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Personal exposure to static and time-varying magnetic fields during MRI procedures in clinical practice in the UK

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ABSTRACT

Background MRI has developed into one of the most important medical diagnostic imaging modalities, but it exposes staff to static magnetic fields (SMF) when present in the vicinity of the MR system, and to radiofrequency and switched gradient electromagnetic fields if they are present during image acquisition. We measured exposure to SMF and motion-induced time-varying magnetic fields (TVMF) in MRI staff in clinical practice in the UK to enable extensive assessment of personal exposure levels and variability, which enables comparison to other countries.

Methods 8 MRI facilities across National Health Service sites in England, Wales and Scotland were included, and staff randomly selected during the days when measurements were performed were invited to wear a personal MRI-compatible dosimeter and keep a diary to record all procedures and tasks performed during the measured shift.

Results 98 participants, primarily radiographers (71%) but also other healthcare staff, anaesthetists and other medical staff were included, resulting in 149 measurements. Average geometric mean peak SMF and TVMF exposures were 448 mT (range 20–2891) and 1083 mT/s (9–12 355 mT/s), and were highest for radiographers (GM=559 mT and GM=734 mT/s). Time-weighted exposures to SMF and TVMF (GM=16 mT (range 5–64) and GM=14 mT/s (range 9–105)) and exposed-time-weighted exposures to SMF and TVMF (GM=27 mT (range 11–89) and GM=17 mT/s (range 9–124)) were overall relative low—primarily because staff were not in the MRI suite for most of their shifts—and did not differ significantly between occupations.

Conclusions These results are comparable to the few data available from the UK but they differ from recent data collected in the Netherlands, indicating that UK staff are exposed for shorter periods but to higher levels. These data indicate that exposure to SMF and TVMF from MRI scanners cannot be extrapolated across countries.

What this paper adds

- Staff working with MRI are exposed to static magnetic fields and motion-induced time-varying magnetic fields when present near MR systems.
- Data on personal exposure of MRI staff in clinical practice to static and motion-induced time-varying magnetic fields are scarce
- In this UK-based study, time-weighted average exposure was highest for MR radiographers, compared to other healthcare staff, anaesthetists and other medical staff.
- Exposure patterns were comparable between the UK and the Netherlands, but levels and correlations between different exposure metrics differed substantially.
- The results indicate that exposures in different countries differ, probably as a result of differences in practices, implying that exposure prediction models cannot be straightforwardly extended across different countries.

demonstrable clinical benefits as well as elimination of ionising radiation exposure for both patients and healthcare workers. An estimated 60 million MRI scans are performed annually worldwide,¹ and the growing importance of the modality is illustrated by the number of scanners in the UK, which has increased from approximately 10 in 1991 to over 500 in 2008, doing over 1.4 million scans a year (2.5% of the population having a scan annually).² This figure has further increased subsequently with additional scanners purchased by the UK National Health Service (NHS).³ Alongside increased use of MRI, the strength of the magnetic field used has increased from as low as 0.04 tesla (T) in the 1980s to up to 11.7 T with the introduction of ultra-high field scanner systems.⁴

Despite the advantages of MRI, a potential disadvantage is increased exposure of patients and staff to static magnetic fields (SMFs) as well as radiofrequency and switched gradient electromagnetic fields (EMF). MRI staff are exposed to static fields when present in the vicinity of the MR system during, for example, patient positioning



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INTRODUCTION

Magnetic resonance imaging (MRI) has developed into one of the most important medical diagnostic imaging modalities and has an important role in preclinical research in, for example, the pharmaceutical industry. The advantages of MRI include

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prior to scanning. Exposure to switched gradient fields may also occur when staff are present during image acquisition; for example, during interventional procedures guided by MRI, anaesthetists monitoring anaesthetised patients or nurses accompanying anxious or young patients.⁵ Medical diagnosis using MRI is now the main source of exposure of humans to high SMFs, and while in, for example, welding, aluminium production, the chloralkali industry and direct current train systems⁶ people are exposed to SMFs in the microtesla (μT) range, MRI in routine clinical settings exposes patients to SMFs in the range of 0.5 to 3.0 T, while personnel are exposed in the millitesla (mT) to tesla range.⁷ Exposure will most likely continue to increase in the future because of increase in the number of scans, advent of systems with stronger fields, and development of new interventional procedures guided by real-time MRI.⁸

