MRSO Exam Prep Course

Module 1

Introduction and Basic Physics

Introduction

Are you ready to become a Magnetic Resonance Safety Officer (MRSO)? This course is designed to help prepare you for the MRSO exam. You will learn to identify safety risks and implement safety procedures around MRIs so that you are better prepared to pass the MRSO exam and become a Magnetic Resonance Safety Officer.

The exam itself will consist of 100 multiple-choice questions and you'll have 3 hours to complete it. When you're ready to take the exam, simply visit www.abmrs.org to schedule it.

This course will cover all the topics listed in the American Board of Magnetic Resonance Safety (ABMRS) syllabus. Throughout the course, we'll cover everything you need to know to be successful, including the standards established by the International Electrotechnical Commission (IEC).

At the end of the course, you will also have the opportunity to take some practice exams that closely mimic the actual MRSO exam. It is highly encouraged that you take all practice exams and have a thorough knowledge of each of the questions being asked prior to taking the real exam. The course is divided into 15 modules, which are detailed below.

MODULE 1 – Introduction and Basic Physics

- ✓ Basic Physics
- ✓ Types of Magnetism
  - Diamagnetic Materials
  - Paramagnetic Materials
  - Ferromagnetic Materials
- ✓ The Primary Magnet
- ✓ Types of Primary Magnets
  - Permanent Magnet
  - Resistive Magnet
  - Superconducting Magnet
- ✓ Field Lines/Gradients
  - MR Conditional Objects

MODULE 2 – Biological Effects of the Static Magnetic Field

- ✓ Magnetophosphenes
- ✓ Magnetohydrodynamic Effect
- ✓ Vertigo, Dizziness/Nystagmus, and Nausea
- ✓ Teratogenesis
- ✓ Pregnancy-Related Issues
  - Pregnancy and MR Safety
  - Clinical Applications of MR Procedures in Pregnant Patients

- Pregnant Healthcare Workers in the MR Environment

MODULE 3 – Translational and Rotational Force

MODULE 4 – Active Shielding and Passive Shielding

- ✓ Active Shielding
- ✓ Passive Shielding
- ✓ Considerations When Designing Your MR Suite
    - Choice of Location
    - Magnetic Fringe Field Considerations

MODULE 5 – Faraday's Law of Induction

- ✓ Faraday's Law
    - Eddy Currents
- ✓ Lenz's Law
    - Lenz's Force

MODULE 6 – Time-Varying Magnetic Field and Current Density

- ✓ Time-Varying Magnetic Field
    - Near and Far-Field
    - Slew Rate
- ✓ Current Density
    - Tissue Properties – Conductivity & Dielectric Constant

MODULE 7 – Rapidly Changing RF Magnetic Fields

- ✓ Understanding Radiofrequency Fields
- ✓ Potential Biological Concerns
    - Effects of Radiofrequency Fields
    - Potential Thermal Concerns
    - MR Safety Standards
- ✓ Safety Considerations
    - RF Coil Heating and Transplants
    - RF Coil Heating and Pulse Sequences
    - Possible Health Effects Associated with SAR
- ✓ Characteristics of RF Energy-Induced Heating
    - Other Factors Contributing to Heating
    - RF Energy-Induced Heating and Thermal-Sensitive Organs
    - MR Procedures and "Hot Spots"
- ✓ SAR Modes
    - Normal Operating Mode

    - First Level Controlled Operating Mode
    - Second Level Controlled Operating Mode
- ✓ Transmitting RF Coil
    - Orientation of Induced Current Loop Relative to RF Transmitted Power
    - Protection of Patient from Heating

MODULE 8 – Slowly Changing Gradient Magnetic Fields

- ✓ Acoustic/Auditory Considerations
- ✓ Acoustic Noise Control Techniques
    - Passive Noise Control
    - Active Noise Control
    - Minimizing the Gradient Effects
- ✓ Peripheral Nerve Stimulation

MODULE 9 – System Quench

- ✓ Quench
    - Quench Vent
    - What Happens After a Quench?

MODULE 10 – The MRI Process

- ✓ Steps to Performing a Scan
    - Preparation
    - Excitation
    - Relaxation T1
    - Relaxation T2
- ✓ Signal-to-Noise Ratio Influencing Factors
    - Pulse Sequence

MODULE 11 – Gadolinium Based Contrast (GBCA)

- ✓ Short Term Effects
- ✓ Long Term Effects
    - Nephrogenic Systemic Fibrosis
    - Transmetallation
    - Anthropogenic Gadolinium
- ✓ Approaches to Contrast Enhancement
    - Altering Hydrogen Content
    - Altering the Local Magnetic Field
- ✓ Gadolinium Chelates
    - Differentiation of the Gadolinium Chelates
- ✓ Off-Label Use of Gadolinium Chelates

- Infants
- Dose
- Renal Failure
- Pregnancy
- Oral Contrast Media

- ✓ Gadolinium
  - Physical Characteristics
  - Chemical Characteristics
  - Applications
  - Additional Side Effects of Gadolinium
- ✓ Risks of GBCAs
  - Nephrogenic Systemic Fibrosis (NSF)
  - People at Risk and the Causes
  - Treatment and Testing
- ✓ Bonding Structures and Contrast Stability
  - Ionic and Non-Ionic Bonds
  - MRI Contrast Stability

MODULE 12 – Artifacts

- ✓ Reconstruction Artifacts
  - Aliasing
  - Partial Volume Averaging
  - Truncation
  - Zero Frequency
- ✓ Noise-Induced Artifacts
  - Voluntary / Involuntary Motion Artifacts
  - Misregistration
  - Off-Resonance Artifacts
- ✓ Magnetic & Radiofrequency Field Distortion Artifacts
  - Magnetic Susceptibility Artifacts
  - Body Shape, Conductivity, and Extension
  - Chemical Shift Artifacts
  - Gradient Field Artifacts
- ✓ Other Artifacts
  - Metal Artifacts
  - Gibbs Artifacts
  - Flow Artifacts

MODULE 13 – Implant Safety Considerations

- ✓ Body Expression
  - Jewelry
  - Dermal Anchors

- ✓ Passive Implants
  - o Dental Implant
  - o Breast Implants
  - o Ocular Implants
  - o Wires/Leads/Sutures
  - o Staples
  - o Stents/Filters
  - o Foil Backed Medication Patches
  - o Copper 7 / Copper T
  - o Foreign Body
- ✓ Active Implants
  - o Pacemakers
  - o Implantable Cardioverter Defibrillator (ICD)
  - o Neurostimulator
  - o Bone Growth Stimulator
  - o Pain/Insulin Pump
  - o Loop Recorders

MODULE 14 – American College of Radiology (ACR) Manual on MR Safety

- ✓ MR Professionals
- ✓ MRI Zones

MODULE 15 – Other Standards

- ✓ American Society of Testing and Materials (ASTM)
  - o MR Safe
  - o MR Conditional
  - o MR Unsafe
- ✓ International Electrotechnical Commission (IEC)
- ✓ Marking Requirements of ME Equipment of Parts
  - o Physiological Effects
  - o Accompanying Documents
  - o Dose
- ✓ Food and Drug Administration (FDA)
- ✓ International Commission on Non-Ionizing Radiation Protection (ICNIRP)

Note that we may introduce additional content above and beyond what the ABMRS may test throughout the course. This is to better equip you, the learner and exam-taker, with the information you need to pass the MRSO exam.

Quick Overview of an MRI

Let's dive into the fascinating world of MRI scanners! Magnetic Resonance Imaging (MRI) is a highly advanced medical imaging technology that utilizes the principles of magnetic resonance to generate detailed images of the human body. The MRI machine employs super powerful magnets to align the protons that are normally randomly oriented within the body's fat and water molecules of the tissue being examined. Below is an image of the entire magnetic resonance imaging system, which shows the three different magnets in the system.

