Overview of Device Interactions
within the MR environment

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Keywords: magnetic resonance imaging, MR safety, MR compatibility, MR environment, MR interventions, instruments, devices, MR testing,

Introduction

MR safety and compatibility are important issues for medical devices. The number of MRI scans is increasing followed by a number of various clinical applications and interventions to be guided by MRI. Implants, Interventional instruments, external fixation system and surgical assist tools, endoscopes, robots and manipulator systems as well as MR accessories have been developed for use with MRI. Besides usual basic interactions such as induced forces and torques, RF heating and induced voltages, additional safety issues specific to a particular situation must be considered to evaluate and test devices for MR safe/MR conditional labeling and including a precise and reliable functionality within an MR environment [1]. In addition, the MR operator has to be educated about MR safety relevant interactions in order to safely scan patients during interventions and science processes of acquisition of data.

Interactions

Magnetically induced displacement forces and torque due to the static magnetic field

A basic interaction is the static magnetically induced displacement force on materials susceptible to a magnetic field. For diamagnetic, paramagnetic and ferromagnetic materials in devices below their magnetic saturation when exposed to a magnetic field, the maximum deflection (angle) occurs at the point where the gradient product $|\mathbf{B}| \cdot |\nabla \mathbf{B}|$ is maximal. For ferromagnetic materials in devices that are magnetically saturated, the maximum deflection is measured where $|\nabla \mathbf{B}|$ is maximal [2]. Thus, especially for devices or parts within the magnet bore entrance, the maximum magnetically induced displacement force is dependent on the extent of the static magnetic field and influenced by the active shielding of the magnet, the field decay, and is also dependent on the magnetic saturation of the test object material and the magnetic property of the material itself. In order to generate a worst-case for the force test, specific information is required about the device material and the real magnitude of the static magnetic field including the magnet shield characteristics, to determine the appropriate test position.

In addition to the static magnetically induced force, a dynamic magnetically induced force due to Lenz's Law can be detected for electrically conductive device parts of a larger size and having closed electrically conductive loop-structures that are translated.
through the spatial gradient of the static field or across magnetic field lines in the homogeneous isocenter area. The interaction is dependent upon the speed of the movement, the magnitude of the spatial gradient magnetic field and the effective area of induction as well as on the conductivity of the component’s material. Thus an eddy current brake effect will interact potentially moving components and the usual handling of instruments in the magnetic field during an intervention.

The static magnetic torque is another basic interaction that can affect a device or system. Forces and torques can be static or dynamic. Considering the static magnetic induced torque, the magnitude of the torque depends on the device dimensions and the magnetic saturation of the material, if assuming a device, which is completely magnetically saturated. Additionally, it depends on the strength of the static magnetic field, if the device is not completely saturated. The maximum static torque will be experienced by the device at the isocenter of the magnet where the static magnetic field is homogeneous and maximum.

The dynamic torque, which can occur in the static magnetic field, becomes detectable if electrically conductive parts are rotated within the static magnetic field. Device parts with high conductivity and a significant area of induction of eddy currents will especially exhibit a counter torque that influences the handling of the device.

Furthermore, the operator must also be aware of mechanical forces such as Lorenz forces and resulting torques caused by large electric currents in wires within the electromagnetic or static magnetic field of the MR system.

*Induced heating, voltages and vibrations due to electromagnetic and switched gradient magnetic fields*

Radio frequency (RF) induced heating is complex concern and dependent upon multiple parameters. RF pulses in the MHz frequency range apply the primary source of heating energy compared to switched gradient magnetic fields in the kHz range. However, it should be noted that if specific induction criteria are met for interaction with switched gradient magnetic fields, heating could take place in electrically conductive structures, too.

Not only device properties like electrical conductivity, dimensions, etc. have to be considered, but also the geometric arrangement relative to the specific MR transmit coil and the parameter adjustments of the MR sequence which results into the local electromagnetic field. Loop closing contacts for example the insertion of an instrument can be dangerous for the patient due to induction and coupling with the RF field. Sparking [3] because of induced high voltage is possible for device parts touching the skin of the patient or the interventionalist. In this area of RF fields, computer simulation of electromagnetic fields, SAR and temperature distribution is being developed to assist in analyzing heating and issues of induced voltage for devices [4], [5], [6].

Switched gradient magnetic fields, currently, for instance, 45 mT/m gradient strength and 200 mT/m/ms gradient slew rate (see IEC 60601-2-33 for limits [7]) are used in
MRI to provide the spatial encoding of MR signals. Induced voltages due to switched gradient fields as well as the above-described RF environment can interfere with conductive device parts as well as cables and can cause of malfunction or unintended tissue stimulation (if having contact to individuals). In addition, dynamic forces and torques can be generated by induction resulting in vibration of the device because of interaction with the static magnetic field. The magnitude of such vibration is dependent of the geometric position, arrangement of the device relative to the gradient coils (x,y,z) and the gradient parameters (duty cycle, gradient, slew rate) as well as on the size and mass of the device and its surrounding. Gradient induced vibration is having its source inside electrically conductive devices and components.

