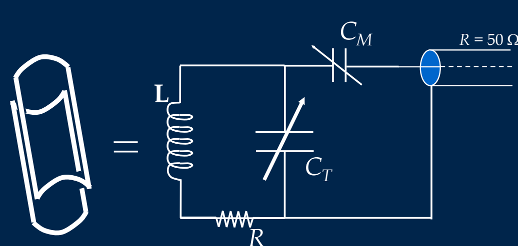
Introduction to MR Hardware

RF Coils

Dominik v. Elverfeldt

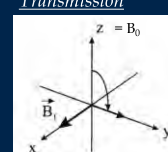
Sep 5th 2012



$\omega = \gamma * B_0$

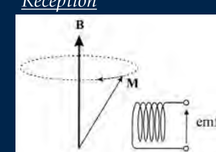
$\omega = \frac{1}{\sqrt{L \cdot C_T}}$

Transmission



- Oscillating with Lamor frequency ω.
- B_1 – field perpendicular to M
- $\alpha = -\gamma * B_1 * t_{pulse}$
  e.g. 90°, 100µs ➔ ~10^{-4} T
- ~ W - kW

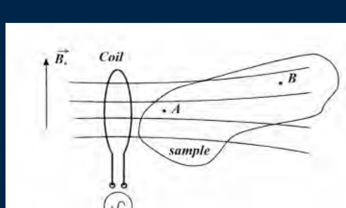
Reception



- Rotating magnetization produces alternating magnetic field
- Induces electromotive force (emf): principle of induction
  $U_{ind} \sim \gamma B_0 * B_{1,xy} * M_0$
- ~ µW - mW

Reciprocity Theorem

The sensitivity of a magnetic resonance assembly, used as a receiver, to nuclides present at a point A is proportional to that assembly's efficiency, when used as a transmitter, to generate at that same location A a radiofrequency field B_1.



RF-coil requirements

- Low distortion of the B_0 field
- Mechanical stability
- Comfortable access to the sample
- Homogeneous B_1 field
- High SNR

SNR

Signal:

$U_{ind} \sim \gamma B_0 * B_{1,xy} * M_0$

Noise:

$U_{R,eff} = \sqrt{4 \cdot kT \cdot \Delta\nu \cdot R}$

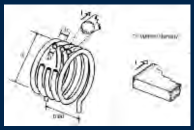
$R = R_{coil} + R_{object}$

$R_{coil} = R_{Johnson} + R_{skin} + R_{prox}$

$R_{object} = R_{mag} + R_{el}$

$R_{Johnson}$
- Brownian motion
- Heat dissipated

R_{skin}
- AC flows in a skin on the wiresurface
- Decrease of effective wire cross section
- Skin depth: $\delta \sim \omega_0^{-1/2}$



R_{prox}
- Crosstalk between close conductors through emf
- May increase R up to 10 times
- Coil geometry dependent

SNR

Signal:

$U_{ind} \sim \gamma B_0 * B_{1,xy} * M_0, \sim B_0^2$

Noise:

$U_{R,eff} = \sqrt{4 \cdot kT \cdot \Delta\nu \cdot R}$

$R = R_{coil} + R_{object}$

$R_{coil} = R_{Johnson} + R_{skin} + R_{prox}$

$R_{object} = R_{mag} + R_{el}$

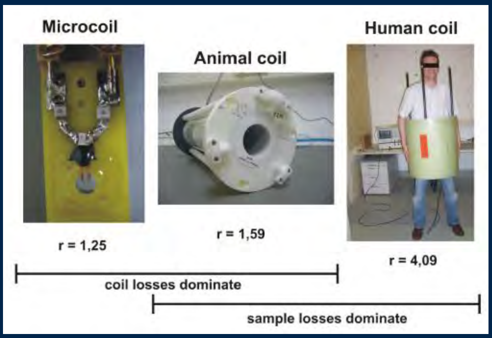
R_{mag}
- RF induces currents in conductive material
- Dissipated transmit power
- $R_{mag} \sim b^5$!
- Noise mechanism during reception
- Dominant effect for high fields and large samples

