Safety Considerations in Magnetic Resonance Imaging (MRI)

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Summary

MRI is now an important diagnostic tool in medical management. There are numerous safety issues to be considered by the clinicians prior to requesting an MRI examination for their patients. These include those related to the magnetic field, gradient magnetic fields, the patient and contrast medium. This paper discusses the dangers and necessary precautions essential to reduce the risk of untoward complications from MRI.

Key Words: Magnetic Resonance Imaging, Safety

MRI is playing an increasing role in the diagnosis and management of numerous medical conditions. What really is MRI? The physics is very confusing even for those who do it often. The simplified version will suffice to help appreciate the safety issues in MR imaging. MR imaging uses a strong magnetic field into which the patient is placed. The slice selection is done by the use of additional magnetic gradients which are switched on intermittently using separate gradient coils placed inside the main magnet bore. The required images are obtained using a series of radiofrequency (RF) pulses which are used to stimulate the region of interest and then turned off while the signal is collected. The MR scanner is placed in a specially designed room which is shielded against any extraneous magnetic or RF interference.

The increasing role of MRI is due to its superb soft tissue contrast resolution, its multiplanar ability, the absence of ionizing radiation and its ability to provide functional information. MRI is now the modality of choice in the investigation of the central nervous system (CNS) and the musculoskeletal system (MS) and plays an increasing role in the cardiovascular system. No long term adverse biological effects of MRI have been documented. and although MRI may be quoted as being completely safe this is only true if certain precautions are taken. In addition, there are also reversible effects of MRI.

MR imaging equipment produces three kinds of magnetic fields; the main magnetic field from the magnet itself, the rapidly changing gradient field and the oscillating radiofrequency field.

The safety considerations can be divided into those pertaining to the magnetic field, the gradient coils, the radiofrequency pulses, the patient itself and the contrast media that may be used.

The main magnetic field

This field is on permanently and is the strongest of the three mentioned earlier. Its effect is maximal at the center of the magnet i.e. the isocenter. The magnetic field is required for the proper alignment of the protons and depending on the type of magnet used the alignment may either be along the bore of the magnet or perpendicular to it.

I. Biological effects of the static magnetic field

To date there has been no known biological long term effects of the static magnetic field on tissue despite extensive research being carried out[1-3]. The vast

majority of studies show no effect on humans for static fields below 2.5T (where T is the magnetic field strength in tesla.) One tesla is equivalent to 10,000 gauss. Just to allow some comparison the magnetic field strength of the earth varies between 0.3 to 0.7 gauss between the equator and poles respectively. Exposure of volunteers to a field strength of 4.0T has resulted in dizziness, nausea and visual sensations of flashes of lights[4].

II. Fringe fields

The stray magnetic field that is felt outside the bore of the magnet is called the fringe magnetic field since the static magnetic field is not confined totally to the conventional walls, floors or ceiling. A practical way of determining the effect of the fringe field is to define the distance from the isocenter at which the magnetic field strength falls off to 5G. This is limited by the use of shielding (this can either be shielding of the room and/or magnet) which helps confine the fringe to an acceptable distance from the bore either within the room or truck if the machine is a mobile MRI. The shielding for the magnet can either be active or passive. This is an important consideration in planning especially at the time of installation. However for safety reasons patients with implants e.g. cardiac pacemakers are advised against being too close to the MRI room i.e. outside the 5G

III. Projectiles

This is a major safety concern to patients and medical personnel who enter the MRI room. Any ferromagnetic objects (earrings, scissors, hairpins, pagers, clamps, tie-pins or screwdrivers) may become airborne and accelerate towards the center of the bore of the magnet. Anyone coming between the airborne object and the magnet may become impaled by it. Ferromagnetic objects may reach velocities in excess of 66 km/h or 40 m.p.h. in the presence of a 1.5T magnet. It is therefore essential that any medical personnel entering the MRI suite pass through a metal detector to detect the presence of any metal. This can however be a problem especially during an emergency when in haste, screening is not done thus endangering all the staff within the MRI suite. The effect of the magnetic field may not be felt gradually but instead be sudden not allowing time for the person involved to react to the movement. In addition any credit or bank cards may be erased and wrist watches may be damaged if taken into the MRI suite.

