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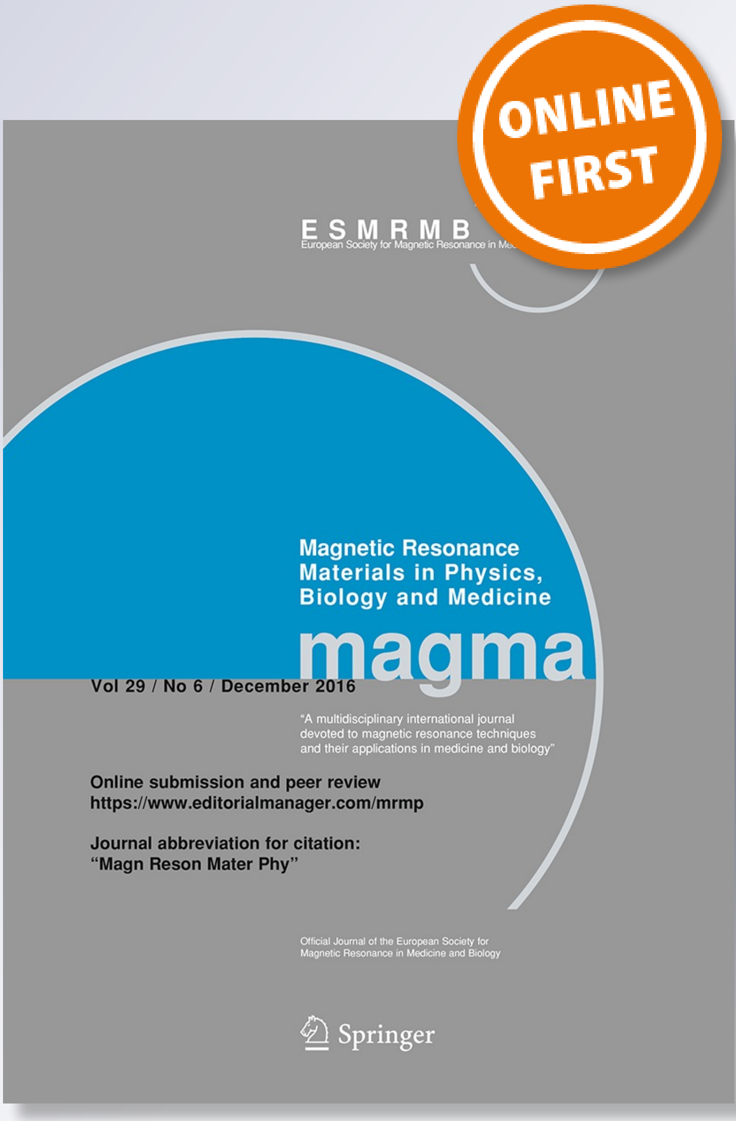

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RESEARCH ARTICLE

Evaluation of exposure to (ultra) high static magnetic fields during activities around human MRI scanners

Mahsa Fatahi[1] · Jolanta Karpowicz[2] · Krzysztof Gryz[2] · Amirmohammad Fattahi[3] · Georg Rose[4] · Oliver Speck[1,5,6,7]

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Abstract
Objective To assess the individual exposure to the static magnetic field (SMF) and the motion-induced time-varying magnetic field (TVMF) generated by activities in an inhomogeneous SMF near high and ultra-high field magnetic resonance imaging (MRI) scanners. The study provides information on the level of exposure to high and ultra-high field MRI scanners during research activities.
Materials and methods A three-axis Hall magnetometer was used to determine the SMF and TVMF around human 3- and 7-Tesla (T) MRI systems. The 7-T MRI scanner used in this study was passively shielded and the 3-T scanner was actively shielded and both were from the same manufacturer. The results were compared with the exposure restrictions given by the International Commission on Non-Ionizing Radiation Protection (ICNIRP).
Results The recorded exposure was highly variable between individuals, although they followed the same instructions for moving near the scanners. Maximum exposure values of $B = 2057$ mT and $\mathrm{d}B/\mathrm{d}t = 4347$ mT/s for the 3-T scanner and $B = 2890$ mT, $\mathrm{d}B/\mathrm{d}t = 3900$ mT/s for 7 T were recorded. No correlation was found between reporting the MRI-related sensory effects and exceeding the reference values.
Conclusions According to the results of our single-center study with five subjects, violation of the ICNIRP restrictions for max B in MRI research environments was quite unlikely at 3 and 7 T. Occasions of exceeding the $\mathrm{d}B/\mathrm{d}t$ limit at 3 and 7 T were almost similar (30% of 60 exposure scenarios) and highly variable among the individuals.

Keywords Occupational exposure · Exposure assessment · Electromagnetic fields · Static magnetic field · Time-varying field

Abbreviations

UHF MRI	Ultra-high field magnetic resonance imaging
SMF	Static magnetic field
GMF	Gradient magnetic field
TVMF	Time-varying magnetic field
ICNIRP	International Commission on Non-Ionizing Radiation Protection

M. Fatahi and J. Karpowicz contributed equally to this work.

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Introduction

Recent advances in high and ultra-high field magnetic resonance imaging (UHF MRI) and their emerging applications have inevitably led to the increased occupational exposure to MRI-generated magnetic fields. It has been

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well-established that the human body moving in the stray field of MRI scanners induces electric currents inside the body and these currents may cause transient sensory effects experienced by MRI workers, such as vertigo, metallic taste, nausea and headache [1].