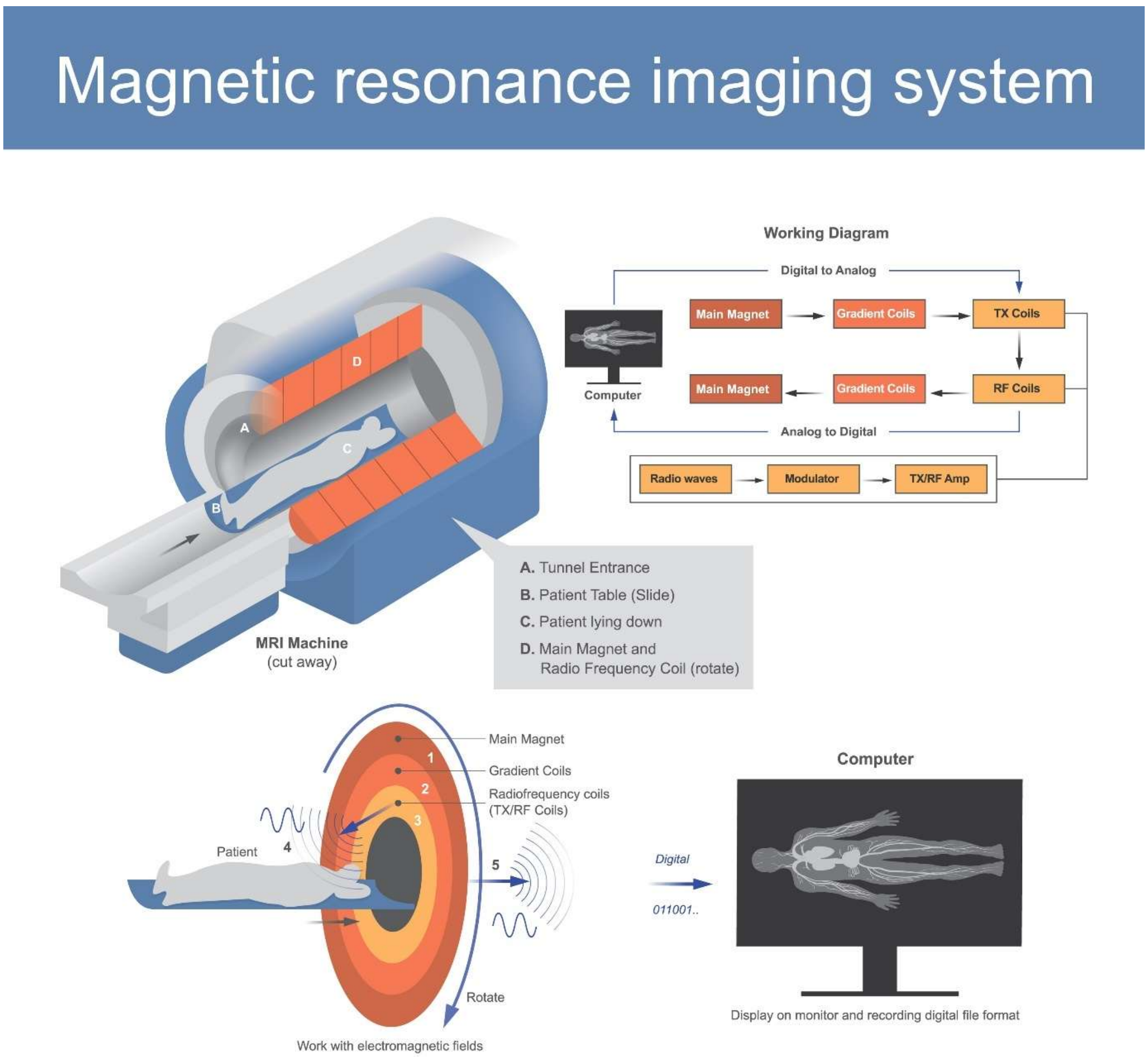


Image 1.1

The MRSO certification program is designed to bring more safety awareness and mitigation around MRIs. The MRSO must know the safety risks and hazards at the MRI suite. But to accomplish this, we must reverse-engineer from the hazards to the magnets to determine why the hazards occurred in the first place. Among other things, this course will introduce you to the three main components and the physics behind the system. Let's look at a quick overview of this system.

When an electric current flows through a wire, it creates a magnetic field around the wire. This is known as electromagnetism. The strength of the magnetic field is directly proportional to the amount of current flowing through the wire. By coiling the wire into a solenoid or other shapes, the magnetic field can be concentrated or directed in specific ways. This principle applies to the overall design of the MRI unit. The bore of the MRI unit constitutes an intricate network of miles of tightly wound electrical wiring. This extensive array of wiring plays a pivotal role in shaping and directing the overall magnitude and direction of the gravitational force within the MRI unit.

The discovery of magnetism through electricity moving through a wire, led to the development of the first component of the MRI unit, the primary magnet, or the static magnetic field. We give the static magnetic field the designation of B_o. MRI scanners use three different magnetic fields to generate images:

- B_o: The static magnetic field
- B_1: The radiofrequency (RF) field
- dB/dx, dB/dy, dB/dz: The magnetic field gradients in the three spatial directions

As an MRSO, it will be your job to ensure the overall safety of all medical professionals, visitors, and patients in the MRI suite. Understanding the physics behind the MRI system is essential for effectively mitigating its inherent risks. This deep understanding serves as the cornerstone for all MRSOs operating in this industry. The next section will discuss the physics behind the static magnetic field.

Section 1.1 Basic Physics

This section delves into the fundamental physics of the static magnetic field, with a focus on MRI technology. The static magnetic field is crucial to the functioning of MRI, and while it is a well-known safety risk, there is no alternative to its use. The static magnetic field can be produced using various methods, which all share the property of generating a powerful magnetic field that can align hydrogen nuclei in the human body to a vector of the magnetic field. The strength of magnetic fields is measured in Gauss or Tesla units. The magnetic field that moves a compass needle on Earth is roughly 0.5 Gauss, while one Tesla equals 10,000 Gauss. Therefore, the magnetic field in a 1.5 Tesla (T) unit is 30,000 times stronger than the magnetic field on Earth, while a 3 T unit is 60,000 times stronger.

Faraday's Law

In 1830, Michael Faraday made a groundbreaking discovery when he established a profound connection between electrical fields and magnetic fields. This pivotal finding, known as Faraday's Law of Induction, fundamentally revolutionized our understanding of electromagnetism. It revealed that an electrical field is intricately intertwined with a magnetic field, and this correlation has far-reaching implications across various scientific and technological applications.

We find that most electrical equipment made today has both electrical and magnetic fields as they are operating. Although, there are some that only produce one or the other. For instance, a permanent magnet exclusively possesses a magnetic field without an accompanying electrical field, while static electricity is characterized solely as an electrical field with no magnetic field. Michael Faraday's experiments demonstrated that by coiling a wire and passing an electrical current through it, a magnetic field is generated. However, it was also revealed that simply moving a coiled wire in the presence of a magnetic field induces a voltage in the wire.

This phenomenon is governed by a proportional relationship between the coils of wire and the magnetic flux. Magnetic flux is a measurement of the total magnetic field strength which passes through a given area.

The more coils of wire present in the conductor, the higher the voltage induced when exposed to magnetic flux. Similarly, increasing the strength of the magnetic field amplifies the voltage produced when interacting with the coils of wire. This fundamental principle forms the basis for numerous applications in the field of electromagnetism and has significantly contributed to the development of various technologies.

Lenz's Law

Per the previous section, Faraday's Law of Induction describes how a changing magnetic field induces an electromotive force in a conductor. This electromotive force leads to the generation of an electric current in the conductor. It is the fundamental principle behind both electric motors and generators.

An important aspect of this phenomenon is Lenz's Law, which states that the induced electromotive force and the induced current will always be in such a direction as to oppose the change that produced it. This means that when an induced current flows, the resulting magnetic field will always oppose the magnetic field that produced it.

With the discovery of Lenz's Law, we now see that induction is a two-way street. If you move a non-ferrous metal in a magnetic field, it induces a current, and if you run a current through a piece of metal, it induces a magnetic field. This is the underlying principle behind electromagnets, where a magnetic field is induced by a current, and electric generators, where a current is induced by a magnetic field. Now, let’s cover some fundamental electrical terminology.

Voltage

There is often confusion about what voltage is and how it differs from current. Voltage indicates the ability to move electricity. In other words, it is the electrical potential in the circuit. Voltage (measured in volts) is not what you feel when you touch a live wire but is merely the highway to which electrical current travels. When you touch a live wire, you feel the electrical current. To further explain, if we compare the traffic volume on a rural dirt road to an urban downtown city center, we can think of the vehicles as the "current" and the road itself as the "voltage."

Current

Current is the rate of flow of positive electric charge. It takes the form of a sudden discharge of static electricity. When you touch a live wire, the current passes through your body, and you feel the electricity sensation. It is also a dangerous part of the circuit. In the previous discussion about voltage, we use the analogy that voltage is the highway that allows the current to travel. So, considering this analogy, we can assume that the vehicles on the highway will behave like current in a circuit.

Resistance

Resistance is a fundamental concept in electrical engineering that refers to the ability of materials to hinder the flow of electric charge. This behavior is represented using a component known as a resistor, which is pivotal in the design and analysis of electrical circuits. Understanding resistance entails visualizing the interaction between the electrons constituting an electrical current and the atomic structure of the material through which they travel. While nearly all materials demonstrate some level of resistance, the extent of resistance varies depending on the material. Materials with low resistance, such as copper and aluminum, are commonly referred to as conductors and are well-suited for transmitting electricity through wiring due to their conductive properties.

Ohm’s Law

Ohm’s Law describes the relationship between voltage, current, and resistance.

$$\mathbf{V = IR}$$

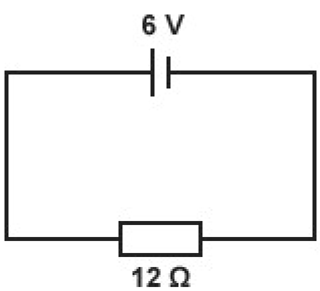
- V = Voltage within the circuit (volts)
- I = Current passing through the circuit (amps)
- R = Resistance in the circuit (ohms)

The relationship described by the equation is known as Ohm's Law, which states that the current (I) flowing through a conductor between two points is directly proportional to the voltage (V) across the two points as long as the resistance remains constant.

When the voltage across a conductor is increased, the current passing through it will also increase as long as the resistance remains constant. This is because a higher voltage provides more "push" for the electrical charge to flow through the conductor, resulting in a greater current.

