Health risks for medical personnel due to magnetic fields in magnetic resonance imaging

Gesundheitsrisiken für medizinisches Personal durch Magnetfelder in der Magnetresonanztomographie

Authors
Alexander Marc König, Antje Pöschke, Andreas H. Mahnken

Affiliations
Diagnostic and Interventional Radiology, Philipps University of Marburg, Marburg, Germany

Keywords
MR-imaging, physics, safety

Schlüsselwörter
MR-imaging, physics, safety

received 18.1.2024
accepted after revision 19.3.2024
published online 19.7.2024

Bibliography
Rofo 2025; 197: 135–143
DOI 10.1055/a-2296-3860
ISSN 1438-9029

Georg Thieme Verlag KG, Oswald-Hesse-Straße 50, 70469 Stuttgart, Germany

Correspondence
Alexander Marc König
Diagnostic and Interventional Radiology, Philipps University of Marburg, Baldingerstrasse, 35043 Marburg, Germany
AKoenig@med.uni-marburg.de

Supplementary Material is available at https://doi.org/10.1055/a-2296-3860.

Deutsche Version unter: https://doi.org/10.1055/a-2296-3860.

ABSTRACT

Background The current state of medical and scientific knowledge on the effects of exposure to electromagnetic fields on workers in the field of clinical magnetic resonance imaging (MRI) is summarized here.

Method A systematic literature search was conducted to analyze the health risks to medical personnel from magnetic fields in MRI. A total of 7273 sources were identified, with 7139 being excluded after screening of the title and abstract. After full-text screening, 34 sources remained and were included in this paper.

Conclusion There are a number of scientific publications on the occurrence of short-term sensory effects such as vertigo, metallic taste, phosphenes as well as on the occurrence of neurocognitive and neurobehavioral effects. For example, short-term exposure to clinical magnetic fields has been reported to result in a 4 % reduction in speed and precision and a 16 % reduction in visual contrast sensitivity at close range. Both eye-hand precision and coordination speed are affected. The long-term studies concern, among other things, the influence of magnetic fields on sleep quality, which could be linked to an increased risk of accidents. The data on the exposure of healthcare workers to magnetic fields during pregnancy is consistently outdated. However, it has been concluded that there are no particular deviations with regard to the duration of pregnancy, premature births, miscarriages, and birth weight. Epidemiological studies are lacking. With a focus on healthcare personnel, there is a considerable need for high-quality data, particularly on the consequences of long-term exposure to electromagnetic fields from clinical MRI and the effects on pregnancy.

Key Points
- Short-term sensory effects such as vertigo, metallic taste, phosphenes as well as neurocognitive and neurological behavioral effects may occur upon exposure to magnetic fields.
- Long-term effects mainly concern quality of sleep, which can be associated with an increased risk of accidents.
- When pregnant women were exposed to magnetic fields, no particular deviations were found with regard to the duration of pregnancy, premature births, miscarriages, and birth weight.

Citation Format
- König AM, Pöschke A, Mahnken AH. Health risks for medical personnel due to magnetic fields in magnetic resonance imaging. Rofo 2025; 197: 135–143

ZUSAMMENFASSUNG

Hintergrund Es wird der aktuelle medizinisch-wissenschaftliche Stand zu Wirkungen der Exposition gegenüber elektromagnetischen Feldern auf die Beschäftigten im Bereich der klinischen Magnetresonanztomografie (MRT) zusammengefasst.

Methode In einer systematischen Literaturrecherche wurden die Gesundheitsrisiken für das medizinische Personal durch Magnetfelder in der MRT analysiert. Es wurden insgesamt 7273 Zitate identifiziert, von denen nach Titel-und-Abstract-Screening 7139 Zitierungen ausgeschlossen werden konnten. Nach Volltext-Screening verblieben 34 Quellen, die Eingang in diese Arbeit gefunden haben.

Schlussfolgerung Es gibt eine Reihe von wissenschaftlichen Veröffentlichungen zum Auftreten von kurzzeitigen sensorischen Effekten wie Vertigo, metallischem Geschmack, Phosphenen sowie zum Auftreten von neurokognitiven sowie neurologischen Verhaltenseffekten. Durch kurzzeitige Exposition gegenüber klinischen Magnetfeldern wurden beispielsweise eine 4 %-ige Reduktion der Geschwindigkeit und der Präzision sowie eine 16 %-ige Reduktion der visuellen Kontrastempfindlichkeit im Nahbereich berichtet. Es werden sowohl Auge-Hand-Präzision als auch Koordinationsgeschwindigkeit beeinflusst. Die Langzeitstudien betreffen u. a. den Einfluss von Magnetfeldern auf die Schlafqualität, welche in Zusammenhang mit einem erhöhten Unfallrisiko stehen könnten. Die Daten zur Exposition von Mitarbeiterinnen im Gesundheitswesen gegenüber magnetischen Feldern während der Schwangerschaft sind durchgehend veraltet. Es wird jedoch geschlussfolgert, dass es zu keinen besonderen Abweichungen bezüglich der Schwangerschaftsdauer, der Frühgeburten, der Fehlgeburten und des Geburtsgewichtes kommt. Epidemiologische Arbeiten fehlen. Mit Fokus auf das Personal im Gesundheitswesen besteht ein erheblicher Bedarf an qualitativ hochwertigen Daten v. a. zu Folgen einer Langzeitexposition gegenüber elektromagnetischen Feldern durch die klinische MRT sowie zu deren Effekten auf eine Schwangerschaft.

Kernaussagen

- Es können bei Exposition von Magnetfeldern kurzzeitige sensorische Effekte wie Vertigo, metallischer Geschmack, Phosphenen sowie neurokognitive und neurologische Verhaltenseffekte auftreten.
- Langzeiteffekte betreffen vor allem die Schlafqualität, welche in Zusammenhang mit einem erhöhten Unfallrisiko gebracht werden kann.
- Bei Magnetfeldexposition auf schwangere Mitarbeiterinnen konnten keine besonderen Abweichungen bezüglich der Schwangerschaftsdauer, der Frühgeburten, der Fehlgeburten und des Geburtsgewichtes gefunden werden.