Data on individual exposure of UHF MRI personnel to static magnetic fields (SMF) and motion-induced time-varying magnetic fields (TVMF) is scarce. Only limited data are currently available on occupational exposure to high and ultra-high SMF, and most of them are focused on the occupational exposure levels among personnel in clinical MRI facilities, but not research facilities [2–6]. The fringe fields from radio-frequency excitation (B_1) and gradients (G_x, G_y, G_z) decrease very rapidly with distance from the bore, and are only active during the image acquisition [7]. However, the SMF is continuously present and extends beyond the scanner bore, so most of the personnel who enter the area around the scanner are subject to a strong and inhomogeneous SMF. In research as well as clinical practice, workers may lean into the MRI magnet to attach accessories such as coils to the patients or volunteers, or to communicate with or comfort them. Therefore, in extreme cases, MRI personnel may be exposed to almost the same extent as patients and volunteers. However, due to the fact that they usually move faster close to the MRI scanner than the patients who are lying down on the patient table, they may even be exposed to a larger TVMF.

In the current study, the data on individual exposure to high [$B_0 = 3$ Tesla (T)] and ultra-high ($B_0 \geq 7$ T) magnetic fields during research activities close to the MRI scanners were collected, both to assess compliance with exposure restrictions proposed by the current guidelines and for future epidemiological study on the potential adverse effects (if any) of SMF.

The focus of the current work is on MRI research-related activities which can also be relevant for the clinical use of scanners. However, due to the fact that medical personnel have a relatively standardised shift length, work protocol and consequently, a similar pattern of exposure [8], which is not the case for the work of MRI researchers that varies a lot, ranging from scanning patients and volunteers to testing coils or phantoms performed at different locations around the magnet, the level of exposure in these two groups could be different.

Materials and methods

Questionnaire

A baseline questionnaire was completed by the participants prior to the experiment. The questionnaire included questions regarding age, height, weight, current job title and incidence of MRI-related symptoms and their perception of safety. In addition to the questionnaire, we conducted a short interview with the participants to obtain information on their typical activities and movements around the scanner. Based on the interview results, three simplified trajectories, including lateral motions and rotation around the body axes (leaning forward and bending over), were chosen as the most common elements of movements by the MRI research personnel around the scanner.

Measurement strategies and data collection

The study protocol was approved by the local ethics committee. The individual exposure to the SMF generated by MRI scanners was assessed for $n = 5$ MRI researchers in two scanners, 3 and 7 T (Siemens Healthcare, Erlangen, Germany). The 7-T MRI scanner used in this study was passively shielded and the 3-T scanner was actively shielded. Individual exposure to the SMF was measured and the motion-induced TVMF ($\mathrm{d}B/\mathrm{d}t$) was calculated for the selected combined motions covering a range of normal human gait and typical exposure scenarios for researchers in close proximity to the 3- and 7-T human MRI scanners. The measurement of the SMF was carried out using a three-axis Hall magnetometer (THM1176-HF, Metrolab, Geneva, Switzerland) with a resolution of ±0.5 mT and a sampling frequency of up to 6.5 Hz. All three orthogonal components of B (B_x, B_y, B_z) were recorded as a function of time. The absolute values of B and $\mathrm{d}B/\mathrm{d}t$ were calculated according to Eqs. 1–3. Taking into account that the international guidelines [1] do not specify the formula to analyse the rate of time variability of the magnetic flux density vector, $\mathrm{d}B/\mathrm{d}t$ can be evaluated using two different equations (Eqs. 2, 3), which may result in slightly different values.

$$B(t) = \sqrt{(B_x)^2 + (B_y)^2 + (B_z)^2} \tag{1}$$

$$\mathrm{d}B_V/\mathrm{d}t = \left| \frac{B(t_2) - B(t_1)}{t_2 - t_1} \right| \tag{2}$$

$$\mathrm{d}B_{xyz}/\mathrm{d}t = \sqrt{(\mathrm{d}B_x/\mathrm{d}t)^2 + (\mathrm{d}B_y/\mathrm{d}t)^2 + (\mathrm{d}B_z/\mathrm{d}t)^2} \tag{3}$$

We used Eq. 2 to calculate the $\mathrm{d}B/\mathrm{d}t$ throughout the manuscript. The subjects of the study were five MRI researchers, three males and two females with an average height of 169 ± 13 cm. Participants were asked to follow the defined paths, while the Hall sensor was attached to their head or chest with an elastic strap and connected to the data logger (Fig. 1). A zero-field adjustment of the sensor was carried out before starting the experiment.

To assess the exposure variability among the individuals, the three paths (a, b, c) shown schematically in Fig. 2 were followed by five participants of different heights, weights

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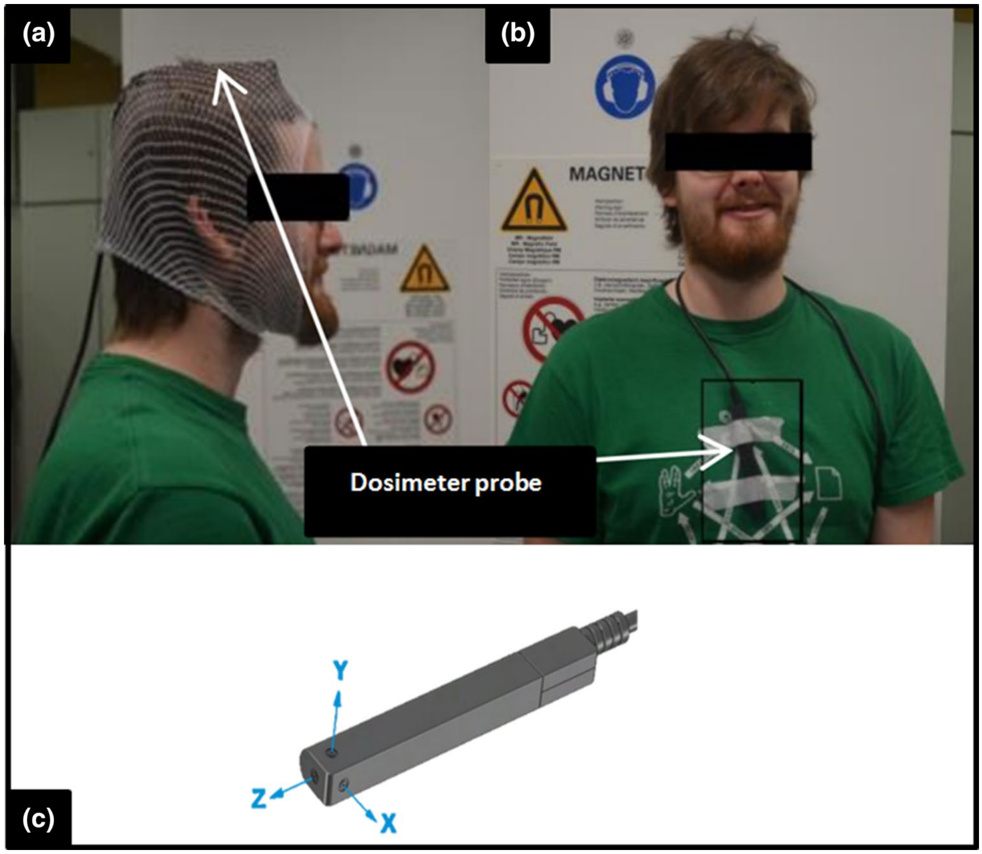

