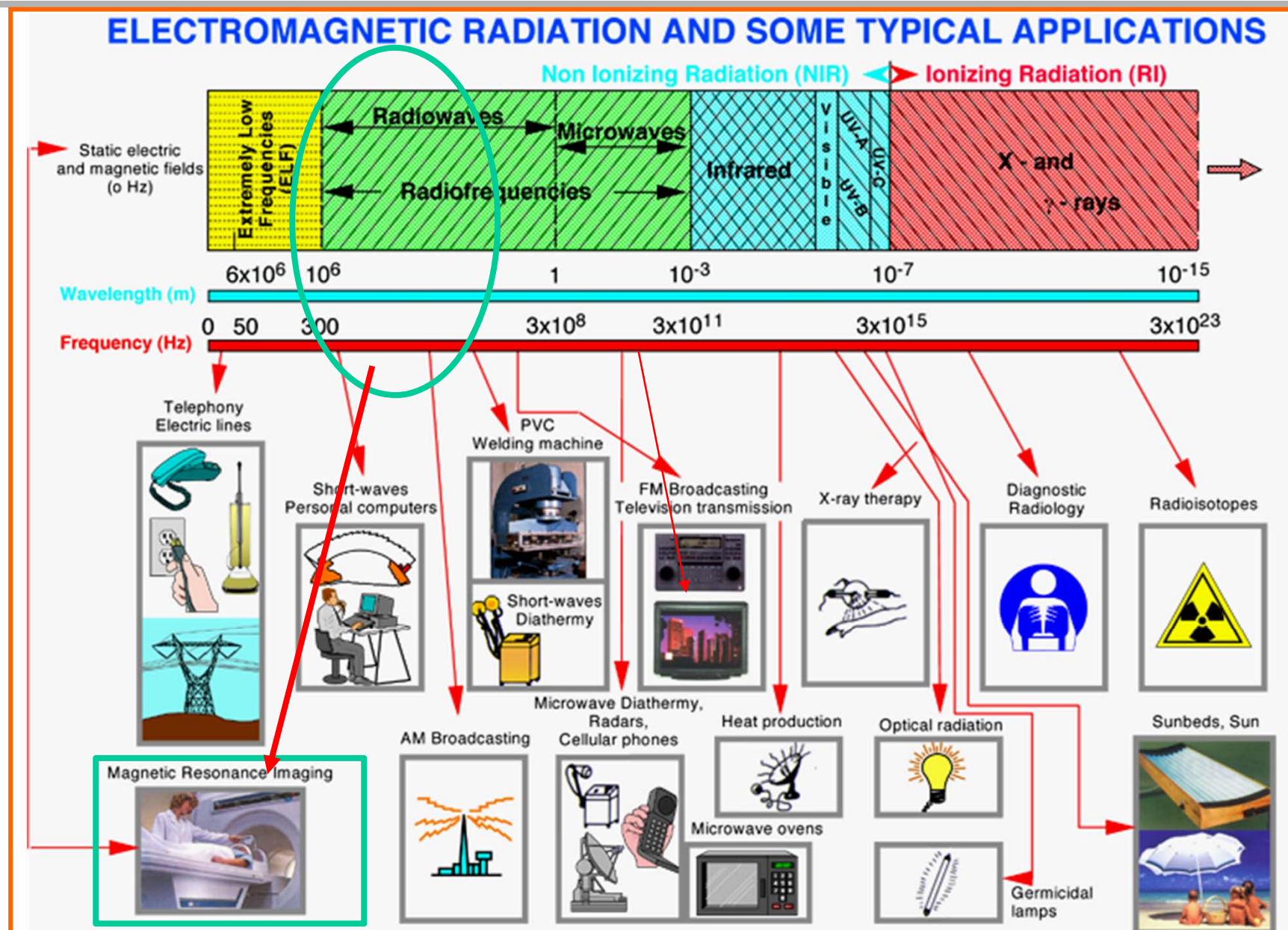


*Tecniche diagnostiche*

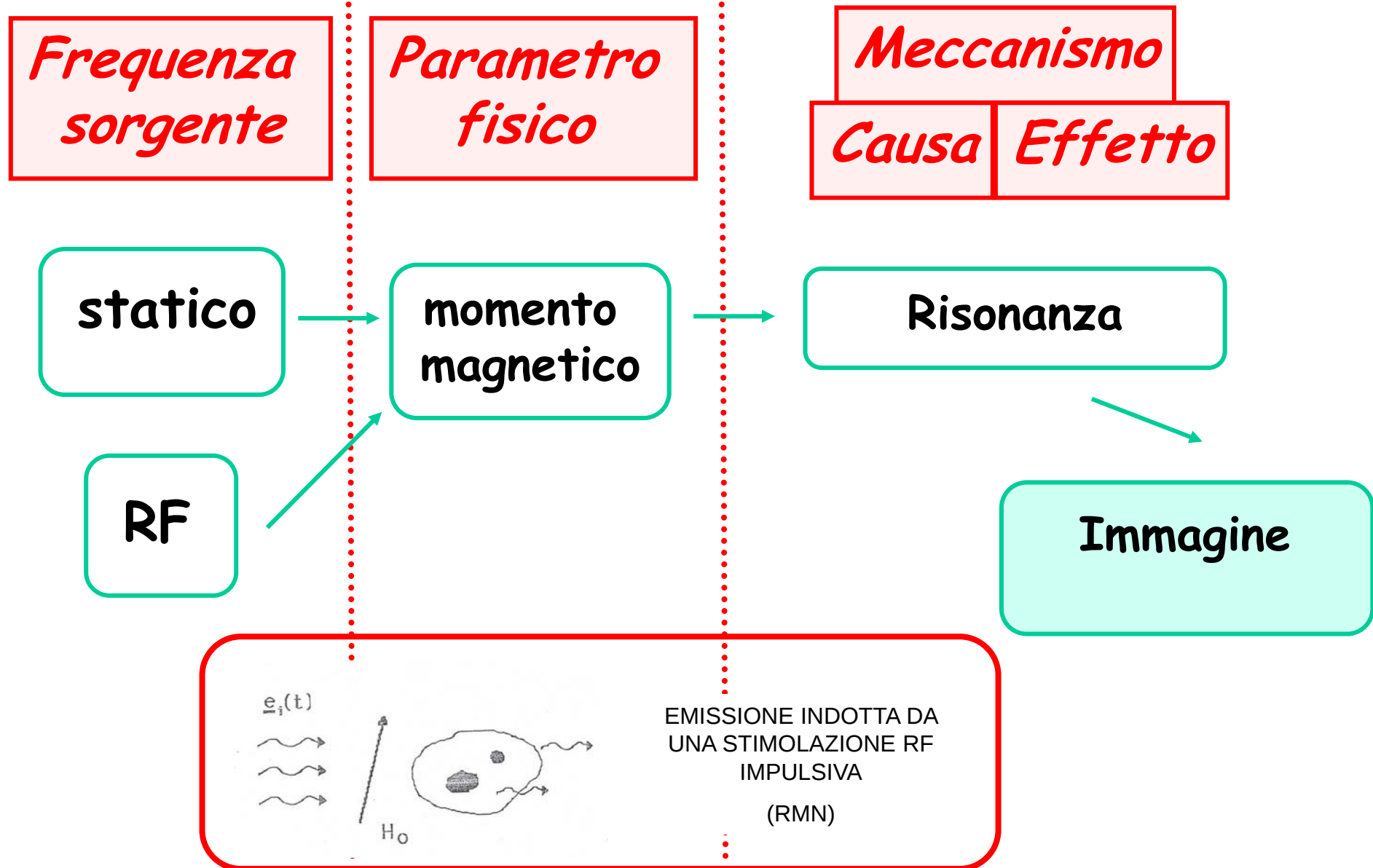
# MRI – Risonanza magnetica

MARTA CAVAGNARO

# Introduzione



## Obiettivo: immagine



# *Magnetic Resonance Imaging*

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MR imaging has evolved from unpromising beginnings in the 1970s to become nowadays the imaging method of choice for a large proportion of radiological examinations and the ‘jewel in the crown’ of medical technology.

D W. McRobbie, E A. Moore, M J. Graves and M R. Prince, *MRI From Picture to Proton*, Cambridge University Press, 2006

## *So what is it?*

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It is an imaging method based principally upon sensitivity to the presence and properties of water, which makes up 70% to 90% of most tissues. The properties and amount of water in tissue can alter dramatically with disease and injury which makes MR very sensitive as a diagnostic technique. MR detects subtle changes in the magnetism of the nucleus, the tiny entity that lies at the heart of the atom. This is probing deeper than X-rays, which interact with the clouds or shells of the electrons that orbit the nucleus. MR is a truly powerful modality.

## *In the beginning...*

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- In the early days, the scanners were the domain of the physicists and engineers who invented and built them, and the technique was called NMR imaging (NMR stands for nuclear magnetic resonance). The cynics may say that the technique really took off clinically when the 'N-word' was dropped. This was sensible as the term 'nuclear', although scientifically accurate, implied a connection with nuclear energy and, in the last of the cold war years, resonated in the public's mind with the spectre of nuclear weapons.
- Because of the diversity of sciences and technologies that gave birth to and continue to nurture MR, it is an extremely hard subject to learn.

# A brief history of medical imaging

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**Radiology** began after the accidental discovery of 'Xrays' by Roentgen in 1895.

Within a couple of years most of the basic techniques of radiography were established, e.g.

- the use of fluorescent screens (Pupin 1896),
- contrast media (Lindenthal 1896),
- even the principle of angiography.

Early fluoroscopy entailed direct viewing from a fluorescent plate, i.e. putting your head in the main beam, a practice frowned upon today! Unfortunately radiation protection followed slightly too late for the pioneers of radiology.

## *.....radiology continue..*

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- The next real technical breakthrough was the development of the image intensifier in the 1950s, but the basis of conventional radiography remained the same until the recent IT and digital revolutions.
- **Computed Tomography (CT)** was a huge breakthrough earning Hounsfield and Cormack the Nobel Prize for medicine and physiology in 1979. X-ray CT was unique in producing tomographic images or slices of the living human body for the first time and with a higher contrast than achievable by conventional planar techniques. The combination of a moving X-ray gantry and the computing power necessary to reconstruct from projections made CT possible.

