MRSO Exam Prep Course

Module 7

Rapidly Changing RF Magnetic Fields

The third major component in the MRI unit is utilized to produce the rapidly changing radiofrequency (RF) field. The RF field is similar to the time-varying gradient sequences, but the RF magnetic field changes much faster.

To induce resonance in the targeted hydrogen nuclei, a time-varying RF device is utilized. The B_1 field refers to the radio frequencies utilized in MRI. This field is applied to a patient at a 90° angle from the vector (B_0) of our static magnetic field.

It is critical to comprehend what a radiofrequency is. A radiofrequency is a type of electromagnetic energy composed of a rapidly changing magnetic field. A radiofrequency exhibits a rise in magnetic strength followed by a drop in magnetic strength. This is when the term "rapidly changing RF field" enters the picture. This shifting magnetic field happens quickly, and the sort of energy we're dealing with depends on how fast it happens. If we graphed the increase and fall in magnetic field strength caused by the time-varying radiofrequency system, we would see a sine wave. A frequency is defined as the number of peaks visible in this graph of sine waves every second. The number of peaks, or amplitudes, shown every second is measured in hertz. A wavelength is a distance between each peak or amplitude.

The frequency of electromagnetic radiation rises as the wavelength decreases. Radiofrequency waves have the shortest wavelength and the lowest frequency. On the electromagnetic spectrum, microwaves follow radiofrequency waves. We progress from microwave energy to infrared energy, and eventually to visible light as we increase in frequency. We attain UV energy after passing through visible light. We begin to experience ionizing radiation at this time. Following ultraviolet energy are x-rays and gamma radiation.

We are dealing with radiofrequency energy in MRI. The purpose is to extract the precessional frequency of the hydrogen nuclei located in the area of our patient that we want to sample. We emit a radiofrequency that matches the precessional frequencies of these hydrogen nuclei once we have calculated their precessional frequencies. This will cause a phenomenon known as resonance.

We shift these targeted hydrogen nuclei from a low energy state to a higher energy by providing energy to them. Because of the hydrogen nuclei we want to detect the point in the direction of our static magnetic field's vector, resonance pushes them away from longitudinal magnetization. The RF transmitter is shut off when these hydrogen nuclei achieve transverse magnetization. The hydrogen nuclei exhibit longitudinal magnetization relaxation (T1) and transverse magnetization loss (T2) immediately after the RF transmitter is turned off (T2).

To comprehend the resonance and data collecting process, as well as the safety issues involved with the RF transmitter, we must first revisit Faraday's Law of Induction. Recall from Faraday's Law of Induction that when a current is sent through a wire, a magnetic field is formed at a 90° angle to the current. It also describes how an electrical current will be generated in a wire placed in a changing magnetic field. The most fundamental idea in MRI is the concept of Faraday's Law of Induction. We can grasp the safety issues linked with the RF transmitter if we understand this. We incur the danger of creating electrical currents in cables or other things in our patients since the radio frequencies produced in MRI consist of a changing magnetic field. These electrical currents are known as e-fields.

It is also necessary to explain radiofrequency receiver coils. These, too, are based on Faraday's Law of Induction principles. We should already be aware that each hydrogen nucleus has its own magnetic field. This is known as a magnetic moment. Also, as our patient is placed in the high static magnetic field, a number of hydrogen nuclei align parallel to the magnetic field vector and anti-parallel to the static magnetic field vector. There will always be a majority of hydrogen nuclei pointing in the direction of our static magnetic field's vector or B_0. This happens because lower energy hydrogen nuclei point in this direction whereas higher energy nuclei point perpendicular to the vector of our static magnetic field. Weaker hydrogen nuclei will always exist alongside stronger hydrogen nuclei. As a result, more hydrogen nuclei will point in the direction of our static magnetic field's vector. Because each hydrogen nuclei has its own magnetic moment, the sum of all magnetic moments directed towards the vector results in net magnetism. This net magnetism moves from the longitudinal to the transverse axis once resonance occurs. The transverse axis contains the radiofrequency receiver coil, and when these nuclei change from one access to the other, a changing magnetic field is created. This will cause an electrical current to flow through our receiver coil, which will be recorded. The quantity of signal or electrical current produced in a receiver coil determines how that tissue appears in our vision.

The body coil, which is positioned in the gantry of an MR machine, may generate radiofrequency radiation. As you may expect, when we use the body coil to generate radio frequencies, we will expose a vast amount of tissue. In other words, we will apply this non-ionizing radiation to regions of the body that are not visible to us. The RF energy rapidly diminishes near the edge of the body coil volume. The radiofrequency energy is confined to the volume of tissue within the coil when utilizing a transmit-receive-only radiofrequency coil. This means that non-ionizing radiation will affect less tissue.

Other notions to comprehend when working with radiofrequency radiation and e-fields include near-fields and far-fields. The term "near-field" refers to the area immediately around our RF emitter. The far-field is the area that is more isocenter and further away from the RF emitter.

The RF coils comprise two electromagnetic coils – the transmitter and receiver. RF coils create an oscillating magnetic field (B_1). The magnetic direction of B_1 is perpendicular to the magnetic direction of B_0. A traditional MRI shows the B_0 moving in the horizontal direction along the bore and the B_1 moving in the vertical direction.

The B_1 field is typically turned on for a small amount of time (1 – 3 milliseconds), and these intervals are known as **RF pulses.** By adjusting the magnitude or duration of the RF pulses, the spin system can be rotated by variable **Flip Angles.** Most of the flip angles occur at 90° and 180°.