R_{el}

Near field:
- Dissipative displacement currents in dielectric media

Far Field
- Energy loss due to far field radiation
- Only for large coils at very high fields

R_{coil} vs R_{object}



Courtesy of Hans Weber, Freiburg

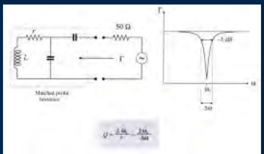
The quality factor Q

$$Q = 2\pi * \frac{\text{Energy stored in circuit}}{\text{Energy lost per cycle}} = L_{coil}\,\omega_0 \,/\, R = 2\omega_0 \,/\, \Delta\omega$$

→ Measure for resistive losses

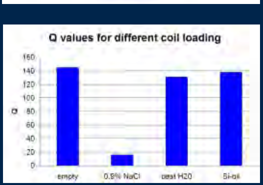
Via Network analyzer:

- S_{11} measurement



Relative contributions of loss mechanisms:

$Q_{\text{damping ratio}} = Q_{\text{unloaded}} / Q_{\text{loaded}}$



Coil Design

The ideal coil structure:

- Sphere with surface currents parallel to equator, sinusoidal ly modulated:

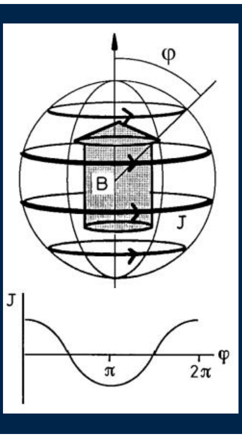
$$J(\varphi) \sim \sin\varphi$$

Drawbacks:

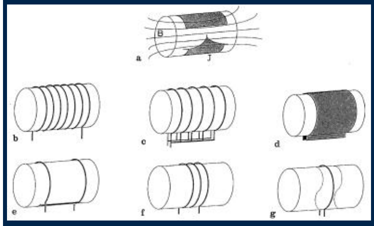
- Spherically limited sample shape
- Limited access to sensitive Volume

Better are cylindrical geometries with

- Longitudinal Fields
- Transversal Fields



Cylindrical desigs with longitudinal fields



a. Ideal longitud. B_1 field
b. Solenoid (if l >> r)
c. Parallel loops
d. Loop-gap-resonator
e. Helmholtz coil
f. Multi turn surface coil
g. Single turn surface coil

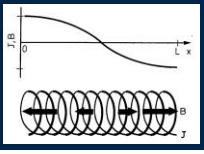
Drawbacks:

- Geometry conflicts

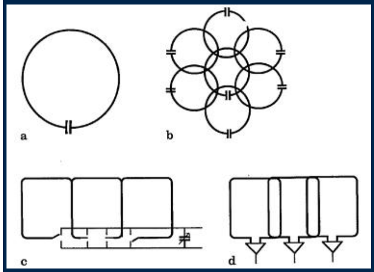
created field needs to be perpendicular to B0
→ limited access in biomedical applications

- Self- resonance

Standing wave effects, if the total solenoid length approaches the wavelength $\lambda = 2\pi c/\omega$.



Surface array coils

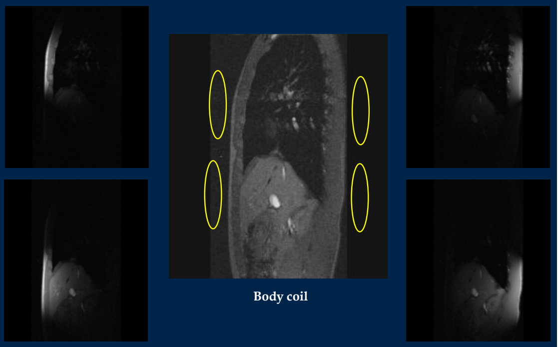


a. Single surface coil
b. Petal resonator
c. Switched-array coil
d. Phased-array coil

Advantages:

- Planar field of view adaptable to the region of interest
- Increased SNR
- Option for parallel imaging techniques