Conversely, if the resistance of the conductor is increased, the current passing through it will decrease as long as the voltage remains constant. This is because higher resistance restricts the flow of electrical charge, resulting in a lower current for a given voltage.

EXERCISE:



Q: What is the current in this circuit?

A: V= I R

V = 6 V

R = 12 Ohms

I = V / R

I = 6 / 12 = 0.5 A

Section 1.2 Types of Magnetism

When an object is placed within a magnetic field, it exhibits fascinating behaviors. To understand this, we must first comprehend the atomic structure of matter (see Image 1.2). Within an atom's nucleus, we find protons and sometimes neutrons, while electrons move in not-quite-circular orbitals.

When a single electron occupies an orbital, it generates a small force in a static magnetic field due to its intrinsic magnetic moment, creating a phenomenon known as paramagnetism. This occurs because the electron acts as a tiny magnet, aligning itself partially with the external magnetic field. As a result, there is a net attractive force towards the field. This behavior is a fundamental concept in quantum mechanics and has significant implications in understanding the behavior of materials in the presence of magnetic fields. To summarize, different materials respond in unique ways when exposed to a magnetic field due to their distinct atomic structures.

Now, let's delve into three distinct types of magnetism: diamagnetic, paramagnetic, and ferromagnetic.

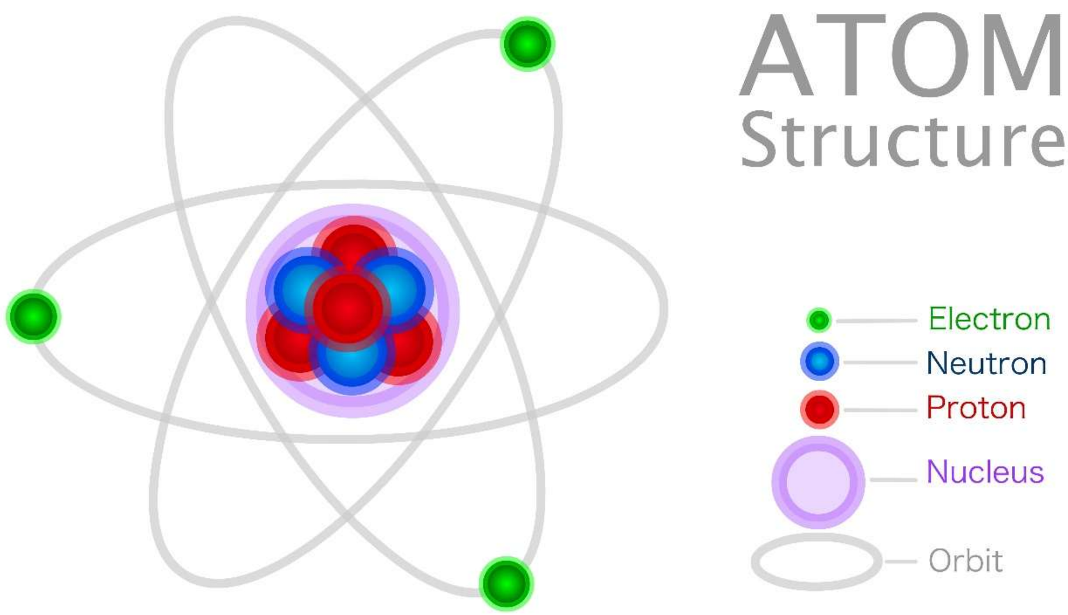


Image 1.2

1.2.1 Diamagnetic Materials

We have all witnessed that various materials respond differently when exposed to a magnetic field. Some materials will move away from the field, some will move towards the field, while some remain unaffected. Some materials show a slight attraction towards the magnetic field, while some are strongly attracted to it.

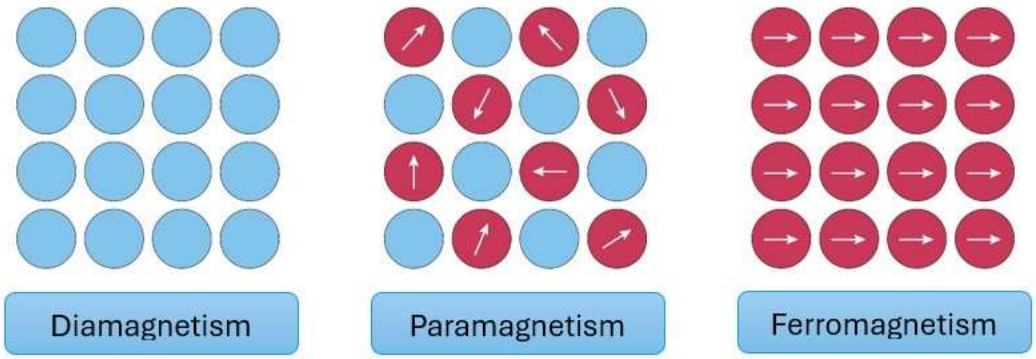


Image 1.3

Diamagnetism is a fundamental property of matter that arises due to the response of electrons within a substance to an external magnetic field. In diamagnetic materials, the electrons pair up and their spinning motion cancels out the magnetic field they generate. Consequently, when a diamagnetic material is exposed to a magnetic field, it experiences a repulsive force due to the induced magnetic fields that oppose the applied magnetic field. In other words, diamagnetic materials have a negative magnetic susceptibility and weakly oppose the magnetic field. This phenomenon is observed in a wide range of materials including superconductors, some metals, and organic compounds.

To best classify these three types of materials, we must understand their relative permeability (μr). Permeability is a quantity measuring the influence of a substance on the magnetic flux in the region it occupies. Relative permeability is the ratio of the permeability of a specific medium to the permeability (μ) of free space (μ_0). For the MRSO position, we do not need to remember and utilize the relative permeability equation. However, relative permeability is still helpful in understanding material properties and how they react to the MR environment.

Diamagnetic materials have a relative permeability of less than one. Some diamagnetic metals have the following permeability values:

- Copper (Cu): μ_r = 0.99999
- Mercury (Hg): μ_r = 0.99997
- Bismuth (Bi): μ_r = 0.99984

Other Diamagnetic Metals:

- Zinc (Zn)
- Magnesium (Mg)
- Gold (Au)

Diamagnetic Materials That Are Not Metals:

- Silicon (Si)
- Phosphorus (P)
- Water
- Graphite
- DNA and other proteins

We classify these materials as MR-Safe. The symbol for an MR-Safe material is shown in Image 1.4 below.

Image 1.4

1.2.2 Paramagnetic Materials

When you put certain materials in a static magnetic field, they exhibit exciting behaviors. Paramagnetic materials create a weak, measurable, attractive force you cannot see but can feel. This happens because single electrons in one or more orbitals lead to magnetism. The strength of the attractive force depends on the material's temperature and the number of orbitals with single electrons. Gadolinium is an excellent example of a paramagnetic material we will explore later.

Paramagnetic materials have a relative permeability of slightly greater than one. This means that when paramagnetic materials are exposed to an external magnetic field, they become somewhat magnetized in the direction of the magnetic field. Internal induced magnetic fields form within these objects in the same direction as the applied field.

Some paramagnetic metals consist of:

- Platinum (Pt): $\mu_r = 1.000265$
- Aluminum (Al): $\mu_r = 1.000022$
- Titanium (Ti): $\mu_r = 1.000022$
- 304 stainless steel (essential to know): $\mu_r = 1.002$
- Austenitic stainless steel (important to know): $\mu_r = 1.003$

Paramagnetic materials have such a slight reaction to the static magnetic field that they are not considered hazardous in the MR environment. However, as we progress through this course, we will show that these material reactions can still significantly affect MR safety. We classify these materials as MR-Conditional (Image 1.5).

Image 1.5

1.2.3 Ferrous Materials

Ferromagnetic materials are materials that are highly attracted to static magnetic fields and retain their magnetic field even after leaving the static magnetic field for a certain period. Ferromagnetic materials have directional field domains that align with the vector of a static magnetic field.

Ferrous materials, like paramagnetic materials, have a relative permeability of greater than one. However, the significant difference is that the relative permeability of ferrous materials is substantially larger than that of paramagnetic materials. The term "ferrous" generally means "containing iron," and iron has a relative permeability of approximately 5500. When introduced to a magnetic field, ferromagnetic materials will become highly magnetized in the direction of the magnetic field.

If one introduces such a highly magnetized material to a static magnetic field, the magnet will exert a translational force on the ferromagnetic object. These forces are so strong that they can pull ferromagnetic objects, making them airborne and causing them to collide with the scanner's magnet bore. This effect is known as the missile effect and can result in catastrophic consequences for individuals near the scanner as well as significant damage to equipment. To avoid serious or fatal injury from projectiles, MRSOs and MR personnel must understand the principles of the missile effect and properly screen individuals for ferromagnetic objects before entering the scanner room. We classify these materials as MR-Unsafe (Image 1.6).

Image 1.6

When a ferrous object is exposed to a magnetic field, it can also experience a rotational force. This is different than the translational force previously discussed. Rotational force happens because the magnetic object is attracted towards the magnetic bore and simultaneously tries to align itself to the magnetic vector. To achieve this alignment, the object applies torque, which can be dangerous for implants. If an implant rotates inside a patient, it can cause catastrophic injury. Therefore, it is crucial to be aware of this potential danger and take necessary precautions when dealing with ferrous objects in a magnetic field.

