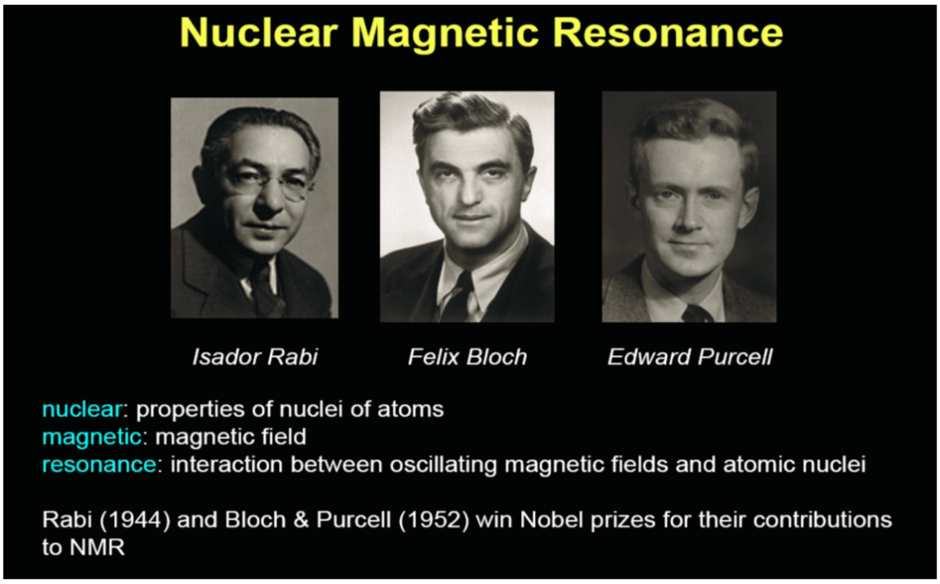
Corso di Strumentazione e Tecniche per
la Diagnostica

RMN

UN PO' DI STORIA



Nuclear Magnetic Resonance

Isador Rabi *Felix Bloch* *Edward Purcell*

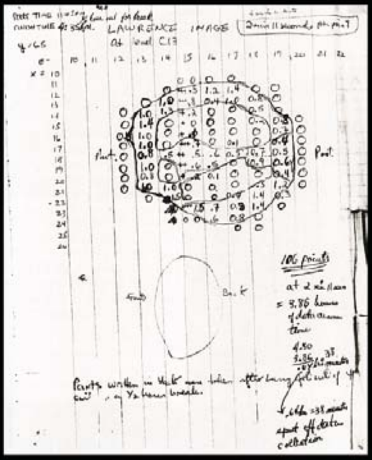
nuclear: properties of nuclei of atoms
magnetic: magnetic field
resonance: interaction between oscillating magnetic fields and atomic nuclei

Rabi (1944) and Bloch & Purcell (1952) win Nobel prizes for their contributions to NMR


Damadian in 1977 with prototype of first MR scanner

First Human MR Image

Damadian's postdoc, Larry Minkoff



Source: Huettel et al. slides

- 0.05T, only homogeneous in small volume at centre
- sampled image one voxel at a time, 2+ min/voxel * 106 voxels = 4 hours!

Source: Jody Culham's fMRI for Dummies web site

First Human MR Image

Human Attempt 11:0's PM 7/2/77

X = 18, 15 = Z, Y = 6½

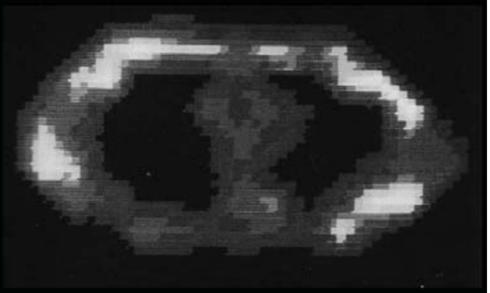
[illegible] 3¼" from bottom surface of [illegible] to magnet [illegible] surface

FANTASTIC SUCCESS!

4:45 AM First Human Image

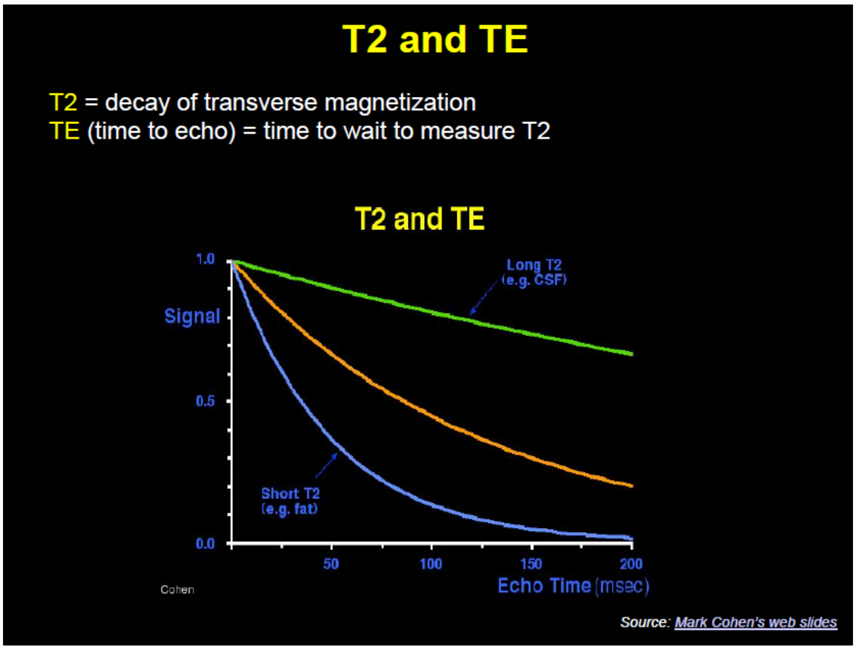
Complete in Amazing Detail

Showing Heart
Lungs
Vertebra
Musculature



Source: Huettel et al. slides

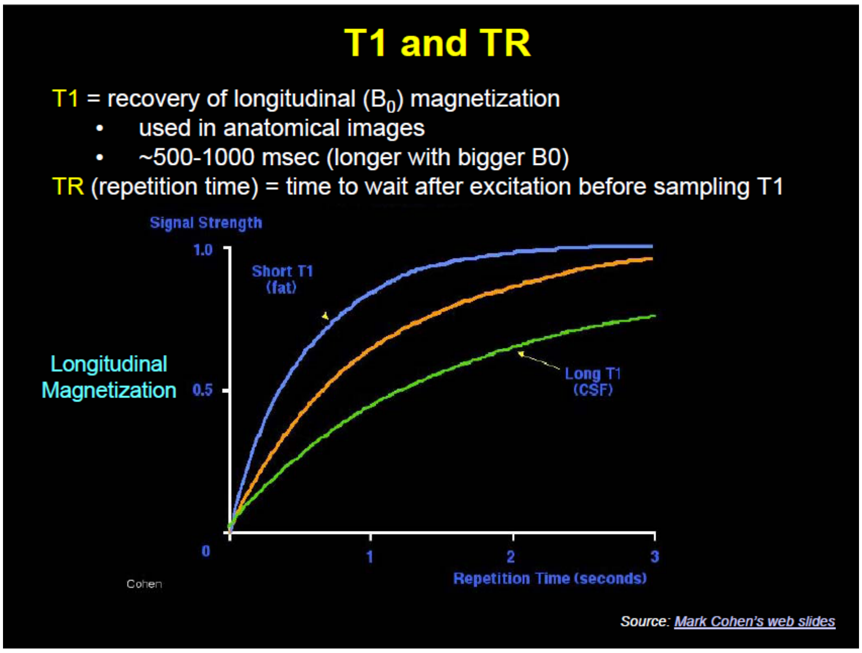
BLOCH.EXE



T2 and TE

T2 = decay of transverse magnetization
TE (time to echo) = time to wait to measure T2

Source: Mark Cohen's web slides

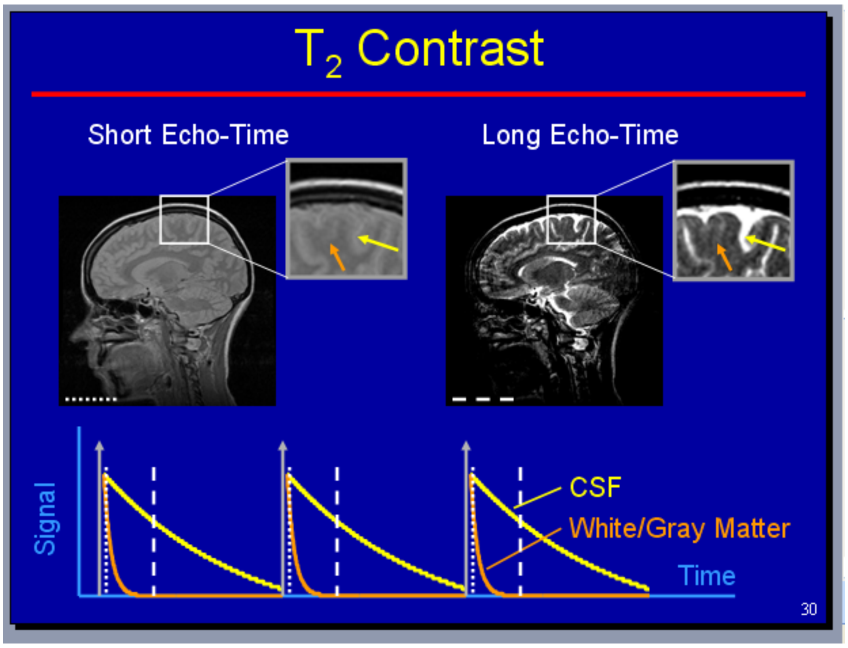


T1 and TR

T1 = recovery of longitudinal (B_0) magnetization
- used in anatomical images
- ~500-1000 msec (longer with bigger B0)

