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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

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ABSTRACT

Clinical and research staff who work around magnetic resonance imaging (MRI) scanners are exposed to the static magnetic stray fields of these scanners. Although the past decade has seen strong developments in the assessment of occupational exposure to electromagnetic fields from MRI scanners, there is insufficient insight into the exposure variability that characterizes routine MRI work practice. However, this is an essential component of risk assessment and epidemiological studies. This paper describes the results of a measurement survey of shift-based personal exposure to static magnetic fields (SMF) (*B*) and motion-induced time-varying magnetic fields (dB/dt) among workers at 15 MRI facilities in the Netherlands. With the use of portable magnetic field dosimeters, >400 full-shift and partial shift exposure measurements were collected among various jobs involved in clinical and research MRI. Various full-shift exposure metrics for *B* and motion-induced dB/dt exposure were calculated from the measurements, including instantaneous peak exposure and time-weighted average (TWA) exposures. We found strong correlations between levels of static (*B*) and time-varying (dB/dt) exposure ($r = 0.88–0.92$) and between different metrics (i.e. peak exposure, TWA exposure) to express full-shift exposure ($r = 0.69–0.78$). On average, participants were exposed to MRI-related SMFs during only 3.7% of their work shift. Average and peak B and dB/dt exposure levels during the work inside the MRI scanner room were highest among technical staff, research staff, and radiographers. Average and peak B exposure levels were lowest among cleaners, while dB/dt levels were lowest among anaesthesiology staff. Although modest exposure variability between workplaces and occupations was observed, variation between individuals of the same occupation was substantial, especially among research staff. This relatively large variability between workers with the same job suggests that exposure classification based solely on job title may not be an optimal grouping strategy for epidemiological purposes.

KEYWORDS: EMF; exposure assessment; exposure variability; MRI; MRI staff; occupational exposure; static magnetic fields; time-varying magnetic fields

INTRODUCTION

During the past decade, occupational exposure to electromagnetic fields (EMF) from magnetic resonance imaging (MRI) scanners has gained significant attention in the research field of MRI safety. The main source of MRI-related EMF exposure for MRI staff is the static magnetic stray fields that surround each scanner. These stray fields expose MRI staff to static magnetic fields (SMF) of 0 Hz [*B*, expressed in Tesla (T)]. In addition, workers are exposed to time-varying magnetic fields (dB/dt, expressed in T s^{-1}), resulting from movement through these spatially non-uniform stray fields.

In 2013, a new European Physical Agents Directive was officially adopted by the European Parliament and Council (Directive 2013/35/EU, European Union, 2013) to protect against short-term and acute effects of occupational exposure to EMF in the 0 Hz–300 GHz range. This Directive shall be brought into force in the EU member states by 1 July 2016. The Directive has adopted SMF exposure limit values (ELVs) for peak external magnetic flux density (*B*) exposure of 2 T (normal working conditions) and 8 T (controlled working conditions or localized limb exposure), based on evaluations from the International Commission on Non-Ionizing Radiation Protection (ICNIRP) (2009). In accordance with Faraday's law of induction, a time-varying magnetic field can induce an electric current in the body, which has been linked to adverse health effects (Reilly, 1989; International Commission on Non-Ionizing Radiation Protection (ICNIRP), 2009). For the low-frequency ranges relevant for motion-induced time-varying magnetic field exposure, the Directive therefore sets exposure limit values for the maximum internal electric field induced in the body of the exposed subject. The ELV is 1.1 V m^{-1} (at 1 Hz–3 kHz) for health effects, while for sensory effects the ELV is dependant on the frequency (*f*, in Hz): $0.7/f$ V m^{-1} (at 1–10 Hz) and applies specifically to exposures to the head. Because internally induced electric fields cannot be easily assessed, low and high action levels are provided as a tool to assess compliance with the sensory effect ELVs and health effect ELVs, respectively. For the frequency range of 1–8 Hz the low action level for root-mean-square flux density (RMS *B*) is $2 \times 10^5/f^2$ μT and the high action level is $2 \times 10^5/f$ μT. These action levels represent maximum values at the workers' body position. As long as these action levels are not exceeded, compliance with the associated ELVs is assumed. An important aspect of the new Directive for the MRI community is the fact that 'exposure may exceed the ELVs if the exposure is related to the installation, testing, use, development, maintenance of or research related to MRI equipment for patients in the health sector' (Directive 2013/35/EU, European Union, 2013, p. 8). This implies that the above mentioned ELVs do not apply to MRI staff. This derogation is allowed, provided that the circumstances justify exceeding the ELVs; more specifically that characteristics of the workplace, equipment, and work practice have been taken into account, technical and organisational measures have been applied and the employer demonstrates that workers are still protected against adverse health effects and against safety risks. This underlines the need for risk assessment for these workers.

