

A Brief History of (Nuclear) Magnetic Resonance Imaging

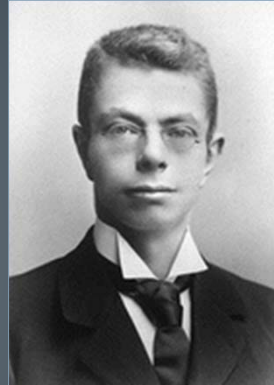
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Overview

- Discovery of Nuclear Magnetic Resonance
- Invention of MR Imaging Methods
- Advancements in MRI Hardware and Imaging Methods
- Trends in MRI Utilization

Pieter Zeeman

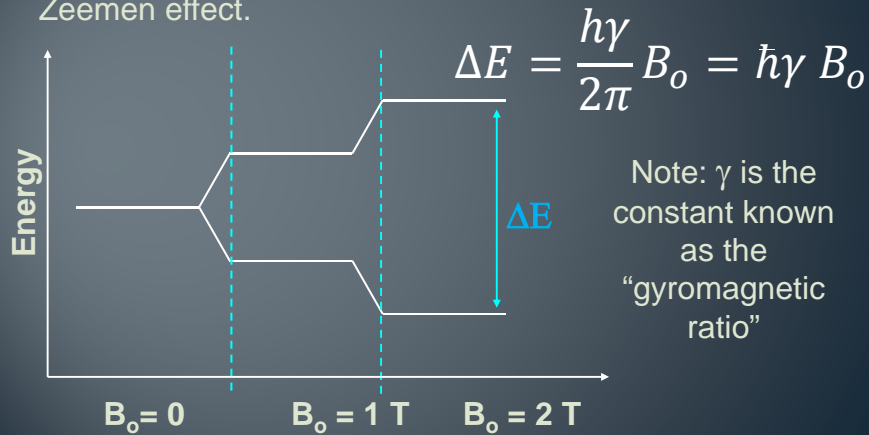
- 1902 Nobel Laureate in Physics
- *In recognition of the extraordinary service he (and HA Lorentz) rendered by their researches into the influence of magnetism upon radiation phenomena.*
- *Spectral lines split into even more lines in the presence of a static magnetic field.*



} Zeeman Effect

Anomalous Zeeman Effect

Where several lines appear, forming a complex pattern, is actually more common than the normal Zeeman effect.



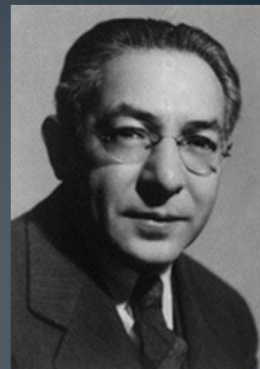
Discovery of Quantum Spin

- Wolfgang Pauli hypothesized to existence of “spin” in c.1925
- “Spin” is inherent to PAM Dirac’s 1928 formulation of relativistic quantum mechanics.
- Physicists realize that charged particles with “spin” should exhibit magnetic properties



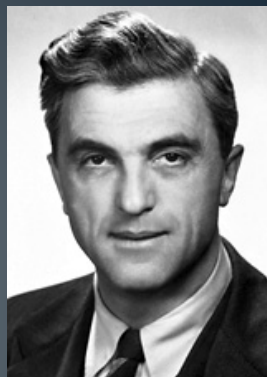
Isador I. Rabi

- 1944 Nobel Laureate in Physics
- ***for his resonance method for recording the magnetic properties of atomic nuclei.***
- *In 1937 he showed that nuclei were magnetic by measuring their deflection in a magnetic field.*



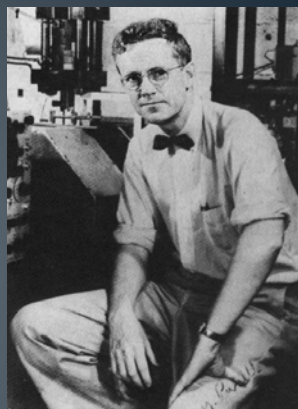
Felix Bloch

- From Stanford, 1952 Nobel Laureate in Physics
- **With Purcell for development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith (1946).**
- Was an expert on the design of strong magnets
- Demonstrated NMR in water samples



Edward M. Purcell

- From MIT, 1952 Nobel Laureate in Physics
- **With Bloch for their development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith.**
- Demonstrated NMR in paraffin.



