Safety concerns related to magnetic field exposure

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Abstract The recent development of superconducting magnets has resulted in a huge increase in human exposure to very large static magnetic fields of up to several teslas (T). Considering the rapid advances in applications and the great increases in the strength of magnetic fields used, especially in magnetic resonance imaging, safety concerns about magnetic field exposure have become a key issue. This paper points out some of these safety concerns and gives an overview of the findings about this theme, focusing mainly on mechanisms of magnetic field interaction with living organisms and the consequent effects.

Introduction

All human beings are continually exposed to the magnetic field of the earth, which is approximately

0.5 G, yet people are generally unaware of its existence because it is weak and unobtrusive. Only with the introduction of electromagnets in the early 19th century did exposure to strong fields take place, even though only a relatively small number of people involved in specific professions actually came in contact with them [1]. A new degree of human exposure to magnetic fields began when whole-body magnets in clinical magnetic resonance imaging (MRI) were introduced in the early 1980s. This technique has implied patients' exposure to an intense magnetic field of a strength not previously experienced on a wide scale by humans [2].

Magnetic resonance imaging has become a very important standard medical imaging modality, due to its advantages: extreme imaging flexibility, high patient acceptance, capability to evaluate both anatomic and physiologic parameters, and acquisition of unique clinical information. Besides, the technique is non-invasive, and no ionizing radiation is used [3]. Medical diagnosis using MRI is one of the main sources of exposure of humans to large static fields [4]. As the technology improves, the areas of application and numbers of patients exposed to magnetic fields increases. MRI also involves exposing staff to static magnetic fields. The largest group of workers occupationally exposed to static magnetic fields are radiographers. Another class of staff exposed to static fields are the engineers who are involved in constructing the MRI scanners [4].

In the future, the intensity of the field will increase [5]. Higher magnetic field strength is expected to afford higher spatial resolution and/or a decrease in the length of total scan time due to its higher signal intensity [6].

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Ever since the introduction of MR, imaging with 1.5 T has been considered the gold standard for the study of all body areas [4, 7]. FDA has approved exposure of adults to 8 T fields and exposure of neonates (age <1 month) to 4 T fields [8]. For the whole-body MRI systems, magnetic field strengths can be divided into high field (1.0–3.0 T), very high field (3.0–7.0 T), and ultra high field (>7 T) [9]. The ultimate safe limits of static magnetic field strength are not known and the factors that will eventually determine the maximum field strength are yet to be determined [2]. At present, the practical limitations to increasing magnetic field strength are the costs and inconvenience of installing a high field magnet. Ultimately, one would expect that acute effects of magnetic fields on patients or staff might limit the increase in magnetic field strength. However, there is no evidence that this limit has already been reached [4]. Given the magnetic field strengths and the rapid expansion of MRI, health impacts related to magnetic field exposure need to be properly assessed [10].

Interaction mechanisms

In spite of the low magnetic susceptibility of human tissues, a broad spectrum of interaction mechanisms can occur between magnetic fields and living organisms [11]. The most relevant mechanisms [1, 2, 12] are the following: magnetic forces due to tissue susceptibility differences, magnetic torques due to anisotropic susceptibilities, flow or motion-induced currents causing nerve or muscle stimulation, changes in chemical reaction rates, magnetohydrodynamic forces and pressures, and magnetic excitation of sensory receptors leading to sensations such as nausea, vertigo, and magnetophosphenes.

As will be described below, static magnetic fields may interact with living tissues in a number of ways, although the most likely means of causing health effects are via field-induced alterations in the rate of chemical reactions and effects on flow potentials [13].

The magnetic field effect on the rate of radical pair recombination is the best understood mechanism by which magnetic fields interact with biological systems. However, its health relevance is uncertain [14], and such a mechanism is not able to explain all magnetic field effects.

Magnetic forces due to tissue susceptibility differences

Body components differ in their magnetic susceptibility. Theoretically, this could lead to a movement of the

more paramagnetic¹ components toward high field regions [1]. For instance, red blood cells, which are slightly less diamagnetic¹ than plasma, experience a magnetic force tending to move them toward regions of stronger magnetic fields [2]. Normal erythrocytes in suspension present some degree of orientation by fields of 1 T and almost all of them are oriented when exposed to a field of 4 T [12].

Considering the example of a 4-T magnet, it is possible to calculate the ratio of magnetic to gravitational forces, F_m/F_g . In this example, the magnetic force on the red cells is <4% of the gravitational force. Such effect is very weak and does not have practical significance in living tissues even in very intense static fields [1, 2].