Proper risk assessment requires knowledge of workers' exposure levels and patterns. Various techniques have been used to estimate personal occupational exposure to MRI-related SMFs and motion-induced time-varying magnetic fields. These techniques include spot measurements (Karpowicz and Gryz, 2006; Riches *et al.*, 2007), measurements of simulated movements of MRI staff during standard procedures (Glover and Bowtell, 2008; Kännälä et al., 2009; Andreuccetti *et al.*, 2013; Laakso *et al.*, 2013), estimates of MRI staff exposure by combining video observations of movements in the scanner room with measurements of the spatial distribution of the stray field around the scanner (de Vocht *et al.*, 2006; Capstick *et al.*, 2008), and numerical calculations of induced electric fields in anatomical models (Crozier and Liu, 2005; Crozier *et al.*, 2007; Wang *et al.*, 2008; Ilvonen and Laakso, 2009; Chiampi and Zilberti, 2011; Laakso *et al.*, 2013). These studies provide informative estimates of MR radiographers' external *B* or dB/dt exposure or internal induced currents during standard work practice or worst-case exposure situations. However, they have not been able to provide sufficient insight into the exposure variability that characterizes routine work practice, including variability between different jobs and between individuals with the same job title, as well as day-to-day and within-day variability in exposure levels.

A method of exposure assessment that more closely resembles real exposure patterns is the use of a magnetic field sensor worn at the body surface of the MRI worker. Portable SMF dosimeters have been available for a few years (Cavin *et al.*, 2006; Bradley *et al.*, 2007; Fuentes *et al.*, 2008). These dosimeters can be used to register personal exposure to static and sometimes time-varying magnetic fields. Exposure assessment using Hall effect probes or SMF dosimeters has proven useful to measure actual exposure patterns during a period of up to several hours and have been applied for task-based and shift-based exposure measurements among clinical and research MRI staff (Bradley *et al.*, 2007; Fuentes *et al.*, 2008; Karpowicz and Gryz, 2010; Karpowicz and Gryz, 2013; Yamaguchi-Sekino *et al.*, 2014) and MRI engineers in an MRI manufacturing plant (de Vocht *et al.*, 2009). These measurements revealed a wide range in levels of exposure to SMFs, even when the same type of procedure was considered.

MRI is increasingly being used as a diagnostic imaging technique; not only it is used for clinical imaging in hospitals, but also to perform research on patients, volunteers, and experimental animals. Several veterinary clinics are now also using MRI scanners for diagnostic imaging of pets and horses. Consequently, clinical staff, researchers, technical support staff, and cleaners at these facilities are also involved in MRI and get exposed to SMFs (Schaap *et al.*, 2013). A comprehensive exposure assessment describing exposure levels among different groups of MRI workers and analysing exposure variability between and within persons, is therefore an essential component of risk assessment and epidemiological studies.

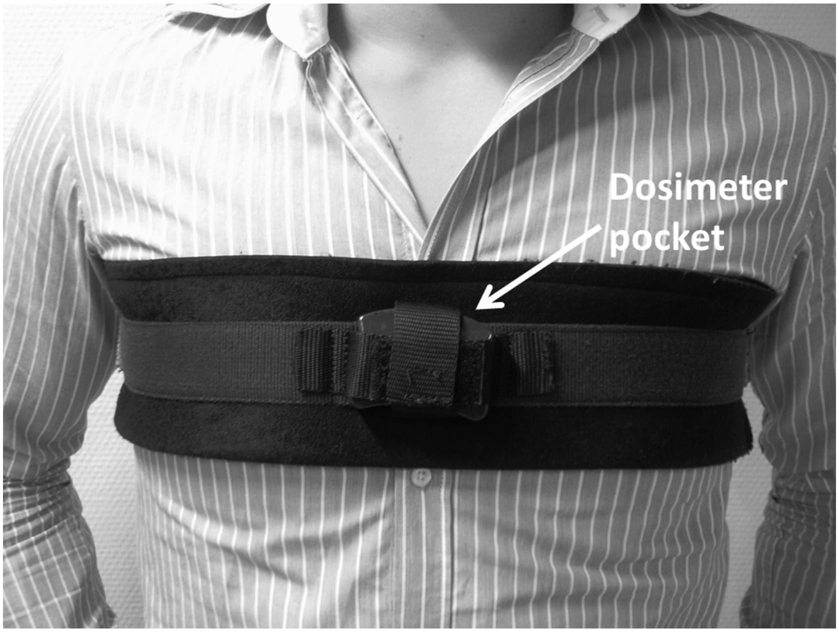
This paper describes the results of a large exposure measurement survey among MRI staff working at healthcare and research MRI facilities throughout the Netherlands. Personal exposure to B and dB/dt was measured during complete work shifts, using portable dosimeters. We aimed (i) to provide an overview of everyday B and dB/dt exposure levels and to identify highly exposed groups of workers, and (ii) to assess variability in exposure levels between jobs, between workers with the same job, and temporal day-to-day variability.