Fig. 1 A three-axis Hall probe of the magnetometer **a** attached to the subject's head, **b** attached to the subject's chest and **c** top schematic view of the Hall sensor probe

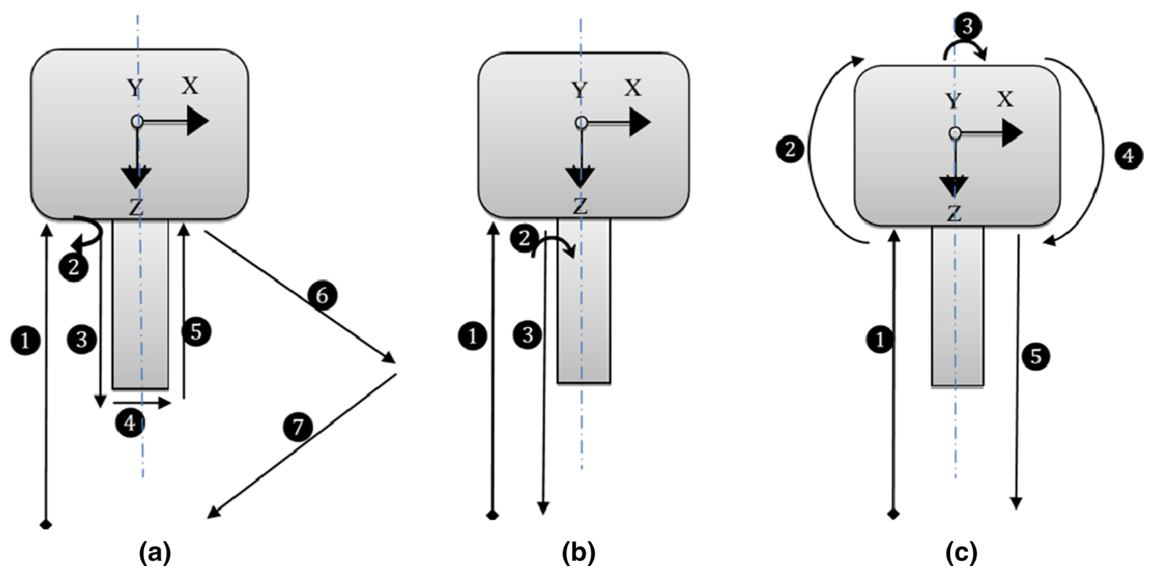

Fig. 2 Schematic top view of the trajectories (path: **a**, **b**, **c**) considered for the measurement assessment as the typical exposure scenarios around the scanner

and walking pace, while having the Hall probe attached to two different positions, on the head and chest, at two different scanners (3 and 7 T). Overall, 60 expositmetric samples were analysed.

Path *a* (1–7) was designed to mimic activities related to the MRI patient/volunteer positioning and adjustment of the coil. It included movements along the bed and the long axis of the magnet (*Z* axis) while facing the scanner

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bore. It was started from one corner of the scanner room, followed by a 180° rotation around the *Y* axis, a movement along the *Z* axis, 90° rotation around the *Y* axis, followed by a movement along *X* axis, 90° rotation around the *Y* axis and another movement along the *Z* axis. Finally, the participants were asked to follow an orthogonal path in the *X*–*Z* plane toward the coils shelves and to end the path by walking toward the outside of the scanner room.

Path *b* (1–3) mimicked activities related to an experimental setup and positioning of a phantom at the entrance or partially inside the scanner bore. This path covered movement along the *Z* axis; 90° rotation around the *Y* axis and two bendings of the upper body about 90° around the *Z axis* (leaning towards the table), followed by a bending in *X*–*Z* plane (leaning towards the inside of the magnet bore). It was ended by a 90° rotation around the *Y* axis and walking the way back along the *Z* axis.

Path *c* (1–5) mimicked some unusual movements around the scanner, e.g. accessing the MRI patient or volunteer from the end of the bore, the adjustment of peripherals, such as a camera, mirror or cable by bending toward the inside from the end of the bore. It included movement along the *Z* axis, followed by a semi-circular path toward the end of the magnet, rotation of the upper body around the *Z* axis and a similar path in the opposite direction to get to the end point.

Participants were requested to follow the paths at the same speed they usually walk near the scanner during their daily work. The spot measurement of the SMF was also carried out along the patient table to characterize the spatial distribution of the field for both scanners. Participants were asked about the incidence of MRI-related symptoms and potential discomfort during and right after the experiments.