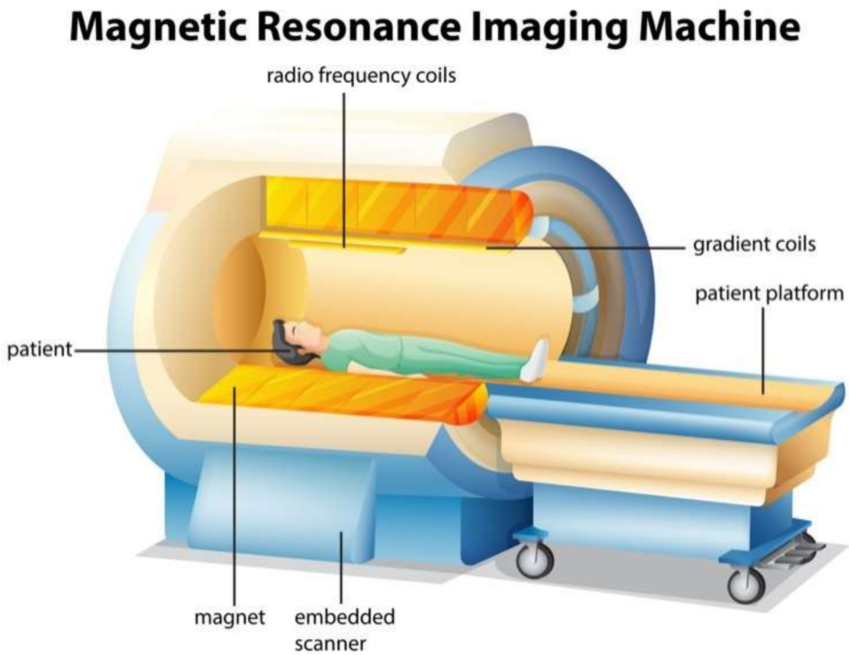

Image 7.1

Section 7.1 Understanding Radiofrequency Fields

In MRI, the RF ranges between 10 and 200 megahertz (MHz). This energy field is comprised of an oscillating electric field and an orthogonal oscillating magnetic field. At the same time, these fields interact with matter. The interaction might take many forms depending on the nature of the imaging. The electric field component can heat materials and cause high-frequency electric currents to flow, whereas the magnetic field component acts as a transient magnetic field. This is important because MRI can heat both superficial and deep tissues.

The electric field is often well protected from the patient's body due to the arrangement of guard rings in the RF coil design. We use an antenna (or RF coil) to monitor the movement of hydrogen in our patient. This is recorded and placed in a data space known as the “k-space.” We then transform the changed k-space into an image using an algorithm.

The magnetic component of the RF field is essential for imaging. In addition to flipping proton spins, it generates Eddy currents within the body's conducting tissues. As a result, heat accumulates, which worsens as the frequency increases.

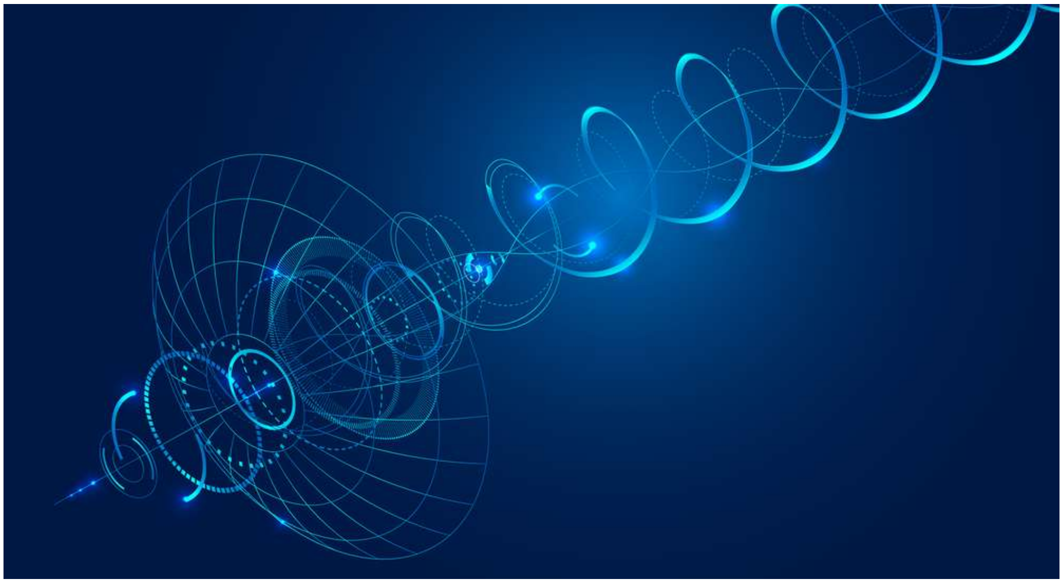

Image 7.2

Section 7.2 Potential Biological Concerns

Although MRI is generally safe, radiobiologists will spend years honing their ability to detect human reactions to the various magnetic and electrical fields used.

In addition to a threshold intensity response relationship, these fields have a time-intensity relationship. Above this threshold, shorter exposure times induce the same response.

7.2.1 Effects of Radiofrequency Fields

The hazards of RF radiation exposure are linked to heating. Thermal impacts on tissue have a connection between their frequency and waveform. Such effects have been observed in both experimental animals and patients. The heating of avascular structures, such as the eye's lens, causes cataracts. This has been observed in people and empirically confirmed in animals.

According to some evidence, ship-bound sailors who worked near radio towers and were exposed to high-intensity RF developed cataracts as a result. Intense RF exposure has been linked to a variety of blood changes, the most notable of which is lymphocytic depression. This was assumed when U.S. embassy staffers in Moscow were purportedly exposed to RF by sources outside the post a few years ago.

Image 7.3

Patient Evaluation

Patients should fill out a patient information form when they come for an MRI to ensure no contraindications. Completing the form, however, is insufficient since patients do not understand what is and is not significant enough to prevent them from getting an MRI examination. The receptionist or MRI technologist should give each patient enough time to explain the nature of the examination and determine the patient's condition (e.g., pregnancy, pacemaker, prosthesis, metallic implant, occupational history).