MATERIALS AND METHODS

Study population and measurement design

Measurements of personal exposure to SMFs were performed at 15 MRI facilities in the Netherlands, where patients, volunteers, or live animals were scanned. Some of these facilities additionally scanned *ex-vivo* samples, and some performed phantom scans for hardware testing and development. Each MRI facility was visited for 1 or 2 weeks, depending on the size of the department. Measurement locations were selected in order to obtain a range in potential determinants of exposure variability such as scanner types, magnetic flux density of the scanners, scan procedures, patient types, department sizes, and occupations. All employees who worked at the MRI facility during the days of the visit were asked if they would volunteer as participants in the measurement survey. Study participants wore a SMF dosimeter during one or more work shifts at the MRI facility. The aim was to include repeated measurements within subjects, where the work schedule allowed for this. The dosimeter was worn on an elastic strap around the breast, with the measurement device placed in a pocket at the front of the upper body (Fig. 1). One MRI facility, a veterinary clinic, was used as a pilot location for the study. Here, the dosimeter was attached at similar height to the upper arm on the preference hand side of the participant. Because this method was regarded as less comfortable and less practical, the placement of the dosimeter was changed to the chest for the remaining 14 study locations.

Participants registered the total duration of their shift in a diary. Shift-based measurements were collected for the majority of participants. Participants such as medical doctors, anaesthesiologists, researchers, and cleaners, who worked in other hospital departments too, were monitored only while they were present at the MRI facility. Since it was known that these participants were not exposed to MRI-related SMF during the unmeasured part of their shift, it was possible to derive full-shift exposure estimates for these individuals. Exposure levels are presented for three different types of MRI facilities: those scanning human subjects for either clinical or research aims; those scanning animals for experimental aims; and those scanning veterinary patients. In addition, exposure levels are presented for each individual occupational group. Measurements that lasted <50% of the actual time spent at the MRI facility were excluded from statistical analyses. The study was approved by the Medical Research Ethics Committee of the Utrecht University Medical Center.



1 Dosimeter strap.

Measurement devices

The exposure measurements were performed with 10 portable magnetic field dosimeters (Magnetic Field Dosimeter, University of Queensland; also see Fuentes *et al.,* 2008). The dosimeters continuously measured SMFs (*B*, in mT) and motion-induced time-varying magnetic fields (dB/dt, in mT s^{-1}) in three orthogonal directions (x, y, z), with a sampling rate of 20 ms (i.e. 50 measurements per second). They were used in static field mode, which is suitable for measuring SMFs and time-varying magnetic fields of very low frequencies, which are typical for movement-induced fields (Chiampi and Zilberti, 2011). The dosimeters had a measurement range of 0.5–7000 mT for static fields and 2–25 000 mT s^{-1} for time-varying fields.

Handling of the exposure measurement data

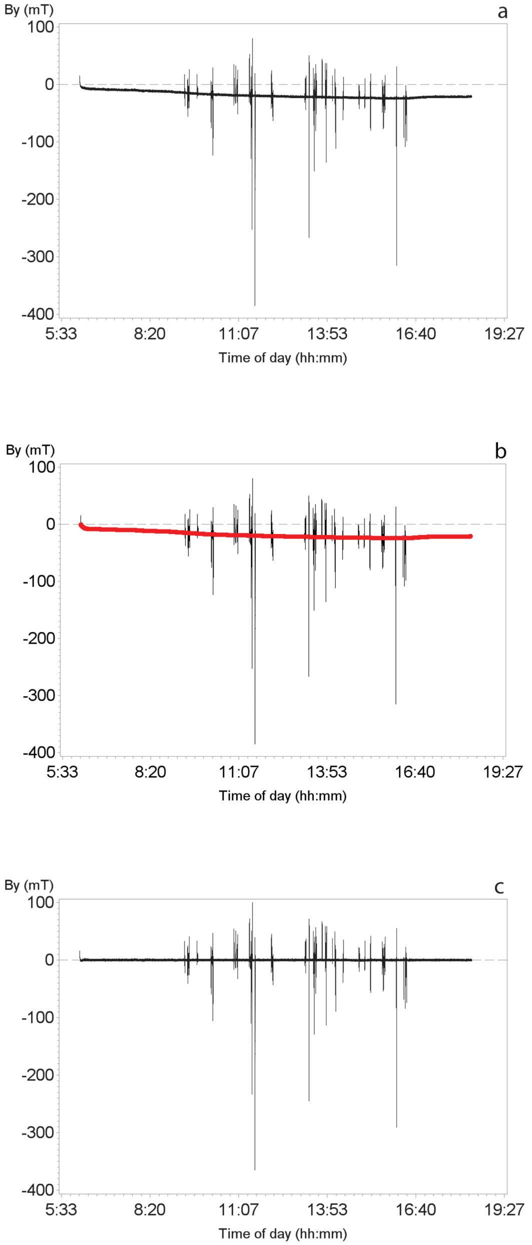
The data files were converted to text files with a reduced measurement rate of 100 ms. The dosimeters showed temporal changes ('drift') in the baseline of the SMF measurements of B_x, B_y and B_z (e.g. see Fig. 2a), which was probably due to heating of the battery. We used a flexible semi-parametric modelling approach using the 'mgcv' package in R (version 2.15.2; R Foundation for Statistical Computing, Vienna, Austria) to estimate the value of this 'drifting' baseline for each single measurement point of B_x, B_y, and B_z in each individual measurement file (Fig. 2b). Subsequently, the estimated values of the baseline were subtracted from each single measurement point, therewith removing the drift in the baseline (Fig. 2c).

