MRSO Exam Prep Course

Module 6

Time-Varying Magnetic Field and Current Density

In the previous modules, we discussed the static magnetic field B_o, which is a constant low-frequency magnetic field. Contrary to the static magnetic field, the time-varying gradient magnetic field is constantly changing with high and low frequencies.

As stated previously, the purpose of the static magnetic field is to align the protons to the vector of the magnetic field. So, when our patient enters the MRI, our patient's protons will align to the vector of B_o. This establishes a baseline to which we can now begin to excite the protons utilizing the time-varying gradient magnetic field. By manipulating the protons in this way, we can measure the resulting change, which ultimately helps create the image we need. Now, let's talk about exciting the protons. How does the time-varying gradient magnetic field come into play?

Section 6.1 Time-Varying Magnetic Field

Gradient coils (or gradients) in MRI play a crucial role in the spatial encoding of the MR signal. Gradient coils consist of loops of wire or thin conductive sheets arranged on a cylindrical shell inside the bore of an MR scanner. There are three different gradient coils—one associated with each axis:

- **x-gradient coil, Golay coil**: right and left side of the patient
- **y-gradient coil, Golay coil**: front and back side of the patient (i.e. up and down)
- **z-gradient coil, Maxwell coil**: top and bottom of the patient (i.e. direction of table movement)

Image 6.1 below shows the three different gradient coils.

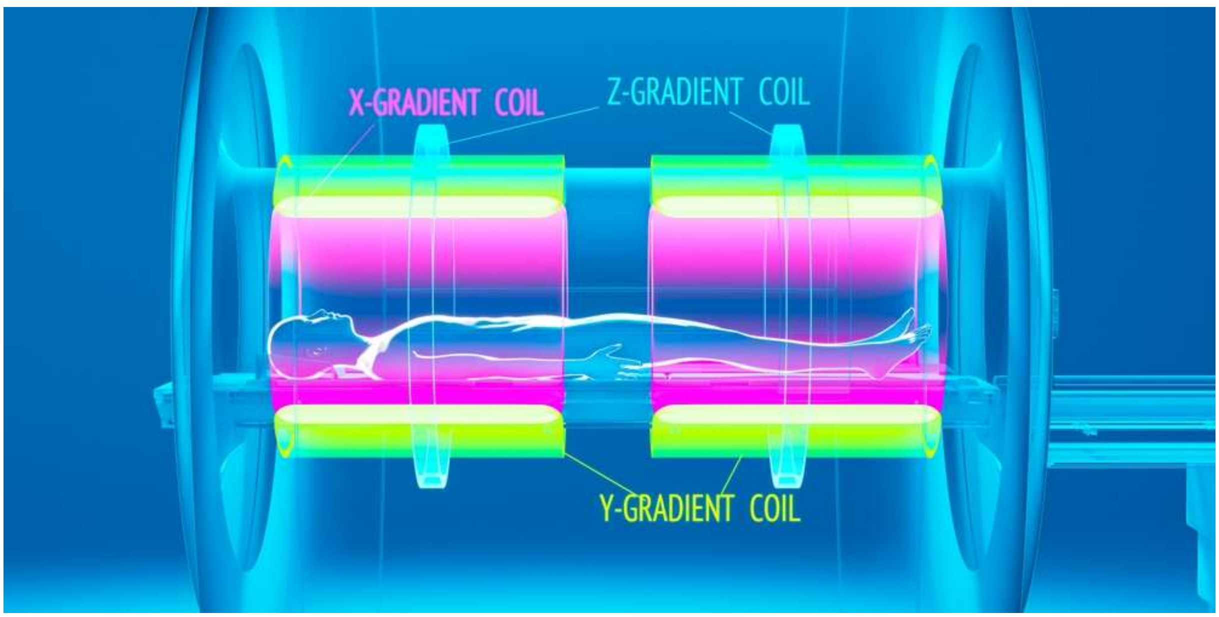

Image 6.1

These gradient coils apply a magnetic gradient that superimposes over the static magnetic field. A secondary magnetic field is generated when a current is passed through these coils, which slightly distorts the main magnetic field in a predictable pattern. This distortion causes the resonance frequency of protons to vary as a function of position, enabling spatial encoding of the MR signal. If the gradient is activated during slice selection and again during signal readout, a slice can be selected perpendicular to the gradient direction. For example, turning on the z-gradient in a specific fashion can create a transverse slice in a supine patient. Additionally, oblique slices can be obtained by simultaneously turning on two or more gradients.