Large ferromagnetic objects like anaesthetic trolleys, wheelchairs and patient trolleys if taken into the MR suite may cause injury to the personnel as well as to the machine itself. Special non-ferromagnetic equipment should be used in the MR suite to overcome this problem.

To this end there are hazard signs at the entrance to all MRI facilities which warn against the dangers of taking metallic objects into the MRI suite.

IV. Biomedical implants and prostheses

Devices made of ferromagnetic materials (iron, nickel and cobalt) pose a hazard due to object movement from torque (pulled towards the magnet) and effects of heating. The magnetic attraction can dislodge unanchored implants or can cause movement which may damage adjacent structures. These effects are maximal when the patient enters or exits the magnet. There is a general misconception that stainless steel is non-ferromagnetic. However this not true. Some types are indeed ferromagnetic. It is therefore essential that the patients are properly screened prior to any MRI examination especially if there has been any surgical procedures done.

It is very important to remember that any list of the biocompatibility of implant devices is only valid at the time of publication. The manufacturer may change the composition of the implants/prostheses without having to notify the supplier. It is also not necessary for them to inform the relevant regulatory body unless it affects the biomechanical performance of the prostheses/ implants.

Implants that have been firmly fixed in place are generally safe. This includes most orthopaedic implants (plates, screws, nails and rod), surgical implants (haemostatic clips, wires and drains), dental implants and even some neurosurgical implants (plates, drain and plates).

Those implants which are non-ferromagnetic materials

are not immune to hazards since they may heat-up during the scanning as a result of the radiofrequency pulses used. Even though the temperature rise is minimal, the patient may feel this and may result in motion artifacts if not warned.

The magnet must have an excellent field homogeneity to produce optimal images and the presence of any distortion of this field by the implants or prostheses may result in non-diagnostic studies. This is especially so with gradient-echo pulses. The size and type of metallic implant directly affect the severity of the artifacts[5]. Artifacts may not be considered to have any direct biological effects but the consequences of this to the patient if the artifacts results in an improper assessment or wrong diagnosis may be quite serious.

There is a misconception that the magnetic and RF pulse effects only affect the part of the body that is being scanned (like with the radiation effects of CT) and therefore if the part with the implant or prostheses lies outside the bore then it is safe. Unfortunately this is not so. The entire body is subjected to the effects of the magnetic field.

The following metallic implants or prostheses are contraindications to MRI.

a. Intracranial aneursymal clips

This is an absolute contraindication to MRI because it can cause death due to haemorrhage, ischaemia and stroke as a result of clip motion. A significant number of intracranial aneursymal clips are made of ferromagnetic materials and are therefore subjected to torque during the MRI study. More recent introductions using titanium are considered safe for MRI but it is strongly recommended the exact nature of the clip be determined prior to scanning. The artifacts due to non-ferromagnetic clips may still cause images of the brain to be poor.

The patient must be warned about the dangers related to the MRI procedure following implant if the clips are ferromagnetic. This must also be clearly documented in the notes.

b. Vascular clips

Vascular clips used to secure haemostasis in other parts of the body may be safe for MRI provided that they have been in place for more than 6 months to ensure there has been enough fibrosis to prevent motion. They may result in significant artifacts obscuring the area of interest.

The movement of ferromagnetic material is dependent on the changing magnetic field and thus the speed at which the patient is subjected will also affect the torque. With such patients the movement in and out of the bore of the magnet is done slowly.

c. Cardiac pacemakers

This is an absolute contraindication to MRI, therefore anyone with a pacemaker must be prohibited from entering the MR unit. The RF pulses used may actually take over pacing of the heart and result in ventricular arrhythmias. In addition the magnetic field may affect the proper functioning of the pacemaker itself (the so called "reed switch"). Thus because of the sensitivity of pacemakers to magnetic fields there should be ample warning signs to alert staff and patient to this danger.