After this correction of the temporal changes in the baseline of B_x, B_y, and B_z, the resultant exposure values of *B* and dB/dt were calculated by the following formulae:

$$B_{\mathrm{res}} = \sqrt{\left(B_x^{\ 2} + B_y^{\ 2} + B_z^{\ 2}\right)} \qquad (1)$$

$$\mathrm{dB/dt}_{\mathrm{res}} = \sqrt{\left(\mathrm{dB/dt}_x^{\ 2} + \mathrm{dB/dt}_y^{\ 2} + \mathrm{dB/dt}_z^{\ 2}\right)} \qquad (2)$$

The resultant *B* and dB/dt were subsequently corrected for baseline noise of the measurement devices. The maximum baseline noise of *B* and dB/dt was determined for each of the 10 measurement devices individually, based on measurements performed at background exposure level (i.e. outside any MRI scanner room, where MRI-related *B* exposure was expected to be 0). This maximum baseline per dosimeter varied from 5–7 mT for *B* and 33–57 mT s^{-1} for dB/dt. To correct for this noise, the dosimeter-specific maximum noise values were subtracted from each measurement point and resulting negative values were



2 Example of measured B level in the y-direction of a single 7:15-h measurement file. (a) Original By level, showing a temporal change (‘drift’) in the baseline; (b) original By level (black) with estimated By baseline drift (red); (c) adjusted By level after subtraction of the modelled baseline drift. Color figure can be viewed in the online issue.

attributed a value of zero. A value of zero was chosen since this study only considers magnetic field exposure due to MRI and not from other sources.

The use of SMF dosimeters allowed for the assessment of various *B* and dB/dt exposure metrics. The following *B* and dB/dt summary exposure metrics were calculated from each measurement work shift: instantaneous peak (peak), full-shift time-weighted average (TWA; TWA based on the total duration of the shift), and SMF-exposed TWA (TWA based on the time exposed to a SMF; i.e. where $B \neq 0$ mT). In addition, for each measured work shift we calculated the proportion during which the worker was exposed to SMF (i.e. $B \neq 0$ mT). For the ‘partial shift’ measurements where only the time at the MRI facility was measured, exposure values of 0 mT and 0 mT s^{-1} were assumed for the time spent outside the MRI facility in order to calculate the full-shift TWA. Pearson correlation coefficients between the exposure metrics were estimated in SAS 9.2 (SAS Institute Inc., Cary, NC, USA).

The resulting exposure distributions resembled log-normal distributions. Therefore, the exposure metrics were log-transformed before descriptive statistics were estimated. To enable log-transformation of the data, measurement files with a 0 value for peak exposure, full-shift TWA, SMF-exposed TWA, or percentage of shift exposed (n = 2–30, depending on the exposure metric) were attributed a random value between the lowest non-zero value and a factor 10 lower than this value by means of maximum likelihood imputation, using a censored regression model for the log-normal distribution in SAS 9.2 (Lubin *et al.*, 2004).

For each exposure metric we estimated the arithmetic mean and the geometric mean (GM). In addition, the within- and between-worker components of exposure variability were expressed by the within- and between-worker geometric standard deviations (GSD) and range ratio ($R_{0.95}$). The range ratio between workers expresses the ratio between the 97.5th and 2.5th percentiles of the log-normally distributed worker mean exposures (Rappaport, 1991; Burdorf, 2007).

In addition, we estimated the probability (P) that the *B* or dB/dt peak exposure value of a work shift in a specific group of workers exceeded exposure limit values. This ‘probability of noncompliance’ is based on the GM and GSD of the peak exposure levels per sector or job, and thus takes exposure variability into account (Leidel *et al.*, 1977). Limit values were selected from European Physical Agents Directive

2013/25/EU (2013). Peak *B* exposure was compared to the 2 and 8 T exposure limit values for instantaneous peak *B* exposure. Limit values for instantaneous peak dB/dt exposure were calculated by applying the weighted peak method (see formula 3), as proposed by Jokela (2007) and used by McRobbie (2012), to the RMS action level in the Directive. The RMS low action level for frequencies of 1–8 Hz as proposed in Table B2 of the Directive is $2\times10^5/f^2$ μT. This results in a peak dB/dt of $1.78/f$ T s^{-1}. For the frequency range of 1–8 Hz this gives a minimum action level of 223 mT s^{-1} at 8 Hz and a maximum action level of 1780 mT s^{-1} at 1 Hz. The high action level of $2\times10^5/f$ μT is equal to the low action level at a frequency of 1 Hz, which is 1780 mT s^{-1}.

$$(\mathrm{dB}/\mathrm{dt})_{\mathrm{pk}} = \surd 2 \times 2\pi f \times B_{\mathrm{L}} \tag{3}$$

where f is the frequency in Hz and B_{L} is the RMS action level.