## Nuclear medicine

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- At about the same time of X-rays (1896) Becquerel and the Curies were discovering **radioactivity** and radium and making possible the future development of nuclear medicine.
- In **nuclear medicine** a similar evolution was occurring, from the development of the gamma camera by Anger in 1958 to tomographic imaging in the form of **Single Photon Emission Computed Tomography (SPECT)** and **Positron Emission Tomography (PET)** which is ongoing today. PET's clinical use is increasing, particularly in detecting metastases in oncology. Its ability to image minute concentrations of metabolites is unique and makes it a powerful research tool in the aetiology of disease and the effects of drugs

# Ultrasound

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- **Ultrasound** was developed in the 1950s following the development of SONAR in World War II and was unique in involving no ionizing radiation and offering the possibility of safe, non-invasive imaging. Its ability to image in real time and its sensitivity to flow, through the Doppler effect, have been key factors in its widespread role in obstetrics, cardiology, abdominal and vascular disease, real-time biopsy guidance and minimally invasive surgery.

## *Magnetic resonance imaging...*

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- ‘Nuclear induction’, as it was first described, was discovered in 1945, soon after the close of World War II, by Bloch and independently by Purcell and Pound

# Nuclear induction

## Physical Review, 1946

*Phys. Rev.* **69**, 37 (1946)

### Resonance Absorption by Nuclear Magnetic Moments in a Solid

E. M. PURCELL, H. C. TORREY, AND R. V. POUND\*  
*Radiation Laboratory, Massachusetts Institute of Technology,  
Cambridge, Massachusetts*  
December 24, 1945

IN the well-known magnetic resonance method for the determination of nuclear magnetic moments by molecular beams,<sup>1</sup> transitions are induced between energy levels which correspond to different orientations of the nuclear spin in a strong, constant, applied magnetic field. We have observed the absorption of radiofrequency energy, due to such transitions, in a *solid* material (paraffin) containing protons. In this case there are two levels, the separation of which corresponds to a frequency,  $\nu$ , near 30 megacycles/sec., at the magnetic field strength,  $H$ , used in our experiment, according to the relation  $h\nu = 2\mu H$ . Al-

*Phys. Rev.* **70**, 460 (1946)

### Nuclear Induction

F. BLOCH  
*Stanford University, California*  
(Received July 19, 1946)

We shall further denote by  $\mathbf{M}$  the vector, representing the nuclear polarization, i.e., the resultant nuclear moment per unit volume; it is the variation with time of this vector in which we are primarily interested.

To obtain this variation does not require the solution of the Schrödinger equation. It is enough to remember the general fact that the quantum-mechanical expectation value of any quantity follows in its time dependence exactly the classical equations of motion and that the magnetic and angular momenta of each nucleus are parallel to each other.

## *Magnetic resonance imaging...*

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- ‘Nuclear induction’, as it was first described, was discovered in 1945, soon after the close of World War II, by Bloch and independently by Purcell and Pound
- As early as 1959, J. R. Singer at the University of California, Berkeley, proposed that **NMR** could be used as a non-invasive tool to measure in vivo blood flow.
- In 1971 Raymond Damadian discovered that certain mouse **tumours** displayed elevated relaxation times compared with normal tissues in vitro. This opened the door for a complete new way of imaging the human body where the potential contrast between tissues and disease was many times greater than that offered by Xray technology and ultrasound.

## *.....the firsts attempts...*

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- Damadian and his colleagues at the State University of New York went so far as to design and build their own superconducting magnet operating in their Brooklyn laboratory **and the first human body image by NMR is attributed to them.** There is some dispute about who actually is the founder of modern **M**agnetic **R**esonance **I**maging (MRI), but one thing is certain, Damadian coined the first MR acronym, namely FONAR (**F**ield **f**Ocussed **N**uclear **m**Agnetic **R**esonance).

.....patent...

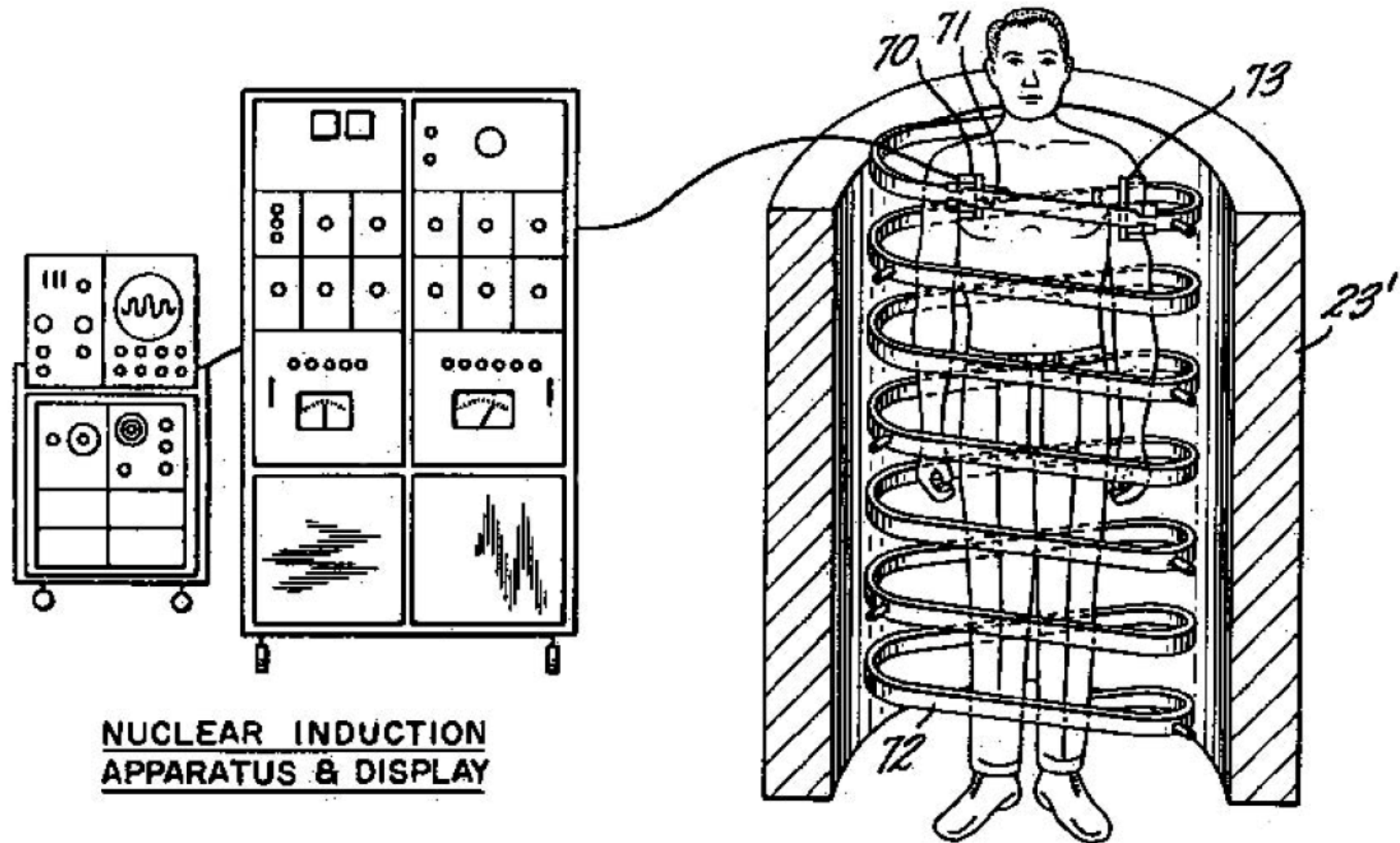


Figure 1.2 Raymond Damadian's "Apparatus and method for detecting cancer in tissue". US patent 3789832 filed 17 March 1972, issued 5 February 1974. Image from the US Patent and Trademark Office.

## ...gradients.....

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- In 1973, in an article in Nature, Paul Lauterbur proposed using magnetic field **gradients** to distinguish between NMR signals originating from different locations combining this with a form of reconstruction from projections (as used in CT). The use of gradients still forms the basis of all modern MRI as recognised by the Nobel Committee in 2003.
- Unfortunately Lauterbur's brilliant invention was not accompanied by a brilliant acronym; he coined the obscure term '**zeugmatography**', meaning imaging from a joining together (of the main field and the gradients). In contemporary MR terms Lauterbur can be said to have invented frequency encoding. Whilst the term 'zeugmatography' sunk without trace, fortunately the technique it described has gone from strength to strength.

## *...image slices...*

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- **Selective excitation**, or the sensitization of tomographic image slices, was invented at the University of Nottingham, England in 1974 by Sir Peter Mansfield's group, a contribution also recognised by the 2003 Nobel Committee, whilst in 1975 Richard Ernst's group in Zurich invented two-dimensional Fourier transform imaging (2D FT). The first practical 2D FT imaging method, dubbed 'spin warp', was developed by Edelstein and Hutchison at the University of Aberdeen, Scotland in 1980.
- At the same time developments in cryogenics, or the study of very low temperatures, made the development of whole-body superconducting magnets possible.
- Many other researchers contributed to the early development of MR, and in this short introduction it is impossible to do justice to them all.

## And what of the commercial development?

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EMI, the creators of X-ray CT through Sir Godfrey Hounsfield, were involved from very early on. Clow and Young produced the first published human head image in 1978 (figure 1.3).



Figure 1.3 First ever human head image using MRI at 0.1 T from EMI Central Research Laboratories. For this image CT type “back projection” was used. Courtesy of Ian Young.

## And what of the commercial development?

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EMI sold their research interest to Picker International, which became Marconi and is now part of Philips. The 'Neptune' 0.15T superconducting system installed at the Hammersmith Hospital, London, was the first commercial clinical system. Elsewhere in Europe, Philips Medical Systems also dedicated substantial early investment (figure 1.4). General Electric introduced high field (1.5T) systems in around 1984.