Subclinical effects on well-being have been reported by staff routinely working with MRI.^{9–13} Recently, increased risk of accidents among MR engineers has also been reported.¹⁴ However, epidemiological data on the long-term health effects of protracted exposure to the magnetic fields required for MRI are non-existent and therefore, it cannot entirely be ruled out that such effects may exist.⁶ In controlled trials, exposure of humans and animals to magnetic fields—more specifically to temporal changes in SMF exposure caused by movement in the static fields around MRI scanners—has been associated with acute and temporal neurobehavioural effects^{15–19} and biological mechanisms for these interactions have been proposed.^{20–22}

To address the acute effects, limits on exposure to static and time-varying electromagnetic fields have been proposed by various organisations, including the International Commission on Non-ionizing Radiation Protection (ICNIRP)²³ and in the UK, the National Radiological Protection Board (NRPB).²⁴ In the European Union, The Physical Agents (EMF) Directive (2013/35/EU), which is largely based on the ICNIRP guidelines, will need to be implemented by member states by 1 July 2016.²⁵ In this Directive, MRI is considered as a controlled environment and is subject to a specific, non-discretionary derogation from exposure limits during the installation, testing, use, development, maintenance of or research related to MRI equipment for patients in the health sector, and as long as certain conditions are met. However, due to the absence of data, at present these exposure limit values explicitly exclude consideration of long-term health effects.

It is important to collect data on exposure of staff to SMFs, and to time-varying magnetic fields as a result of movement in the stray fields surrounding MRI systems, both to assess compliance with exposure limits and for (future) epidemiological studies to determine whether protracted occupational exposure may be associated with adverse health effects. Exposure to SMF has been estimated using a variety of methods,^{10 26–29} but only recently have personal dosimeters become available that enable individual measurement. Only limited data are currently available on actual personal occupational exposure levels. In the Netherlands, personal exposure studies have been conducted in human MRI facilities, experimental animal research and veterinary clinics,²⁹ and specifically for engineers in an MRI manufacturing department.¹⁰ Other studies have been conducted in the UK (for MRI radiographers),³⁰ in Australia (for a small number of healthcare workers),³¹ in Spain (for extremely low frequency magnetic fields, rather than SMFs, for hospital personnel),³² in Japan for four technologists only,³³ and for nurses during contrast administration in Poland.³⁴ Since it is known that standard MRI procedures can differ between countries, for example, for administration of contrast medium in the Netherlands compared

to Poland,^{29 34} extrapolating results from one country to the other may not be possible.

This paper describes the results of a large personal exposure measurement survey among healthcare staff routinely working with MRI throughout the UK. Here, we will assess MRI-related exposure to static and motion-induced time-varying magnetic fields, variability in this exposure between different occupations and between workers with the same occupations.

MATERIALS AND METHODS

Study design

MRI facilities across NHS sites in England, Wales and Scotland were invited to participate in the study through researchers' contacts and via an open call for participants at the Institute of Physics and Engineering in Medicine (IPEM) annual conference (2012). Once a site had agreed to participate, a researcher (AM or FV) visited the site on 2–5 consecutive days. Staff working in the MRI facility on the days of the visits were asked to participate in the study. On arrival of the staff in the morning, all were provided with a study information sheet and written consent was obtained prior to distributing any questionnaires and conducting measurements. The number of participants measured on a given day was limited by the number of available dosimeters; this was generally three, although for some site visits six dosimeters were available.

Ethical approval was obtained from the University of Manchester's Research Ethics Committee (reference number: 12066) and NHS R&D approval was obtained individually for each of the participating sites.

Data acquisition

Personal exposure to SMF (B) and to motion-induced time-varying magnetic fields (dB/dt) was measured during work shifts in the MRI facilities, using personal dosimeters with a resolution of ± 0.5 mT and ± 2 mT/s, and an accuracy of ± 10 mT (50 mT between 1 and 7 T) and ± 10 mT/s for static field and gradient field measurements, respectively (Magnetic Dosimeter, University of Queensland³¹). The dosimeter was worn on the hip (on participant's preferred side) of the participant for the entire duration of the shift.

