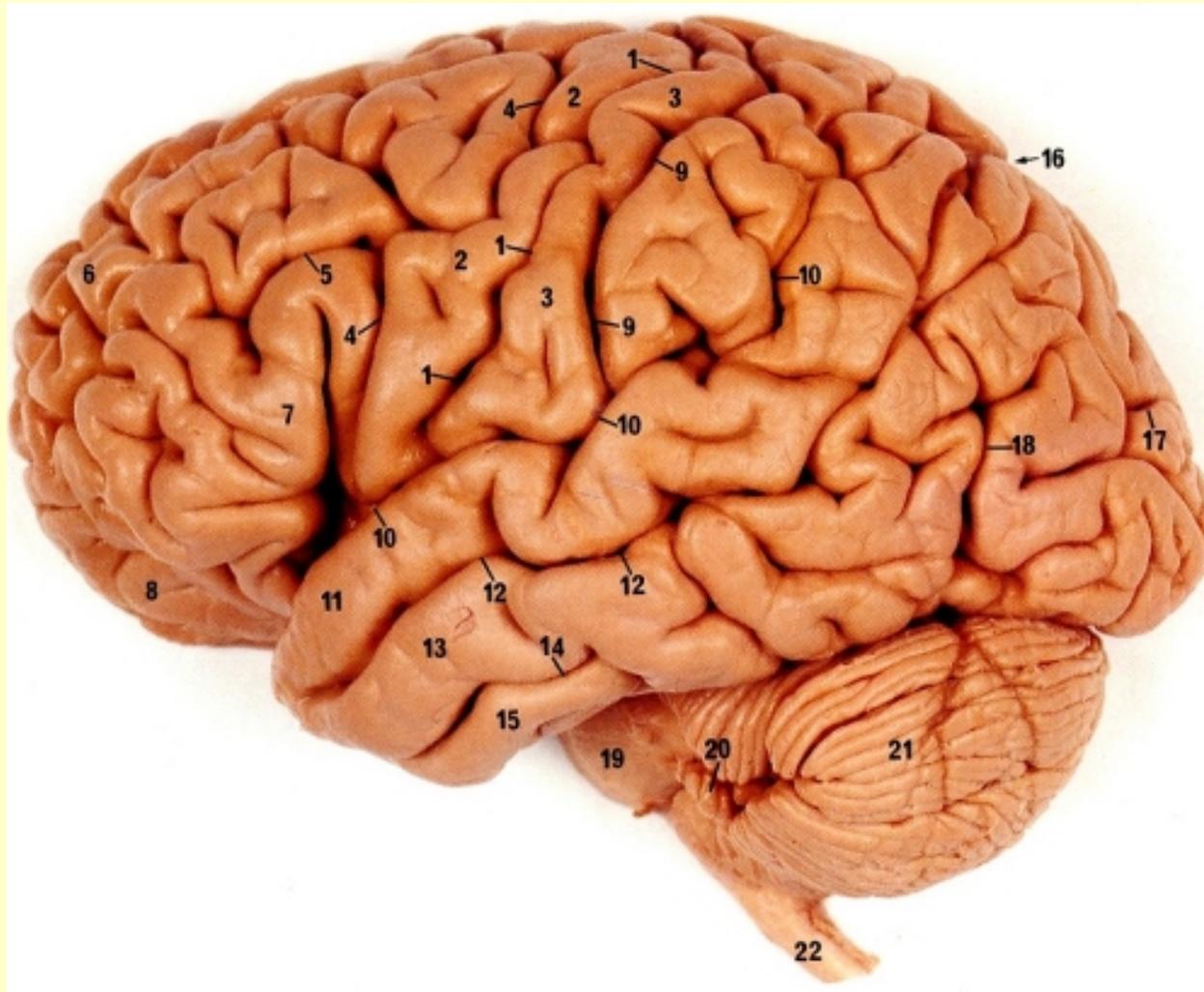
3D Volume Data Sets



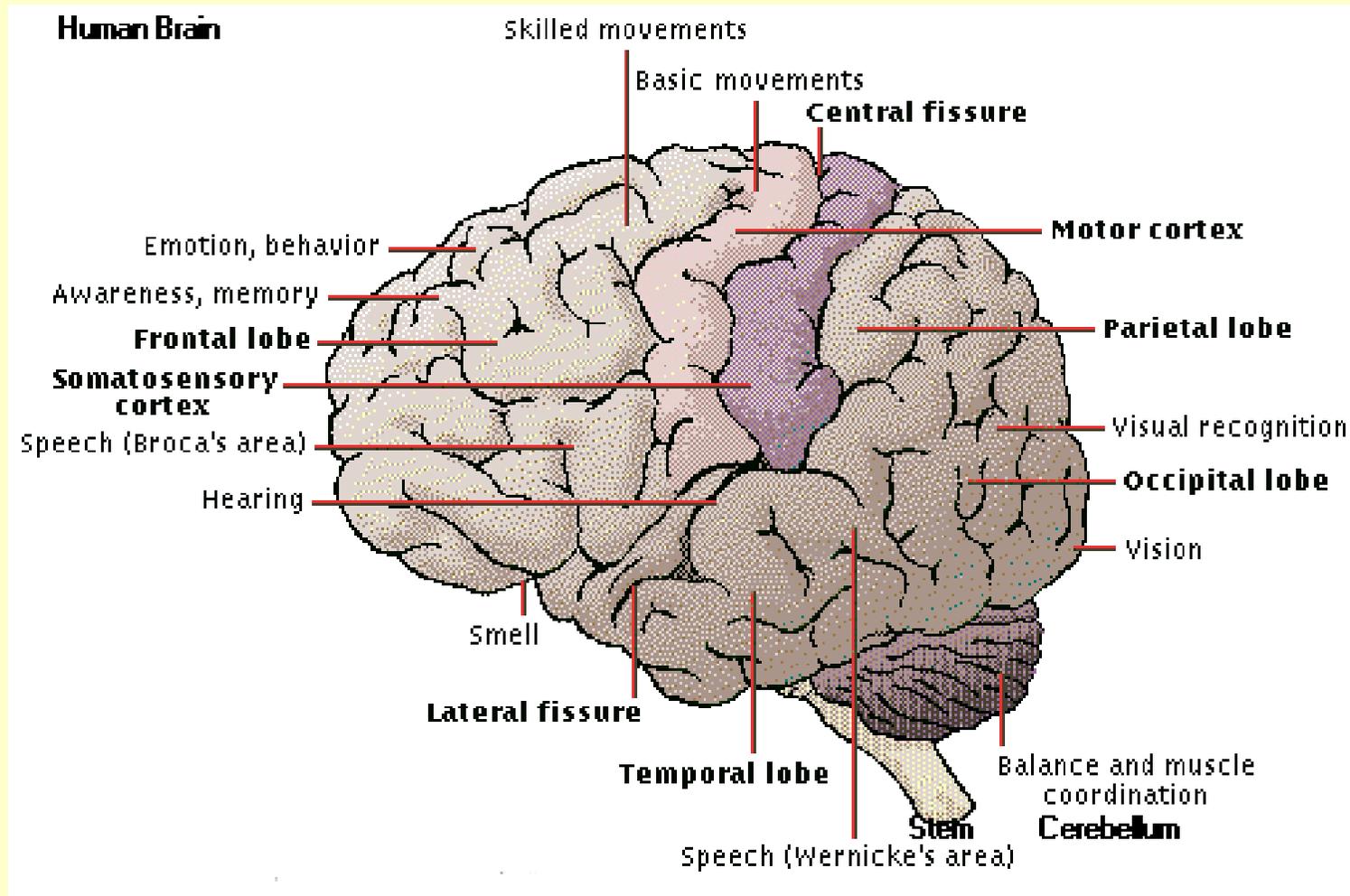
Things to do with MRI

- Anatomy: proton density, T1, T2 etc
- Flow – cardiac
- Diffusion – trace neural pathways
- Whole Body – cancer staging
- Functional imaging
 - research
 - surgical planning
- Interventional

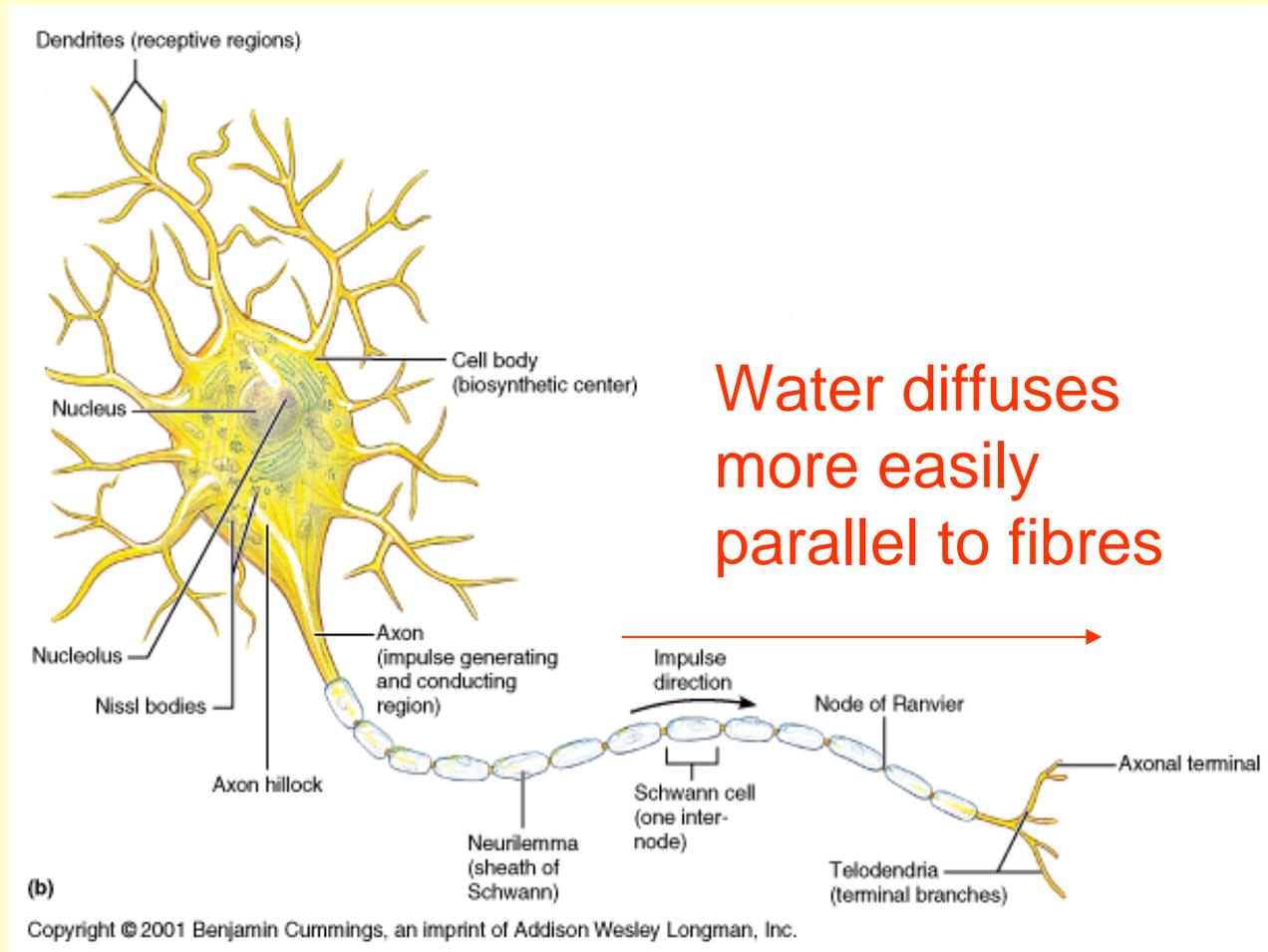
It's about the BRAIN!