Exposure metrics and evaluation criteria

Exposure at the head (H) and chest (C) have been analysed based on the set of magnetic flux density (*B*) exposimetric samples, recorded during the movements, expressed in mili-Tesla (mT). The metrics of exposure including actual value [$B(t)$], actual value of time derivative (dB/dt, using Eq. 2) and the changes of *B* over any 3-s motion ($\Delta B_{3\ s}$) have been taken into consideration to be compliant with the restrictions for workers' exposure provided by three ICNIRP guidelines (SMF exposure [9]; time-varying exposure at frequencies exceeding 1 Hz [10]; and, time-varying exposure at frequencies below 1 Hz, caused by movement near the source of SMF [1]). ICNIRP defines two sets of guidelines for exposure in controlled and uncontrolled working environments. Guidelines for a controlled environment accept higher levels of exposure for workers and apply when appropriate work practices are implemented to control movement-induced sensory effects [1].

In the event of exposure in an uncontrolled environment, the following exposure restrictions are provided: 2000 mT as the limit of the spatial peak magnetic flux density in exposure of the head and trunk to protect against vertigo due to movement in the SMF [1, 9], and 2000 mT to be the maximum change of *B* over any 3-s motion to protect against vertigo due to TVMF exposure, with a frequency not exceeding 1 Hz [1]. In extremities and controlled exposure of the head and trunk, the limit goes up to 8 T [1, 9] but this case was not evaluated in our study, as neither scanners exceed 8 T. Additional basic restrictions have been provided with regard to the electric field induced in the body due to movement in SMF or exposure to time-varying *B* fields at frequencies of 0–25 Hz. They are set to protect against potential adverse effects in the peripheral nervous system (in an controlled environment) or to protect against magnetophosphenes (in an uncontrolled environment) [1, 10].

Since such basic restrictions are not easily measurable at the workplace, compliance should be assessed by the reference levels expressed by dB/dt, at a fixed level 2700 mT/s (with respect to the controlled environment), or a frequency-dependent level: 2700 mT/s up to 0.66 Hz and 1800/f mT/s at higher frequencies (with respect to the uncontrolled environment).

Based on this structure of ICNIRP restrictions, the following standardised parameters characterising the exposure over the recorded exposimetric samples were analysed. $L_1 = B(t)/2000$; $L_2 = |dB/dt|/2700$; $L_3 = |dB/dt|/(1800 \times 2 \times \Delta t)$; $L_4 = |\Delta B_{3\ s}|/2000$. Each metric ($L_1$, L_2, L_3, L_4) was standardised based on the particular ICNIRP limits, i.e. exceeding the value of one, when overexposure was detected. Metrics were analysed with respect to their maximum value over particular subsets of data, as well as the statistical distribution (median and 95th percentile in the set of samples) in the subsets of results spread between the head (H) and chest (C), between paths (*a*, *b*, *c* over a group of all five subjects), between subjects (1, 2, 3, 4, 5 over a group of all three paths) and at 3- and 7-T scanners separately. Since MRI environment is considered as a controlled environment, parameters L_2 and L_4 were the most relevant metrics to assess compliance with the exposure restrictions.

Results

Table 1 shows the maximum SMF values recorded for all five subjects at both field strengths. At 3 T, a max *B* of 2057 mT was recorded, which is about 68% of the B_0, and at 7 T, a max *B* of 2890 mT, which is about 41% of the

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Table 1 The SMF exposure in 60 samples of exposimetric *B* measurements (five subjects, three paths, two scanners and two locations for the Hall sensor)

	Height (cm)	SMF strength (T)	Max *B* on the head (mT)			Max *B* on the chest (mT)		
			Path *a*	Path *b*	Path *c*	Path *a*	Path *b*	Path *c*
Subject 1	183	3	140	1246	759	282	548	313
		7	698	1977	1317	1018	1127	939
Subject 2	175	3	246	2057	1671	282	1098	878
		7	900	2890	2672	1113	1439	1279
Subject 3	171	3	126	1909	2000	388	651	732
		7	680	2505	1894	1102	1105	1000
Subject 4	169	3	195	1600	1138	465	642	537
		7	806	1942	834	1188	1247	982
Subject 5	147	3	512	550	673	176	1464	1440
		7	983	2026	2265	1387	1200	1267