Introduction

As one of the most important medical imaging methods of the last decade, magnetic resonance imaging (MRI) has become increasingly significant [1, 2, 3]. In Germany, 145 MRI examinations per 1000 inhabitants were registered in the year 2019 [4]. An estimated 50 000 MRI scanners are currently in use internationally [5]. According to Modense et al., approximately 2 000 000 employees worldwide are exposed to high static magnetic fields as a result of medical MRI [6]. This includes not only radiologists and radiology assistants but also anesthesiologists, nursing staff, technical personnel, and cleaning staff [2], as well as employees working in research facilities with MRI systems and those who install and service MRI devices. The group with the greatest exposure is radiology assistants [7]. However, effects on personnel, primarily long-term effects, have only been minimally researched. To provide an overview of these effects and to identify gaps in the research, a systematic literature search was performed.

To prevent disruptive and harmful effects on human beings, Directive 2013/35/EU was issued. This defines the minimum requirements for protecting the safety and health of employees from risks due to physical effects (electromagnetic fields). The long-term effects of exposure to these fields were not taken into consideration in this directive since verified scientific data on this topic was not available when the directive was issued. Protection against and prevention of damaging effects when using systems involving non-ionizing radiation in medicine and dentistry as well as for industrial purposes are ensured and regulated by the “act on protection against non-ionizing radiation in humans” [8]. The scope of this law includes systems using electric, magnetic, and electromagnetic radiation in frequency ranges from 0 hertz to 300 gigahertz for medical and industrial purposes. It also regulates, for example, user requirements such as the necessity of a license or certificate of specialist training. Almost all national and international regulations on protection against electric, magnetic, and electromagnetic fields are based on recommendations of the ICNIRP (*International Commission on Non-Ionizing Radiation Protection*) [9].

Directive 2013/35/EU is based in part on Research Report 400-D by the Federal Ministry of Labor and Social Affairs from the year 2011 [10]. This report provides limit values and trigger thresholds for exposure to electric, magnetic, and electromagnetic fields. The limit values and trigger thresholds defined in Research Report 400-D are primarily based on the goal of protecting the human body against undesired effects from electromagnetic fields (nerve stimulation, tissue heating, etc.). These values essentially relate to short-term interactions with different types of electromagnetic fields.

The present study provides an overview of the current status of research regarding the effects of exposure of the human body to high static and low-frequency magnetic fields and high-frequency electromagnetic fields. The analysis focuses on the exposure for personnel in the field of clinical MRI. The magnetic field strength (magnetic flux density) typically used today is 1.5 T to 3 T. 10 ultra-high-field human MRI scanners in the range of 7 T to 9.4 T are currently operated in Germany in the field of research. The first 7 T MRI device received clinical approval for use in patient care in 2017 [11, 12, 13]. The magnetic flux densities of MRI scanners used in research (experimental and small animal MRI) are currently up to 17.6 T [12]. Magnetic flux densities of up to 28 T have been used for magnetic resonance spectroscopy (MRS) [10, 14].

This review summarizes the current medical-scientific data on the effects of exposure to electromagnetic fields under consideration of the long-term exposure. The focus is on those working in the field of clinical magnetic resonance imaging.

Research method

The inclusion and exclusion criteria for the literature search are summarized in ▶ **Table 1**.

Since the study explicitly relates to the effects of electromagnetic fields on people, i. e., medical personnel, the search was limited to human studies or combined studies (human/experimental animal) within the target group. The articles that were not included due to this limitation were checked separately for relevance. Any insight relevant to this study is included in the discussion section of this article.

The databases that were used for the search are listed in ▶ **Table 2**. An expert search (expanded search, advanced search) was performed to search the databases. Boolean operators, truncation, and search phrases were also used.

The general PICO scheme was modified to obtain a suitable search matrix for the underlying questions (▶ **Table 3**).

A collection of thematically relevant key words were used for the search. Synonyms and abbreviations were taken into consideration.

All search terms were entered either as an MeSH term (e. g., "Cognition Disorders"[MeSH]) or as a term or phrase in the title/abstract (e. g., "Cognition*"[Title/Abstract]). Some MeSH terms were entered with the limitation "No Exp" for "no exploded" (e. g., "health personnel"[Mesh:NoExp]). In this case, only a search for the MeSH term itself and not its subterms was performed.

The individual search blocks from ▶ **Table 4** were then linked with the Boolean operator **AND**. After linking of the three search blocks, the PubMed search yielded 6428 hits. After restricting the language (1) and target group (2), 5372 hits remained for further analysis.

There were 571 hits in the Cochrane Library and 1494 in ClinicalTrials.gov. Combining all three databases excluding duplicates yielded a total of 7273 hits. The title and abstract of these studies were then screened and reviewed for relevance. After the title/abstract screening, 134 studies were selected for full text screening (▶ **Fig. 1**). Cited studies and internet sources were included in the further course of the search.

▶ **Table 1** Inclusion and exclusion criteria of the systematic literature search.

	Inclusion criteria	Exclusion criteria
Language	English, German	Other languages
Target group	Human studies (employees) or (combined studies – human/experimental animal)	Only experimental animal studies
Availability	Full text is available	Access only to title or abstract

▶ **Table 2** Selected databases.

Database	URL	Type of database
PubMed	https://pubmed.ncbi.nlm.nih.gov/	Medical database with articles from the entire field of biomedicine (access to MEDLINE)
Cochrane Library	https://www.cochranelibrary.com/	Online library includes three scientific databases (systematic reviews, Central Register of Controlled Trials, and Cochrane Clinical Answers)
ClinicalTrials	https://www.ClinicalTrials.gov/	Database of clinical studies of the U.S. National Library of Medicine

▶ **Table 3** Modified PICO scheme for this study.