TR (repetition time) = time to wait after excitation before sampling T1

Source: Mark Cohen's web slides



T_2 Contrast

Short Echo-Time

Long Echo-Time

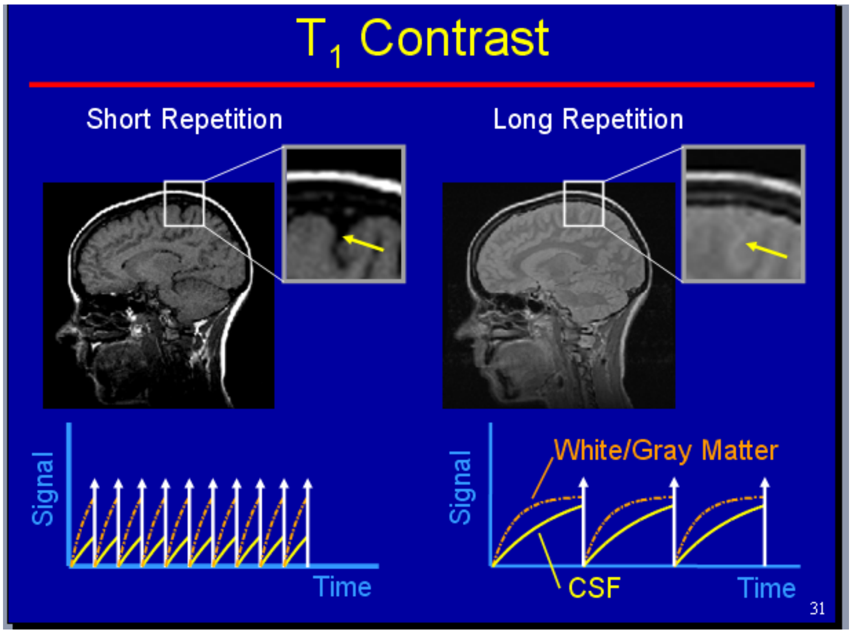
Signal

CSF

White/Gray Matter

Time

30



T_1 Contrast

Short Repetition

Long Repetition

Signal

Time

Signal

White/Gray Matter

CSF

Time

31

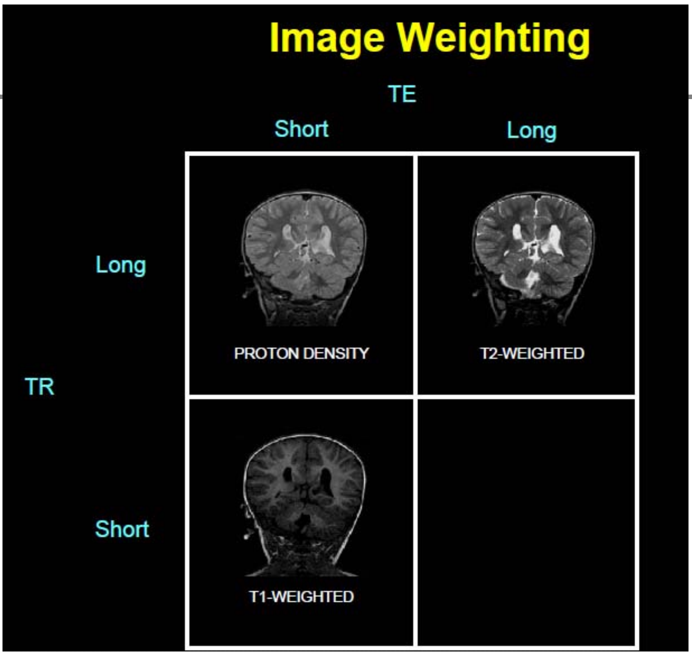


Image Weighting

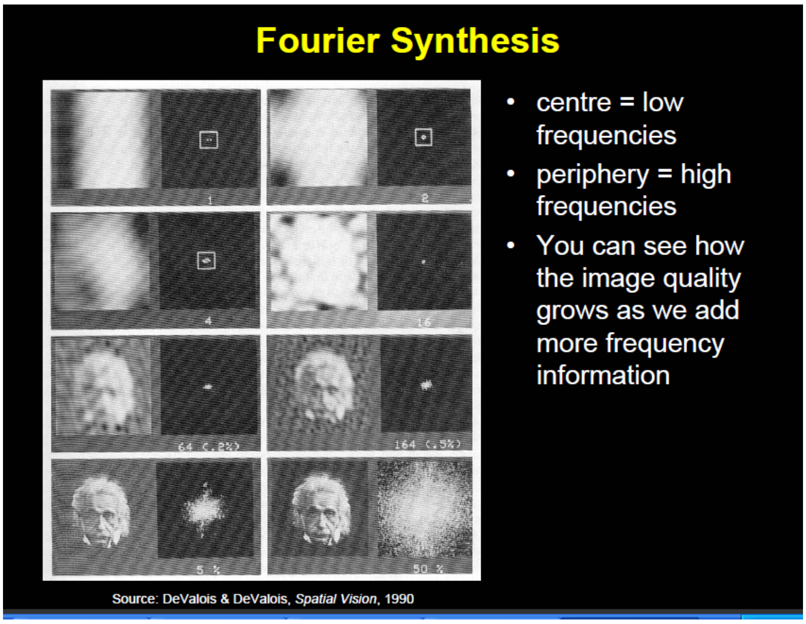
TE

Short Long

TR

Long: PROTON DENSITY | T2-WEIGHTED

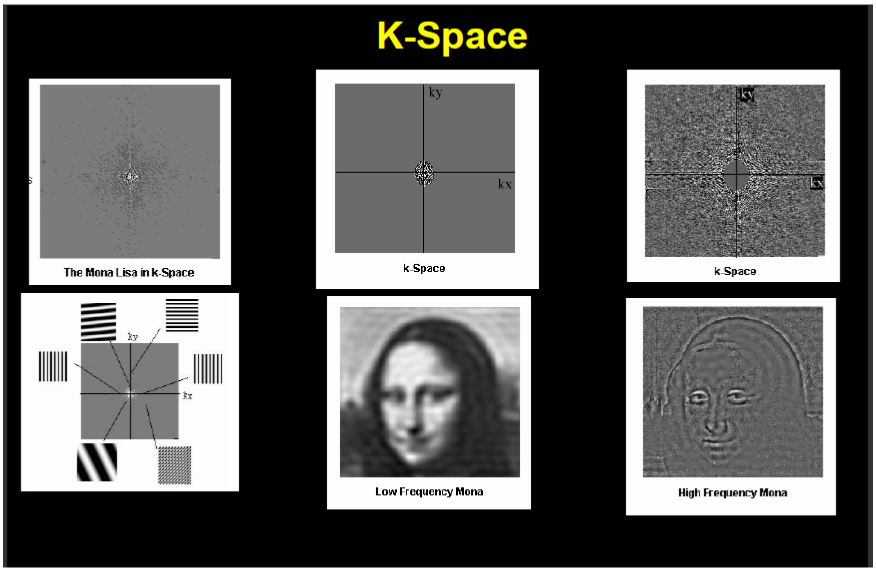
Short: T1-WEIGHTED



Fourier Synthesis

- centre = low frequencies
- periphery = high frequencies
- You can see how the image quality grows as we add more frequency information

Source: DeValois & DeValois, *Spatial Vision*, 1990



K-Space

The Mona Lisa in k-Space

k-Space

k-Space

Low Frequency Mona

High Frequency Mona

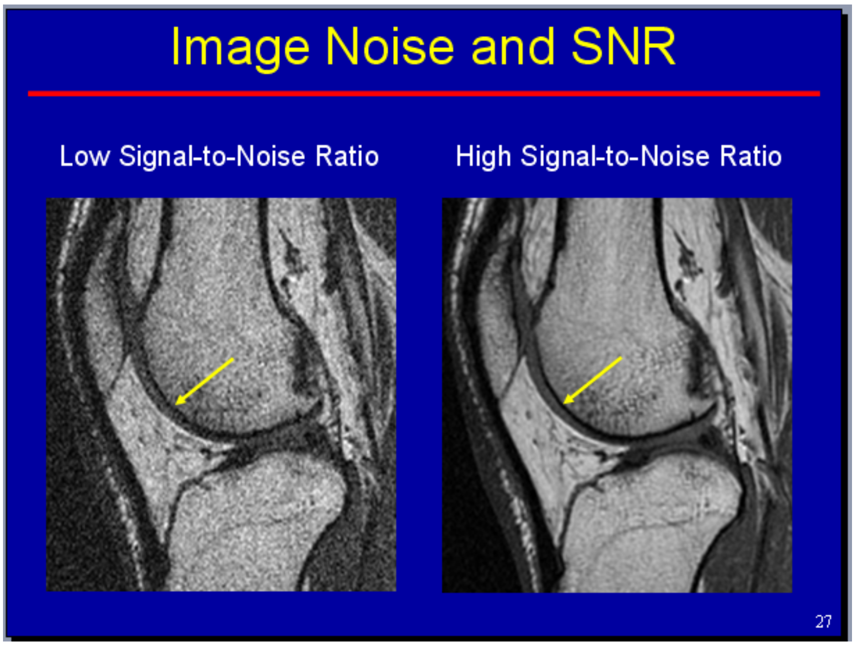


Image Noise and SNR

Low Signal-to-Noise Ratio

High Signal-to-Noise Ratio

Diffusion MRI
Diffusion-weighted imaging (DWI)

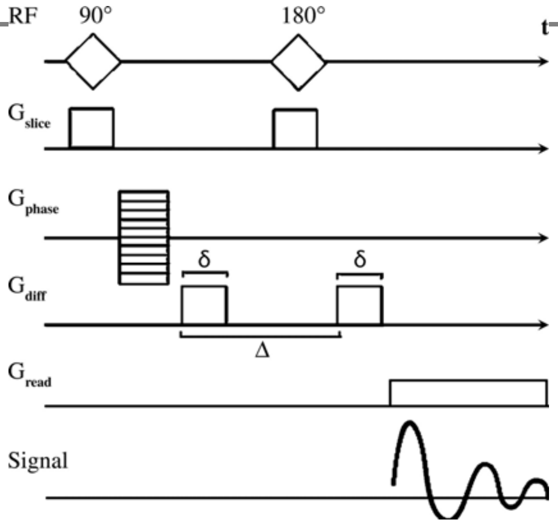
- Confrontata con la classica spin eco la sequenza spin eco a gradiente impulsato che si usa per la diffusion MRI include due ulteriori gradienti di campo magnetico

- Per effetto del primo gradiente, i protoni in un pixel varieranno la loro velocità di un fattore che dipende dal valore del campo magnetico in quel pixel. Questa variazione di velocità darà luogo ad una perdita di coerenza.

- In seguito è applicato un altro gradiente nella stessa direzione ma di ampiezza opposta il quale tenderebbe a rifocalizzare (rifasare) gli spin.

- Tuttavia la rifocalizzazione non sarà perfetta perché, alcuni protoni (molecole d'acqua) hanno abbandonato, per diffusione, il voxel nel tempo che intercorre tra i due impulsi. Quindi il segnale misurato dalla macchina MRI sarà ridotto.

Figure 9. Diagram shows the pulsed gradient SE sequence used for diffusion MR imaging.



Hagmann P et al. Radiographics 2006;26:S205-S223

RadioGraphics

- La riduzione del segnale può essere correlata alla diffusione con un'equazione del tipo:

$$\frac{S}{S_0} = \exp(-bD)$$

- Dove S_0 è l'intensità del segnale senza i gradienti di diffusione, S è il segnale in presenza dei gradienti, D è il coefficiente di diffusione e b un parametro proporzionale al ritardo Δ trai due impulsi.

- Maggiore è b maggiore è il decremento del segnale. D viene estrapolato effettuando più misure con diversi b (diversi Δ).