Developments in NMR

- **Erwin L. Hahn** (1950) discovered the phenomenon called the “spin echo” advancing the field of NMR relaxometry.
- **Weston Anderson** in 1960’s at Varian (with Ernst and Hahn) applied the FT to the NMR signal for spectroscopy – also developed early gradient coil designs for diffusion studies.
- 1960’s-1980’s **J.R. Singer** at UC Berkeley & **J.H. Batocletti** at Wisconsin develop non-imaging monitors of blood flow *in-vivo*.

Approaches to NMR

Spectroscopy

- Identifies the NMR signal strength as a function of frequency
- Required moving the magnetic field or RF excitation frequency
- Related to electron interactions with nucleus

Relaxometry

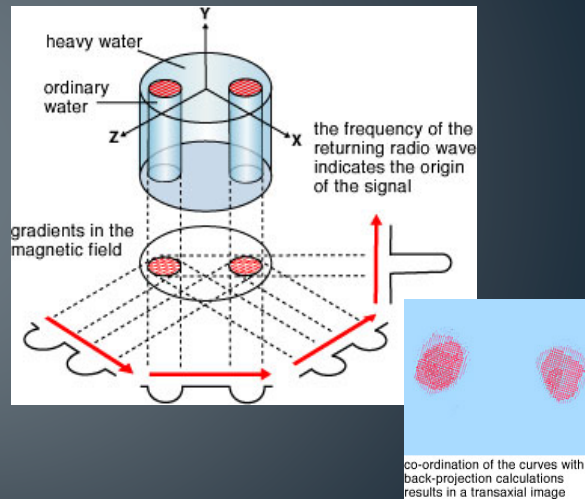
- Evaluates the dynamic properties of excited spin systems
- Requires RF energy delivered in short pulses
- Related to electron-nuclear & nuclear-nuclear interactions



Paul Lauterbur

- 2003 Nobel Laureate in Medicine

In 1973, he described how addition of gradient magnets to the main magnet made it possible to visualize a cross section of tubes with ordinary water surrounded by heavy water.



CT & MRI Timelines

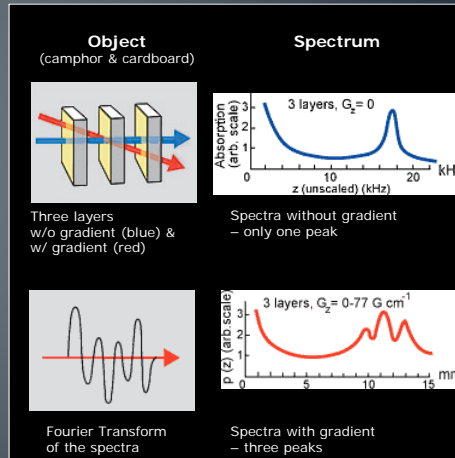
- 1973 G. N. Hounsfield. Computerized transverse axial scanning (tomography): Part 1. Description of system. British Journal of Radiology
- 1973 Paul M. Lauterbur. Image Formation by Induced Local Interactions: Examples Employing Nuclear Magnetic Resonance. Nature
- By June 1974 EMI had delivered 35 scanners at \$390,000 each
- 1983. 1st commercial MRI system installed in at the University of Manchester.