P	**Population**	Which population is being examined?	Employees (particularly in the health care industry)
I	Intervention: In this case **exposure**	What kind of exposure is described?	Electromagnetic fields, MRI
O	Outcome, in this case: **Effects**	Effects to be observed after exposure to electromagnetic fields	Effects (also long-term effects), impairment

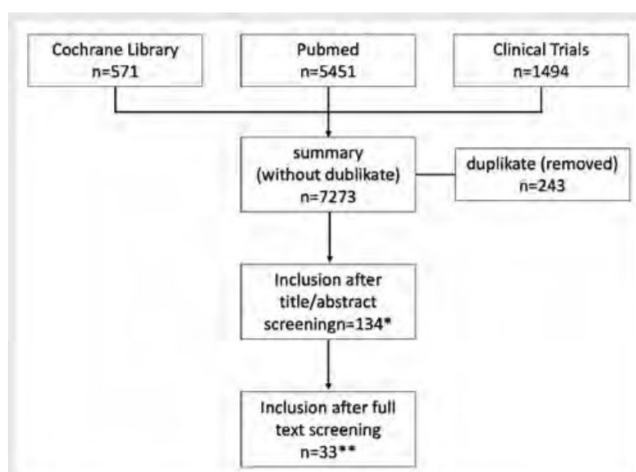
▸ **Table 4** Compilation of search terms (Pubmed).

	No.	Query	Hits
P	#1	"Occupational Medicine"[MeSH] OR "Occupation*"[Title/Abstract] OR "Occupational Diseases"[Mesh:NoExp] OR "Occupational Exposure"[MeSH] OR "Staff*"[Title/Abstract] OR "personnel*"[Title/Abstract] OR "Radiologists"[MeSH] OR "Medical Laboratory Personnel"[MeSH] OR "physicians"[Mesh:NoExp] OR "nurses"[MeSH] OR "medical staff"[MeSH] OR "nursing staff"[MeSH] OR "personnel, Hospital"[Mesh:NoExp] OR "Health personnel"[Mesh:NoExp] OR "Occupational Health"[MeSH] OR "Health occupations"[Mesh:NoExp] OR "employment*"[Title/Abstract] OR "workplace*"[Title/Abstract] OR "workstation*"[Title/Abstract]	872 419
I	#2	"Magnetic Resonance Imaging"[Mesh:NoExp] OR "fMRI"[Title/Abstract] OR "Magnetic Resonance*"[Title/Abstract] OR "MR Tomograph*"[Title/Abstract] OR "NMR Imaging*"[Title/Abstract] OR "NMR Tomograph*"[Title/Abstract] OR "MRI"[Title/Abstract] OR "Magnetic Fields"[MeSH] OR "Magnetic Field*"[Title/Abstract] OR "Electromagnetic Field*"[Title/Abstract] OR "Electromagnetic Radiation"[MeSH] OR "Electromagnetic Radiation*"[Title/Abstract] OR "magnetic resonance"[Title/Abstract]	1 079 485
O	#3	"Cognition Disorders"[MeSH] OR "Cognition*"[Title/Abstract] OR "Cognition"[MeSH] OR "Cognitive*"[Title/Abstract] OR "Sensation Disorders"[MeSH] OR "sensitivit*"[Title/Abstract] OR "senes*"[Title/Abstract] OR "Sensation*"[Title/Abstract] OR "Sensor*"[Title/Abstract] OR "hearing*"[Title/Abstract] OR "Tinnitus"[Title/Abstract] OR "smell*"[Title/Abstract] OR "taste*"[Title/Abstract] OR "metallic*"[Title/Abstract] OR "Phosphenes"[MeSH] OR "phosphene*"[Title/Abstract] OR "light phenomen*"[Title/Abstract] OR "eye-hand*"[Title/Abstract] OR "Dysgeusia"[Title/Abstract] OR "vision*"[Title/Abstract] OR "visual*"[Title/Abstract] OR "Dizzi*"[Title/Abstract] OR "Dizzy*"[Title/Abstract] OR "Vertigo"[MeSH] OR "Vertigo*"[Title/Abstract] OR "spinning*"[Title/Abstract] OR "Nausea"[MeSH] OR "Nausea"[Title/Abstract] OR "Neurocognitive Disorders"[MeSH] OR "Neurocognitiv*"[Title/Abstract] OR "Sleep Disorders, Circadian Rhythm"[MeSH] OR "Sleep*"[Title/Abstract] OR "nerve stimulation*"[Title/Abstract] OR "tactil*"[Title/Abstract] OR "tissue heating*"[Title/Abstract] OR "neuropsychological Tests"[MeSH] OR "neuropsychological Tests"[Title/Abstract] OR "Embryonic Development"[MeSH] OR "embryonic development*"[Title/Abstract] OR "Congenital Abnormalities"[MeSH] OR "malformation*"[Title/Abstract] OR "Pregnancy"[MeSH] OR "pregnan*"[Title/Abstract] OR "Fertility"[MeSH] OR "Fertil*"[Title/Abstract] OR "fetal development*"[Title/Abstract] OR "fetal development"[MeSH] OR "teratogen*"[Title/Abstract] OR "Neoplasms"[MeSH] OR "Neoplasm*"[Title/Abstract] OR "cancer*"[Title/Abstract] OR "carcinog*"[Title/Abstract] OR "Blood Circulation"[MeSH] OR "Blood Circulation*"[Title/Abstract] OR "blood flow*"[Title/Abstract] OR "adverse effects"[sh] OR "adverse effect*"[Title/Abstract] OR "Time Factors"[MeSH] OR "limit value*"[Title/Abstract] OR "specific absorption rate*"[Title/Abstract]	11 083 102