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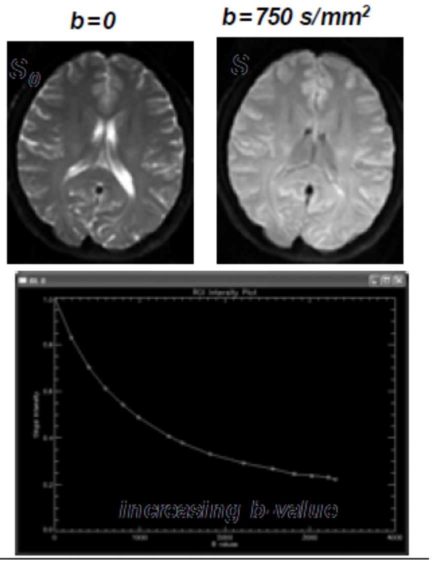
b-value vs. Signal

- ***MRI signals are sensitive to diffusion***

$$S = S_0 \exp(-bD)$$

b: b-factor

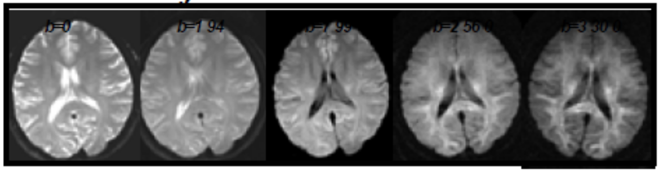
D: diffusion coefficient



Impact of b-value

- *For high b-value*
  - *better diffusion contrast*

- *For low b-value*
  - *better SNR*
  - *shorter TE*
  - *less artifacts*



- *For most clinical use, b = 750-1000 s/mm²*

Nuclear magnetic resonance spectroscopy MRS

- I diversi protoni di una molecola possono risonare a frequenze leggermente diverse in funzione dell'ambiente chimico locale.

- Poiché sia lo shift in frequenza che la frequenza di risonanza fondamentale sono direttamente proporzionali all'intensità del campo magnetico lo shift è convertito in un parametro adimensionale noto come chemical shift.

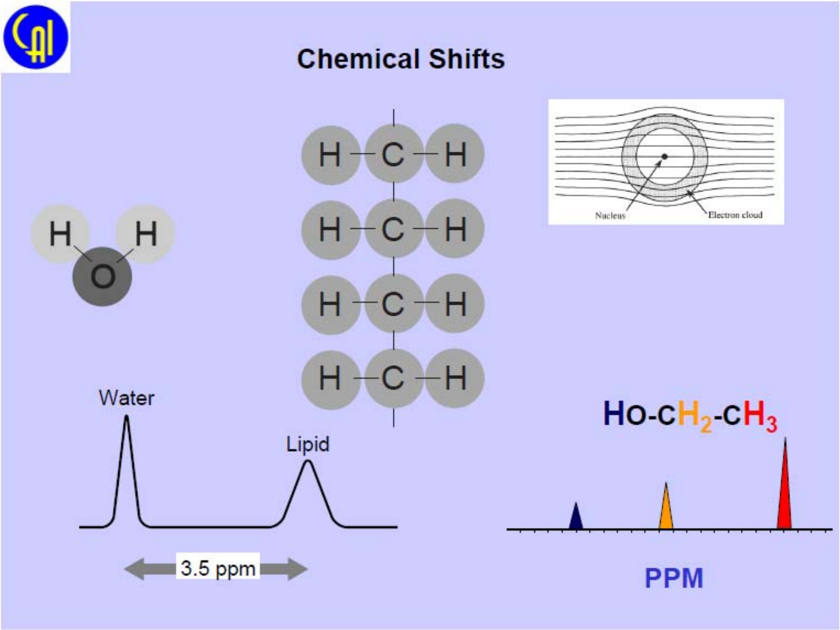
- il chemical shift è riportato come una misura relativa rispetto ad una assegnata frequenza di risonanza. In particolare per i nuclei 1H, 13C, and 29Si, il TMS (tetramethylsilane) è comunemente utilizzato come riferimento.

- Il chemical shift è ottenuto facendo la differenza fra la frequenza di risonanza dell'elemento e la frequenza del riferimento e dividendo il risultato per la frequenza del riferimento

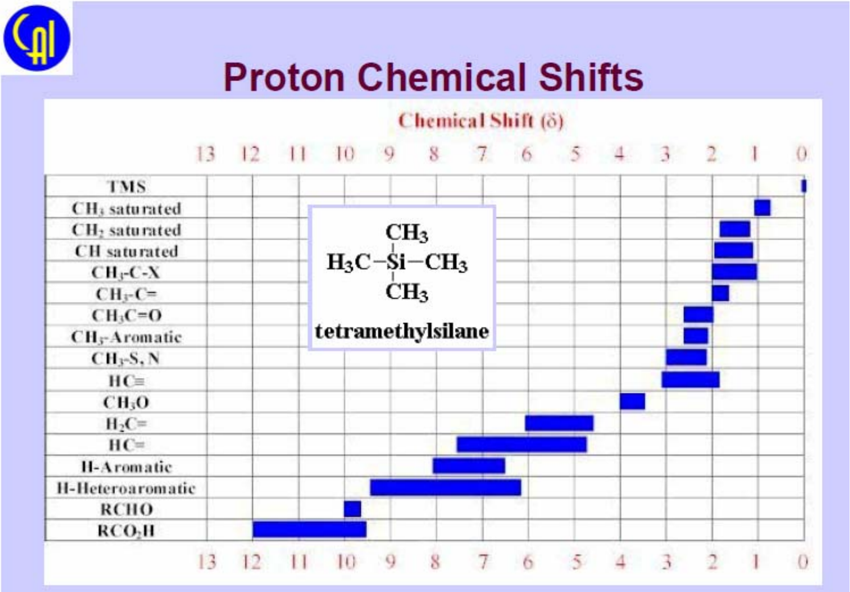
- Gli shift che si ottengono sono estremamente piccoli rispetto alla fondamentale frequenza della RMN. Un tipico shift in frequenza è dell’ordine dei 100 Hz confrontato con una frequenza fondamentale di 64 MHz

- Per questo motivo lo shift chimico è generalmente espresso in parti per milione (ppm).

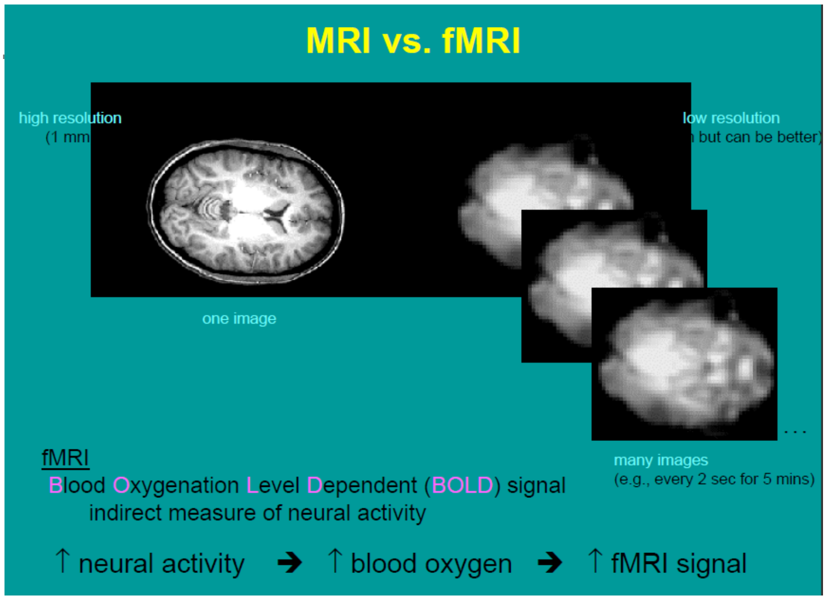
- Per poter rilevare differenze così piccole il campo magnetico applicato deve essere estremamente costante su tutto il volume del campione. A tal fine spesso si usano delle ulteriori bobine dette shims per migliorare l’omogeneità del campo.



Chemical Shifts



Proton Chemical Shifts



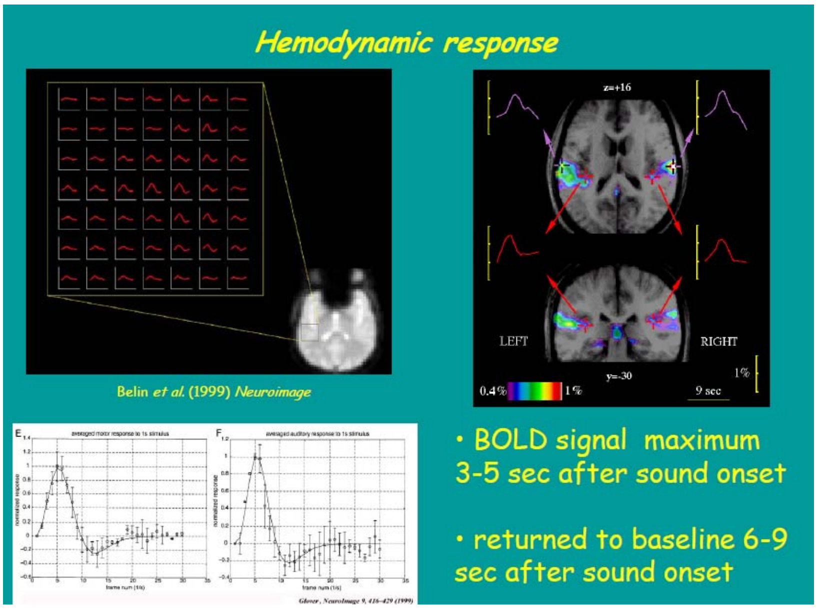
MRI vs. fMRI

fMRI

Blood Oxygenation Level Dependent (BOLD) signal

indirect measure of neural activity

↑ neural activity ➔ ↑ blood oxygen ➔ ↑ fMRI signal l'emoglobina de-ossigenata possiede infatti proprietà paramagnetiche, a differenza dell'emoglobina ossigenata. L'aumento di concentrazione di deossiemoglobina provoca quindi cadute di segnale RM, la sua diminuzione causa un aumento di segnale, permettendo così di utilizzare l'emoglobina come mezzo di contrasto endogeno nello studio delle regioni cerebrali coinvolte dalla funzione studiata.