Each personal dosimeter measured, simultaneously, the SMF ($B_{x,y,z}$) and temporal changes in the SMF ($\text{dB}_{x,y,z}/\text{dt}$) in all three orthogonal directions (x, y, z) with a sampling frequency of 50 Hz. The data files were converted to text files and through averaging, reduced to a measurement rate of 10 Hz to enable data handling. The exposure values of B (in mT) and dB/dt (in mT/s) were calculated using the following formulae:

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

and

$$\frac{\text{dB}}{\text{dt}} = \sqrt{\left(\frac{\text{dB}}{\text{dt}_x^2} + \frac{\text{dB}}{\text{dt}_y^2} + \frac{\text{dB}}{\text{dt}_z^2}\right)} \quad (2)$$

In this study, second generation dosimeters were used, removing the need to correct for baseline drift as in previous studies using first generation dosimeters.²⁹

To adjust for the dosimeter limit of detection (LOD), which was determined by averaging exposure of the controls within the study (ie, staff not working within the MRI suite), all SMF values below the LOD, (10 mT), were replaced with a random

number between 0.05 mT (the average value of the earth's magnetic field) and 10 mT. There was no need to impute dB/dt values for LOD.

Questionnaire and diary

A baseline questionnaire was completed on the first measurement day by all participants. The questionnaire included questions regarding current job title, occupation history, types of MRI systems used, personal characteristics and incidence of symptoms that might be related to exposure. A work practice diary was also provided to each participant to keep a record of all procedures that required access to the MRI suite on the measurement days and details of the MRI systems used. The questionnaires and associations with effects on health and well-being were reported in more detail in de Vocht *et al.*⁹

For the purpose of the analyses in this paper, occupations were aggregated into four groups: radiographers, other healthcare professionals (OHCP) (eg, radiographer assistants and staff nurses), medical staff (eg, consultant cardiologists and clinical fellows) and anaesthetists; although anaesthetists are also medical staff, they were classified separately because a priori we expected that their exposure would differ significantly from that of other medical staff due to the nature of the tasks performed.

Statistical analysis

As the exposure data was positively skewed, all data were log-transformed prior to analysis. For each measurement file, we calculated the following B and dB/dt exposure metrics: instantaneous peak, shift-weighted average (SWA) and exposure-weighted average (XWA) exposures; the latter being calculated by post hoc processing of the data as average exposure during the periods that the staff were in the MRI room, thus excluding, for example, periods of image acquisition when staff were in a separate control room. For each exposure metric, we estimated the arithmetic mean (AM) and the geometric mean (GM). Also, we estimated the within-person and between-person geometric standard deviation (GSD) and Pearson correlation coefficients between the exposure metrics. In addition, and for comparability with the study in the Netherlands,²⁹ the probability (p) of non-compliance with exposure limit values from the European Union Physical Agents (EMF) Directive was also estimated. Peak B exposure was compared to the 2 and 8 T exposure limit values for instantaneous peak B exposure. Exposure limit values for time-varying magnetic fields in the directive are expressed in terms of induced electric field strength, which cannot be measured directly, with subsidiary action levels given in terms of magnetic flux density calculated from the exposure limits using a conservative model. In order to compare our dB/dt exposure measurements with these action levels, we derived dB/dt action levels using equation 3, as proposed by McRobbie.¹ The root-mean-square (RMS) low action level for frequencies (f) of 1–8 Hz as proposed in the EMF Directive²⁵ is $2 \times 10^5 / f^2$ mT, resulting in a minimum dB/dt action level at 8 Hz of 222.5 mT/s and a maximum action level at 1 Hz of 1780 mT/s.

$$\left(\frac{dB}{dt}\right)_{pk} = \sqrt{2 \times 2\pi f \times B_L} \quad (3)$$

Exposure data were modelled for each job type using multilevel mixed effect models, where job type was considered as a fixed effect. Data was analysed using Stata V.13 (StataCorp 2013) using the *runmlwin* command.³⁵

RESULTS

A total of 115 participants across 8 NHS sites were recruited and 175 personal SMF exposure measurements were collected. Ten participants were non-exposed controls (at least one per site) and were excluded from analysis (but used to determine the dosimeters' LOD). Of the remaining 105 participants, exposure information was not retrieved for 1 health worker—this participant was also excluded from the analysis, resulting in 104 participants in total. In addition, 11 measurement files (of 6 participants) had to be excluded due to faulty dosimeters. Thus in total, 98 participants and 149 personal SMF exposure measurements were included in this analysis. Table 1 shows the descriptive characteristics of the participants.