Results and discussion

Effects of static, low-frequency, and movement-induced magnetic fields

Strong static magnetic fields are capable of penetrating the human body virtually unhindered. Thus, electrodynamic interactions can have an effect on charged moving particles in the body [15, 16]. Charged particles that can be influenced magnetohydrodynamically by these interactions [15] are also found in the bloodstream. Kinouchi et al. provided a theoretical approach in the year 1996 with the help of the finite element analysis [15]. It was calculated in this study that an approximate decrease in blood volume flow of 5 % or 10 % can be expected at flux densities of 10 T and 15 T [15]. The results also show that voltages in the aorta induced by blood flow can propagate into the heart and could disrupt autonomic cardiac function [15, 17]. In the year 2003, Chakeres et al. performed 14 measurements on 25 people at different locations in the vicinity of an 8 T MRI scanner inside and outside the magnetic field (high-frequency electromagnetic fields were not used) [18]. Five measurements were performed inside the magnetic field at locations corresponding to different field strengths (8; 6; 4.5; 3, and 1.5 T). Various vital functions (heart rate, electrocardiogram (EKG), systolic and diastolic blood pressure) were measured with the help of a monitoring system. The oxygen saturation and body temperature were also measured. The only statistically significant change that was identified was a slight, clinically insignificant increase in systolic blood pressure at 8 T [18]. The other measured vital functions did not show any significant, clinically relevant changes in relation to exposure to dif-



▸ **Fig. 1** Flowchart of the literature search (* = appendix 1; ** = appendix 2).

▶ **Table 5** Frequency of maximum sensitivity to certain physiological effects in the low-frequency range (modified according to FB 400-D).

Frequency of max. sensitivity	Physiological effect	Interaction site
<< 1 Hz	*Metallic taste sensations*	*Taste receptors of the tongue (changes in ionic gradients)*
< 0.1–2 Hz	▪ *Vertigo, nausea* ▪ *Electric fields in tissue induced by blood flow*	*Inner ear (vestibular apparatus)* *Irritation of nerves and muscles (disruption of autonomic cardiac function)*
~ 20 Hz	*Magnetophosphenes*	*Retina*
~ 50 Hz	▪ *Tactile and painful sensations* ▪ *Loss of muscle control* ▪ *Impaired autonomic cardiac function*	*Peripheral nerves* *Peripheral nerves, muscles* *Heart*

ferent field strengths [18]. These results are in agreement with the data from Kangarlu et al., who were not able to detect any significant cardiac and cognitive effects in both pigs and human volunteers at a field strength of 8 T [19]. A more recent study by Bongers et al. from the year 2018 showed that long-term exposure to static magnetic fields might be associated with the development of high blood pressure among workers manufacturing MRI devices [20]. In this study, the first and last available blood pressure measurements of workers (n = 538) were linked to the modeled cumulative exposure to static magnetic fields (facility-related exposure matrix and individual job histories). The study came to the conclusion that high cumulative exposure to static magnetic fields can result in the development of high blood pressure [20]. The strength and intensity of the exposure had a greater effect on the risk of developing high blood pressure than the total duration of exposure [20]. In this connection and in light of the constant increases in the strength of static magnetic fields in MRI, additional studies are needed to confirm the results of this study and any possible long-term effects.

Time-varying, low-frequency magnetic fields (100–1000 Hz) and movement in a static magnetic field as well as movement along a field gradient can induce eddy currents [21, 22, 23]. In the case of constant movements (constant speed of movement), the strength of the induced electrical fields in the body can be estimated [24]. There are natural field strengths from 5–50 mV in the human body [25]. The induction of electrical fields exceeding certain threshold values can thus result in sensory effects and health risks [25]. Furthermore, the interaction of strong static magnetic fields with moving, charged particles in the fluids and cells of the body can result in temporary sensory disruption. This is the result of magnetic induction due to the development of Lorentz forces. In a static magnetic field, it is assumed that Lorentz forces act, for example, on ionic currents in the vestibular endolymph fluid and in the hair cells [3, 26]. ▶ **Table 5** shows the frequency of maximum sensitivity (maximum effect) for certain physiological effects. Schaap et al. examined the occurrence of temporary symptoms in 361 employees in 14 hospitals and research facilities [27]. The scanner strength ranged from 0.5 to 11.7 T. The study showed that defined symptoms (vertigo, nausea, tinnitus, magnetophosphenes, and metallic taste) associated with exposure to static magnetic fields occurred in 16–39 % of work shifts. The symptoms correlated positively with an increasing magnetic flux density. Vertigo, which can present a safety risk, was observed in 6 % of employees [7]. In 2015, Schaap et al. published a study on the exposure of MRI employees to magnetic fields and the occurrence of vertigo [28]. In this study, the exposure was not estimated but rather was calculated with wearable magnetic field dosimeters. The clearest connection between vertigo and exposure was seen in the case of movement-induced time-varying magnetic fields [28]. However, there are also studies that have shown that subjects experience vertigo even without movement in the MRI scanner [29, 30], which can be caused by ionic currents in the endolymph in the semicircular canals [3, 26, 30, 31]. Particularly when the presence of an employee is required during a medical intervention, episodes of vertigo present a risk for the employee as well as for the patient [3, 32]. In light of the constant increases in the magnetic flux densities of MRI systems, an increase in related symptoms can also be expected [27].

The effects mentioned above are summarized as sensory effects. They can disrupt sensory organs and cause minimal changes in brain function among employees. However, in general, they are generally considered harmless since they are usually very brief. The health effects include the stimulation of nerve and muscle tissue at higher field strengths. The frequency of the maximum sensitivity for peripheral nerve and muscle stimulation is approximately 50 Hz. At a frequency of 50 Hz, the international basic threshold value is an electrical field strength of 20 mV/m [25]. Starting at a threshold of 50 mV/m, phosphenes are released and starting at electrical field strengths of 4000–6000 mV/m, irritation of the peripheral nerve cells and muscle cells occurs [25]. Starting at approximately 12,000 mV/m, cardiac function can be impaired (additional contractions and even ventricular fibrillation) [33].

Acute effects of electromagnetic fields on cognition and behavior

The acute effects of electromagnetic fields on cognition and behavior are summarized in ▶ **Table 6**. While eye-hand coordination was affected in the first study by De Vocht et al. [34], coordination speed was reduced in a second study [35]. These differences could be affected by exposure differences or also a relatively small test group size. This study also showed that there are exposure-effect relationships for visual and auditory working memory,

▶ **Table 6** Acute effects of electromagnetic fields on cognition and behavior.

