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ORIGINAL RESEARCH ARTICLE

Magnetic resonance imaging: Recent research on the biological impacts of static magnetic and high-frequency electromagnetic fields

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ABSTRACT

Problem: in recent years, new studies have been published on biological effects of strong static magnetic fields and on thermal effects of high-frequency electromagnetic fields as used in magnetic resonance imaging (MRI). Many of these studies have not yet been incorporated into current safety recommendations. **Method:** scientific publications from 2010 onwards on the biological effects of static and electromagnetic fields of MRI were searched and evaluated. **Results:** new studies confirm older work that has already described effects of static magnetic fields on sensory organs and the central nervous system accompanied by sensory perception. A new result is the direct effect of Lorentz forces on ionic currents in the semicircular canals of the vestibular organ. Recent studies on thermal effects of radiofrequency fields focused on the development of anatomically realistic body models and more accurate simulation of exposure scenarios. **Recommendation for practice:** strong static magnetic fields can cause unpleasant perceptions, especially dizziness. In addition, they can impair the performance of the medical personnel and thus potentially endanger patient safety. As a precaution, medical personnel should move slowly in the field gradient. High-frequency electromagnetic fields cause tissues and organs to heat up in patients. This must be taken into account in particular for patients with impaired thermoregulation as well as for pregnant women and newborns; exposure in these cases must be kept as low as possible.

Keywords: Patient Safety; Body Temperature; Sensory Organs; Biological Models; Cognition

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1. Introduction

Magnetic resonance imaging (MRI) has established itself clinically as one of the most important and widely used imaging modalities in medicine[1]. In addition to the increase in the frequency of examinations, the clinical spectrum of examinations has expanded quite considerably. Today, patients with impaired vital functions—for example, patients with cardiovascular diseases are also frequently examined.

The progress achieved in MRI is due to technological developments, which, however, have also greatly increased the exposure of patients to magnetic and electromagnetic fields. The unintended use of modern MRI systems can not only be associated with unpleasant perceptions for patients, but also poses health risks.

The aim of this study is to present and summarize recent studies from around 2010 on the biological effects of static magnetic fields (SMF) and radiofrequency electromagnetic fields (RF) in MRI. The majority of these studies have not yet been incorporated into current safety recommendations.

2. Static magnetic fields

Inside an MR system, the SMF is homogeneous, whereas near the magnetization field gradients occur. SMF can affect biological tissues and organs through various biophysical mechanisms. With regard to safety aspects of MRI, magneto- and hydromechanical effects are of particular importance and are explained in more detail in **Table 1**.

3. Effects on sensory organs

The above-mentioned biophysical effects can stimulate sensory organs and lead to perceptions.

A large study of 1419 patients[2], examined in tomographs with flux densities of 7 and 9.4 T showed that the most frequently reported sensations were dizziness (19% at 7 T, 28% at 9.4 T), followed by metallic taste, nausea, and magnetophosphenes (each less than 10%). These sensations were more pronounced, especially for dizziness, during exposure in the field gradient (19%) than in the isocenter (2%). Women were generally more sensitive than men.

Studies of medical personnel (361 participants) showed[3] that the occurrence of the above symptoms increases with the magnetic flux density during activities at the opening of the tomographs (1.5–7 T). Dizziness was reported by 6% of the respondents, which may pose a potential safety risk to patients.

In another recent study of 44 healthy subjects[4], it was found that subjects reported dizziness and magneto-phosphenes in the isocenter of a 7 T tomograph and/or during movement at its entrance in the first place. The dizziness became more intense with the speed of movement in the field gradient, which speaks for the involvement of induced currents, but also occurred in the isocenter.

In a double-blind scenario, 30 healthy volunteers were tested in the field gradient of a 7 T tomograph[5]. They performed standardized head movements at different positions in the stray field of the tomograph while standing, which led to an exposure to temporally varying magnetic fields of 0.49 and 0.7 T/s. The subjects were then immediately placed in the same position and continued to stand. Immediately thereafter, in the same position and still standing, the subjects were subjected to a balance test by measuring body sway with eyes closed. A dose-dependent negative influence of the inhomogeneous magnetic fields on the equilibrium was found.