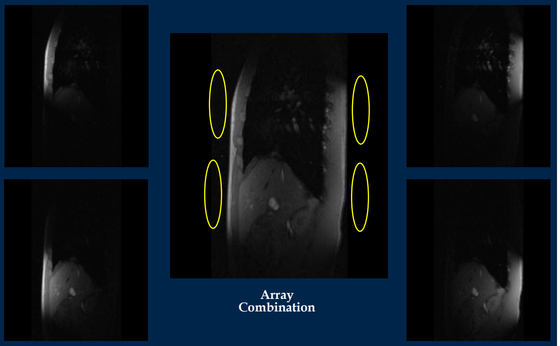
Phased array coils



Body coil

Courtesy of Michael Bock, Heidelberg + Freiburg

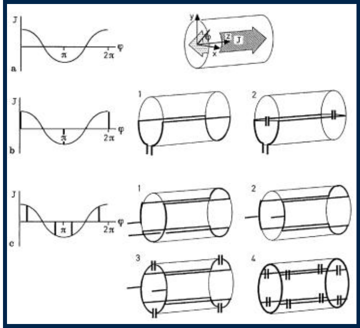
Phased array coils



Array Combination

Courtesy of Michael Bock, Heidelberg + Freiburg

Cylindrical designs with transversal fields I

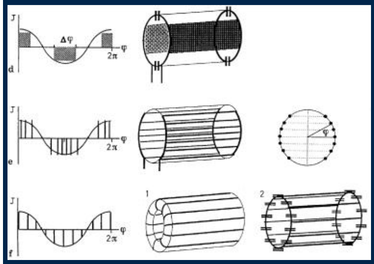


a. Ideal surface current
$\mathbf{J}=J_0 \cos \varphi \mathbf{z} \rightarrow \mathbf{B}_1=(0,B_1,0)$

b. Single loop
@ highest current density

c. Saddle resonator
Mimics ideal current distribution @ 6 positions.

Cylindrical designs with transversal fields II



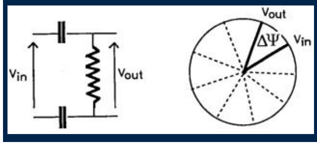
d. Alderman-Grant coil
e. Filament approx.
f. The Birdcage coil (2)

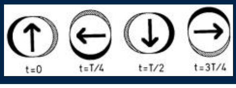
i) $\Delta\Psi(\omega)$

ii) $N*\Delta\Psi(\omega) = 2\pi$

iii) $J_n = J_0 \cos(\varphi_n - \omega t)$

iv) $\mathbf{B}_1=B_1(\sin \omega t, \cos \omega t, 0)$





Human RF - Coils

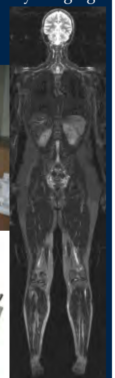
- Volume Coils

- Surface Coils

Courtesy of Michael Bock, Heidelberg + Freiburg

Human RF - Coils

- Whole Body Imaging
- PhasedArray - Head
- Phased Array Body



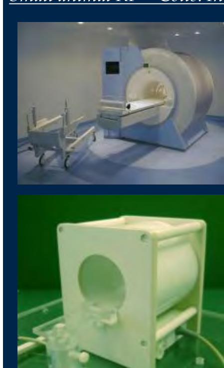
Courtesy of Michael Bock, Heidelberg + Freiburg

From Men to Mice

Volume/SNR – Reduction from ~(1mm)^3 to (100µm)^3 equals factor >100

Compensation: Higher B0 Fields, dedicated RF - coils

Small animal RF – Coils: In human MR-Systems



Advantages

- **Transferability of image contrast**
- **Usage of standard imaging protocols**
- **Large magnet bore**
  - **→ Multi animal scanning**
- Availability

Drawbacks

- Low SNR → high t_{acq}
- Weak gradients
- Low T2* contrast
- Hygiene
- High costs

