NMR/MRI and PET

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Outline:

- Overview of MRI industry
  - History of MRI
  - Types of magnets
- Overview of MRI physics
  - Physics of polarization, SNR vs B
- Overview of imaging protocols
  - T1, T2 weighting
  - Propeller, Parallel, Interventional
  - fMRI, DWI, DTI
- MRI and PET
- Vision of Future
  - Ultrahigh field imaging
  - Ultralow field imaging
  - Alternate approaches

Some milestones in MRI:

(primarily from Clinical Magnetic Resonance Imaging, Edelman et al.)

1937 Rabi- resonance method for recording magnetic properties of atomic nuclei
1946 Block & Purcell – nuclear magnetic precision measurements and discoveries in connection therewith

1971 Damadian - different relaxation times for healthy and abnormal tissues

1973 Lauterbur – First MR images on samples

1975 Ernst – introduction of Fourier transform methods

1977 Mansfield – First clinical MR images

1978 Philips 0.15T MR scanner

1979 Siemens 0.2T MR scanner

1983 GE generates images with 1.5T scanner

1991 fMRI invented

~1994 Diffusion Tensor Imaging invented

2002 ~ 20,000 MR scanners worldwide, 60 million MR scans completed
http://www.berr.gov.uk/files/file28050.pdf

2011 ~ 30,000 MR scanners worldwide

MRI Magnet Requirements

Image quality and specifics of clinical use behind main requirements

B_0: the higher, the better; 1.5T standard, constant drive for higher IQ (SNR , resolution)

Homogeneity - typical ~10^{-5} (10 ppm pk-pk) @ 30 to 50 cm DSV, also Elliptical FOVs

B_0 temporal stability - long term: B_0 <0.1 ppm/hr (0.09% / yr) – keep RF bandwidth

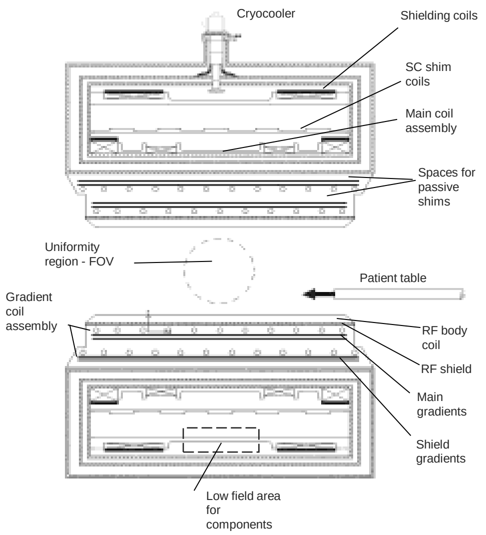
B_0 temporal stability - short term: dictated by IQ. EC from gradients – shielded gradients

Reliability: high stability, self-protected quench. Emergency discharge

Siting: 5 gauss line as small as possible, access controlled. Active or passive shielding.

Life cost and maintenance: high volume commercial product – design / manufacture cost reduction. Invisible for user (advances in cryocoolers – 0BO)

Typical Cylindrical Whole Body MRI System



Subsystems and patient compete for space inside bore and other areas

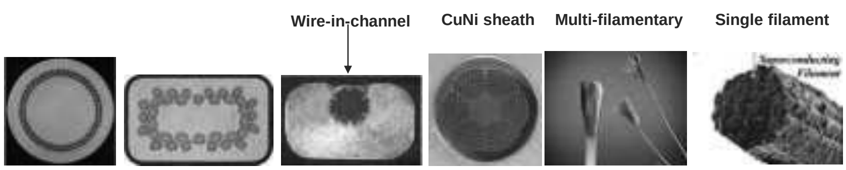
60 cm patient bore translates into magnet warm bore of ~90 cm

Magnet interaction w/ gradients:

- Geometrical : shared space, incl. shims
- EM: eddy current effects
- Mechanical – vibrations
- Thermal - heating

Conventional NbTi Materials

- Discovered in 1962, a few years after Nb_3Sn
- Metallic alloy
- Very ductile (c.f. other superconductors)
- Tc = 9.2 K
- Bc_2 = 15 T
- Jc ~ 4,000 A/mm^2 at 5T, 4.2K
- Workhorse among superconductors
- Lowest cost among all superconducting wires

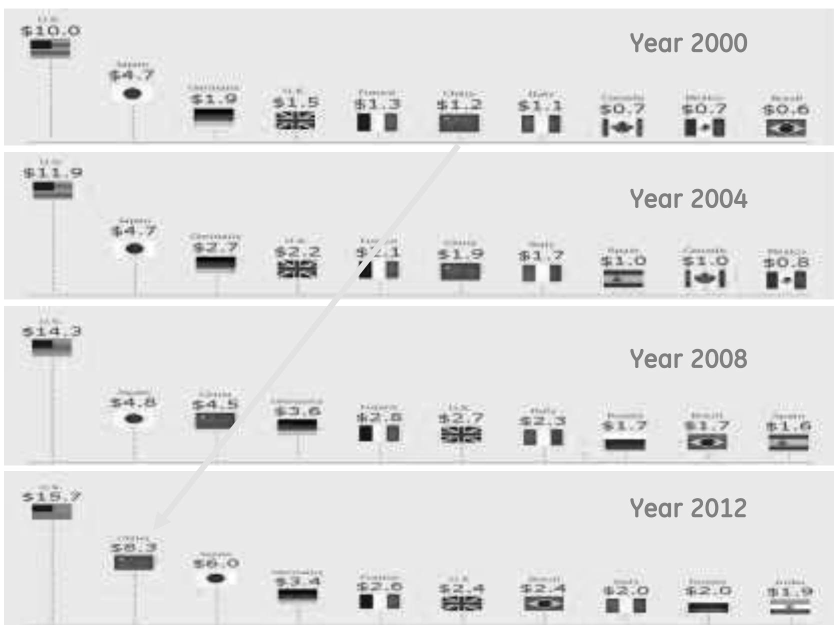


Conventional superconducting magnets

- About 30,000 NbTi superconducting MRI installed worldwide
- Over 10 billion meters of NbTi wires used in magnets

Sources: Company Websites

The World Economic Map Changed Dramatically, World's largest economies (in GDP)