The technique developed rapidly through the late 1980s to become the method of choice for non-trauma neurological scanning. By 1996 there were in excess of 10 000 scanners worldwide.

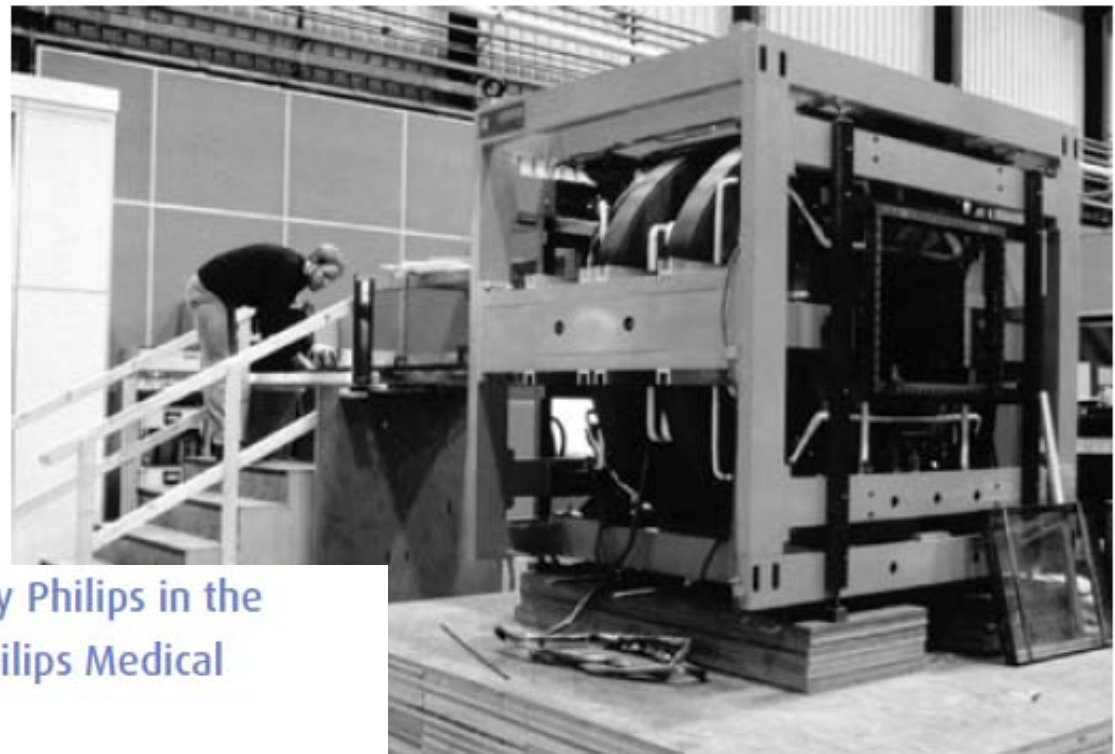


Figure 1.4 0.15T resistive magnet used by Philips in the early development of MRI. Courtesy of Philips Medical Systems.

## *..the last developments..*

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Due to problems of low signal and high sensitivity to motion, body MR did not really take off until the 1990s. The key factors were the development of fast imaging techniques, particularly gradient echo, and phased array coil technology. The 1990s also saw the coming of age of earlier developments, namely cardiac MRI and **E**cho **P**lanar **I**maging (EPI). EPI, which is the fastest and one of the most cutting edge methods, was actually one of the first imaging methods to be proposed, by Sir Peter Mansfield. EPI is now extensively used in neurological imaging through functional MRI (fMRI) and diffusion imaging.

## Acronyms anonymous....

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- There are literally hundreds of pulse sequences. Every year at MR conferences around the world scores of new pulse sequences are launched and, in the tradition of the MR scientific community, all sporting stylish acronyms. The trouble with acronyms is that despite sounding memorable and snappy (e.g. FLASH, HASTE, DRESS, SLIT-DRESS, DIET, PEPSI, etc.) it's virtually impossible to remember what they stand for, and therefore what they do. Moreover, MR manufacturers have the annoying tendency to use different names for the same things. Whilst the end-point of an acquisition can be expressed in terms of  $T_1$  or  $T_2$  weighting, **there are numerous ways of achieving this – few destinations but many routes....**
- there are two major pulse sequence families: spin echo (SE) and gradient echo (GE)...

## Sequence comparison for major manufacturers

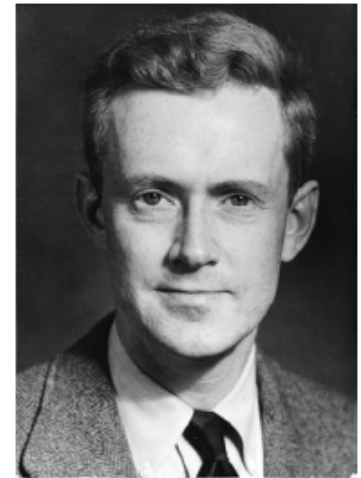
| Family        | Generic name                                         | General Electric              | Marconi<br>(formerly Picker) | Philips      | Siemens       | Toshiba              |
|---------------|------------------------------------------------------|-------------------------------|------------------------------|--------------|---------------|----------------------|
| Spin echo     | RARE (rapid acquisition with relaxation enhancement) | FSE                           | FSE                          | TSE          | TSE           | FSE                  |
|               | IR-RARE                                              | FSE-IR                        | Fast IR                      | IR-TSE       | Turbo-IR      | Fast IR              |
|               | Single-shot RARE                                     | SS-FSE, SSFSE-IR              | Express                      | UFSE         | SS-TSE, HASTE | FASE, DIET SuperFASE |
|               | GRASE (gradient and spin echo)                       | –                             | –                            | GRASE        | TGSE          | –                    |
| Gradient echo | Spoiled GE                                           | SPGR, MPSPGR                  | RF-FAST                      | T1-FFE       | FLASH         | RF-spoiled FE        |
|               | Rewound GE                                           | MPGR, GRE                     | FAST                         | FFE          | FISP          | FE                   |
|               | Fully rewound GE                                     | FIESTA (cardiac systems only) | –                            | Balanced FFE | True-FISP     | –                    |
|               | SSFP (steady-state free precession) GE               | SSFP                          | CE-FAST                      | T2 FFE       | PSIF          | –                    |
|               | Dual echo GE                                         | –                             | FADE                         | –            | DESS          | –                    |
|               | Constructive interference GE                         | –                             | –                            | –            | CISS          | –                    |

## *Nobel laureates...*

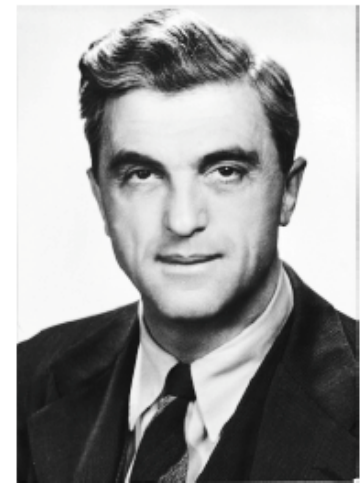
- In 1952 Edward Purcell (Harvard) and Felix Bloch (Stanford) jointly received the Nobel Prize for physics ‘for their development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith’.
- Of Purcell’s discovery, the Boston Herald reported that ‘it wouldn’t revolutionize industry or help the housewife’. Purcell himself stated that ‘we are dealing not merely with a new tool but a new subject which I have simply called nuclear magnetism. If you will think of the history of ordinary magnetism, the electronic kind, you will remember that it has been rich in difficult and provocative problems and full of surprises.’

It seems that the Boston Herald misjudged the importance of NMR!

- Bloch, a Swiss-born Jew and friend of quantum physicist Werner Heisenberg, quit his post in Leipzig in 1933 in disgust at the Nazi’s expulsion of German Jews (as a Swiss citizen, Bloch himself was exempt). Bloch’s subsequent career at Stanford was crammed with major contributions to physics and he has been called ‘the father of solid state physics’.



Purcell 1912 - 1997



Bloch 1901 - 1999

.....

- Nicolaas Bloembergen, a Dutch citizen, was forced to hide from the Nazis for the duration of the War, reputedly living on boiled tulip bulbs, until becoming Purcell's first graduate student at Harvard two months after the discovery of NMR. With Purcell and Robert Pound he developed the theory of NMR relaxation, known now by their initials BPP. In 1981 he won a Nobel Prize for his work in laser spectroscopy.
- In 1991 Richard Ernst joined the MRI Nobel Laureates 'for his contributions to the development of the methodology of high resolution nuclear magnetic resonance spectroscopy'. You could say Richard Ernst achieved the same trick twice: by his novel applications of 2D FT in both spectroscopy and imaging.



Bloembergen b. 1920



Ernst b. 1933

.....

- The 2003 Nobel Prize for Physiology or Medicine was awarded to Professor Paul Lauterbur and Sir Peter Mansfield 'for their discoveries concerning magnetic resonance imaging'.
- Paul Lauterbur is said to have been inspired to use field gradients to produce an image whilst eating a hamburger. His seminal paper 'Image Formation by Induced Local Interactions. Examples Employing Nuclear Magnetic Resonance' (*Nature* **242**, March 16, 1973) was originally rejected. 30 years later, *Nature* placed this work in a book of the 21 most influential scientific papers of the 20th century.
- Peter Mansfield left school at 15 with no qualifications, aiming to become a printer. His scientific curiosity was sparked by the V1 and V2 flying bombs and rockets that fell on London in 1944, when he was 11. After working as a scientific assistant at the Jet Propulsion Laboratory and a spell in the army, he went back to college to complete his education, eventually becoming Professor of Physics at the University of Nottingham. He was knighted in 1993.



