Magnetic resonance imaging: Bioeffects and safety concerns

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Magnetic resonance imaging (MRI) is the state-of-the-art noninvasive imaging modality in clinical diagnosis. During MRI examination, the patient is exposed to three different forms of electromagnetic radiation: (i) a static magnetic field, (ii) gradient magnetic fields, and (iii) radiofrequency (RF) fields. Each of these may cause significant adverse bioeffects if applied at sufficiently high exposure levels. This article describes in some detail the areas of health concern for both the patient and the health practitioner with respect to the use of clinical MRI, in addition to describing the potential bioeffects of electromagnetic radiations used in this sophisticated imaging modality.

Introduction

Magnetic resonance imaging (MRI) is presently an accepted and widely used clinical diagnostic procedure. This noninvasive anatomic/pathologic imaging technique utilizes magnetic fields and radiofrequency (RF) energy to manipulate atomic nuclei present in human tissues. The most commonly used nucleus in MRI is hydrogen (proton) because of its relatively strong signal and 99% natural abundance in biologic tissues. Most of these protons are associated with water and, to a lesser extent, fat. When placed in a strong magnetic field, these protons behave like tiny bar magnets and tend to orient in a direction along the magnetic field. An RF field applied at right angles will change the orientation of the protons within the magnetic field. Transfer of energy occurs as a "resonance" specific to both the nuclei (i.e., protons) studied and the precise magnetic field surrounding it. After the termination of the RF excitation, the protons are free to return to their normal orientation in the field (relaxation) by giving up the energy they have absorbed which is detected by a receiver coil as a signal (free induction decay, FID). Through the use of magnetic field gradients and RF pulses, the location of the nuclei in 3-D space, as well as the information about its surrounding environment, can be encoded into the returned signal. The excitation and detection process is repeated several times to uniquely encode each part of the object. Computer processing of the set of signals (FIDs) provides the final image(s) of the spatial distribution of the nuclei within the object. Thus, it is clear that MRI represents one of the most sophisticated techniques with a composite of diverse technological components such as a powerful static magnetic field, radiofrequency (RF) fields, rapidly switching local magnetic fields called gradients, vast amounts of cryogens and powerful computers. Thus, during the MRI investigational procedure, the patient is exposed to three different forms of electromagnetic radiation: (i) a static magnetic field, (ii) gradient magnetic fields, and (iii) radiofrequency fields. Each of these, individually or collectively, may cause significant bioeffects, if applied at sufficiently high exposure levels.

Various safety considerations of clinical MRI have been investigated by a number of groups. No conclusive evidence of significant health hazard due to exposure of these radiations in human subjects has been reported by these investigations. In addition to the bioeffects related to exposure to electromagnetic fields used in this imaging modality, this article describes in some detail the areas of health concern for both the patient and the health practitioner. However, before proceeding further, it may be mentioned emphatically that MRI is a noninvasive technique with no ionizing radiation and therefore poses no radiation hazard to health.

Static magnetic fields

The most important component of the MR scanner is the magnet which produces a constant static magnetic field. The magnet in a typical MRI scanner in use today produces a field between 0.2 T and 2.0 T in terms of the familiar magnetic field units of Tesla (T), 1T = 10,000 gauss. No scientific evidence exists...
to show that magnetic fields of above range produce harmful effects in mammals. Hence, it is totally safe while the patient is inside the MRI magnet. MRI scanners, presently in use, are 'shielded' whereby the above field strengths are mostly confined inside the MRI suite, and only very weak residual or 'fringe' fields (-0.5 mT or 5 gauss) pervade a small perimeter around the MRI magnet.