Another study on 46 subjects showed[6] that after 30 min exposure to a 7 T system, equilibrium disturbances persisted for at least 2 min after leaving the field, but subsided within 15 min. In contrast, fields with a flux density of 1.5 or 3 T or a short-term (1 min) exposure at 7 T had no aftereffects.

Model calculations showed[7] that in a pure static SMF, Lorentz forces act on the ionic currents in the cupula of the vestibular organ, which can be sufficient to induce nystagmus. A functional MRI (fMRI) study of 30 healthy volunteers at 1.5 and 3 T showed[8] that they developed nystagmus in the SMF. At the same time, a modulation of the fMRI signal was observed in the brain, which could be attributed to a stimulation of the vestibular organ. Another study[9] on 17 subjects in a 7 T scanner showed that the nystagmus was not affected by the speed of the movements in the field gradient. This argues against the involvement of induced currents in the generation of the nystagmus. Model calculations in an improved model showed that the Lorentz forces acting on the ionic currents in the endolymph of the labyrinth in the7 T tomograph were strong enough to cause deformation of the cupulae of the semicircular canals. This then leads, mediated by the vestibulo-ocular reflex, to nystagmus. The extent of nystagmus observed in the 17 subjects was as expected from the model calculations[9].

Subjects also experience dizziness when lying motionless on their back in the isocenter of a tomograph[10]. It is perceived as a rotational movement in the horizontal plane—as if lying on a rotating plate. The threshold for the occurrence of this perception is higher (~5 T) than for nystagmus (~1.7 T). If the head is rotated or lifted[11], the perceived direction of rotation changes in accordance with the hypothesis that depending on the orientation of the head in the magnetic field, the maximum Lorentz forces act on a different one of the 3 semicircular canals of the vestibular organ.

Abstract: SMF can affect sensory organs and cause unpleasant temporary perceptions, especially dizziness. If these symptoms occur in medical personnel during activities at the opening of the tomograph, this may pose a potential safety risk for patients.

Table 1. Biophysical effects of static and time-varying magnetic fields

Static magnetic fields:
Static magnetic fields (SMF) can affect biological tissues and organisms via various physical mechanisms. With regard to safety aspects in MRI, magneto- and hydromechanical effects are of particular importance.

Magnetomechanical effects. If molecules or molecular aggregates (e.g., DNA, actin, collagen, microtubules) or cells (e.g., erythrocytes) have a field-induced (diamagnetic) or permanent (paramagnetic) magnetic moment, a weak torque acts on them in a homogeneous external magnetic field, which can lead to an alignment (**Figure 1a**). A prerequisite for this is that the structures are not spherical and/or that their intrinsic magnetic properties are anisotropically distributed. However, at higher temperatures, such as in the human body, the thermal motion (Brownian motion) opposes an orientation of molecules or cells with a weak magnetic moment. In the inhomogeneous magnetic field, e.g., in the vicinity of the magneticöffnung of an MR system, paramagnetic and especially ferromagnetic structures are also subject to attractive forces (**Figure 1b**).

Magnetohydromechanical effects. On particles with a charge q moving in a magnetic field $\vec{B}$ with the velocity $\vec{v}$ (such as ions in nerve cells and blood vessels), the Lorentz force works

$$\vec{F} = q \cdot \left(\vec{v} \times \vec{B}\right),$$

which leads to a deflection of the charge carriers perpendicular to the field and the direction of motion. Since positively and negatively charged ions are deflected in opposite directions, a potential difference (voltage) is formed, as shown schematically in **Figure 2**.