7.2.2 Potential Thermal Concerns

Non-ionizing radiation is indeed used in MRI. As a result, the energy employed is not known to cause any harm to our patient's cells. This is not to say that the impact of our RF transmitter will not affect our patients. As stated previously, the most severe issue with RF transmitters is the possibility of heating. To mitigate this risk, we need to study how much energy our patient is absorbing. The more energy that is being absorbed by our patient, the more likely heating will occur. The specific absorption rate (SAR) is used to measure how much energy our patient is absorbing during a scan. SAR unit of measure is in watts per kilogram (W/kg). In other words, SAR determines how much energy is deposited in each kilogram of tissue. Many factors influence the quantity of absorbed energy in our patients.

One aspect that influences the quantity of temperature produced in our patients is body habitus. The ratio of surface area to body mass has the greatest influence on this. The amount of surface area determines how much energy our patient can regulate. Their body mass will determine the amount of energy put in our patients. Because of this idea, obese patients will create more heat. Infants, on the other hand, will have a huge surface area but little body mass.

As a result, heating is not a significant worry. Body weight, gender, age, and patient height are all characteristics that may influence the SAR.

Four heat dissipation systems regulate the body's temperature:

- The first method is evaporation. When a person's body temperature rises, they may begin to sweat. As perspiration evaporates, it cools the surface of an individual's skin, decreasing core body temperature.
- Convection is the second mechanism. This idea addresses the movement of heat away from its source. As air travels over a patient, this causes heat to rise away from the body. We may cool our patient by convection by turning on the fan within the gantry.
- Conduction is the third thermoregulatory step. Putting an ice pack on our patient will cool the region where it is placed. Heat will be transferred as blood arteries pump cooled blood across the body.
- Radiation is the last thermoregulatory process. This term refers to heat radiating from or away from the body to keep it cool.

We will now consider what happens if our absorption rate is too high for the body's thermoregulatory system to tolerate. This may cause our patients to overheat, which could be dangerous. The MRI technologist knows how to restrict and reduce SAR in our patients. The system will monitor the SAR and establish heating thresholds. The technology will restrict the specific absorption rate to 0.5°C if the MR technician operates in regular operating mode. If this level is reached, the MR technician must adjust their settings to decrease the amount of warmth within the body. They may also increase the particular absorption rate limit. Before compelling an MR technician to adjust their parameters, the first level operation-controlled mode will restrict patient heating to 1°C. Heating to 2°C is possible with a level 2 operation-controlled mode. This level is exclusively available to our physicists, not MR technologists.

Let us review some strategies for lowering the particular absorption rate. The MRI pulse sequence might allow for additional heating in our patient. A 90° excitation RF pulse is employed in the spin echo pulse sequence to induce resonance in our patient. Following this, one or more 180° radiofrequency refocusing pulses are delivered. These 180° refocusing pulses promote phase coherency, allowing for more precise picture contrast (T2 contrast). It is critical to understand that by doubling the radiofrequency flip angle provided to our patient, we quadruple the quantity of energy deposited in our patient. As a result, a 180-degree radiofrequency pulse has four times the energy of a 90-degree radiofrequency pulse. Understanding a spin echo pulse sequence may dissuade a MR technologist from attempting to reduce our patient's particular absorption rate.

A gradient echo pulse sequence is another option available to the MR technician. This pulse sequence comprises a radiofrequency pulse with a flip angle stimulation but no 180° refocusing pulse. Depending on the gradient echo pulse sequence type used, the flip angle might range from 90° to less than 90°. When attempting to lower patient warmth, this may be a preferable option.

Another parameter that may be utilized to reduce our absorption rate is the number of concatenations or acquisitions. This setting allows us to capture echoes across numerous repeat periods. Our repetition time is the time between one excitation pulse and the next. We might enable more heat to be released from our patients if we increase our repeat time. We would employ ten 180° refocusing pulses to create ten echoes inside each repetition time if we had a repetition period of 1000 milliseconds and an echo train length of 10. We would need to employ 1000 millisecond repetition durations to obtain five echoes inside each concatenation of two. This process may aid in lessening the heat generated by our patients.

Another approach that might assist in minimizing patient warmth is parallel imaging. This procedure necessitates using two or more coil components in the phase direction of the scanned volume. This procedure can also occur if two or more coils are situated in the slice direction. With parallel imaging methods, each coil element may gather an echo independently throughout each repeating period. This implies that fewer radiofrequency pulses are required to acquire all the data required to generate a picture. As a result, there is less patient heating.

We found that the spin echo sequence uses the most radiofrequency pulses per repetition period, resulting in the highest heating. Sometimes, the spin echo sequence may be the most effective at displaying patient anatomy/pathology. We may be able to lessen warmth in our patients by increasing the distance between each 180° refocusing pulse. This is referred to as increasing the echo gap. This can be accomplished by reducing receiver bandwidth or raising the frequency encoding value. We would enhance our sample time by lowering receiver bandwidth. As a result, the acquisition window would be expanded, forcing a bigger echo space. Furthermore, by raising the frequency encoding value in our picture matrix, we would capture more data and extend our collection window.

Some procedures could boost the temperature of our patients. When we increase our phase encoding stages, we require more echoes to be captured, which increases patient heating. Additional RF pulses will be shown using techniques such as chemical pre-saturation (fat saturation). This method involves delivering numerous 90° radiofrequency pulses prior to an excitation pulse at a frequency corresponding to the fat's precessional speed. We can apply a technique analogous to spatial pre-saturation (saturation band) to remove tissues from our picture. Before the excitation pulse, a band is placed across these tissues and repeated 90° radiofrequency pulses are administered at the precessional speed of the tissues inside this band. As a result, these tissues will be removed from our picture. Both of these methods will raise the temperature of the sufferer.

