MRI Hardware – Magnet, Gradient, RF Coils

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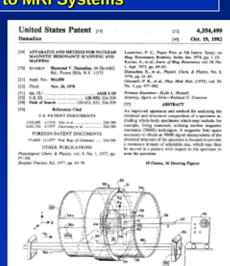
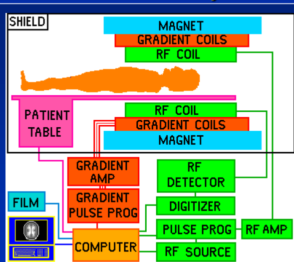
Outline

- Introduction to MRI Systems
- Static Magnetic Field
  - Permanent magnets
  - Resistive magnets
  - Superconductive magnets
- Gradient Coils
  - Gradient coil design and functionality
- RF Coils
  - Transmit-receive coils
  - Receive-only coils and arrays

Introduction to MRI Systems



Introduction to MRI Systems



JP Hornak, Ph.D., The Basics of MRI, http://www.cis.rit.edu/htbooks/mri/

Permanent Magnets

Permanent Magnet (up to 0.4T)

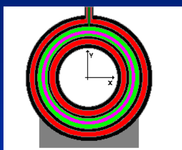
- ✓ Open configuration
- ✓ No cryogen for cooling
- ✓ Inexpensive to run: low initial cost, low operating cost
- ✓ Poor homogeneity of the field
- ✓ Magnet cannot be switched off
- ✓ Heavy weight, some more than 100 tons

Resistive Magnets

Resistive Magnets (up to 0.7T)

- ✓ Ability to turn off the magnet in case of emergency
- ✓ Better confined fringe fields
- ✓ Low initial cost
- ✓ Poor homogeneity of the field, requires high temperature stability
- ✓ High operating cost: large currents and necessity of cooling of coils

Superconductive Magnets



- Vacuum
- Liquid Helium
- Liquid Nitrogen
- Container & Support
- Superconducting Coil

- Superconducting coil is kept at a temperature of 4.2K
- The coil and liquid helium is kept in a large Dewar
- Dewar is surrounded by liquid nitrogen at a temperature of 77.4K in a larger Dewar cylinder

Superconductive Magnets

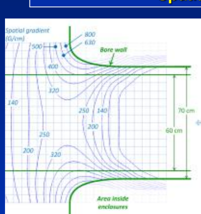
✓Higher field strength, most commonly used 1.5T and 3.0T

✓Better homogeneity of the field (about 1 ppm in 40 cm^3)

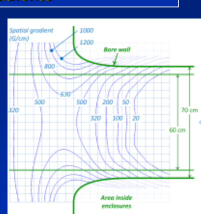
✓Initial high capital costs (siting), cryogen costs

✓Difficult to turn off the magnet (need to quench the magnet in case of emergency), potential of spontaneous quenching

Spatial Gradients



1.5 T



3.0 T

GE Healthcare, Waukesha, WI

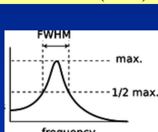
Magnetic Field Homogeneity

- The uniformity of the main magnetic field strength B_0 over a designated volume.
- Sources of inhomogenities:
  - ✓ imperfections in the magnet manufacturing
  - ✓ external ferromagnetic structures
  - ✓ presence of the patient within the field
- The most common problem caused by magnet inhomogenities:
  - ✓ difficulty in obtaining uniform fat suppression
  - ✓ geometrical distortion of images
  - ✓ increased severity of wrap up artifacts
  - ✓ compromised SNR

Magnetic Field Homogeneity

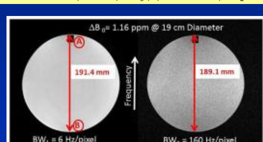
- Spectral Peak Option

$$FWHM(ppm) = \frac{FWHM(Hz)}{42.576\,(MHz/T) \cdot B0(T)}$$



- Bandwidth-Difference Option

$$\Delta B_0\ (ppm) = \frac{(BW_1 \times BW_2)\ x\ (d_1 - d_2)}{42.576(MHz/T) \times B_0(T)\ x\ FOVx \times (BW_2 - BW_1)}$$



Chen HH, Boykin RD, Clarke GD. Routine testing of magnetic field homogeneity on clinical MRI systems. Medical Physics. 2006;33:4299-4306.

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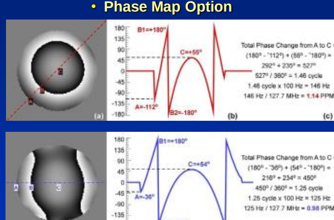
Magnetic Field Homogeneity

- Phase Map Option



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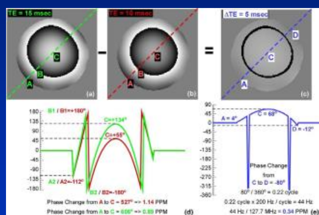
Magnetic Field Homogeneity

- Phase-Difference Map Option



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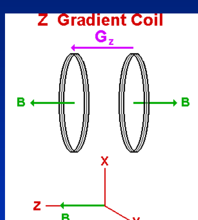
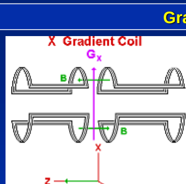
Gradient Coils