The attractive force of the magnet on ferromagnetic objects has the potential to adversely affect the safety of the patient as well as the MR personnel. Such attractive forces include both translational (i.e., attraction by the magnet) and torsional (attractive force causing the long axis of the ferrous objects to align with the magnetic field). 'Ferromagnetics' are materials that contain iron and are strongly attracted by a magnet. In addition, metals like nickel and cobalt are also strongly ferromagnetic. Metals such as copper, aluminium, silver, and gold are non-ferromagnetic. It is essential to screen objects both in and around the patient as well as those within the patient. In the former group, objects ranging from forklifts, wheel chairs and isolets, to pens, pencils, and paper clips have been reported as having been inadvertently attracted to an MR scanner. Due to attractive forces produced by a whole body MR scanner, even fairly light objects may cause significant injury. For example, a paper clip in a 1.5T MR system reaches a terminal velocity of approximately 40 mph. It is our experience that adequate restriction of access to the magnet, continual education and screening of MR personnel, and appropriate patient screening helps to prevent such incidents. At our site, the patient screening procedure consists of (a) a careful written query, (b) scanning the patient top-to-toe with a hand held metal detector (after the removal of keys, coins, hairpins, credit cards, etc., and (c) checking any previous radiological films/images of the patient that may show implanted objects.

Another area of concern is the magnetically sensitive equipments/objects, the function of which may be adversely affected by the magnetic field and MR imaging would be contraindicated even more strongly. The most common of these items is the cardiac pacemakers as well as other implantable electronic devices such as intraocular metal, Cochlear implants, ferrous intracranial aneurysm clips and sharpnail in critical locations. It is found that field strengths greater than 10 mT are sufficient to close the magnetic reed switch of the pacemaker, switching it to an asynchronous mode. Although this is usually not a threat to the patient for short periods, the possibility that some harm can result does exist. For example, the lithium battery which powers the pacemaker may also become dislodged in magnetic fields. In view of this the public access to areas with fields of 0.5 mT and greater must be posted with warnings, or access controlled.

In addition, the 0.5 mT fringe field may also affect the working of other vital medical devices such as patient monitoring equipment, respirators, colour television monitors, magnetic tapes, floppy disks, etc. Necessary precautionary measures have to be taken for proper functioning of these equipments. Attention must also be given to the placement of suitable anaesthesia close to the MRI suite, necessity of shielding them magnetically, etc. should be assessed from MRI manufacturers before installation.

Exposure to static magnetic field does not alter skin and body temperatures in humans according to a recent study at 1.5 T performed using a special fluoroptic thermometry. Therefore, skin and body temperatures on human subjects are believed to be unaffected by exposure to static magnetic fields of upto 1.5 Tesla.

In addition to the harmful effects from metal objects and ferromagnetic prosthesis being attracted by the magnetic field, there are several biophysical mechanisms whereby static magnetic fields might influence biological processes or organisational behaviour. (i) Changes in enzyme kinetics by conformational changes, by perturbation of free radical mobility, or by quenching superconductivity thought to be present in biomolecular systems. A wide variety of experiments at fields upto 45 T have not shown any effect on enzyme systems. (ii) Orientation changes of macromolecules and living cell subcellular components, leading to changes in chemical kinetics and membrane permeability. (iii) Distortion of ion currents leading to a reduction of nerve conduction velocity. Theoretically, electrical impulse conduction in nerve tissue may be affected by exposure to static magnetic fields. At present, exposure to static magnetic fields of up to 2.0 T do not appear to significantly influence bioelectric properties of neurons in humans. (iv) Induced electric potentials and currents in the cardio-vascular system. The induced voltage for a field at right angles to the flow direction is given by
Thus the amplitude of the electric potential is greatest there. The experimentally observed induced potential in a magnet occurs during the T-wave of the electrocardiograph (EKG). The threshold field for a perceptible T-wave change is below 0.3 Tesla. The T-wave abnormality increases with field strength, however, this induced voltage does not result in any physiological changes. (v) Magnetohydrodynamic effects leading to blood velocity decrease and blood pressure elevations. The electrolytic interaction of stationary magnetic fields with flowing, electrically conductive fluids has a retardation effect as fluid motion which can result in an increase in the blood pressure needed to deliver a given volume of blood to peripheral tissues. These effects are not significant either in theory or from experiments up to 1.5 T. However, a significant blood pressure increase of 28% in the aorta and venocava is theoretically predicted for a field of 10 T. There should be no effect on the blood pressure in the rest of the vessels in the vasculature since the effect is proportional to the square of the vessel radius. Several experiments carried out revealed that there is no significant magnetohydrodynamic pressure increase even at 10 Tesla.