Non-ionizing electromagnetic radiation in the frequency range of 0 to 3000 GHz is referred to as RF energy, as opposed to the extremely high photon energies and frequencies associated with ionizing electromagnetic radiation (e.g., gamma and X-rays).

It is crucial to consider the potential risks associated with rapidly changing radiofrequency regarding patient safety. Radiofrequencies in the megahertz range can result in heat deposition in the patient's tissues, determined by their conductivity and permeability to radiofrequency exposure. The amount of energy deposited is measured in joules (J), and we use an estimated

SAR to limit the amount of energy deposited and prevent excessive heating. However, it's important to note that SAR is only an approximation, and it's subject to the patient's thermoregulatory system, which determines how effectively the patient can dissipate the received energy.

In addition to the potential for heat deposition, time-varying radiofrequencies can pose a risk of burns, particularly in cases where the patient's tissue is exposed to high-energy radiofrequencies in the near-field. Electrical fields generated by implants can also cause burns through ohmic heating processes. Implants or foreign bodies more significant than 2 cm can cause enough electrical fields to induce burns, which can increase as the implant size approaches half the wavelength of the radiofrequencies used. The maximum heating temperatures occur when the length or diameter of the implant is equal to half the wavelength of the radiofrequencies used.

Radiofrequencies are generated using a transmit coil surrounding the patient or specific RF coils. In MRI, the transmit coil surrounding the patient may also be used as a receiving coil, known as a "transmit-receive" coil.

The isocenter is where the most radiofrequency deposition occurs, and hotspots or zones of greater energy radiofrequencies may be produced in the near-field or beneath the multiple transmitters around the patient. Certain factors can increase the likelihood of patient heating or burns in these areas, but the RF energy deposition decreases significantly as we move away from the isocenter.

The patient absorbs some of the transmitted RF energy during an MR procedure, which might cause tissue heating. As a result, the principal safety issues connected with the absorption of RF radiation are whole-body and localized heating. It's worth noting that raising core body temperatures to dangerously high levels can be fatal. The critical safety concern with local transmission coils is to avoid burns by limiting localized heating.

The number of pictures per unit of time and peak RF power is proportional to the average RF power (and SAR). During RF energy transmission, peak RF power is dependent on:

- Patient dimensions
- RF waveform
- Tip angle, and
- Whether the system's RF coil works in a linear or quadrature mode.

7.2.3 MR Safety Standards

The Food and Drug Administration (FDA) of the United States has issued "Non-Significant Risk Criteria" for MRI devices. If the SAR exceeds the following levels, an investigational device exemption (IDE) is required for clinical MR examinations.

- 4 W/kg (averaged over the whole body over any 15 minutes)

- 3 W/kg (averaged over the head over any 10-min period)
- 8 W/kg in any gram (head or torso, averaged over any 5-min period)
- 12 W/kg in any gram (extremities, averaged over any 5-min period)

A widely utilized MR safety standard was also produced by the International Electrotechnical Commission (IEC). The IEC MR Safety standard is divided into three levels.

- The normal operating mode is the first tier used for routine patient scanning.
- The first level control operating mode makes up the second tier. The MR system operator must take conscious action to enter the first control operating mode.
- The second control operating mode is the third tier, which is solely utilized for research reasons and is governed by an investigational review board (IRB).

Image 7.4

Section 7.3 Safety Considerations

7.3.1 RF Coil Heating and Transplants

Image 7.5 is an RF Drop-Off Diagram. The RF coil manufacturer typically provides these diagrams. The Y-axis shows the energy deposition, while the X-axis shows the distance from the isocenter. When considering local SAR, we can use this diagram to determine if an implant will exceed the maximum allowed SAR levels based on where the implant is situated inside the MRI unit.

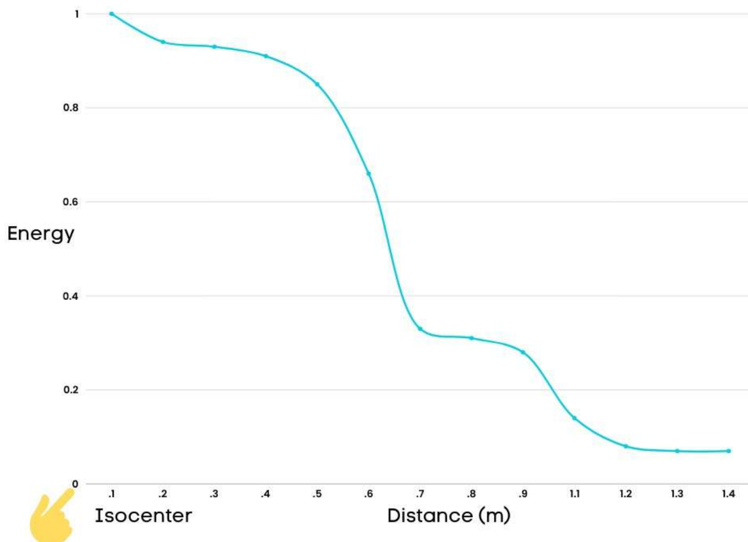

Image 7.5

To calculate the amount of RF deposition at a specific site in a patient, we need to determine where the patient will be orientated concerning the MRI unit's isocenter. Then, we must measure the distance the implant is located to the isocenter. The manufacturer can supply an RF drop-off diagram, which can help. For those who need to calculate the energy deposition in the implant, here's an example of how to do it.

Let's say we have a patient with an implant in their chest. Their head will be placed at the isocenter and that the distance between the patient's head and their implant is 0.45 meters. Now, we can identify RF energy deposition by drawing a vertical line from the distance of the implant to the plotted line. From that point, we draw a line horizontally until we reach the heating.

For this example, when we draw a vertical line from 0.45m, we determine that the implant will have a heating of approximately 0.82.