Source: CNN Money Website

China Healthcare System and Market

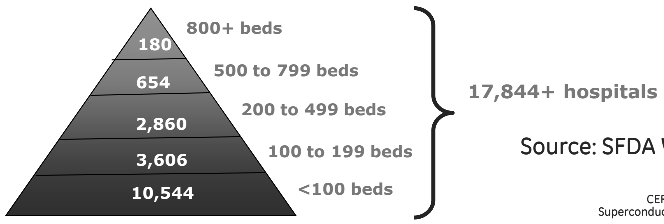
The Healthcare System

- more than 17,000 hospitals in 650+ cities
- A cost-effective three-tier health care system
- Majority hospitals are government-owned
- The majority of hospital continue to operate as non-profit institutes

The market growth has been driven by

-The strong economy
-Rising standard of living
-Increasing level of education and health awareness

Hospitals Classified by Bed Size



Source: SFDA Website

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MRI and PET

China Local MRI Supplier landscape

	U.S.	China
Total Population	315M	1.35B
MRIs/Million	~40	~3
Hospital	6850	18,000
Hospital with MRI	~5000	~2,000
%	~75%	11%

China has ~4X population with ~3X hospitals

Source: SFDA Website

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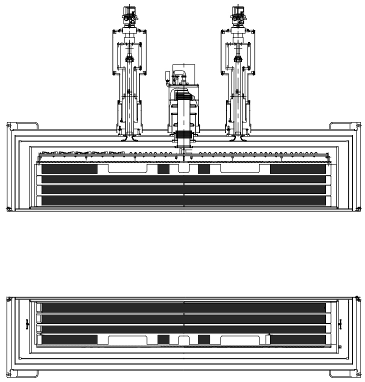
Demand for higher fields

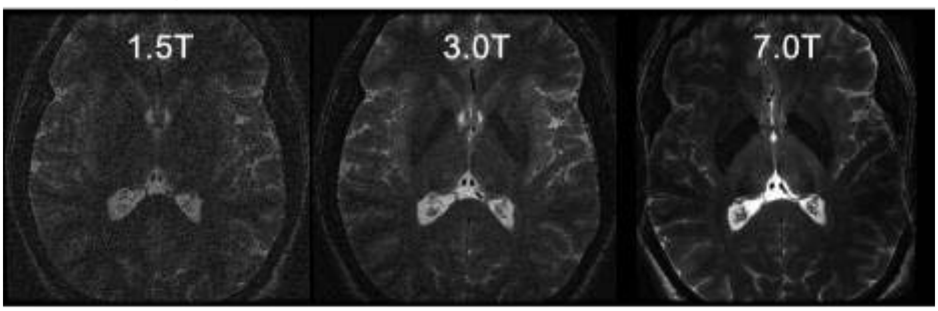
GE 3 T Whole Body MRI Magnet



GE 7 T MRI Magnet Layout

Systematic cross-field SNR comparison

T2w FSE, equal scan time



Relative SNR	1.5	2.85	6.0

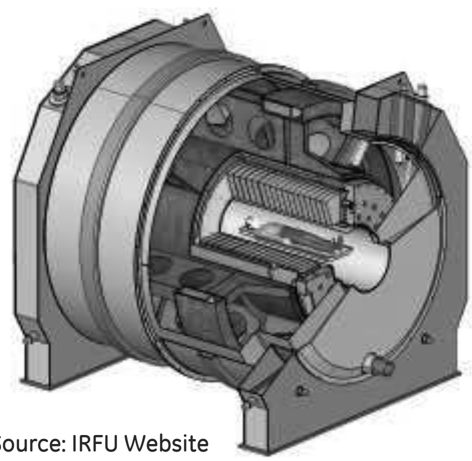
SNR increase *not quite linear* with B_0

2010 ISMRM UHF Workshop

GE 9.4 T MRI Magnet

Parameters	
Central Field B_0 (T)	9.4
B_{peak}/B_0	1.024
Uniformity @ 40cm DSV, peak-to-peak	5 ppm
Stored energy (MJ)	140
Conductor length (km)	540
Conductor weight (ton)	30
Magnet weight (ton)	45
Magnet length (m)	3.1
Room shielding weight (ton)	520

11.7 Iseult Magnet for Neurospin



Source: IRFU Website

Energy	= 338 MJ
Inductance	= 308 H
Diameter	= 5 m
Length	= 5.2m
Warmbore	= 90 cm
Current	= 1483 A
Lhe temperature	= 1.8K

Source: Vedrine, P et al, IEEE Transactions on Applied Superconductivity, June 2010 V20.3, p696-701

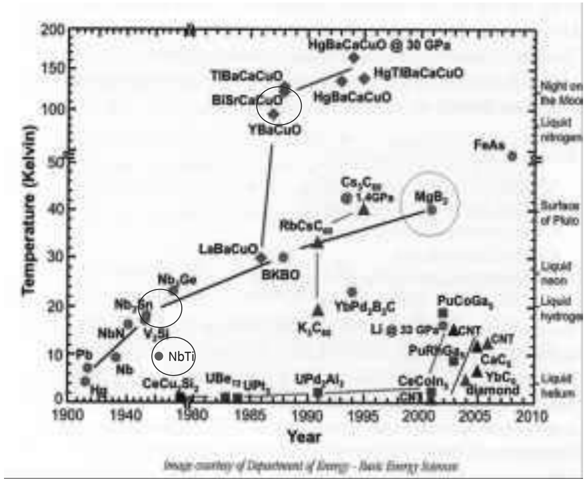
Superconducting Materials

Superconducting materials for large scale applications – long length wires

NbTi ~$1/kA-m at 3T, 4K

Nb_3Sn ~ $3-5/kA-m, @3T, 4K
HTS $40-100/kA-m @ 1T, 27K

MgB_2 ~$20/kA-m, @ 4T, 10K



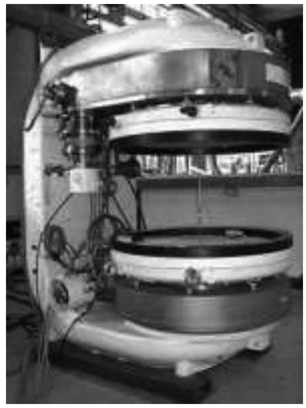
Chronicles of superconductor discoveries

Nb_3Sn Magnet – GE Signa SP ~ 1995

0.5T Magnet, 30 cm DSV FOV
58 cm Gap, 60cm Patient bore
Conduction cooled, 2 Cryocoolers
10K operation, 12K design
0.2 mm x 3 mm tape conductor
More than 10,0000 procedures
    Surgery, biopsy, thermal ablation
Challenge – MRI compatible equipment