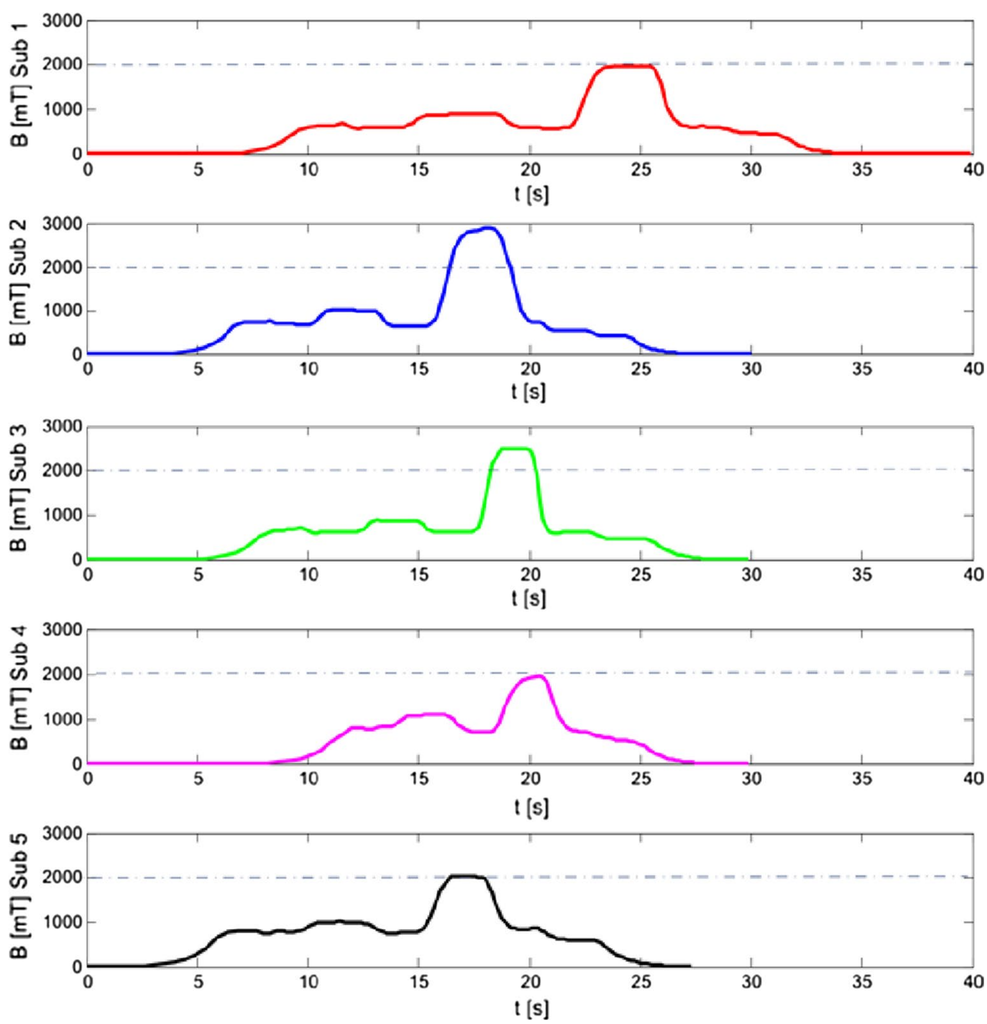

Fig. 3 SMF exposure measurement for five subjects recorded from the starting point to the end point during path *b* in close proximity to the 7-T MRI scanner

B_0, was recorded. Figure 3 summarises the SMF exposure level recorded on the head of five participants along path *b*, at the 7-T MRI scanner. The figure shows a similar pattern of exposure for all the participants; however, the exposure level is different among them.

Since this study only included 3- and 7-T scanners, the 8-T limit for exposure of the extremities and head or trunk under a controlled condition was never exceeded.

Figures 4 and 5 present statistical distributions of standardized metrics L_1–L_4 of exposure near 3- and 7-T

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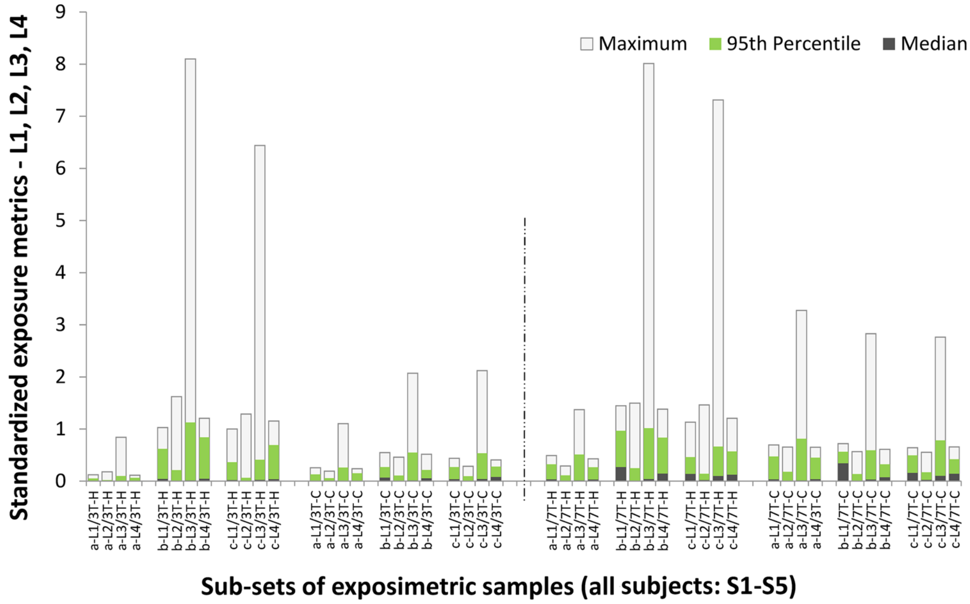

Fig. 4 Distribution of standardised values of exposure metrics (L_1–L_4) in sub-sets covering exposure of all subjects (S_1–S_5), during particular movements (*a*, *b*, *c*), at the head (H) and at the chest (C), near 3- and 7-T scanners. *Black areas* show medians, *green bars* show the 95th percentile