It's about the BRAIN!



Diffusion Imaging

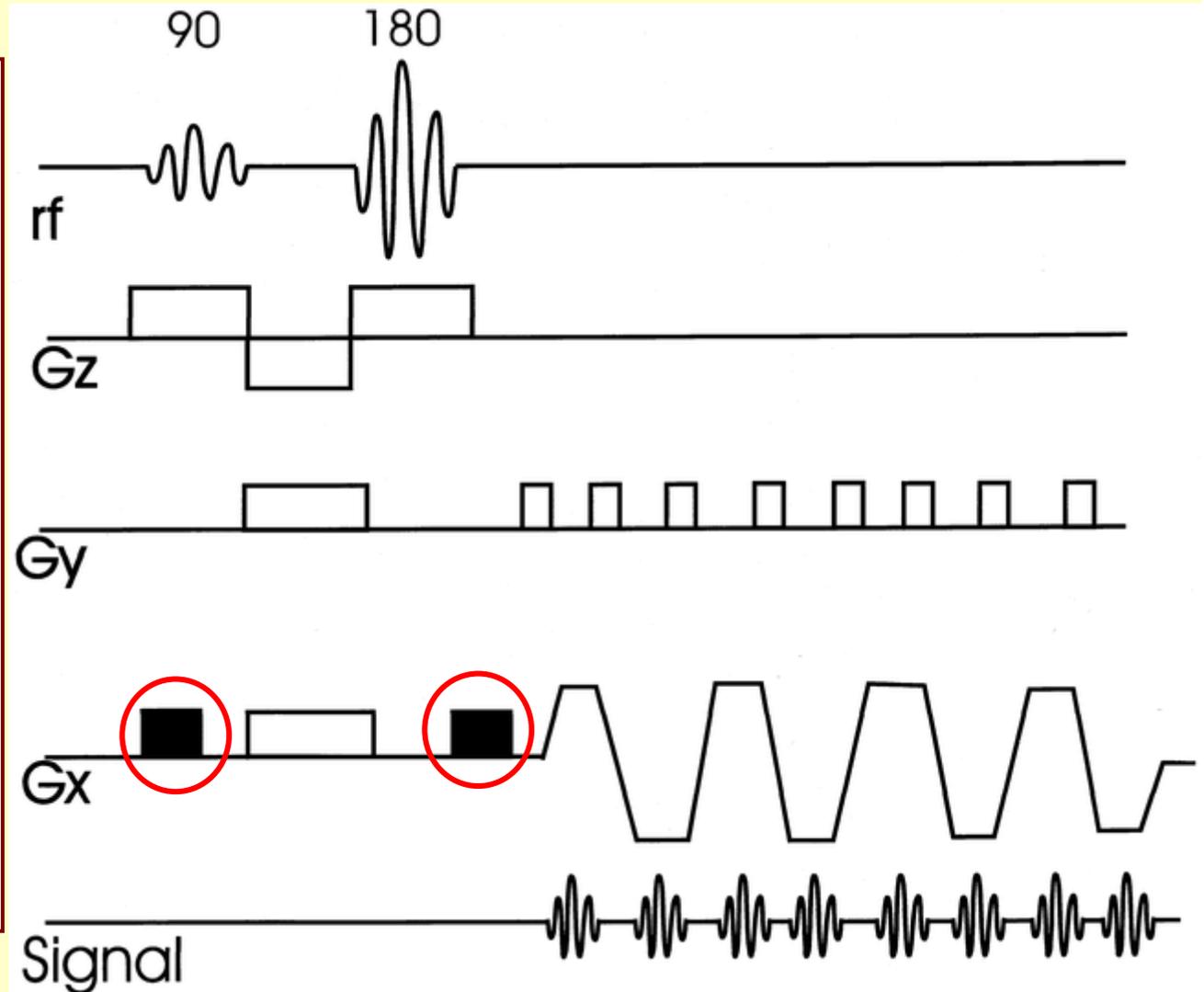


Diffusion EPI

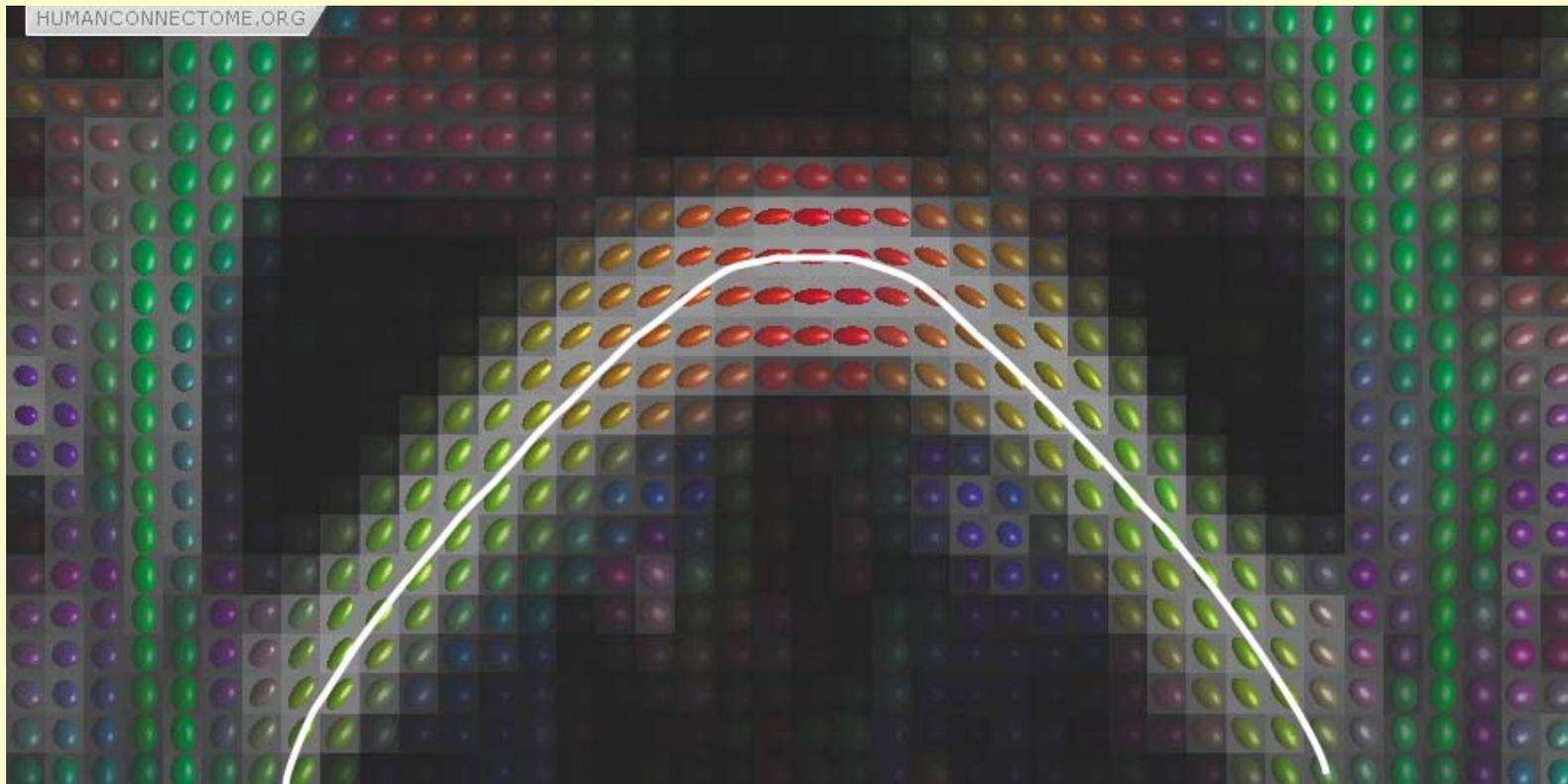
Use additional gradients to spoil
 180° pulse for
protons that
diffuse in selected
direction.