Peter Mansfield

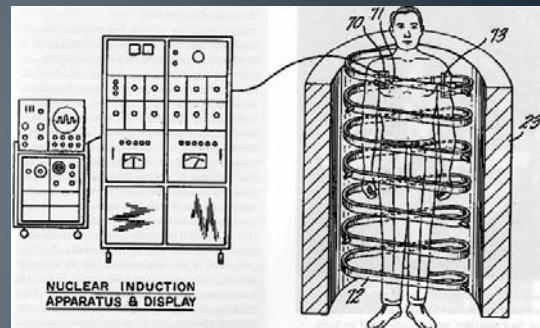
- 2003 Nobel Laureate in Medicine

Discovered that gradients in the magnetic field could be used to select a slice for an image. Also showed how extremely rapid imaging could be achieved by very fast gradient variations (echo-planar scanning).



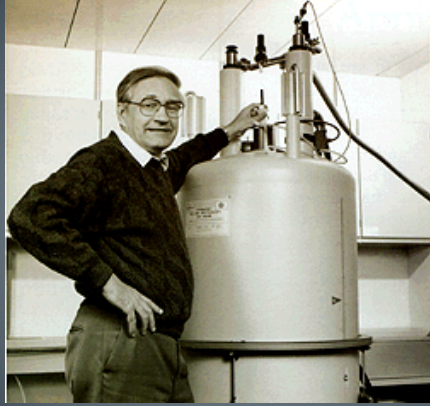
Biological Application of NMR

- **Raymond Damadian** (Brooklyn, 1971) reports that NMR relaxation properties of tumors were different from healthy tissues, building on work of Erik Oldeblad.



*Raymond Damadian's
"Apparatus and method for
detecting cancer in tissue."*

Richard R. Ernst

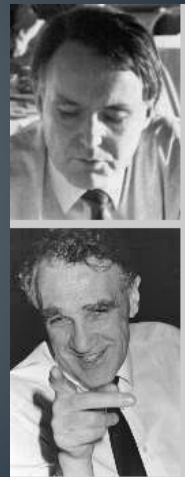
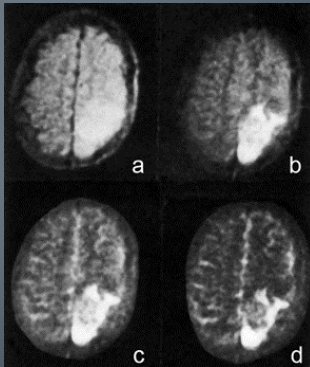


- 1991 Nobel Laureate in Chemistry
- *for his contributions to the development of the methodology of high resolution nuclear magnetic resonance (NMR) spectroscopy.*

Swiss chemist who in 1975 developed two-dimensional Fourier transform nuclear magnetic resonance (2DFT-NMR). The first application of this method was to magnetic resonance imaging.

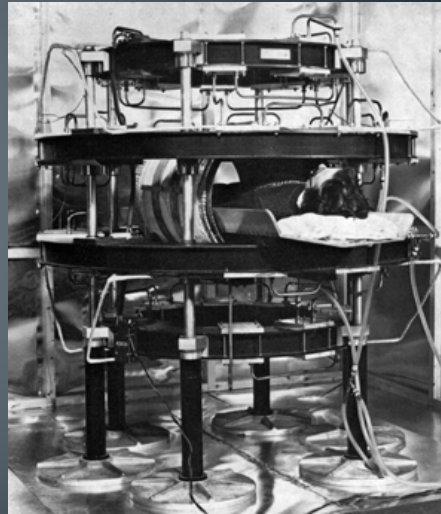
Clinical MRI – Hammersmith Hospital 1982-1983

- Ian R. Young and Graeme M. Bydder were the moving forces.