**Malfunction of the devices due to the static magnetic field, electromagnetic and switched gradient magnetic fields**

Evaluating the safe function/malfunction of passive and especially active systems includes both the correct function of the device within the MR environment and the safe operation of the MR system. Here the influence on the image quality is a major consideration. RF emission by actuators or other active electrical parts (e.g. microcontroller, oscillator) can significantly decrease the image quality of the MR system. Interference can be visible in the MR image, appearing as, for example but not limited to: noisy images due to spikes, dots or stripes/dotted lines [8]. Other degradations, disturbances or inaccuracies of the MR image are likely (decrease in signal-to-noise ratio (SNR) or B$_0$ field homogeneity, etc.).

The inhibition of electrical circuits or mechanical magnetic components such as springs or levers are examples of how an MR system can affect the safe function of a device. Magnetic saturation, forces and torque and forced orientation by the static magnetic field as well as RF and switched gradient interactions are sources of direct or indirect impact.

The maximum peak acoustic noise level of the MR system during scanning is not allowed to exceed 140 dB relative to 20 µPa in an accessible area of the MR equipment [7]. Thus the acoustic noise could also be an issue for certain sensors under such extreme conditions. Finally, the interaction among different devices or systems should be important to be considered.

**MR image artifacts**

In most cases MR image artifacts do not primarily affect the patient safety. However if exact positions are needed e.g. for needles [10] or implantation of x-ray markers or radioactive seeds, the safety issue becomes critical for the whole diagnostic procedure. Susceptibility [9] and RF artifacts [11] depend on different parameters such as the magnitude and orientation of B$_0$, the alignment of the medical device relative to B$_0$ and MR pulse sequence parameter adjustments. Artifacts can lead to diagnostic misinterpretation by significant lack of information. RF artifacts are likely due to coupling of electrically conductive structures with the electromagnetic field e.g. by the instrument introduced into the patient. The coupling can result in signal shielding (Faraday cage effect), distortion or even intended amplification of the signal (mainly by designed structures, e.g. coils), which can be used for active device visualization such as tip
tracking. The usage of “near real tissue” susceptibility materials such as plastics or ceramics will minimize artifacts. However, plastic parts can contain remaining hydrogen protons, thus noise signals can occur if folded by Fourier transformation into the field of view from outside the volume.

Summary and discussion

In the MR environment the static magnetic, the switched gradient and the electromagnetic fields are being the source for simple to complex interactions between devices and the MR system resulting in serious issues for MR safety and compatibility of such devices. Currently several committees are working on standards and guidance for addressing all identified interactions in order to provide appropriate test methods for devices used with MRI.

Appendix: MR interactions and their parameters

Below, the most important parameters are listed as summary for the different MR interactions

1. Magnetic induced displacement force (static, dynamic)
   for ferro- and paramagnetic materials (all metals) depend on
   • the static magnetic field (saturation)
   • the static field gradient of the fringe field
   • the magnetic saturation property of the device material

2. Magnetic induced torque (static, dynamic)
   torque depends on
   • the static magnetic field (saturation)
   • the device dimensions
   • the magnetic saturation property of the material.
   (1. and 2.) Dynamic forces and torques are possible for electrically conductive devices and structures which are translated in the magnetic field. This interaction depends on
   • the speed of the movement
   • the magnitude of the spatial gradient magnetic field
   • the effective area of induction
   • the conductivity of the device material.

3a. Radio frequency (RF) induced heating (also 4a. RF induced voltages (stimulation, activation))

Radio frequency (RF) induced heating is a complex and multi-parameter dependent issue. Parameters are:
• electric conductivity and permittivity of the device (impedance of connected device components if electric)
• geometric dimension of the device and configuration
• surrounding tissue conductivity and permittivity
• geometric arrangement relative to
• the patient body relative to
• the specific used MR coil (electromagnetic field characteristic)
• center frequency of the specific MR system

3b. Gradient-induced heating (also 4b. Gradient-induced voltages (stimulation, activation), 5 Gradient-induced vibration) due to switched gradient magnetic fields depending on
• gradient amplitude (x,y,z)
• effective stimulation time of gradient pulse
• (both above = gradient slew rate and gradient pulse shape)
• device position within the gradient coil
• device orientation within the gradient coil
• effective area of induction
• the conductivity of the device’s material vibration
• static magnetic field (providing counterpart)

6. Safe operation of the device within the MR environment (dependent on individual demands) and

7. Safe operation of the MR system = image quality issues (SNR, B₀-homogeneity, etc. addressed by MR manufacturer individual limits)

Interferences to or by a medical device are individually based on interactions described above. Static and dynamic magnetic fields, the switched gradient magnetic field as well as RF electromagnetic fields and the acoustic noise pressure level can inhibit or distort the safe operation to a certain determinable amount. Device configurations and orientations in the MR environment are always a considerable parameter matrix.

References
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