The majority of the participants were females (71%) and radiographers (71%). All participants worked with cylindrical MRI systems, with magnet strengths of 1.5 T, 3.0 T or both. Participants worked, on average, about 8 h per shift in the MRI facility. Radiographers and most OHCP spend their whole working shifts in the MRI facility, mainly in the control room where exposure was minimal. The longest shift duration, about 12.5 h, was observed for a radiographer, followed by an OHCP (12.4 h). Exposure of medical staff (for this purpose including anaesthetists) was only measured during work in the MRI facility, since full shift measurements would have been difficult logistically and there is no exposure elsewhere. This generally resulted in shorter measurement durations, with the shortest being 0.7 h for a radiologist present during scanning of one patient only. Radiographers reported that they work in MRI, on average, about 30 h per week, followed by OHCP (23 h), while medical staff (18 h) and anaesthetists (3 h) were in the MRI facility for much shorter periods. In total, 4809 individual MRI scans were recorded during the measurement sessions. In these 4809 recorded MRI scans, radiographers were involved in 2210 scans, OHCPs in 427, anaesthetists in 39 scans and other medical staff in 39 (only staff for whom exposure measurements were performed are included in these figures).

For illustrative purposes, typical static field and motion-induced time-varying magnetic field exposure patterns for two randomly selected radiographers are shown in online supplementary figures S1 and S2.

Table 2 indicates that low to moderate correlations (range $r=0.13$ – 0.54) were observed between the different exposure metrics, with the exception of a very high correlation between

Table 1 Descriptive characteristics of participants

Number of participants (proportion—%), by gender	
Female	71 (72.4)
Male	27 (27.6)
Average age in years (range)	40 (23–65)
Average height in cm (SD)	167 (9.8)
Average weight in kg (SD)	73 (17.4)
Median number of exposure measurements per person (range)	1 (1–4)
Average shift duration in hours (range)	8 (0.7–12.5)
Hours worked in MRI per week (range)	28 (0.5–40)
Number of participants (proportion—%) by job title	
Radiographer	71 (72)
OHCP	21 (21)
Medical	3 (3)
Anaesthetist	3 (3)

OHCP, other healthcare professionals.

Table 2 Pearson's correlation coefficients for exposure measures

Exposure type	Metric	B Peak	B SWA	B XWA	dB/dt Peak	dB/dt SWA	dB/dt XWA
B	Peak	1	0.13	0.46	0.54	0.19	0.28
B	SWA		1	0.38	0.20	0.25	0.13
B	XWA			1	0.17	0.17	0.34
dB/dt	Peak				1	0.54	0.54
dB/dt	SWA					1	0.96
dB/dt	XWA						1

Peak, instantaneous peak exposure; SWA, shift-weighted average; XWA, exposure-weighted average.

shift-weighted average (SWA) and exposure-weighted average (XWA) dB/dt levels ($r=0.96$).

Table 3 shows that the highest peak exposures were measured for radiographers (peak B=559 mT; peak dB/dt=734 mT/s). The anaesthetists in our study have the lowest peak exposures, both for B (127 mT) and dB/dt (98 mT/s). In this population, average static field and time-varying magnetic field exposure (weighted for shift duration) was observed for the OHCP group, although dB/dt was comparable to that of radiographers. OHCP, on average, spent a larger proportion of their time in the MRI facility in the scanner room itself, followed by medical staff (66%), radiographers (56%, but note that, in contrast to other occupations, radiographers are in the MRI facility for virtually their complete shifts) and anaesthetists (52%). When in the MR scanner room itself, the highest B and dB/dt exposure was observed for radiographers (28 mT and 17 mT/s, respectively).