HTS Magnets

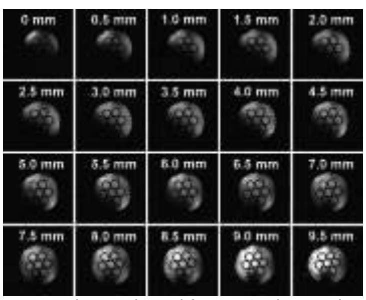
- Siemens 0.2T HTS open magnet
- 2 teams: Oxford & Siemens – one coil each
- BSCCO-2223 tapes from VAC and NST
- Pancake windings (10 and 12)
- Operated with separated PS (74A & 49A)
- Cooled with separated coolers (16K & 20K)
- No thermal shields
- Too expensive to market



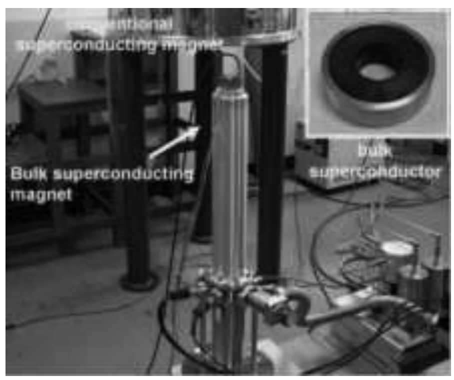
HTS Magnets

Development of an MRI system using a high Tc bulk superconducting magnet
K. Ogawa, T. Nakamura, Y. Terada, K. Kose, and T. Haishi; #627, Proc. Intl. Soc. Mag. Reson. Med. 19 (2011)

Annular bulk superconductors (outer diameter = 60 mm, inner diameter = 28 mm, height = 20 mm) made of c-axis oriented single-grain EuBa2Cu3Oy were stacked and energized by trapping flux of an external 4.7T magnet.



2D cross sections selected from a 3D image dataset of a water phantom. Numbers in the images are vertical height of the images.



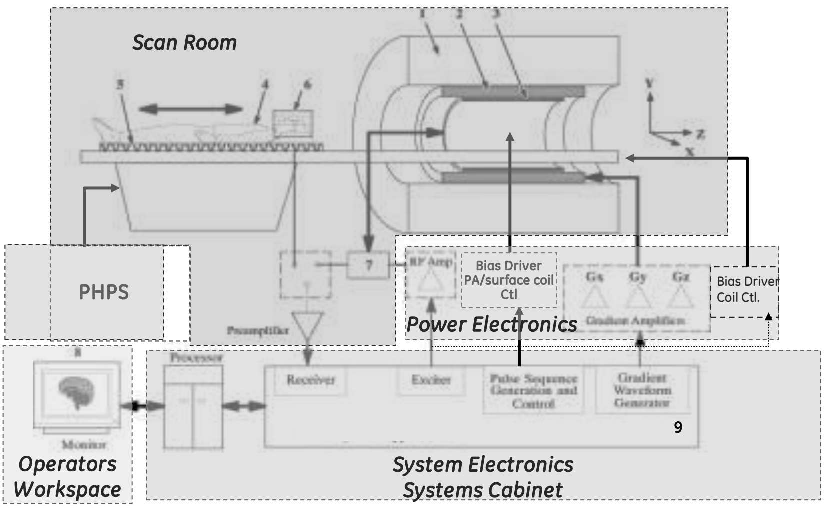
Bulk superconducting magnet, outer diameter = 88 mm, room temperature bore diameter = 20 mm.

$MgBr_2$

0.5T MR System
Conduction cooled

Source: Paramed Medical Systems Website

MR Imaging System and MR Physics



1) Cylindrical magnet, 2) Gradient coil, 3) RF body coil, 4) Patient, 5) Patient table, 6) Head coil, 7) Transmit/receive chain, 8) Imaging display, 9) Data Acquisition Control

Typical MR Block Diagram

Why is MRI so useful?

Versatility

Protons are the source of the MR signal … most of the body is H_20

No ionizing radiation

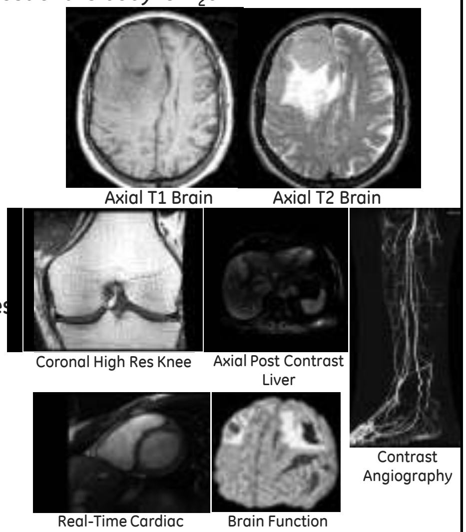
Arbitrary orientation and scan plane

1D, 2D, 3D, 4D Imaging

Structure and Function

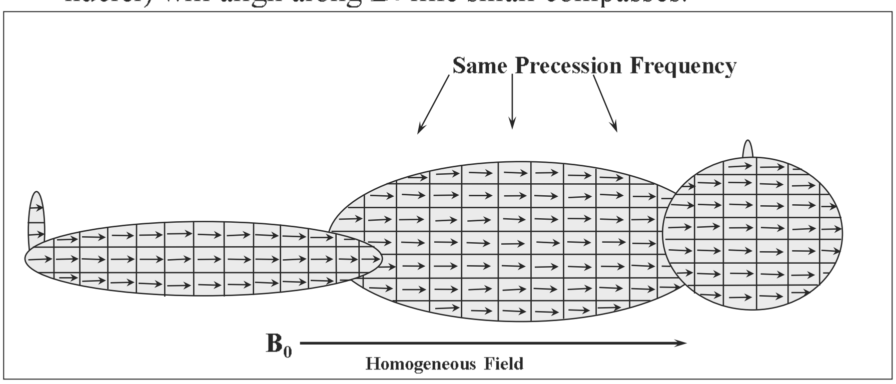
MR signal is sensitive to many parameters

- Proton Density
- Relaxation Times (T1, T2, T2*)
- Chemical Species (Fat/Water/Metabolites
- Motion
  - Flow
  - Microscopic Motion (Diffusion)
- Contrast Agents
  - T1, T2, Iron Oxide, Vascular



MR Imaging System and MR Physics

- The magnetization vectors (the sum of the individual ^{1}H nuclei) will align along $\mathbf{B}_0$ like small compasses.