Hemodynamic response

Belin *et al.* (1999) *Neuroimage*

- BOLD signal maximum 3-5 sec after sound onset
- returned to baseline 6-9 sec after sound onset

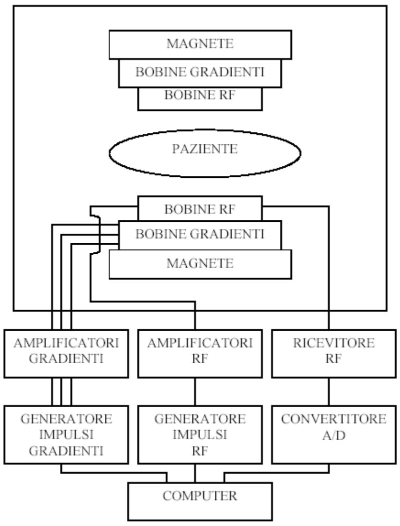
Glover, NeuroImage 9, 416–429 (1999)

Corso di Strumentazione Biomedica III

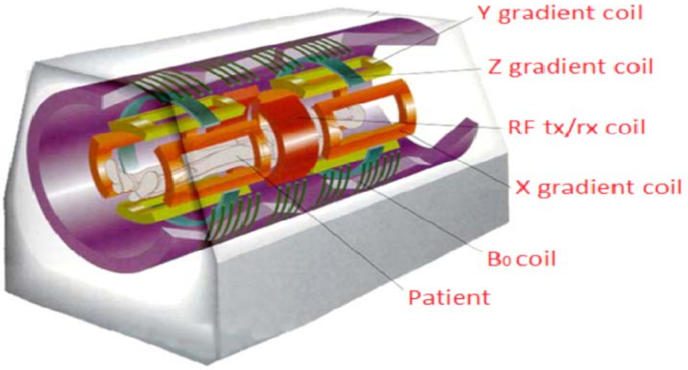
ANTENNE

NEI SISTEMI RMN

Struttura dei sistemi RMN

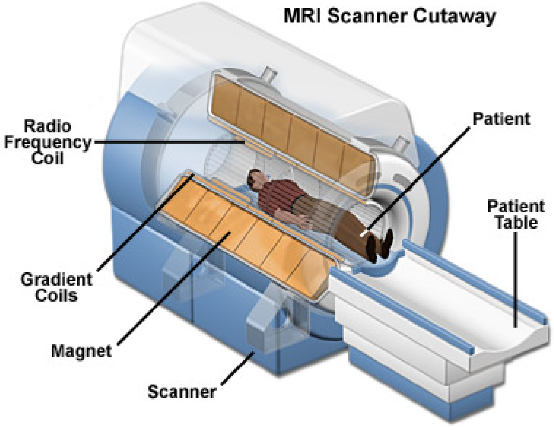


MRI Tomograph

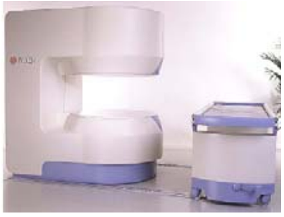


- MRI tomographs are composed of five coils: one for the main static magnetic
- field B_0, one for the RF transmission/reception, and three for the gradients

MRI Funzionamento e Struttura

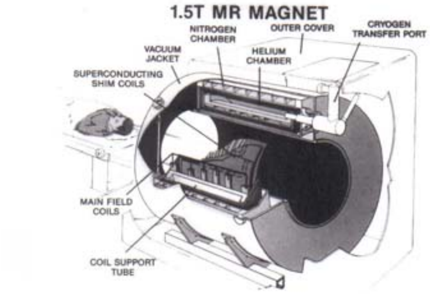


Magneti



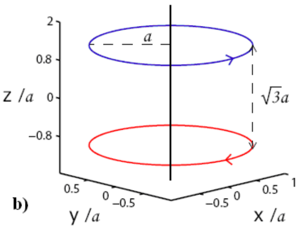
elettromagnete

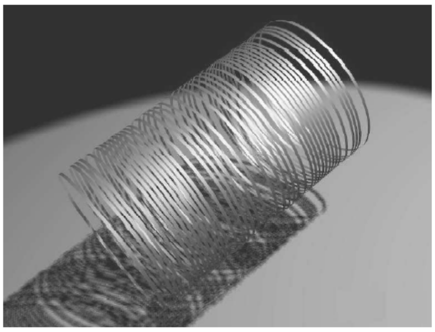
magnete resistivo

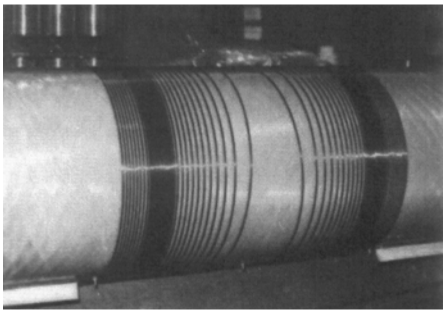


magnete superconduttore

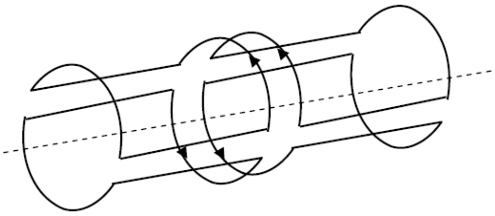
Bobine per gradiente z

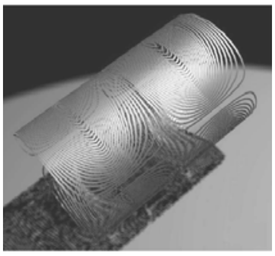


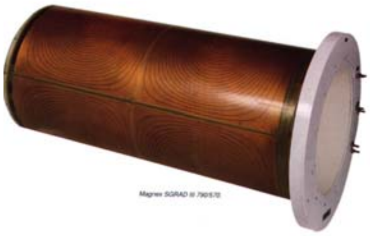




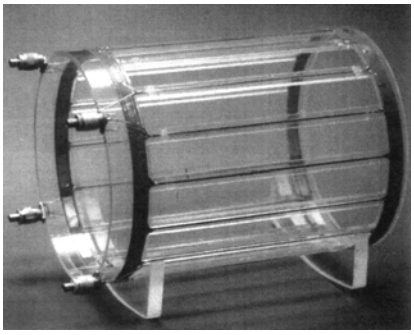
Bobine per gradiente x y



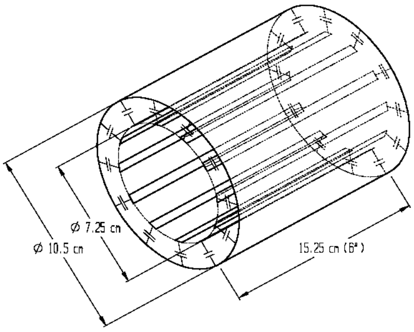




Bobine RF di volume

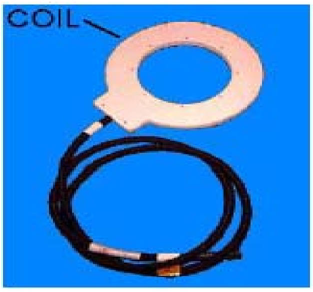


birdcage



TEM

Bobine RF di superficie (coils)

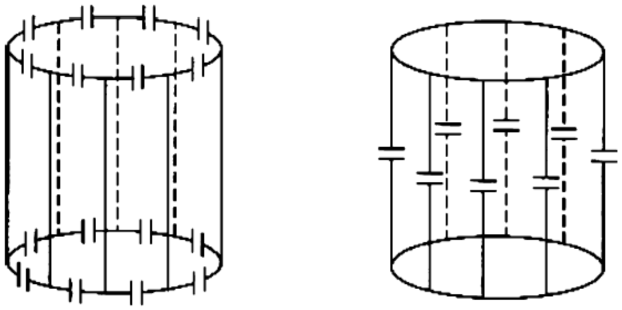


Bobine RF locali

A fast and accurate simulator for the design of birdcage coils in MRI

Giulio Giovannetti [a,*], Luigi Landini [b], Maria Filomena Santarelli [a], Vincenzo Positano [a]

[a] *Institute of Clinical Physiology, National Council of Researches, Via Moruzzi 1, 56124 S. Cataldo, Pisa, Italy*
[b] *Department of Information Engineering, University of Pisa, Pisa, Italy*



(a) (b)

Fig. 1. (a) High-pass birdcage coil (b) Low-pass birdcage coil.

Modello circuitale

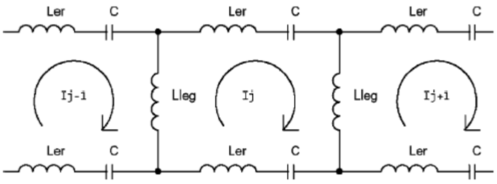


Fig. 2. Segment of the equivalent circuit for a high-pass birdcage coil.

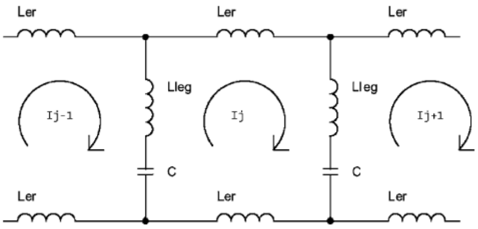
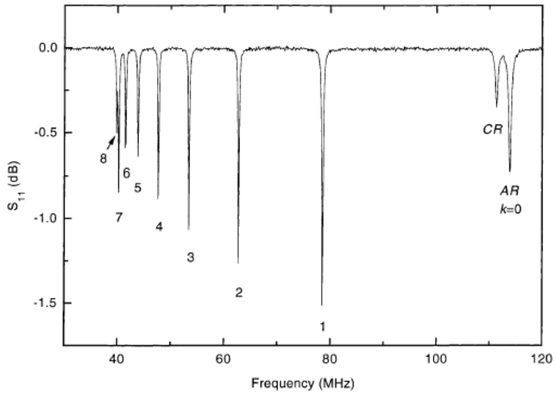


Fig. 3. Segment of the equialent circuit for a low-pass birdcage coil.

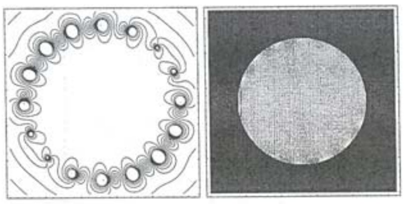
Versione semplificata

$$\omega_k = [C\,(Ler + 2Lleg\sin^2\frac{\pi k}{N}]^{-1/2} \qquad (k = 0, 1, 2, \ldots., N/2)$$



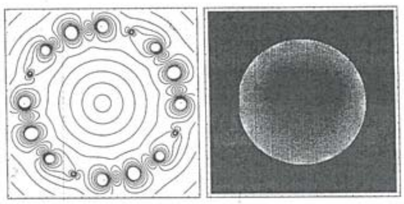
Mappe di campo
Birdcage 16 Leg

modi



k = 1

(a)



k = 3

(b)

BirdcageBuilder: Design of Specified-Geometry Birdcage Coils with Desired Current Pattern and Resonant Frequency

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BERNARD J. DARDZINSKI,[3] MICHAEL B. SMITH[1]

[1] *Center for NMR Research, Department of Radiology, Pennsylvania State University, College of Medicine, Hershey, Pennsylvania* 17033
[2] *IGC-Medical Advances Inc., Milwaukee, Wisconsin* 53288
[3] *Imaging Research Center, Children's Hospital Medical Center, Cincinnati, Ohio* 45229