Patients with previous pacemakers should also be contraindicated for MRI because if the previous leads are still within the body, they can act as antennae and cause fibrillation by the induced currents. The electrical components may also be damaged and dislodgment of the batteries may occur.

d. Intra-ocular ferrous foreign bodies

This is a serious problem with MRI. Unless the patient is specifically asked about any history of having intra-ocular ferrous foreign bodies or having worked with metal this information may not be forthcoming. The intra-ocular ferrous foreign bodies may move or be displaced during scanning resulting in damage to the globe of the eye or the surrounding tissue such as the optic nerve.

How does one go about excluding intra-ocular ferrous foreign bodies in a suspected patient? Are plain films good enough or is CT mandatory? Plain films are adequate. Studies show that if a radio-opaque foreign body is not seen on the plain film then, it is safe to perform the MR even though CT may show small

foreign bodies more clearly. If a foreign body is very small it will not undergo any significant displacement.

How do we know that an intra-ocular foreign body is ferrous? The answer is that we do not know but have to assume that it is so. It will have to be removed prior to MR being done.

e. Heart valves

These are no longer much of a major problem except for those that were manufactured prior to 1965 (Starr-Edward) which may contain ferromagnetic material and may be hazardous. The more recent heart valves (biological and mechanical) are safe and the artifacts generated are not significant and are limited to the region of the valve ring[6]. Thus MR imaging of mitral valve regurgitation and aortic obstruction may be diagnostic despite the presence of small localized artifacts.

f. Electronically, magnetically or mechanically activated or electronically conductive implanted devices

These implants include:

i. Cardiac pacemakers
   As discussed earlier.
ii. Cochlear implants
   This is a problem with cochlear implants and MR is definitely contraindicated. Patients should be advised about this.
iii. Ocular prostheses.
iv. Neurostimulators.
v. Bone growth stimulators
vi. Implantable drug infusion pumps.

In the presence of a strong magnetic field the function of the above mentioned implants is impaired and therefore MR examination should be avoided in such patients. Other devices (magnetic prosthetic devices, magnetic stoma or magnetic prostheses) which depend on magnetization to be fixed to the patient may also be damaged.

g. Orthopedic implants, materials and devices

Most of these prostheses are non ferromagnetic but a large prosthesis like that of the hip may undergo heating due to the eddy currents within the prosthesis generated by the magnetic fields and the RF pulses. Even though the rise in temperature may not be significant it may cause problems to the study if the patient moves as a result of local heating.

h. Dental prostheses-fixed and movable

Even though there is a significant number of dental prostheses which undergo movement in the magnetic field, they are not thought to pose any danger and MR studies can be safely carried out in this group of patients. However, the artifacts resulting from them (stainless steel wires, dentures and orthodontic braces) may result in a non-diagnostic study especially for the head and neck region. Dental amalgam and 14K gold do not produce any artifacts.

i. Bullets and other shrapnel

It is advisable that MRI in patients with bullets or shrapnel be done with extreme caution. This is because even though the majority of ammunition is non-ferrous, traces of ferromagnetic alloys have been detected.

j. Surgical clips and pins

These are usually not a safety hazard because they become anchored in the tissue and are not likely to move in the magnetic field. However, the hazard of a misdiagnosis or a non-diagnostic study may result due to the artifacts generated. These artifacts may be due to distortion of the images due to the magnetic susceptibility.

k. Biopsy needles

With the advent of the "open" MR system, interventional or operative procedures under direct visualization are becoming more common place and this has necessitated the development of MR compatible equipment. However at the present moment most commercially available equipment are not MR compatible.