As further shown in table 3, between-participant variability was generally larger than within-participant variability,

regardless of exposure metric, and accounted for 58% to 100% of the total exposure variability. Table 4 shows the exposure metrics stratified by strength of the MR scanner magnet, of which the majority (94%) were at 1.5 T systems. Peak static field exposure was about twice as high when 3 T systems were used (GM=1249–1274 mT) compared to when scanning was only performed on 1.5 T systems (GM=417 mT). The highest peak exposure observed at a 1.5 T system in this study was almost 3 T. When being present very close to the bore entrance of a 1.5 T scanner, for example, when leading into the bore, exposure to the static field can be considerably higher than 1.5 T as a result of the interplay of the primary and shielding coils towards the end of the magnet. Depending on the cryostat arrangement, the field just inside the bore nearest to the coil can be as high as 3 T.³¹ However, it can also not be excluded that this may have occurred when a staff member working with a 1.5 T system also entered a 3 T system MRI suite during their shift, but this was not recorded. Interestingly, arithmetic mean peak exposure to motion-induced time-varying magnetic fields is about 50% higher when scanning involves 3 T systems (1560–1848 mT/s) compared to 1.5 T systems only (1048 mT), while geometric mean peak exposure is three times as high, indicating that high peaks at 1.5 T are relatively rare. Average static field exposure was only 18–24 mT (SWA) or 28–50 mT (XWA), with average dB/dt exposure being similarly low (SWA 16 mT/s; XWA 19 mT/s), indicating that during most of the shifts staff are not in the scanner room, and when they are they are not very close to the MR system itself for most of the time.

Although the ratios of within-worker and between-worker variabilities differ for the different exposure metrics, overall these are relatively comparable; indicating that exposures differ as much between different staff as they do when staff are measured on multiple days. The probability of exceeding the 2 T limit was only 1.7% for radiographers, while during these

Table 3 Exposure metrics by job category: instantaneous peak exposure levels, average exposure levels weighted for the duration of the shift (shift-weighted average; SWA) and average exposure levels weighted for the time exposed to SMF (exposure-weighted average; XWA)

	N _{obs}	N _{sub}	B (mT)					dB/dt (mT/s)				
			AM	GM	GSD _{BW}	GSD _{WW}	Range	AM	GM	GSD _{BW}	GSD _{WW}	Range
<i>Occupation</i>												
<i>Instantaneous peak exposure</i>												
Radiographers	116	71	695	559	1.73	1.59	37–2891	1131	734	2.03	1.83	37–12 455
Other HCP	26	21	467	201	3.19	2.16	27–1895	1080	258	4.65	2.97	9–5968
Medical	4	3	366	337	1.41	1.23	197–558	344	305	1.21	1.63	133–542
Anaesthetists	3	3	256	127	2.20	–*	20–570	214	98	4.30	–	14–497
Total	149	98	637	448	6.37	1.57	20–2891	1083	574	7.34	1.80	9–12 455
<i>SWA</i>												
Radiographers	116	71	18	16	1.32	1.43	8–48	16	14	1.36	1.38	9–105
Other HCP	26	21	22	18	1.00	1.89	6–64	17	14	1.00	1.65	9–94
Medical	4	3	20	17	1.57	1.27	10–35	15	14	1.43	1.01	9–21
Anaesthetists	3	3	11	10	1.59	–	5–16	10	10	1.07	–	9–11
Total	149	98	19	16	2.03	1.43	5–64	16	14	2.03	1.36	9–105
<i>XWA</i>												
Radiographers	116	71	30	28	1.23	1.35	13–89	20	17	1.37	1.40	10–124
Other HCP	26	21	28	24	1.00	1.64	11–64	20	16	1.60	1.38	9–120
Medical	4	3	26	25	1.00	1.26	18–35	16	16	1.28	1.00	12–21
Anaesthetists	3	3	16	15	1.35	–	11–22	11	11	1.12	–	9–12
Total	149	98	29	27	2.40	1.33	11–89	20	17	2.17	1.39	9–124

*No within-participant repeats were available for anaesthetists.