In summary, there is no conclusive evidence of irreversible or hazardous biological effects related to acute, short-term exposures of humans to static magnetic fields of strengths up to 2.0 T. However, there are several 3.0 T and 4.0 T whole body MR systems now operational at various centers worldwide. A preliminary study has indicated that workers and volunteers exposed to 4.0 T MR system have experienced vertigo, nausea, headaches, a metallic taste in their mouths, and magnetosphoenes (which are visual flashes). Therefore, more research is required to study the mechanisms responsible for these bioeffects and to determine the possible means, if any, to counter balance them.

\[ F=q(v\times B) \quad \ldots \ (1) \]

where \( q \) is the charge, \( v \) is the velocity and \( B \) is the magnetic field. Therefore,

\[ V=vBd \quad \ldots \ (2) \]

Here \( V \) is the voltage, and \( d \) is the diameter of a vessel (meters) through which there is a uniform velocity of \( v \) in m/sec. The maximum flow velocity in the cardiovascular system occurs in the large arteries. Thus the amplitude of the electric potential is greatest there. The experimentally observed induced potential in a magnet occurs during the T-wave of the electrocardiograph (EKG). The threshold field for a perceptible T-wave change is below 0.3 Tesla. The T-wave abnormality increases with field strength, however, this induced voltage does not result in any physiological changes. (v) Magnetohydrodynamic effects leading to blood velocity decrease and blood pressure elevations. The electrolytic interaction of stationary magnetic fields with flowing, electrically conductive fluids has a retardation effect as fluid motion which can result in an increase in the blood pressure needed to deliver a given volume of blood to peripheral tissues. These effects are not significant either in theory or from experiments up to 1.5 T. However, a significant blood pressure increase of 28% in the aorta and venocava is theoretically predicted for a field of 10 T. There should be no effect on the blood pressure in the rest of the vessels in the vasculature since the effect is proportional to the square of the vessel radius. Several experiments carried out revealed that there is no significant magnetohydrodynamic pressure increase even at 10 Tesla.

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Cryogens

All superconductive MR systems in clinical use today utilize liquid helium. Liquid helium will achieve gaseous state ('boil off') at \(-268.9\) °C (4.22 K). If due to some reason the helium cryostat warms up, it develops 'hot spots' and there will be an alarmingly fast boil off of helium. In view of this, an enormous pressure builds up and the excess gas has to be vented out of the building through proper outlets. On the other hand, if this safety valve frosts up and fails to work, a seal in the cryostat would rupture and vast quantities of the cryogenic gas would fill the MRI suite and this phenomenon is known as "magnet quench". Asphyxiation and frostbite are possible if a person is exposed to helium vapour for a long time. Recently, better cryostat design and insulation have allowed the use of only liquid helium in many of the newer superconducting magnets. However, in the older versions of superconducting MRI magnets, both liquid nitrogen and liquid helium are used. Liquid nitrogen within the cryostat acts as a buffer between the liquid helium and the outside atmosphere, boiling off at 77.3 K. In the event of an accidental release of liquid nitrogen into the ambient atmosphere of the imaging room, there is a possibility for frostbite, similar to that encountered with the gaseous helium release. A pure nitrogen environment is hazardous and unconsciousness generally results as early as 5 to 10 seconds after exposure. Patients and health personnel should be evacuated from the area as soon as it is recognized that nitrogen or helium gas is being released into the MRI scan room, and they should not return until appropriate corrective measures have been taken to clear the gas from the room.

In general, cryogens present a potential concern in clinical MRI despite an overwhelmingly safe record over the 20 years of clinical service. An oxygen monitor with an audible alarm, situated at an appropriate height within each imaging room, should be a mandatory minimum safety measure for all sites.

