4. Magnetic Resonance Imaging(3)

Lectures 21, 22

Medical Imaging Systems

Jae Gwan Kim

jaekim@gist.ac.kr , X 2220

Department of **B**io**M**edical **S**cience and **E**ngineering

Gwangju **I**nstitute of **S**ciences and **T**echnology

Copyright. Most figures/tables/texts in this lecture are from the textbook "Introduction to Medical Imaging: Physics, Engineering and Clinical Applications by Nadine Barrie Smith Andrew Webb 2011" and this material is only for those who take this class and cannot be distributed to anyone without the permission from the lecturer.

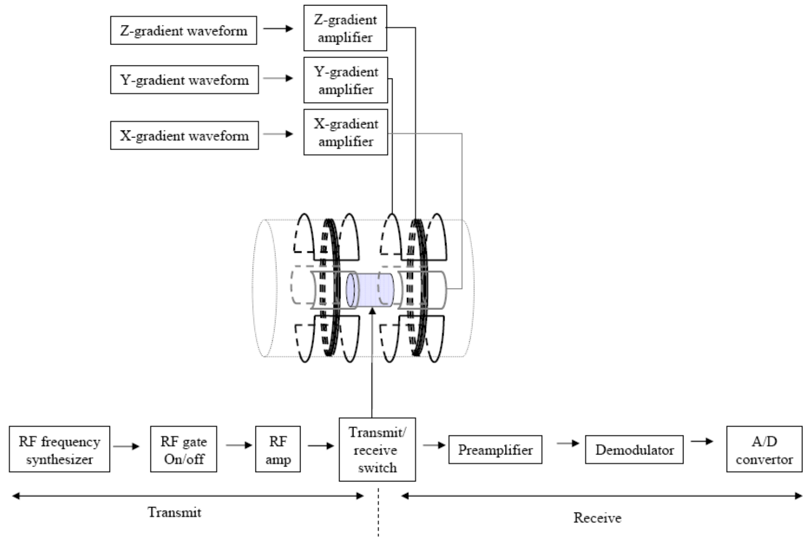
Contents

MRI INSTRUMENTATION

B_o Field

- Higher static field → greater polarization of the spins → more signal
- $B_o < 0.5T$: permanent magnets (large, heavy, but low maintenance)
- $0.5T < B_o < 2T$: electromagnets (large, heavy, consume high power during operations)
- $B_o > 2T$: superconducting magnets (large, heavy, expensive, require liquid nitrogen and helium cooling)
- B_o must be highly uniform

MRI system hardware components



Superconducting magnet design

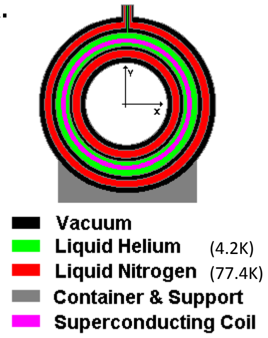
- Two major aims of magnet design
  1. To produce the most homogeneous magnetic field to have a longest T_2^* relaxation time
  2. To produce a stable magnetic field to minimize a drift during MR scanning
- The most common geometry is based on a solenoid
- At the center of solenoid, the magnetic field is

$$B = \frac{\mu_0 n I}{\sqrt{L^2 + 4R^2}}$$

where μ_0 is the permeability of free space (1.257 X 10^{-6} T/mA), n is the number of turns, I is the current, L is the length and R is the radius of solenoid

Superconducting magnet design

- The very high current (100~300A) produces a heat
- To minimize the heat, superconducting materials are used as a wire (ex: niobium-titanium alloy)
- Standard number of solenoids used in MR scanner is 6~10 to increase the homogeneity of magnetic field.
- The wires are wound in recessed slots in aluminum formers and are fixed in place using epoxy adhesive
- The entire windings are housed in a stainless steel can, called cryostat, which contains liquid helium (~4.2K)
- Vacuum vessels are used to minimize the liquid helium vaporization