Time-varying magnetic fields:
According to Faraday's law of induction, a time-varying magnetic field $\vec{B}(t)$, as used in magnetic resonance imaging (MRI) for excitation and preparation of the spin system or occurring during the movement of persons in spatially inhomogeneous static magnetic fields, always induces an alternating electric field. The electric field strength is proportional to the rate of change over time $d\vec{B}(t)/dt$. The induced electric field in turn leads to electric currents in conductive tissues.
Due to this Effect, radio frequency (RF) electromagnetic fields cause energy absorption in tissue. The spatial distribution of energy absorption in the body depends strongly on the size, orientation, and internal tissue structure of the exposed body section as well as the frequency of the RF field. Theoretical and experimental studies show that absorption is maximal when the wavelength of the RF field corresponds to typical magnitudes of the body. Unfortunately, the wavelengths of the RF fields used in MRI are exactly in this resonance range. The energy absorbed in the tissue per unit mass and time is called the specific absorption rate (SAR in W/kg). It increases approximately with the square of the magnetic flux density B_0 of the static magnetic field, so that RF absorption is a safety-relevant Effect that must be carefully considered in high- and very-high-field MR systems. With increasing flux density B_0, the wavelength of the RF field also decreases, so that local minima and maxima of the field distribution form in the body, which can lead not only to inhomogeneous RF excitation (i.e., varying pulse angles) but also to local SAR hotspots. So-called RF shimming is used to try to minimize these effects technically.
The essential biophysical effect of electromagnetic RF fields is the heating of the tissue. It is determined not only by the local power absorption and the duration of exposure, but also very significantly by the thermal conductivity and perfusion of the exposed tissues and organs.

4. Effects on cognitive performance and brain

SMF can impair cognitive performance such as attention, responsiveness, memory, etc., either mediated by sensory stimulation or as a direct effect on the brain. This can affect the performance of medical staff and also potentially affect patient safety. For this reason, various studies have been conducted on this complex of topics.

A series of older studies summarized in a comprehensive pooled analysis[12] showed that controlled head movements in the stray field of a tomograph lead to impairments of visual orientation and eye-hand coordination. However, the extent of the impairment was small and depended on the magnetic flux density. Such impairments, however, could potentially endanger patients in the case of physicians performing interventional measures on often tomographs. The effects described are effectively related to the speed of movement in the gradient of the SMF and the resulting induced electric fields in the head. A follow-up study[13] showed that movements leading to a temporal change in magnetic flux density of at least 1.2–2.4 T/s caused disturbances in attention, responsiveness, and spatial orientation. Memory remained unaffected.

In another study[14], the cognitive performance of 41 subjects was investigated both during quiet movement in the isocenter of a tomograph and during continuous movement in a field gradient (temporal change in magnetic flux density of 0.8 T/s). The investigations were performed in a 1.5 T, 3 T and 7 T tomograph as well as in a mock system (0 T). For all scenarios, 10 different cognition tests showed no influence on attention, reaction time, visual discrimination, eye-hand coordination, and memory. In the same study, a possible stress response of the subjects before, during and after a stay in the ho- mogenic SMF or a movement in the field gradient was investigated by serum levels of catecholamines and salivary cortisol content[15]. No increase in stress hormone was detected.

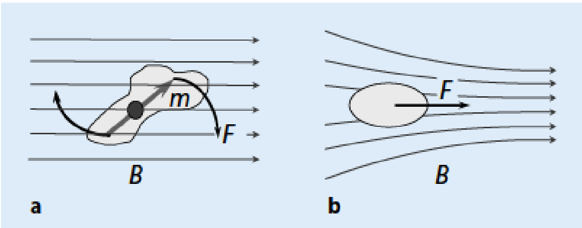

Figure 1. Magneto-mechanical effects. **a**: Rotation of a molecule with magnetic moment $\vec{m}$ in a homogeneous magnetic field; **b**: attraction of a para- or ferromagnetic structure in an inhomogeneous magnetic field. The direction of the forces acting in each case $\vec{F}$ is indicated by the arrows. (From the literature of Brix[16]).

Another study[17] compared the influence of a SMF (1 T) on resting subjects and after standardized head movements of the subjects in the field gradient, which resulted in a temporal change in magnetic flux density of 2.4 T/s. Thirty-six healthy subjects were studied in a double-blind study design compared with a corresponding sham exposition. The static field alone had no influence on cognitive performance, whereas the time-varying field had a negative Influence on memory and visual acuity. Concentration and attention were slightly, but not significantly, negaflvely affected.

A study of 24 subjects[18] in an SMF without exercise in field gradients showed no influence on reaction times and test scores on attention and memory at 3 T.