Laurterbur b. 1929



Mansfield b. 1933

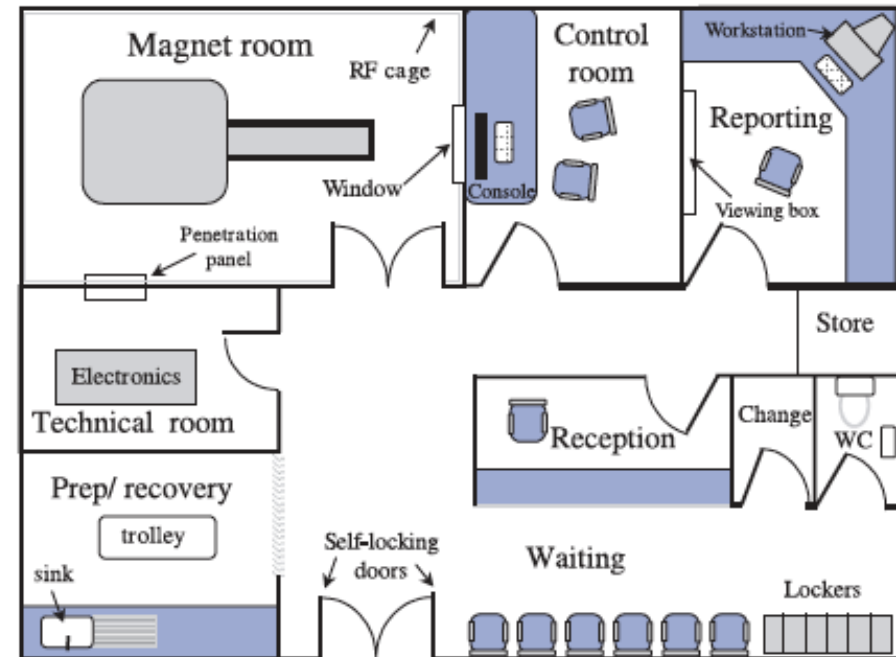
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- Other Nobel Laureates associated with NMR include
  - Norman Ramsey (1989), a spectroscopy pioneer who developed the theory of the chemical shift,
  - Isidor Rabi (1944), Ramsey's PhD mentor, 'for his resonance method for recording the magnetic properties of atomic nuclei' and
  - Kurt Wüthrich (2002) for his development of NMR spectroscopy for determination of the three-dimensional structure of biological macromolecules in solution.

## Welcome to the MRI unit...

In general accommodation may comprise:

- facilities for patient management: reception, waiting areas, changing facilities, toilets, anaesthesia and recovery area, counselling room;
- facilities for staff: reception/office, administration office, reporting rooms;
- MR system: the MRI scanner room (magnet room), control room, computer/technical room and film printing area.



In the control room you operate the MR scanner by entering patient details, selecting and modifying the scan acquisition parameters, viewing and post-processing images, selecting images for hard copy on a remote laser imager and archiving images. There may be an adjacent reporting room and one or more independent image viewing and post-processing workstations

- dedicated storage areas: trolley bay, general store, resuscitation trolley bay, cleaner's store.

# MR system

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The MR system itself consists of:

- a magnet that produces a strong, constant magnetic field;
- magnetic field gradients, which localize the MR signals;
- radiofrequency transmit and receive coils, which excite and detect the MR signal;
- a computer system for scanner control, image display and archiving;
- patient couch, comfort and positioning aids;
- physiological monitoring equipment.

The preoccupation with security and the 'separateness' of the MR suite is principally to prevent anyone introducing ferromagnetic items into the vicinity of the magnet, where the outcome could be disastrous.



## Fringe field...

- The magnetic field extends beyond the physical covers of the scanner. This is referred to as the *fringe field*. The strength of the fringe field decreases rapidly with distance and has implications for safety and for the proper functioning of nearby sensitive electronic equipment (see table 2.1).

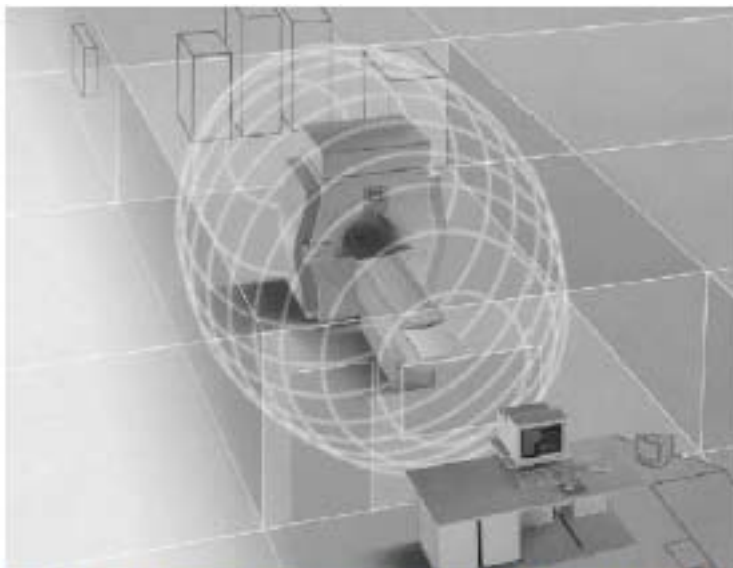


Figure 2.3 Extent of the 0.5 mT fringe field around a 1.5 T system. Courtesy of Philips Medical Systems.

Table 2.1 Limit of fringe field for various objects affected by the scanner. Values are typical for a 1.5 T MR system

| Fringe field (mT) | Item                     | Minimum distance (m) |          |
|-------------------|--------------------------|----------------------|----------|
|                   |                          | On axis              | Radially |
| 3                 | Magnetic media           | 2.8                  | 2.0      |
|                   | Computer hard disks      | 3.4                  | 2.2      |
| 1                 | Shielded colour monitors |                      |          |
|                   | X-ray tubes              |                      |          |
|                   | Pacemakers               | 4.0                  | 2.5      |
| 0.5               | Colour monitors          | 5.6                  | 3.0      |
| 0.1               | Image intensifiers       |                      |          |
|                   | CT scanners              |                      |          |
|                   | Photomultiplier tubes    | 6.8                  | 3.7      |
|                   | Linear accelerators      |                      |          |
| 0.05              | Gamma cameras            |                      |          |

To ensure safety a *controlled area* is defined within the vicinity of the magnet

## *Safety first*

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- MRI is a relatively safe imaging technique in that it does not involve ionizing radiation and there are no clearly demonstrated biological effects
- However, the MRI system and its environment are potentially very hazardous to both patients and staff working in the MRI unit if metal objects get pulled into the magnet bore.

## *Campo statico*

- The primary hazard associated with the static magnetic field is that of ferromagnetic attraction.
- Secondo, la presenza di criogeni necessari per la realizzazione di elevati campi magnetici statici possono (in caso di perdita) avere effetti nocivi...
- e poi ci sono gli effetti diretti sull'uomo legati al campo magnetico variabile nello spazio

# Criogeni

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Per ottenere il campo magnetico statico alcuni sistemi usano le proprietà di alcuni materiali che, a temperature prossime dello 0 assoluto ( $-273.16^{\circ}\text{C}$ ) hanno resistenza elettrica nulla.

La temperatura viene mantenuta inserendo il materiale in un criostato (una camera che contiene elio o azoto liquido) a sua volta inserito in una camera sottovuoto.

Se si perde la condizione di vuoto, o si aumenta la temperatura, il gas evapora...

- ⇒ boil off (evaporazione lenta)
- ⇒ quench (evaporazione rapida – pochi secondi...)

I gas criogeni sono inodori e non infiammabili, ma anche nocivi..

# Quench

## Pericoli:

- 1.ustioni da freddo
- 2.condensazione dell'ossigeno (rischio incendio)
- 3 soffocamento: per ogni litro di elio o azoto liquido si formano circa 700 litri di gas.... se  $O_2$  sotto il 17% non basta a respirare...

## Sicurezza:

1. tubazioni permettono la fuoriuscita dei gas
2. monitor del livello di ossigeno

## Procedure:

- 1.avvio estrazione forzata aria
- 2.evacuare la sala per 20 min (estrarre eventuale paziente dal magnete)
- 3.se la porta non si apre per l'aumento della pressione interna... rompere il vetro!

*Agire sempre in 2!!!*

# Forces on ferromagnetic objects

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When a ferromagnetic object, e.g. one containing iron or steel, is brought close to the magnet, it will experience a force. If sufficiently close, this can turn the object into a dangerous projectile.

The bigger the object the stronger the forces involved and there has recently been a death caused by an oxygen cylinder being accidentally taken too close to the magnet. This attractive force requires the field to be changing over position, as in the fringe field. Even in the absence of a field change any ferromagnetic object will twist with a force considerably greater than its mass in an attempt to align its long axis with the static magnetic field lines of force.

## Force fields

The translational force ( $F$ ) on a volume  $V$  with magnetic susceptibility  $\chi$  is proportional to the product of the static field ( $B$ ) and its spatial gradient:

$$F \propto \chi V B \cdot \frac{dB}{dr}$$

where  $dB/dr$  is the rate of change of  $B$  with position ( $r$ ).  $F$  gets stronger the closer you are to the opening of the magnet bore. The torque ( $T$ ) is proportional to the square of the static field

$$T \propto \chi^2 V B^2$$

Thus ferromagnetic objects will experience a torque even in a uniform field.

## *Implanted medical devices...*

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- Implanted ferromagnetic items such as vascular aneurysm clips may also experience these forces and torques. There has been at least one reported death of a patient scanned with a ferromagnetic aneurysm clip that moved, rupturing the blood vessel, as they were moved into the magnet. Similar hazards arise with patients who may have metallic foreign bodies located in high-risk areas such as the eye. Alternatively the function of implanted medical devices such as pacemakers or cochlear implants may be severely impaired by the static magnetic field and persons with pacemakers are normally excluded from the 0.5-mT fringe field.
- The same rules apply to any pieces of medical equipment that may also need to be taken into the room; for example, a pulse oximeter for monitoring a sedated patient. Devices such as these must be MR compatible. Even though the device may be labelled as MR compatible it may have a maximum operating proximity to the magnet and care must be taken that the device is not moved any closer.