RESULTS

A total number of 475 personal SMF exposure measurements were collected. The facilities utilized various types of MRI scanners, including closed bore, open bore, extremity, upright and small-bore scanners, with magnetic flux densities ranging between 0.2 T (open bore) to 11.7 T (small-bore experimental animal scanner). Measurement files that were damaged or could not be read out (n = 25), measurement files for which additional information about the shift or person measured was unavailable (n = 8), measurements of unexposed or non-MRI shifts (n = 10), and measurements that included <50% of the actual time spent at the MRI facility (n = 19) were excluded from statistical analyses. This resulted in statistical analysis of 413 measurements from 271 participants. More than 95% of the people who were approached for participation in the study, agreed to participate. Fifty-eight percent of the measurements were shift-based; the other 42% were collected as partial shift measurements (i.e. only the time at the MRI facility was measured). Table 1 presents an overview of the collected data. Most of the participants (83%) were either radiographer or researcher. Participants worked on average slightly over 8 h per shift, with a maximum duration of just over 13 h for some researchers.

Pearson correlations between instantaneous peak, full-shift TWA, and SMF-exposed TWA exposure ranged between 0.69 and 0.71 for *B* and between 0.70 and 0.78 for dB/dt (Table 2). Correlations between the proportion of shift time exposed to SMF on one hand and peak and full-shift TWA B and dB/dt levels on the other, ranged between 0.25 and 0.45. Correlations between the proportion of shift time-exposed and SMF-exposed TWA *B* and dB/dt were very low but negative (r = −0.08 to −0.11). The negative sign was determined by a small group of researchers with short exposure duration and very high SMF-exposed TWA exposures. Levels of B and dB/dt were strongly correlated for each of the three exposure metrics (peak, full-shift TWA, SMF-exposed TWA; r = 0.88–0.92).

The summary statistics of the exposure measurements are presented in Tables 3–6. Overall, exposure levels were highest at human clinical and research MRI facilities and lowest at the veterinary clinic. On average, participants were exposed to SMF during only 3.7% of their shift, with GMs ranging from 0.3% for cleaners to 6.3% for radiographers. Scientific staff was on average exposed during 2.4% of their shift (Table 3). The highest peak exposure levels (represented by the GM per category in Table 4) were measured among MRI radiographers (peak *B* = 531 mT; peak dB/dt = 839 mT s^{-1}). Cleaners had the lowest peak B exposure (79 mT), while anaesthesiology staff showed the lowest peak dB/dt exposure (124 mT s^{-1}). When calculated over the duration of the work shift, TWA *B* exposure levels were highest for radiographers and research staff and lowest for cleaners (3.9, 2.1, and 0.1 mT, respectively; Table 5). Similar patterns were seen for full-shift TWA dB/dt exposure, ranging from 0.02 to 0.8 mT s^{-1} per job. When only the time exposed to SMF was considered in estimating TWAss (Table 6), average B exposure levels were highest among technical and scientific staff (83 and 77 mT, respectively), while the lowest *B* exposure levels were observed among cleaners (12 mT). The highest levels of SMF-exposed TWA dB/dt exposure were observed among technical staff and radiographers (14 and 12 mT s^{-1}, respectively), while the lowest levels were measured among anaesthesiology staff (1 mT s^{-1}). Among human MRI facilities the between-worker variability (expressed by GSD$_{\mathrm{BW}}$) was larger than the day-to-day variability (expressed by GSD$_{\mathrm{WW}}$) for most of the exposure metrics (Tables 3–6). Between-worker variability in

Table 1. Description of participants and collected data

Participating MRI facilities (*N*)	15
General hospital (included scanners: 0.5 T and 1.5 T closed bore, 0.6 T upright)	4
Academic hospital (included scanners: 1.5 T, 3 T, and 7 T closed bore, 1 T open bore, 1 T and 1.5 T extremity)	4
Academic children's hospital (included scanner: 1.5 T closed bore)	1
Human neuroscientific research institute (included scanners: 3 T and 7 T closed bore)	1
Animal research institute (included scanners: 4.7 T, 6.3 T, 7 T, 9.4 T, and 11.7 T small-bore)	4
Academic veterinary clinic (included scanner: 0.2 T open bore)	1
Participants (*N*)	271
Radiographer, radiography student, or intern	123
Medical doctor or medical specialist (including radiographers)	6
Anaesthesiology staff	28
Scientist, researcher, research student	101
Technical staff (medical, maintenance) and medical physicists	5
Lab assistant or lab technician	3
Cleaner	5
Proportion of female participants (%)	55%
Average age in years (range)	36 (19–65)
Median number of measurements per person (range)	1 (1–6)
Average shift duration in hh:mm (range)	8:16 (2:00–13:40)
Average measurement duration in hh:mm (range)	6:11 (0:05–13:27)