Time-varying (gradient) magnetic fields

During MRI procedure, a human body is exposed to rapid variations of magnetic fields due to transient application of time varying gradient magnetic fields during the imaging sequence to obtain three-dimensional spatial information. These gradient magnetic fields can induce electrical fields and currents in conductive media (including biological tissues) according to Faraday's law of induction. The
interaction between gradient magnetic fields and biologic tissue is dependent on the fundamental field frequency, the maximum flux density, the average flux density, the presence of harmonic frequencies, the waveform characteristics of the signal, the polarity of the signal, the current distribution in the body, and the electrical properties and sensitivity of the particular cell membrane. In animals and human subjects, the induced current is proportional to the conductivity of the biologic tissue and the rate of change of the magnetic flux density.

\[ J = \frac{\sigma r dB}{2 \, dt} \]  

where \( J \) is the current density in Am\(^{-2}\), \( \frac{dB}{dt} \) in T sec\(^{-1}\), \( r \) is in meters and \( J \) the tissue conductivity in Sm\(^{-1}\) (Siemens). Suppose we assume an effective radius of 0.1m (10 cm) for the head, \( \frac{dB}{dt} \) of 1 T sec\(^{-1}\), and \( \sigma = 0.2 \) Sm\(^{-1}\), then

\[ J = 10^2 \, \text{A/m}^2 \text{ or } 1 \mu\text{A/cm}^2. \]

Thus, changes in magnetic fields of 4 T/sec can induce current densities of 4 \mu\text{A/cm}^2, and if this is applied for a sufficient time in one direction, nonthermal biologic effects (not necessarily harmful) can be expected. The current density will be enhanced at higher frequencies and magnetic flux densities will be further accentuated by a larger tissue radius with a greater tissue conductivity. Moreover, differences in tissue types also affect the current density and its path; tissues with low conductivity (e.g. adipose and bone) will change the pattern of the induced current.

As mentioned earlier, bioeffects of induced currents are caused either by the power deposited by the induced currents (thermal effects) or by direct effects of the current (nonthermal effects). Thermal effects due to switched gradients used in MRI are negligible and are not believed to be clinically significant. The possible nonthermal effects of induced currents include (a) stimulation of nerve or muscle cells, (b) stimulation of visual flash sensations, (c) bone healing, (d) electro shock anesthesia (therapy), (e) increased brain mannitol space, (f) induction of ventricular fibrillation, and (g) epileptogenic potential. The threshold currents required for nerve stimulation and ventricular fibrillation are known to be much higher than the estimated current densities that will be induced under routine clinical MRI conditions. Infact, stimulation of muscles by means of time varying magnetic fields requires current densities of nearly 10 times greater than that used in MRI strategies. Pulsed fields of the order of \( 10^4 \) T/sec have been used to stimulate peripheral nerve tracts.

In addition, a visual phenomenon may be produced if the patient moves his head rapidly in a magnetic field above about 10 mT. This phenomenon, known as magnetophosphenes, is not thought to affect vision permanently and ceases immediately following magnetic field exposure. Although there have been no reported cases of magnetophosphenes for fields of 2 T or less, magnetophosphenes have been reported in volunteers working in and around a 4.0 T MR research system. In addition, a metallic taste and symptoms of vertigo also seemed to be reproducible being reported at these 4.0 T systems.

The rates of change of gradient field strength used in MRI are of the same order of magnitude as the changing field component of extremely low frequency (ELF) electromagnetic fields used in the normal domestic transmission and distribution electric lines. Even though there has been no study to conclusively prove the carcinogenic effects from exposure to time varying magnetic fields of various intensities and durations, several reports suggest that an association between the two is still plausible.
Radiofrequency (RF) effects