## *Campo magnetico statico: effetto proiettile*

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<http://mrimetaldetector.com/blog/2008/08/mri-missile-effect-accident-pictures/>

## *Video...*

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- <http://www.imrser.org/genpg.asp?pgname=VideoList>

ECRI “Patient Death illustrates the importance of adhering to safety precautions in Magnetic Resonance environments”

[www.ecri.org](http://www.ecri.org), 6 Agosto 2001

A recent incident, widely reported in the news media, occurred in a magnetic resonance (MR) scan room of a hospital near New York City. According to reports, a young patient suffered a fatal blow to the head from a metal oxygen canister that flew into the MR system where the patient was lying. While the details of the incident have not yet been disclosed, the *New York Times* account of the incident (July 31, 2001) stated that a “metal oxygen tank somehow made it into the examination room.”

Projectile incidents have on occasion resulted in patient injuries, some of which were serious. However, to our knowledge, the recent report from the New York hospital describes the first fatality that can be directly attributed to an object being drawn toward a patient in an MR system.

Even devices that might appear safe have become projectiles in the MR environment. For example, although sandbags are often assumed to contain only sand, some also contain ferromagnetic pellets that can be attracted by the MR system. (These pellets are included to add weight to the bag without increasing its size.) In several instances reported in the literature, such sandbags have been pulled into an MR system. ECRI detailed one such instance in a Hazard Report published in the July 1998 issue of its monthly journal *Health Devices* (ECRI 1998).

Patrick M. Colletti **Size “H” Oxygen Cylinder: Accidental MR Projectile at 1.5 Tesla** JOURNAL OF MAGNETIC RESONANCE IMAGING 19:141–143 (2004)

### CASE REPORT

A 47-YEAR-OLD FEMALE ... was sent to a free standing, hospital-associated MR center for thoracic spine, lumbar spine, and brain MR. A 1.5-Tesla unshielded system (Horizon LX; General Electric, Milwaukee, WI) was used. She entered the magnet headfirst. Due to her confused state, she was sedated with 1.0 mg of lorazepam given intravenously.

She was monitored with a pulse oximeter (OmniTrak; Invivo Research, Inc., Orlando, FL). After four sequences, her pulse increased from 97 to 113 bpm and her oxygen saturation decreased from 78% to 68%.

Due to the patient's reduced O<sub>2</sub> saturation, the decision was made to remove the patient from the magnet. As the technologist and technologist assistant were initiating the removal of the patient, the patient's physician wheeled a large size “H” oxygen cylinder into the scanner room.

## *Bombola ossigeno*

- The fully-pressurized, 130-cm high, 22.8-cm diameter “H”-type cylinder holds 6500 liters of oxygen at 2015 psi. Fully loaded, with its wheeled cart, it has a total mass of 80.6 kg.
- As the cylinder passed to the right of the foot of the imaging table, it was suddenly pulled toward the magnet. The technologist assistant, also at the right of the table, was barely able to dodge the incoming projectile as he moved toward the table to avoid direct impact. He escaped with several 10 cm superficial abrasions and a minor lateral contusion to his left arm.



**Figure 2.** The size “H” oxygen cylinder after the regulator was sheared off. Note the scrapes on the cylinder and the bent beam on the cart.

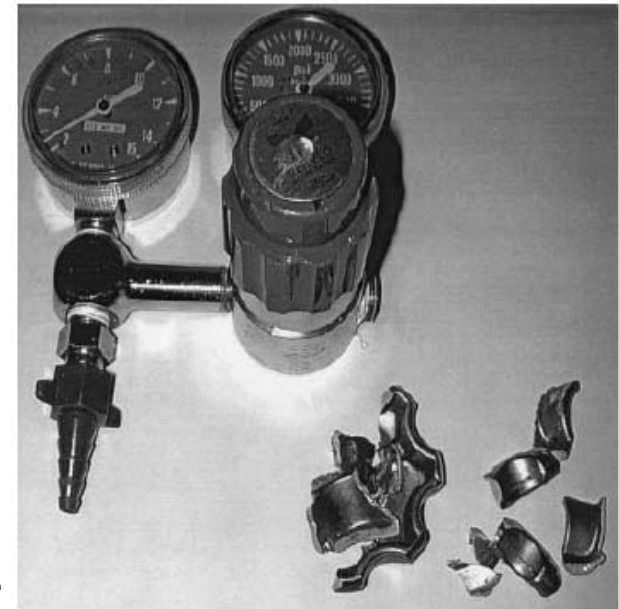
## *Bombola ossigeno*

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The flow regulator (Fig. 1) was sheared off of the cylinder (Fig. 2) and the cylinder impaled the scanner cowling at the one o'clock position (Fig. 3). The cylinder oscillated precariously, pivoting on the point of impalement.

The physician and technologist were able to help the technologist assistant move past the nearly stable cylinder. At that point, in order to stabilize the cylinder and extract the uninjured but hypoxic patient, the chief technologist decided to perform an emergency ramp down of the system.

The system ramped down to a negligible field in less than two minutes. With this “controlled quench,” helium rapidly escaped via the overhead safety vent. The vent cap was damaged during this process and required replacement prior to cryogen refill. The in-room oxygen level monitor did not detect reduced oxygen levels. Within two minutes of the incident, as two assistants controlled and carefully removed the cylinder, the patient was removed from the magnet. She responded rapidly to oxygen administration.



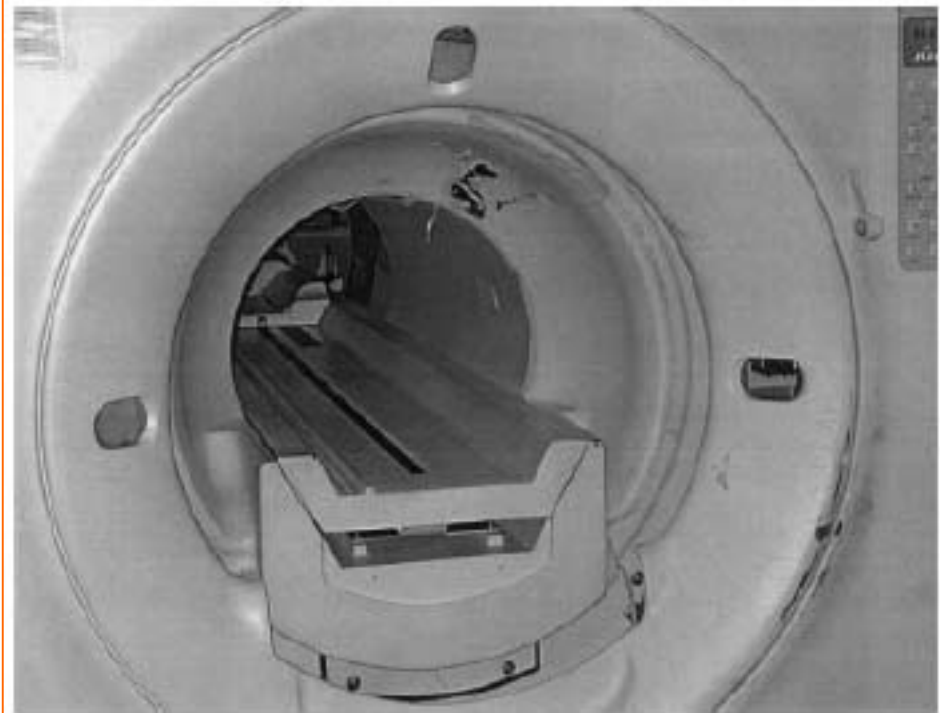
**Figure 1.** The flow regulator that was sheared off of the cylinder and the nonferromagnetic valve handle that fragmented upon impact with the table.

## *Bombola ossigeno*

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Damages and costs included:

1. A 15-cm hole in the magnet cowling (Fig. 3); the cowling had to be replaced.
2. The 1600-lb gradient coils were displaced 1 cm and were rotated slightly; special tools were required for adjustment.
3. The scanning table was damaged; replacement was required, at a cost of \$8000.
4. The quenched magnet required an emergency fill of 600 liters of liquid helium (five flasks of 120 liters each), at a total cost of \$10,000.
5. Emergency after-hours service: 60 person-hours; at a cost of \$93,000.
6. Use of the scanner was lost for 34 hours.



**Figure 3.** This 15-cm hole in the magnet cowling required the replacement of the cowling.

### Ferromagnetic Sandbags Are Hazardous in Magnetic Resonance Imaging (MRI) Environments ***Health Devices Jul 1998;27(7):266-7***

#### **Problem**

A member hospital reported that a sandbag containing ferromagnetic pellets was inadvertently brought into the magnetic field of a 1.5-tesla magnetic resonance imaging (MRI) unit. The sandbag, which had been placed in the vicinity of a patient's groin for site compression and the control of bleeding, had been obscured from the MRI staff's view by a blanket. As the patient was brought toward the MRI unit, the sandbag was violently pulled from its position and became pinned to the wall of the MRI tube. The patient received bruises to her chest and head. Although the MRI unit sustained no damage, two men were required to remove the sandbag from the bore of the magnet.

#### **Discussion**

While sandbags are often assumed to contain only sand, some contain ferrous pellets or iron oxides that add weight to the sandbag without increasing its size. Several journal articles report cases of a sandbag containing ferrous pellets creating a hazard in an MRI environment.



Gary A. Ulaner, Patrick M. Colletti, **An Unsuspected MR Projectile: A “Wooden” Chair with Metal Bracing**, Letter to the Editor JOURNAL OF MAGNETIC RESONANCE IMAGING 23:781–782 (2006)

We were recently involved in a case that demonstrates how an apparently “wooden” object can become a projectile and injure a patient, hospital staff member, or observer in an MR environment..

A patient was having his abdomen imaged on a Siemens 1.5-T, actively-shielded, Symphony Maestro Class MR unit. His wife was sitting within the room comforting him. The wooden chair she was seated on had resided within the confines on the MR suite since its opening 10 months prior. As she stood up and moved the chair closer to the MR unit to talk with her husband, the chair unexpectedly began moving toward the MR unit. She instinctively reached out her hands to hold the chair back. The chair accelerated toward the magnet and forcefully trapped the fifth finger of her right hand between the MR unit and the chair. Two people were required to separate the chair from the MR unit

## *Sedia “di legno”*

Examination of the wooden chair revealed that beneath the cushioned seat was a square, black metallic bracing plate, approximately 52 cm to a side. This large plate was not visible until the chair was inverted

This event occurred during a late evening, “after hours,” imaging session. The chair was removed from the MR suite by the radiology resident, who administered first aid to the injured woman. By the time the resident returned the next morning, the chair had been put back in the MR suite. A general memorandum was issued to warn all physicians and technologists that the chair was not to be placed in the MR suite again.