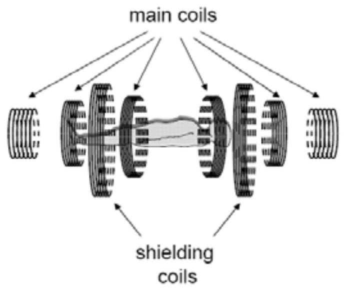


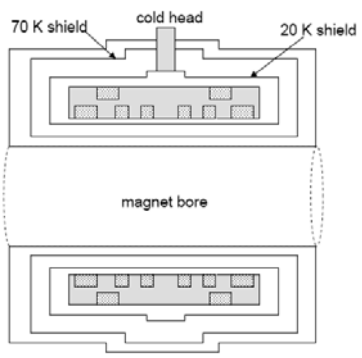
http://www.cis.rit.edu/htbooks/mri/chap-9/chap-9.htm

광주과학기술원

Superconducting magnet design

- Once the magnet is energized, the current is circulating the magnet even after the power source is removed due to superconductivity.
- Shim coils are used to have a fine tuning of magnetic field





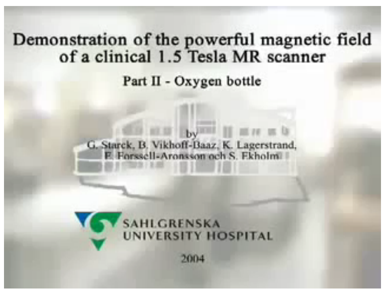
광주과학기술원

Superconducting magnet design

- Fringe field: magnetic fields outside of magnets is strong for MR scanner
- This can cause a dangerous case
  http://youtu.be/6BBx8BwLhqg
  http://youtu.be/plvIEf7JsKo

- To protect fringe field,
  - a secondary shielding coils are added to cancel the magnetic field or,
  - Annealed low carbon steel is added to the room to confine the stray magnetic field

Dangers of MRI

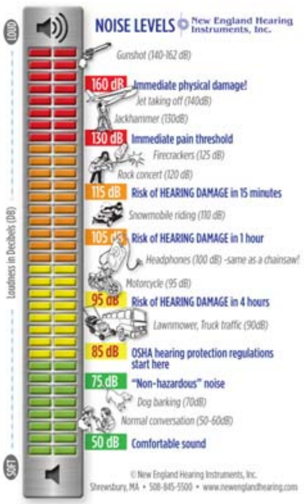


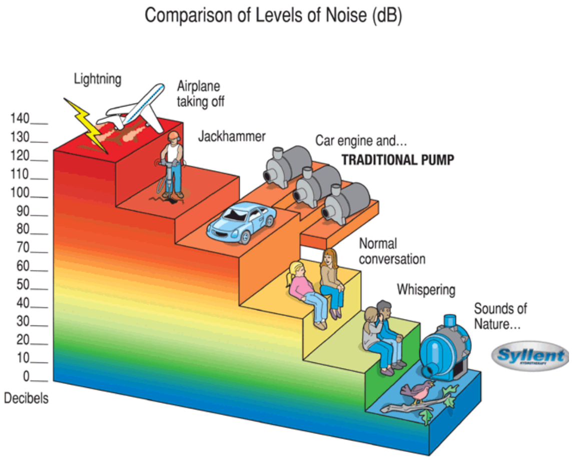
Magnetic field gradient coils

- The current (~hundreds A) from each amplifier can be switched on and off in less than 1 ms
- The gradient coils are copper cooled with water
- The loud sound of MRI scan is from the whole cylinder vibrating since the current passing the wire produces Lorenz forces within the magnetic field
- When the switch is on, there is an outward force all along the coil.
- the force on the coil goes from zero to huge in just milliseconds, causing the coil to expand slightly, which makes a loud "click"
- Therefore, an acoustic damping is used to minimize the noise, but the noise level is well above 100 dB