Note that the pink x-gradient coil and the yellow y-gradient coil are perpendicular to each other inside the bore. This arrangement means that the opposing magnetic fields will eventually cancel each other out at the center of the bore. This area is known as the isocenter. The isocenter is a crucial area within the magnetic field created by a scanner. Technologically speaking, the isocenter is the center of the magnet. At this point, the magnet is the most homogeneous, the gradient fields are the most linear, and the large RF coils provide the strongest signal.

The term "homogeneous" refers to the uniformity of something. In the context of a magnetic field, homogeneity describes how consistent the magnetic field remains over its field of view. If homogeneity decreases at the edge of the magnet, the resulting image may be degraded or lose resolution.

The z-axis represents the direction along the bore of the magnet, The patient will lay on the gantry table along the z-axis. The two blue z-gradient coils also cancel each other out due to their opposing magnetic fields.

Note that the static magnetic field aligns with the z-axis (see Image 6.2). And when we apply electrical current through the gradient coils, a magnetic field is generated that superimposes over the static magnetic field.

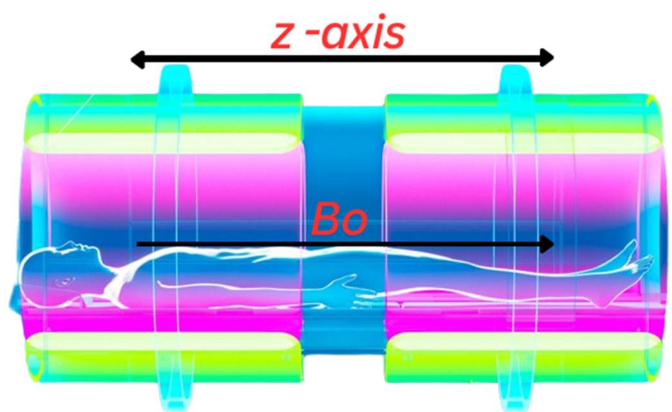

Image 6.2

For example, if we supply electricity *counterclockwise* through the z-coil near the patient's head, the resulting magnetic field will *oppose* the static field (see Image 6.3). Conversely, if we supply electricity *clockwise* through the z-coil near the patient's knees, the generated magnetic field will *add to* the static field. We determine this direction using the "right-hand rule." To apply the right-hand rule, curl your fingers in the direction of the current flow. Your thumb then points in the direction of the produced magnetic force.