Flow or motion-induced currents causing nerve or muscle stimulation

Ionic currents interact with magnetic fields as a result of the Lorentz force exerted on moving charges. This electrodynamic interaction gives rise to an induced electric field, $\vec{E}$, which is equal to the negative vector cross-product of the velocity of the moving charges, $\vec{v}$, and the magnetic flux density, $\vec{B}$ [15]:

$$\vec{E} = -\vec{v} \times \vec{B} \quad (1)$$

This physical phenomenon is the basis of the Hall effect in solid-state materials, and also occurs in biological processes that involve the flow of electrolytes in an aqueous medium. Examples of such processes are the ionic current flows associated with nerve impulse propagation and blood circulation [15].

In spite of such phenomena, exposure of frog sciatic nerves to a 1.0-T field did not lead to any alteration in the threshold for neural excitation [16]. On the other hand, static magnetic fields induced flow potentials in arterial flows in and around the heart that have been detected as distortions in the electrocardiograms. The resultant currents flowing through the myocardium could alter the rate or rhythm of the heart. The initiation of ectopic beats and the occurrence of re-entrant arrhythmias would be expected to have a threshold, or steep sigmoidal, dependence on static field intensity.

¹ Paramagnetism is the tendency of the atomic magnetic dipoles to align with an external magnetic field. Paramagnetic materials are attracted when subjected to an applied magnetic field. Diamagnetism is a property of all materials and opposes applied magnetic fields, but is very weak. Paramagnetism, when present, is stronger than diamagnetism and produces magnetization in the direction of the applied field, and proportional to the applied field.

However, no such changes have been observed in animal experiments, or with humans, in static fields up to 8 T [17].

Magnetohydrodynamic forces and pressures

Flowing liquids experience magnetohydrodynamic forces and pressures in the presence of a magnetic field. Such forces and pressures are substantial in liquid metals, such as mercury, for instance. However, flowing physiological fluids such as blood have much lower electrical conductivities than does mercury, and magnetohydrodynamic forces on flowing blood are very small compared with the naturally occurring hemodynamic forces in the vascular system. Magnetohydrodynamic interactions are predicted to reduce the volume flow rate of blood in the human aorta by a maximum of 1.3, 4.9, and 10.4% at field levels of 5, 10, and 15 T, respectively [1, 15].

Magnetic field effect on chemical reactions

It has been known since the 1960s that the rates and yields of certain classes of chemical reactions are sensitive to applied magnetic fields. In optimized chemical systems, the change in reaction rate or product yield is typically less than 50% [18]. Reactions that undergo a change from diamagnetic substrates to paramagnetic intermediates, products, or transition states, might be expected to be accelerated by a magnetic field that imparts a stabilizing interaction to the paramagnetic species [14]. However, the equilibrium position of such chemical reactions is not significantly affected [1].

Another mechanism has been shown to allow magnetic fields to alter somewhat the dynamics of certain chemical reactions. Specifically, this refers to the dissociation of a binary molecule, AB, present in some solvent, where A and B are joined by a non-magnetic electron pair bond, into two radicals, A* and B*. In the bound state the two electrons have opposite spins so that together they form a singlet state with total spin equal to zero. If AB spontaneously dissociates, because of thermal agitation, into separate radicals A* and B*, each radical can, for a short time, be considered as residing within a cage of surrounding solvent molecules that impedes the complete separation of the radicals from one to another. If A* and B* recombine before separating from one to another, the process is called geminate recombination, and the so-called cage product, AB, is formed. On the other hand, if they ultimately diffuse apart an escape product, A* and B*, is formed. If an applied magnetic field is present, and if the magnetic moments are not the same for the two

radicals, the spins of the two separating radicals will precess at somewhat different rates. Geminate recombination is only possible if the two radicals are still in a singlet state (total spin of zero) when they reencounter one another. If the differing rates of spin precession have given a significant portion of triplet character to the total spin wave function, the probability of bond reformation will be reduced and the yield of escape products increased [14].

In the light of many studies, the importance of the radical pair mechanism has been pointed out as an explanation for magnetic field effects in chemical and biochemical reactions involving species having unpaired electrons [19]. In fact, both chemical and enzymatic reactions may take place via radical pairs. However, a set of rules should be fulfilled in order to observe magnetic field effects on an enzymatic reaction [14]:

1. There must be at least one step in the reaction that generates a pair of spin-correlated radicals or paramagnetic particles;
2. The radical pair must be weakly coupled;
3. A physical mechanism must exist to promote magnetic field-dependent interconversion of singlet (antiparallel electron spins) and triplet (parallel electron spins) states of the radical pair;
4. The observed rate of the enzymatic reaction must be sensitive to the concentration of the radical pair;
5. The radical pair must live long enough to allow significant singlet–triplet interconversion to take place;
6. The reaction steps that precede the formation of the enzyme–substrate complex must be reversible such that the commitment to catalysis is low.