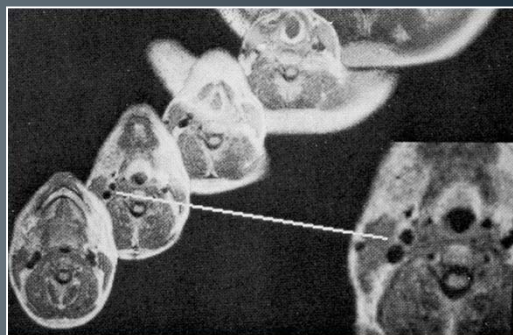
2DFT – SpinWarp MRI Method

- **James Hutchinson** and (University of Aberdeen with John Mallard in 1975) describes the 2DFT NMR imaging method, dubbed “spin warp” imaging



Multi-Slice MRI

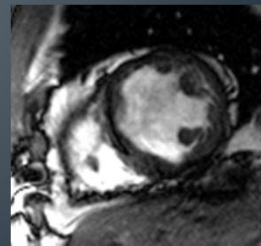
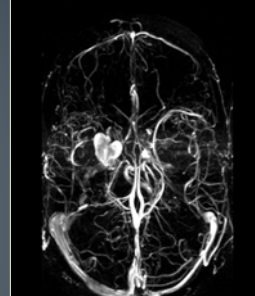
Larry Crooks (at UCSF with Leon Kaufman 1982) refines “spin warp” – uses spin echoes & multiple slice imaging to produce the 1st clinically practical MRI system



Early multi-slice spin echo images depicted vessels in the neck as signal voids

Gradient Echo Imaging Methods

- Circa 1985 at Max-Planck-Institute, Göttingen, by **Axel Haase, Jens Frahm**, et al.
- Enabled by development of fast-switching gradient systems
- Allowed the development of
 - MR angiography
 - MR rapid cardiac multi-gated images



Fast Spin Echo MRI

- **Jürgen Hennig** at the Univ. of Freiburg introduced RARE (rapid acquisition with relaxation enhancement) imaging in 1986.
- Enabled clinically by introduction of shielded gradient coils in 1989
- Allowed acquisition of fast, T2-weight MR images

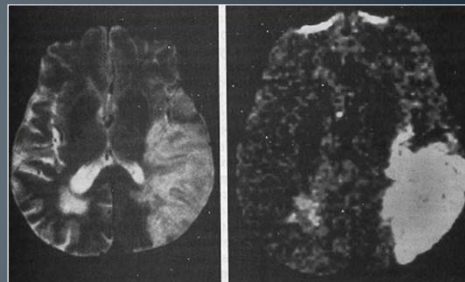


Echo-Planar Imaging (EPI)

- Echo-planar imaging was invented by Peter Mansfield in 1977 as a method to produce fast cardiac images.
- It was enabled in the early 1990's by further advances in gradient coil technologies.
- However the major applications of EPI have turned out to be neurological. These include:
 - BOLD contrast functional brain MRI
 - Diffusion-weighted MR imaging
 - Contrast-enhanced MRI for tissue perfusion
 - Arterial Spin Labeled perfusion imaging

Diffusion-Weighted Imaging

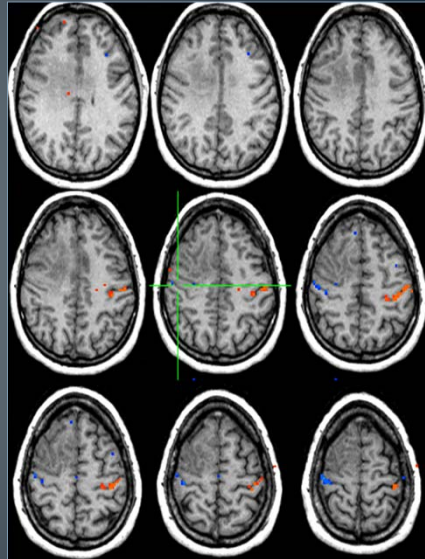
- Diffusion NMR exploits the random diffusional motion of water molecules.
- Fundamental work in 1965 by **E.O. Stejskal and J.E. Tanner** at the Univ. Wisconsin.
- **D. LeBihan** developed methods for diffusion-weighted MRI in 1986.