In addition to the above-mentioned studies on the sole effect of SMF on cognitive performance, this endpoint has also been investigated in 2 studies using all 3 field types of MRI. In the first study[19], 25 subjects performed memory and attention cognition tests before and after imaging at 1.5 and 7 TC. Of 11 parameters evaluated, two were improved at 1.5 T and four at 7 T; otherwise, there were no significant differences. In the authors' opinion, this was a learning effect and not an Influence of MRI. In the second study[20], two consecutive MRI examinations at 9.4 T were performed in 14 subjects. Before and after these examinations, cognition tests on learning and memory were performed at different positions with local magnetic flux densities of <0.5 mT, 0.3 T, and 9.4 T. The results of the first study were not significant. There was no influence of the magnetic flux density, only in one test a learning effect that depended exclusively on the order of the tests and not on the magnetic field. This is consistent with the results of the tests in a pure SMF, which showed that only the movement in the field gradient, but not the homogeneous field, has an influence on cognition.

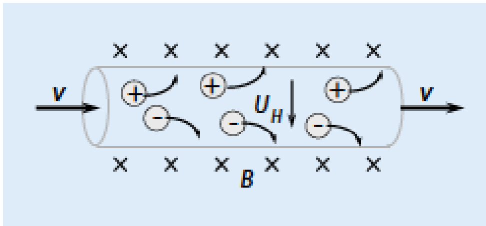

Figure 2. Magnetohydrodynamic effect. Positively and negatively charged ions moving with velocity $\vec{v}$ in nerve cells or a blood vessel perpendicular to the magnetic field are deflected in different directions so that a potential difference or voltage U is formed locally. The crosses indicates the direction of the magnetic field into the papier plane. (From the literature of Brix[16]).

Direct effects of an SMF on brain activity were investigated in two studies, taking into account the technical measurement artifacts caused by the field. In 8 subjects, the first study[21] showed an increase in electroencephalography (EEG) intensity in the theta band at a flux density of 1.5 T during performance of an acoustic discrimination task. All other frequency bands remained unchanged. The outcome of this task was not influenced by the SMF. In the second study[22], 14 subjects performed tests of visual perception and motor responsiveness without field Influence and in the homogeneous SMF of a 3 T tomograph. Brain evoked potentials were recorded. In the field, the latencies of these potentials were prolonged, the amplitudes were decreased, and the reaction times of the subjects were prolonged.

Conclusion: SMF can affect cognitive performance. Primarily, movements in the field gradient are decisive, which lead to induced fields in sensory organs and in the brain. Effects generally occur with movements that lead to a temporal change in magnetic flux density of more than 1 T/s.

5. High frequency electro-magnetic fields

The quantity relevant for the assessment of the physiological effect of electromagnetic RF fields is the temperature increase in the tissue, which depends not only on the local power absorption and the exposure duration, but also on the thermal conductivity and perfusion of the exposed tissues and organs. The energy absorbed per unit mass and time in the body is characterized by the specific absorption rate (SAR in W/kg). Details can be found in **Table 1** for details.

Body heating by RF fields is usually calculated numerically in complex body models. For this purpose, a virtual population of body models of different sex and age was developed[23]. These mathematical models also take thermoregulation into account. The simulations performed using these models showed that the energy absorbed by the body varies depending on anatomy and body size. Children and fetuses absorb significantly less energy than adults[24]. Particularly large and corpulent adults absorb up to 2.5 times more energy than children[25].

In a study[26] on 18 subjects, body heating was measured in a 3 T tomograph at a whole-body SAR value of 4 W/kg. The highest temperature increases of about 1 ℃ were achieved in the pelvic region and were also subjectively perceived as heating.

In recent studies on energy absorption and body heating, the use of modern MR technologies has been investigated. For example, phase array coils can improve the quality of MR imaging. However, depending on the body anatomy, they can also lead to an increase in energy absorption. It has been reported that in studies on a 3 T tomograph, the whole-body SAR was increased by a factor of 1.4–1.6 compared with conventional technology, and the local SAR was increased by a factor of 5 to 13[27]. In a 7 T tomograph with parallel transmission, a local SAR of 10 W/kg can lead to a heating of the head up to 39 ℃ after 30 min and a heating of the eyes by more than 1 ℃[28].