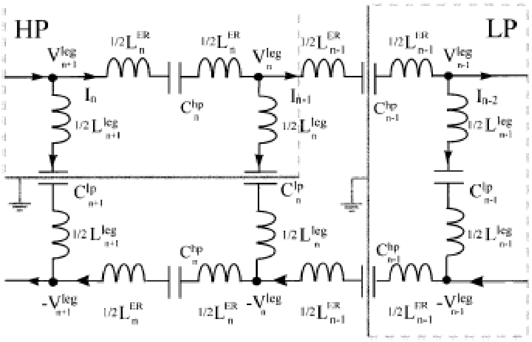
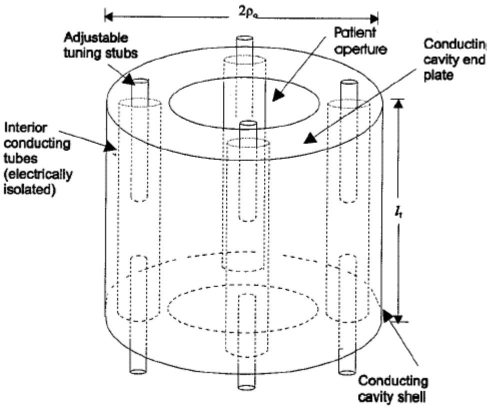
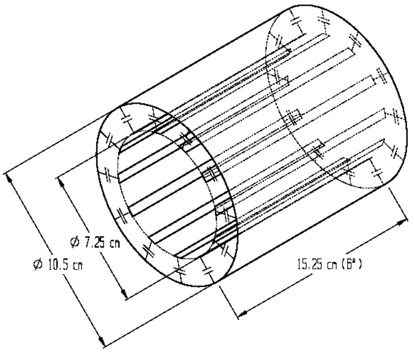


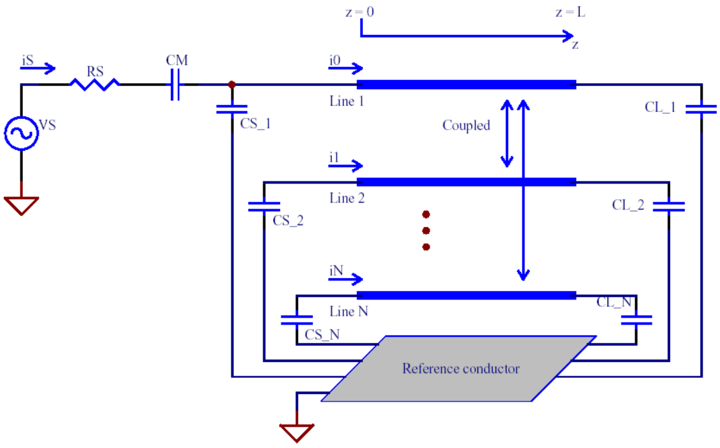
Figure 1 A circuit model for a band-pass birdcage coil design. The L_n and L_n^{ER} are the effective inductances of the *n*th leg and ER segment, respectively; C_n^{lp} and C_n^{hp} are the capacitances on the *n*th leg and ER segment, respectively; and I_n is the current intensity in the *n*th loop. The voltage at the end point of the *n*th leg is V_n^{leg}. When C_n^{lp} is given, the virtual ground is assumed at the middle of the legs (see the left box labeled HP); if C_n^{hp} is known, a virtual ground is inserted at the middle of the $(n-1)$th ER segments on both ER planes (see the right box labeled LP).

TEM coils





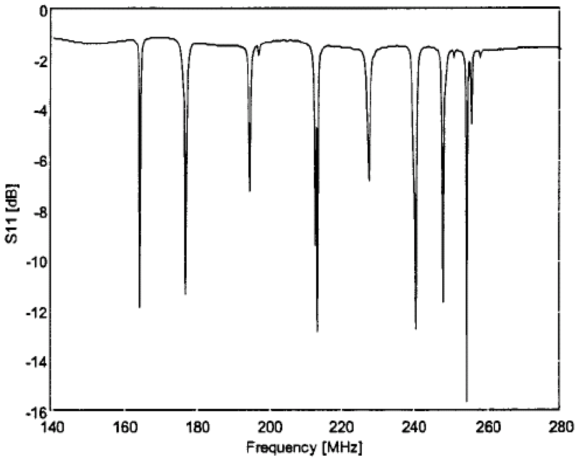
Modello per le TEM coils



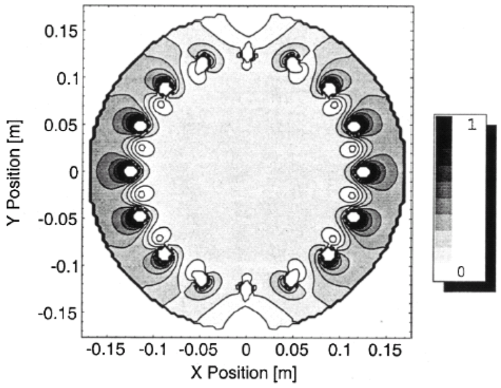
$$\frac{d}{dz}\underline{\mathbf{V}} = -\underline{\underline{Z}}\,\underline{\mathbf{I}} \qquad \frac{d}{dz}\underline{\mathbf{I}} = -\underline{\underline{Y}}\,\underline{\mathbf{V}}$$

Frequenze di risonanza

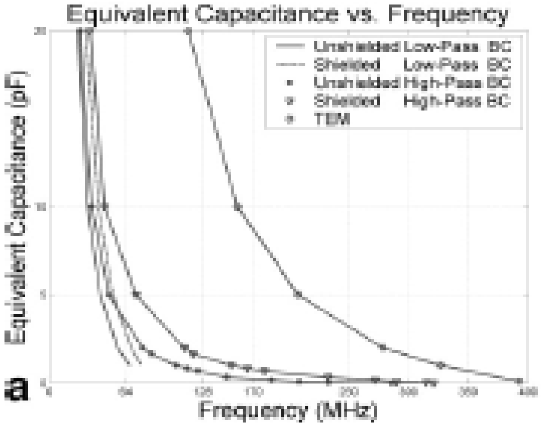
$$\prod_{n=1}^{N}(1-\Gamma_n^{+}\Gamma_n^{-}\,e^{-2\gamma l})=0 \qquad \omega_n = -jc\gamma_n$$



Mappe di campo TEM 16 elementi



Confronto Birdcage-TEM



Philips

Sistemi 1.5 T e 3 T

Siemens

Sistemi
1.5 T e 3 T

Sistemi 0.35 T

General Electric (GE)

1.5 T e 3 T

Open
0.2 T e 0.35 T

G-scan Brio

Un approccio RM rivoluzionario per tutte le applicazioni muscolo-scheletriche per diagnosi più precise e affidabili.

O-scan

Ecco a voi il miglior sistema per RM degli arti: O-scan garantisce eccezionale qualità di immagine, imaging semplice e facilità di utilizzo, in linea con la tradizione Esaote.

S-scan

Lo scanner RM dedicato S-scan rappresenta l'ultima evoluzione della tecnologia Esaote nell'ambito della tomografia RM.

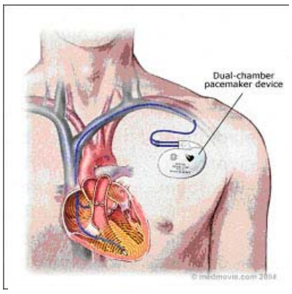
Corso di Strumentazione Biomedica III

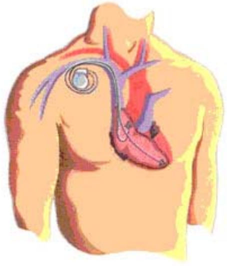
Interazione RMN
Portatori di pacemaker

#Università degli Studi di Roma "La Sapienza"
Dipartimento di Ingegneria Elettronica
& Istituto Superiore di Sanità, Roma

Il pacemaker è costituito da un involucro in titanio e da un catetere che porta l'impulso elettrico al cuore passando attraverso il sistema venoso

Il pacemaker si applica a pazienti con patologie del tessuto cardiaco che ne abbiano compromesso la capacità spontanea a depolarizzarsi





ICNIRP Statement on: "Medical MR procedures: protection of patients" (2004)

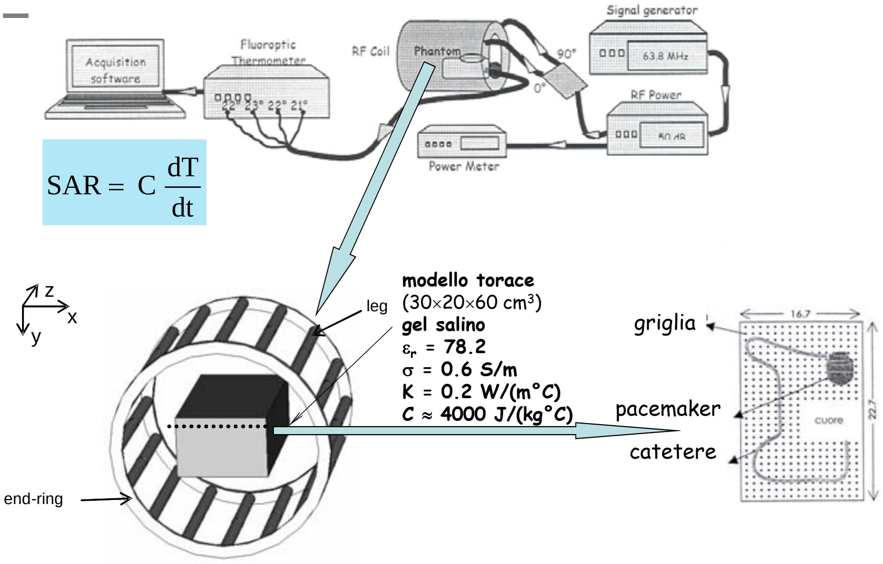
In Italia la RMN è preclusa per legge ai portatori di pacemaker

- No adverse health effects are expected if the increase in body core temperature is less than 1 °C
- Adverse effects are avoided if temperatures in localized regions of the head remain lower than 38 °C ($\Delta T < 1$ °C), lower than 39 °C in the trunk ($\Delta T < 2$ °C), less than 40 °C in the limbs ($\Delta T < 3$ °C)
- SAR_{WB} should not exceed 2 W/kg, local SAR (averaged over 10 g) is limited to 20 W/kg in the extremities and 10 W/kg in the head and trunk

Electrotechnical Commission (IEC) 2010

- The International Electrotechnical Commission (IEC) considers that, to prevent tissue damage in the body, the radiofrequency field should induce temperature increases in the body core lower than 0.5 °C for normal operating mode and 1 °C for first level controlled operating mode, where medical supervision of the patient is required.
- Moreover, local tissue temperature should not exceed 39 °C and 40 °C for normal and first level controlled operating modes, respectively.
- Consequently, limitations have been reported with reference to the specific absorption rate (SAR). In particular, the whole body SAR (SAR_{WB}) should not exceed 2 W/kg and 4 W/kg in normal and first level controlled operating modes, respectively.