Repeat for
typically 30
directions

Long acquisition
times

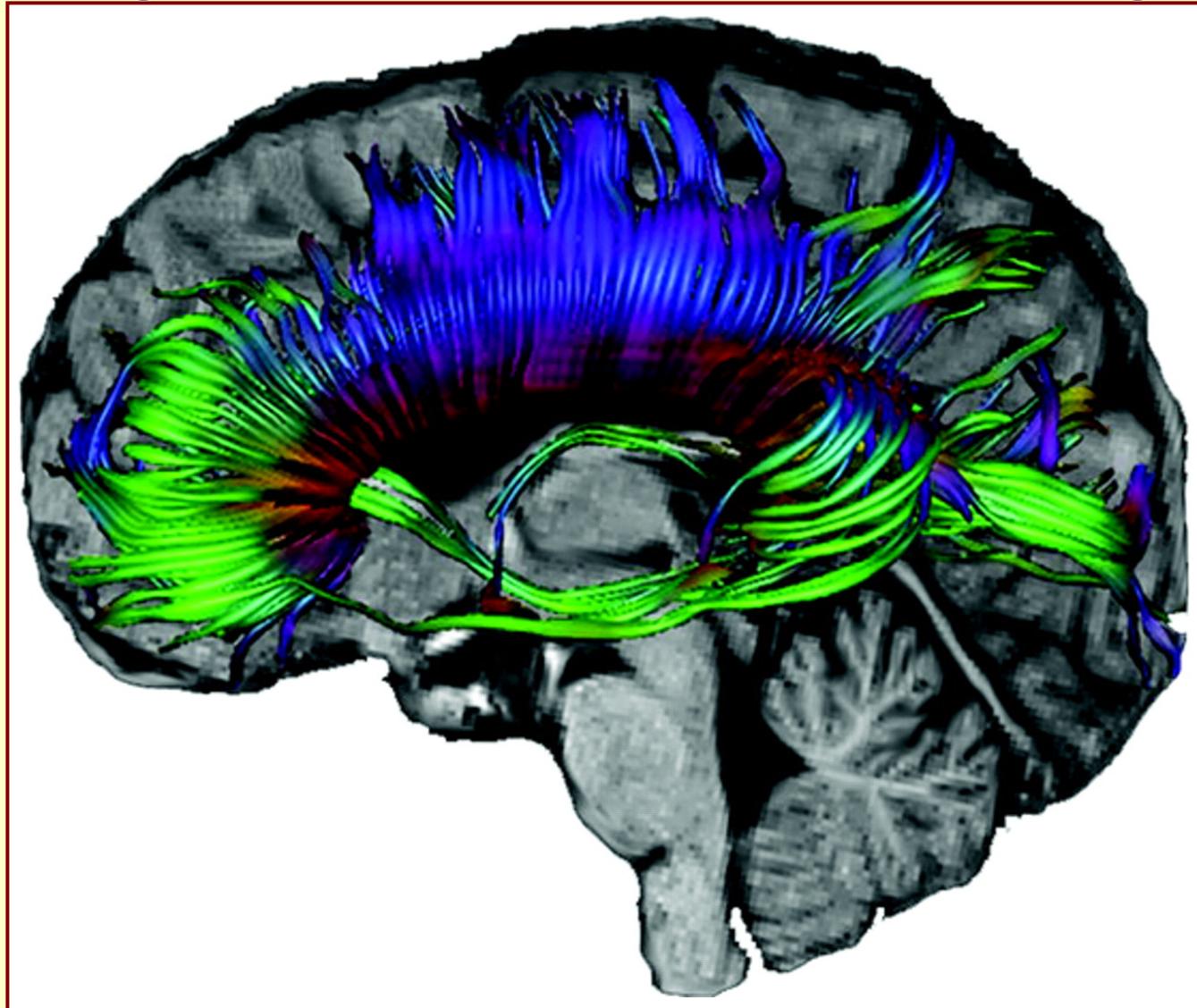


Tractography

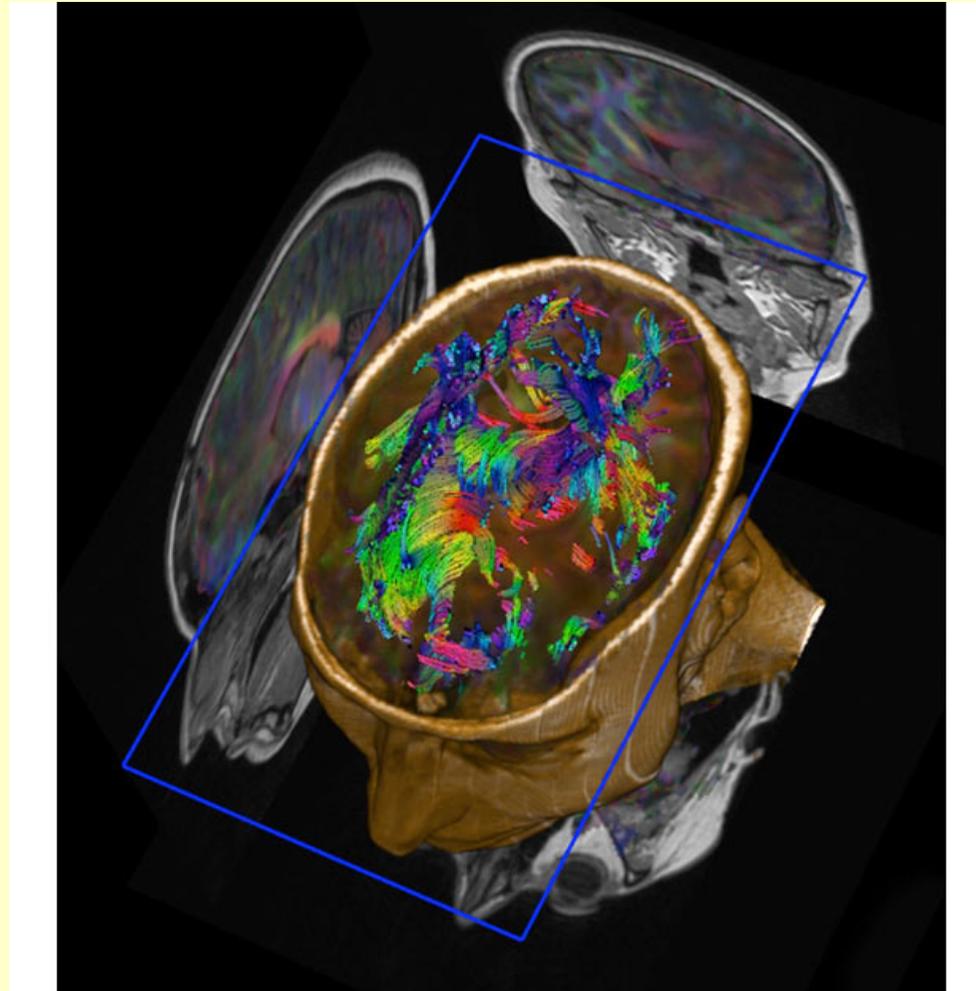


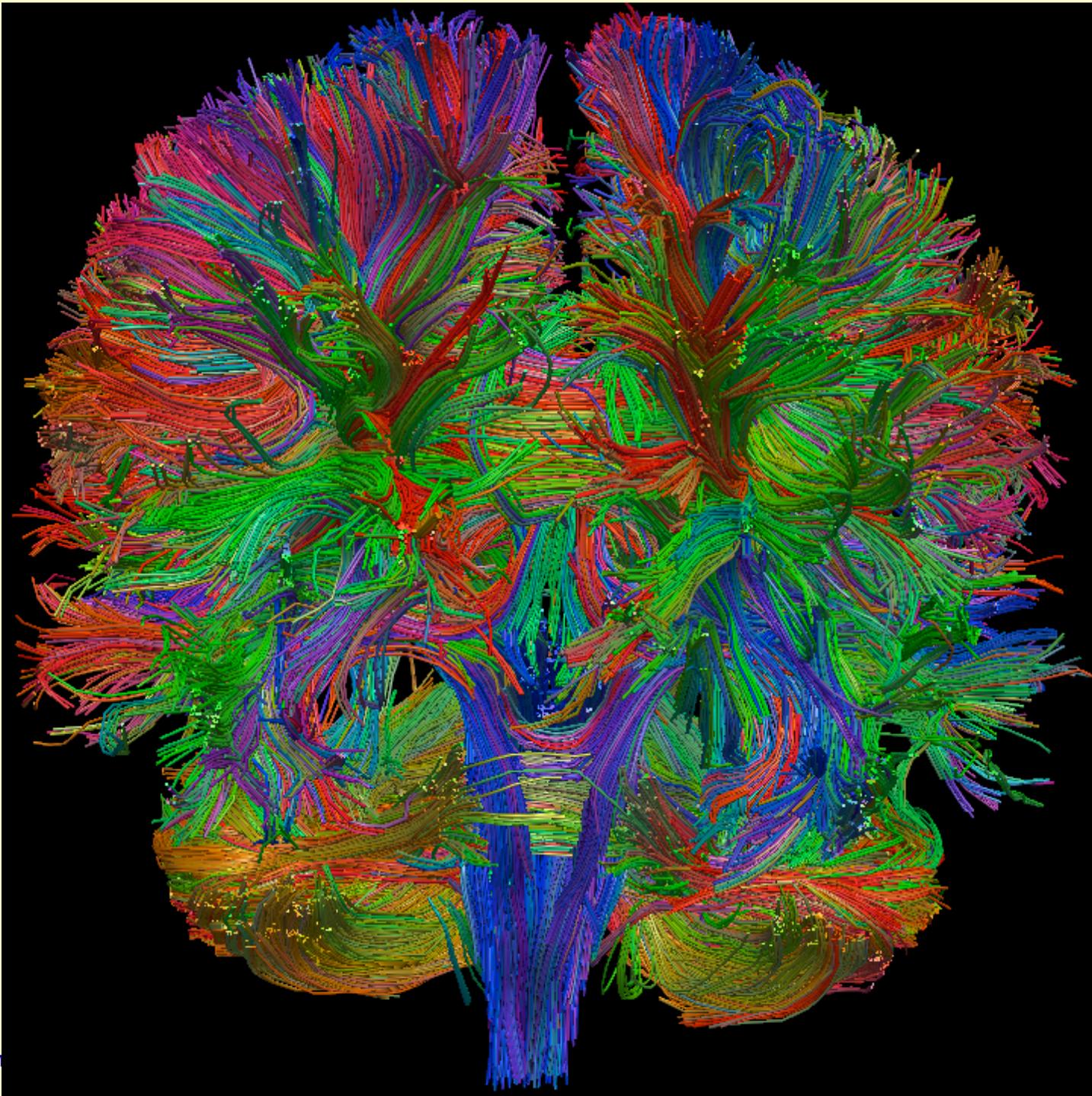
Preferred diffusion directions are shown as the long axes of diffusion ellipsoids. The colour is a complementary way of coding the preferred direction where red denotes left-right, green denotes back-front and blue up-down (out of the image plane). The white line shows the streamline obtained by connecting up a set of pixels based on their preferred directions and is an example of deterministic tractography.