AM, arithmetic mean; GM, geometric mean; GSD_{BW}, between-participant geometric SD; GSD_{WW}, within-participant geometric SD; HCP, healthcare professional; N_{obs}, number of observations; N_{sub}, number of individual participants; SMF, static magnetic fields.

Table 4 Exposure metrics by MR magnet strength: instantaneous peak exposure levels, average exposure levels weighted for the duration of the shift (shift-weighted average; SWA) and average exposure levels weighted for the time exposed to SMF (exposure-weighted average; XWA)

	N _{obs}	N _{sub}	B (mT)					dB/dt (mT/s)				
			AM	GM	GSD _{BW}	GSD _{WW}	Range	AM	GM	GSD _{BW}	GSD _{WW}	Range
<i>Magnet strength</i>												
Instantaneous Peak exposure												
1.5 T	138	94	594	417	2.38	1.72	20–2891	1048	539	3.01	2.05	9–12 455
3.0 T	6	5	1261	1249	1.13	1.06	1069–1588	1560	1427	1.23	1.11	961–1903
1.5 and 3.0T	3	3	1283	1274	1.13	–*	1069–1412	1848	1731	1.42	–	1263–2833
Total	147†	102‡	635	447	2.23	2.41	20–2891	1082	574	2.81	2.78	9–12 455
SWA												
1.5 T	138	94	18	16	1.29	1.53	5–64	16	14	1.32	1.43	9–105
3.0 T	6	5	24	23	2.15	1.00	15–38	18	17	1.35	1.04	10–23
1.5 and 3.0 T	3	3	22	19	1.67	–	12–40	27	26	1.36	–	19–39
Total	147	102	19	16	1.39	1.64	5–64	16	14	1.33	1.58	9–105
XWA												
1.5 T	138	94	28	26	1.20	1.40	11–64	19	16	1.36	1.43	9–124
3.0 T	6	5	50	47	1.50	1.00	27–89	27	25	1.53	1.05	16–46
1.5 and 3.0 T	3	3	37	35	1.42	–	22–50	31	30	1.22	–	25–40
Total	147	102	29	27	1.34	1.57	11–89	19	17	1.37	1.60	9–124

*No within-participant repeats were available for 1.5 and 3.0 T MR systems.

†No information on magnet strength was reported in two MR procedures.

‡Higher number of participants (compared to table 3) because some of the participants worked on different MR systems from day-to-day.

AM, arithmetic mean; GM, geometric mean; GSD_{BW}, between-participant geometric SD; GSD_{WW}, within-participant geometric SD; N_{obs}, number of observations; N_{sub}, number of individual participants; SMF, static magnetic fields.

measurements other healthcare professionals, medical staff and anaesthetists did not exceed the 2 T limit (table 5). Since this study only included 1.5 and 3 T MR systems the 8 T level was never exceeded. Peak dB/dt exposure during a shift exceeded the 222.5 mT/s action level (relevant to 8 Hz field variation) during most shifts, and the action level was most often exceeded by radiographers (93% of shifts), while the 1780 mT/s threshold (relevant to 1 Hz field variation) was exceeded during only 10% of shifts; most often by OHCP (23%). For time-varying magnetic fields, the lower 222.5 mT/s threshold was exceeded in the vast majority of procedures using 1.5 T systems (95%) and in all 3 T procedures, while the higher 1780 mT/s threshold was exceeded in only 9% (1.5 T) and 17% (3 T) of shifts.

DISCUSSION

This paper describes the results of a large measurement survey of shift-based personal exposure to SMFs and motion-induced time-varying magnetic fields among healthcare staff routinely

working with MRI in the NHS. To our knowledge, this is the most comprehensive study to date of personal occupational exposure to MRI-related SMF and time-varying magnetic fields among healthcare staff in the UK.