these facilities accounted for 52 and 41%, 65 and 72%, 68 and 70% of the total variability in exposure levels for peak, full-shift TWA and SMF-exposed TWA metrics of B and dB/dt, respectively, and 72% of the total variability in exposure levels for proportion of shift exposed (data not shown). Experimental animal research facilities showed larger between-worker differences for peak and TWA exposures than the other two sectors. In these facilities, between-worker differences accounted for 84 to 94% of the total exposure variability (data not shown). Only for the 'proportion of shift exposed' metric, the between-worker variability at animal research facilities was considered lower than the within-worker variability, accounting for 42% of the total exposure variability. For measurements performed at the veterinary clinic, day-to-day differences accounted for almost all of the variability in peak and SMF-exposed TWA exposure (84–100%; data not shown). Among radiographers, lab assistants/technicians, and anaesthesiology staff the between-worker differences in average exposures were relatively small (most GSD_{BW} below 2) and day-to-day variability was mostly larger than between-worker variability. Between-worker variability was largest among medical specialists, researchers, and technical staff.

The probabilities of non-compliance in Table 7 represent the estimated proportion of MRI shifts during which the maximum individual exposure level (peak B or peak dB/dt) will exceed the specified limit value for this metric. In the current study sample, the probability of exceeding the 2 T limit value was estimated to be between 0 and 10%, depending on the worker's

Table 2. Pearson correlations between exposure metrics

Exposure type	Metric	*B*	*B*	*B*	dB/dt	dB/dt	dB/dt	% Exposed
		Peak	**Full-shift TWA**	**SMF-exposed TWA**	**Peak**	**Full-shift TWA**	**SMF-exposed TWA**	
B	Peak	1	0.70	0.69	0.88	0.73	0.67	0.25
B	Full-shift TWA		1	0.71	0.70	0.92	0.59	0.45
B	SMF-exposed TWA			1	0.68	0.72	0.92	−0.08
dB/dt	Peak				1	0.78	0.73	0.25
dB/dt	Full-shift TWA					1	0.70	0.35
dB/dt	SMF-exposed TWA						1	−0.11
	% Exposed							1

Peak = instantaneous peak exposure; Full-shift TWA = TWA based on the total duration of the shift; SMF-exposed TWA = TWA based on the time exposed to a SMF (i.e. $B \neq 0$ mT); % exposed = percentage of total shift duration exposed to a SMF (i.e. $B \neq 0$ mT).

Table 3. Percentage of total shift duration exposed to a SMF per sector and job

	N_{obs}	N_{sub}	% Of shift					$R_{0.95}$
			AM	**GM**	**GSD_{BW}**	**GSD_{WW}**	**Range**	
Sector								
Human MRI facilities[a]	341	230	5.8	4.3	2.34	1.71	<0.1–22.5	28
Experimental animal research	49	31	4.4	2.7	2.39	2.81	<0.1–14.6	30
Veterinary clinic	23	10	1.5	0.8	2.88	1.73	<0.1–6.0	63
Job								
Radiographer, radiography student, or intern	216	123	7.2	6.3	1.49	1.63	0.1–16.8	5
Medical doctor or medical specialist	7	6	2.3	1.3	1.00	3.32	0.2–8.0	1
Anaesthesiology staff	35	28	4.0	1.8	3.31	1.75	<0.1–22.5	109
Scientist, researcher, research student	137	101	3.6	2.4	2.20	2.27	<0.1–14.6	22
Technical staff (medical, maintenance) and medical physicists	7	5	2.2	1.6	1.00	2.36	0.5–5.1	1
Lab assistant or lab technician	6	3	2.1	1.8	1.00	1.82	0.9–3.4	1
Cleaner	5	5	0.4	0.3	1.85[b]		0.2–0.8	4
Total	413	271	5.4	3.7	2.56	1.83	<0.1–22.5	40

N_{obs} = number of observations; N_{sub} = number of individual workers; AM = arithmetic mean; GSD_{BW} = between-worker geometric standard deviation; GSD_{WW} = within-worker geometric standard deviation; $R_{0.95}$ = range ratio for between-worker variability.

[a] Includes facilities scanning human subjects for either clinical or research purpose.

[b] No within-worker repeats were available for cleaners. Therefore, only the total GSD is reported for this group.

job title. Exceedance was not calculated for the peak B limit value of 8 T, since all of the measured values were far below 8 T. The probability that peak dB/dt exposure during a shift would exceed 223 or 1780 mT s^{-1} was estimated to be 38–97 and 0–24% per job category, respectively. The highest probabilities