The maximum local SAR is 2 W/kg. So, we compute the following:

$$2\,\frac{W}{kg} * 0.82 = 1.64\,\frac{W}{kg}$$

This means that the implant alone will contribute to 1.64 W/kg of SAR.

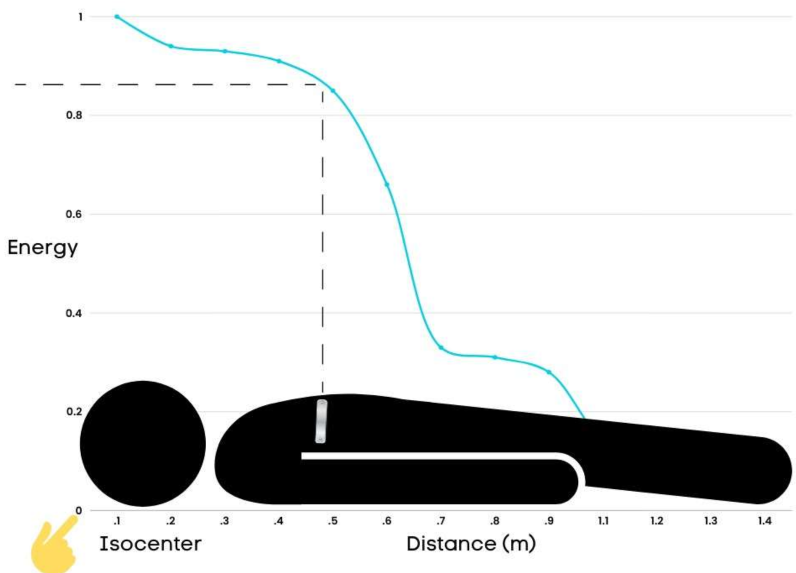

Image 7.6

7.3.2 RF Coil Heating and Pulse Sequences

During an MRI scan, pulse sequences produce images of the patient's body. These sequences are created using gradient coils and a radiofrequency transmitter in a specific way. The heat generated during scanning is closely linked to the pulse sequence used. As a result, we have several pulse sequences at our disposal, each with its unique way of creating images and affecting the amount of heat deposited in the patient's body.

One of the most commonly used pulse sequences is the spin echo sequence. This sequence consists of a 90° radiofrequency pulse followed by one or more 180° refocusing pulses. Of all the spin echo sequences, this one deposits the least amount of RF energy and causes the most negligible heating in the patient's body, making it the safest option.

However, other spin-echo sequences produce different levels of heat. For example, the rapid spin echo sequence uses a 90° radiofrequency pulse followed by multiple 180° refocusing pulses, leading to considerable warmth in our patients. Another spin echo sequence, HASTE, provides enough 180° refocusing pulses to cover the entire k-space.

Another option is the DRIVE pulse sequence, which involves a 270° RF pulse before the next repetition period. However, this sequence may cause substantial warmth in our patients.

It is crucial to understand the different pulse sequence options and their associated risks to ensure the safety and well-being of our patients during MRI scans. By considering each pulse sequence's potential risks and benefits, we can make informed decisions about which sequences to use for each patient's specific needs.

7.3.3 Possible Health Effects Associated with SAR

The temperature sensitivity of most biological functions causes thermal consequences. Each 50°F increase in temperature doubles the rate of chemical reactions. Temperatures of around 113°F are required for protein denaturation. The temperature influences the fluidity of cell membranes. Thermal impacts can be induced by heating the organism's entire body or by localized tissue heating. While just the body parts in the RF transmit coil are exposed to RF magnetic fields during an MR treatment, thermal reactions may impact the entire body.

RF fields are too high in frequency to excite excitable tissue electrically. As a result, heating is the only well-established mechanism for RF energy-related physiological impacts. The SAR threshold is 100 W/kg. The safest core temperature for workers is 103.9°F. The temperature at which teratogenic effects occur in pregnant women is 102°F. The pain threshold for the skin is 109°F. Finally, the resting metabolic rate is 1.3 W/kg, whereas it can reach 18 W/kg during intensive activity in highly trained athletes.

When subjected to a SAR of 1.0 W/kg for 1 hour, the insulated tissue will rise roughly 34°F. At any finite SAR, insulated tissue would reach infinite temperature in infinite time. When in operation, the human body's physiological heat dissipation processes limit temperature rise to a steady-state value. A body radiates to its surroundings since its surface temperature is higher than the ambient temperature.

The body temperature rises when subjected to RF power deposition until steady-state conditions predominate**.** The body wastes energy to the environment at the same rate as it absorbs energy from RF power deposition in a stable state. The temperature rises at first. Then, it gradually approaches the final steady-state value.

Section 7.4 Characteristics of RF Energy-Induced Heating

The relative amount and pattern of RF energy absorbed by the human body are determined by the physical dimensions and anatomic configurations of biological tissues concerning the incident wavelength. When the tissue's size is big compared to the incident wavelength, for example, RF energy is absorbed primarily on the surface. When it is modest compared to the wavelength, there is less RF power absorption, and the heating effects are minimized.

Most tissue heating caused by RF energy used for an MR procedure is due to magnetic induction, with only a minor contribution from electric fields. The ohmic heating of tissue is highest near the surface or periphery of human individuals' bodies and minimal at the center. This temperature distribution pattern is supported by predictive calculations and measurements conducted in phantoms, laboratory animals, and human individuals subjected to MRI utilizing 1.5 T or less MR systems.

7.4.1 Other Factors Contributing to Heating

As previously stated, the increase in tissue temperature generated by RF energy exposure during an MR treatment depends on several physiological, physical, and environmental parameters. The pace at which RF energy is deposited, the patient's thermoregulatory system's status, the presence of an underlying health condition or drugs, and the ambient conditions within the MR system are all factors to consider.

Although RF radiation is the primary cause of tissue heating during MR operations, it should be noted that exposure to the high static magnetic fields employed in MR techniques has been linked to temperature changes in some studies.