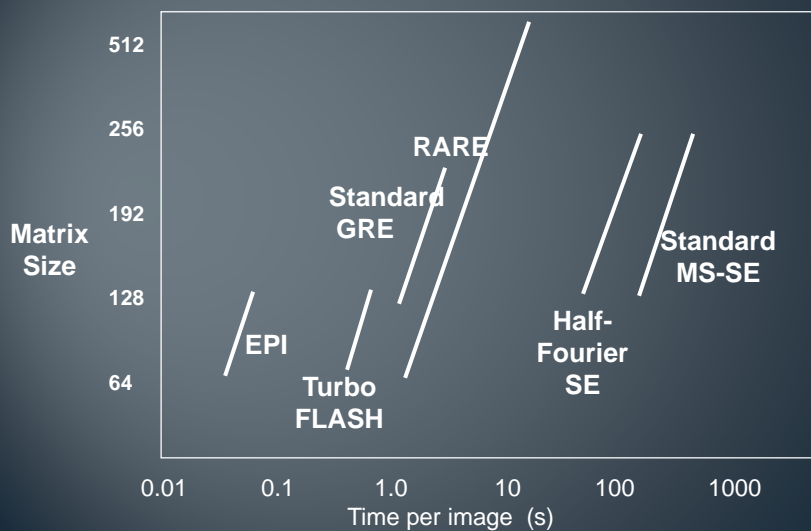
Left: T2-weighted SE image.
Right: DWI with $b = 1205 \text{ s mm}^{-1}$

Blood Oxygen Level Dependent Contrast (BOLD)

- **Seiji Ogawa** et al. at Bell Labs developed the idea of using EPI to monitor brain activity after stimulation in 1990.
- Further contributions by Turner, Kwong, Belliveau and others.
- Used clinically and as neuroscience research tool.

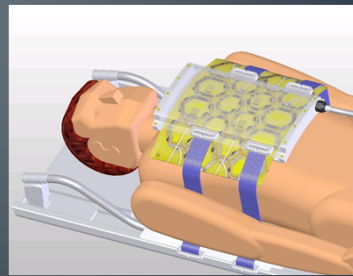
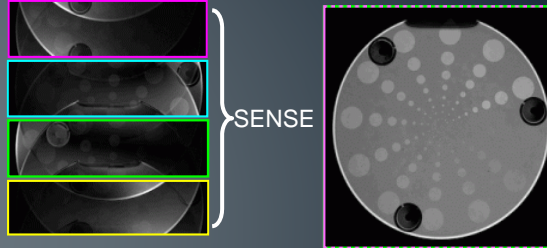


MRI Methods and Image Speed








Partially Parallel MR Imaging

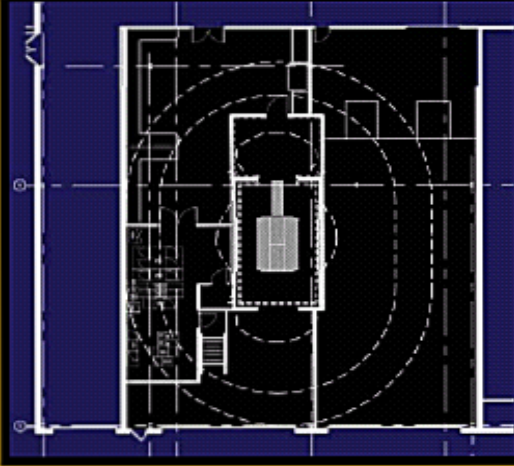
- In 1999 a new concept in MRI was introduced by Klaas Pruessmann and Markus Weiger and expanded by Mark A. Griswold.
- Used Phased-Array RF coils to speed up MR Imaging.
- Enabling technology for 3 Tesla MRI.



Recent Technology Advances

- Sparsely Sampled MR Angiography
- Ultra-short TE MRI for bones, tendons
- B₁-field shimming (transmit SENSE)
- Hybrid PET-MRI Systems
- 7 Tesla and higher whole-body magnets
- High-Temperature Superconductors...