Some ferromagnetic metals consist of:

- Iron (Fe)
- Nickel (Ni)
- Cobalt (Co)
- Manganese (Mn)
- Ferritic Stainless Steel
- Martensitic Stainless Steel

Image 1.7 shows how the different types of material protons react to the MR environment.

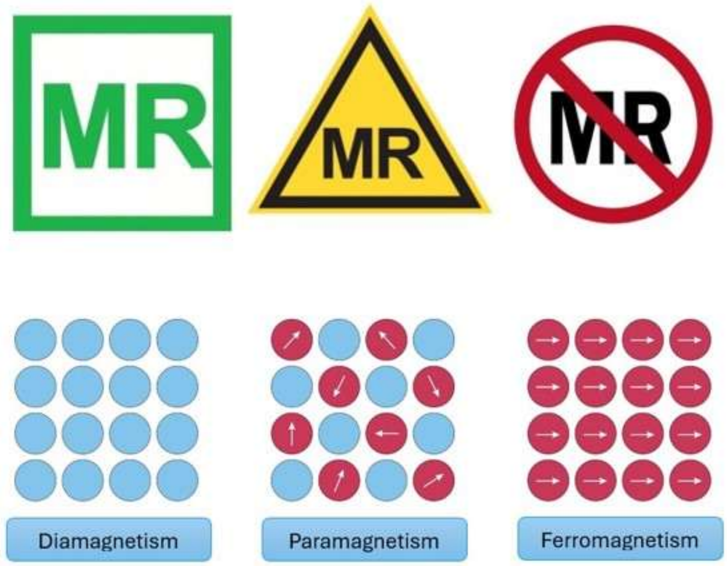


Image 1.7

EXERCISE:

QUESTION: What is the risk of a non-ferrous electrically conductive implant in Zone IV (the magnet room)?

A. Rotational Force
B. Translational Force
C. Lenz's Force
D. All of the Above

ANSWER: Lenz's Force

Since the implant is non-ferrous, it will not react with rotational or translational forces. Since it is electrically conductive, it will respond by producing a current in the implant. This induced current will cause it to repulse against the B_0 due to Lenz's Force. If you advance the patient slowly toward the MRI, the patient should not experience Lenz's Force. The slower, the better.

Section 1.3 The Primary Magnet

It's important to note that the primary magnet in an MRI machine is ALWAYS ON. Image 1.8 below illustrates the movement of hydrogen atoms in your body before you enter the MRI suite, when there is no external magnet present, and the atoms can move in a random and unobstructed manner.

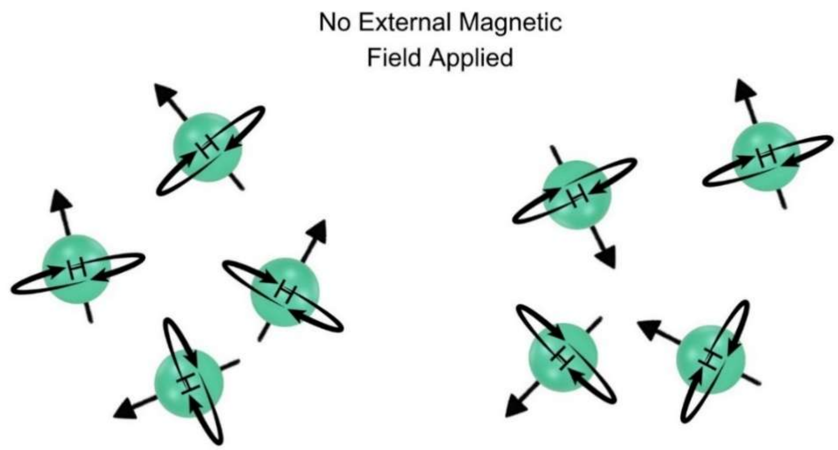


Image 1.8

However, when you enter the MRI suite, your hydrogen atoms are exposed to a static magnetic field from the primary magnet, which alters their behavior. As a result, the hydrogen atoms in your body align themselves with the magnetic field, leading to a change in their motion. Image 1.9 below demonstrates this behavior.

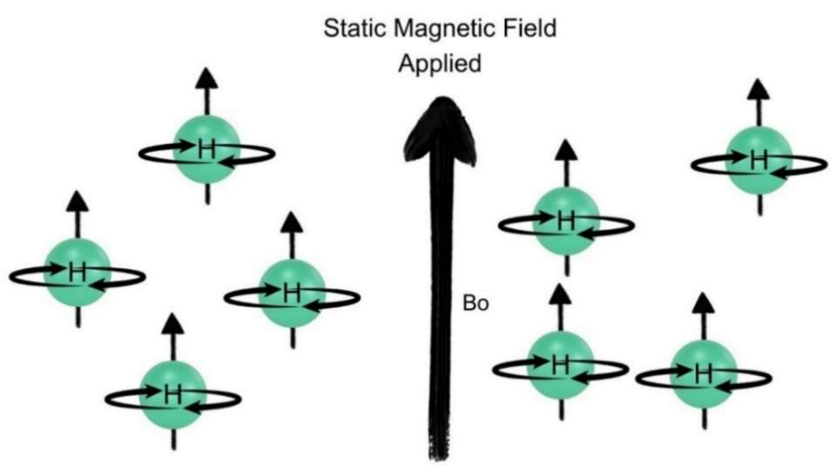


Image 1.9

In an MRI, the primary magnet is in place to align the hydrogen protons in the patient's body with its direction. This creates resonance, which helps us to identify unhealthy atoms in the body. When the patient leaves the MRI suite, the healthy atoms return to their typical rotational sequences, while the unhealthy atoms take longer to do so. Once in resonance, the atoms will depict behavior similar to Image 1.9. Resonance is a crucial step in the MRI process.

We use the variable B_0 to represent the static magnet's magnetic flux density (i.e. the strength of the static magnetic field). This is measured in Tesla, with 1.5 Tesla or 3 Tesla being the most common strengths. Greater magnetic strength leads to higher quality images. Research magnets can reach up to 60 Tesla.

Earth's magnetic field, or magnetosphere, protects us from harmful solar winds. Without it, our atmosphere would erode, eventually leading to the end of life on our planet. Our planet's magnetic field varies between 30-65 micro-Tesla (μT) (refer to Image 1.10 below).

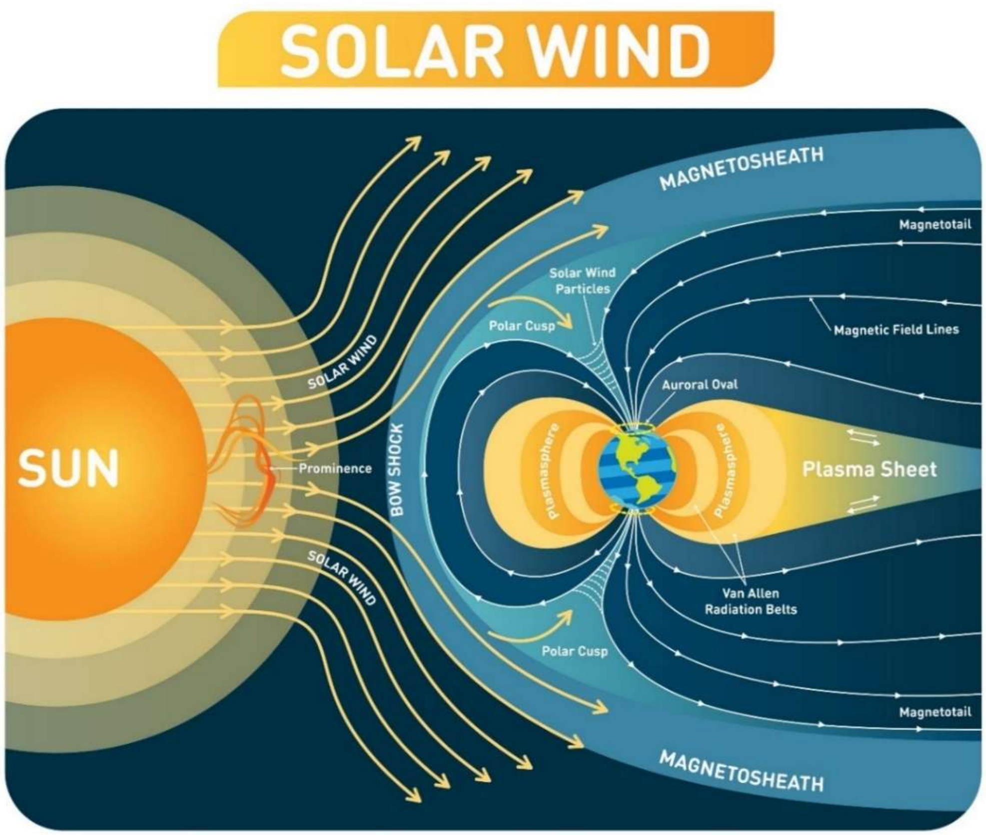


Image 1.10

It's important to note that the magnetic field strength of Earth is incredibly weak in comparison to an MRI. In fact, an MRI unit has a magnetic field strength that is over 50,000 times stronger than the magnetic field strength of our planet. This remarkable strength is what enables MRI machines to capture highly detailed images of the body's internal structures. It is indeed a remarkable achievement of modern science and technology and has contributed significantly to the field of medical diagnosis and treatment.

