Principles of Biomedical Systems & Devices

Lecture 22
Magnetic Resonance Imaging
Fundamentals of radiation imaging … nah…
X-ray …you already know this…
Computerized tomography …same thing as x-ray
Positron emission tomography …too complicated!
Ultrasonic imaging …you wish…
Magnetic resonance imaging …yes…yes..we will do this…!
The EM Spectrum

The Electromagnetic Spectrum

- Wavelength (in meters)
- Size of a wavelength
- Common name of wave
- Sources
- Frequency (waves per second)
- Energy of one photon (electron volts)
Magnetic resonance imaging (MRI) is a tomographic imaging technique that produces images of internal physical and chemical characteristics of an object from externally measured nuclear magnetic (NMR) resonance signals.

Tomography comes from tomos (τοµοσ) meaning cut in Greek.
- Graphical representation of different cuts of an internal structure
- Imaging of internal organs without cutting it open (!)

Among all other tomographic techniques, such as X-ray, CT-scan, PET scan, etc., MRI owes its popularity to its remarkable soft-tissue contrast.
- While many tomographic techniques can distinguish soft tissue from hard tissue (such as X-ray, CT), only MRI has an exceptional ability to distinguish different types of soft tissue from each other.
MRI Machines
MRI - An Overview

☞ **M is for Magnetic:**

☞ MRI exploits the induced nuclear magnetism in the patient, where materials with odd number of protons (such as H) possess a weak but observable nuclear magnetic moment, when placed in large magnetic fields.

☞ **R is for Resonance:**

☞ The protons naturally precess (spins) on an axis, which are randomly oriented. The orientation of these spins line up when the protons are subject to a large magnetic field. Protons that are lined up can be knocked out of this alignment when they are hit with an RF pulse at their resonance frequency.

☞ **I is for Imaging:**

☞ When the RF pulse is removed, the protons return to their previous alignment over a period of time. The time required for realigning (relaxation time) depends in part to the tissue. Different tissues have different relaxation times. The relaxation time of different tissues can be plotted creating an image, which is known as the MRI.
Felix Bloch and Edward Purcell discovered the NMR phenomenon in 1946, and awarded the Nobel price in 1952 for their discovery.

1950 ~ 1970 NMR was used for displaying molecular structures

In 1971 Raymond Damadian showed that the nuclear magnetic relaxation times of tissues and tumors differed, thus motivating scientists to consider magnetic resonance for the detection of disease.

In 1975 Richard Ernst proposed magnetic resonance imaging using phase and frequency encoding, and the Fourier Transform. This technique is the basis of current MRI techniques.

In 1977, Raymond Damadian demonstrated MRI of the whole body.

In 1993 functional MRI (fMRI) was developed. This technique allows the mapping of the function of the various regions of the human brain.
Magnetism

The largest component of the MRI machine is a magnet that creates large magnetic fields

- Current MRI machines create a magnetic field of 0.2 ~ 2 T (Tesla). 1.5 ~ 2 T is about the strength of the magnets used in car junk yards.
- 1 Tesla = 10000 Gauss
- Earth’s magnetic field: 0.5 Gauss (!)
Due to large magnetic fields, metal objects are not allowed in the scan room

- Paperclips, pens, keys, scissors, hemostats, stethoscopes and any other small objects can be pulled out of pockets and off the body without warning, fly toward the opening of the magnet (where the patient is placed) at very high speeds, posing a threat to everyone in the room.

- Mop buckets, vacuum cleaners, IV poles, patient stretchers, oxygen tanks, heart monitors, even a fully loaded pallet jack have been sucked into the bore of an MRI.

- People with pacemakers, aneurysm clips in the brain, certain dental implants, metallic fragments in the eye CANNOT be scanned using an MRI.
Beware of Magnetic Fields!

http://electronics.howstuffworks.com/mri2.htm
There are three basic types of magnets used in MRI systems

Resistive magnets consist of many windings or coils of wire wrapped around a cylinder or bore through which an electric current is passed. This causes a magnetic field to be generated.