Basic NMR relations:

$\mu = \gamma \cdot J$

$E_{1,2} = \mp \gamma \hbar B_z / 2$

$\omega_0 = \Delta E / \hbar = \gamma B_z$

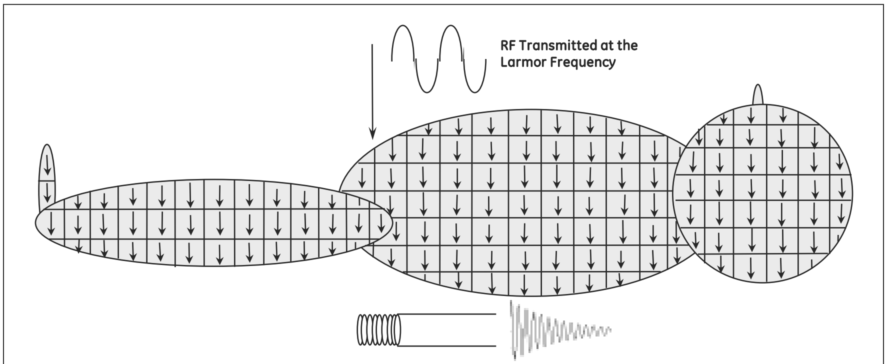
$n_1/n_2 = \exp(-\Delta E/kT)$

$M = (n_1 - n_2) \mid \mu \mid = n \frac{\gamma^2 \hbar^2}{4kT} B_z$

Fraction of spins aligned at 300K and 1T ~ 3ppm
Proportional to B

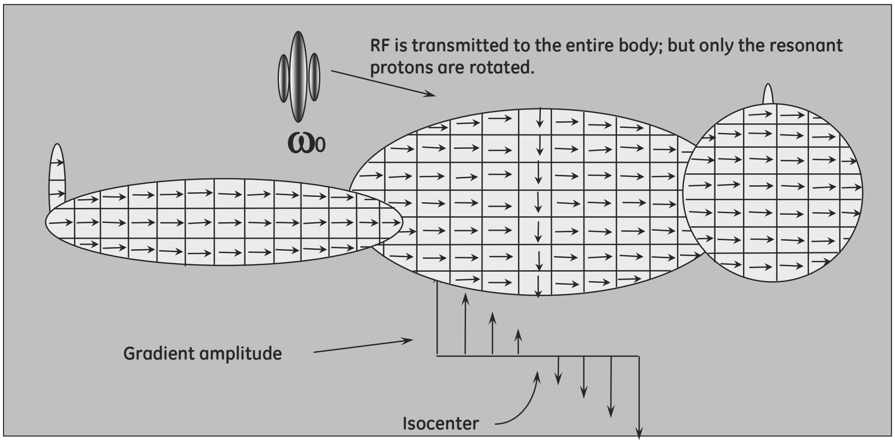
Apply RF signal at Larmor frequency

- All the magnetization vectors will interact with the RF field and rotate as long as the RF field is applied. In this case by 90 degrees.



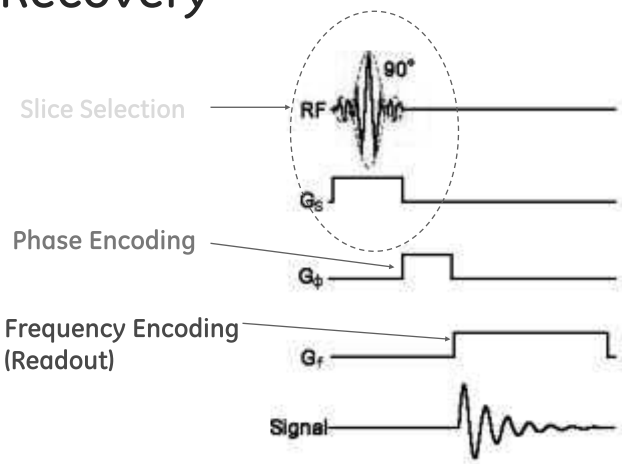
RF & Gradients: Slice Selection at Isocenter

- While a slice selection gradient is turned on, a shaped RF pulse is transmitted at ω_0. Only those protons precessing in a narrow range around w_0 are excited (rotated) by the pulse.



Slice selection followed by gradient fields applied in X and Y generates location of signal

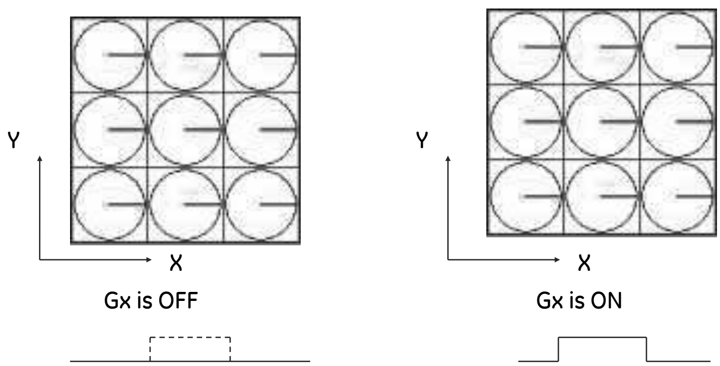
A Simple Pulse Sequence: Saturation Recovery



FDA guideline - gradient dB/dt < 20T/s

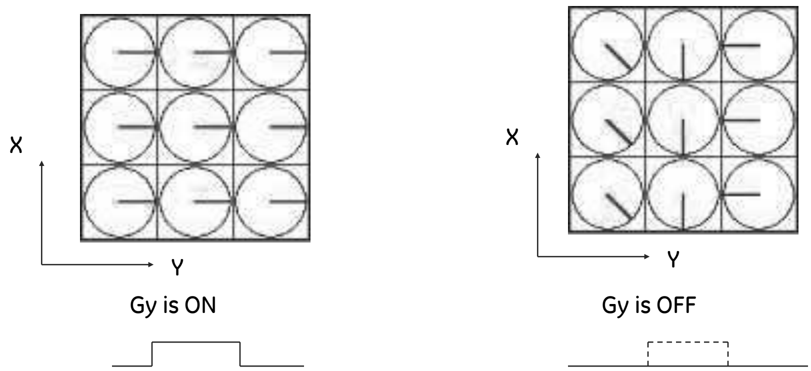
Frequency Encoding

- During the echo (signal) acquisition, the frequency encoding gradient is turned on. It causes a known, spatially dependent variation of precessional frequencies in the direction of the frequency axis.



Phase Encoding

- Phase encoding occurs after slice selection/excitation. The precessional phase in the direction of the phase axis varies in space according to the magnitude of the phase encoding gradient.



