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MRI Thermal Impacts

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Abstract

Subject: MRI (Magnetic Resonance Imaging) Thermal Impacts

Everyone knows how bio-implants solve significant health issues and make life easy. However, on the other side, the manufacturers and developers understand the complexities and safety measures that need to take while developing these devices. With the rising needs and usage of bioimplants, some significant problems are rising parallelly. There have been numerous reports of thermal injuries during MRI procedures. Nowadays, people with bioimplants are strictly advised not to take MRIs. We will see the basic buildup of the generic MRI machine, the principle on which it works, and discuss its components briefly. Possible factors responsible for heating mechanisms during MRI will be addressed. This report summarizes different papers and discusses potential heating aspects during MRI and SAR at implant locations. A simulation of a phantom with an implant inside an MRI is done to visualize the SAR. This simulation was done with the help of SIM4Life software.

Outline

Introduction

* Background
* Safety

Device Characteristics

Theory

* Possible Heating Mechanism During MRI
* MRI induced heating in Pacemaker

Discussion

* Safety concerns and guidelines and Short and long-term exposure effects.
* Risk-benefit analysis

Computer Analysis

* Simulation Settings
* Results (Modified location)
* Results (Original Location)

Introduction

Background

Magnetic Resonance Imaging (MRI) are scanners that use static, gradient, electromagnetic field, and radiofrequency to produce high-quality anatomical images. They emit Electromagnetic Frequency (EF) at 64 MHz (1.5 T MRI) and 128 MHz (3.0 T MRI), which induces a strong electromagnetic field and causes heating of tissues. This becomes even more dangerous if a patient is carrying an implant. Temperature increases for purely biological bodies and even for body-carrying implants. Cases have been seen where the whole body and local tissue-specific absorption rate (SAR) changes. The entire situation becomes more drastic if the implant is conductive. It couples with the induced field and results in local amplification of electric areas and localized hotspots (Yao et al., 2019).

If we consider the physical interactions, the risk taken by a patient undergoing MRI with an implant can be categorized into basic four categories: Forces and torques exerted by the static magnetic field on ferromagnetic objects; forces, also known as Lenz forces, and corresponding torques exerted by the static magnetic field on moving metallic objects. Failure of an active device, such as a cardiac pacemaker, because of high EM fields in MRI, resulting in missing support for essential functions or possibly functional damage due to erratic behavior; local heating and tissue damage caused by currents created by time-varying RF and gradient fields in the implant (Winter et al., 2020).

Commercially MRI scanners range from 0.2 Tesla (T) to 3.0 tesla (T). Few research units have the authorization to operate above 3 T. Though most scanners involve for general diagnostic purposes are 1.5 T in strength [1]. The medical device that relies on power generated by the human body or gravity for its active functioning rather than depending on any external power source is called a passive implantable device. At the same time, active medical devices rely on any power source or an electrical supply for their operational functioning. These devices are totally or partially introduced into the human body surgically. And they are intended to remain inside the body after the procedure [2].

Safety

Typically, scanners are made to give anatomical views of biological tissues and not deal with conductive objects. By no means can they detect any metallic device and can adjust the safety measures like changing the scanning parameters or rejecting the subject. There has been a considerable gap where safety concerns need to be implemented to deal with this type of situation. Technologies like this are still far from realistic; until then, safety concerns need to be followed for patients with implants (Winter et al., 2020). Patients undergoing MRI with ICDs, influence strong EM field, which might result in malfunctioning of the ICD, or might even show unpredictable functions and may result in essential support of critical functions. These devices like Pacemakers/ Cardioverter – Defibrillators heat up at the lead (tip) and the rings. The heating of leads depends on numerous things. Later in the text, the discussion is made on the heating of leads depending upon the configuration of pacemakers and its dependency on heating in the role of lead structure.

Device Characteristics

A typical MRI system consists of a Magnet, gradient coil, RF coil, scanner, and patient table. Most clinical MRI machine uses 150 watts at (1.5 T) 64 Mhz to generate anatomical images (Mattei et al., 2010). The idea is visualized by image construction and viewing control processing. The diagram below shows the MRI system in brief.

Diagram

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Theory

Possible Heating Mechanism During MRI

Electromagnetic induction is the primary reason behind causing burns during MRI. This can be minimized by reducing the number of loops in the cable and keeping electrodes as close together as possible (Dempsey & Condon, 2001). However, heating can be induced by time-varying magnetic fields employed in MRI through a variety of mechanisms:

Electromagnetic Induction Heating

Time-varying gradient magnetic fields and radiofrequency electromagnetic fields used in MRI can generate voltages and currents in conductive materials. These circulating currents impel power loss by ohmic heating, called induction heating. The primary cause of thermal damage encountered during MRI has frequently been thought to be electromagnetic induction heating of monitoring wires. The formation of a loop in the monitor cable would increase the circuit's inductance, resulting in more enormous currents with increased cable heating (Dempsey et al., 2001). An electromotive force (EMF) is created when magnetic induction flux changes in a fixed circuit. The EMF lasts as long as the flux changes. The induced EMF's magnitude is related to the flux change rate. The changing magnetic field induces eddy currents, which cause joule heating of the conducting specimen (Dempsey & Condon, 2001).