High resolution diffusion image

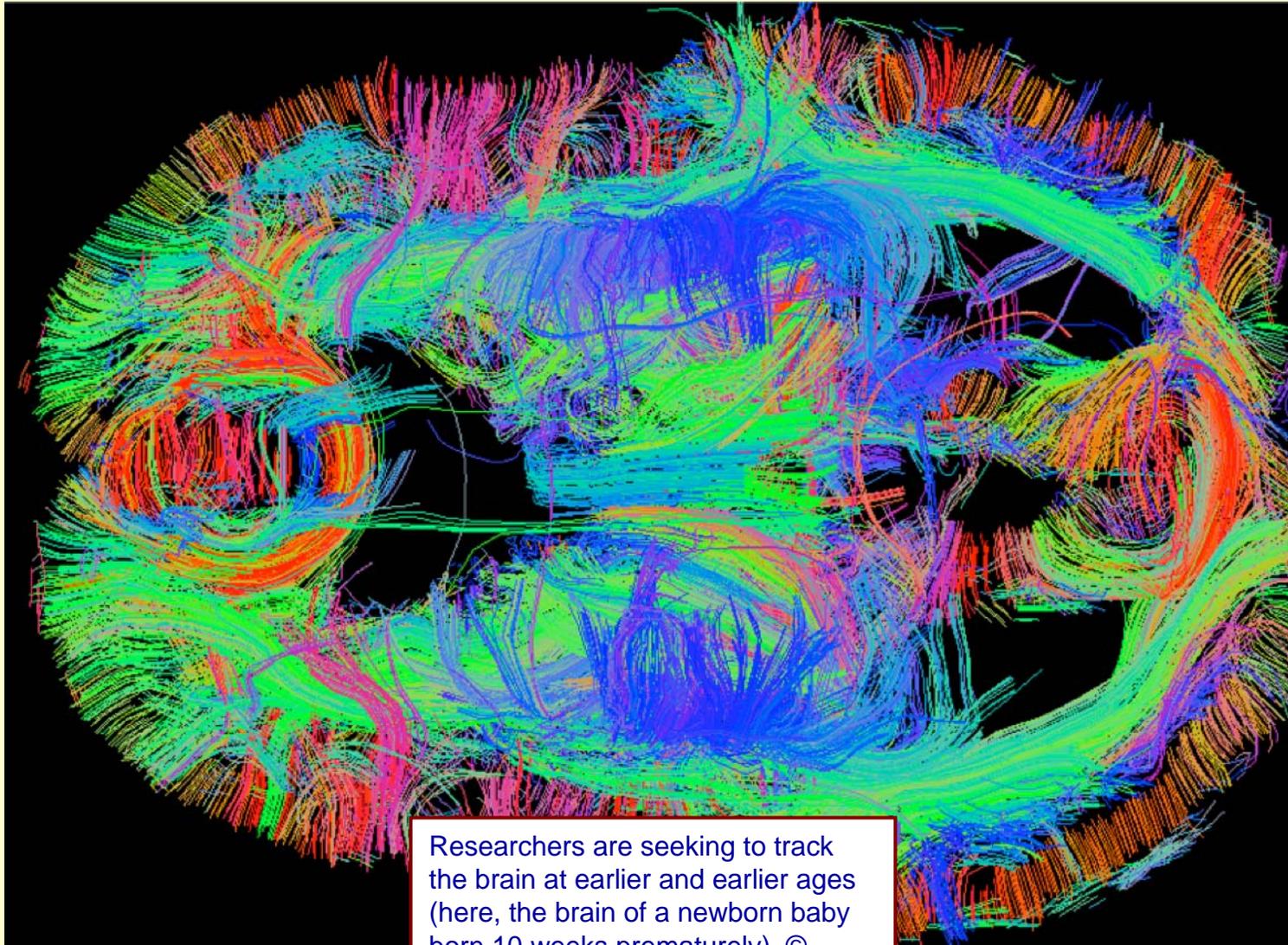


High resolution diffusion image



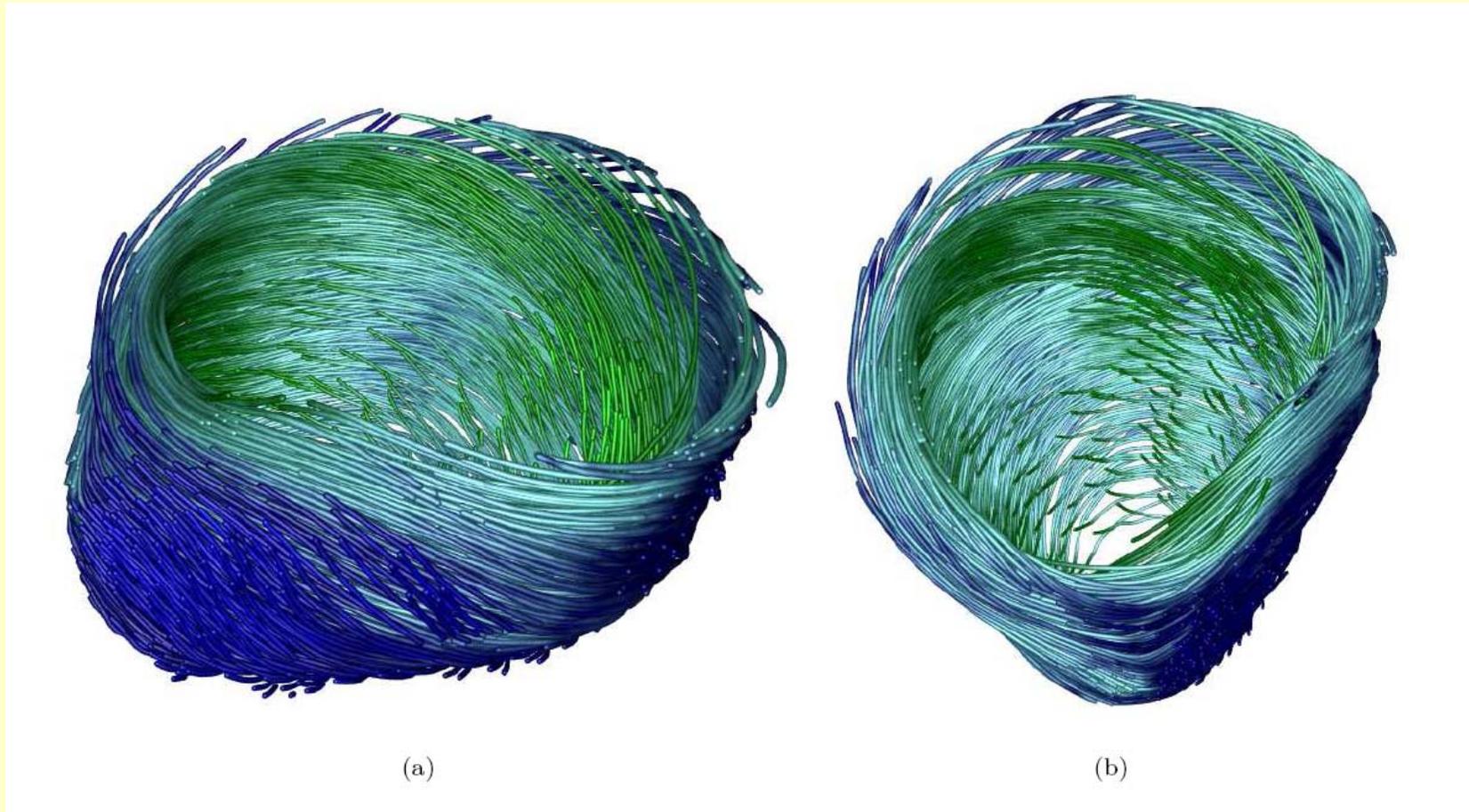


High resolution diffusion image



Researchers are seeking to track the brain at earlier and earlier ages (here, the brain of a newborn baby born 10 weeks prematurely). © FNNDSC 2011

Muscle Fibres in Human Heart

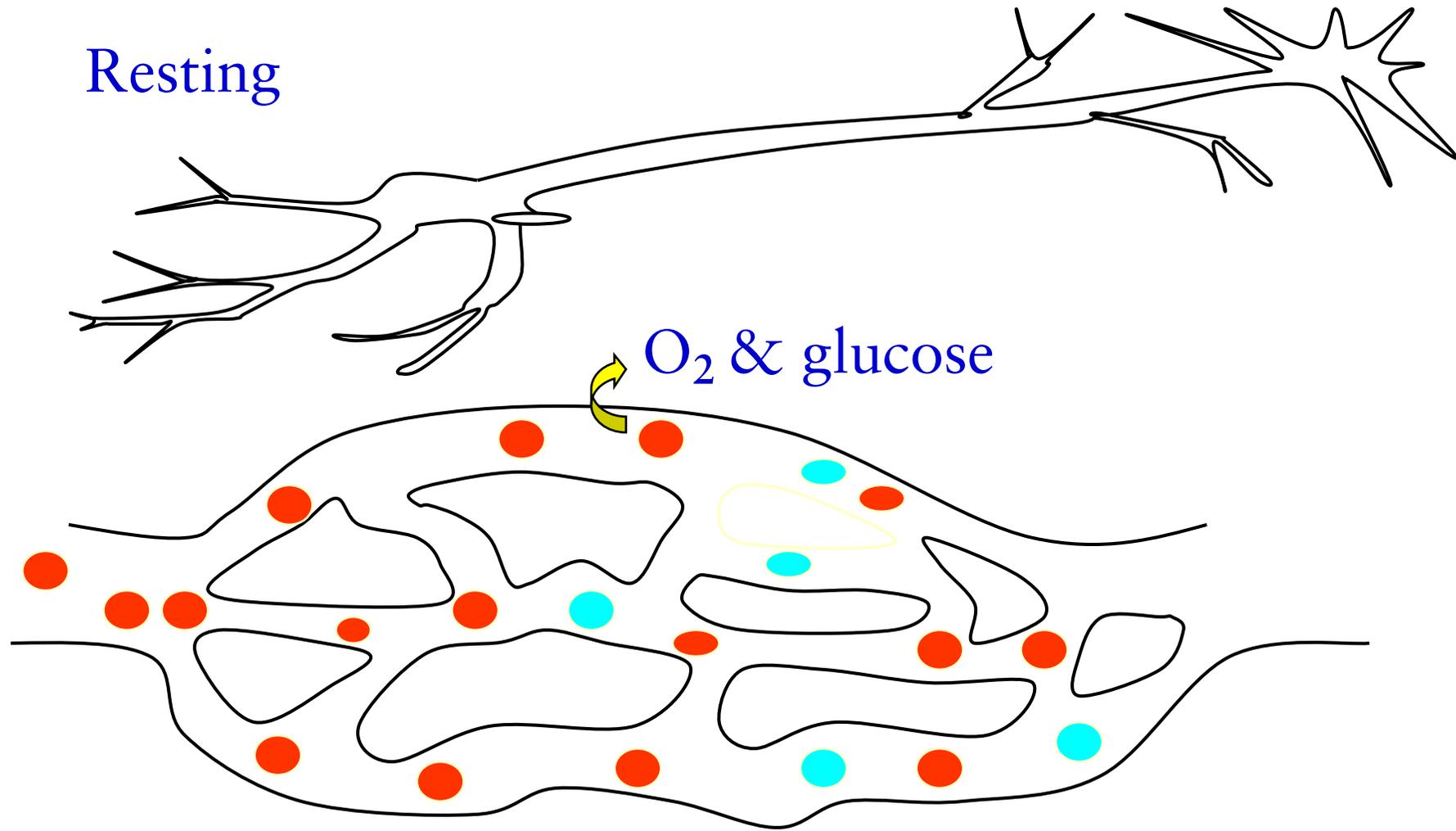


Computed fits to Diffusion MRI of Human Heart

Functional MRI (fMRI)