The strength of a magnetic field can be measured in Tesla or Gauss, where Tesla are much larger than Gauss. Refer to the following measurement conversions:

- 1T = 10,000G
- 1T = 1000mT
- 1mT = 10G
- 1μT = 0.01G

Section 1.4 Types of Primary Magnets

There are various types of MRI units, each with its unique way of creating a static magnetic field. Each type of magnet has its strengths and weaknesses. The different types of magnets have been developed to effectively cater towards various medical facilities. We are now going to discuss three different types of magnets – permanent magnets, resistive magnets and superconducting magnets.

1.4.1 Permanent Magnet

One type of MRI is the permanent MR unit, which generates a magnetic field using a collection of permanent magnetic bricks. Each brick has a weak magnetic field, which combines to produce a strong magnetic field of up to 0.4 T. The magnetic fields generated by this unit usually have a vertical vector. To understand the concept of a permanent MR unit, imagine a large iron bar that has been magnetized and twisted into a C-shape. The patient enters the MRI and slides into the cavity formed from the C-shaped magnetized iron. They are one of the least expensive MRIs, but their drawbacks are:

1. They are cumbersome. With a piece of iron weighing up to 30 tons, most medical facilities are limited to where to place the MRI due to weight and logistics.
2. They have a low magnetic strength, ranging from 0.15 T to 0.4 T, which produces lower image quality.

1.4.2 Resistive Magnet

Resistive magnets work the same way as superconducting magnets. However, resistive magnets require a much more considerable amount of energy to operate, along with significant cooling. The one benefit of resistive magnets is that they do not need cryogen (discussed later). However, they will need a constant power supply to maintain the homogenous magnetic field. This can be a significant electricity expense to maintain.

There are two types of resistive magnets, iron core and air core, discussed next.

Iron Core Resistive Magnet

These magnets operate with a vertically orientated magnetic field. The iron core is comprised of wound-up soft copper around iron. When the copper wire supplies this electrical current to the MRI, the iron core in the center of the wire acts as a magnet, supplying a magnetic field of up to 0.6T around the unit.

Considering the magnetic field vector moving vertically, we can reduce safety issues related to the “missile effect” as most missile effect risks come from a ferrous object aligning with a horizontal field vector.

The drawback to these units is that they require extensive electrical power to maintain and are much heavier than air core resistive magnets.

Air Core Resistive Magnet

Air core resistive magnets have a horizontal magnetic field. There is no iron in the center of these magnets, eliminating the vertical magnetic field. Image 1.11 below depicts the difference between an Air Core (left) and an Iron Core (Right) resistive magnet. Notice the iron core is not present in air core resistive magnet, only a coil of wire. The coil acts as the magnetic field, changing it from vertical to horizontal. Without the iron to absorb and retain much of the electrical energy that travels through the coils, the air core units require more electricity to maintain the homogeneous magnetic field. However, the units are less expensive and lighter than the iron core. They still only provide limited magnetic strength like the iron core units.

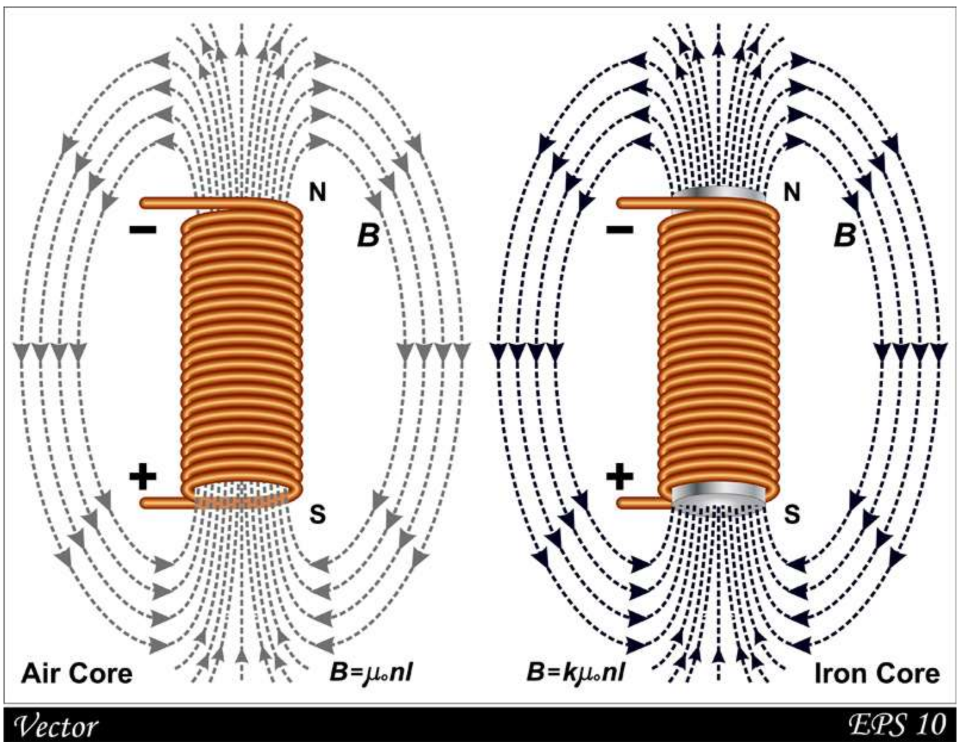


Image 1.11

1.4.3 Superconducting Magnet

Superconductive MRI magnets are generally the preferred choice for MRI scanners due to the lower energy and maintenance costs to keep the units operational as compared to resistive magnet units. It was determined that if you could altogether remove resistance, an energized MRI unit could hold on to the electricity and would not need any more electricity to maintain its homogeneous magnetic field. Superconductive MRI magnets are comprised of a solenoid-shaped coil with tin or titanium alloys. These alloys have a property of zero electrical resistance if they are cooled enough, around 4.2 Kelvin (-452.11 °F). As long as cryogen is present in the system, the unit will not lose energy. So, once the magnet is charged, it is unplugged, and the power remains in the system. Using traditional energy methods, it would be challenging to cool an MRI unit this cold without a substantial amount of power. This is where cryogen comes in (liquid helium). Introducing cryogen into an MRI environment is intended to eliminate resistance in the circuit so that the electricity never dissipates. This greatly reduces energy costs once the MRI is energized.

The transmission of electricity through a series of aligned superconducting coils submerged in liquid helium produces a magnetic homogeneity area down the coils' common centers. It allows us to increase the strength of the static magnetic field.

Superconducting magnets have the highest field strengths and the most stable fields of all the current magnet designs. The stronger the static magnetic field, the greater the image quality and the shorter the examination duration.

Image 1.12 below shows a superconducting MRI.

Image 1.12

Section 1.5 Field Lines/Gradients

The static magnetic field is an invisible constant that describes the magnetic influence on magnetic objects. As previously discussed, the static magnetic field of an MRI is very powerful. We need the static field because it allows us to align the hydrogen molecules in our patient to the static magnetic field vector. Let's revisit the image of the atoms when a static magnetic field is applied (see Image 1.13 below). The constant homogeneous B_0 and the aligned hydrogen atoms in our patient will allow us to maintain quality image resolution and uniformity. We will excite these hydrogen atoms during the scan using various RF frequencies. RF frequencies will be discussed later in this course. For now, understand that the primary purpose of the static magnetic field is to prepare the hydrogen atoms for recognizable and uniform imaging.