The fact that the chair was put back in the MR suite the following morning emphasizes how following established routines can lead to unanticipated dangerous situations. Safe MR operation requires continuous vigilance.



... Wooden chair, frontal oblique view (a) and under-oblique view demonstrating the metallic frame (ar-

## Effetti diretti sull'uomo

---

When the static magnetic field exceeds a threshold of approximately 2 T, the movement-induced electric field in the head may be high enough to evoke **vertigo and other sensory perceptions such as nausea, visual sensations (magnetophosphenes) and a metallic taste in the mouth**

There is also the possibility of acute neurocognitive effects, with subtle changes in **attention**, concentration and visuospatial orientation

All these effects are not considered to be hazardous per se, but they can be disturbing and may impair working ability. **For normal movements, the threshold for peripheral nerve stimulation is unlikely to be reached with exposures below 8 T, although it is possible that the basic restrictions for peripheral nerve stimulation (ICNIRP 2010) may slightly be exceeded by very fast movements**

In addition to these movement-induced effects, static magnetic fields may cause direct effects arising from (1) induction of electrical 'flow' potentials across blood vessels due to the movement of electrolytes in the blood, (2) forces on paramagnetic and diamagnetic components of tissues, (3) changes in chemical reactions due to altered spin chemistry and (4) deflection of ionic currents due to magnetic (Lorentz) force. **These direct interaction mechanisms are not considered to have a significant health effect when the magnetic flux density is below 7 T (WHO 2006; ICNIRP 2009a), above 7 T there is too little research for any firm conclusions.**

# *Gradienti*

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Sono campi magnetici variabili nello spazio che vengono attivati/disattivati durante le sequenze, quindi variano nel tempo

Creano correnti indotte di intensità maggiore verso i tessuti periferici in quanto in genere i gradienti aumentano dal centro alla periferia del magnete

## Effetti diretti sull'uomo

I campi variabili nel tempo generati dall'accensione e spegnimento dei gradienti ricadono nella parte dello spettro elettromagnetico delle ELF.

Questi campi generano nel corpo delle correnti, secondo la legge di Faraday

$$FEM = -\frac{\partial \Phi_B}{\partial t} = -\frac{\partial \int_{\Sigma} B dS}{\partial t}$$

per una spira di area A si ha

$$FEM = -\pi r^2 \frac{\partial B}{\partial t}$$

e per il campo elettrico

$$FEM = \oint_{\partial \Sigma} E d\ell = -\pi r^2 \frac{\partial B}{\partial t}$$

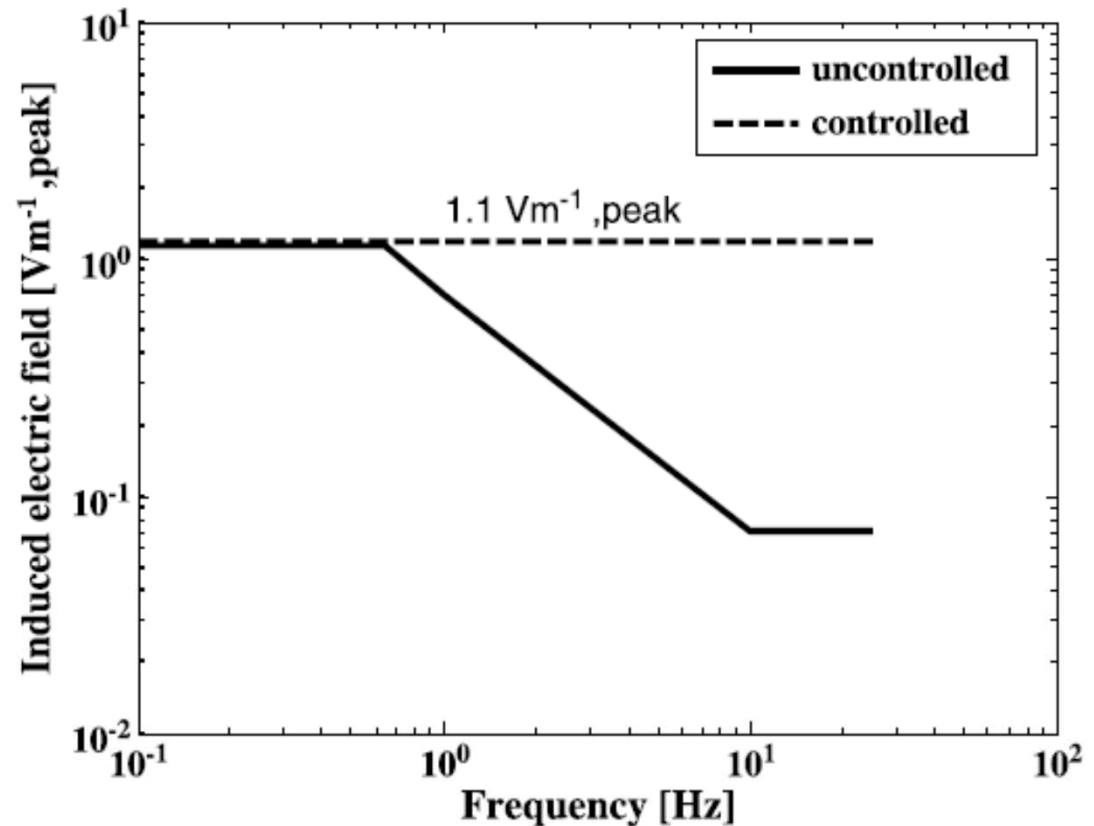
$$2\pi r E = -\pi r^2 \frac{\partial B}{\partial t}$$

$$E = -\frac{r}{2} \frac{\partial B}{\partial t}$$

In order to avoid the induction of magnetophosphenes, the strength of the induced electric field should not exceed the basic restrictions for occupational exposure defined by ICNIRP (2010) for time-varying magnetic fields with an extension to frequencies below 1 Hz (ICNIRP 2014)

# Stimolazione nervosa

In modern EPI-capable MR systems, the rapidly changing magnetic field associated with the switching of the magnetic field gradients is able to generate currents in tissue, which may exceed the nerve depolarization threshold and cause peripheral nerve stimulation (PNS). The possibility also exists, at least theoretically, of stimulating cardiac muscle, thus presenting a hazard. Stimulation of motor nerves and skeletal muscle may be disconcerting to the patient (discomfort being reported for levels 50% to 100% greater than the sensation threshold) but is not itself hazardous and will not normally occur in routine clinical scans. Another well-documented effect is magnetophosphenes, or experiencing the harmless sensation of flashes of light. This is thought to originate from retinal stimulation by induced currents. The same effect has been reported for sudden head movements within strong static fields



**Fig. 2.** Basic restrictions for the induced electric field for uncontrolled and controlled exposure conditions. The basic restrictions for uncontrolled exposures are based on protection against magnetophosphenes and peripheral nerve stimulation. The basic restrictions for controlled exposures are based on protection against peripheral nerve stimulation only. Above 1 Hz, the basic restrictions are equal to the occupational basic restrictions in ICNIRP (2010).

## Limiti

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In IEC 60601–2–33, **cardiac** stimulation is assumed to be avoided when the combined gradient output of all gradient units of the gradient system satisfies

$$\frac{dB}{dt} < 20 \left( 1 + \frac{3}{ts} \right)$$

where dB/dt is in T/s and ts is the duration of the gradient field change (i.e. the time to ramp from maximum negative to maximum positive) in ms.

Più in generale, per la stimolazione delle fibre nervose e dei muscoli, si può scrivere

$$\left( \frac{dB}{dt} \right)_{threshold} = C \, rb \left( 1 + \frac{\tau_{chron}}{ts} \right)$$

Dove a primo membro vi è la soglia per la stimolazione, ts è la durata del cambiamento del campo gradiente,  $\tau_{chron}$  è una costante tipica di ogni tessuto (e.g. 0.4 ms for a peripheral nerve and 3.0 ms for cardiac muscle). rb is known as the ‘rheobase’, the threshold below which no further excitation is possible, independent of the stimulus duration. C is a constant taking into account the tissue radius and the gradient orientation.

Theoretical hyperbolic SD curves for cardiac stimulation and the PNS limits for the IEC L01 and L12 operating modes are illustrated in figure 10.2. Interestingly we see that the lowest thresholds occur for the longest ramp times and therefore gradients that switch faster, i.e. have very short rise times, actually allow much greater amplitude changes as well.