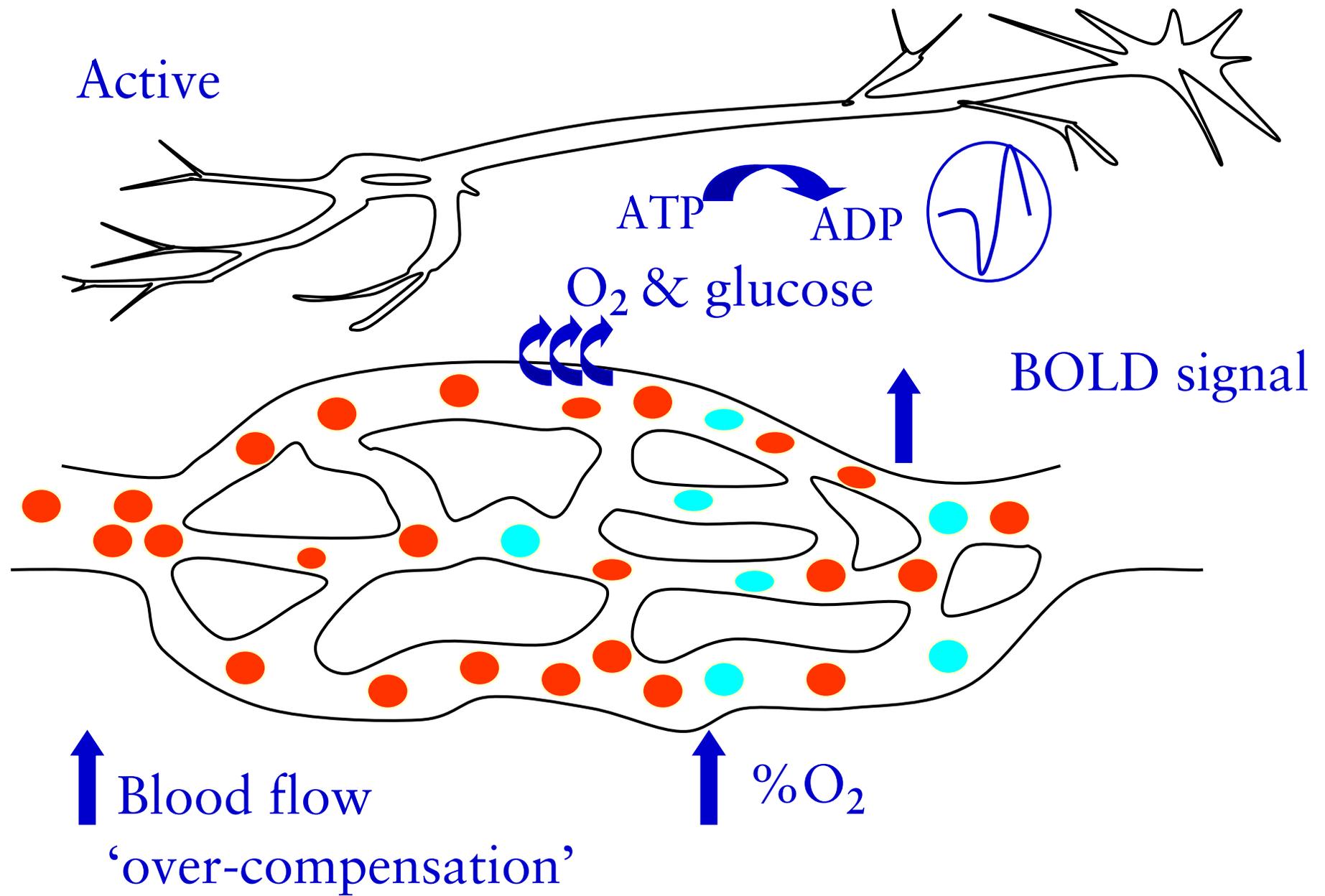
- Monitor T2 or T2* contrast during cognitive task
- Acquire 20-30 slices every 4 seconds
- Design experiment to have alternating blocks of task and control condition
- Look for statistically significant signal intensity changes correlated with task blocks

Resting



● oxyhaemoglobin

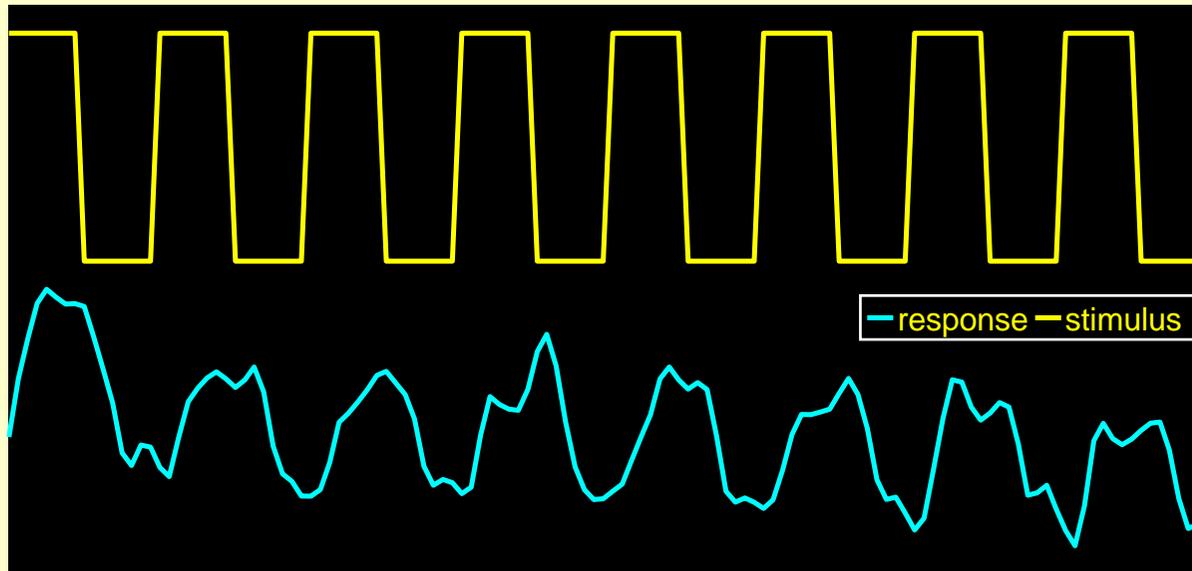
● deoxyhaemoglobin



Finger Tapping Experiment

Echo-Planar fMRI – Typical Data

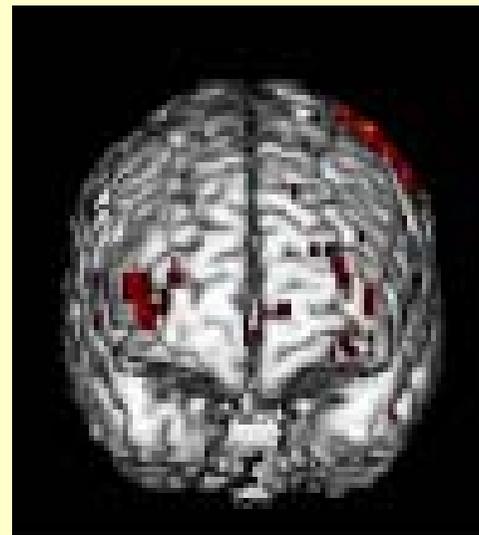
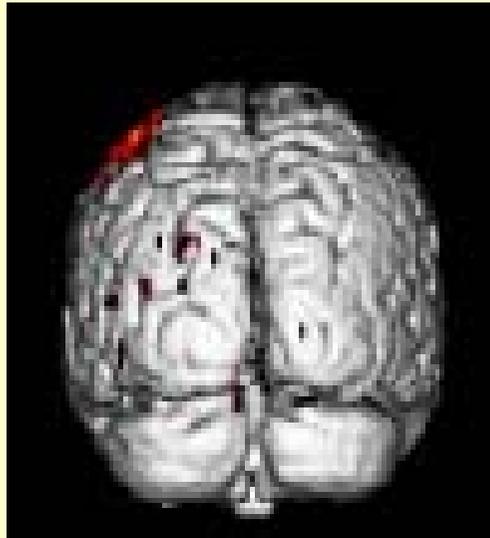
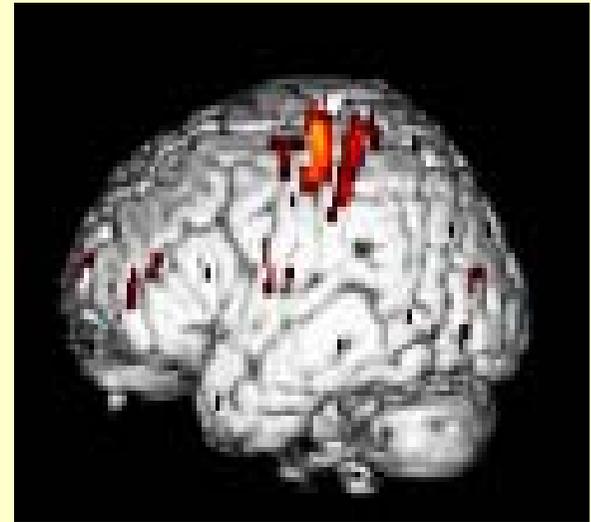
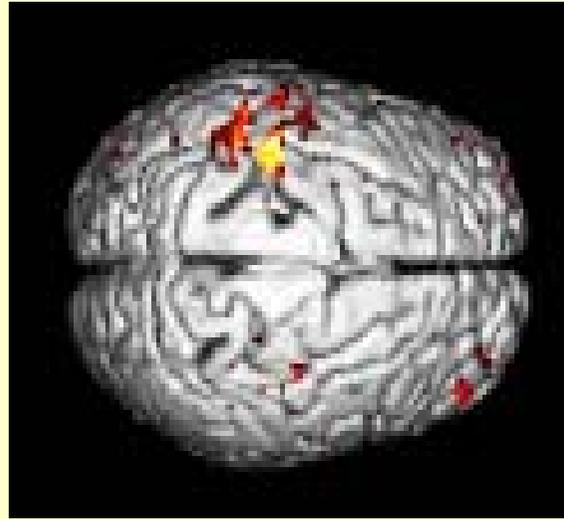
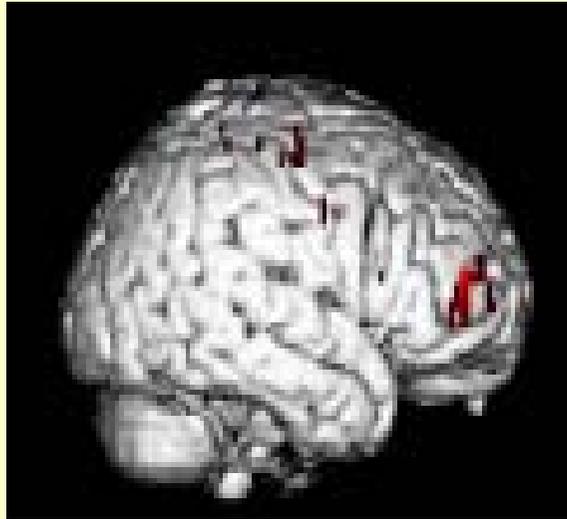
N.B. Signal/Noise ratio is generally poor