Magnetic field gradient coils

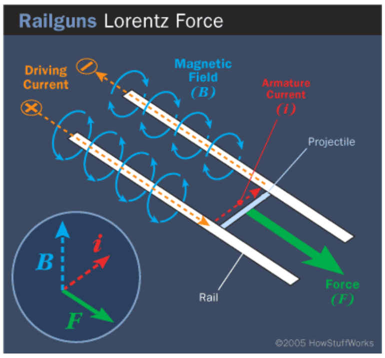
- Noise Levels





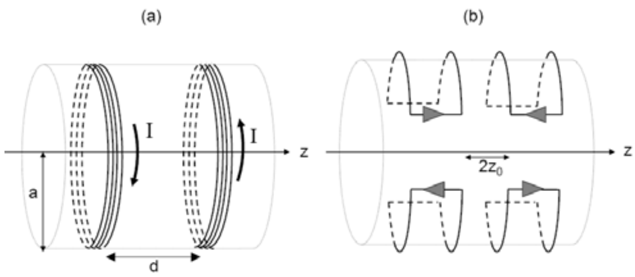
Magnetic field gradient coils

- Railgun Video
  http://youtu.be/xtD6NEmhEwk



Magnetic field gradient coils

- The aims of gradient coil design are
  1. To produce the max gradient per unit current
  2. To minimize the ‘rise’ time of the gradient
  3. To achieve the max volume of gradient linearity
- The simple design for z direction is Maxwell coil pair and for x or y direction is saddle geometry



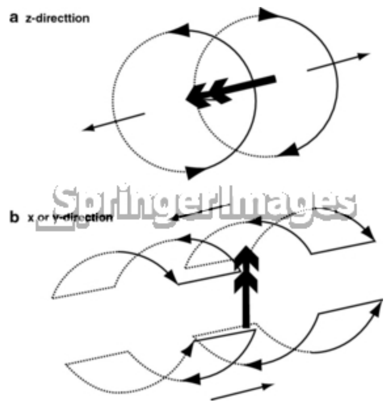
Magnetic field gradient coils

Fig 43 Two types of gradient coil used in the scanner.

(**a**) A Maxwell pair is used to vary the field in the z-direction.

(**b**) Two sets of Golay coils, one rotated at 90° from the other, are used to produce the x or y gradients.

The directions of the current (arrow), magnetic field (thin arrow), and gradient (double arrow) is shown in each case



http://www.springerimages.com/Images/MedicineAndPublicHealth/1-10.1007_978-1-84996-135-6_1-42

광주과학기술원

Magnetic field gradient coils

- Maxwell pair: consists of two loops
  - the loops are separated by √3 times the radius of each loop
  - The magnetic field is zero at the center
  - The gradient is linearly dependent on position in the z-direction over about 1/3 of the separation of the two loops
  - The gradient efficiency is
    $$\eta = \frac{8.058\ X\ 10^{-7} nI}{a^2} Tm^{-1}$$
    where n is the number of turns, I is the current, and a is the radius of loop

광주과학기술원

Magnetic field gradient coils

- Golay coil: each arc subtends an angle of 120°
  - The separation between the arcs along z axis = 0.8 x gradient coil radius
  - The length of each arc = 2.57 x gradient coil radius
  - The gradient efficiency is

$$\eta = \frac{9.18\ X\ 10^{-7} nI}{a^2} Tm^{-1}$$

where n is the number of turns, I is the current, and a is the radius of loop

광주과학기술원

Magnetic field gradient coils

- 3 criteria (homogeneity, switching speed and efficiency) of gradient coils can be expressed by so-called 'figure-of-merit'

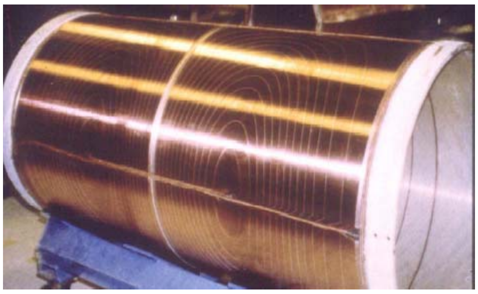
$$\beta = \frac{\eta^2}{L\sqrt{\frac{1}{V}\int\left(\frac{B(r)}{B_0(r)} - 1\right)^2 d^3r}}$$

Where L is the inductance of the coil, $B_0(r)$ is the 'desired' magnetic field and $B(r)$ is the actual magnetic field, V is the volume of interest over which the integral is evaluated, and d is the separation between two coils.