V. Superconducting magnet quench

Superconductiong magnets use cryogen (helium and nitrogen) to keep the magnet coils cool to the superconducting temperature. A quench occurs when the temperature rises and causes the cryogen to boil off rapidly. The static magnetic field is lost. A quench

may occur spontaneously or may be intentional e.g. in the event of a fire. The exhaust cryogen should be vented out of the room. However, in the event of the exhaust system failing, the cryogen may accumulate in the room and result in either asphyxiation or frostbite. In the event of any quench, all staff and patients should immediately vacate the premises. Generally there is a monitor in the MR suite that checks the level of oxygen to prevent any accidents from the cryogen leaking into the room.

The gradient magnetic field

Once the magnetic gradients have been switched on, the particular slice/s will be stimulated by specific radiofrequency pulses (RF) of the megahertz (MHz) frequency range. The radiofrequency pulses are usually of very short duration, typically only a few milliseconds in length. The exact frequency of these pulses is determined by the applied magnetic fields (both the main magnetic as well the gradient magnetic fields).

What are the effects of the RF pulses? The first effect is that of an increase in the temperature of the area examined. In normal patients, this increase in the body is not significant and is easily dissipated[7]. However, in patients with impaired themoregulation e.g. the elderly, those with fever or cardiovascular disease, there may be a perceptible increase in the temperature.

The RF pulses may also disrupt normal function of electronic devices like pacemakers, cochlear implants or bone growth stimulators and therefore these patients must not be examined with MRI. Also the RF pulses may cause local heating of large prostheses. Burns may also occur if there are coils lying close to the patient. This occurs secondary to the currents generated in the coils which results in heating.

The patient

I. Pregnancy

There has been a general consensus that even though there has been no documented side effects of MRI on the development of the foetus[1,3] it has not been proven safe. Thus MRI is not advised in the first trimester of pregnancy [National Radiation Protection Board[1] and the Safety Committee of the Society for Magnetic Resonance Imaging[2]] unless there are overriding considerations which put the safety of the mother at risk and there is no other imaging modality that can give the same information. The information derived from the study must be able to change the therapy or result in intervention to the mother or foetus during the pregnancy. If absolutely necessary, it advised that the lowest possible magnetic fields be use i.e. in terms of the number of sequences, number of slices and the duration of the examination.

Is the use of Gadolinium in pregnancy safe? No, it is not and is therefore not advised. Gadolinium crosses the placenta readily and is excreted into the urine. The foetus will swallow the amniotic fluid and there will be repeated cycles. Thus, there will be prolonged exposure to Gadolinium and there is no data available on the excretion of Gadolinium from the amniotic fluid. Therefore Gadolinium is not recommended in pregnancy until further data regarding its safety becomes available.

Is it safe for pregnant personnel to continue to work in the MRI suite? A study[8] showed that there was no clear correlation with the rate of abortion, low birth weight, infertility and gender of offspring. Also, there was no correlation found between the MR workers and any specific modifications of the menstrual cycle.

Despite this the British Department of Health[9] does recommend that pregnant personnel be given the option not to work within the magnet room within the first trimester. Any other pregnant medical personnel or members of the general public should not be allowed to be in the vicinity of the MRI suite in the first trimester.

II. Claustrophobia

The psychological reactions of being within the bore of the magnet include anxiety and panic attacks due to claustrophobia. These problems with MRI have been well documented. The incidence has been reported to be as high as 65%[10]. This is in contrast to our own experience where the incidence is less than 10% (unpublished data). The result is that the study becomes suboptimal, delayed or has to be abandoned.

The reasons for these sensations of anxiety, panic attack, or claustrophobia are varied and are most likely to be multifactorial. The reasons include the rather narrow diameter of the bore of the magnet, the sense of loss of control, the feeling of isolation, the prolonged duration of the study, the loud banging sound of the gradient coils, as well as the loss of mobility[10-14]. There are several options used to overcome this problem as shown in Table I.