Our results show that staff routinely working with MRI to scan patients, not surprisingly, are exposed to SMFs from the magnet and to time-varying magnetic fields as a result of motion to and from the scanner in the stray field of the magnet. Exposure to the static as well as to the motion-induced time-varying fields is highly variable within as well as between subjects and between shifts, and is driven by movement close to the MRI system. Nonetheless, on average, exposures are 2–3 times higher when working with 3 T systems compared to working with 1.5 T systems. Staff moving through the SMF will experience transient magnetic field changes containing a range of frequency components, making comparison of our results with ICNIRP limits complex. A 222.5 mT/s action level derived from the time-varying magnetic field exposure limit at 8 Hz is exceeded in the majority of shifts, while a value of 1780 mT/s derived from the limit at 1 Hz, as well as 2 T limit for static fields, are only exceeded in a few situations. With respect to the 17% of shifts on 3 T systems during which the 1780 mT/s value is exceeded, it is important to further determine if these are for specific procedures only so that possible changes to these procedures to lower exposure may be explored. Reference levels to prevent peripheral nerve stimulation and phosphenes due to field changes of <1 Hz have been provided by ICNIRP²³ for controlled (2.7 T/s) and uncontrolled (2.7 T/s or 1.8/f T/s, depending on the exposure condition) environments. If we consider MRI to be a controlled environment, we noted 10 occurrences in which peak dB/dt exposure exceeded the 2.7 T/s reference level.

Average exposure levels to both the static and the time-varying magnetic fields are comparable between different occupations; this is primarily because staff are not present in the MRI room during most of their shifts. Instantaneous peak

Table 5 Probability (p) (%) of non-compliance with exposure limit value of 2 T and derived action levels of 222.5 mT/s and 1780 mT/s

	N _{obs}	N _{sub}	p (2 T)	p (222.5 mT/s)	p (1780 mT/s)
Occupation					
Radiographers	116	71	1.7	93.1	8.6
Other HCP	26	21	0.0	57.7	23.1
Medical	4	3	0.0	75.0	0.0
Anaesthetists	3	3	0.0	33.3	0.0
Overall	149	98	1.3	85.2	10.7
Magnet strength					
1.5 T only	138	94	1.5	84.8	9.4
3.0 T only	6	5	0.0	100.0	16.7

HCP, healthcare professional; N_{obs}, number of observations; N_{sub}, number of individual participants; p, probability, expressed in %.

exposures, however, were on average highest for radiographers compared to other staff, with geometric mean peaks (both B and dB/dt) about 1.5 to three times as high as those of other healthcare staff and medical staff. Since radiographers prepare the MRI room for the next patient and generally accompany patients to prepare them for the scan or guide them out of the MR room after the scan, these results confirm our a priori hypothesis. For example, we observed that in most monitored hospitals, patients were cannulated in the scan room, that is, while sitting on the patient table right next to the scanner. These results are also in line with recent work in the Netherlands where magnetic field strength and the specific tasks in the MRI room performed by staff were identified as main determinants of exposure.³⁶

Previous personal exposure data from the UK are available,³⁰ but it is difficult to directly compare the results of the studies because different measurement equipment were used, circumstances differed and data from the 2007 study were not stratified by occupation. Nonetheless, with respect to the strength of the magnets, our results are broadly comparable to those reported in Bradley *et al.*³⁰ Internationally not much data is available, but our study is most comparable to a recent study conducted in the Netherlands.²⁹ When interpreting these results, it is important to note that the study in the Netherlands included participants working with MRI systems with magnetic field strengths of up to 7 T, and also included data from non-clinical settings. Schaap *et al.* further measured personal exposure at chest level (using a custom-designed harness) while we measured at the hip. Nonetheless, compared to the Dutch study, correlations between the different exposure metrics in our study are 33–81% lower for peak exposures, depending on exposure metric and field strength. Correlation between shift-weighted and exposure-weighted metrics for static exposure are much lower in our study (about 46%), while it is higher (about 19%), and nearly perfect, for time-varying magnetic fields. Overall, instantaneous B peak exposure in healthcare (human MRI facilities) in the Dutch study was 15–28% higher (depending on magnetic field) than the exposure we measured in the UK, while the relative between-participant variability was much higher in our study; this may indicate that tasks are more standardised in the Netherlands. Regarding overall shift-weighted average exposure in healthcare, exposure-weighted averages are 2.5-fold higher and 1.3-fold lower for SMF and time-varying magnetic field, respectively, in the Dutch study. Although hypothetical, this seems to indicate that the Dutch staff moved more slowly through the stray fields, but stayed in the MRI suite for a longer time. An alternative explanation for the observed differences in exposure is that in the Dutch study the dosimeters were attached to a harness around the breast, while in our study, these were worn at the hip. No data are available that directly compare the impact of these different positions of the dosimeter on exposure levels, but it is likely that exposure measured at the upper body is generally higher than that measured at the hip because more rotational movements are made and also staff will lean forward during certain tasks which puts their torso closer to the magnet bore than the hip. Different methods of data handling between both studies may also, to some extent, explain any differences. We observed the highest exposure for radiographers compared to other occupations in our study, but since the occupations differ from those in the Dutch study, these results cannot be directly compared.