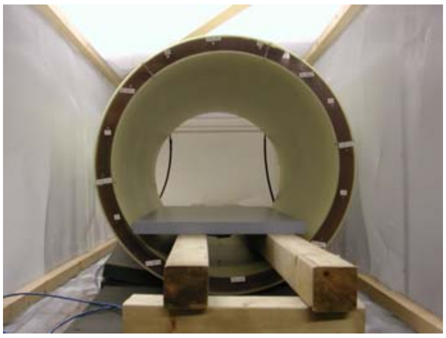
Setup sperimentale ISS



$$\mathrm{SAR} = C\,\frac{dT}{dt}$$

modello torace
$(30 \times 20 \times 60\ \mathrm{cm}^3)$
gel salino
$\varepsilon_r = 78.2$
$\sigma = 0.6\ \mathrm{S/m}$
$K = 0.2\ \mathrm{W/(m\,°C)}$
$C \approx 4000\ \mathrm{J/(kg\,°C)}$

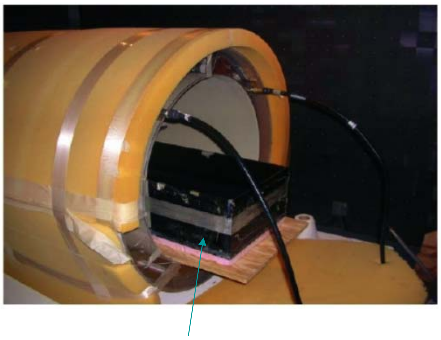
MRI Apparatus



MRI apparatus:
Birdcage Coil (64 MHz)
ISS

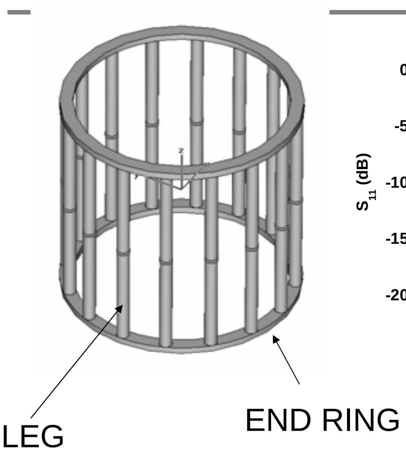
MRI apparatus:
Siemens Magnetom Sonata Maestro
(1.5 T – 64 MHz)
Mater Dei Hospital in Rome

Birdcage and Phanthoms



Physical phantom
BOX (30 × 20 × 60 cm^3) gelled saline material
Electric properties: $\varepsilon_r = 78.2$; $\sigma = 0.6$ S/m
Thermal conductivity = 0.2 W/ (m°C)
Specific heat ≈ 4000 J/(kg°C)

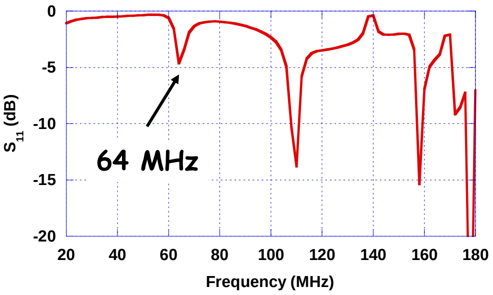
Birdcage Model



LEG

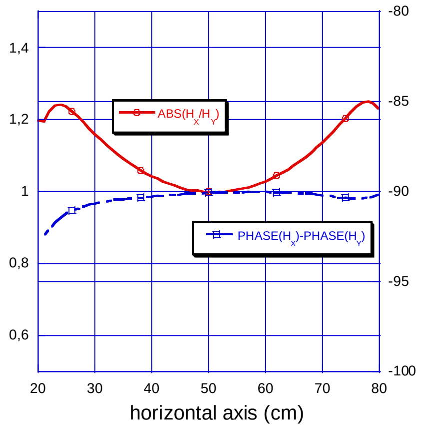
END RING

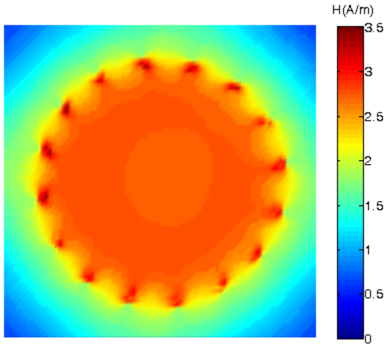
16 Leg Birdcage



tuning capacitances of 0.3 pF
at the leg center (low-pass birdcage)

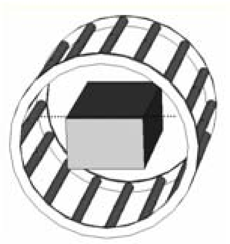
Birdcage Magnetic Field

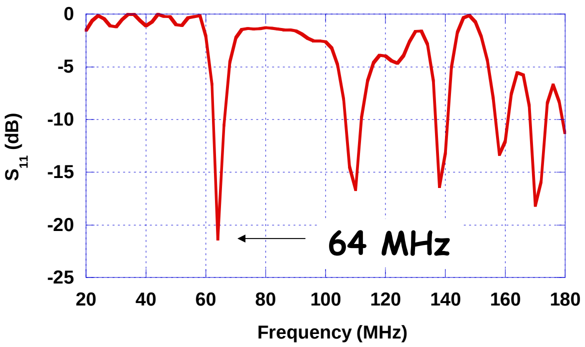




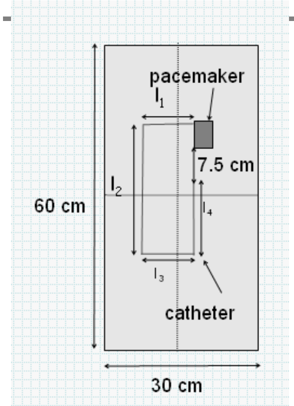
Birdcage and Box Model of the Thorax

The thorax is modeled as a dielectric box 30x20x60 cm^3
Electric constants $\varepsilon_r = 78.2$ $\sigma = 0.6$ S/m

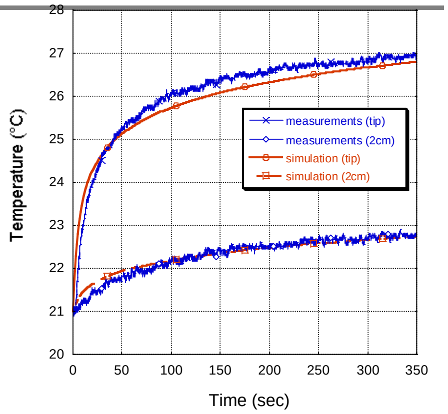




Birdcage, Thorax and PM Model



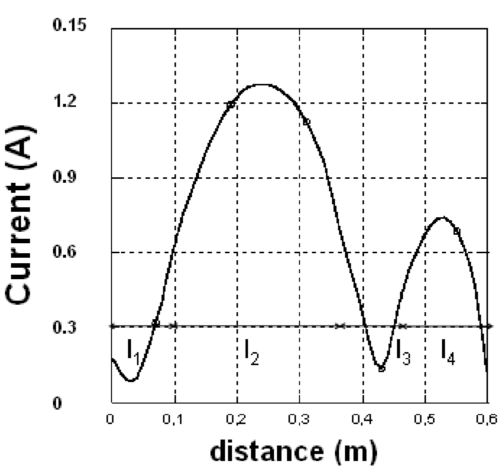
Section of the phantom model
1 cm below the phantom surface

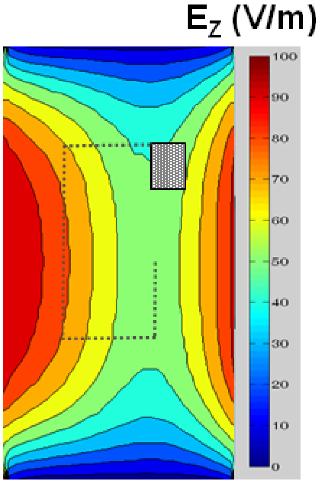


Radiated power 100 W at 64 MHz (SAR_{WB} = 1 W/kg) SAR_{PEAK}= 2400 W/kg

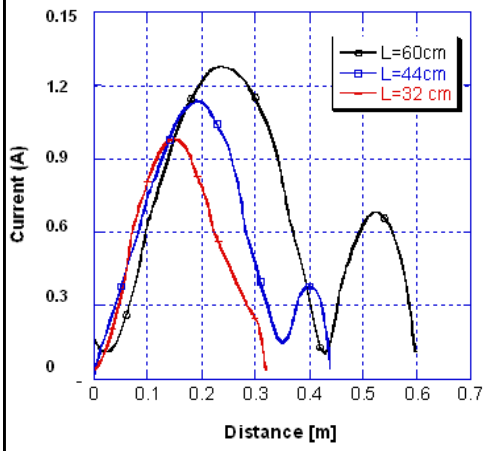
S. Pisa, G. Calcagnini, M. Cavagnaro, E. Piuzzi, E. Mattei, and P. Bernardi, "A study of the interaction between implanted pacemakers and the radio-frequency field produced by magnetic resonance imaging apparatus", *IEEE Trans. Electromag. Compat.*, vol. 50, no. 1, pp. 35-42, February 2008.

Current Along the Catheter





Influence of the Catheter Length



L = 60 cm -> SAR_{PEAK}= 2400 W/kg

L = 44 cm -> SAR_{PEAK}= 1400 W/kg

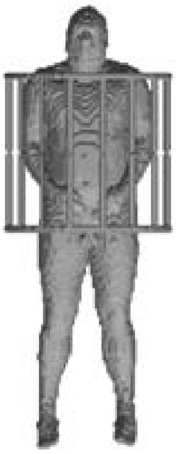
L = 32 cm -> SAR_{PEAK}= 1000 W/kg

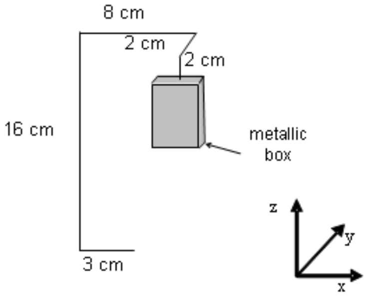
"NPAC Visible Human Viewer"

- Applet Java che consente di visualizzare le immagini fotografiche delle sezioni
- Le immagini originarie (sezioni orizzontali) sono state elaborate per ottenere anche le sezioni verticali. Si hanno quindi a disposizione sezioni assiali, sagittali e coronali

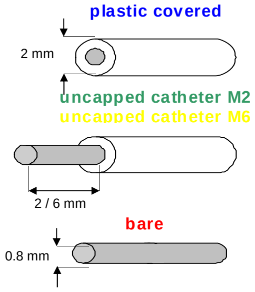
http://rockefeller.univ-lyon1.fr/ VisibleHumanProjectEnglish/ VisibleHuman.html

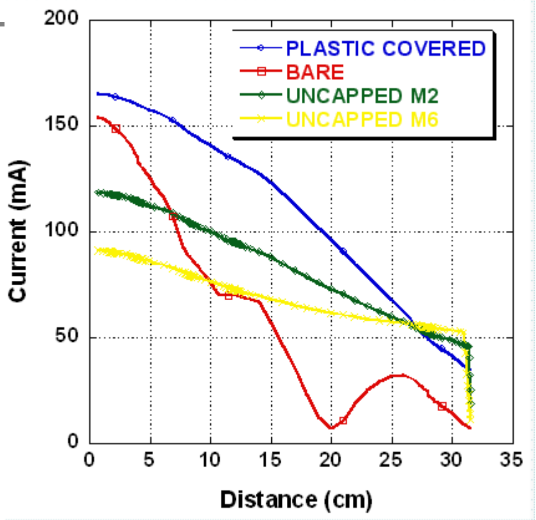
Birdcage and VH Model of the Thorax





Current Along the Catheter





S. Pisa, P. Bernardi, M. Cavagnaro, and E. Piuzzi, and, "Power Absorption and Temperature Elevation Produced by Magnetic Resonance Apparatus in the Thorax of Patients With Implanted Pacemakers ", *IEEE Trans. Electromag. Compat.*, vol. 54, no. 1, February 2010.