The quality of MR imaging can be improved by high-frequency shimming (**Table 1**). Calculations have shown[29] that as a result of RF shimming, the energy absorption in a 3 T tomograph can increase significantly. Under worst-case conditions (whole-body SAR 4 W/kg, exposition over 60 min, unfavorable anatomy), maximum local temperatures of 42.5 ℃ were calculated for patients with intact thermoregulation and up to 45.6 ℃ for patients with impaired thermoregulation.

Conclusion: The use of modern MR technologies can lead to significant temperature increases in tissues and organs if appropriate safety precautions are not taken. For the evaluation of different exposure scenarios, model calculations based on realistic human models are a suitable approach to complement experimental studies.

6. Exposure in pregnant women and newborns

In fetal diagnostics, MRI is used primarily to clarify unclear ultrasound findings. Since the fetus is particularly sensitive to temperature, heating due to energy absorption plays a special role.

Model calculations for a realistic anatomical model of a pregnant woman in the 28th month of pregnancy showed[30] that the energy absorption in the mother's body is higher than in the fetus. Depending on the frequency of the RF fields, the maximum local energy absorption of the fetus reached about 40–60% of the value of the mother at 64 MHz (1.5 T) and 50–70% at 128 MHz (3 T).

In another study[31], changes in temperature were calculated at 64 and 128 MHz for a 26-week-old fetus at a whole-body SAR level of the mother of 2 W/kg and an exposure duration of 30 min. The fetus itself absorbed less energy than the uterine wall and the highly conductive amniotic fluid. Directly due to the exposure, the fetus warmed up by 0.2 ℃, the uterine wall by 0.3 ℃, and the amniotic fluid by up to 1 ℃. As a result, heat was transferred to the fetus, but its age body temperature remained below 38 ℃.

The interface between the head and the amniotic fluid could reach a temperature of up to 38.9 °C after 30 minutes of exposure.

Another model calculation taking thermoregulation into account[32] showed at 64 MHz and a whole-body SAR of 2 W/kg a maximum increase of 0.47 °C in core temperature and 0.61 °C in fetal temperature after thermal equilibrium was reached for the pregnant woman. For shorter whole-body exposures of up to 40 min at 2 W/kg or up to 10 min at 4 W/kg, the temperature increase remained below 0.5 °C for the fetus.

The application of RF shimming can decrease the energy absorption of the mother, but at the same time increase that of the fetus[33]. Under worst-case conditions (whole-body SAR of the mother 2 W/kg, exposure over 60 min, 7th month of pregnancy), local heating up to 40.8 °C was calculated for the fetus. This resulted primarily from the stronger heating of the amniotic fluid.

MRI examinations on 3 T systems allow better image quality compared to 1.5 T systems, but generally also lead to higher thermal stress. In a study[34] of 25 newborns a few days old, in whom thermoregulation is not yet fully developed, rectal temperature was measured during brain examinations. No significant temperature changes were observed during the course of the examinations at 3 T with an average duration of 55 min.

Conclusion: The warming of the fetus can be estimated with the help of anatomical body models. An increased temperature rise can occur primarily as a result of the high energy absorption in the amniotic fluid. When examining unborn and newborn babies, RF exposure should always be kept as low as possible, e.g., by using suitable examination conditions.

7. Conclusion for practice

● Sensory organs are stimulated by electric currents induced as a result of motion in the inhomogeneous SMF at the edge of an MR tomograph. In the equilibrium organ, additional Lorentz forces act directly on ionic currents.

● The resulting perceptions are temporary and not relevant to patients' health, but may affect the performance of medical staff.

● SMFs may also act directly on the brain with consequent impairment of cognitive performance.

● Due to the availability of realistic human models, RF exposures can be investigated in detail for different study scenarios.

● During MRI examinations of vulnerable persons, such as patients with impaired thermoregulation, pregnant women and newborns, relevant temperature increases may occur, which should be limited as far as possible by carefully optimizing the examination technique.

Conflict of interest

The authors declare that they have no conflict of interest.

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