The problems with adverse psychological reactions to the MR should be explained to the patient but it is not necessary to forewarn patients of claustrophobia. Rather it should be highlighted that the MR study is essential to the overall management of the patient and that the options other than MR may be more invasive. The clinician, radiologist and radiographer should instruct the patient to cooperate as best as they can to obtain the optimal results.

III. The ill or unstable patient

This is an area of difficulty with MR examination since the patients within the MR suite are relatively isolated and routine monitoring and observation of the patients are difficult. In addition, access to the patient in the event of an emergency may be complicated.

There are, however, several groups of patients that require monitoring of the vital signs during the MR examination. These include those patients that have been given sedation and this is especially important for the children and infants. Even paediatric patients without sedation will require monitoring. Patients on ventilatory support as well as those too sick to communicate are another group. The Safety Committee of the Society of Magnetic Resonance Imaging[16] recommends that it is good practice to maintain verbal and visual contact with all patients undergoing MR examinations. They further state that all patients who are sedated, anaesthetized or incapable of communication should be physically monitored for ECG, respiration, heart rate and blood pressure. If these are done using electrical or mechanical devices, then MR compatibility must be ensured prior to usage. The use of MR incompatible equipment may result in the equipment becoming a projectile, the RF pulses used affecting the normal function or the monitor creating artifacts in the MR images. Also, currents may be generated in MR incompatible conductive materials resulting in thermal burns on the patient[16].

Most modern MR systems have some monitoring devices like an intercom system that allows the radiographer to keep constant contact with the

Table I
Techniques that can be used to reduce the incidence of adverse psychological problem during MR imaging

1. Providing clear information about the procedure itself.
2. Explaining the importance of the MR study in the overall management of the patients.
3. Allowing a friend or a relative to remain with the patient throughout the study.
4. maintaining constant verbal contact with the patient during the procedure.
5. Allowing the patient to listen to music of their choice during the procedure using special MR compatible headphones.
6. Placing the patient prone within the bore of the magnet or installing special prism glasses or mirrors which allow the patient to see outside the system.
7. Placing the patient feet first instead of head first.
8. Changing the environment within the bore with better lighting and air-conditioning as well as providing devices to alert the radiographer if any emergency occurs.
9. Using relaxation techniques, systemic desensitization, and the use of hypnosis and sedatives.

patient within the bore of the magnet. In addition there are panic "bulbs" given to the patient which he/she squeezes in the event of an emergency. Surveillance cameras are also available that allow visual monitoring of the patient during the procedure. However it must be admitted that these cameras do not have the resolution to detect changes in the patients breathing pattern or level of consciousness. In general these devices are inadequate in the above groups of patients.

Another area of potential problem is that of resuscitation. MR compatible resuscitative equipment must be available in the MR suite. In addition the resuscitation team must be aware of the safety precautions before entering the MR suite. It has been suggested that the patient be transported out of the MR suite as soon as is feasible and the resuscitation efforts be continued[7]. This is to prevent unscreened staff and resuscitation equipment from being taken into the MR suite. Another problem in the resuscitation efforts may be the lack of knowledge of the site of the MR suites as these tend to be placed in the basement or other not so accessible areas.

Contrast medium

The contrast medium used in MRI is not iodine based like that used for X-ray based investigations. Most of the intravenous MR contrast medium is Gadolinium (Gd) based. Gadolinium is a heavy metal and is toxic on its own but once chelated onto certain chemicals e.g. DTPA, its toxicity is markedly reduced. There are at the moment both ionic and nonionic types of Gadolinium-based contrast available and there are no known contraindication to the use of any of the Gadolinium based contrast medium (unlike iodine based X-ray contrast medium where a history of asthma or allergy carries an increased risk of adverse reactions). Numerous studies[17-22] have demonstrated the safety of various MR contrast media. Gadolinium based MR contrast media have a high safety index compared to iodinated contrast medium though they are not really comparable since the volumes and osmotic loads used are very different. The volumes used for CT for example are on the average 100 ml. Whereas only 10-20 ml. of Gd-based contrast medium is used with MRI.