광주과학기술원

Magnetic field gradient coils

- A fingerprint gradient set, used to produce a y-gradient



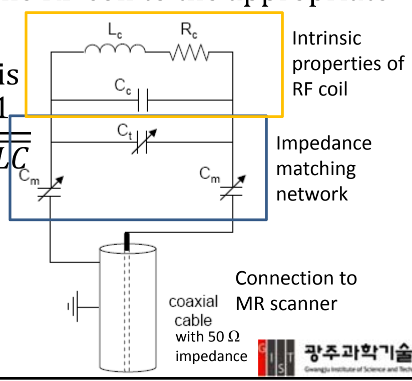
Radiofrequency coils

- RF coil has dual role:
  1. Transmit RF pulses
  2. Detect precessing magnetization

  Either single coil or separate coils are being used
- The 'LC' circuit is used to tune the RF coil to the appropriate frequency
- The resonant frequency of 'LC' is

$$\omega_{res} \approx \frac{1}{\sqrt{LC}}$$

- The highest efficiency can be obtained by matching the size of RF coil to the size of objects to be imaged



Radiofrequency coils

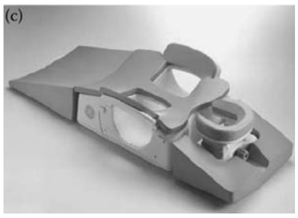
- In most systems, a large cylindrical body coil is integrated into the MRI system inside of gradient coils→ used to image abdominal parts
- For smaller parts (knee, head, and etc.), a smaller cylindrical RF coil is used as shown below

(a)

Knee coil for a 3T MRI

(b)

Head coil for fMRI



Breast coil

Radiofrequency coils

- On the receive side, the MR signal detected is of the order of several tens of μV ~ a few mV.
- Noise is mainly from the resistance of the body which produces random voltages
- Coil array: a large number of smaller more sensitive coils to cover the region of interest → each coil is closer to the body, but pick up less noise since the noise is from smaller part of the body

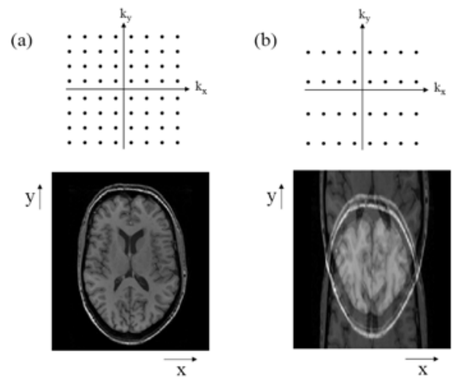
A large perivascular array that has 24 separate receive coils. Each element is electrically decoupled from the other elements.

Receiver design

1. Acquire the small voltages (XXμV~XmV)
2. Preamplified
3. Demodulated to a lower frequency (63.9MHz at 1.5T →10.7MHz)
4. Digitized at 80MHz with 14bit resolution
5. This bandwidth is much higher than the actually required for the imaging experiment → oversampling advantages
6. Stored in memory
7. Inverse FFT
8. Magnitude MR image

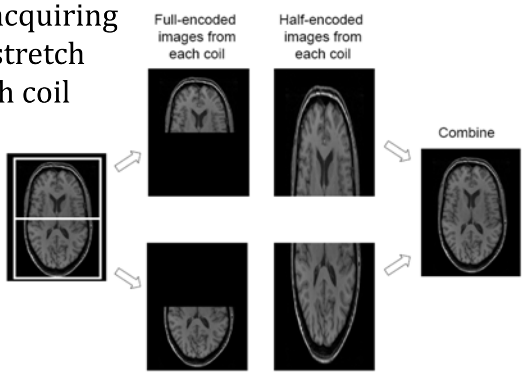
Parallel imaging using coil arrays

- Parallel imaging techniques: acquire only a certain fraction (1/4~1/2) of the k-space data to increase imaging speed with a given hardware setup (perhaps, this is the greatest technology breakthrough in the past ten years in MRI)
  → but this causes aliasing of the image