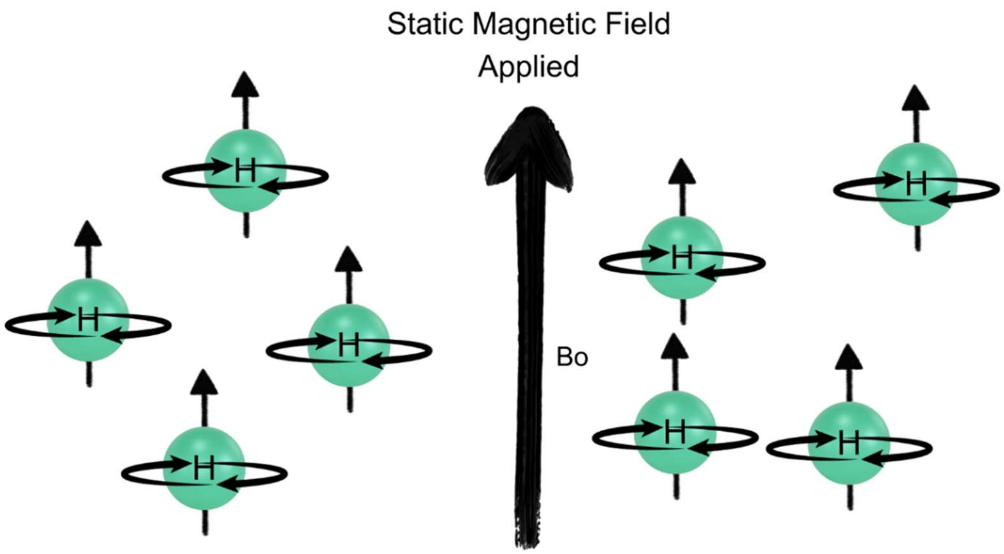
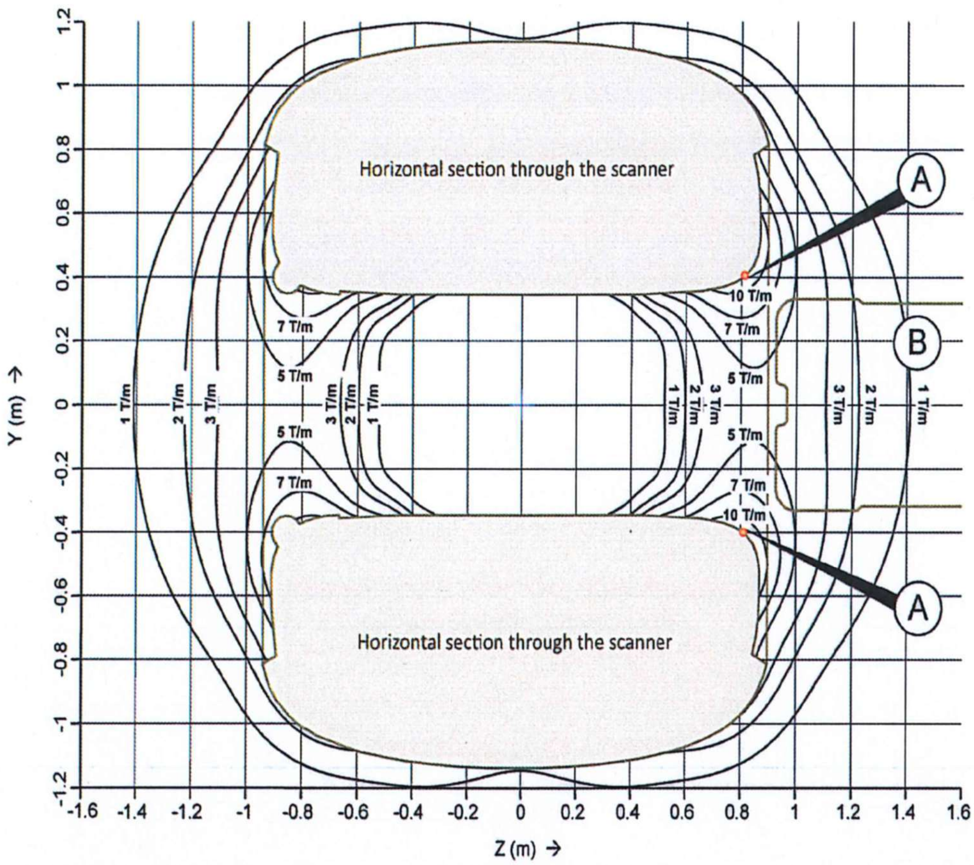


Image 1.13

Though this field is uniform and constant, it decreases strength as we move away from the isocenter. The stray magnetic field, which is outside of the magnet bore, is known as the fringe field or spatial gradient magnetic field. It is important to reduce the fringe field for safety and to protect sensitive equipment like pacemakers, computer monitors, etc. Superconducting magnets use active or passive shielding, which confines the fringe field to the scan room. The perimeter around an MR scanner within which the static magnetic fields are higher than five Gauss is called the 5 Gauss line. This is ten times higher than the average Earth's magnetic field. The 5 Gauss line is a safety boundary that marks the point where the magnetic field is considered safe for the general public.

The gradient in magnetic field strength at various places around the MR unit is known as the magnetic spatial gradient and is measured in Tesla per meter (T/m) or Gauss per centimeter (G/cm). Images 1.14 and 1.15 show the spatial gradient of the static magnetic field on a “Philips Ingenia 3.0T” model from a bird’s eye view. “B” is the gantry table, and " A " marks the highest gradients locally on a surface at 17 T/m. To see the whole spatial gradient field, the top section of the MRI is cut out.



Horizontal section through the scanner
Horizontal section through the scanner
A
A
B
10 T/m
7 T/m
5 T/m
3 T/m
2 T/m
1 T/m
Y (m) →
Z (m) →

Image 1.14

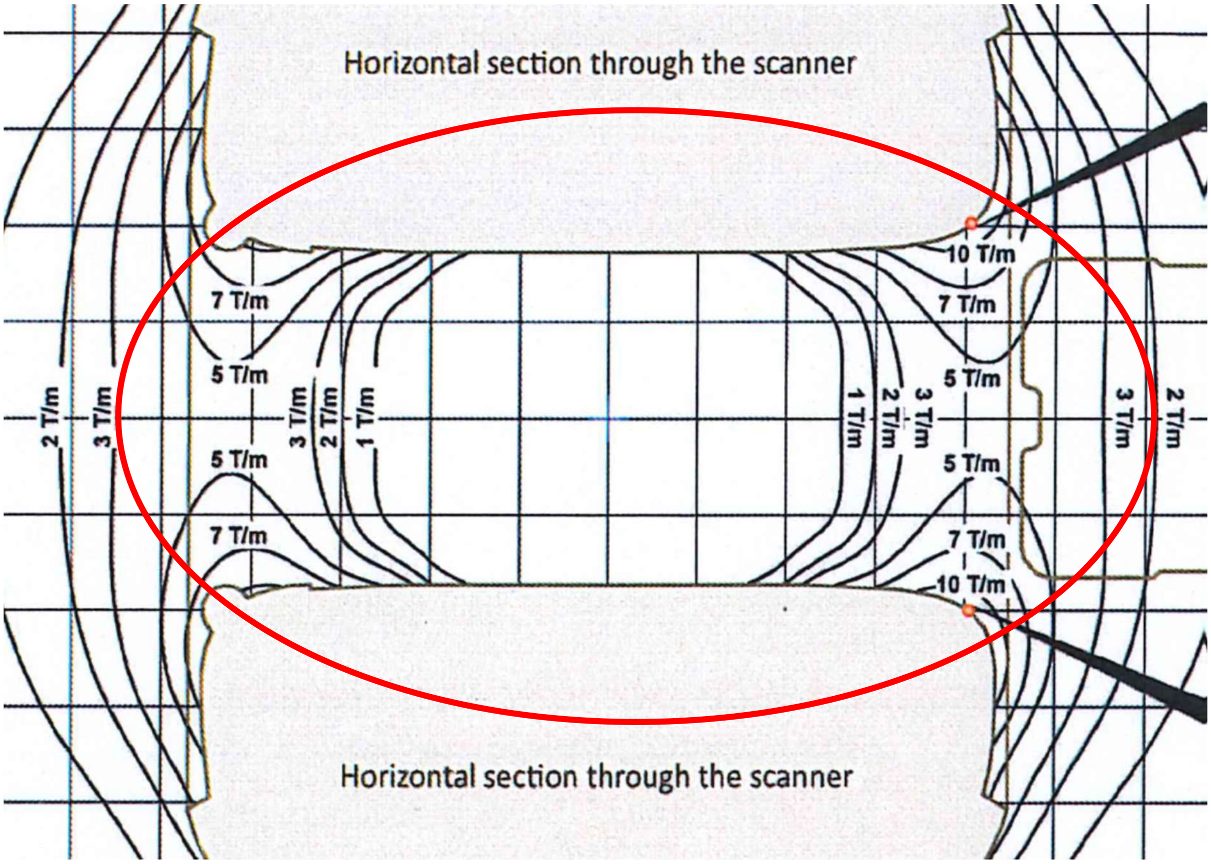

Horizontal section through the scanner
10 T/m
7 T/m
7 T/m
5 T/m
5 T/m
2 T/m
3 T/m
3 T/m
2 T/m
1 T/m
1 T/m
2 T/m
3 T/m
3 T/m
2 T/m
5 T/m
5 T/m
7 T/m
7 T/m
10 T/m
Horizontal section through the scanner

Image 1.15

The red lines in Image 1.16 below show where the magnetic field is at its strongest, ranging from 5 T/m to 17 T/m. Notice that at 1.4 m along the z-axis (gantry table), the spatial magnetic field will drop down to 1 T/m. This is because the gantry is weakening (or obstructing) the field. We can see the thicker the walls of the gantry there are, the weaker the field becomes.