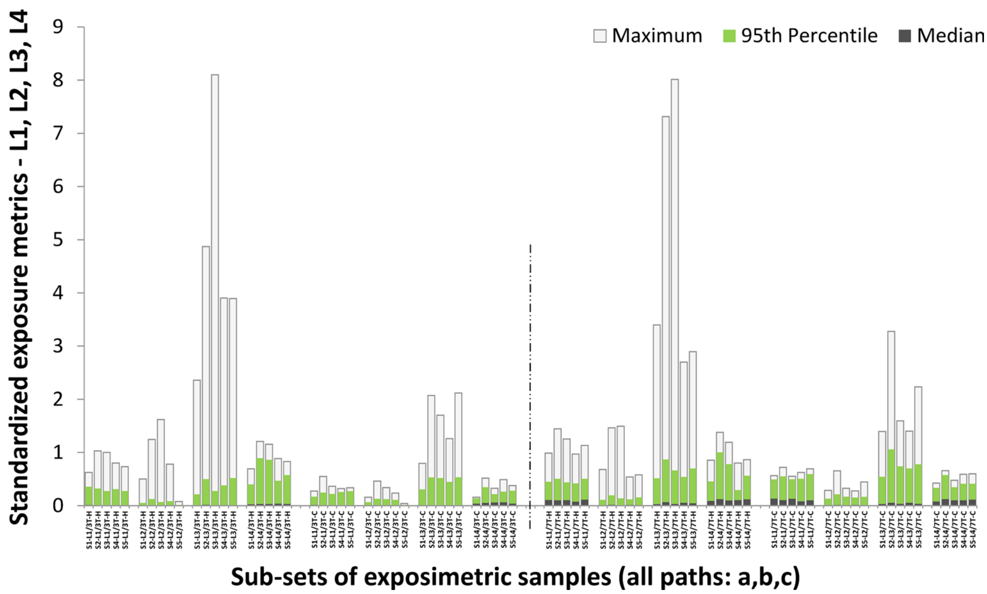

Fig. 5 Distribution of standardised values of exposure metrics (L_1–L_4) in sub-sets covering exposure during all movements (*a*, *b*, *c*), performed by particular subjects (S_1–S_5), at the head (H) and at the chest (C), near 3- and 7-T scanners. *Black areas* show medians, *green bars* show the 95th percentile

scanners, in the subsets of results spread between the head (H) and chest (C), between paths (*a*, *b*, *c* over a group of all five subjects) and between subjects (1, 2, 3, 4, 5 over a group of all three paths).

Exposure to time-varying fields arising from movement within the *B* fringe field resulted in a max d*B*/d*t* of 4347 mT/s for the head and 1200 mT/s for the chest at 3 T. For 7 T, the measured max d*B*/d*t* values were 3900 and 1700 mT/s for the head and the chest, respectively.

The repeatability of the measurement result for path *c* was tested at the 3-T scanner using nine recordings of head exposure. The metric of intra-subject variability for maximum exposures was defined as VR_H = [(maximum value − minimum value)/average value] × 100%. Parameter VR_H showed a higher value in d*B*/d*t* than in *B* values (in maximum values of *B* at the head, the repeatability was $VR_H = 39\%$, while in maximum value of d*B*/d*t*, the repeatability was $VR_H = 57\%$). The VR_H parameters for the 95th percentiles of exposure levels for *B* and d*B*/d*t* were 35% and 46%, respectively. On average, max *B* values over nine recordings at the head during movements of the same subjects in path *c* was 756 mT (with an average 95th percentile value of 490 mT and an average value of 105 mT). In this set of samples, the average value for max d*B*/d*t*

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was 2220 mT/s (with the average 95th percentile value of 543 mT/s and an average value of 105 mT/s).

The results indicate that the exposure to the SMF as well as the TVMF was highly variable among individuals, although they worked with the same scanner in the same manner and they followed the same paths near the scanner. The metric of inter-subject variability for maximum exposure was defined as VS = [(maximum value − minimum value)/average value] × 100%. The parameter VS_H for maximum values in head exposure at the 3-T scanner were 32 and 169%, for *B* and d*B*/d*t*, respectively. In chest exposure, VS_C = 74% for *B* and 170% for d*B*/d*t*.

At the 7-T scanner, VS_C = 19 and 68%, VSH = 20 and 116%, for *B* and d*B*/d*t*, respectively. In general, VS showed a higher variability at the 3-T scanner than at the 7-T scanner. It was also higher in the head exposures than in the chest exposures. In the head exposures, the VS_H parameter for the 95th percentiles of exposure level has similar values to the mentioned values for maximum levels, whereas in the chest exposures, variability in values of the 95th percentiles is roughly twice as low.

On average, max *B* values over subjects and paths was approximately twice as high when working with a 7-T scanner (1300 mT) compared to working with a 3-T scanner (820 mT). However, this average for max d*B*/d*t* was not much higher for the 7-T scanner (1822 mT/s) than for the 3-T scanner (1475 mT/s). More detailed distributions of particular metrics of exposure near both scanners are shown in Figs. 4 and 5. The plots indicate that the parameter which exceeded the ICNIRP restrictions the most at both scanners is $L_3 = |dB/dt|/(1800 \times 2 \times \Delta t)$, which is more relevant for an uncontrolled environment, whereas exceeding the restrictions for a controlled environment (L_2 and L_4) happened only in a few cases during path *b* and *c*, where rotation and bending were included in the movement.

In general, overexposures were not found up to the 95th percentiles. They happened in an extremely small percentage of recorded samples, i.e. less than 5% of exposure duration was related to exposures exceeding the recommendations for workers' exposure in a controlled environment.

Considering the incidence of sensory effects during and after the experiment, only one of the participants (subject #5) reported feelings of vertigo and headache right after completing each path (*a*, *b*, *c*). Other participants did not report any adverse feeling or discomfort related to the magnetic fields, regardless of their exposure level covered by the range of movements in this study. In the results of the exposimetric measurements of SMF exposure, we did not find any significant difference between the exposure pattern of subject #5 and the other subjects. All the participants stated that they feel safe while working with the scanner.

Discussion

Currently, no standardised assessment procedure dealing with SMF and movements in SMF is available in the literature. Such a procedure, however, is a prerequisite for determining compliance with the proposed restrictions and guidelines regarding B and dB/dt, in particular, for motion around the MRI magnet. A proper exposure assessment requires the knowledge of workers' exposure patterns. There are many studies in which occupational exposure to MRI-generated SMF and TVMF are estimated using different methods, including measurements of simulated movements of MRI personnel [11–14], measurement of the fields at various points around the scanner [15] or numerical calculations in anatomical models [16, 17]. These studies provided an estimation of MRI workers' exposure. However, they were more focused on the job titles and have not been able to provide exposure variability either among different individuals with the same job title, or in different movement patterns around the scanner. Therefore, it is difficult to directly compare the results of those studies, since different strategies and measuring equipment were used.