Field strength	Literature source	Cognitive effects
0.7 T **Static magnetic field with and without movement of the subject**	*De Vocht et al.* [37]	▪ 4 % reduction of speed and precision ▪ 16 % reduction of visual contrast sensitivity at close range
Scatter field of 0.6–1 T for 1.5 T and 3 T MRI	*De Vocht et al.* [38]	*Negative exposure-effect relationships for visual and auditory working memory (eye-hand coordination speed and visual tracking tasks)*
Static magnetic field of 0.05 T and 8 T (Without movement)	*Chakeres et al.* [42]	*No relationship between exposure to a static magnetic field and cognitive ability*
Variable	*De Vocht et al.* [35]	▪ *Vertigo, trouble concentrating, metallic taste, and tinnitus significantly more common in the exposure group* ▪ *Number of defined symptoms significantly higher with an increased duration of exposure, magnetic flux density, and speed of movements* ▪ *No significant impairment of cognitive ability like motor response*
1600 mT, 800 mT, and 0 mT **(static and induced time-varying magnetic fields)**	*De Vocht et al.* [36]	*Slight and insignificant effects on the visual-sensory domain and eye-hand coordination*
Head movement in the scatter field of a 7 T scanner at 0.5 T and 1 T or without exposure at 0 T	*Van Nierop et al.* [43]	▪ *Negative effect on concentration and attention as well as impairment of visual-spatial orientation* ▪ *Effect on attention and concentration particularly in the case of high working memory performance*
Head movement in the scatter field of a 7 T scanner **(1 T in front of the bore of a 7 T scanner with or without 2.4 T/s motion-induced exposure)**	*van Nierop et al.* [44]	▪ *Static magnetic fields in combination with motion-induced, time-varying magnetic fields significantly affect verbal memory performance and visual acuity* ▪ *Attention and concentration negatively affected* ▪ *Sole exposure to a static magnetic field did not show any significant effects*

eye-hand coordination speed, and visual tracking tasks. It was unclear whether the effects on neurological behavior are triggered in the majority of cases by the static magnetic field or the speed of movement within the stray field [36]. In contrast, a study by Chakeres et al. was not able to show a relationship between exposure to static magnetic fields of 0.05 T and 8 T and cognitive function [37]. Not only employees working with MRI but also those involved in the manufacture of such devices have high levels of exposure to the described electromagnetic fields. In a study of people manufacturing and installing MRI systems, De Vocht et al. were able to show that the occurrence of vertigo, concentration problems, metallic taste, and tinnitus was significantly higher but cognitive function was not affected [38]. Since the cognitive tests were performed immediately before and after a shift, De Vocht et al. concluded that cognitive impairment is only of an acute and temporary nature and disappears relatively quickly following exposure [38]. A further study by Vocht et al. showed mild effects on the visual sensory domain and hand-eye coordination in test persons in the immediate vicinity of the MRI system, but this was not significant with respect to the control group [39]. The studies by Van Nierop et al. essentially showed that movement in the static magnetic field had a negative effect on concentration, memory, attention, and visual acuity [40, 41].

Effects of long-term exposure to static and low-frequency fields

There are only a few studies or minimal data regarding the long-term effects of occupational exposure to strong static magnetic fields [45]. When analyzing acute effects in relation to neurocognition, neurobehavior, and sensory effects, it is necessary to examine whether regularly occurring reactions could result in long-term impairment [46]. In a retrospective cohort study, Bongers et al. examined the effect of occupational exposure to strong static magnetic fields in a manufacturing facility for MRI devices [46]. The goal of this study was to examine the relationship between exposure to strong static magnetic fields and the accident risk for employees. A connection between exposure to static magnetic fields and an elevated accident risk was seen. In addition, the occurrence of accidents or near accidents on the way to work (less on the way home) was also dependent on occupational exposure and recent exposure to static magnetic fields. Huss et al. confirmed this observation among radiology assistants [47]. An elevated risk for commuting accidents was seen in this study when study participants when study participants worked more frequently on or near an MRI device in the year before the accident. The risk increased with an increase in the number of exposure days per year. In addition, a higher magnetic flux density resulted in an increase in the risk. A limiting factor of this study was the low return rate of the questionnaire (~ 30 %) and the possibility that persons had accidents in the time period prior to the study period but were categorized as accident-free in the study.

Huss et al. showed that sleep quality among other factors could be a reason for the previously observed increase in accident risk [48]. Employees in the scanner room during image acquisition also reported an increase in sleep disturbances.

Pregnant employees in clinical MRI

There are a number of studies examining the benefits and risks of MRI examination of pregnant patients [3, 49, 50, 51].

However, in relation to long-term effects and safety for pregnant employees in the field of MRI, the study by Kanal et a. from the year 1993 is often the only study cited [42, 43]. In this study, a survey of employees at MRI facilities was used to record various parameters like duration of pregnancy, premature births, miscarriages, birth weight, cycle duration, etc. [42]. 1915 questionnaires were included in this study and 1421 pregnancies (in 770 women) were registered. Of the 1421 registered pregnancies, 280 involved employees who were magnetic resonance imaging workers at the time of pregnancy. Kanal et al. concluded that there are no particular deviations regarding pregnancy parameters, i. e., no increased risk for pregnant employees and their unborn children [42]. This study is often cited in connection with risks in the field of MRI with respect to pregnant employees [44, 51, 52] and in national and international regulations [21, 53]. According to these regulations, it is not recommended for pregnant employees to be present in the scanner room. However, working in the control room is not prohibited as cited by the German Commission on Radiological Protection in their report from 2003 [54, 55]. Mühlenweg et al. point out that the lack of limit values results in pregnant employees being allowed to enter the MRI room in many hospitals and practices when scans are not being performed based on the recommendation of standard IEC 60601–2-33:2010/A2 [54]. In the USA, according to the "*ACR Guidance Document on MR Safe Practices: 2013*" by Kanal et al., pregnant employees are allowed to work in the scanner room even during scans during the entire pregnancy [53].