The consequence of RF exposure of the levels used in MRI is the generation of heat in the tissue as a result of resistive losses. Therefore, the main bioeffects associated with exposure to RF energy are related to the thermogenic qualities of this electromagnetic field. The amount of heat or energy produced is a function of the frequency, RF power, duration of the exposure and coupling between the RF coil and the subject. The important biological factors are: conductivity, specific heat of the tissue, size of the current loop, circulation and the ability of the body to lose heat. The measure of energy or heat delivered to tissue is the power deposited times the duration of exposure. The absorbed power per unit of mass of tissue is known as the specific absorption rate (SAR) which is expressed in units of Watt per kg (W/kg). The energy per time (power) imparted to charged particles by an E field is E x J. Thus, the average power absorbed per unit mass of the induced average electric field \( E/\sqrt{2} \) is

\[
\text{SAR} = \frac{E}{\sqrt{2}} \times \sigma E \times \frac{1}{\sqrt{2}} \times \frac{1}{\text{mass}} \times \frac{E^2}{2M} = \frac{E^2 \sigma}{2M} \quad \text{(4)}
\]

where the energy absorbed (heat) is the product of SAR and time.

Using fluoroptic thermometry probes it was demonstrated that human subjects exposed to MRI and SAR levels up to 4.0 W/kg have no statistically significant increase in body temperature and elevations in skin temperature, and they are not believed to be clinically hazardous. These results imply that the suggested exposure level of 0.4 W/kg for RF energy using MRI is too conservative for individuals with normal thermoregulatory function. It is important to point out that several protection mechanisms inbuilt in the MR scanner are programmed such that the above SAR limits are always obeyed.

Human organs such as testis and eye have reduced capabilities for heat dissipation and are particularly primary sites of potential harmful effects if RF energy exposures during MRI are excessive. One can thus calculate the temperature elevation by using the specific heat of tissue which relates the temperature change to heat absorbed. The expected theoretical temperature rise, \( \Delta t \), using a soft tissue specific heat of 0.83 k cal/kg/°C (3.5 kJ/kg/°C) assuming no heat loss is given by

\[
\Delta t({}^\circ \text{C}) = \frac{\text{SAR} \times \text{Time}}{3.5} \quad \text{(5)}
\]

where SAR is in W/kg and time in seconds.

Studies carried out to measure scrotal skin temperatures in volunteer subjects undergoing MRI at a whole-body averaged SAR of 1.1 W/kg, revealed that the largest change in scrotal skin temperature recorded was 34.2°C. These temperature changes were below the threshold known to impair testicular function. Dissipation of heat from the eye is slow and inefficient because of lack of vascularization. Constant exposures of RF energy to the eyes or heads of laboratory animals have been demonstrated to be cataractogenic as a result of the thermal disruption of ocular tissues. Corneal temperatures have been measured in patients undergoing MRI of the brain using a send receive head coil at local SARs up to 3.1 W/kg. The largest corneal temperature change was 1.8°C and the highest temperature measured was 34°C. Animal model studies have demonstrated cataractogenesis between 41° to 55°C for acute, nearfield exposure. Therefore, it does not appear that clinical MRI using a head coil has the potential to cause thermal damage to ocular tissue.

In addition to global temperature rise, there is some concern that "hot spots" could occur. These are caused by an uneven distribution of RF power and in view of this electric current pathways become narrowed in tissue with little vascularity. The presence of foreign materials such as ferromagnetic prostheses complicates the estimate of local heating. Moreover, exposed wires or metal conductors should never touch any part of the patient, and no part of the patient's body should become an induced current loop, e.g. ECG monitoring. These may induce RF burns.

RF shielding is important in many MRI suites for two reasons: (a) protection of the environment from the RF fields produced by MRI transmitters, and (b) protection of MRI from external RF sources such as TV transmitters, radio broadcasts, emergency radio services and pagers. This 'Faraday Cage', as it is called, is made of thin copper foil sheet 'walls' grounded at one point. The cage has at one place a door to allow entry of patient and staff and another place to provide 'a filter plate' entry for electrical wires, anaesthesia gases, etc.