- If the electricity is turned off, the magnetic field dies out.
- These magnets are lower in cost to construct than a superconducting magnet, but require huge amounts of electricity (up to 50 kilowatts) to operate because of the natural resistance in the wire.
- To operate this type of magnet above about the 0.3-tesla level would be prohibitively expensive.
The Magnets

Permanent magnet is just that -- permanent.

- Its magnetic field is always there and always on full strength, so it costs nothing to maintain the field.
- The major drawback is that these magnets are extremely heavy: They weigh many, many tons at the 0.4-tesla level.
- A stronger field would require a magnet too heavy to construct. Permanent magnets are getting smaller, but are still limited to low field strengths.

Superconducting magnets are by far the most commonly used, somewhat similar to a resistive magnet

- Coils or windings of wire through which a current of electricity is passed create the magnetic field. The important difference is that the wire is continually bathed in liquid helium (a cryogenic) at -270 °C (-452.4 °F).
- This almost unimaginable cold causes the resistance in the wire to drop to zero, reducing the electrical requirement for the system dramatically and making it much more economical to operate.
- Superconductive systems are still very expensive, but they can easily generate 0.5-tesla to 2.0-tesla fields, allowing for much higher-quality imaging.
The main magnet creates the static magnetic field $B_0$ which causes all Hydrogen protons to align along the direction of $B_0$.

Another type of magnet found in every MRI system is the **gradient magnet**. The main magnet immerses the patient in a **stable** and very intense magnetic field, while the gradient magnets create a **variable** field.

- There are three gradient magnets inside the MRI machine. The fields generated by these magnets are of very low strength compared to the main magnetic field; they may range in strength from 180 ~ 270 gauss, or 18 ~ 27 millitesla.

- These magnets are primarily used to produce deliberate variations in the main magnetic field ($B_0$). The variation in the magnetic field permits localization of image slices, as well as phase and frequency encoding.
The protons (of H atom) are all acting as little magnets (H atoms are particularly magnetic and abundant in the human body) each aligned in a different direction. When a large magnetic field is applied they all try to line up along the external magnetic field. However, instead of physically moving to line up with the magnet, they precess in that direction.

Precession is similar to what happens to a spinning top just before it falls over. The top wobbles towards the ground due to the force applied by gravity. In MRI it is the magnetic field that causes the wobble. In this case the wobble is towards the magnetic field, rather than towards the ground.

When not in a magnetic field, the H protons spin around their axis in randomly aligned directions. In a magnetic field, the protons line up along the axis of the magnet, with slightly more arranged in the direction of the field, $B_0$. 
Inside the bore (gantry) of the scanner, the magnetic field runs straight along the center of the tube in which the patient is placed.

- The hydrogen protons in patient’s body line up in the direction of either the feet or the head.
- The vast majority of these protons will cancel each other out -- that is, for each one lined up toward the feet, one toward the head will cancel it out. Only a couple of protons out of every million are not canceled out, as slightly more atoms will line up along the direction of $B_0$, then the opposite direction. This is because, aligning along the direction of $B_0$ requires slightly less energy.
- A couple in a million may not sound like many, but the sheer number of hydrogen atoms in the body gives a significant number of excess H atoms not cancelled out.
- These (unaccounted for) atoms create a net magnetization (nuclear moment) $M$, which is crucial in generating the MR image.
Then What Happens...?

The nuclear moment (magnetization) \( M \), created by the mismatched atoms is far too weak to be measured, because it is too small with respect to the applied static magnetic field.

- The ratio of induced nuclear magnetization to the applied field is around \( 4 \times 10^{-9} \) (!) (the collection of nuclear moments is often referred to as magnetization or spins).

This is where the ingenious discovery / invention of Bloch and Purcell (late 1940s) come into play.

- The idea is to measure the magnetic moment while it oscillates in a plane that is perpendicular to the static field, therefore, the effect of the large static field is avoided.
- However, this requires the moments to be tipped away from the static field, so that they line perpendicular to the \( B_0 \).
In order to tip the spin away from $B_0$, the MRI machine applies an RF pulse whose frequency is specific only to hydrogen.