The main advantages of our study is that with the use of the personal dosimeters, we were able to collect a large number (about 150) of personal shift measurements for staff routinely

working with MRI in NHS healthcare in the UK, thereby providing reference exposure estimates for comparison with other countries and for use in quantitative exposure estimates in future epidemiological studies. The random selection of hospital sites, measurement days and participating staff should ensure that our results describe exposure conditions in England, Wales and Scotland; however, given the nature of the participating sites, the exposure estimates are more representative of larger tertiary sites than smaller sites. Another advantage of this study was that we were able to use second generation dosimeters which did not require additional, somewhat arbitrary, data manipulation to account for baseline drifts as was required in earlier studies.

Unfortunately, within the time frame of this study we were not able to collect more exposure data from occupations other than radiographers, and we were also not able to collect data from other occupations such as, for example, hospital cleaners who can also receive high exposure to MRI-generated magnetic fields in these settings.²⁹ Another limitation of our methodology was that, for reasons of logistics, we were not able to perform measurements for the full shifts of medical staff who were only in the MRI facility for a short time. Although this is likely to be negligible, since in most cases they would not have received additional exposure, we cannot completely exclude these. Also, it makes exposure-weighted average exposure measures more comparable with radiographers' exposures than shift-weighted averages, although again, the differences are likely to be minimal. We performed measurements at the hip, which was done so that wearing the dosimeter would not interfere with participants' work, but as outlined above this may have underestimated exposure to the head, which is generally considered the target organ for the observed effects.³⁷ We opted not to measure nearer the head, for example, at the chest as was done in the Dutch study,²⁹ because it is fairly unlikely that if in the future routine monitoring of staff is introduced, it will be carried out using relatively inconvenient protocols. Nonetheless, as it is difficult to determine whether the location of the dosimeter at the hip systematically overestimates or underestimates exposure measured at the chest, future work will need to assess correlations of exposures measured at different places on the body during simultaneous measurements of different movement patterns.

CONCLUSIONS

In summary, these personal exposure data from a random sample of staff routinely working with MRI in the NHS in England, Wales and Scotland indicate that staff, especially radiographers, are exposed to strong magnetic fields as a result of their work. Relatively large between-worker and within-worker variability indicates that despite having broadly similar jobs or doing the same job on different days, exposure can differ significantly and depends to a large extent on other factors such as the MRI system, the number of patients scanned during a shift, specific tasks performed, and personal behaviour as was also recently shown for the Netherlands.³⁶ As such, further more detailed studies of exposure patterns will be required to identify the most appropriate targets for exposure reduction. Comparison to the most appropriate other data set of personal exposure available, data from the Netherlands, our work indicates that exposure of UK staff is, on average, over a shorter time period during a shift, but is at somewhat higher levels (when working with systems of 1.5 and 3 T). To some extent this can probably be explained by different positioning of the dosimeters on the body of participants during measurements,

but it may also imply that differences between procedures exist, leading to different exposure patterns in the two countries: UK staff seem to be in the MR suites for shorter duration than their Dutch colleagues, but either moved faster (on average), maybe because more patients had to be scanned in a shift, or were closer to the bore, maybe to assist or comfort patients prior to a scan.

Future analyses at task level will hopefully shed some light on this because for exposure prediction it is important to gain as much insight as possible into determinants of exposure differences. With respect to future cohort studies of long-term health effects, these data indicate that exposure prediction models cannot be straightforwardly adopted by different countries, and that a measurement of baseline exposure in normal practice is needed for each country.

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