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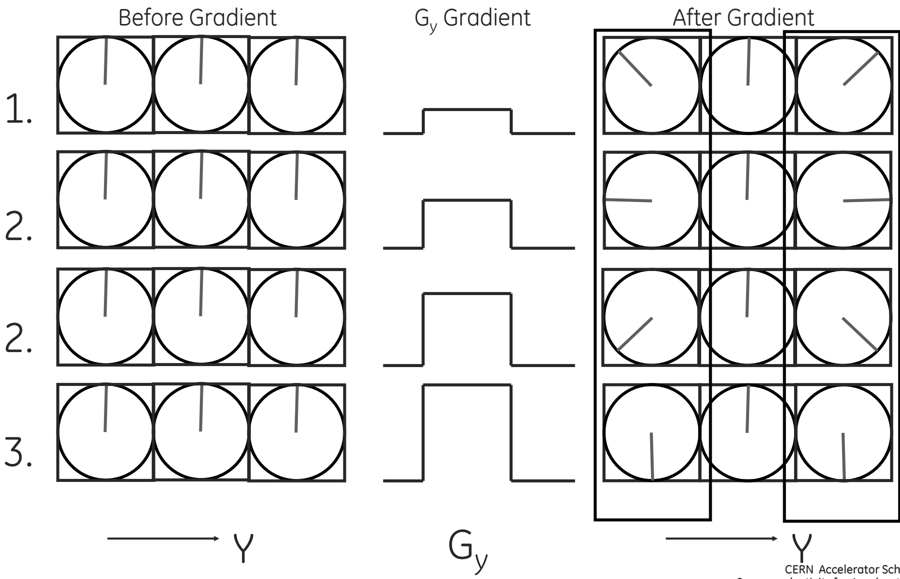
More on Phase Encoding



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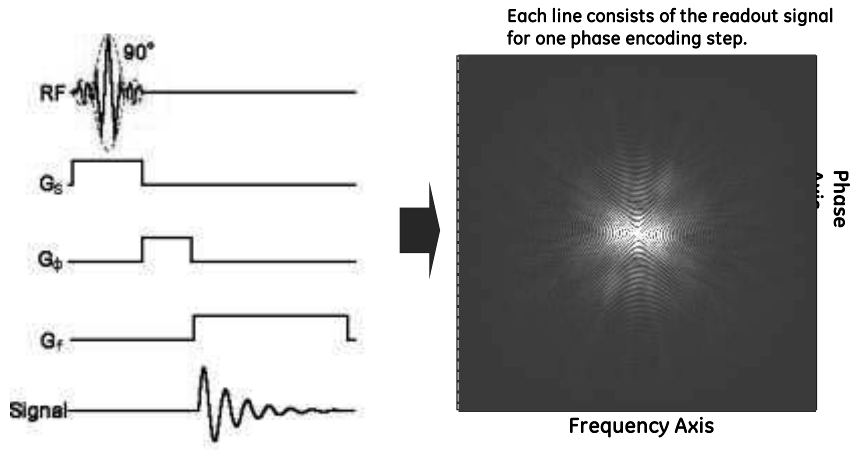
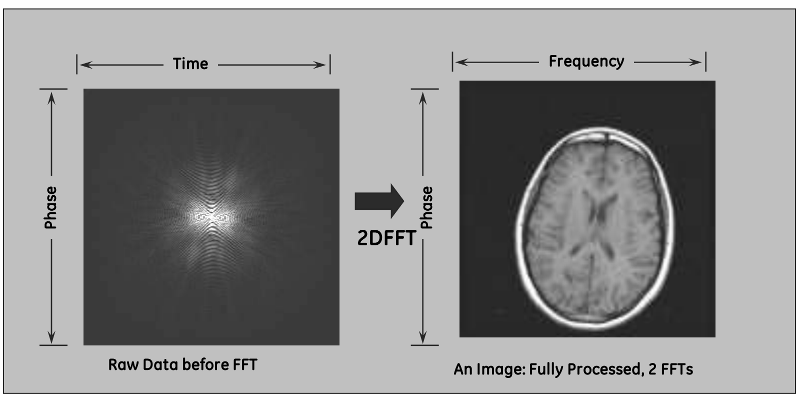
Raw Data



Reconstruction: 2 D FFT

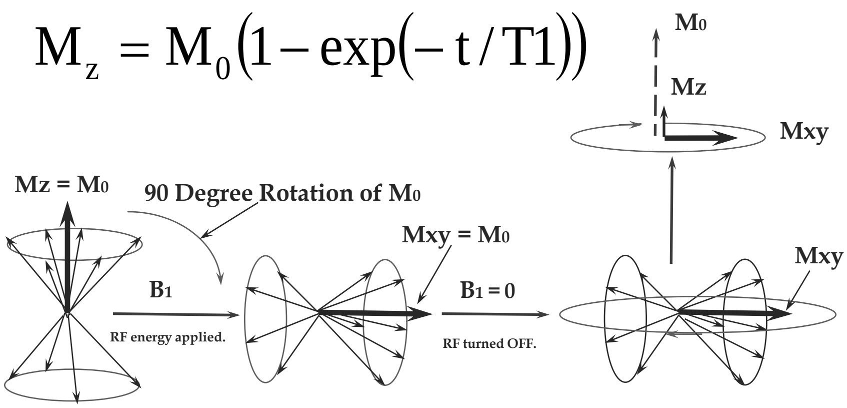
- The 2D FFT produces the image.
- 2D FFT = Row 1D FFT and Column 1D FFT



T1, T2 Relaxation Times

T1 is a measure of the time for Mz to return to 63% of its equilibrium value (M_0).

$$M_z = M_0\left(1 - \exp\left(-t/T1\right)\right)$$

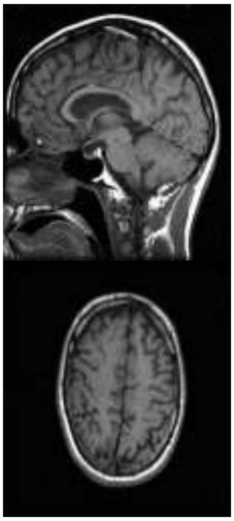


Properties of Body Tissues – 1.5 T

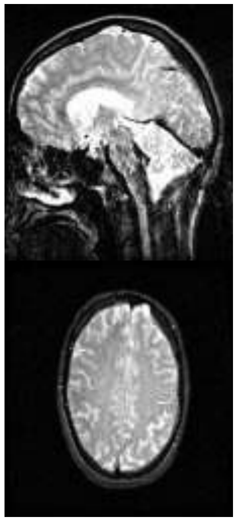
Tissue	T1 (ms)	T2 (ms)
Grey Matter (GM)	950	100
White Matter (WM)	600	80
Muscle	900	50
Cerebrospinal Fluid (CSF)	4500	2200
Fat	250	60
Blood	1200	100-200

MRI has high contrast for different tissue types! Scan parameters can highlight different tissues, diseases.