The system directs the pulse toward the area of the body we want to examine (this is where gradient magnets come into play).

The RF pulse causes the protons in that area to absorb the energy, causing them to spin, (or precess), in a different direction, preferably away from $B_0$.

This is the "resonance" part of MRI. The RF pulse forces those protons (only the one or two extra unmatched protons per million) to spin at a particular frequency, in a particular direction.

The specific frequency of resonance (rotation / spin) is called the Larmor frequency and is calculated based on the particular tissue being imaged and the strength of the main magnetic field.

\[ \omega_0 = -\gamma B_0 \]

- **Larmor frequency**: Gyromagnetic ratio (constant specific to the nucleus).
- **Main magnetic field**: Strength (along $z$ direction).
An RF pulse of sufficient duration at the Larmour frequency to cause a 90° rotation in the magnetization is known as a 90-degree pulse.

A 180° pulse completely reverses the direction of magnetization.

When the hydrogen is subjected to the RF pulse at the Larmour frequency, the change in orientation of the magnetic axes causes the protons to jump to a higher energy state.

After the RF is switched off the protons gradually realign themselves along the external magnetic field. They achieve this by releasing the energy in the form of radio waves.
RF & Gradient Coils

- The RF pulses are usually applied through a coil. MRI machines come with many different coils designed for different parts of the body, which conform to the contour of the body part being imaged, or at least reside very close to it during the exam.

- This is where the three gradient magnets, aligned one in each of $x$, $y$, $z$ directions, jump into the act. They are arranged in such a manner inside the main magnet that when they are turned on and off very rapidly in a specific manner, they alter the main magnetic field on a very local level.

- This allows the MRI machine to pick the precise area to be scanned. In MRI terminology, these areas are referred to as slices, typically $3 \sim 10$ mm wide.

- We can "slice" any part of the body in any direction, giving us a significant advantage over any other imaging modalities.

- Unlike the CT imaging system, MRI machine need not be moved / rotated to get an image from a different direction. The MRI system can pick a specific location through a particular rapid sequence of time-dependent gradient fields created by the gradient magnets.
The rate at which gradient coils can be switched determines the imaging capabilities of the MRI system.

In a typical system, the gradient coils have a resistance of $1 \Omega$ and an inductance of $1 \text{mH}$, and the gradient field can be switched from 0 to $10 \text{ mT/m (1 Gauss/cm)}$ in about 0.5 ms.

This requires a current $I$ to be switched from 0 to about 100 A (!) in this interval (0.5 ms) \( \Rightarrow \) The instantaneous voltage induced on the coils, $L \frac{dI}{dt}$, is about 200V.

The power dissipation during this switching interval is about 20kW (equivalent to the total power of an actual radio station!), which puts a significant demand on the power system \( \Rightarrow \) Each gradient coil has its own power supply, controlled by the computer.
The RF coils are used to transmit and receive the signals at the resonant frequency of the H protons.

The Larmour frequency for H is 42.58 MHz/T. For whole body scanners with $B_0$ in the 0.2 ~ 4 T range, this corresponds to 0.85 ~ 170.3 MHz (which includes the range for TV signals – e.g. Channel 3 is 60-66 MHz).

The electronics for MRI transmitter / receiver closely resembles those in TV systems, the main difference is TV systems operate at far field of the RF waves, whereas MRI systems operate at near-field region.
Yes...yes...RF Coils...Whatever... but where is the D%^% image...?

Strong magnetization to align the H protons
RF signals to tip off the misaligned magnets
Gradient coils to pick a particular scanning area

Preparatory steps

When the RF pulse is turned off, the hydrogen protons slowly (relatively speaking) return to their natural alignment within the magnetic field and release their excess stored energy.

When they do this, they give off a signal from each point of the body being imaged that the RF coil picks up and sends to the computer system.

The frequency of this signal depends on the type of tissue and its position within the body (as well as factors kept constant during the scan, such as $B_0$).

The RF signal received by the coils generates an electric current, which is subsequently digitized by an analog-to-digital converter. What the system receives is mathematical data that is converted, through the use of a Fourier transform, into a picture that can be displayed. That is the "imaging" part of MRI.
The tremendous clinical utility of MRI is due to the various mechanisms through which contrast images can be created.