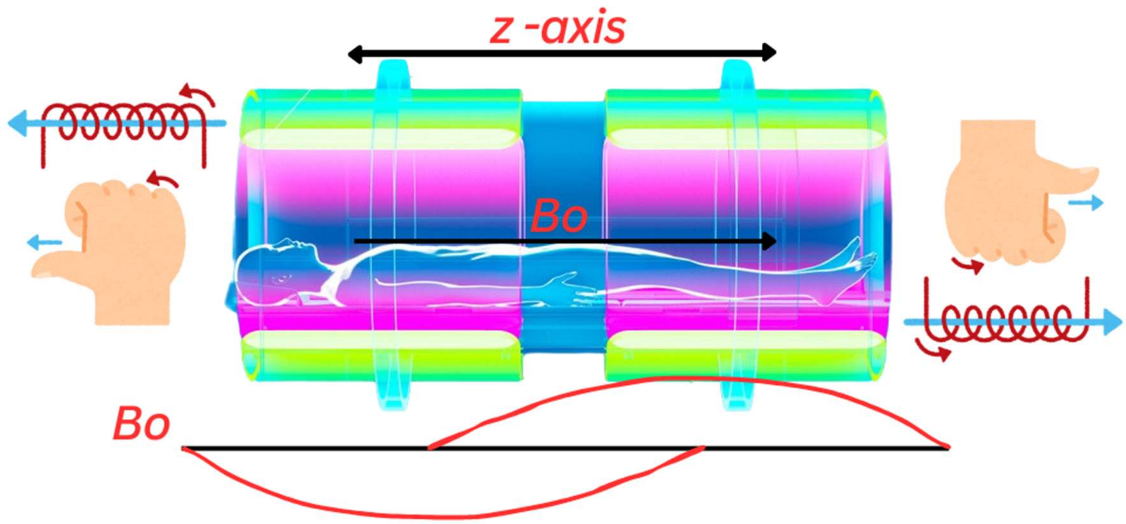

Image 6.3

Understanding dB/dt

When the gradient coils are activated, they rapidly switch on and off, generating an alternating magnetic field. According to Faraday's law of electromagnetic induction, this can create an electrical current in our patient. "dB/dt" represents the rate of change of a magnetic field over time, essentially signifying how quickly a magnetic field is changing at a given point. It is a measure of the time-varying magnetic field, where "dB" is the change in magnetic field strength and "dt" is the corresponding change in time. Understanding the concept of dB/dt is crucial for MRSOs and it plays a significant role in the development of technologies and safety protocols related to electromagnetic fields.

Key points about dB/dt:

1. Faraday's Law: A time-varying magnetic field induces an electric field according to Faraday's Law of Electromagnetic Induction. This law is fundamental to the understanding of electromagnetic induction and is widely used in various engineering and physics applications.
2. Units: dB/dt is typically measured in units like Tesla per second (T/s). This unit represents the rate of change of magnetic field strength over time and is commonly used in scientific and engineering contexts.
3. Application in MRI: dB/dt is particularly important as it relates to the strength of induced currents in the body during gradient switching. The rapid changes in magnetic field strength during MRI scans can potentially stimulate nerves if the rate of change is too high, leading to safety considerations and specific design requirements for MRI systems.

We can estimate the time-varying gradient magnetic field by measuring the change in the static magnetic field over a specific time. Recognizing that the time-varying gradient magnetic field takes precedence over the static magnetic field is crucial. In other words, the gradient magnetic field overlaps the static magnetic field. The gradient coils are positioned in the gantry around the patient, and when triggered, they enhance the magnetic field alternately on each side of the patient. This means that near the isocenter, the time-varying gradient magnetic field has minimal influence, while at the patient's periphery, the time-varying gradient magnetic field has a substantial effect.

Understanding dB/dx

Aside from knowing the change in the magnetic field over time, it is also important to know the change in the magnetic field over a certain distance. This is known as the magnetic spatial gradient and is denoted as dB/dx, where:

- dB = the change in the static magnetic flux
- dx = the change in distance

The spatial gradient magnetic field is the magnetic field that varies in intensity over a distance. The unit of measurement for the magnetic spatial gradient is Tesla per meter (T/m) or Gauss per centimeter (G/cm). Note: 1 T/m = 100 G/cm.

Image 6.4 shows how the MRI will behave (magnetically) at a certain distance around the room. This graph is known as the Magnetic Spatial Gradient Map. MRI manufacturers will provide this map to the user. It is an essential document, so the user knows how to design the room and operate around the MR unit. A 1.5T MRI will have a field strength of 1.5T at isocenter. The isocenter is located inside the bore of the scanner. The maximum magnetic spatial gradient will be located close to the bore entrance on all MRIs. According to the chart in Image 6.4, you will be exposed to the static magnetic field approximately 4 meters from the isocenter.