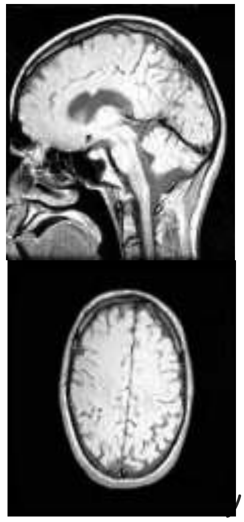
MRI of the Brain – 1.5T



T_E = 14 ms
T_R = 400 ms

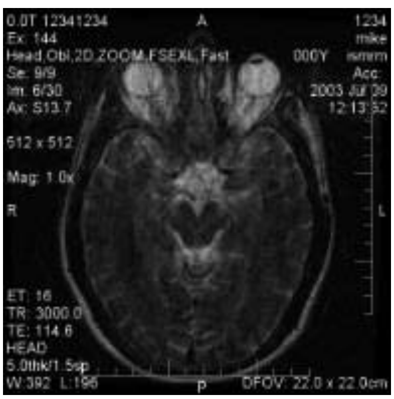


T_E = 100 ms
T_R = 1500 ms



T_E = 14 ms
T_R = 1500 ms

Propeller motion artifact reduction (tremors, etc)
Multiple scans, chosen wisely



FSE

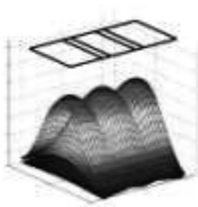
PROPELLER

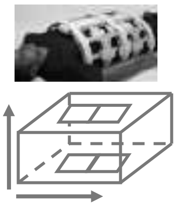
imagination at work

Parallel Imaging

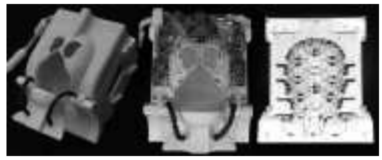
- Using multiple receive coils to scan faster

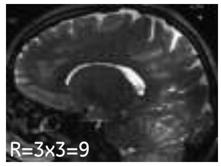
Concept: use information in the receive coil B1 field spatial profile (sensitivity) to reduce scan time





Optimal phase encoding direction





- Gather some spatial information from multiple receive coils, reduce scan times by 4 or more.

- A 64-Channel Array Coil for 3T Head/Neck/C-Spine Imaging, *Proc. Intl. Soc. Mag. Reson. Med. 19 (2011)*
- B. Keil1, S. Biber2, R. Rehner2, V. Tountcheva1, K. Wohlfarth2, P. Hoecht3, M. Hamm3, H. Meyer2, H. Fischer2, and L. L. Wald1,4

Interventional MR… growing clinical value

Non-invasive → Surgical

MR Intvl

MRgFUS Neuro

MR DBS/Drug Delivery

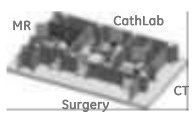
MR Surgical Suite

Non-ionizing Imaging
- Expanding Apps for MRI
- MR–soft tissue detail / MRS – biological targeting sub-volumes
- Target & verify tumor resection

Therapy Expansion

MRgFUS - Oncology

PetCT +MR



Hybrid Suites

Hybrid Suites
- Multi-modality… Co-location of interventional imaging MR-Angio-PETCT-CT-OR
- MR combined with focused US for therapy guidance

Real Time/Thermal

MR Guided Radio Therapy

MR Thermal Therapies

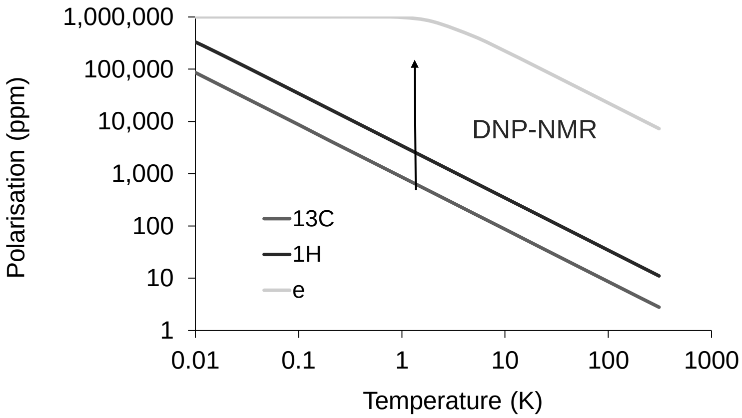
MR Robotic Surgery

Imaging for Therapy
- Visualization & treatment of microscopic disease
- Precise treatment dosimetry
- Robotic surgery guidance
- Thermal Ablation FUS, Cryo, RF, Laser,Microwave

GE ISMRM 2005 – ^{13}C MRI

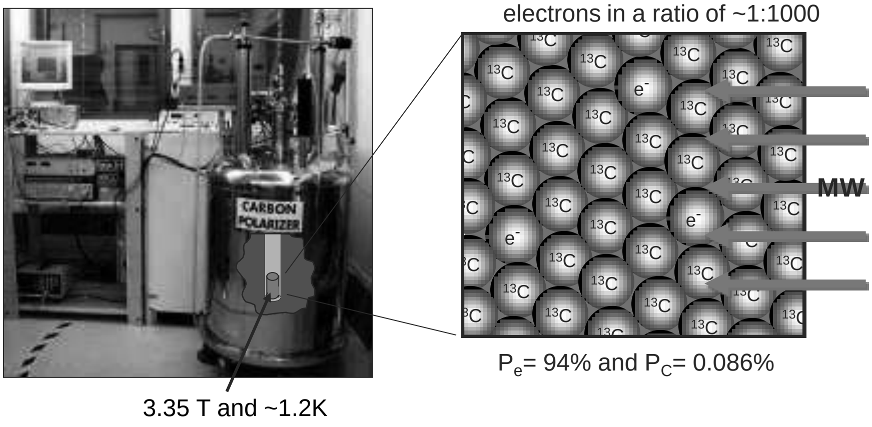
Jan Henrik Ardenkjaer-Larsen, et al

Thermal polarization at 3.35T



Dynamic Nuclear Polarization (DNP)