These severe requirements suggest that many enzymes with radical intermediates will not satisfy all of the necessary conditions (especially 1 and 4) to produce magnetic field-dependent reaction kinetics [14]. Therefore, magnetic field effects may not take place in a great extent. Actually, the effects are not large and depend on the field strength in a complicated way. Important effects on reactions of biochemical significance have not been reported [1], but it is still a matter of controversy. On the one hand, some enzymes may be inhibited, such as acetylcholinesterase [20]. On the other hand, others may not be affected by magnetic field, such as trypsin [21].

Magnetic field effects on biological systems

Living cells and organisms are capable of responding to their environment. Cells sense both intracellular and

extracellular changes and react in a manner to fulfill their programmed function. Depending on the stimulus, a cell may alter its functions to compensate for the change or simply ignore the alteration. Some effects occur only after prolonged environmental change [22]. The cellular and molecular modifications induced when magnetic fields interact with biological materials are dependent on the duration of exposure, tissue penetration, and heat generation, which in turn are related to their intensity and frequency [23].

The fundamental parameter that controls the strength of the magnetic field effects is usually the magnetic susceptibility, χ , of the object submitted to the magnetic field. Therefore, the very low magnetic susceptibility of human tissues and the fact they normally lack any substantial amount of ferromagnetic material may explain the relative weakness of magnetic field interactions [2]. Almost all human tissues are diamagnetic and have susceptibilities in a narrow range of about $\pm 20\%$ from the susceptibility of water, which is $\chi_{\text{H}_2\text{O}} = -9.05 \times 10^{-6}$ in SI units. In fact, the diamagnetic susceptibility of tissues is of very small magnitude, and the forces of diamagnetic repulsion away from a static field are usually so small as to be negligible and unnoticed [2]. In spite of the low magnetic susceptibility, some magnetic field effects have been reported in biological systems. An overview is presented below.

Magnetic field effects on cellular structures and functions

Some of the magnetic field effects observed in cells and cellular structures, most of which are exposure time-

and cell type-dependent, are summarized in Table 1 [20, 23–28]. In spite of many effects cited, studies have shown that a static magnetic field alone does not have a detrimental effect on the basic properties of cell growth and survival under normal culture conditions, regardless of the magnetic density [29]. Moderate-intensity static magnetic fields (1 mT to 1 T) on cells are not cytotoxic. However, while the perturbations to cells caused by moderate-intensity static magnetic field are sub-lethal, they may, especially at longer times of exposure, cause a progressive accumulation of modifications, e.g., to gene expression, which in turn may act as co-tumorigenic or co-carcinogenic factors. Further studies need to be carried out to ascertain whether, at exposure times longer than those reported in the literature, the sub-lethal perturbations of the cells are permanent or reversible [23].

Teratogenic, reproductive, and mutagenic effect of magnetic field

In order to examine teratogenic and reproductive effects of magnetic field, studies have been conducted with mice. After exposure of animals to a 4.7-T magnetic field and evaluation of fetal growth, adult growth, and testicular development no conclusive results were achieved [30]. However, exposure of human fetuses in the third trimester of pregnancy did not lead to observation of harmful effects of static magnetic field (1.5 T) [31].

Possible mutagenic and co-mutagenic effects of strong static magnetic fields were also investigated. Mutagenic potential of static magnetic fields up to 5 T was not detected by a bacterial mutagenicity test [11].

Table 1 Reported magnetic field effects on cellular structures and functions [20, 23–28]

Cellular structure/function	Effect
Plasma membrane	Reorientation of diamagnetic molecular domains; proteic pattern changes; rotation of the membrane's phospholipids
[Ca ²⁺]	Intracellular and extracellular fluxes; transport across cell membrane; Ca ²⁺ signaling
Cell shape	Elongation for in suspension growing cells; detachment for in adhesion growing cells; lamellar or bubble-like microvilli
Apoptosis	Perturbation of the apoptotic rate (increase as well as decrease)
Proliferation	Perturbation of the proliferative index (increase as well as decrease)
Necrosis	Not induced
Apoptotic-related genes	Modulation (increase as well as decrease)
Apoptotic cell surface	Partially reverted the expression of 'eat me' epitopes
Phagocytosis of apoptotic cells	Decreased
Differentiation of macrophages	Delayed
Fibrin fibers	Polymerization and the dissolution of fibrin fibers is accelerated
DNA distribution	No significant influence
DNA synthesis	Not altered
Cell cycle	Not altered
Proliferation kinetics	Not altered
Mitotic apparatus	Changes in its orientation

Concerning the co-mutagenicity evaluation, it was found that the mutagenic potential of chemical mutagens was significantly enhanced by exposure to a magnetic field [11]. In certain cases, such enhancement depended on the period of exposure to the magnetic field. However, the increase in the mutation frequency became saturated after 24-h exposure. Different mechanisms may be involved, namely, the production of radical pairs, magnetic field effects on metabolic pathways, alterations of membrane permeability, or even the effect of magnetic fields on DNA repair [11].