Epidemiological studies

There is no explicit epidemiological data for the field of clinical MRI. This was also explicitly noted by Bongers et al. in a retrospective study from the year 2014, which examined the health consequences of long-term exposure to static magnetic fields [56]. In 2005, Feychting et al. stated the need for studies on the long-term effects of exposure to static magnetic fields [45]. Epidemiological studies regarding chronic exposure to static magnetic fields have also been recommended by other organizations [16, 57, 58]. Low-frequency fields have been repeatedly connected to neurodegenerative diseases (amyotrophic lateral sclerosis (ALS), Alzheimer's, Parkinson's). However, the results are inconclusive [59, 60, 61, 62, 63]. Low-frequency magnetic fields have continued to be categorized by the International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) as class 2B "possibly cancer-causing" based on the results of epidemiological studies showing an elevated risk for pediatric leukemia at magnetic flux densities of over 0.3–0.4 μT [64, 65]. However, the mechanism of action is currently not known, and the results could not be confirmed in animal experiments [64, 65].

Conclusion

Magnetic fields can result in sensory and cognitive disturbance. However, this disturbance is typically transient. A possible predisposition for high blood pressure and sleep disturbances were shown as long-term effects. Pregnancy parameters in pregnant employees do not deviate from the standard. However, there are only very few publications on the long-term effects on pregnant employees. Thus, there is a significant need for research here.

Funding Information

BGW (ext FF_1455)

Conflict of Interest

The authors declare that they have no conflict of interest.

Literatur

[1] Nekolla EA, Schegerer AA, Griebel J et al. Häufigkeit und Dosis diagnostischer und interventioneller Röntgenanwendungen: Trends zwischen 2007 und 2014. Radiologe 2017; 57: 555–562. doi:10.1007/s00117-017-0242-y

[2] Hartwig V, Virgili G, Mattei FE et al. Occupational exposure to electromagnetic fields in magnetic resonance environment: an update on regulation, exposure assessment techniques, health risk evaluation, and surveillance. Med Biol Eng Comput 2022: 297–320. doi:10.1007/s11517-021-02435-6

[3] Pophof B, Brix G. Magnetic resonance imaging: Recent studies on biological effects of static magnetic and high-frequency electromagnetic fields. Radiologe 2017; 57: 563–568. doi:10.1007/s00117-017-0260-9

[4] Health at a Glance 2021. OECD; 2021. doi:10.1787/ae3016b9-en

[5] 21–01 | Facts and figures: Organ distribution of MRI studies – Number of MRI machines worldwide – Field strength of MRI machines. Last update October 2018 | MRI NMR Magnetic Resonance • Essentials, introduction, basic principles, facts, history | The primer of EMRF/TRTF (30.05.2019). Accessed February 13, 2022 at: https://www.magnetic-resonance.org/ch/21–01.html

[6] Modenese A, Gobba F. Occupational Exposure to Electromagnetic Fields and Health Surveillance According to the European Directive 2013/35/EU. Int J Environ Res Public Health 2021; 18. doi:10.3390/ijerph18041730

[7] Schaap K, Christopher-De Vries Y, Slottje P et al. Inventory of MRI applications and workers exposed to MRI-related electromagnetic fields in the Netherlands. Eur J Radiol 2013; 82: 2279–2285. doi:10.1016/j.ejrad.2013.07.023

[8] NiSG – Gesetz zum Schutz vor nichtionisierender Strahlung bei der Anwendung am Menschen*) (07.06.2022). Accessed June 07, 2022 at: https://www.gesetze-im-internet.de/nisg/BJNR243310009.html

[9] ICNIRP. ICNIRP (25.02.2022). Accessed February 25, 2022 at: https://www.icnirp.org/

[10] BMAS. BMAS – Forschungsbericht „Elektromagnetische Felder am Arbeitsplatz“ (25.02.2022). Accessed February 25, 2022 at: https://www.bmas.de/DE/Service/Publikationen/Forschungsberichte/fb400-elektromagnetische-felder.html

[11] Klinische Zulassung für 7-Tesla Hochfeld-MR-Bildgebung | Friedrich-Alexander-Universität Erlangen-Nürnberg (28.02.2022). Accessed February 28, 2022 at: https://www.fau.de/2017/10/news/wissenschaft/klinische-zulassung-fuer-7-tesla-hochfeld-mr-bildgebung/

[12] Über GUFI (12.06.2022). Accessed June 12, 2022 at: https://mr-gufi.de/index.php/was-ist-gufi

[13] Bundesamt für Strahlenschutz. BfS-Forschungsvorhaben zur Wirkung starker statischer Magnetfelder (12.06.2022). Accessed June 12, 2022 at: https://www.bfs.de/DE/bfs/wissenschaft-forschung/ergebnisse/starke-statische-magnetfelder/starke-statische-magnetfelder_node.html;jsessionid = B7AC71CD2B5A430BB9E28ED389A736A3.2_cid374

[14] NMR-Spektrometer der Superlative (13.04.2022). Accessed April 13, 2022 at: https://www.mpg.de/15185601/0721-bich-056839-eines-der-drei-staerksten-hochaufloesenden-1–2-ghz-nmr-spektrometer-weltweit-steht-nun-in-goettingen

[15] Kinouchi Y, Yamaguchi H, Tenforde TS. Theoretical analysis of magnetic field interactions with aortic blood flow. Bioelectromagnetics 1996; 17: 21–32. doi:10.1002/(SICI)1521-186X(1996)17:13.0.CO;2-8

[16] Karine. ICNIRP | Static Magnetic Fields (0 Hz) (11.04.2022). Accessed April 11, 2022 at: https://www.icnirp.org/en/frequencies/static-magnetic-fields-0-hz/index.html