## Limiti

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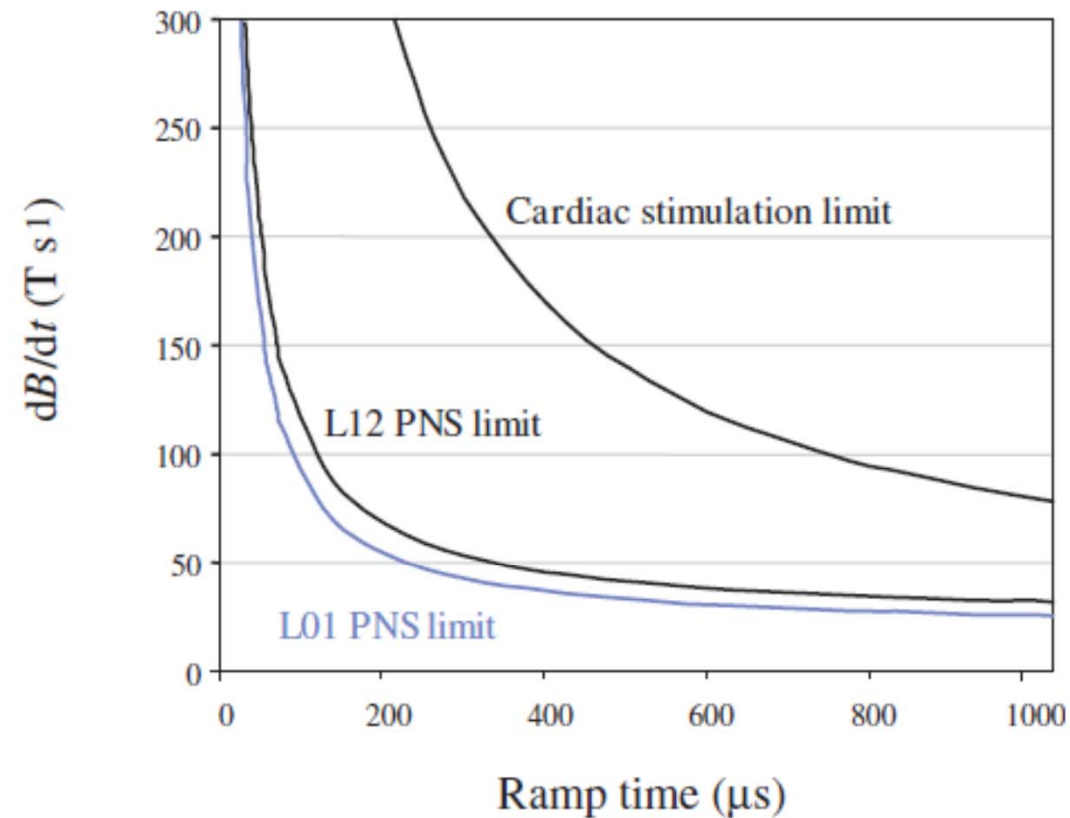


Figure 10.2 Derived hyperbolic strength–duration (SD) curves for the IEC 60601-2-33 limits for cardiac stimulation and the normal (L01) and first-level controlled (L12) operating modes for peripheral nerve stimulation (PNS).

## Acoustic noise

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- All MR images are produced using a *pulse sequence*, which is stored in the scanner computer. The sequence contains *radiofrequency (RF) pulses* and *gradient pulses* which have carefully controlled durations and timings. The gradient pulses make the characteristic ‘knocking’ noise when the imager is acquiring a scan.
- The knocking or drilling noise heard when an MRI sequence is in progress can be considered simply the result of the Lorentz force generated by the coils when a current is pulsed through them in the presence of the static magnetic field. The noise is caused by the movement of the coils against their mountings, and can be in excess of 100 dB for some manufacturer’s sequences. This is why hearing protection is recommended for patients during MRI scanning.
- The reduction of gradient noise is an active area of development for system manufacturers. Some newer magnets use vacuum isolation of the gradients to reduce the gradient switching noise to a lower level, however we recommend you use ear-plugs with all patients.

## *Campo a radiofrequenza*

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Viene eccitato in impulsi di diversa durata e/o ampiezza per portare il sistema fuori equilibrio e quindi generare il segnale

Viene assorbito dal corpo e si trasforma in calore

ECRI, Thermal Injuries and Patient Monitoring during MRI Studies  
Health Devices Sep 1991;20(9):362-3

### **Problem**

We received several reports of incidents in which patients undergoing MRI studies have sustained second- and third-degree burns. Such thermal injuries usually occur where the skin is in contact with a monitoring sensor or cable (e.g., ECG electrode or cable, pulse oximeter sensor) or an MRI accessory (e.g., surface coil). Although some of the reported thermal injuries have been serious enough to require skin grafts, no life-threatening incidents have been reported.

The risk of burns is increased by proximity to the RF coils. In addition, the power and frequency of the pulsed RF field increases with the field strength of the magnet, so that thermal injuries seem to be more likely with high-field MRI systems.....

## *Precauzioni*

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In using physiologic monitoring equipment during MRI studies, a number of precautions can be taken to minimize the likelihood of burns. These precautions include not looping sensor cables, using high-resistance graphite electrodes and cables, and placing the sensor and cable away from the RF coil. Also, an electrically conducting path can be eliminated altogether by using certain monitoring equipment. For example, end-tidal CO<sub>2</sub> monitors often require only a plastic nasal cannula on the patient and a plastic airway tube to the monitor; noninvasive blood pressure measurements require only a plastic tube connected between the monitor and the pressure cuff on the patient.

# SAR

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The RF exposure is measured in terms of the SAR defined as the total power in watts (W) per kilogram of tissue. This is why you need to enter the patient's mass when registering them.

SAR is under the control of the MR operator. Some factors that help to reduce the SAR are:

- the use of quadrature rather than linear coils for transmission;
- avoiding the use of the body coil for certain examinations, i.e. when you have a head, knee or other coils that can transmit as well as receive;
- increasing TR;
- using fewer slices;
- reducing echo train length (ETL, turbo factor) in fast or turbo spin echo (FSE/TSE) sequences;
- reducing the refocusing pulse flip angle, especially in FSE sequences

The IEC 60601-2-33 standard is based upon limiting RF induced core temperature rises to  $0.7^{\circ}\text{C}$  or  $1^{\circ}\text{C}$  for normal and first-level controlled operations, respectively. This translates into SAR terms as **2 and 4 W/kg averaged over 6 min**

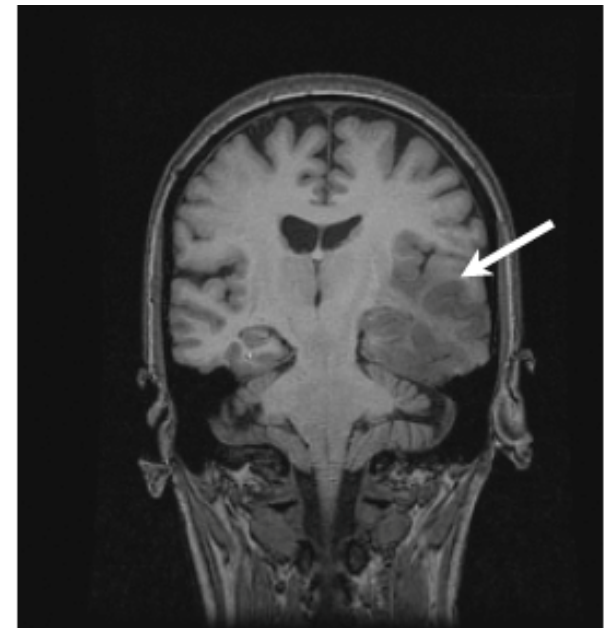
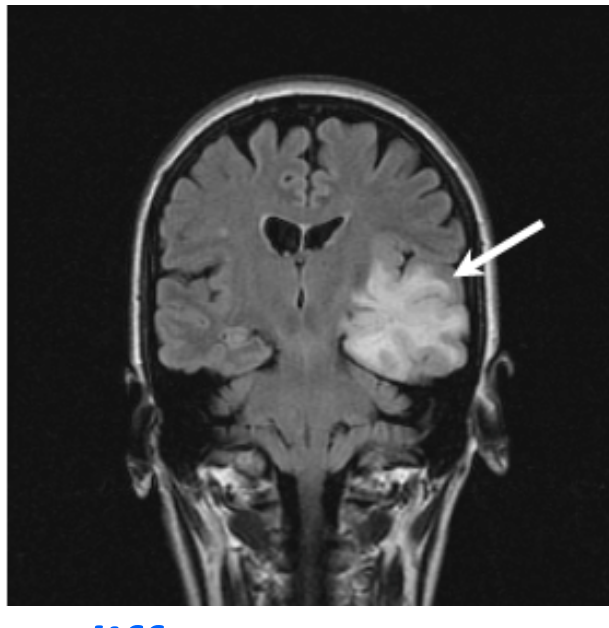


ICNIRP...

## *Some basic stuff*

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- The various tissues have different signal intensities, or brightness, on MR images. The differences are described as the image contrast, and allow us to see the boundaries between tissues. For example, if a tumour is bright and brain tissue is mid-grey, we can detect the extent of the tumour (figure 3.1(a)). MRI allows us to produce a wide range of contrasts by using different imaging techniques (known as pulse sequences) and by controlling the timing of the sequences. So it is also possible to make the tumour dark and brain tissue brighter (figure 3.1(b)).
- Compare this with Computerized Tomography (CT) images. CT contrast depends only on the attenuation of X-rays by the tissues (measured in Hounsfield units). We can produce 'soft tissue' or 'bony' windows by changing the reconstruction algorithm, but bone will always be the brightest tissue and grey matter will always be darker than white matter.



*Different pulse sequences different outputs...*

## Different types of image...

---

- MRI uses the natural properties of hydrogen which, as part of water or lipids, makes up 75–80% of the human body. The most important properties are the *proton density* (often abbreviated to PD), and two characteristic times called *spin-lattice relaxation time* and *spin-spin relaxation time*, denoted  $T_1$  and  $T_2$  respectively.
- Proton density is related to the number of hydrogen atoms in a particular volume; fluids such as CSF and blood have higher PD than tendon and bone.
- Relaxation times describe how long the tissue takes to get back to equilibrium after an RF pulse.  $T_1$  and  $T_2$  depend on the different tissues. Fluids have long  $T_1$ s (e.g. 1500–2000 ms), water-based tissues are usually mid-range (e.g. 400–1200 ms), and fat-based tissues generally have short  $T_1$ s (e.g. 100–150 ms).
- $T_2$  is always shorter than  $T_1$  for a given tissue. Fluids have the longest  $T_2$  (700–1200 ms), while water-based tissues tend to have longer  $T_2$ s than fat-based tissue (40–200 ms and 10–100 ms respectively).
- In general images have contrast which depends on either PD,  $T_1$  or  $T_2$ .

## *Different images*

---

- In PD images, high PDs give high signal intensities which in turn have bright pixels on the image.
- In  $T_2$ -weighted images, tissues with long  $T_2$  give the highest signal intensities, producing a bright appearance.
- $T_1$ -weighted images are completely different; long  $T_1$  tissues give the weakest signal, i.e. bright pixels on  $T_1$  are associated with short  $T_1$ s.