Controlled use of static magnetic fields together with therapeutic agents may offer improvement in the treatment of certain diseases [32]. The effects induced by the static magnetic fields might affect the processes of cancer induction and/or progression by altering cellular responses to some known carcinogens (chemicals, radiation) and it was therefore suggested that co-exposure effects should be examined in more detail [33].

Magnetic field effects on vital signs

In order to investigate high magnetic field effects, 25 normal subjects, consisting of 19 men and 6 women, ages 24–53 years, were evaluated. The electrocardiograms and vital signs of the subjects were measured. This included the heart rate, respiratory rate, systolic and diastolic blood pressures, finger pulse oxygenation levels, core body temperature via the external auditory canal temperature, and fiber optic core body sublingual temperatures. As a result, the only statistically significant effect of magnetic field strength was observed on systolic blood pressure. An average increase of 3.6 mmHg in systolic blood pressure was seen with 8-T exposure. Electrocardiogram rhythm strip analysis demonstrated no significant post-exposure changes [34].

Neuro-cognitive and behavioral effects

In order to investigate neuro-cognitive and behavioral effects of magnetic fields, human subjects were evaluated after magnetic field exposure (8 T). The mean reduction in test performance was –4% for eye–hand coordination and –16% for visual contrast sensitivity. Dexterity, visuomotor speed, visuoverbal interference, and verbal attention were not affected. In spite of these findings, there was no evidence of any clinically relevant alteration in human neuro-cognitive function related to static magnetic field exposure [3, 35].

The behavioral effects on rats were investigated after exposure to static magnetic fields of 4–19.4 T. Rearing was suppressed after exposure to 4 T and above; circling was observed after 7 T and above;

conditioned taste aversion was acquired after 14 T and above; and exposure to +14 T induced counter-clockwise circling, while exposure to –14 T induced clockwise circling. These effects of exposure to high magnetic fields were consistent with stimulation of the vestibular apparatus [36].

Safety concerns related to magnetic field exposure

Some concerns related to magnetic field exposure may be considered in order to assure safety. Actually, accidents may be avoided by adopting some of the measures discussed below.

Ferromagnetic objects

Ferromagnetic objects should not be introduced near the magnetic field to avoid transforming them into bullets [7]. Besides, ferromagnetic objects (foreign bodies) within the patient may also represent life-threatening risks [2]. A ferromagnetic object can react to the magnetic field in two ways—as a translational force and as a rotational force. A translational force is operating when an object is strongly pulled to the center of the magnetic field. A rotational force (also known as *torque*) occurs when an object within the magnetic field tries to align itself with the magnet. Torque can cause a stationary ferromagnetic object, even one within a person's body, to twist and rotate in position [37]. Similarly, the magnetic field might displace or distort prostheses (intra-cranial vascular and surgical clips, cochlear implants, and all metal devices close to vital anatomical structures) and induce electrical currents or heat. Further limitations regard patients who have splinters of ferromagnetic materials lodged in their body and those with tattoos or permanent make-up containing ferromagnetic pigments. In the last two groups of patients, a few cases of skin irritation and swelling have been reported. Contraindications are also connected with prostheses and/or fixed or mobile metal implants, internal metal and non-metal prostheses, crystalline lens prostheses, and intra-uterine devices [3, 7].

In the magnetic field environment, magnetic field-related translational attraction and torque may really cause hazards to patients and individuals with such implants. The risks are proportional to the strength of the static magnetic field, the strength of the spatial gradient, the mass of the object, its shape, and its magnetic susceptibility [38]. The maximal torque is proportional to the square of the magnetization for objects made from a single material [39].