[17] Holden AV. The sensitivity of the heart to static magnetic fields. Prog Biophys Mol Biol 2005; 87: 289–320. doi:10.1016/j.pbiomolbio.2004.08.015

[18] Chakeres DW, Kangarlu A, Boudoulas H et al. Effect of static magnetic field exposure of up to 8 Tesla on sequential human vital sign measurements. J Magn Reson Imaging 2003; 18: 346–352. doi:10.1002/jmri.10367

[19] Kangarlu A, Burgess RE, Zhu H et al. Cognitive, cardiac, and physiological safety studies in ultra high field magnetic resonance imaging. Magn Reson Imaging 1999; 17: 1407–1416. doi:10.1016/S0730-725X(99)00086-7

[20] Bongers S, Slottje P, Kromhout H. Development of hypertension after long-term exposure to static magnetic fields among workers from a magnetic resonance imaging device manufacturing facility. Environ Res 2018; 164: 565–573. doi:10.1016/j.envres.2018.03.008

[21] ICNIRP. Guidelines on limits of exposure to static magnetic fields. Health Phys 2009; 96: 504–514. doi:10.1097/01.HP.0000343164.27920.4a

[22] ICNIRP. ICNIRP Statement on Diagnostic Devices Using Non-ionizing Radiation: Existing Regulations and Potential Health Risks. Health Phys 2017; 112: 305–321. doi:10.1097/HP.0000000000000654

[23] ICNIRP. Guidelines for limiting exposure to electric fields induced by movement of the human body in a static magnetic field and by time-varying magnetic fields below 1 Hz. Health Phys 2014; 106: 418–425. doi:10.1097/HP.0b013e31829e5580

[24] Crozier S, Liu F. Numerical evaluation of the fields induced by body motion in or near high-field MRI scanners. Prog Biophys Mol Biol 2005; 87: 267–278. doi:10.1016/j.pbiomolbio.2004.08.002

[25] Bundesamt für Strahlenschutz. Nachgewiesene Wirkungen niederfrequenter Felder (11.04.2022). Accessed April 11, 2022 at: https://www.bfs.de/DE/themen/emf/nff/wirkung/nff-nachgewiesen/nff-nachgewiesen.html

[26] Antunes A, Glover PM, Li Y et al. Magnetic field effects on the vestibular system: calculation of the pressure on the cupula due to ionic current-induced Lorentz force. Phys Med Biol 2012; 57: 4477–4487. doi:10.1088/0031-9155/57/14/4477

[27] Schaap K, Christopher-De Vries Y, Mason CK et al. Occupational exposure of healthcare and research staff to static magnetic stray fields from 1.5–7 Tesla MRI scanners is associated with reporting of transient symptoms. Occup Environ Med 2014; 71: 423–429. doi:10.1136/oemed-2013-101890

[28] Schaap K, Portengen L, Kromhout H. Exposure to MRI-related magnetic fields and vertigo in MRI workers. Occup Environ Med 2016; 73: 161–166. doi:10.1136/oemed-2015-103019

[29] Mian OS, Li Y, Antunes A et al. On the vertigo due to static magnetic fields. PLoS One 2013; 8: e78748. doi:10.1371/journal.pone.0078748

[30] Boegle R, Stephan T, Ertl M et al. Magnetic vestibular stimulation modulates default mode network fluctuations. Neuroimage 2016; 127: 409–421. doi:10.1016/j.neuroimage.2015.11.065

[31] Glover PM, Li Y, Antunes A et al. A dynamic model of the eye nystagmus response to high magnetic fields. Phys Med Biol 2014; 59: 631–645. doi:10.1088/0031-9155/59/3/631

[32] Gorlin A, Hoxworth JM, Pavlicek W et al. Acute vertigo in an anesthesia provider during exposure to a 3 T MRI scanner. Med Devices (Auckl) 2015; 8: 161–166. doi:10.2147/MDER.S76474

[33] Bundesamt für Strahlenschutz. Elektromagnetische Felder (22.02.2022). Accessed February 22, 2022 at: https://www.bfs.de/DE/themen/emf/emf_node.html;jsessionid = BDC28775FD3FF418F7BAE4F07034AD42.1_cid391

[34] Vocht F de, van-Wendel-de-Joode B, Engels H et al. Neurobehavioral effects among subjects exposed to high static and gradient magnetic fields from a 1.5 Tesla magnetic resonance imaging system–a case-crossover pilot study. Magn Reson Med 2003; 50: 670–674. doi:10.1002/mrm.10604

[35] Vocht F de, Stevens T, van Wendel-de-Joode B et al. Acute neurobehavioral effects of exposure to static magnetic fields: analyses of exposure-response relations. J Magn Reson Imaging 2006; 23: 291–297. doi:10.1002/jmri.20510

[36] Vocht F de, Muller F, Engels H et al. Personal exposure to static and time-varying magnetic fields during MRI system test procedures. J Magn Reson Imaging 2009; 30: 1223–1228. doi:10.1002/jmri.21952

[37] Chakeres DW, Bornstein R, Kangarlu A. Randomized comparison of cognitive function in humans at 0 and 8 Tesla. J Magn Reson Imaging 2003; 18: 342–345. doi:10.1002/jmri.10366

[38] Vocht F de, van Drooge H, Engels H et al. Exposure, health complaints and cognitive performance among employees of an MRI scanners manufacturing department. J Magn Reson Imaging 2006; 23: 197–204. doi:10.1002/jmri.20485

[39] Vocht F de, Stevens T, Glover P et al. Cognitive effects of head-movements in stray fields generated by a 7 Tesla whole-body MRI magnet. Bioelectromagnetics 2007; 28: 247–255. doi:10.1002/bem.20311

[40] van Nierop LE, Slottje P, van Zandvoort MJE et al. Effects of magnetic stray fields from a 7 tesla MRI scanner on neurocognition: a double-blind randomised crossover study. Occup Environ Med 2012; 69: 759–766. doi:10.1136/oemed-2011-100468