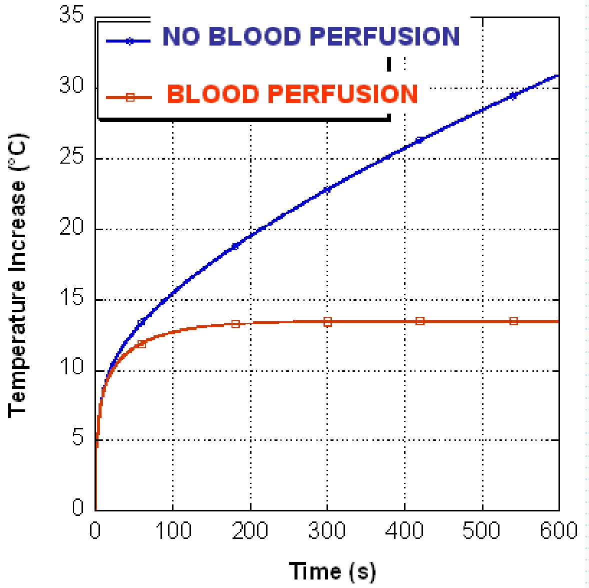
SAR and Temperature Results

	Bare	UC-M6	UC-M2	PC
SAR_1 [W/kg]	15	700	2400	11900
SAR_{10g} [W/kg]	5.6	5.6	7.9	9.8
SAR_{WB} [W/kg]	0.5	0.5	0.5	0.5

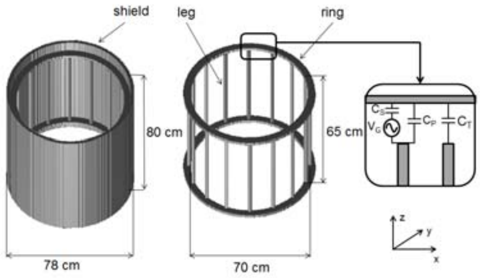
Temp. Increm.* [°C]	0.2	1.9	5.8	13.5

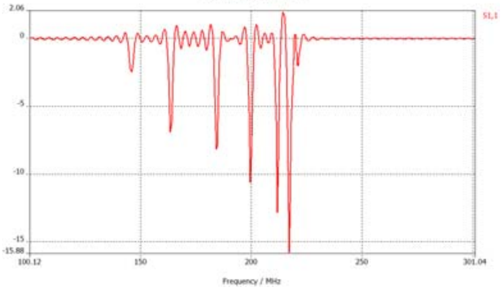
* After 10 min exposure and in the presence of blood perfusion

Tempertaure at the Cateter Tip



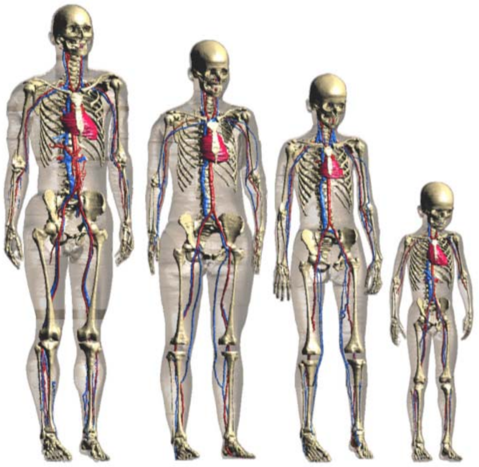
TEM Coils

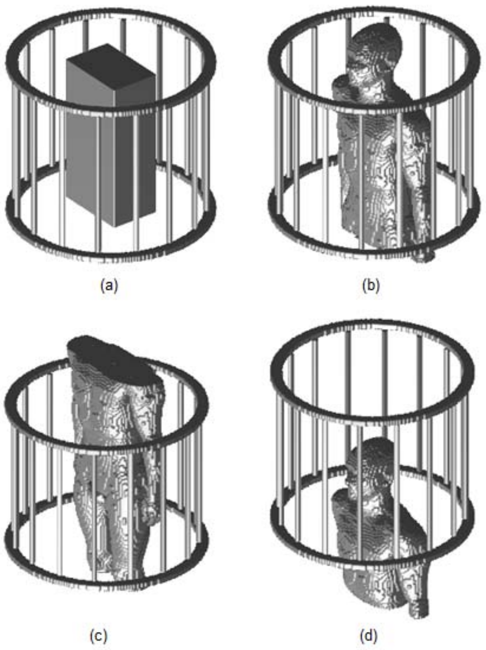




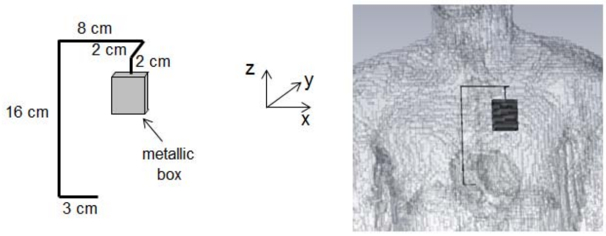
N/2 + 1
resonances

Virtual family

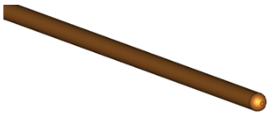




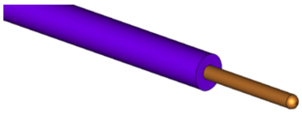
PM Implanted Inside Duke



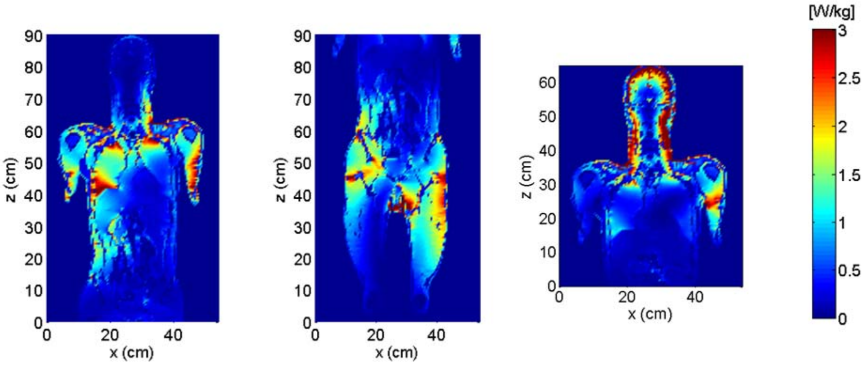
BARE



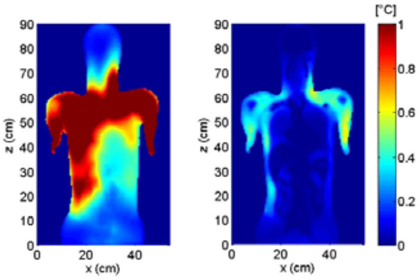
UC-6M

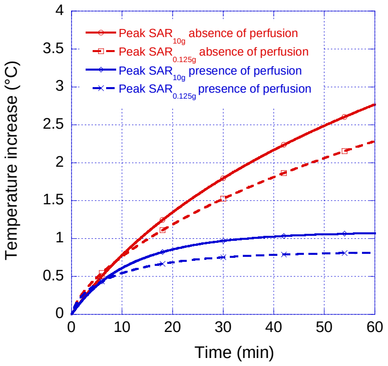


SAR Distribution Inside Duke

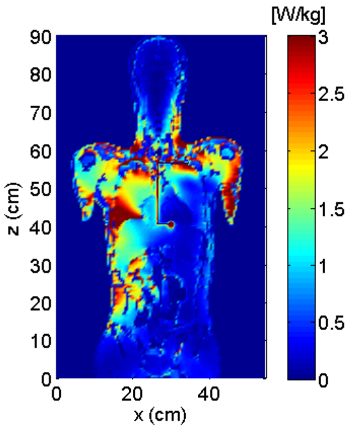


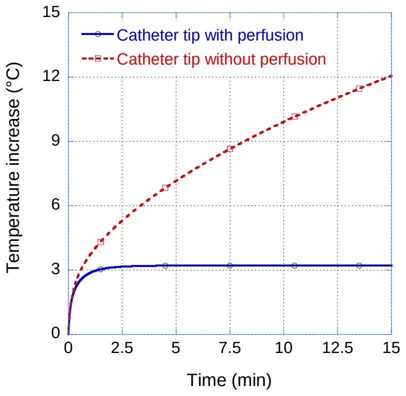
Temperature Distribution Inside Duke





SAR Distribution Inside Duke with pacemaker





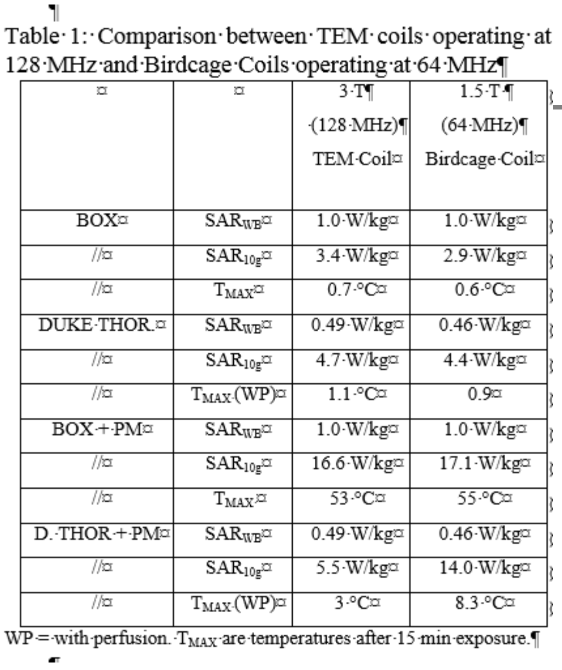


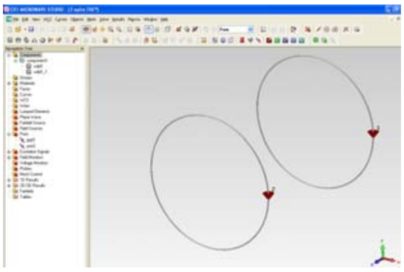
Table 1: Comparison between TEM coils operating at 128 MHz and Birdcage Coils operating at 64 MHz