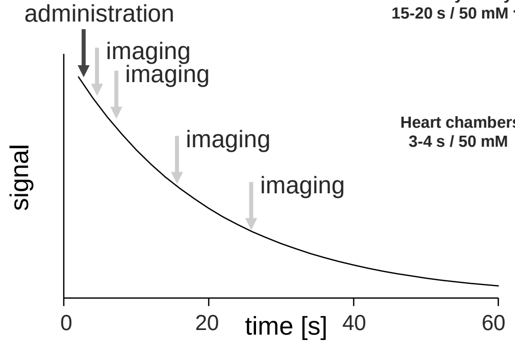
Solid material doped with unpaired electrons in a ratio of ~1:1000

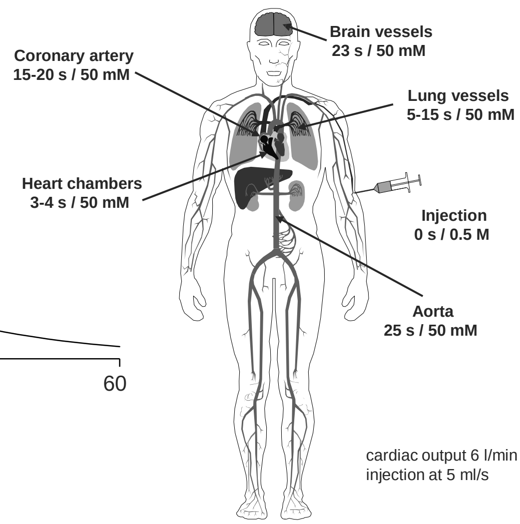


P_e= 94% and P_C= 0.086%

Microwaves transfer polarization from electrons to nuclei can generate 20-30% polarized ^{13}C

The signal decays due to relaxation and dilution





cardiac output 6 l/min
injection at 5 ml/s

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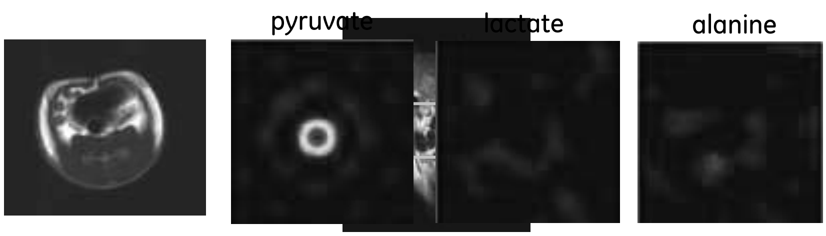
Metabolic imaging of rat skeletal muscle with hyperpolarized ^{13}C-pyruvate



Can study effectiveness of drugs on cancer by monitoring the metabolic processes.

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Diffusion-Weighted Magnetic Resonance Imaging in Acute Stroke
K.J. van Everdingen, MD; J. van der Grond, PhD; L.J. Kappelle, MD, PhD; L.M.P. Ramos, MD; ;W.P.T.M. Mali, MD, PhD; Stroke. 1998;29:1783-1790

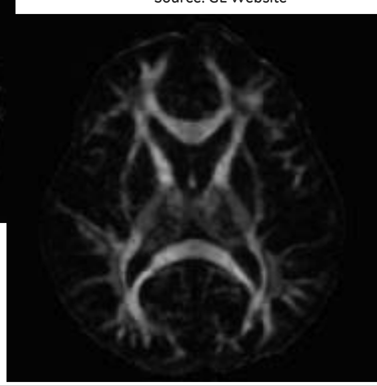
Figure 1. Fifty-five–year-old man with an acute left-sided hemiparesis 6 hours before the first MRI examination (patient 10). On the early PD-w (A) and T2-w (B) images, no ischemic lesion was visible.
The early DWI scan (C) shows a right-sided hyperintensity in the frontal lobe (territory of the pericallosal artery), which can be appreciated as a hypointensity on the ADC trace map (D).

The follow-up MRI (E) was performed 6 days after the onset of symptoms and confirms the infarct. However, on the follow-up scan the infarct extended into the corpus callosum

Diffusion Tensor Imaging

Source: GE Website

Source: GE Website



Source: Wickipedia.org

fMRI and BOLD

Blood-oxygen-level dependence (BOLD) is the MRI contrast of blood deoxyhemoglobin, first discovered in 1990 by Seiji Ogawa.

Image Source: Wikipedia

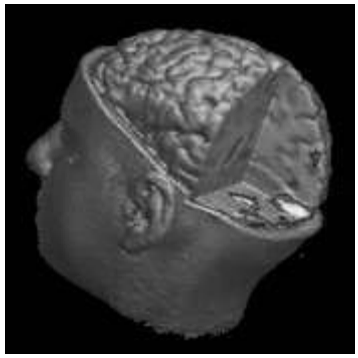


Image Source: www.csulb.edu

2011 ISMRM Lauterbur Lecture: fMRI at 20-Has it Changed the World?

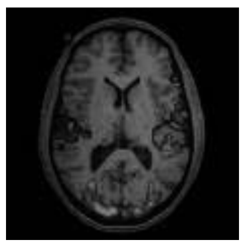
Bruce Rosen MD, PhD, Mass Gen Hospital

Selected Awards/Societies

Sigma Xi, MIT Chapter of the Scientific Research Society

Gold Medal, International Society of Magnetic Resonance in Medicine

Fellow of the International Society of Magnetic Resonance in Medicine



Has it changed the world?

- Research – 21,382 publications - yes
- Clinical – pre-clinical scanning – but not yet
- Cognitive neuroscience – YES
  - language processing in occipital cortex in congenital blind, brain remaps in ~5 days in blindfolded, brain plasticity.
  - Journal of Cognitive Neuroscience – fMRI #1 tool, 70% of publications
  - Top 10 psychology depts own their own MRI (except Yale)

Lauterbur Lecture: fMRI at 20-Has it changed the world?

Bruce Rosen MD, PhD, MGH

Has it changed the world?

- Mental Illness – YES
  - Brain circuitry – functional interconnections between brain regions, changing from neurochemical based to circuitry – using DBS for depression
  - Helping shift mental illness from "psychological" to "biological" based on imaging data
  - Changing public policy – 2008 mental health bill covers mental illness similar to physical illness – based on fMRI data ... Senator Domenici wanted equivalent of "broken arm image"... fMRI gave him that.

Lauterbur Lecture: fMRI at 20-Has it changed the world?

Bruce Rosen MD, PhD, MGH

Has it changed the world?

- Consciousness – YES
  - Judgement of right and wrong – interesting studies on philosophical decisions – pull train track switch to transfer trains from 4 people line to 1 person line....but push man off bridge to save more people not accepted by most...right and wrong activate different parts of the brain
  - Free will – they see changes in the brain 10 seconds before a person knows they've decided

Society – YES!