## Spin echo sequences

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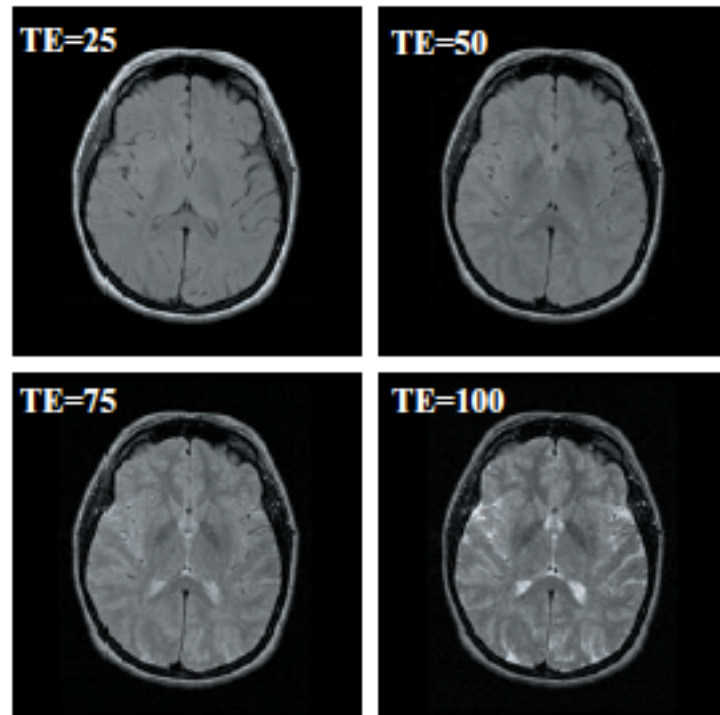
All MR images are produced using a *pulse sequence*.

- There are many different types of sequences, but they all have timing values called TR, and TE, which can be modified. Usually the operator set TR and TE in order to get the required image contrast.
- There are two principle types of pulse sequence, called *spin echo* and *gradient echo*, abbreviated *SE* and *GE*.
- SE sequences use two RF pulses to create the echo which measures the signal intensity. SE can produce T1-, T2-, or PD-weighted images depending on the choice of TR and TE as shown in the table 3.1.
- SE sequences generally produce the best quality images but they take a relatively long time – several minutes rather than seconds.

Table 3.1 Choice of TR and TE for conventional spin echo sequences

| TR                       | TE                       |                          |
|--------------------------|--------------------------|--------------------------|
|                          | Short (less than 40 ms)  | Long (more than 75 ms)   |
| Short (less than 750 ms) | T <sub>1</sub> -weighted | Not useful               |
| Long (more than 1500 ms) | PD-weighted              | T <sub>2</sub> -weighted |

# Spin echo sequences



(a)

Figure 3.6 (a) SE brain images with TR = 1500 ms and various TE.

Table 3.1 Choice of TR and TE for conventional spin echo sequences

| TR                       | TE                       |                          |
|--------------------------|--------------------------|--------------------------|
|                          | Short (less than 40 ms)  | Long (more than 75 ms)   |
| Short (less than 750 ms) | T <sub>1</sub> -weighted | Not useful               |
| Long (more than 1500 ms) | PD-weighted              | T <sub>2</sub> -weighted |

## Gradient echo sequences

- GE sequences use a single RF pulse followed by a gradient pulse to create the echo, which also measures the signal intensity.
- GE sequences can produce images with T1-, T2- or PD-weighting (see table 3.2) and generally have much shorter TRs than SE, so they have shorter scan times. However, they are influenced by the quality of the main magnetic field (called the *inhomogeneity*) as well as by timing parameters. This affects the apparent spin-spin relaxation time which becomes shorter.
- The combined T2 and magnetic field inhomogeneity is known as T2\* (pronounced 'tee two star'), so GE sequences really depend on T2\* not just T2. However, with modern magnets GE T2\*-weighted images have very similar contrast to SE T2-weighted images, and so we often just refer to 'gradient-echo T2s'.

Table 3.2 Choice of TR, TE and  $\alpha$  for gradient-echo sequences

| Flip angle $\alpha$   | TE                       |                          |
|-----------------------|--------------------------|--------------------------|
|                       | Short (less than 15 ms)  | Long (more than 30 ms)   |
| Small (less than 40°) | PD-weighted              | T <sub>2</sub> -weighted |
| Large (more than 50°) | T <sub>1</sub> -weighted | Not useful               |

*Notes:*

TR is always short (less than 750 ms) compared with SE sequences. (N.B. Longer TRs require larger flip angles to show T<sub>1</sub> weighting; at short TRs even 45° flip angles may have T<sub>1</sub> weighting.)

## $T_1$ -weighted images

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- $T_1$ -weighted images usually have excellent contrast: fluids are very dark (unless they are flowing into the imaging volume), water-based tissues are mid-grey and fat-based tissues are very bright.
- They are often known as 'anatomy scans', as they show most clearly the boundaries between different tissues (figure 3.2).

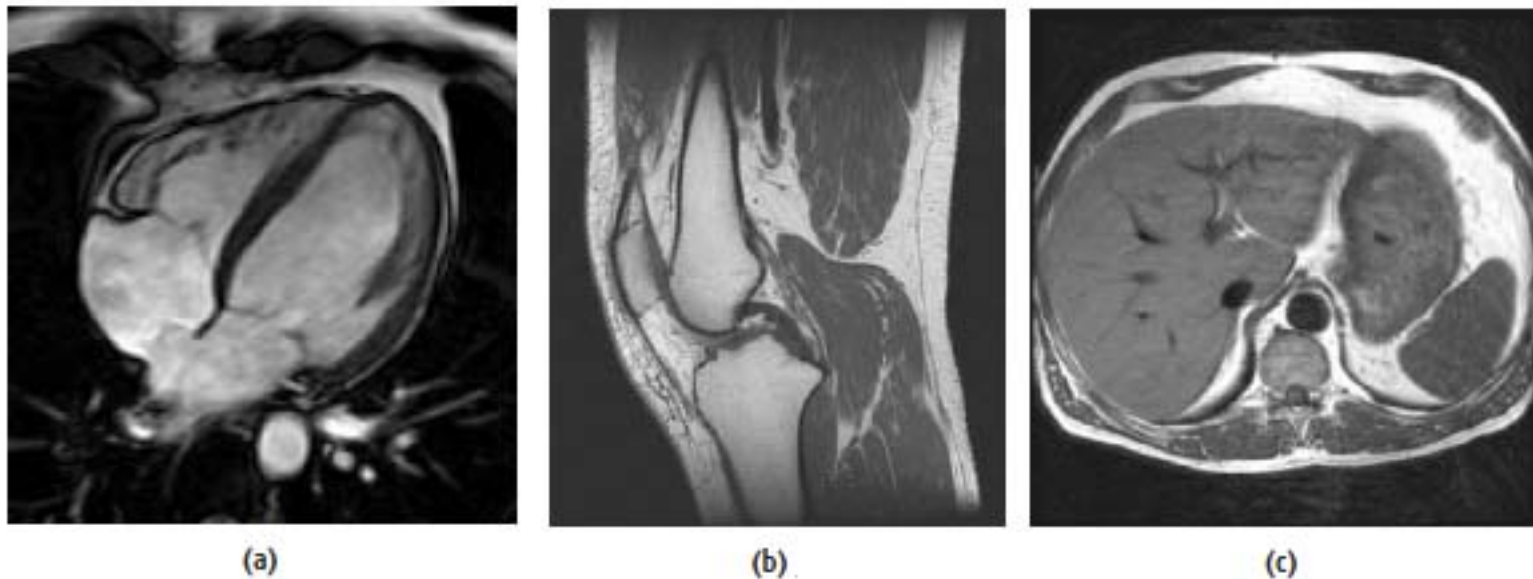


Figure 3.2  $T_1$ -weighted images of normal anatomy. (a) Oblique '4-chamber' view of the heart, (b) sagittal knee, (c) axial liver.

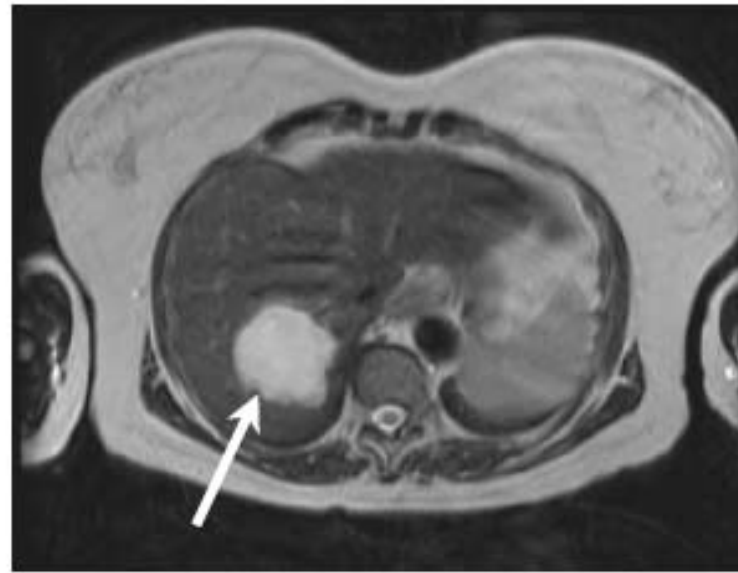
## $T_2$ -weighted images

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- On  $T_2$ -weighted images fluids have the highest intensity, and water- and fat-based tissues are mid-grey.  $T_2$  images are often thought of as 'pathology' scans because collections of abnormal fluid are bright against the darker normal tissue. So for example the meniscal tear in the knee shows up well because the synovial fluid in the tear is brighter than the cartilage (figure 3.5).



(a)



(b)

Figure 3.5  $T_2$ -weighted pathology images. (a) Sagittal image of meniscal tear (arrow) and (b) axial liver scan showing haemangioma.

## *PD-weighted images*

---

- Bearing in mind that the proton densities (i.e. water content) for most tissues are rather similar, you might wonder why we bother to produce PD-weighted images since they will have less contrast than either T1 or T2 images. The reason is partly historical....

.. Of course we have been making some very sweeping statements about contrast, and PD scans do have some useful clinical applications; for example, in the knee you can distinguish articular cartilage from the cortical bone and menisci (figure 3.7).



Figure 3.7 Sagittal PD-weighted image of the knee.