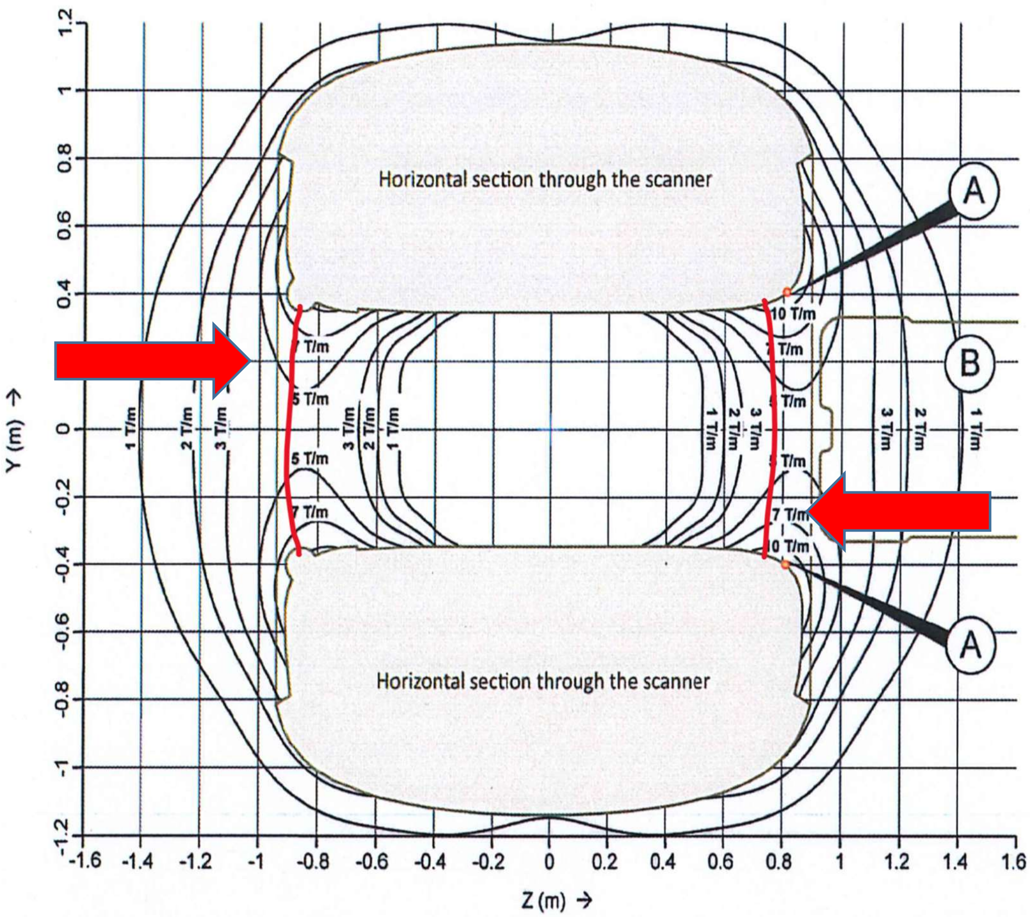


Image 1.16

Notice that there is no spatial magnetic field strength at the isocenter within 0.5m each way on the z-axis and against the walls of the scanner at the center of the unit. The red area in Image 1.17 shows this.

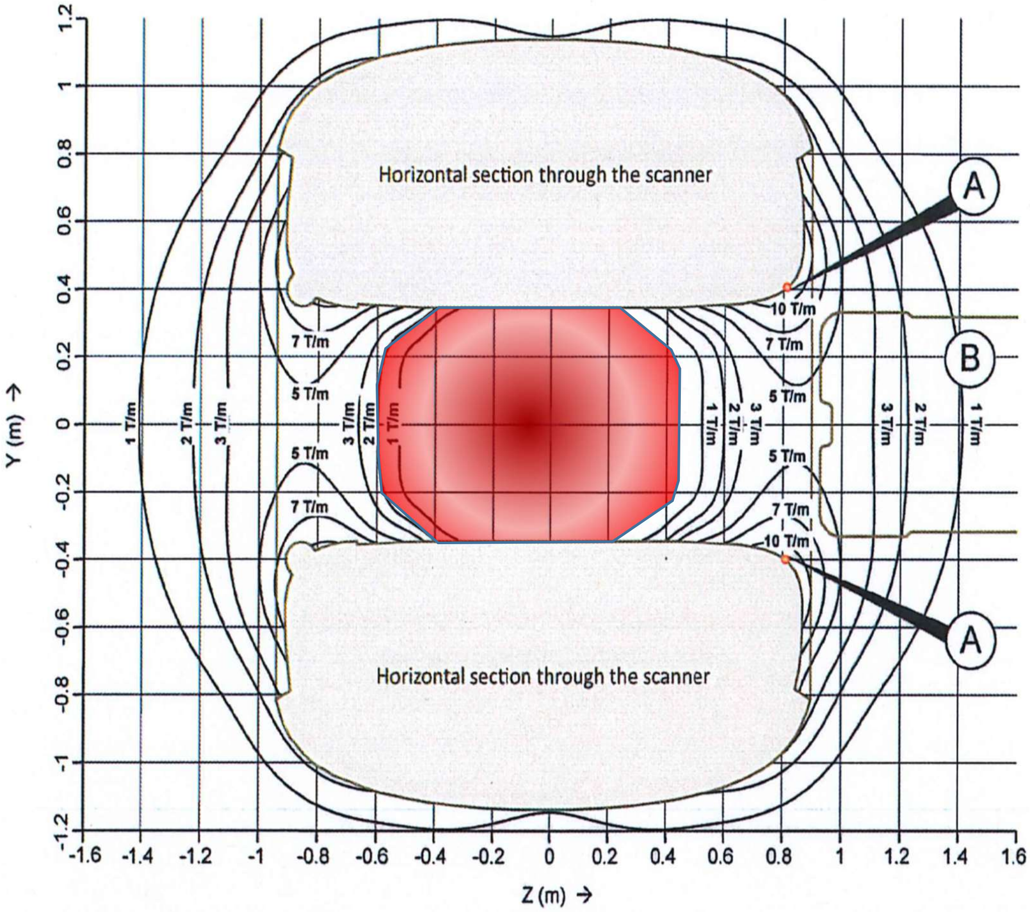

Horizontal section through the scanner
Horizontal section through the scanner
A
A
B
10 T/m
10 T/m
7 T/m
7 T/m
7 T/m
7 T/m
5 T/m
5 T/m
5 T/m
5 T/m
3 T/m
3 T/m
3 T/m
3 T/m
2 T/m
2 T/m
2 T/m
2 T/m
1 T/m
1 T/m
1 T/m
1 T/m
Y (m) →
Z (m) →

Image 1.17

Image 1.18 shows another view from the side of the same MRI model with the side of the MRI unit cut out to see the spatial magnetic gradient. The blue line on the bottom signifies the floor level. Understanding that this magnetic field effects the ground up to 1.2m deep can be helpful when designing the MRI room or moving the MRI into another room. Careful consideration must be taken if there is wire mesh or rebar on the floor underneath the scanner. Like the bird's eye view in the previous section, the strongest magnetic field in this scanner is towards the ends of the gantry. But how does this play into MR safety? We must dive deeper into how materials behave around this magnet to answer this question.

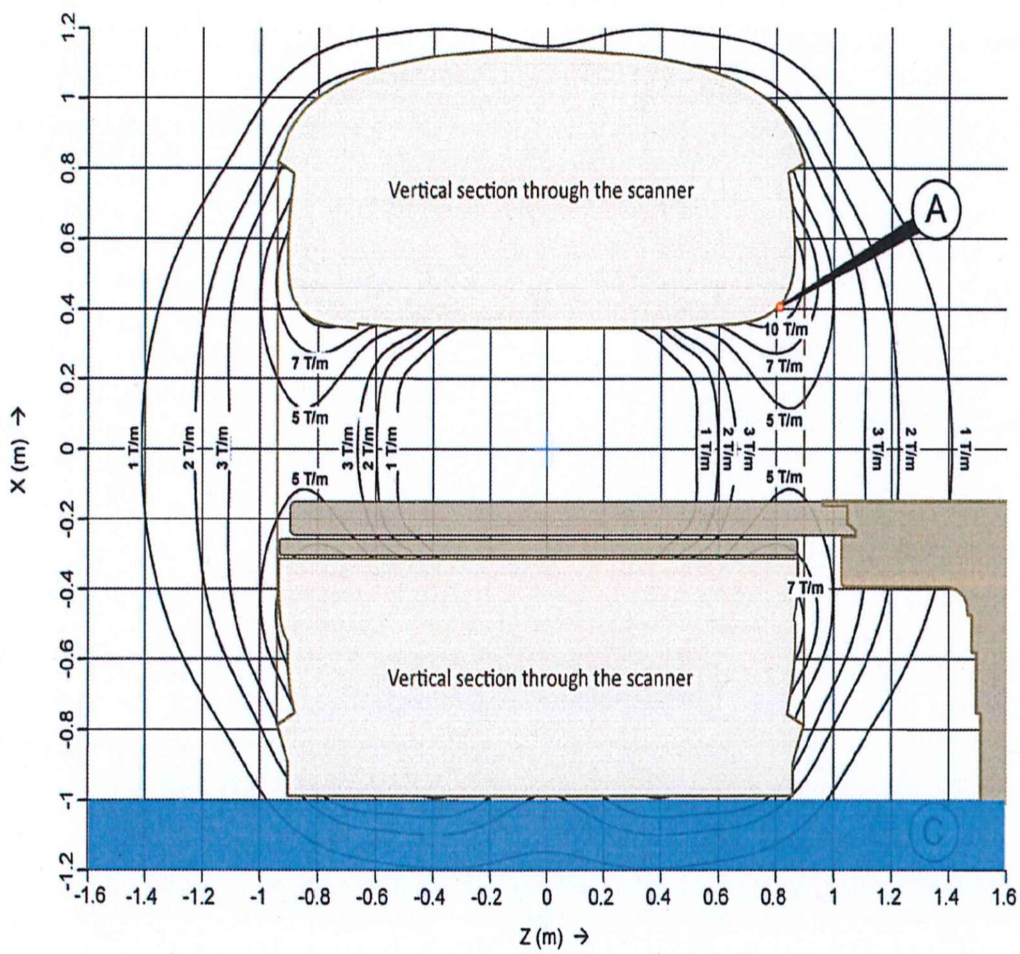


Image 1.18

1.5.1 MR Conditional Objects

We know that we can have MR-Safe objects in the scanner room and that we cannot have MR-Unsafe objects in the scanner room. But what about MR-Conditional objects? MR-Conditional objects do not have a high magnetic attraction to the primary magnet because they are paramagnetic. However, a powerful magnet can still influence paramagnetic material to move slightly depending on the material properties. If the object is an implant, the slightest motion can cause significant injury to our patient. As MRSOs, we must identify all MR-Conditional objects that may be present in the scanner room. This would include any implants present in our patient. Methods for testing implanted devices for conditional use come from ASTM International and the International Standards Organization (ISO). The ASTM standards are somewhat limited but include measurement methods for displacement force (F2052), magnetic torque (2213), RF-induced heating (F1282), and imaging artifacts (F2119).