GE-EPI images
fMRI correlation
maps

Signal response
averaged over
region

Finger Tapping Experiment



Coma (Persistent Vegetative State)

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NEWS HEALTH

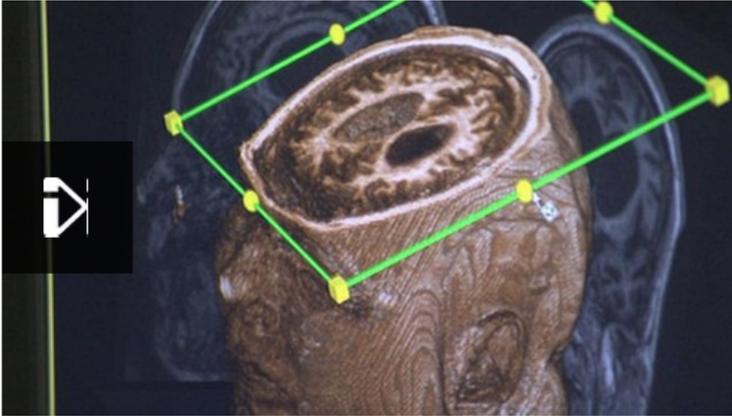
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Vegetative patient Scott Routley says 'I'm not in pain'

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By **Fergus Walsh**
Medical correspondent



The moment when Prof Owen asked patient Scott whether he was in pain

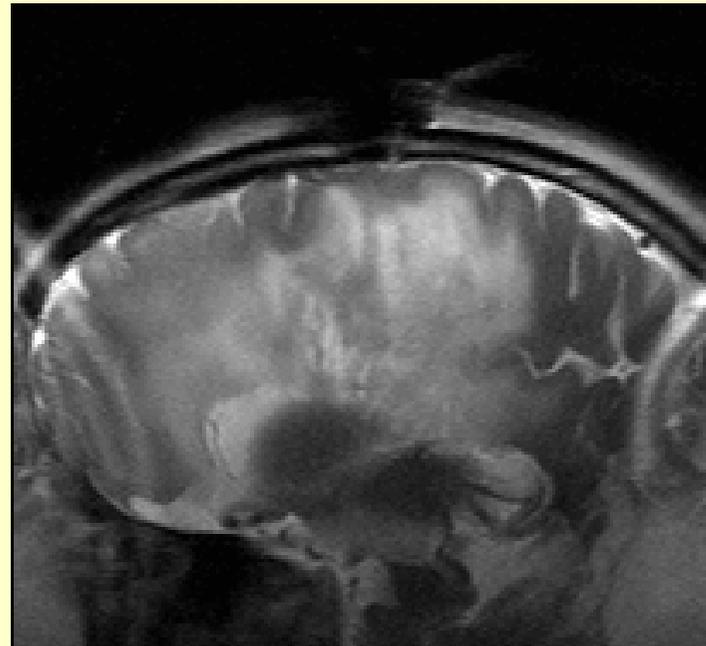
A Canadian man who was believed to have been in a vegetative state for more than a decade, has been able to tell scientists that he is not in any pain.

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Interventional MRI



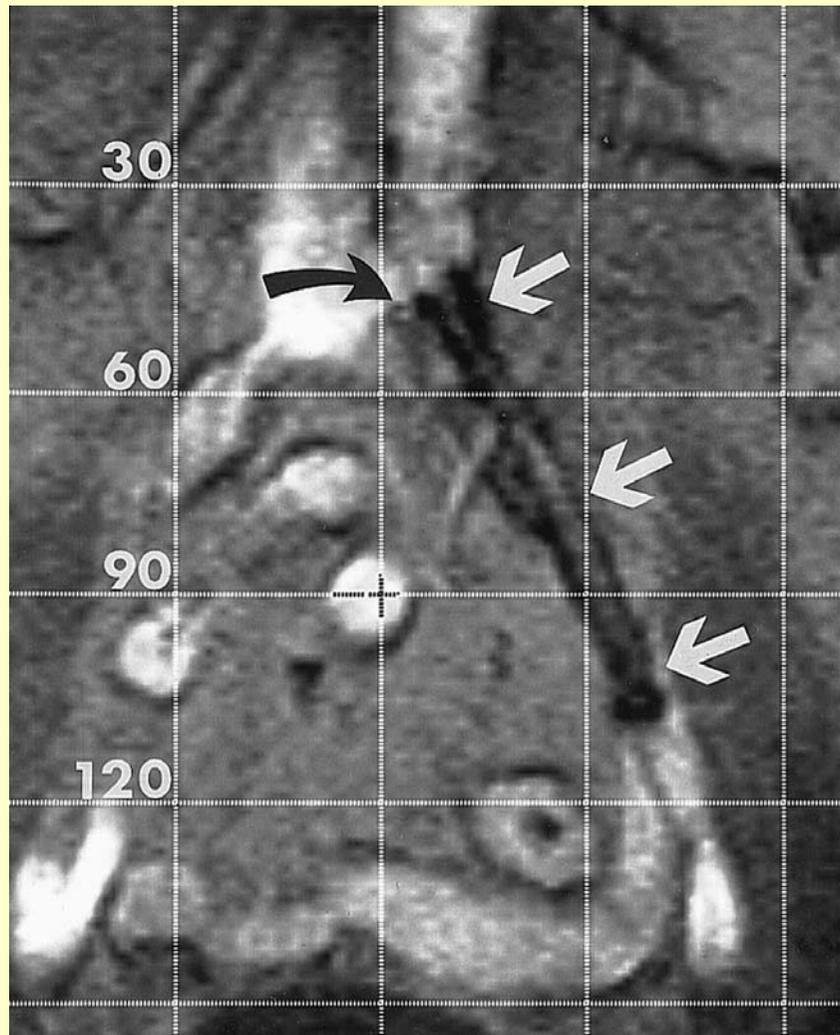
This is still quite rare

Interventional MRI



“Double Doughnut” magnet design

(a) Coronal contrast-enhanced source MR angiogram (4.7/1.9, 25° flip angle) obtained before stent placement shows the intraluminal position of the pigtail catheter within the abdominal aorta.



Manke C et al. Radiology 2001;219:527-534

Radiology

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(a) Coronal contrast-enhanced source MIP MR angiogram (4.7/1.9, 25° flip angle) obtained after stent placement shows a patent left common iliac artery and reduced signal intensity within the stent (arrows).



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Radiology

Whole Body MRI

- Whole-body MRI is a noninvasive screening technique that acquires images of the entire body in the coronal plane only using fast magnetic resonance pulse sequences
- Whole-body MRI is a promising method for screening pediatric patients with small round blue cell tumors for metastases, including lymphoma and neuroblastoma
- Whole-body MRI is also useful for assessing tumor burden in patients with neurofibromatosis and potential detection of malignant transformation
- Whole-body MRI is particularly beneficial for children because there is no exposure to ionizing radiation, making it an ideal imaging modality for serial imaging surveillance

Whole Body MRI

A) Whole body MRI of a lymphoma patient using a STIR sequence shows multiple cervical and mediastinal tumors.

B) Corresponding CT Image of the same patient.



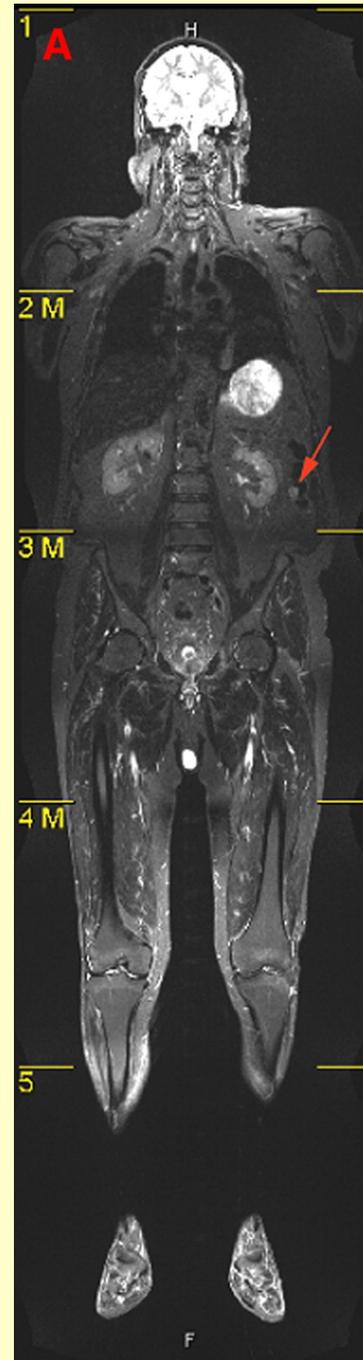
Whole Body MRI

(A) High soft-tissue contrast of MR image is apparent in whole-body MRI tomogram of human.

(B) In contrast, fused PET/CT image shows mainly bone structures. Metabolic PET images

(B and C) clearly depict tumor area (arrow) that appears also in MR image. Anatomic information is most prominent in MR image, whereas PET image can help to guide diagnostic focus toward abnormalities in metabolism. These abnormalities can then also be identified as structural malignancies in PET images.