Table 4. Instantaneous peak exposure levels per sector and job

	B (mT)							$R_{0.95}$	dB/dt (mT s^{-1})					$R_{0.95}$
	N_{obs}	N_{sub}	AM	GM	GSD_{BW}	GSD_{WW}	Range		AM	GM	GSD_{BW}	GSD_{WW}	Range	
Sector														
Human MRI facilities[a]	341	230	681	528	1.79	1.76	13–2661	10	1090	793	1.87	2.11	<1–5016	12
Experimental animal research	49	31	221	133	3.36	1.55	6–605	116	363	143	9.30	1.78	<1–1281	6261
Veterinary clinic	23	10	111	81	1.48	2.46	5–250	5	130	56	1.92	6.59	<1–390	13
Job														
Radiographer, radiography student, or intern	216	123	636	531	1.46	1.68	17–2302	4	1034	839	1.49	1.83	13–4052	5
Medical doctor or medical specialist	7	6	414	203	3.24	1.87	31–1473	100	497	188	5.95	1.91	6–1708	1090
Anaesthesiology staff	35	28	225	143	1.78	2.63	5–726	10	277	124	1.89	6.26	<1–861	12
Scientist, researcher, research student	137	101	676	395	3.12	1.66	6–2661	86	1081	490	5.06	2.33	<1–5016	576
Technical staff (medical, maintenance) and medical physicists	7	5	549	424	2.27	1.30	105–1047	25	644	466	2.50	1.54	99–1292	37
Lab assistant or lab technician	6	3	125	119	1.52	1.17	63–167	5	305	302	1.09	1.14	260–381	1
Cleaner	5	5	88	79	1.65[b]		53–181	7	275	213	2.49[b]		47–561	11
Total	413	271	595	404	2.39	1.78	5-2661	30	950	558	3.13	2.45	<1–5016	87

N_{obs} = number of observations; N_{sub} = number of individual workers; AM = arithmetic mean; GSD_{BW} = between-worker geometric standard deviation; GSD_{WW} = within-worker geometric standard deviation; $R_{0.95}$ = range ratio for between-worker variability.

[a] Includes facilities scanning human subjects for either clinical or research purpose.

[b] No within-worker repeats were available for cleaners. Therefore, only the total GSD is reported for this group.

Table 5. Average exposure levels per sector and job, based on the total duration of the shift (full-shift TWA)

	N_{obs}	N_{sub}	B (mT)					$R_{0.95}$	dB/dt (mT s^{-1})					$R_{0.95}$
			AM	GM	GSD$_{BW}$	GSD$_{WW}$	Range		AM	GM	GSD$_{BW}$	GSD$_{WW}$	Range	
Sector														
Human MRI facilities[a]	341	230	5.3	3.2	2.87	2.16	<0.1–39.9	62	1.3	0.6	4.07	2.39	<0.01–12.7	246
Experimental animal research	49	31	3.0	1.0	4.39	1.89	<0.1–26.9	331	0.4	0.1	5.91	1.82	<0.01–3.8	1056
Veterinary clinic	23	10	0.3	0.2	2.08	1.63	<0.1–1.1	18	<0.1	<0.1	2.62	2.70	<0.01–0.3	43
Job														
Radiographer, radiography student, or intern	216	123	5.3	3.9	1.85	1.98	0.1–30.4	11	1.3	0.8	2.29	2.40	<0.01–6.2	26
Medical doctor or medical specialist	7	6	2.3	0.6	1.00	7.78	0.1–6.6	1	0.4	0.1	7.97	4.11	<0.01–1.8	3414
Anaesthesiology staff	35	28	1.3	0.5	3.68	1.77	<0.1–7.9	166	0.1	<0.1	4.53	2.08	<0.01–1.0	373
Scientist, researcher, research student	137	101	5.3	2.1	4.21	2.09	<0.1–39.9	280	1.2	0.3	6.10	2.06	<0.01–12.7	1199
Technical staff (medical, maintenance) and medical physicists	7	5	2.9	1.6	3.46	1.73	0.2–7.0	130	0.8	0.3	7.66	1.53	<0.01–1.9	2918
Lab assistant or lab technician	6	3	0.9	0.8	1.41	1.58	0.4–2.0	4	0.1	0.1	1.58	1.86	<0.01–0.3	6
Cleaner	5	5	0.1	0.1	1.24[b]		0.1–0.1	1	<0.1	<0.1	2.38[b]		All <0.1	9
Total	413	271	4.8	2.4	3.67	2.04	<0.1–39.9	163	1.1	0.4	5.44	2.31	<0.01–12.7	766

N_{obs} = number of observations; N_{sub} = number of individual workers; AM = arithmetic mean; GSD$_{BW}$ = between-worker geometric standard deviation; GSD$_{WW}$ = within-worker geometric standard deviation; $R_{0.95}$ = range ratio for between-worker variability.

[a] Includes facilities scanning human subjects for either clinical or research purpose.

[b] No within-worker repeats were available for cleaners. Therefore, only the total GSD is reported for this group.