Implants can cause significant anxiety for patients undergoing an MRI scan. ASTM and ISO perform tests on these implants to determine their degree of attraction to the static magnetic field at a particular spatial magnetic gradient field, referred to as deflection. To measure deflection, the object under test is suspended from a string and moved into a static magnetic field, and the amount of magnetic field deflection or attraction is recorded. The assumption behind deflection is that if an object deflects 45°, the translational force exerted on the item by the MRI unit equals gravity. If the deflection is less than 45°, implants do not pose a significant risk to the patient. However, as deflection increases, so does the risk to the patient. If an implant deflects 90° or more, it is unsafe to use in an MRI scan because we cannot predict how much force it will exert on the patient.

Image 1.19 is MR-Conditional information issued from a DBS (deep brain stimulator) implant manufacturer. According to this information, the patient's implant can withstand a maximum spatial gradient of 19 T/m.

MR

MR Conditional – Non-clinical testing has demonstrated that Medtronic DBS Systems have been found to be MR Conditional. If this patient is implanted with a Medtronic DBS System, MRI examinations of the head only or the entire body may be safely performed depending on the DBS system components implanted.

Medtronic DBS Systems that are eligible for MRI scans of the entire body (ie, full-body eligible) must be scanned under the following conditions:

- 1.5-tesla (T) horizontal closed bore
- Maximum spatial gradient of 19 T/m (1900 gauss/cm)
- RF transmit/receive body coil (built-in) or RF transmit/receive head coil
- Maximum RF power of 2.0 μT B1+rms (B1+ root mean squared)
- If B1+rms is not available, a maximum RF power of 0.1 W/kg (0.05 W/lb) whole body and head SAR (specific absorption rate). Using a SAR setting may result in a more restrictive MRI scan.
- Gradient slew rate limited to 200 T/m/s

Image 1.19

EXERCISE:

We have a patient needing a head scan but has an MR-Conditional knee implant. To conduct the head scan, we can use the spatial magnetic gradient for the primary magnet and get an idea of where the patient will be relative to the static magnetic field strength. We need to determine if the patient's knee implant will pose a safety risk.

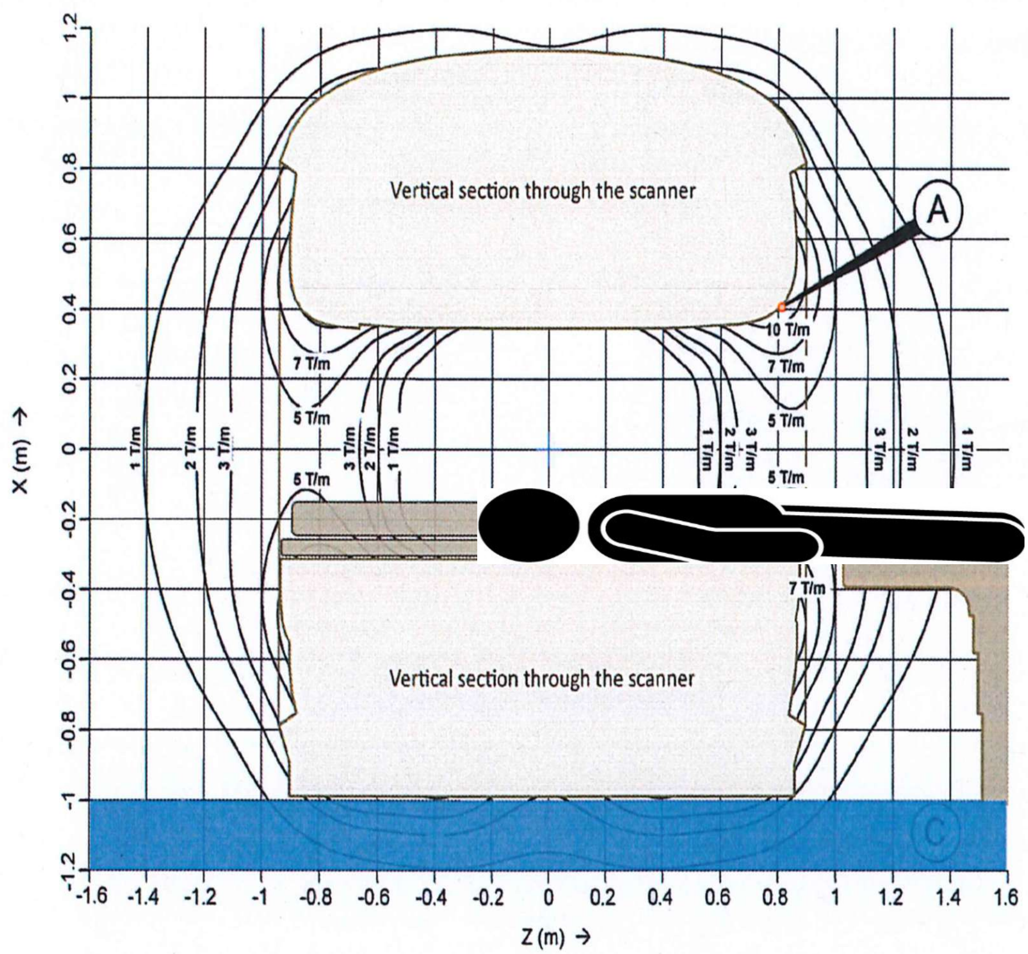


Image 1.20

After reading the ASTM International and ISO standards on the patient's MR conditional implant, it has been determined that the implant can receive a spatial magnetic gradient of no more than 19 T/m. We plan on placing the patient at isocenter. We then measure the distance between the center of the patient's head to the knee implant. After reviewing the spatial magnetic field chart given to us by the MRI manufacturer, we are able to determine where our patient's knee implant will be and the strength of the magnetic field it will experience. At this location, the patient's knee implant will experience a spatial gradient of 3 T/m. We can determine that the patient's implant will not reach its maximum spatial gradient threshold, and thus will not be affected by the magnet during this scan.

Summary

Using strong magnetic fields in MRI induces net magnetism in the measured tissues. This strong magnetic field, also known as a static magnetic field, remains uniform and does not change. A uniform magnetic field occurs within the isocenter of the static magnetic field, but the magnetic field changes as one moves away from the isocenter, creating the magnetic spatial gradient. Hazards associated with the static magnetic field are mainly caused by this, including translational and rotational forces. We will be discussing more about translational and rotational forces later in this course

Various measuring units are utilized to measure static magnetic field intensity, with Tesla being the most significant magnetic field measurement unit. Experimenting with different field strengths has produced intriguing results, with field strengths more significant than 2 T linked to biological impacts such as headaches, dizziness, and magnetophosphenes. We will be discussing biological impacts in Module 2. Other units of measurement used in MRI include the Gauss (G) and milli Tesla (mT), where one Tesla equals 1000 mT, and 1 Gauss equals 0.1 mT.

The 5 Gauss line is a crucial boundary in the MRI environment that affects implant safety, and any electrical or active implant should not cross this line since it may cause implant dysfunction. The gradient in magnetic field strength at various places around the MR unit is known as the magnetic spatial gradient and is measured in Tesla per meter (T/m) or Gauss per centimeter (G/cm). The maximum spatial gradient considers the MR's total field strength, with the highest spatial gradient at 3 Tesla being 720 G/cm, meaning that an implant safe at 720 G/cm is safe at 3 Tesla.

There are distinctions between 3.0 Tesla and 1.5 Tesla MR systems, with the former having twice the power of the latter. A 3.0 Tesla MR unit has four times the heating capability of a 1.5T MR device, impacting implants differently due to the varied frequencies employed between the two. Linear or looping implants may heat up at a shorter length in a 3T Tesla MR unit due to its higher frequency and shorter wavelength. Long-bore and short-bore MR systems also have differences in spatial gradient magnetic field, impacting the deflection of implants at varying distances from the MR unit.

This concludes our discussion of essential physics associated with the static magnetic field.