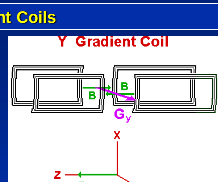


- Currents in two coils flow in opposite directions creating a magnetic field gradient along the Z-direction
- The B-field at one coil adds to B_0-field and the B-field at other coil subtracts from B_0-field

JP Hornak, Ph.D., The Basics of MRI, http://www.cis.rit.edu/htbooks/mri/

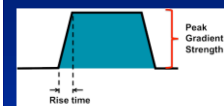
Gradient Coils





http://xrayphysics.com/spatial.html

Gradient Coils – Specifications



http://mri-q.com/gradient-specifications.html

- Gradient strength is typically expressed in mT/m or in G/cm
- Maximum Gradient Strength:
  - ✓ for 1.5T or 3.0T magnets, 30-80 mT/m
  - ✓ for lower fields, 15-25 mT/m

- Slew Rate = Peak Gradient Strength / Rise Time:
  - for 1.5T or 3.0T magnets, 120-200 T/m/s,
  - for lower fields, about 50 T/m/s

Gradient Coils

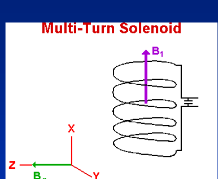
Gradient coil

http://hospitalequipmentservices.nl

Schematic diagram of a gradient coil

http://mriquestions.com

RF Coils



$$f = \frac{1}{2\pi\sqrt{LC}}$$

- RF coils create B_1-field which rotates net magnetization during transmission
- RF coils detect the transverse magnetization as it precesses in the XY-plane during the receive phase
- Types of RF coils
  - Transmit-receive coils
  - Transmit-only coils
  - Receive-only coils

RF Coils - Characteristics

- Coil must be properly tuned to the MR frequency in order to transmit or receive RF signals
- Electrical impedance of the coil must match the impedance of the transmitter or receiver electronics
- Q-factor measures the efficiency with which the coil converts an electrical signal into RF
- Filling factor indicates which fraction of a coil's sensitive volume is occupied by sample

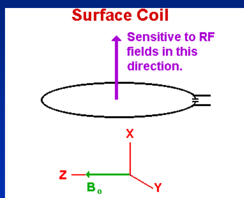
RF Coils - Transmitters

- Low-power component for generating pulsed alternating current signals with phase and amplitude modulation
- High-power component for amplifying low-level signal and coupling to transmitter coil
- MRI scanner uses 15-25 kW amplifiers
- Linearity and stability (minimal variation in gain) are extremely important characteristics of RF amplifier

RF Coils – Receivers

- Receiver chain amplifies the MR signal, filters and separates real and imaginary components, and digitizes for further processing
- Initial amplification occurs at the pre-amplifying stage at precession frequency
- Filters are set to ensure minimal attenuation within a selected spectral width

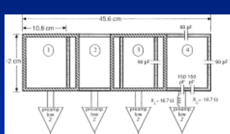
RF Coils – Surface Coils



JP Hornak, Ph.D., The Basics of MRI, http://www.cis.rit.edu/htbooks/mri/

- RF surface coils are receive-only coils
- Surface coils have high signal-to-noise ratio (SNR) for tissues adjacent to the coil
- Uniformity of these coils is low

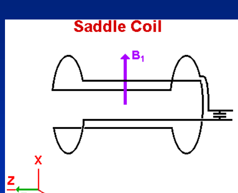
RF Coils – Phased Arrays



PB Roemer et al., MRM, 16, 192-225, 1990.

- Phased arrays simultaneously receive MR signal from multiple overlapping RF coils
- Increased SNR compared to that of the same size single element coil
- Parallel imaging applications with multichannel arrays

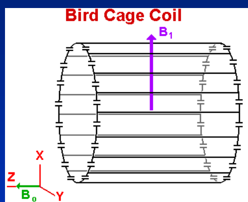
RF Coils – Saddle Coils



JP Hornak, Ph.D., The Basics of MRI, http://www.cis.rit.edu/htbooks/mri/

- Saddle and Helmholtz coils can be receive only and transmit-receive coils
- Uniformity of these coils is higher compared to the surface coils

RF Coils – Birdcage Coils



- Birdcage coils are transmit-receive coils
- Birdcage coils have higher uniformity compared to the surface coils

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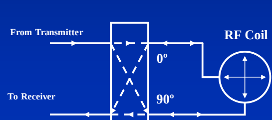
RF Coils – Birdcage Coils

- Current flows in a longitudinal direction, $I_Z = I_0 \cos\varphi$ creating a magnetic field in the transverse plane
- With the appropriate capacitors, the RF wavelength along this structure can be chosen to be equal to the circumference of the coil
- Linearly polarized B_1 field can be decomposed into two counter-rotating or circularly polarized components, i.e.

$$B = \hat{x} B1 \cos \omega t = \frac{1}{2} B1(\hat{x}\cos \omega t + \hat{y}\sin \omega t) + \frac{1}{2} B1(\hat{x}\cos \omega t - \hat{y}\sin \omega t)$$

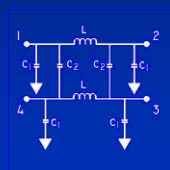
RF Coils – Birdcage Coils

- In linear mode, only one component, which rotates in the same direction as the spins, excites the magnetization. The other component is wasted.
- In quadrature mode, the RF coil produces a circularly polarized field by summing the two components.