Acoustic noise

Rapidly-switching magnetic field gradients in MRI produces large oscillating Lorentz forces which in turn produce coil vibrations against the magnet cryostat with an associated rat-tat noise.
repetitive sound is enhanced by higher gradient duty cycles and sharper pulse transitions. Acoustic noise is thus likely to increase with decreases in section thicknesses, decreased fields of view, repetition times and echo times. The noise levels in MR scanners are in the range of 65-95 decibels (dB), which is considered to be within the recommended safety guidelines. However, there have been reports that acoustic noise generated during MRI investigation causes patient annoyance, interference with oral communication, and reversible hearing loss in patients who did not wear ear protection\textsuperscript{26,27}. Study of patients undergoing MRI without ear plugs showed temporary hearing loss in 43% of the subjects\textsuperscript{28}. Strategy for reducing sound levels during MRI is being worked out. One method is to use an "antinoise" or destructive interference technique that not only effectively reduces noise but also permits better patient communication\textsuperscript{29}. A recent study found no significant degradation of MR image quality with the use of antinoise method\textsuperscript{29}.

**MRI during pregnancy**

Although MRI is not believed to be hazardous to the fetus, only a few investigations examining the teratogenic potential of this imaging modality are reported. Most of the earlier studies conducted to determine possible unwanted bioeffects during pregnancy showed negative results\textsuperscript{29,30}. Recent studies on mice exposed during mid gestation did not show gross embryotoxic effects but there was a reduction in crown-to-rump length\textsuperscript{30}.

A variety of mechanisms exist that could produce deleterious bioeffects with respect to the developing fetus and the use of electromagnetic fields during MRI\textsuperscript{31,32}. Patients who are pregnant or who suspected to be pregnant are to be assessed for the risks versus the benefits of the MR examination. Care should be exercised during the first trimester to avoid medicolegal implications relative to spontaneous abortions because there is a high spontaneous abortion rate in general population during the first trimester of pregnancy (i.e., >30%). Hence, a cautious approach is recommended for the use of MRI in pregnant patients.

**General considerations**

Approximately 5% to 10% of patients undergoing MRI have claustrophobia and a variety of other psychological sensations including anxiety and panic disorders. These are due to the narrow interior (tunnel) of the scanner, the duration of the examination, gradient induced noise, etc.\textsuperscript{33-37}. Most of these psychological responses, are usually transient. Relaxation methods and detailed briefing of the MRI procedure are found to reduce the anxiety level to certain extent. In recent times, MR system architectures offer a more open design that reduce claustrophobia and the frequency of psychological problems associated with MRI procedures.

Overall, numerous studies performed specifically to study the potential bioeffects of MRI have revealed negative results supporting the widely held view that there is no significant health risks associated with the use of MRI modality\textsuperscript{3}. However, as discussed earlier in this article, patients with internal cardiac pacemakers, implantable cardiac defibrillators, cochlear implants, neurostimulators, bone-growth stimulators, implantable electronic drug infusion pumps, and other similar devices that could adversely be affected by the magnetic field should not be examined by this imaging technique\textsuperscript{37,38,39}. Similarly, MRI is contraindicated for patients who have certain ferromagnetic implants, materials, or foreign bodies, primarily because of the possibility of movement or dislodgement of these objects\textsuperscript{6,8}. Patients with nonferromagnetic aneurysm and hemostatic clips can be imaged. Similarly, one should first make sure that carotid artery vascular clamps, dental devices and materials, heart valves, intravascular coils, filters and stents, ocular implants, orthopedic implants, otologic implants, etc. are to be tested for ferromagnetism before MR investigation. These are easily achieved by written screening and through metal detector tests.

**Conclusion**

The possible health hazards related to MRI investigational procedure under different categories presented above have been duly taken into consideration by the equipment manufacturers and necessary preventive measures are usually incorporated into the scanner. The personnel connected with MRI site are to be well-trained in emergency procedures. The awareness of the numerous areas of concern regarding MRI environments both for patients undergoing MR examination and for MR health practitioners is highly desirable. An understanding of these potential interactions allows a more knowledgeable decision to be made because MRI is now a frequently recommended early diagnostic modality for many soft tissue pathologies.
References

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