The primary mechanism through which contrast images are created is the relaxation of the magnetization.

There are two major types of relaxation, known as

- The spin-lattice relaxation, characterized by relaxation time $T_1$ and
- Spin-spin relaxation, characterized by relaxation time $T_2$.

Images created through these mechanisms are known as $T_1$-weighted image and $T_2$-weighted image, respectively.
The return of excited nuclei from the high energy state to the low energy or ground state is associated with loss of energy to the surrounding nuclei. Nuclear magnetic resonance was originally used to examine solids in the form of lattices, hence the name "spin-lattice" relaxation.

Spin-lattice relaxation describes the rate of recovery of the z-component of the magnetization $M$ toward equilibrium ($M_0$) after it has been disturbed by the RF pulses. The recovery is given by

$$M_z(t) = M_0(1 - e^{-t/T_1}) + M_z(0)e^{-t/T_1}$$

The $T_1$ relaxation time is the time for the magnetization to return to 63% of its original strength. After two $T_1$ times, the magnetization is at 86% of its original strength. Three $T_1$ times results in 95% recovery. Spins are considered completely relaxed after 3-5 $T_1$ times.
Different tissues exhibit different $T_1$ relaxation times, and the differences in these times are used to produce image contrasts by exciting all magnetization and then imaging before the full recovery. A $90^\circ$ RF pulse is used for initial displacement of protons.

The decaying signal sent out as the protons return to the Z-plane is measured over a time known as TR. Early measurement of this signal is required to differentiate between various tissues. To maximize $T_1$-contrast, a short TR sampling time must be used. In $T_1$ imaging you are measuring how the protons realign relative to the external magnetic field.
A 90° pulse is used in T₂ imaging, as in T₁. However, as the protons dephase, a 180° pulse is fired which puts them back in phase, for a second spin, hence the name spin-spin relaxation. After the second pulse is switched off, the protons again dephase.

Spin-spin relaxation describes the rate at which the magnetization in the transverse plane (x-y plane) decays after it has been created.

\[ M_{xy}(t) = M_{xy}(0) \cdot e^{-t/T_2} \]

T₂ relaxation occurs exponentially like T₁ relaxation, with 63% of the transverse magnetization gone after one T₂ period.

In a T₂ image we are looking to emphasize tissues which remain in phase for a long time and therefore maintain a strong signal. This can be achieved by delaying the sampling time after the 180° pulse (a time known as TE). To maximize T₂-contrast a long TE sampling time must be used. In T₂ imaging you are measuring how the protons realign relative to each other.
T$_1$ vs. T$_2$ Images

- T$_1$ and T$_2$ images of identical cranial slices of the same patient. Shorter T$_1$ and longer T$_2$ times appear brighter in the MRI images.

- Bright ring in T$_1$: subcutaneous fat with short T$_1$. White matter also has shorter T$_1$ than gray matter, hence shows up brighter.

- Bright deltas on T$_2$: CSF in the brain ventricles, which has long T$_2$, hence appear brighter. White matter has shorter T$_2$, than that of gray matter, therefore appears darker than gray matter.

In pure water, the T$_2$ and T$_1$ times are approximately the same, 2-3 seconds. In biological materials, the T$_2$ time is considerably shorter than the T$_1$ time. For CSF, T$_1$=1.9 s and T$_2$=0.25 s. For white matter in the brain, T$_1$=0.5 s and T$_2$=0.07 s (70 msec).