Courtesy of Michael Bock, Heidelberg + Freiburg

Small animal RF – Coils: In human MR-Systems

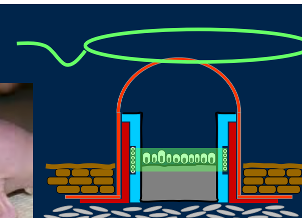
- Isotropic 3D-Imaging

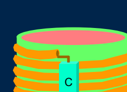
Courtesy of Michael Bock, Heidelberg + Freiburg

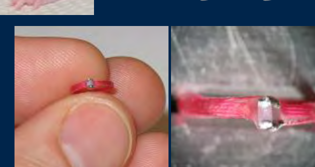
Common small animal RF - Coils

Special small animal RF - Coils

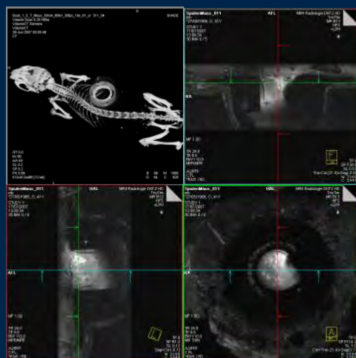
- Skin Chamber Coil







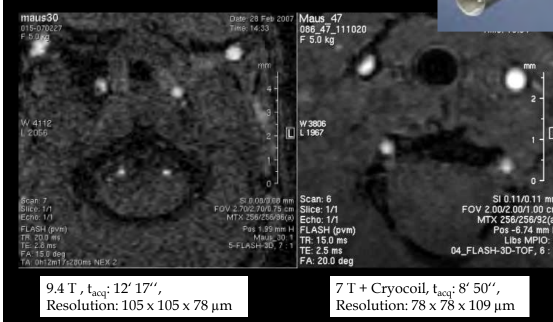
Bock M, et al. *European Patent Application 1 681 017 A1*



Courtesy of Michael Bock, Heidelberg + Freiburg

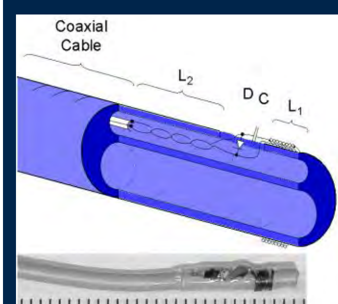
Special small animal RF - Coils

- Cryogenicly cooled surface array



Mircro Coils

- Catheter tracking



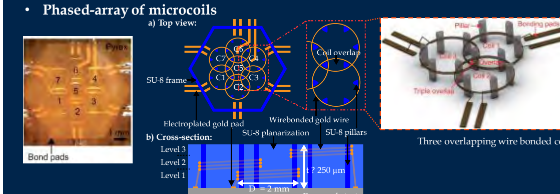
Zühlsdorff S, et al., Magn Reson Med 52: 214-218 (2004)

Mircro Coils

- **Planar single microcoil**

- **3D Micro-solenoids**

- **Phased-array of microcoils**

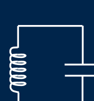


Courtesy of Oliver Gruschke + Vlad Badilita , Freiburg

Purchasing RF coils

- Surface coils
  5000 € - 15.000 €, depending on size and nuclei
- Volume resonators
  15.000 € - 25.000 €, depending on design
- Phased array coils
  35.000 € - 70.0000 €, depending on coil elements
- MRI CryoProbe
  255.000 € - 300.000 €, depending on field strength

What is an RF coil?

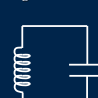


HF-Designer

Engineer

Vendor

Purchasing Dept.



Student

Patient

Operator

Courtesy of Michael Bock, Heidelberg + Freiburg

Suggested literature on basics of MRI RF coils

- Link J, "The design of radiofrequency probes with homogeneous radiofrequency fields."
  NMR Basic Principles and Progress, Vol. 26 1992

- Hoult DI, "Signal to noise ratio of nuclear magnetic resonance experiment"
  Journal of Magnetic Resonance, Vol. 24, 1976

- Hoult DI, "NMR receiver – description and analysis of design"
  Journal of Magnetic Resonance, Vol. 12, 1978

WMIC 2012 Dublin,
Wed. 5th of September, D. Elverfeldt:
"Introduction on MRI Hardware, RF Coils"