The mechanism(s) behind such an effect is still unknown. Nonetheless, the findings of these previously published studies warranted further research on human participants to evaluate whether the static magnetic field contributes to temperature variations reported during an MR operation.

7.4.2 RF Energy-Induced Heating and Thermal-Sensitive Organs

Human subjects' testes and eyes have limited heat dissipation capabilities and may be hurt or damaged by high temperatures. As a result, if RF radiation exposure during an MR operation is high, the testes and eyes are the principal locations of possibly hazardous consequences.

- **Testes:** RF energy-induced heating has been shown to negatively impact testicular function in laboratory studies. Suppose RF radiation causes scrotal and testicular tissue temperatures to rise to 38 to 42°C. In that case, spermatogenesis may be reduced or stopped, sperm motility may be hindered, seminiferous tubules may degenerate, and other pathological situations may occur.
- **Eye:** Due to its lack of vascularization, heat dissipation from the eye is sluggish and inefficient. Because of the thermal disturbance of ocular tissue, acute, near-field RF radiation exposures to the eyes or heads of experimental animals have been demonstrated to cause cataracts.

7.4.3 MR Procedures and “Hot Spots”

Hot spots (excessive concentrations of RF energy) could theoretically emerge during RF exposure due to an uneven distribution of RF power in combination with restrictive conductive patterns. If the RF energy-induced hot spots that arise during an MR treatment cause thermal hot spots, this would be an undesirable outcome.

Thermal hot spots may develop internally during an MR procedure, though. As a result of MRI utilizing relatively high SARs, significant temperature increases occur in the interior organs of laboratory dogs**.** Internal thermal hot spots may emerge as a result of MR operations, according to this data. As a result, the presence of putative interior hot spots in human beings undergoing MR procedures must be adequately investigated. One of the MRI thermometry techniques frequently used to guide therapeutic tissue heating and cooling may likely do this.

Section 7.5 SAR Modes

Time-varying radiofrequency is associated with heating and burn issues. By using radiofrequencies in the megahertz range, we can cause heat deposition in our patients. The conductivity and permeability of the tissue to RF radiation govern this. In joules (J), the energy absorbed by tissue is expressed. To reduce the heat inside our patient, we use an estimated SAR and limit the amount of energy deposited. The unit of measurement for a given absorption rate is watts per kilogram (W/kg). Utilizing SAR estimates allows us to regulate the amount of energy stored for each kilogram of our patient. Numerous factors must be considered when discussing the SAR, making it only a rough dosage estimate.

The first international standards for MR equipment safety were created in the 1990s by the International Electrotechnical Commission (IEC) and the US FDA, and they were codified as IEC 60601-2-33. The research study recognized three scanning modes based on the perceived risk to personnel affected by an MRI scan.

7.5.1 Normal Operating Mode

Normal Operating Mode is the level at which most scans are performed is considered safe for all patients.

IEC and FDA have determined that Whole Body Heating, averaged over any 6-min period, for Normal Operating Mode would be estimated at:

- Increase in core temperature to 0.5 degrees Celsius
- Increase in whole body SAR to less than 2 W/kg
- Head SAR less than or equal to 3.2 W/kg

7.5.2 First Level Controlled Operating Mode

Some imaging parameters may result in physiologic stress at this level (such as peripheral nerve stimulation or tissue heating). Utilizing this technique necessitates active medical supervision to make sure that the advantages and hazards have been carefully weighed. Devices operating in this mode must show and record dB/dt and SAR levels and a warning signal when the first level mode is about to be achieved, according to FDA regulations. Before the scan can begin, the MR scan operator must acknowledge this at the console.

IEC and FDA have determined that Whole Body Heating, averaged over any 6-min period, for First Level Controlled Operating Mode would be estimated at:

- Increase in core temperature to 1.0 degrees Celsius
- Increase in whole body SAR to 4 W/kg
- Head SAR less than or equal to 3.2 W/kg

7.5.3 Second Level Controlled Operating Mode

This level, also known as "research or "testing" mode, occurs when a procedure poses a danger to patients. SAR can operate over the maximum regulated limit (4 W/kg) in this operating mode. Second-level mode is employed only per an authorized ethics/human research procedure. Certain security measures (such as password protection) must be implemented to prevent unauthorized operation in this mode.

IEC and FDA have determined that Whole Body Heating, averaged over any 6-min period, for Second Level Controlled Operating Mode would be estimated at:

- Increase in core temperature to **greater than** 1.0 degrees Celsius
- Increase in whole body SAR to **greater than** 4 W/kg
- Head SAR **greater than** 3.2 W/kg

Section 7.6 Transmitting RF Coil

Nearly two-thirds of patient injuries in MRI are thermal/electrical burns. Most injuries happen to the torso or upper extremities. Common reasons include direct skin-to-skin contact, contact with a conductive device (such as an RF coil, EKG pads or leads, or clothes), and contact with the scanner bore's wall.

There are two physical processes for RF-induced thermal injury:

1) **Inductive Heating**: Faraday's Law states that conductive materials produce electrical currents known as Eddy currents while a magnetic field changes. Due to the ions in

extracellular and intracellular fluids, the human body also acts as a conductor. Metallic foreign objects are also good conductors. Heat is produced when electric currents are directed into a tiny, high-resistance region (such as the contact between metal and skin), which might lead to burns.

While a constant magnetic field does not affect a wire or current loop, a moving or changing magnetic field will cause a voltage to build up across the ends of a current loop, producing an electric current. The current or voltage is known as an induced current or an induced voltage and is the result of electromagnetic induction.

2) **Resonant Loop Heating**: If an electrical circuit forms a loop with components of both capacitance and inductance, it is known that it will resonantly absorb and release energy at a particular frequency. For instance, a coil of wire on a patient's body may provide inductance, but the skin-metal interaction may provide conductance.