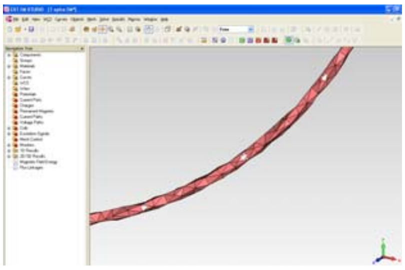
		3 T (128 MHz) TEM Coil	1.5 T (64 MHz) Birdcage Coil
BOX	SAR_{WB}	1.0 W/kg	1.0 W/kg
//	SAR_{10g}	3.4 W/kg	2.9 W/kg
//	T_{MAX}	0.7 °C	0.6 °C
DUKE THOR.	SAR_{WB}	0.49 W/kg	0.46 W/kg
//	SAR_{10g}	4.7 W/kg	4.4 W/kg
//	T_{MAX} (WP)	1.1 °C	0.9
BOX + PM	SAR_{WB}	1.0 W/kg	1.0 W/kg
//	SAR_{10g}	16.6 W/kg	17.1 W/kg
//	T_{MAX}	53 °C	55 °C
D. THOR + PM	SAR_{WB}	0.49 W/kg	0.46 W/kg
//	SAR_{10g}	5.5 W/kg	14.0 W/kg
//	T_{MAX} (WP)	3 °C	8.3 °C

WP = with perfusion. T_{MAX} are temperatures after 15 min exposure.

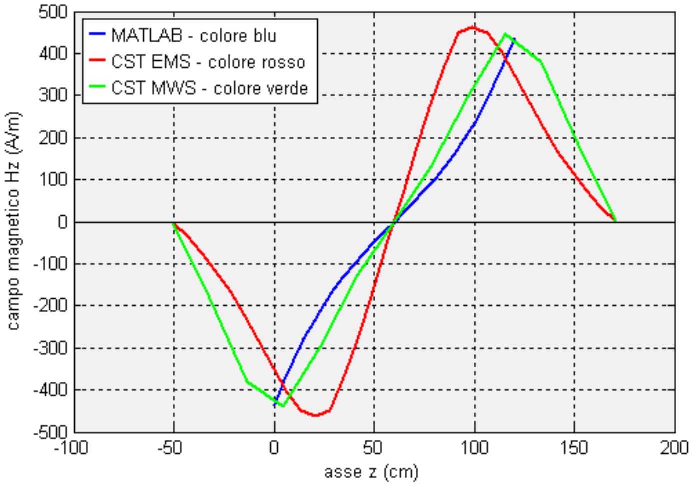
1.2 A/m and
1.6 A/m
at 128 MHz
and 64 MHz,
respectively

Maxwell coils

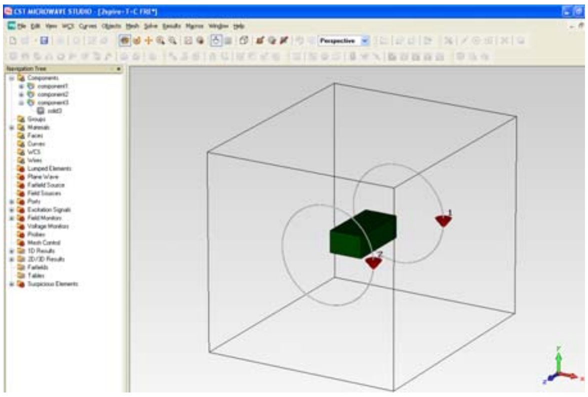




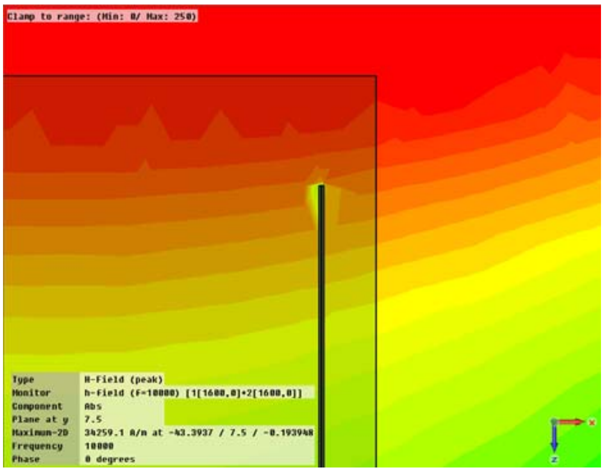
Magnetic field of Maxwell coils



Maxweel coils with the box

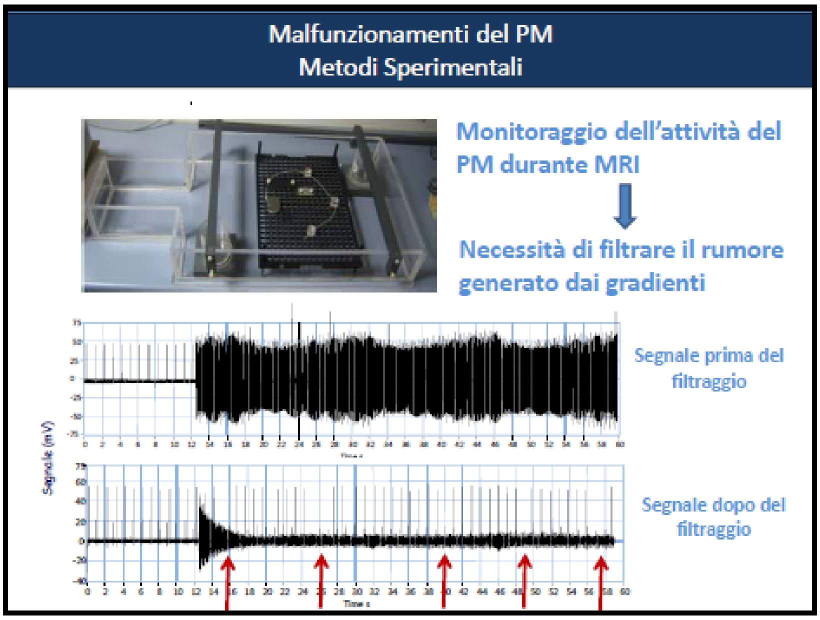


H-field Distribution Inside box with pacemaker



```
Clamp to range: (Min: 0/ Max: 250)
```

```
Type          H-Field (peak)
Monitor       h-Field (F=10000) [1[1600,0]+2[1600,0]]
Component     Abs
Plane at y    7.5
Maximum-2D    34259.1 A/m at -43.3937 / 7.5 / -0.193948
Frequency     10000
Phase         0 degrees
```



Malfunzionamenti del PM
Metodi Sperimentali

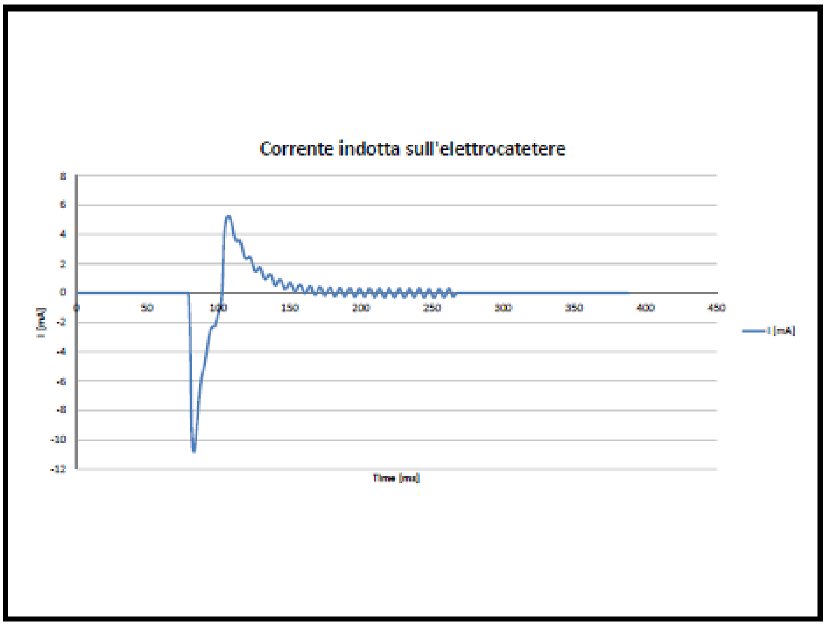
Monitoraggio dell'attività del PM durante MRI

⬇

Necessità di filtrare il rumore generato dai gradienti

Segnale prima del filtraggio

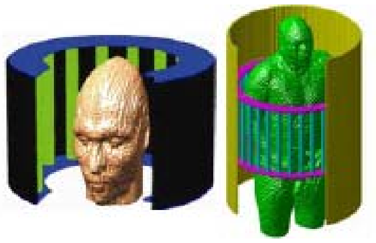
Segnale dopo del filtraggio



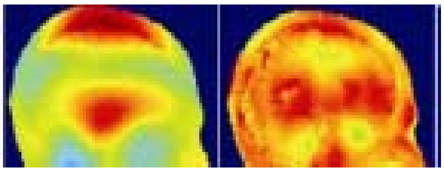
Corrente indotta sull'elettrocatetere

RF Systems for High-Field MRI: Problems and Possible Solutions Based on Computational Electromagnetics

Tamer S. Ibrahim[1,2], Roney Abraham[2], Lin Tang[2], and Doney Abraham[2]
[1]The University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[2]The University of Oklahoma, Norman, Oklahoma, USA



9.4 Tesla => 400 MHz



Standard ottimizzata

SAR Evaluation of Pregnant Woman Models in 64 MHz MRI Birdcage Coil

S. Shamsi, D.G. Wu, J. Chen, R. Liu
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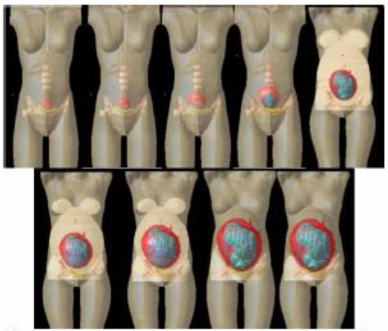

Fig. 3. Nine month pregnant woman models used in this investigation.

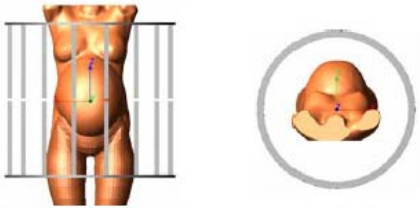

Fig. 4. Positioning of the 8 month model within the MRI RF coil.