Heating in a Resonance Circuit

The maximum heating occurs when the circuit is in a resonant state, this heating is electromagnetic induction heating which also results in maximum current. When a conducting coil is kept under a time-varying magnetic field is equivalent to a circuit having inductance (L), a capacitance (C), a resistance (R), and an oscillating voltage at an angular frequency . Now the peak current in the circuit is denoted by ( =1/(L/C) ^1/2) (Dempsey & Condon, 2001). Thus, resonance occurs at the frequency where the inductance and capacitive impedances are equal and opposite, canceling each other perfectly. As a result, to tune a circuit, either the capacitance or the inductance may be changed until resonance occurs at a given frequency (Dempsey et al., 2001).

Heating due to Antenna Effect

When we think about the current in the whole cable, this wire can also perform as a radiofrequency (RF) wire antenna. These wires have more sensitivity towards the electric components than a magnetic component of the RF radiation. The maximum electric field density is localized at the tip of the antenna. This is the additional electric field induced by currents in the antenna (Dempsey & Condon, 2001). Resonance occurs when the antenna is about half a wavelength long (half-wave dipole antenna). When resonance is reached, the electrical energy is limited to the local area of a certain antinode. As a result, the antennae's strongest electric field is near the tip (Dempsey et al., 2001).

MRI induced heating in Pacemaker

The induced current in pacemakers during an MRI depends on device position and lead pathway inside the body. In most cases studied, current intensities and resulting heating effects are very small. Though, in some conditions of anatomical arrangements, the induced heating can be very high in worst-case scenarios when the lead pathway is along the wall of the phantom. Sensor technique was developed to measure the RF induced current density inside pacemaker lead with utmost precision to bring the resulting values to the lead tip surface under the circumstances (Nordbeck et al., 2009).

The recent studies of 115 pacemaker patients who undergo MRI show no adverse effects, while 4 revealed significant injuries. This can be due to RF-related myocardial injury through the heating of tissues. There are chances of heating effect in several configurations matching the situation in the body. Out of 720 arrangements, 504 showed minor heating of implants; this heating is below 10°C. After this experiment, more studies and analyses were made on the patients undergoing MRI carrying pacemakers. It is observed that some even showed elevation of more than 20°C. Even the minor alterations of almost 2-cm can double or halve the value of implant heating. The fact that implant heating varies so widely, based on the exact configuration of the leads, could explain why a large percentage of pacemaker patients do not exhibit significant tissue heating in the vicinity of the leads on MRI. Other studies report that the phenomenon occurs even when the test is performed under relatively hazardous conditions, for example, with relatively high SAR figures (Nordbeck et al., 2009).

It has also been found that there has been minor heating in a relatively large number of device configurations of about 2.9°C with IPG. Compared to IPG placement in the right pectoral area, the mean temperature elevation, and therefore averaged patient risk, was much lower when the IPG was implanted in the left pectoral region. In some anatomically acceptable configurations, cardiac pacemaker devices implanted in either the left or right pectoral area can produce substantial RF-related implant heating (Nordbeck et al., 2009).

Chart, box and whisker chart

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FIG. 1. The graph depicts the absolute value of pacemaker lead tip heating as a function of IPG placement and lead routing. The lead tip location and thus the lead pathway were altered throughout the surface areas orientated in a coronal plane (ventral, medial, and dorsal) for each position (medial, superior, and lateral in both right and left pectoral regions), thereby encompassing the complete heart volume.

Graphical user interface, text, application, website

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FIG. 2(a).

Graphical user interface

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FIG. 2(b).

FIG. 2. Fluoroptic temperature systems are used as these are considered gold standards in MRI- related implant heating analysis; they also suffer from the RF heating problems as these are very localized to hotspots. 2(a) Pacemaker lead heating of a single chamber system linked to the IPG in the right pectoral area is dependent on lead tip heating. In each arrangement, the induced current intensity inside the implant was measured and translated to lead tip heating values as specified. Maximum (left) and minimum (right) implant heating is shown. 2(b). Pacemaker lead heating of a single chamber system linked to the IPG in the left pectoral area is dependent on lead tip heating. In each arrangement, the induced current intensity inside the implant was measured and translated to lead tip heating values as specified. Maximum (left) and minimum (right) implant heating is shown.