The rate of adverse reactions from all MR contrast media is between 2% to 5%. This compares with the adverse reaction rate of 12% and 3% for ionic and nonionic iodinated contrast media[23]. The most common reactions are those of nausea, vomiting, rashes as well as a sensation of increased temperature over the site of injection. There have been several reports of laryngospasm and /or anaphylactoid reactions in the literature[24-26] and several deaths have been documented. Extravasation of MR contrast medium may result in tissue necrosis[27].

It is generally advised that for those patients with a history of allergy or drug reaction, prolonged observation be carried out following IV injection of the MR contrast medium.

In patients with renal failure, the general consensus is that it is well tolerated and that for a given level of renal function, it may be safer than iodinated contrast medium[28]. Furthermore, Gd-DTPA is readily dialyzable with almost total removal by the third dialysis treatment[29]. At the present moment, there is insufficient data on the safety of repeated administration of MR contrast medium. The concern is that there may be storage or accumulation of free gadolinium after multiple doses. Thus there may be a clinical limitation on the number of doses that may be administered safely to a patient over his lifetime. This may be a problem especially for children who may require repeated contrast enhanced MR studies as part of the follow-up of tumours.

As stated earlier MR contrast medium is not considered safe to be used in pregnancy due to the possibility of prolonged persistence of gadolinium in the amniotic fluid. It is recommended that the use of MR contrast medium be avoided in pregnancy until further data becomes available[30]. Gd-DTPA is excreted in low concentrations in the lactating patients. Shellock[3] recommends that breast feeding be stopped for 36 to 48 hours after IV Gd but that the mothers continue expressing their breast milk. This is despite the significantly reduced absorption of Gd from the gastrointestinal tract[30].

Even though the safety and efficacy of MR contrast medium in infants has not been established, the

preliminary experience suggests that they are comparable for children less than 2 years of age to that of adults[31].

Conclusion

MR imaging is playing an increasing role in the investigation of clinical problems with an ever increasing number being requested. There is therefore a need for the clinicians to be aware of the dangers and the necessary precautions that need to be considered prior to an MR examination being requested. The safety considerations are however a lot more complex than with the other imaging modalities. Hopefully this paper has elaborated on some of the safety considerations in MRI.

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Multiple choice questions for Safety Considerations in MRI

1. The following methods can be used to reduce the incidence of adverse psychological reactions during MRI.

a. Placing the patient feet first
b. By asking the patient to lie prone within the magnet.
c. Allowing a relative to remain with the patient during the procedure.
d. Providing piped-in music
e. Using hypnosis

2. The following are absolute contraindications to performing an MRI examination

a. Pregnancy
b. Intracranial aneurysmal clips
c. Cardiac pacemakers
d. Intra-ocular foreign bodies
e. Dental prostheses

3. Intravenous gadolinium-DTPA

a. Should not be used in pregnancy
b. Is contraindicated in patients with renal failure
c. Has greater risk of contrast medium reactions compared to iodinated intravenous contrast medium
d. On the average is used in volumes of approximately 100 mls.
e. May cause laryngospasm and even death

4. With regard to MRI

a. 1 Gauss is equal to 10,000 Tesla
b. The strength of the main magnetic field of up to 6 Tesla is safe
c. Ferromagnetic materials are not affected by the magnetic field
d. The presence of biomedical implants is an absolute contraindication to MRI
e. Gradient echo pulse sequences are more susceptible to field inhomogeneities

5. In MRI

a. The magnetic field only affects the body area being scanned
b. Vascular clips are safe if present for more 6 months
c. Only plain films are necessary for excluding the presence of intra-ocular foreign bodies
d. The presence of any prosthetic heart valves is not a contraindication
e. The presence of large orthopaedic implants may result in heating during scanning