- Used for marketing studies – neural predictors of "buying"
- US Supreme court – No death penalty for people under 18 based upon fMRI studies on brain development
- Previously mentioned mental health bill

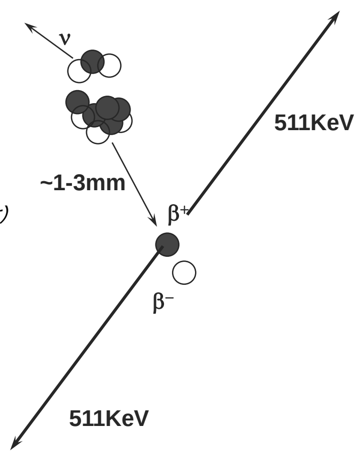
PET Imaging

Where does PET start? Positron decay

Positron Emission Tomography is a technique for measuring biological activity in the human body:

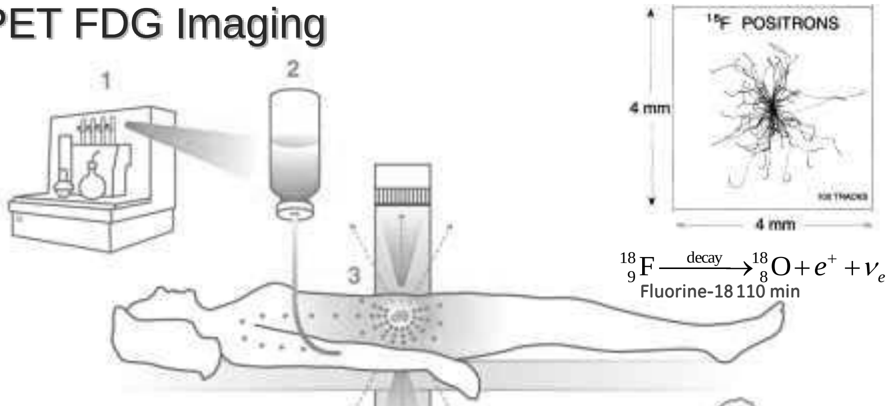
Isotope	Halflife	
^{11}C	20.35	min
^{13}N	9.96	min
^{15}O	2.05	min
^{18}F	109.74	min

Most clinical PET is done with F-18 FDG (fludeoxyglucose, a sugar)



1. Positron travels 1-3mm (depending on energy) before annihilation.
2. Annihilation process conserves:
   - Energy (photons are 511KeV).
   - Momentum: photons are almost exactly co-linear
3. Simultaneous detection of two 511KeV photons --> count events that occur along a line between detectors.

PET FDG Imaging



$$^{18}_{9}F \xrightarrow{\text{decay}} {}^{18}_{8}O + e^{+} + \nu_e$$

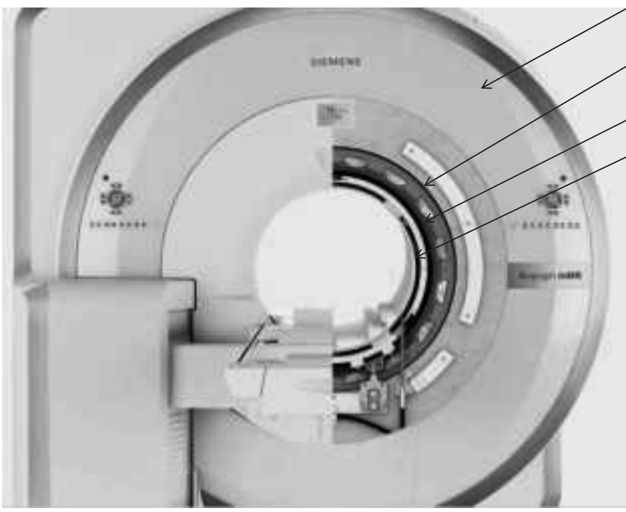
Fluorine-18 110 min

1. F-18 is synthesized into FDG
2. FDG is injected into patient
3. FDG is localized in tumors
4. PET scanner detects concentration of FDG
5. PET images are sent to console for review

•FDG is 2-Fluoro-Deoxy-Glucose. FDG is formed when one of the hydroxyl groups in glucose is exchanged for ^{18}F-fluoride.

•After injection, FDG accumulates in cells in the same way as glucose, thus is an indicator of glucose metabolism

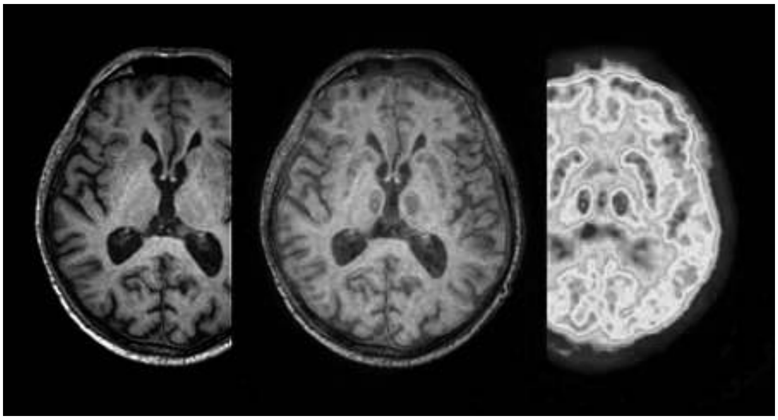
Pet-MR



Magnet
Gradient
PET Detector
RF Coil

Image source: Siemens Healthcare Website

PET-MR Image from Internet



Images of the brain obtained using simultaneous magnetic resonance tomography (left) and through positron emission tomography (right). With the new device, the two techniques can be combined (middle). Even sharper MR images are expected with the 9.4-T-MR-PET.
Source: Forschungszentrum Jülich

My view of the future

- More Ultra High Field systems 7T, 9.4T, 11.7T
  - (~35 7T scanners installed world wide)
- More HTS, MgB_2 scanners
- More niche market scanners
- More RF channels
- More multi-modality scanners
- More “alternate concept” MR scanners
  - Pulsed magnet with low field imaging –
    - **Ultra-low-field MRI system for hybrid MEG-MRIP.** T. Vesanen, J. Hassel, J. S. Penttilä, J. O. Nieminen, J. Dabek, K. Zevenhoven, J. Luomahaara, S. Alanko, N. Catallo, F-H. Lin, J. Simola, A.,Ahonen, and R. J. Ilmoniemi
  - PatLoc – nonlinear gradient coils
  - SWIFT – Sweep Imaging with Fourier Transformation
  - DreMR – contrast tracking MR