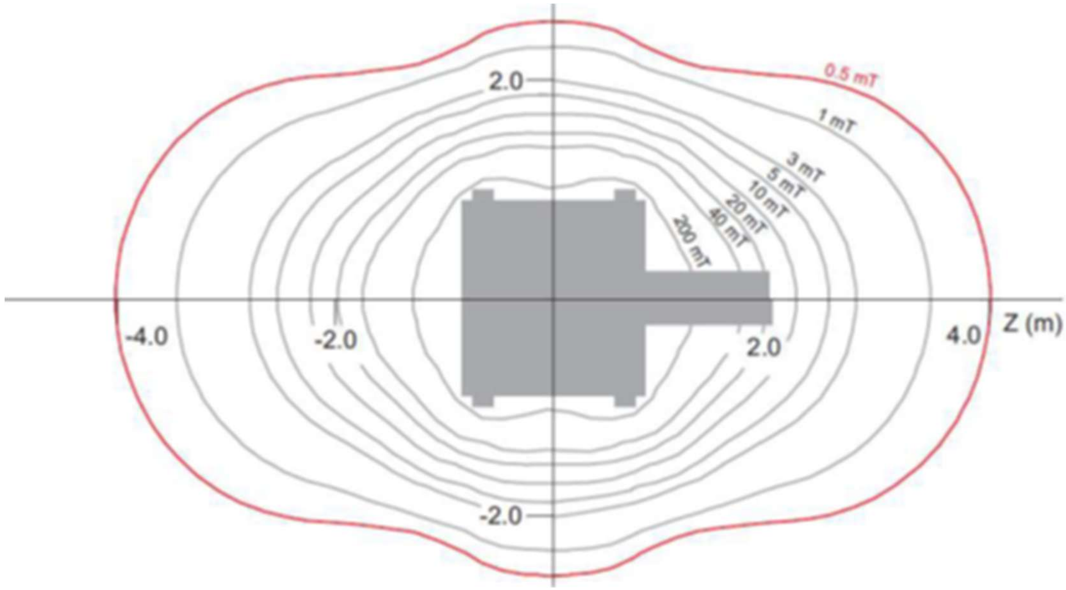

Image 6.4

Why is this important? These changes in the magnetic field strength as we move closer to the MR unit are called spatial magnetic gradients. The individual lines in Image 6.4 are called magnetic flux lines. These lines represent directional forces produced by the primary magnet, and these changes can impact MR unsafe (ferrous) objects and MR conditional (possibly implant) objects. Note that one meter is roughly 3.3 feet. By looking at this chart, we would need to design a room more significant than 27' long by 20' expansive and place the unit directly in the center of the room to contain all of the magnetic flux lines within Zone IV. If the room was smaller or the unit was not placed in the center, the room would have been designed with active or passive shielding to keep the magnetic flux lines within the Zone IV room. Active and passive shielding will be discussed later in this module.

QUESTION:

Which of the following are true of the static magnetic field (Select all that apply)?

a. Will demonstrate a growing magnetic field as we approach the MR unit.
b. The spatial magnetic gradient will impact MR conditional implants.
c. Some attractive forces will be demonstrated on all metals.
d. Will magnetize the patient at the isocenter.

ANSWER: All the choices are correct.

6.1.1 Near and Far Field

The term "near field" refers to the area near the MRI coil where the magnetic field is concentrated and uneven. In contrast, the "far field" pertains to the region farther from the coil, where the magnetic field becomes more uniform and behaves like a plane wave. This uniformity enhances signal reception and image quality over a larger volume. The strength of the electric and magnetic fields will decrease as the distance from the MRI unit increases. In the near field, where the gradient strength is the highest, there is a higher potential for Peripheral Nerve Stimulation (PNS) due to induced electric currents in the body. In the far field, the induced currents are significantly weaker and less likely to cause discomfort from PNS.

6.1.2 Slew Rate

Image 6.5 depicts the rise of the gradient strength over time once the gradient coil is activated and the fall of the gradient strength when the gradient coil is turned off until it reaches the baseline.