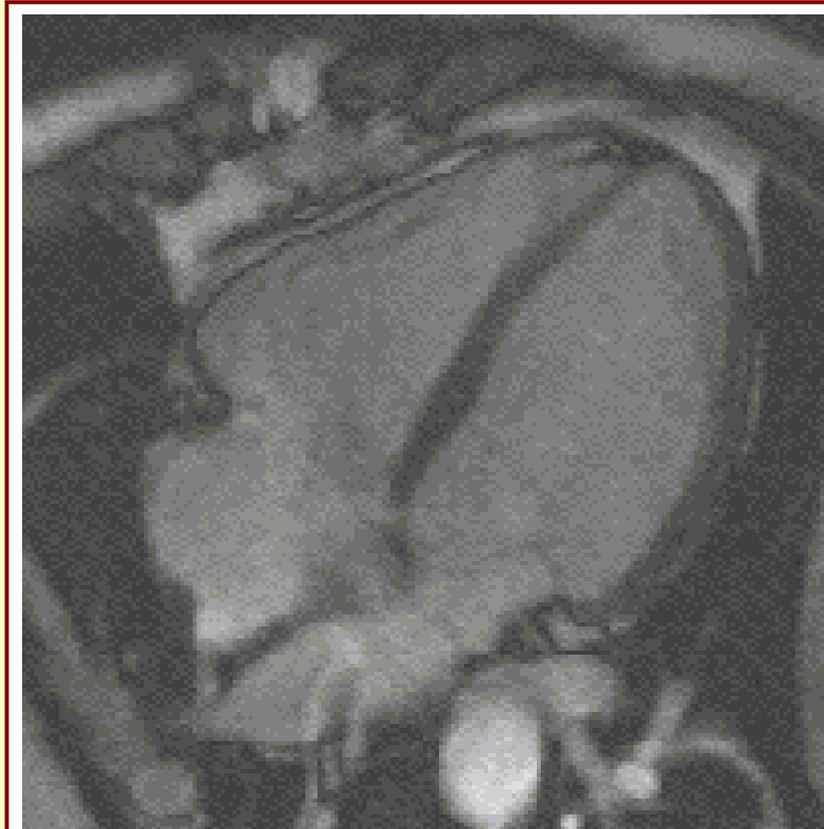
(Courtesy of Heinz-Peter Schlemmer, University of Tübingen.)



Cardiac Imaging

Heart function using cine imaging

Most sequences use ECG gating to acquire images at each stage of the cardiac cycle over several heart beats. This technique forms the basis of functional assessment by CMR. Blood typically appears bright in these sequences due to the contrast properties of blood and its rapid flow.

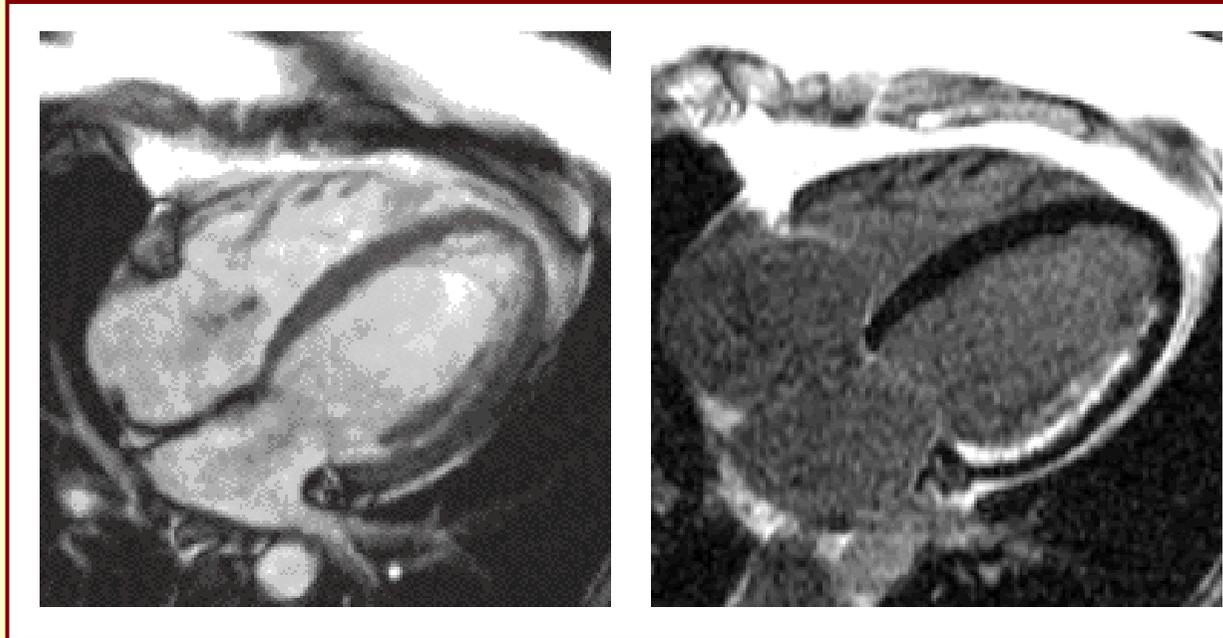


A 4 chamber view of the heart using SSFP cine imaging

Cardiac Imaging

Infarct imaging using contrast

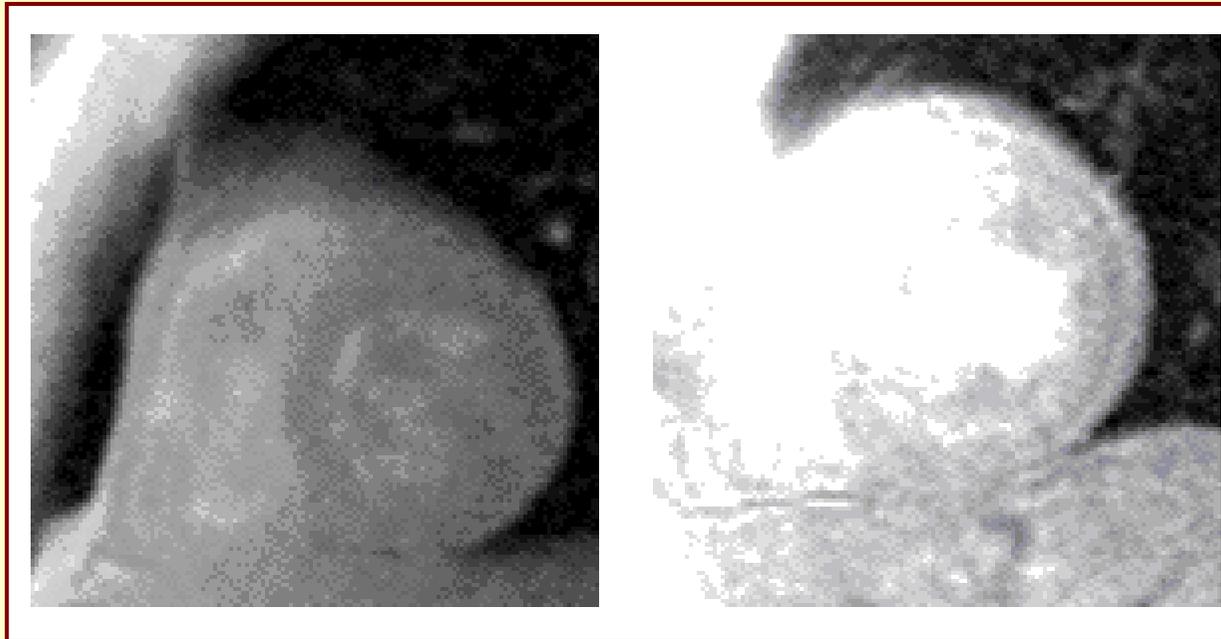
Scar is best seen after giving a contrast agent, typically one containing gadolinium bound to DTPA. With a special sequence, Inversion Recovery (IR) normal heart muscle appears dark, whilst areas of infarction appear bright white.



CMR in the 4 chamber view comparing the cine (left) with the late gadolinium image using inversion recovery (right). The subendocardial infarct is clearly seen. Fat around the heart also appears white.