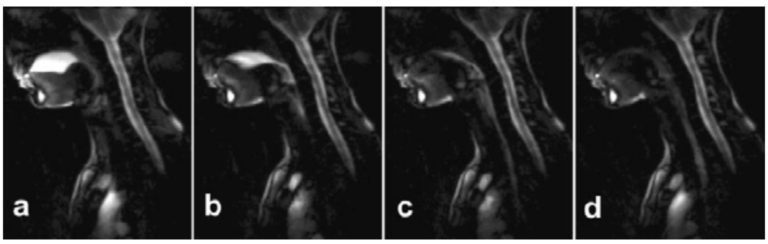
Parallel imaging using coil arrays

- In coil arrays, each coil receives the signal only from the closest part of the body
- For example, if there are two receiver coils, each of them sees only one half of the brain
- In this case, the effect of acquiring alternate lines in k_y is to stretch out the image in y for each coil
- But each coil sees only half of the full field of view in the y-dimension → no aliasing occurs
- Combine them together → faster acquisition



Parallel imaging using coil arrays

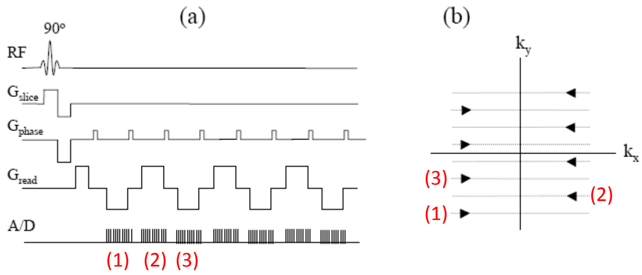
- The trade off in parallel imaging is between a fast acquisition and a reduced SNR
- However, in many clinical case, faster acquisition is required to minimize the motion artifacts

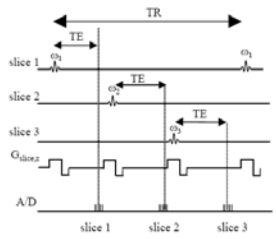


Successive images from a subject who is swallowing water (bright signal). Image acquisition was 4 times faster by using parallel imaging

Fast imaging sequences

- Multi slice gradient-echo sequences can acquire image data sets from the entire brain in tens of second
- However, there are some cases that even faster acquisition is required (diffusion tensor imaging, functional MRI)
- Echo planar imaging (EPI): acquire entire image with a single excitation pulse (a slice with 128 X 128 in less than 100ms)



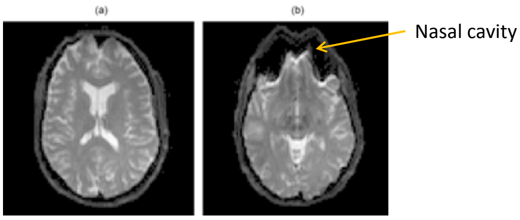


Multi slice gradient-echo

(a) Basic echo planar imaging sequence used for single-shot rapid MRI

Fast imaging sequences

- The major disadvantage of EPI sequence is the signal decays between each successive phase encoding step (in a very short T_2* such as at air/tissue interface)
  → blurring in the phase encoding direction when the image is reconstructed (see below figure)
- To minimize this effect, the EPI sequence is running in 'segmented-mode'
- For example, acquire only every fourth line in k-space then repeat the sequence four times to have a full k-space matrix



Fast imaging sequences

- The major drawback of EPI sequence is that the signal weighted by T_2* can be significantly distorted
- That can be reduced by using a spin-echo rather than gradient-echo sequence
- For fast acquisition, multiple spin echoes can be used → called a turbo spin echo (TSE) sequence
- Technically, it is possible to acquire 128 or 256 echoes which makes it possible to have an entire image in a single-shot
- However, 16 or 32 echoes are more common with 8 or 16 shots
- The major limitation of TSE sequence (especially at high magnetic fields) is the amount of energy deposited in the patient

Fast imaging sequences

- Turbo spin echo imaging sequence in which N_e echoes are acquired for each TR interval. This reduces the imaging acquisition time by a factor of N_e compared to a simple spin echo sequence.