In the current study, we aimed to characterise the most common exposure scenarios to high and ultra-high field MRI in research activities. Maximum exposure values of *B* = 2057 mT and d*B*/d*t* = 4347 mT/s for a 3-T scanner and *B* = 2890 mT and d*B*/d*t* = 3900 mT/s for a 7-T scanner were determined. It should be noted that the movements near the MRI scanners in the current study were not randomly sampled, but were identified using a questionnaire and chosen to include the typical movements of MRI researchers in the vicinity of MRI scanners, including translations and rotations.

Considering the average over subjects and paths, the max *B* value was approximately twice as high when working with a 7-T scanner compared to a 3-T scanner. However, the average for max d*B*/d*t* was not much higher for a 7-T scanner than a 3-T scanner, and even 95th percentiles are comparable in these two cases. Variability of the results, observed between and within subjects shows that the inter-subject variability is larger than the intra-subject variability. The high inter-subject variability can be easily explained by many parameters, such as spatial distribution of the field at different individuals' heights and differences in personal behaviour (i.e. walking velocity and bending angle) [17]. This may explain why d*B*/d*t* recorded near the actively shielded 3-T scanners, where stronger d*B*/d*x* inhomogeneity normally exists (Fig. 6), was higher than d*B*/d*t* around the 7-T scanner. The data plotted in Fig. 6 was measured at a passively shielded 7-T scanner and actively shielded 3-T scanner located in Magdeburg, Germany, and actively shielded 7-T scanner located in Oxford, UK and a passively shielded 3-T scanner located in Warsaw, Poland.

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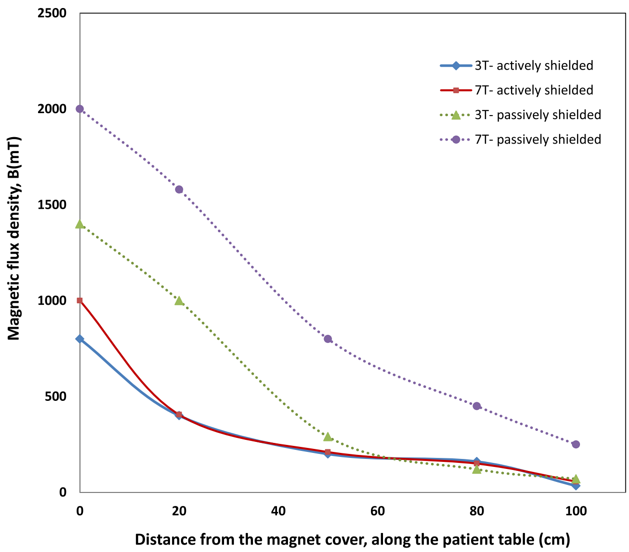

Fig. 6 Spatial distribution of the static magnetic field in front of the actively and passively shielded 3- and 7-T MRI scanners along the axes of the MRI magnet bore

In passive shielding, tons of iron are used to effectively reduce the extent of the fringe field, whereas the concept of active shielding is to include two reverse polarity coils in the coil array, which reduces the field immediately at the entrance of the bore. This design commonly results in smaller fringe fields and, consequently, stronger spatial gradients of the magnetic field close to the magnet. The maximum d*B*/d*t* recorded close to the magnet cover at 7 T in our study was about 1.5 times lower than that in a similar but actively shielded scanner. This difference was smaller between actively and passively shielded 3-T scanners. All measurements were conducted at a Siemens scanner (Siemens Healthcare, Erlangen, Germany). As scanner from other manufacturers may use different designs for the magnet, and they may lead to different outcomes.

Regarding the incident of MR-related sensory effects and the perception of safety, in our previous study, we retrospectively assessed the perception of safety of healthy individuals working with human 7-T MRI [18]. The results from that study indicated the average perception of a moderately safe work environment, which is confirmed in the current study. In the current study, only one subject (20% of subjects involved) reported vertigo and headache right after completing the experiment which is similar to the previous results [23]. Since this particular subject was expecting sensory effects prior to the experiment, due to her previous experience, along with the fact that she was reluctant to bend over the bed completely in path **b,** we hypothesise that this subject appeared to be more sensitive and susceptible to MR-related symptoms than the others. Considering the height (Table 1) and the walking velocity of the subject (Fig. 3), we also hypothesise that both height and walking velocity were significant determinants in exposing that particular subject to higher *B* and d*B*/d*t*, which resulted in experiencing more sensory effects. This may also explain the small value of *B* and d*B*/d*t* in all paths, recorded for subject #1, who was the tallest among the participants and spent more time to complete the paths (i.e. path *b*, shown in Fig. 3). This result could be due to the fact that the head and chest of the taller workers are further away from the strong *B*.

Considering answers from all participants, no correlation was found between reporting the MRI-related sensory effects and exceeding the reference values.

Previous personal exposure data are available, in which the expositmeter was worn on the hip or chest [19, 20]. It is likely accepted that the exposure measured at the head is generally higher than exposure measured at the chest and lower body [20]; however, this is highly dependent on the individual's height and there is no data available that directly compares the impact of various positions for the expositmeter.

Unfortunately, within the time frame of this study, we were not able to collect more exposure data from MRI researchers. Another limitation of our methodology was that, due to the long cable of data transmission, the participants had to be more attentive while walking around the scanner. This might possibly affect (reduce) their walking velocity, though this should not affect their speed of rotation and bending.

Conclusion

The present results from our limited data indicate that violation of the ICNIRP restrictions for max *B* during workers' exposure in the controlled environment at 3- and 7-T MRI scanners was unlikely to happen, which is in accordance with the previous studies [4, 21, 22]. Exceedances of the d*B*/d*t* reference level at 3 and 7 T were almost similar (30% of 60 exposure samples), although this was recorded in a very low percentage of the exposure duration.

Analysis of the max *B* revealed a large variability between participants, even though the paths, and therefore the chance of approaching the bore, were identical for all the participants.