<table>
<thead>
<tr>
<th>Tissue</th>
<th>T$_1$ (ms)</th>
<th>T$_2$ (ms)</th>
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</thead>
<tbody>
<tr>
<td>Gray matter</td>
<td>520</td>
<td>95</td>
</tr>
<tr>
<td>White matter</td>
<td>380</td>
<td>85</td>
</tr>
<tr>
<td>Typical edema or infarction</td>
<td>600</td>
<td>150</td>
</tr>
<tr>
<td>Malignant tumor</td>
<td>800</td>
<td>200</td>
</tr>
<tr>
<td>Fat</td>
<td>160</td>
<td>100</td>
</tr>
<tr>
<td>CSF</td>
<td>2000</td>
<td>1000</td>
</tr>
</tbody>
</table>
$T_1$ vs. $T_2$ Images
## Advantages of MRI

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Non-ionizing radiation</strong></td>
<td>Because MRI does not ionize the tissue it is considered as one of the safest radiological techniques. There are no known physiological side effects of being exposed to a magnetic field.</td>
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<tr>
<td><strong>High soft-tissue contrast</strong></td>
<td>MRI images provide very detailed information about soft tissues. They can differentiate between normal and abnormal tissues and may show damage missed on CT.</td>
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<tr>
<td><strong>Images can be produced in any plane</strong></td>
<td>This is great value in studies of the Central Nervous System.</td>
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<tr>
<td><strong>Visualization of areas deep within bony structures</strong></td>
<td>MRI is thus invaluable for the diagnosis and treatment of brainstem tumors.</td>
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<tr>
<td><strong>Shows vasculature without contrast</strong></td>
<td>Because the patient is not subject to any invasive procedure (i.e. the injection of contrast media), the technique is less unpleasant.</td>
</tr>
<tr>
<td><strong>Good for angiography</strong></td>
<td>MRI is excellent for imaging blood flow and studying heart function. Functional MRI maps changes in blood flow in the brain during specific tasks. This provides valuable information about how the brain works.</td>
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<tr>
<td><strong>3D imaging</strong></td>
<td>Computer manipulation of the digital data can be used to produce exact three-dimensional images of organs. A further development is the production of perfect-replica models of organs using the digital information.</td>
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# Disadvantages of MRI

<table>
<thead>
<tr>
<th>Disadvantage</th>
<th>Details</th>
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<tbody>
<tr>
<td><strong>High cost of equipment</strong></td>
<td>An MRI scanner can cost over $2,400,000.</td>
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<tr>
<td><strong>Claustrophobia</strong></td>
<td>Up to 10% of patients experience claustrophobia during an MRI scan and 1% of scans have to be aborted because of it.</td>
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<tr>
<td><strong>Long imaging time</strong></td>
<td>A complete image may take up to 30min and movement at the wrong time can cause artifacts in the image. However, new techniques have reduced imaging time.</td>
</tr>
<tr>
<td><strong>Strong magnetic field</strong></td>
<td>MRI imaging is unsuitable for many patients with metal implants (e.g. artificial joints) and is especially dangerous for patients with pacemakers, neural stimulators, or cochleal implants. Loose metal objects must be removed before coming near to the scanner otherwise they may be attracted so strongly by the magnet that they fly through the air like tiny missiles!</td>
</tr>
<tr>
<td><strong>Unable to image calcium</strong></td>
<td>Because MRI detects water rather than molecular density, calcium is not well visualized. This means that tissue calcification, a feature of a number of disease processes, can not be detected. Bone is also less obvious than on a CT scan.</td>
</tr>
<tr>
<td><strong>Acoustic noise</strong></td>
<td>Switching on and off of the gradient coils causes repeated loud bangs. Noise levels may reach 95 dB for much of the scan. Ear plugs are advisable to reduce the risk of temporary or even permanent hearing loss.</td>
</tr>
<tr>
<td><strong>Various minor biological effects</strong></td>
<td>At high field strengths direct stimulation of muscles or nerves may be experienced. Some patients experience visual flashes (magnetophosphenes) produced by stimulation of the optic nerve. Although there are no known harmful effects on the fetus, scanning is avoided during pregnancy, especially during the first trimester, unless the alternatives are more dangerous (e.g. ionizing radiation).</td>
</tr>
</tbody>
</table>
References

- http://www.cis.rit.edu/htbooks/mri/
- http://electronics.howstuffworks.com/mri.htm
- J. Enderle, S. Blanchard, J. Bronzino, Introduction to Biomedical Engineering
- J. Bronzino (Ed.) The Biomedical Engineering Handbook
- J. Webster (ed.) Biomedical Instrumentation