7.0T WIP	3.0T	1.5T	1.0T	0.5T
				

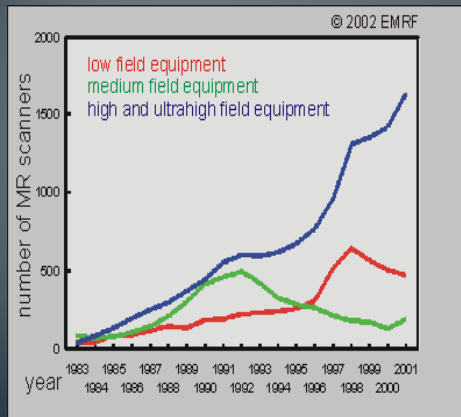


7T MRI
250 tons of steel
35 ton magnet
2"-6" thick concrete slab
 (US\$ 9 -10 M)

- MGH/Harvard Univ.
- Ohio State University
- Stanford University
- NYU Med Center
- U Pennsylvania
- U TX Southwestern
- Yale University
- Kennedy-Krieger, MD

MRI Installed Base

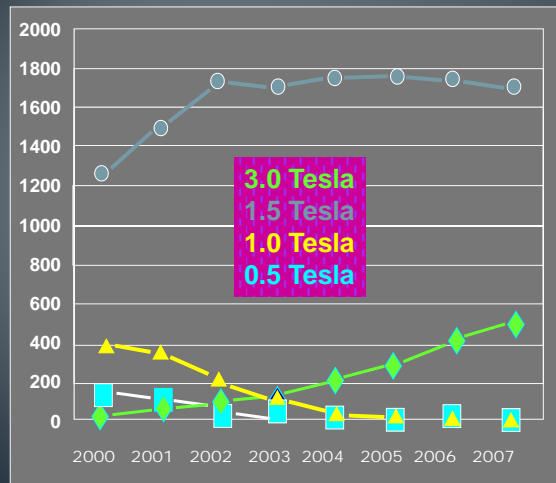
- Approximately 26,000 MRI systems (~10,000 in US)



- 1.5 T systems accounted for over 67% of US installed base in 2004*
- Ultra High field (>2T) scanners comprised 7% of installed MRI systems in 2004*

*IMV, Ltd. Des Plaines, IL

MRI Today



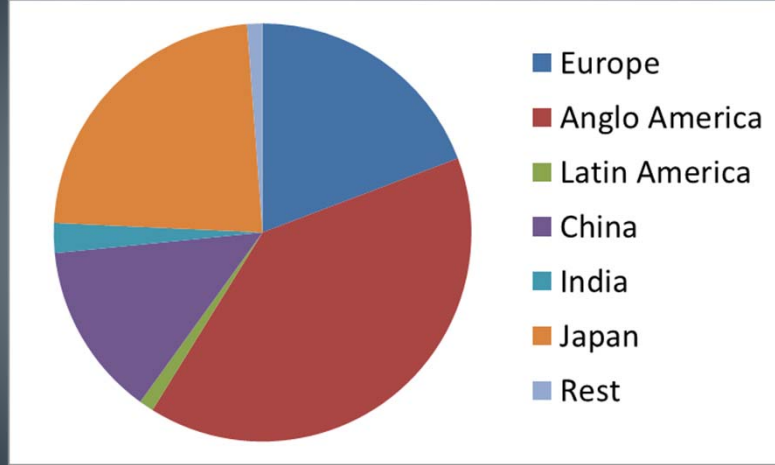
MRI has replaced several invasive modes of examination and reduced the risk and discomfort for many patients

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MRI Today

- Since 1997 the number of scanners in the world has more than tripled to more than 25,000
- Now over 75 million studies using MRI are performed worldwide annually
- MRI has replaced several invasive modes of examination and reduced the risk and discomfort for many patients

MRI Distribution Worldwide



Global market > \$1,000,000,000