Medical devices

The function of electrically, magnetically, or mechanically activated devices, e.g., pacemakers, cardiac catheters, and insulin pumps, can be affected by the magnetic field [7]. The interactions of magnetic fields with such medical devices involve safety risks [40]. Because of theoretical risks, there is a contraindication for a patient with a pacemaker to undergo MRI. However, in some cases, MRI is needed to provide valuable clinical information. Studies have been performed in order to determine whether patients with pacemakers could safely undergo MRI. In one of these studies, 54 patients underwent a total of 62 MRI examinations at 1.5 T. No adverse events occurred. Electrocardiographic changes and patient symptoms were minor and did not require cessation of MRI. Therefore, safety was demonstrated in this series of patients with pacemakers at 1.5 T [41].

At the present time, if MRI procedures are performed in patients with pacemakers because of an overriding medical need, they should be approached thoughtfully and with great caution. Since serious dysrhythmias cannot be excluded during MRI, it would seem advisable that a cardiologist be present in the MR suite during the entire scan [42].

Movement in the magnetic field

Motion in a magnetic field will cause the flow of electric current even if there is no applied electric field. These magnetic field-induced currents manifest themselves any time the patient moves within the field [2]. Sensations reported by patients include feeling of falling, loss of proprioception, and muscle twitching (peripheral nerve stimulation). Others have experienced a transient metallic taste in the mouth, probably due to electrolysis of metallic fillings in the teeth induced from local current generation. A transient sensation of amorphous “lights” in the eyes, called magnetophosphenes, has also been reported. This effect is similar to that observed when squeezing a closed eye tightly. This transient finding is uncommon and is clearly not harmful to the subject, but it is something that should be avoided during interventional procedures [3, 9]. Acute effects of static magnetic fields, e.g., nausea, vertigo, a metallic taste, and phosphenes, can be induced during movements in fields larger than around 2 T. Adverse acute responses do not occur at field strengths below 2 T [43].

In order to better inform the MRI community concerning safe movements in or around an MRI system, theoretical investigations have been performed. In one

of the research studies, a heterogeneous volume conductor model of an adult male along with an efficient finite difference scheme was used to calculate the induced electric field distributions when the human body moves into high field MRI scanners. The simulations showed that the induced fields and currents should not be ignored at ultrahigh fields (≥ 7 T). Extrapolated data of the peak-induced currents have been presented to evaluate the potential safety issue at a variety of field strengths and patient velocities. High values for the induced quantities may be generated for patients who move rapidly in the fields, particularly at the extremities of the magnetic systems [9].

Pregnancy and age-related concerns

The circumstances for the exposure of pregnant women to magnetic field are mainly related to MRI. They include the following situations: the patient may not be aware she is pregnant; the expectant mother may need diagnosis; or direct imaging of the fetus to confirm an abnormality or to provide further information may be required. The exposure of pregnant staff working in MRI is also an essential consideration [44].

The hazards that need to be addressed particularly for pregnant women are the biological effects of the static and time-varying magnetic fields. Data on human fetus exposure in the third trimester of pregnancy have shown no harmful effects of static magnetic fields (1.5 T) [31]. However, conclusive evidence is still needed about the risks to embryos and fetuses [44].

Concerning the other age extremity, MRI (and consequent moderate magnetic field exposure) can be considered highly appropriate for the elderly. Very long MRI sessions were found to be feasible, even in the oldest subjects (age >90 years), and no significant discomfort was associated with magnetic field exposure [45].

Conclusions

The recent development of superconducting magnets in particular has resulted in a huge increase in human exposure to very large static magnetic fields of up to several teslas. MRI, the major exposure factor, has gained widespread use for diagnosis and the magnetic flux densities used are increasing. Since MRI may be considered a safe technique [2, 4, 46], moderate magnetic field exposure seems not to be dangerous. The fundamental parameter that controls the strength of the magnetic field effects is usually the magnetic susceptibility, χ , of the object submitted to the magnetic

field. Therefore, the very low magnetic susceptibility of human tissues and the lack of any substantial amount of ferromagnetic material normally occurring in these tissues may explain the relative weakness of magnetic field interactions [2]. In spite of the low magnetic susceptibility, static magnetic fields may interact with living tissues in a number of ways, but their health relevance is not clear [13, 14]. Within the limits of our knowledge, the main health hazards significantly associated with the exposure to static magnetic fields are related to the presence of ferromagnetic materials or cardiac pacemakers in patients [38]. Acute effects of static magnetic fields, e.g., nausea, vertigo, metallic taste, and phosphenes, can be induced during movements in fields larger than around 2 T. Adverse acute responses do not occur at field strengths below 2 T [43]. Exposure to static magnetic fields alone has no or extremely small effects on cell growth and genetic toxicity regardless of the magnetic density. However, in combination with other external factors such as ionizing radiation and some chemicals, there is evidence to suggest that a static magnetic field modifies their effects. Therefore, co-exposure effects should be examined in more detail [29, 33].

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