Conductance is the reciprocal of resistance. Where resistance, by definition, resists the flow of electrons that can pass through a conductor, conductance is the ease with which electrons can pass through a conductor. Returning to the subject of Resonant Loop Heating, we create a pathway to allow electrons to travel when we place a piece of metal on a patient's skin.

Resonant loops may provide the maximum amount of inductive heating with burns imaginable while being a rather unusual circumstance.

Electromagnetic waves may be captured by wires and other long, conductive objects to generate electricity. When an antenna's length is one-half of the RF wavelength, it produces standing wave patterns of voltage and current that are concentrated around its tips. Therefore, the wires that are most likely to cause heating issues for MRI are those that are around 26 cm at 1.5T or 13 cm at 3.0 T.

Surprisingly, many individuals do not even realize they are burning and may only have minimal discomfort or redness right after the scan. The most likely explanation is that the subcutaneous fat, which lacks pain receptors, sustained most of the damage. More than 24 hours after imaging, patients commonly complain about blistering, increased redness, and discomfort.

7.6.1 Orientation of Induced Current Loop Relative to RF Transmitted Power

When a conductor is moved through a magnetic field, a current is generated because the free electrons in the conductor are pushed and pulled by the magnetic lines of force. *Induction* is the mechanism by which a conductor generates a current when placed in a changing magnetic field. Since the conductor and the magnet are not directly connected, this phenomenon is known as induction. A magnetic field "induces" a current in a conductor.

The conductor, often a wire, must be aligned perpendicular to the magnetic lines of force for electromagnetic induction to occur and exert its full force on the free electrons. The direction of the lines of force and the direction of wire motion in the field define the direction of the induced current. The ammeter (a device used to measure current) lights up whenever electricity flows through the conductor in the preceding animation.

When an alternating current (AC) is sent over a wire, the resulting electromagnetic field expands and contracts at different frequencies. An electrical current can be induced in a second wire by the first wire's expanding and contracting magnetic field. The second wire will carry an alternating current that looks very much like the first wire's current.

You typically see wires wrapped in coils because this wire design will allow us to concentrate the magnetic field's strength out of the coil's ends. The magnetic field may be further focused by wrapping the coil around an iron bar. The magnetic field will be the greatest inside the bar and at its ends (poles).

Because of its correlation to the rate of change of the magnetic field, induction is expressed in units called Henries (H). When the current changes at a rate of one ampere per second, one Henry is the amount of inductance needed to produce an induced voltage of one volt. The term emphasizes current over a magnetic field. This is because the current may produce the magnetic field, which is more amenable to precise measurement and control than magnetic flux.

7.6.2 Protection of Patient from Heating

Focal Heating: During a scan, electrical voltages and currents may be created in electrically conductive materials inside the scanner's bore. This event could cause this material to heat up due to resistance losses. This heat could be intense enough to cause damage to human flesh. One thing that affects how much voltage or current is induced is the diameter of the conductive loops. The larger the diameter, the higher the voltages and currents that could be generated, and the higher the chance that this could cause thermal damage to patient tissue near it.

Proximity Contact Heating: These occur when a patient's skin comes into contact with the gantry's side during acquisition. Obese people are more prone to this, and the burns are most typically observed on the side of the arm and shoulder area. The near-field is vital for energy and can burn tissues that come into contact with the gantry. Pads that meet the MR scanner requirements should be put between the patient's skin and any signal-transmitting RF coil to prevent heat injuries or burns. These pads keep the patient away from the RF coil that sends the signal so that there is space between the coil and the patient's tissues. A single-layer bedsheet does not provide enough protection or space between sheets. It is also essential to know that big conducting loops can be generated in the patient's tissues where skin-to-skin contact occurs, such as between the thighs. Pads may also be needed in these places to keep people from getting burned. Guidelines that have already been written are suggested to keep people from getting too hot and possibly getting burned during MR procedures.

Induced-Current Loops: Looping burns are the second form of burn discovered in an MRI. According to Faraday's Law of Induction, electrical current is created in conductive materials. The human body may act as a conductor, and an electrical current can be created if our patient forms loops. The e-fields, not the magnetic fields, generate the burns associated with MR. E-fields can be generated if our patient's bare arms or calves create a loop. Burns will not occur if these loops have adequate contact between tissue surfaces. Burns can arise when there is little contact between tissue surfaces. These can cause fourth-degree burns.

The easiest way to explain this is to imagine a sprinkler hose. If we ran water through this hose and placed our hands at the end, the water would softly stream over our hands. The water running via this pipe depicts electrons moving through our patient's tissue. If we put our finger over the end of the hose to symbolize a minimum contact interface between tissues, then put our hands in front of it, the water would have to be driven through a smaller aperture, resulting in a higher velocity impacting our hands. If we envision electrons flowing into our patient and then driving the electrons via a smaller contact area, we will generate a stronger e-field and burn. This is exacerbated because the patient's dielectric tissue might behave as a current conductor. Burning will result from the resistance of the flowing current in the patient's tissue. To treat loop burns, place a divider between the tissues of contact, eliminating contact regions between patient tissues and preventing burns.

The size of an induced current loop affects the amount of current that can be generated and, by extension, the amount of heat that loop can cause. So, ensuring that the patient's tissues, such as arms and legs, don't form big electrical loops is essential. There have been reports of burns on the inner legs, fingers, and outer thighs caused by current loops in the patient's tissues that were caused by a big caliber. It is suggested to use the shielding pads that come with the equipment to help stop large-caliber-induced current loops.

More heating issues develop by forced current loops when lines or leads that can conduct electricity are involved. When electrically conductive materials (wires, leads, implants, etc.) need to be entirely or partially inside the volume receiving direct RF irradiation during MRI, care should be taken to make sure that no large electrically conducting loops (including patient tissue) form inside the MR scanner during imaging. The FDA has heard of several cases of significant injuries, like comas and lasting nerve damage, in people with implanted neurological stimulators who had MRIs. In these cases, the burns were caused by the hot electrode tips.