Experimental research in this sector has yielded a wide range of results and indicated that numerous factors could influence the amount of heating created at the lead tip. One of these is the lead's structural parameters. PM/ICD leads inside a human trunk simulator exposed to the RF field of a 1.5T MRI scanner. The birdcage coil is introduced into a cage that acts as an RF shield, and exposure is measured by an RF amplifier that delivers up to 150W at 64 MHz. A temperature variation of 2.1°C to 15°C was observed. A significant amount of heating was marked at the tip and the ring (as high as 4.2°C) (Mattei et al., 2010).

Active fix leads showed a higher temp increase than passive fixed ones (4.7°C vs. 7.4°C). At the implant tip, there were varying results, ranging from 2.1°C-15°C. A significant amount of heating was also observed at most of the rings of bipolar leads. (Temperature changes from 0.1°C to 4.2°C). Temperature increase at the ring was reported for the bipolar tips—the higher the temperature at the ring, the lower the temperature at the tip. Unipolar rings have a higher temperature than bipolar. At bipolar rings, there were no signs of significant temperature increase, so the temperature of the bipolar lead is generally higher than unipolar. A significant difference was observed between active and passive fix leads. The temperature increase for the former was 7.4°C (active), compared to 4.7°C (passive) (Mattei et al., 2010).

Table

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FIG 3. This table summarizes the results; we can see that the higher the temperature at the ring, the lower the temperature at the lead tip, and the lower the temperature at the ring, the higher the temperature at the end. A varying range of temperature was observed at the implant tip.

Chart, bar chart

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FIG. 4(a). FIG. 4(b).

FIG. 4 (a). and (b). from these graphs, we can summarize that active fix leads have higher heating at the tip than passive fix leads. We can see that the temperature increase in the bipolar leads is generally higher than in unipolar leads; this might be due to the development of loops between the polarity in bipolar.

# Discussion

Safety concerns and guidelines and Short and long-term exposure effects.

Before entering the MRI, there have been various guidelines for the physician to check. One of those images is mentioned in Figure 4. A typical MRI should scan from 20 – to 90 minutes, depending on the body being examined. Although MRI guidelines are being categorized into three categories:

MR Safe

"a medical equipment that provides no known risks exposed to any MR environment." MR materials are electrically non-conductive, nonmetallic, and nonmagnetic."

MR Conditional

"A safe medical device in MR environments when used in specified conditions, such as static magnetic fields, time-varying gradient magnetic fields, and radiofrequency fields."

MR Unsafe

"Medical equipment that causes unacceptable dangers to the patient, medical personnel, or other

people in the MR environment" [2].

Graphical user interface, text, application, chat or text message

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FIG. 4.

Table

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FIG. 5. Example of MR conditional labeling for a passive medical device.

Risk-benefit analysis

Before obtaining an MRI, patients should consult with their doctors after reading and analyzing various papers. This will assist physicians in controlling the RF and determining whether or not an MRI is necessary. Despite many case studies, a relatively small percentage of persons experience issues due to heating during MRI. The SAR value, which is relatively low, is also explored later in the study. The tip of the wire is only heated in pacemakers since the rest of the wire is insulated. As a result, the SAR value stays relatively low.

Computer Analysis

Simulation Settings

This simulation was performed to calculate the SAR at different implant locations. This simulation is done at 64 MHz. The software used is Sim4Life. I modified the Tutorial “Generic MRI and Lead Pass.” SAR was calculated at the lower region of the body with the implant. Then, the SAR was calculated at the thoracic region with the implant. ASTM Phantom was used carrying a lead pass. The first simulation is done by considering the original place of the implant, and then the 2D plot was drawn to show the SAR at specific locations. Some of the characteristics of the simulation are: Relative permittivity = 4.2, Mass density = 1000 kg/m^3, electrical conductivity = 0.448 S/m, relative permittivity = 80.38. In the second simulation, the location of the implant was changed. The implant was located at the center of the phantom, and the size of the Huygens source was reduced to one-fourth of the original size to replicate the pacemaker. The size of the implant was also changed, while the rest of the characteristics remained the same as in the tutorial.

A screenshot of a computer

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Description automatically generated with medium confidence

Results (Modified simulation)

Graphical user interface

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SAR is calculated far from the lead pass, and the 2D graph was drawn.

Graphical user interface

Description automatically generated

SAR is calculated near the lead pass, and the 2D graph was drawn.

Results (original location)

A screenshot of a computer

Description automatically generated with medium confidence

A screenshot of a computer

Description automatically generated with medium confidence

The calculated value of SAR is a little above 8.0 x 10^-5

Graphical user interface, application

Description automatically generated

The extra slice at the location of the lead pass

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