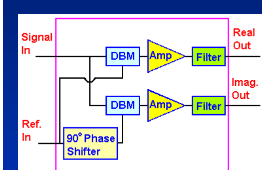


RF Coils – Birdcage Coils

- Quadrature drive is a power splitter with a 90º phase shift
- Converting a single unbalanced power source into two equal power sources



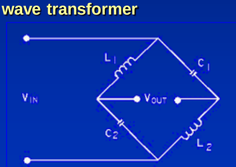
RF Coils – Birdcage Coils

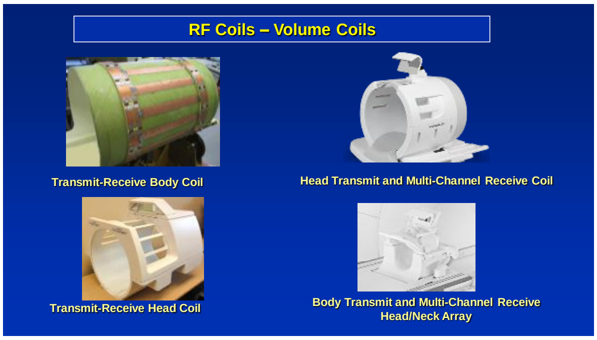


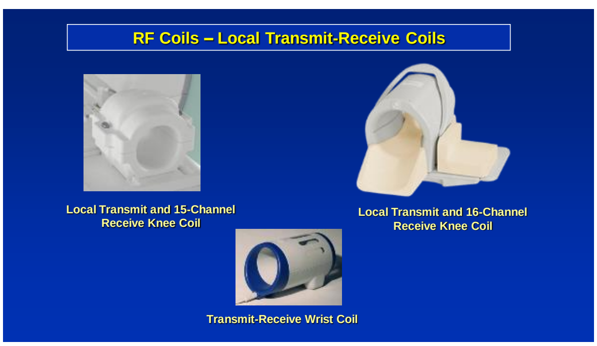
- Quadrature drive reduces power requirements by a factor of 2 (3dB): factor of √ 2 increase in SNR in the image.
- Quadrature excitation and detection can reduce some types of artifacts, caused by dielectric standing wave effects and conduction currents.

RF Coils – Birdcage Coils

- Balun is used for connecting the unbalanced drives to the balanced birdcage coil
- Basic bridge Balun circuit consists of 4 components and is based on a ¼ wave transformer

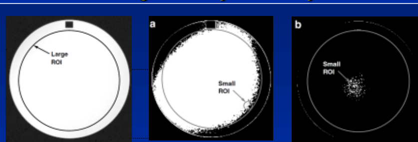



RF Coils – Volume Coils
Transmit-Receive Body Coil
Head Transmit and Multi-Channel Receive Coil
Transmit-Receive Head Coil
Body Transmit and Multi-Channel Receive Head/Neck Array


RF Coils – Local Transmit-Receive Coils
Local Transmit and 15-Channel Receive Knee Coil
Local Transmit and 16-Channel Receive Knee Coil
Transmit-Receive Wrist Coil


RF Coils – Receive Only (phased array) Coils
Body Array
Shoulder Array
Foot/Ankle Array
Body Array

Image Intensity Uniformity



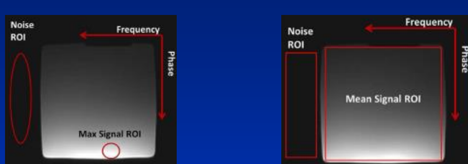
$PIU = 100 \times (1 - \{ (high - low)/(high + low) \})$

Percent Integral Uniformity (PIU) should be greater than or equal to:

- 87.5 % for systems less than 3.0T
- 82.0 % for systems with 3.0T

Large Phantom Test Guidance, ACR, 2005

Surface Coils – Signal-to-Noise Ratio (SNR)



$maxSNR = (Max\ Signal\ in\ Phantom)/\sigma_{air}$

$mean\ SNR = (Mean\ Signal\ in\ Phantom)/\sigma_{air}$

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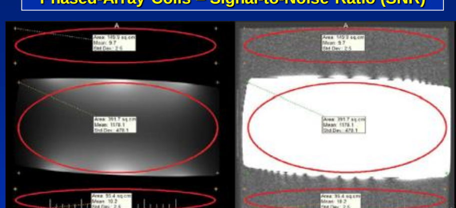
Phased-Array Coils – Signal-to-Noise Ratio (SNR)



$$SNR = (Mean\ Signal\ in\ Phantom)/\sigma_{air}$$

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Thank you !
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