[41] van Nierop LE, Slottje P, van Zandvoort M et al. Simultaneous exposure to MRI-related static and low-frequency movement-induced time-varying magnetic fields affects neurocognitive performance: A double-blind randomized crossover study. Magn Reson Med 2015; 74: 840–849. doi:10.1002/mrm.25443

[42] Kanal E, Gillen J, Evans JA et al. Survey of reproductive health among female MR workers. Radiology 1993; 187: 395–399. doi:10.1148/radiology.187.2.8475280

[43] Evans JA, Savitz DA, Kanal E et al. Infertility and pregnancy outcome among magnetic resonance imaging workers. J Occup Med 1993; 35: 1191–1195

[44] Bulas D, Egloff A. Benefits and risks of MRI in pregnancy. Semin Perinatol 2013; 37: 301–304. doi:10.1053/j.semperi.2013.06.005

[45] Feychting M. Health effects of static magnetic fields–a review of the epidemiological evidence. Prog Biophys Mol Biol 2005; 87: 241–246. doi:10.1016/j.pbiomolbio.2004.08.007

[46] Bongers S, Slottje P, Portengen L et al. Exposure to static magnetic fields and risk of accidents among a cohort of workers from a medical imaging

device manufacturing facility. Magn Reson Med 2016; 75: 2165–2174. doi:10.1002/mrm.25768

[47] Huss A, Schaap K, Kromhout H. MRI-related magnetic field exposures and risk of commuting accidents – A cross-sectional survey among Dutch imaging technicians. Environ Res 2017; 156: 613–618. doi:10.1016/j.envres.2017.04.022

[48] Huss A, Özdemir E, Schaap K et al. Occupational exposure to MRI-related magnetic stray fields and sleep quality among MRI – Technicians – A cross-sectional study in the Netherlands. Int J Hyg Environ Health 2021; 231: 113636. doi:10.1016/j.ijheh.2020.113636

[49] Jabehdar Maralani P, Kapadia A, Liu G et al. Canadian Association of Radiologists Recommendations for the Safe Use of MRI During Pregnancy. Can Assoc Radiol J 2021. doi:10.1177/08465371211015657

[50] Sammet S. Magnetic resonance safety. Abdom Radiol (NY) 2016; 41: 444–451. doi:10.1007/s00261-016-0680-4

[51] Buls N, Covens P, Nieboer K et al. Dealing with pregnancy in radiology: a thin line between science, social and regulatory aspects. JBR-BTR 2009; 92: 271–279

[52] Wilde JP de, Rivers AW, Price DL. A review of the current use of magnetic resonance imaging in pregnancy and safety implications for the fetus. Prog Biophys Mol Biol 2005; 87: 335–353. doi:10.1016/j.pbiomolbio.2004.08.010

[53] Kanal E, Barkovich AJ, Bell C et al. ACR guidance document on MR safe practices: 2013. Journal of Magnetic Resonance Imaging 2013; 37: 501–530. doi:10.1002/jmri.24011

[54] Mühlenweg M, Schaefers G, Trattnig S. New aspects from legislation, guidelines and safety standards for MRI. Radiologe 2015; 55: 691–696. doi:10.1007/s00117-015-2859-z

[55] Die Strahlenschutzkommission – Publikationen – Heft 36: Empfehlungen zur sicheren Anwendung magnetischer Resonanzverfahren in der medizinischen Diagnostik (29.03.2022). Accessed March 29, 2022 at: https://www.ssk.de/SharedDocs/Publikationen/BerichtederSSK/Heft_36.html

[56] Bongers S, Christopher Y, Engels H et al. Retrospective assessment of exposure to static magnetic fields during production and development of magnetic resonance imaging systems. Ann Occup Hyg 2014; 58: 85–102. doi:10.1093/annhyg/met049

[57] Mattsson MO, Auvinen A, Bridges J et al. SCENIHR (Scientific Committee on Emerging and Newly Identified Health Risks), Research needs and methodology to address the remaining knowledge gaps on the potential health effects of EMF, 6 July, 2009. 2009

[58] Research agenda on electromagnetic fields (06.04.2022). Accessed April 12, 2022 at: https://www.who.int/teams/environment-climate-change-and-health/radiation-and-health/non-ionizing/research

[59] EMF-Portal | Neurodegenerative Erkrankungen (Parkinson, Alzheimer, ALS) (12.04.2022). Accessed April 12, 2022 at: https://www.emf-portal.org/de/cms/page/home/effects/low-frequency/neurodegenerative-diseases

[60] Huss A, Koeman T, Kromhout H et al. Extremely Low Frequency Magnetic Field Exposure and Parkinson's Disease–A Systematic Review and Meta-Analysis of the Data. Int J Environ Res Public Health 2015; 12: 7348–7356. doi:10.3390/ijerph120707348

[61] Jalilian H, Teshnizi SH, Röösli M et al. Occupational exposure to extremely low frequency magnetic fields and risk of Alzheimer disease: A systematic review and meta-analysis. Neurotoxicology 2018; 69: 242–252. doi:10.1016/j.neuro.2017.12.005

[62] Vergara X, Kheifets L, Greenland S et al. Occupational exposure to extremely low-frequency magnetic fields and neurodegenerative disease: a meta-analysis. J Occup Environ Med 2013; 55: 135–146. doi:10.1097/JOM.0b013e31827f37f8

[63] van der Mark M, Vermeulen R, Nijssen PCG et al. Extremely low-frequency magnetic field exposure, electrical shocks and risk of Parkinson's disease. Int Arch Occup Environ Health 2015; 88: 227–234. doi:10.1007/s00420-014-0949-2

[64] EMF-Portal | Krebs und Kinderleukämie (12.04.2022). Accessed April 12, 2022 at: https://www.emf-portal.org/de/cms/page/home/effects/low-frequency/cancer-and-childhood-leukemia

[65] Exposure to extremely low frequency fields – backgrounder (06.04.2022). Accessed April 12, 2022 at: https://www.who.int/teams/environment-climate-change-and-health/radiation-and-health/non-ionizing/elff