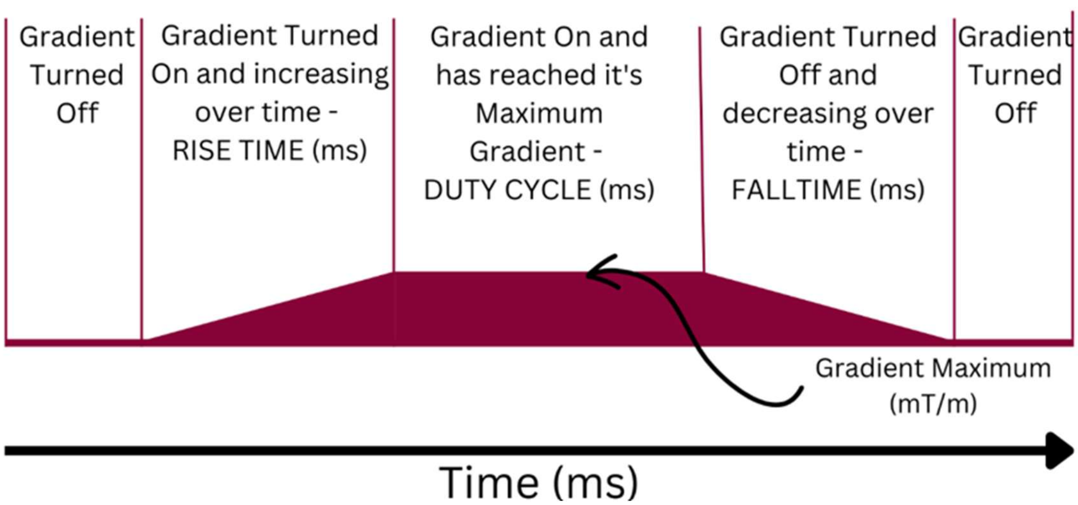

Image 6.5

Once a gradient coil is energized, the magnetic field will grow until it achieves the maximum amplitude. This is referred to as the rise time or ramp time. The speed at which the gradient reaches the maximum is referred to as the rise time or slew rate. On the other hand, the fall time is the time from when the gradient is turned off until it reaches the baseline magnetic field.

The maximal gradient strength is measured in mT/m and normally varies from 30-80mT/m on a high-field MRI device. The two points indicated in Image 6.6 are used to calculate the slew rate by dividing the GRADIENT MAXIMUM STRENGTH by the RISE TIME and is usually expressed in units of Tesla per meter per second (T/m/s).

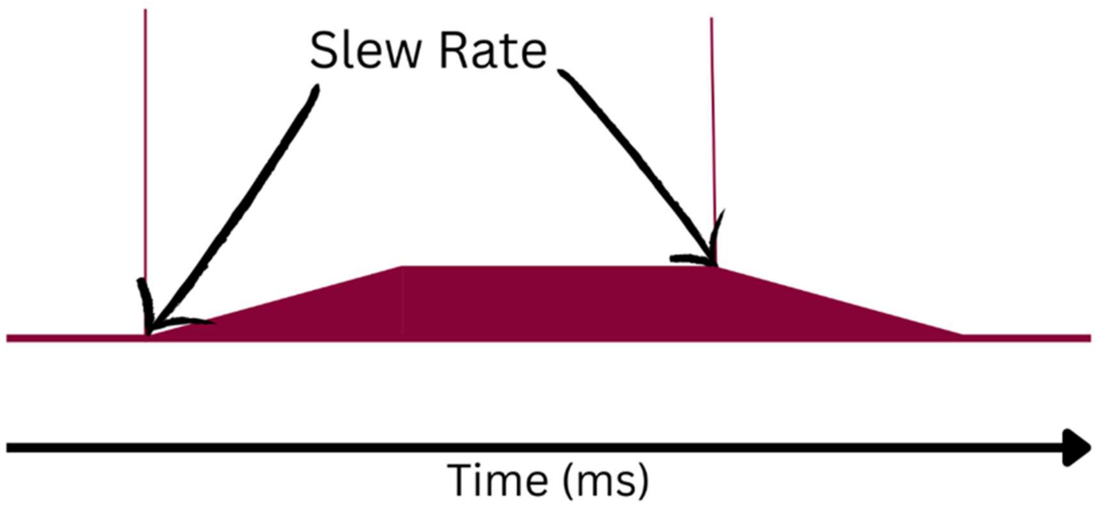

Image 6.6

A higher slew rate allows for faster gradient switching, which enhances image quality in rapid imaging techniques like echo-planar imaging (EPI) by enabling thinner slices and quicker data acquisition. However, high slew rates can also contribute to safety issues such as PNS (discussed later).

Section 6.2 Current Density

As stated before, a time-varying magnetic field generates an electric field. This leads to a current density in a conductor as charges move within the material. From Ohm's Law, we know that the current density is directly proportional to the electric field.