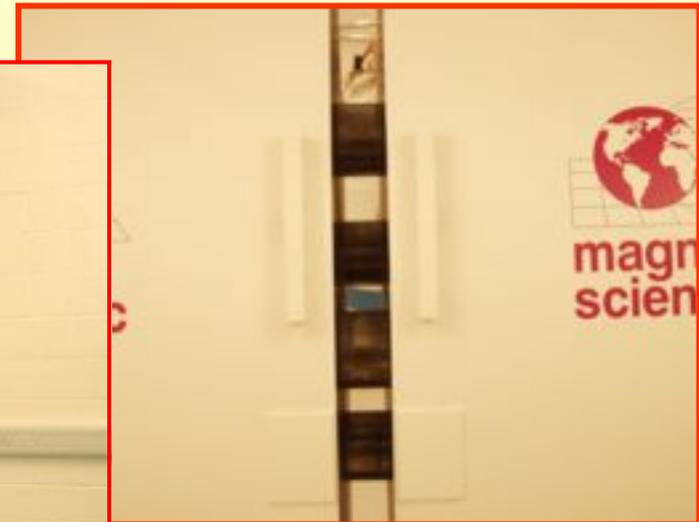
Cardiac Imaging Perfusion

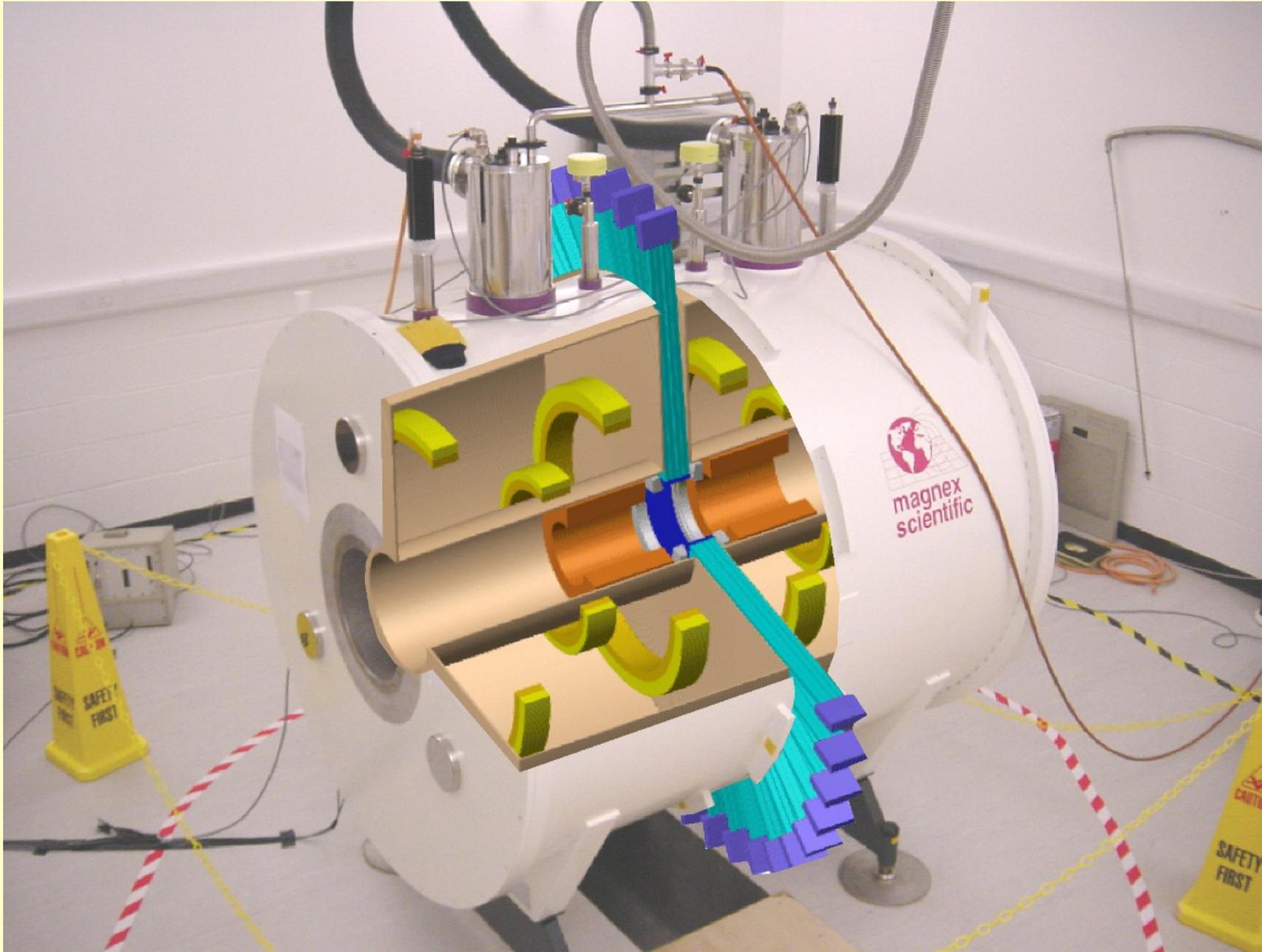
In angina, the heart muscle is starved of oxygen by a coronary artery narrowing, especially during stress. This appears as a transient perfusion defect when a dose of contrast is given into a vein. Knowing whether a perfusion defect is present and where it is helps guide intervention and treatment for coronary artery narrowings.

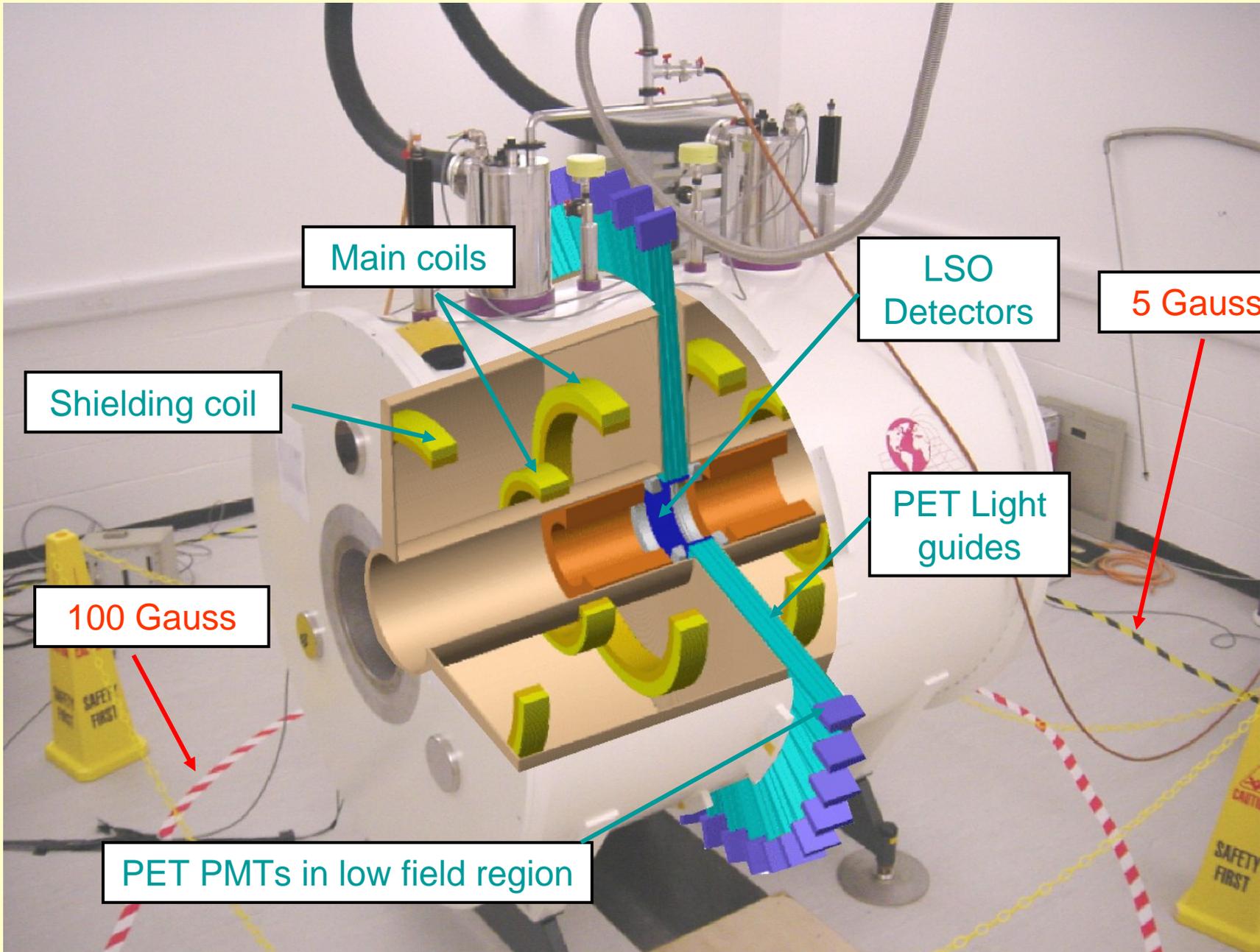


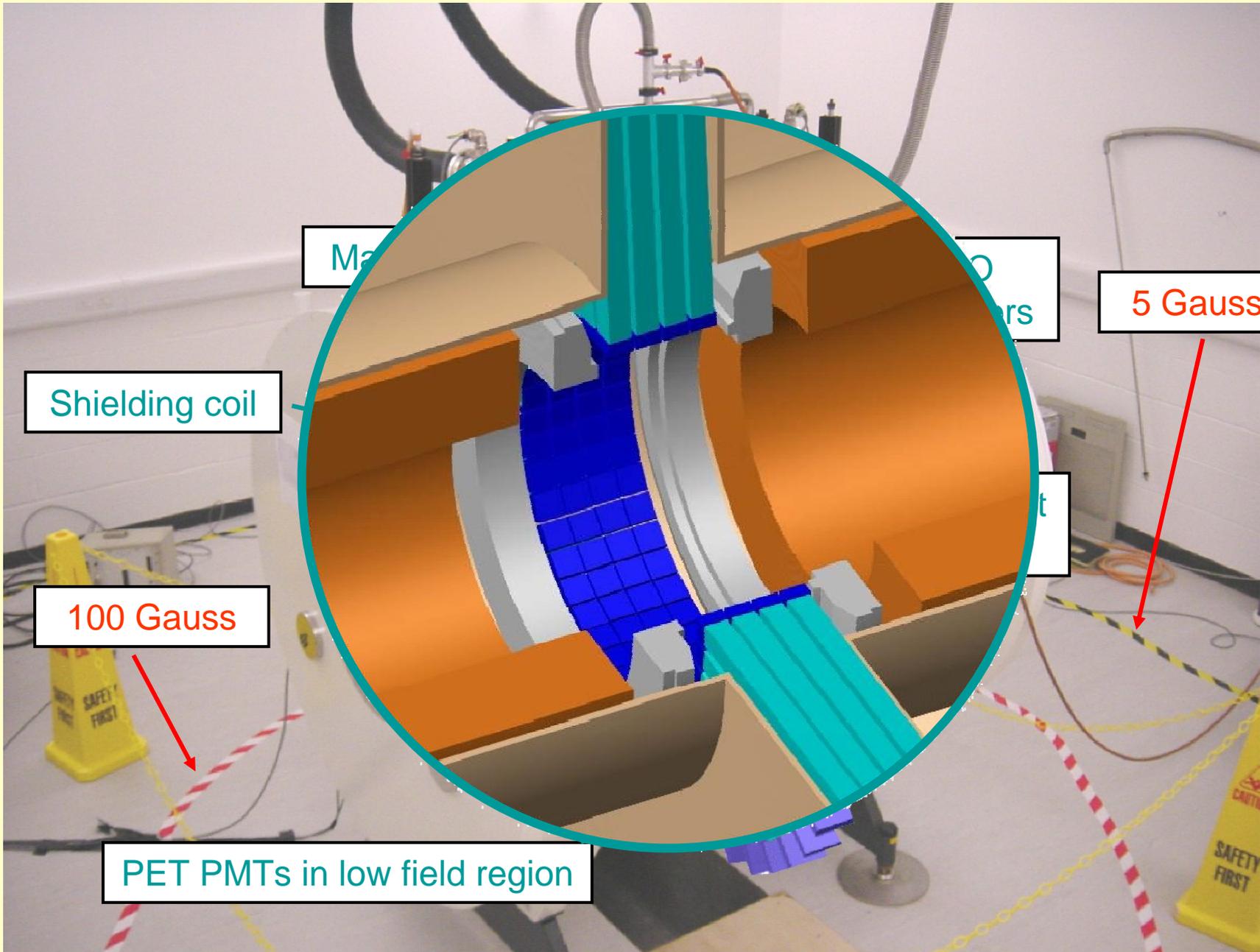
CMR perfusion. Contrast appears in the right ventricle then left ventricle before blushing into the muscle, which is normal (left) and abnormal (right, an inferior perfusion defect).

Combined PET & MRI









Shielding coil

100 Gauss

PET PMTs in low field region

5 Gauss

Addenbrookes Hospital



Thank You