Heating by Resonance: This form of burning is induced by fields in our patient's conductive substance. The antenna effect is another name for this burning. Implants with sharp edges or insulated wires enhance the risk of patient burns. Pacing cables, ECG electrodes, neurostimulator wires, and other similar devices are examples. Wires such as sternal or non-insulated wires pose little risk of patient burns. The length of the cables is also determined by the quantity of heat created in our patients. An e-field may be formed if the length of the wire within our patient is a multiple of the resonant frequency radiated by the radiofrequency transmitter. This indicates that resonant burning is affected by field strength. Our resonance frequency rises as our field strength rises. To compute the resonance frequency of a 1.5 Tesla MR unit using the Larmor equation, multiply the gyromagnetic ratio (42.6 MHz) by 1.5 Tesla.

That is, our resonance frequency is 63.9 MHz. The resonance frequency at 3 Tesla is presently calculated to be 127.8 MHz. This increases the likelihood of resonance heating and more significant field strengths. Any length of wire might endanger the patient. As the length of the wire rises, so does the risk. We also discovered that uninsulated wire implants are less dangerous to patients than insulated ones. Smaller diameter wires, huge loops (indeed when patient tissue completes the loop), placement in the patient (if they are in the near-field), and form are all characteristics that raise the chance of a burn from a wire implant. Also, it is possible to add resonant circuits between the RF power being sent and the lead with the proper setup, lead length, static magnetic field strength, and other settings. This could cause the lead to heat up quickly and significantly, especially at the tips, in seconds. The heating could be strong enough to cause tissue damage or burns. This could also happen with leads or lines implanted, even if they aren't tied to anything else at either end. In a lab setting, it has been shown that heating some devices or lines may not be clinically significant at 1.5 T but is very important at 3 T. But it has also been shown that some devices may not heat up or cause major thermal problems at 3 T. Still, they may heat up to significant levels in seconds at 1.5 T. So, it's essential to carefully and strictly follow the MR conditional labeling and safety rules that have already been set up. These rules should only be used at the static magnetic field strengths at which they were tried. MR scanning at magnetic field strengths that are either bigger or weaker than those studied may cause significant heating where none was seen at the tested field strengths.

For all of the above reasons, electrically sensitive leads or wires should not be exposed to the RF-transmitted power during MR scans unless it is done carefully and the proper steps are taken to ensure the leads or tissues don't get too hot.

When electrically conductive materials outside of the patient need to be in the area of the MR scanner's RF transmitting coil during imaging, care should be taken to put thermal insulation (like air, pads, etc.) between the patient and the electrically conductive material. The electrical conductor should try to stay away from the patient as much as possible. If the body coil is being used for RF transmission, you should try to place the leads or lines as far away from the inside walls of the MR scanner as possible. During imaging, if electrically conductive lines have to touch the patient directly, it might be a good idea to put cold compresses or ice packs on where they touch the patient.

As mentioned above, it has been shown that during MR, resonant circuits can be set up between the RF energy being sent and specific lengths of long, electrically conductive lines or leads, which can then be used as effective antennae. This can make the tips of these lines or leads heat up to more than 90 °C in just a few seconds. So, patients with long electrically conductive leads, such as Swan-Ganz thermodilution cardiac output–capable catheters or Foley catheters with electrically conductive leads, as well as electrically active implants like pacemakers, ICDs, neurostimulators, and cochlear-implants-and-any-leads that go with them, should be considered at risk for MR studies if the body coil is to be used for RF transmission over the region of the electrically conductive lead. This is especially true for higher-field systems (like those with a field strength of more than 0.5 T) and imaging methods that use fast spin-echo or other MR patterns with a high RF duty cycle. Before letting such a patient use the MR machine, a visiting Level 2 MR Physician should conduct a risk-benefit ratio analysis.

The static magnetic field strength of the MR scanner (which determines the RF frequency at which the device works) and the length, orientation, shape, position, and inductance of the electrical conductor in the RF-irradiated volume being studied are just some of the things that affect whether or not there will be significant heating. Almost any piece of lead longer than a few centimeters can release much heat. It is essential to know that out of all electrically conductive implants, lines or "leads" are the ones that pose the most possible thermal risk because they can act as sensors so well.

Reflective Burns: Reflective burns are the ultimate form of burning. This heating occurs when a conductive substance is placed on top of our patient. This substance can cause e-fields and hence burn in our patients. Avoid laying any conductive material on our patient to eliminate reflecting burns. Awareness of items that might enhance the probability of burns is critical. Medication patches with foil backing can generate e-fields that can burn patients. Metals in tattoo ink can also enhance the probability of burns. Even after the tattoo is removed, the metals contained inside the ink are spread throughout the patient's body and may cause burning. Staples put on our patient may potentially cause patient burns. On the contrary, dermal or other piercings have little risk of burning a patient.

A heat sink can reduce the risk of burning from tattoos or piercings. It is a substance that may be utilized to reduce the temperature of our patient in a specific location. A heat sink is something like an ice pack. It can considerably reduce the warmth created in regions where there may be a tattoo or staples. These sorts of burns can be avoided by using a heat sink.

The final point to remember about the hazards connected with radiofrequency transmitters is that only regions exposed to RF radiation may cause burns. Having stated that, neurostimulator wires in the brain will not cause resonant heating when scanning an ankle. This is because these electrodes will not be exposed to RF radiation. Another essential point is that if a transmit-receive coil is employed, implants outside of that coil will not be exposed to radiofrequencies and will not heat up. As a result, it is critical to accurately identify which body areas are being scanned and which are being exposed to radiofrequency energy to estimate the dangers associated with the radiofrequency transmitter.