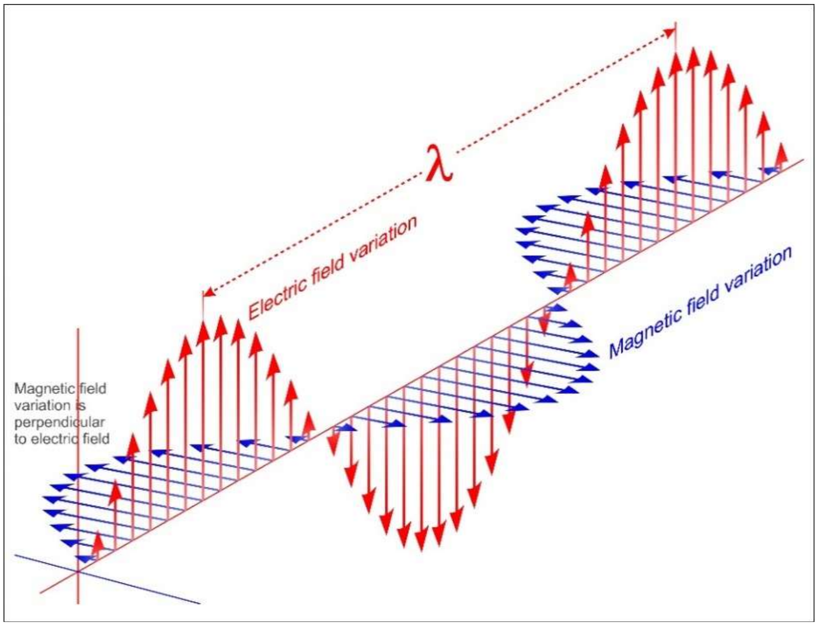

Image 6.7

An electric field will operate at a 90-degree angle from the magnetic field. Electric fields will be created with the activation of the time-varying magnetic field. An electric field is a vector quantity that can be visualized as arrows shown in Image 6.7. The lines and arrows describe the charge's attraction towards and away from other charges.

The formula for current density (J) is:

- J = I/A
- I = Current (amps)
- A = Cross Sectional Area (m^2)

We measure current density in amps per meter squared (A/m^2). This formula allows us to calculate the current density of the current flowing through a patient's transplant when we turn on the time-varying gradient field. Let's go through an example.

QUESTION: A patient's heart stent is made of a $15mm^2$ copper wire. The time-varying gradient field is turned on, and it is observed that the transplant transmits a current flow of 3 milliamps (mA). Determine this current density using the current density formula.

ANSWER: The formula for Current density (J) is:

- $J = I/A$
- I = Current (amps) = 3×10^{-3}
- A = Cross Sectional Area (m^2) = 15×10^{-3}
- $J = 3 \times 10^{-3}/15 \times 10^{-3} = 0.2\ A/m^2$

Based on current medical data, the current density generated during an MRI scan at standard field strengths is not viewed as a serious health risk. However, in rare cases involving very high field strengths, there could be risks such as nerve stimulation or tissue heating, which is why there are safety protocols in place to monitor and control exposure.

6.2.1 Tissue Properties – Conductivity & Dielectric Constant

The conductivity and permittivity of tissue are critical to understanding local radiofrequency (RF) power deposition, also known as local specific absorption rate (local SAR), during magnetic resonance imaging. This regional distribution of RF power has come under increasing study with higher field imaging and multiple transmitters. These two trends have resulted in many numerical studies to evaluate the potential for concentrated RF power deposition (i.e., local hot spots) in the body.

Cite: Bulumulla SB, Lee SK, Yeo DT. Conductivity and permittivity imaging at 3.0T. Concepts Magn Reson Part B Magn Reson Eng. 2012 Feb 1;41B(1):13-21. doi: 10.1002/cmr.b.21204. PMID: 23599691; PMCID: PMC3627401.

The dielectric constant, ε' or permittivity, measures the tissue's ability to store charge or act as a capacitor in an electric field. If we know the dielectric constant of a patient's tissue, we can determine how a patient's tissues will react to the MR environment. All materials have an absolute measure of permittivity (e) and a relative permittivity (e_r). Absolute permittivity (e), also known as permittivity, measures how easily a dielectric material can be polarized by an electric field. Relative permittivity (e_r) is permittivity measured comparable to that of vacuum ($e_0 = 8.854 \times 10^{12}$ F/m):

$$e_{\mathrm{r}} = \frac{e}{\mathrm{e}_0}$$