This result accords well with the study by Schaap et al. [8]. The relatively large variability between subjects may suggest the importance of performing personal exposure measurements instead of relying solely on mathematical calculations. By using a simply designed personal exposure measurement probe for MRI researchers, it will be possible to gather a wide and reliable pool of data on exposure levels during research activities in the proximity of MRI scanners. Such data would assist studies on the possible bioeffects of MRI-generated electromagnetic

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fields. However, we believe that further multi-centred, comprehensive studies assessing exposure levels at different positions around high and ultra-high field MRI scanners, which research personnel encounter during their routine research activities, deserve consideration. The current study was a first attempt to provide a realistic overview of what level of exposure can be expected in typical research activities. The inter-subject variability of exposure levels found in our study may be considered in future instructions for workers in a controlled high and ultra-high field MRI environment.

This result can also be used as a starting point and may help to develop guidelines for the adoption of some simple precautionary rules for researchers' behaviour around MRI scanners to avoid exceeding the limits.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

Ethical approval The study was approved by the local ethics committee of the Otto-von-Guericke-University Magdeburg. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study. Additional informed consent was obtained from all individual participants for whom identifying information is included in this article.

References

1. International Commission on Non-Ionizing Radiation Protection (2014) 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 Phy 106(3):418–425
2. Fuentes MA, Trakic A, Wilson SJ, Crozier S (2008) Analysis and measurements of magnetic field exposures for healthcare workers in selected MR environments. IEEE Trans Biomed Eng 55(4):1355–1364
3. Úbeda A, Martínez MA, Cid MA, Chacón L, Trillo MA, Leal J (2011) Assessment of occupational exposure to extremely low frequency magnetic fields in hospital personnel. Bioelectromagnetics 32(5):378–387
4. Yamaguchi-Sekino S, Nakai T, Imai S, Izawa S, Okuno T (2014) Occupational exposure levels of static magnetic field during routine MRI examination in 3 T MR system. Bioelectromagnetics 35(1):70–75
5. Karpowicz J, Gryz K (2013) The pattern of exposure to static magnetic field of nurses involved in activities related to contrast administration into patients diagnosed in 1.5 T MRI scanners. Electromagn Biol Med 32(2):182–191
6. Bradley JK, Nyekiova M, Price DL, Lopez L, Crawley T (2007) Occupational exposure to static and time-varying gradient magnetic fields in MR units. J Magn Reson Imaging 26(5):1204–1209
7. McRobbie DW (2012) Occupational exposure in MRI. Br J Radiol 85:293–312
8. Schaap K, Christopher-de Vries Y, Crozier S, De Vocht F, Kromhout H (2014) Exposure to static and time-varying magnetic fields from working in the static magnetic stray fields of MRI scanners: a comprehensive survey in The Netherlands. Ann Occup Hyg 58(9):1094–1100
9. International Commission on Non-Ionizing Radiation Protection (2009) Guidelines on limits of exposure to static magnetic fields. Health Phy 96:504–514
10. International Commission on Non-Ionizing Radiation Protection (2010) ICNIRP Guidelines on limiting exposure to time-varying electric and magnetic fields (1 Hz–100 kHz). Health Phy 99:818–836
11. Andreuccetti D, Contessa GM, Falsaperla R, Lodato R, Pinto R, Zoppetti N et al (2013) Weighted-peak assessment of occupational exposure due to MRI gradient fields and movements in a nonhomogeneous static magnetic field. Med Phy 40(1):011910
12. Kännälä S, Toivo T, Alanko T, Jokela K (2009) Occupational exposure measurements of static and pulsed gradient magnetic fields in the vicinity of MRI scanners. Phy Med Biol 54(7):2243
13. Laakso I, Kännälä S, Jokela K (2013) Computational dosimetry of induced electric fields during realistic movements in the vicinity of a 3T MRI scanner. Phy Med Biol 58(8):2625
14. Hartwig V, Giovannetti G, Vanello N, Lombardi M, Landini L, Simi S (2009) Biological effects and safety in magnetic resonance imaging: a review. Int J Environ Res Public Health 6:1778–1798
15. Karpowicz J, Hietanen M, Gryz K (2007) Occupational risk from static magnetic fields of MRI scanners. Environmentalist 27(4):533–538
16. Crozier S, Liu F (2005) Numerical evaluation of the fields induced by body motion in or near high-field MRI scanners. Prog Biophy Mol Biol 87(2):267–278
17. Crozier S, Trakic A, Wang H, Liu F (2007) Numerical study of currents in workers induced by body-motion around high-ultrahigh field MRI magnets. J Magn Reson Imaging 26(5):1261–1277
18. Fatahi M, Demenescu LR, Speck O (2016) Subjective perception of safety in healthy individuals working with 7 T MRI scanners: a retrospective multicenter survey. Mag Reson Mater Phy 29:379
19. Zilberti L, Bottauscio O, Chiampi M (2016) Assessment of exposure to MRI motion-induced fields based on the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines. Magn Reson Med 76:1291–1300
20. Schaap K, Vries CD, Cambron-Goulet E, Kromhout H (2015) Work-related factors associated with occupational exposure to static magnetic stray fields from MRI scanners. Magn Reson Med 75(5):2141–2155
21. Batistatou E, Mölter A, Kromhout H, Van Tongeren M, Crozier S, Schaap K, De Vocht F (2015) Personal exposure to static and

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time-varying magnetic fields during MRI procedures in clinical practice in the UK. Occup Environ Med oemed. doi:10.1136/oemed-2015-103194
22. Acri G, Testagrossa B, Causa F, Tripepi MG, Vermiglio G, Novario R, Quadrelli G (2014) Evaluation of occupational exposure in magnetic resonance sites. Radiol Med (Torino) 119(3):208–213
23. Wilén J, de Vocht F (2011) Health complaints among nurses working near MRI scanners—a descriptive pilot study. Eur J Radiol 80(2):510–513

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