Table 6. Average exposure levels per sector and job, based on the time exposed to SMF (SMF-exposed TWA)

	N_{obs}	N_{sub}	B (mT)					$R_{0.95}$	dB/dt (mT s^{-1})					$R_{0.95}$
			AM	GM	GSD_{BW}	GSD_{WW}	Range		AM	GM	GSD_{BW}	GSD_{WW}	Range	
Sector														
Human MRI facilities[a]	341	230	99	68	2.04	1.64	5–956	16	25	13	3.20	2.13	<0.1–258	95
Experimental animal research	49	31	48	29	3.47	1.42	1–158	131	7	2	6.78	2.04	<0.1–96	1809
Veterinary clinic	23	10	16	12	1.00	2.27	2–41	1	3	1	1.66	5.11	<0.1–11	7
Job														
Radiographer, radiography student, or intern	216	123	67	57	1.42	1.58	5–292	4	16	12	1.82	2.05	<0.1–66	10
Medical doctor or medical specialist	7	6	72	44	2.10	2.36	9–204	18	17	4	11.73	1.39	<0.1–56	15 547
Anaesthesiology staff	35	28	27	18	1.43	2.46	2–111	4	3	1	1.00	5.38	<0.1–15	1
Scientist, researcher, research student	137	101	143	77	3.29	1.46	1–956	107	36	10	6.03	2.20	<0.1–258	1142
Technical staff (medical, maintenance) and medical physicists	7	5	109	83	2.34	1.30	16–219	28	29	14	5.22	1.43	1–75	650
Lab assistant or lab technician	6	3	42	37	1.39	1.66	14–67	4	6	5	1.40	2.10	1–10	4
Cleaner	5	5	13	12	1.51[b]		7–20	2	10	6	3.67[b]		1–26	57
Total	413	271	89	56	2.41	1.67	1–956	31	22	9	4.13	2.36	<0.1–258	260

N_{obs} = number of observations; N_{sub} = number of individual workers; AM = arithmetic mean; GSD_{BW} = between-worker geometric standard deviation; GSD_{WW} = within-worker geometric standard deviation; $R_{0.95}$ = range ratio for between-worker variability.

[a] Includes facilities scanning human subjects for either clinical or research purpose.

[b] No within-worker repeats were available for cleaners. Therefore, only the total GSD is reported for this group.

Table 7. Probability (*P*) of non-compliance to limit values of 2 T, 223 and 1780 mT s^{-1}

	N_{obs}	N_{sub}	*P* (2 T)	*P* (223 mT s^{-1})	*P* (1780 mT s^{-1})
Sector					
Human MRI facilities[a]	341	230	5%	90%	20%
Experimental animal research	49	31	2%	42%	14%
Veterinary clinic	23	10	0%	25%	4%
Job					
Radiographer, radiography student, or intern	216	123	2%	97%	15%
Medical doctor or medical specialist	7	6	4%	46%	12%
Anaesthesiology staff	35	28	1%	38%	9%
Scientist, researcher, research student	137	101	10%	67%	24%
Technical staff (medical, maintenance) and medical physicists	7	5	4%	77%	9%
Lab assistant or lab technician	6	3	0%	97%	0%
Cleaner	5	5	0%	48%	1%
Total	413	271	6%	74%	21%

N_{obs} = number of observations; N_{sub} = number of individual workers; *P* = probability, expressed in %.

[a] Includes facilities scanning human subjects for either clinical or research purpose.

of exceedance of limit values of 2 T (10%) and 1780 mT s^{-1} (24%) existed for research staff. Lab assistants/technicians and radiographers had the highest probability of exceedance of the 223 mT s^{-1} limit value (both 97%).

DISCUSSION

This paper describes the results of a measurement survey of shift-based personal exposure to SMFs and motion-induced time-varying magnetic fields among MRI staff. We performed >400 full-shift and partial shift measurements among various jobs involved in clinical and research MRI, representing the most comprehensive study to date of occupational exposure to MRI-related static and time-varying magnetic fields.

The highest peak and TWA levels of *B* and dB/dt exposure were observed among MRI facilities scanning human subjects. These include clinical MRI departments in general and academic hospitals, and research MRI departments in academic hospitals and research institutes, using MRI scanners with magnetic flux densities ranging from 0.5 to 7 T. At animal research MRI facilities, which used small-bore MRI scanners of 4.7 to 11.7 T, exposure levels were a factor 2.3–6.5 lower than at human MRI departments. This can be explained by the fact that, although the magnetic fields in the isocenters of these scanners were higher, the SMFs are relatively well shielded. As a result, stray fields surrounding these scanners are strongly reduced. This is also illustrated by the low *B*-field values (<30 mT) that were measured around a 7.5 and a 9.39 T nuclear MR spectrometer in a study by Decat (2007). The lowest exposure levels in the current study were measured at a veterinary clinic where a low-field open scanner of 0.2 T was used to scan anaesthetized pets and horses.

TWA exposure levels measured during the actual time spent near the MRI system (i.e. SMF-exposed TWA) were highest among technical staff, research staff, and radiographers, with a ratio between the highest and lowest exposed jobs of 7 and 13 for *B* and dB/dt, respectively. The variation in exposure levels among workers with the same job was often much larger than the variation between different jobs. The range ratio between individuals within job categories ranged from 2 to 107 for SMF-exposed TWA *B* levels and even exceeded 1000 for SMF-exposed TWA dB/dt levels among some jobs (medical specialists and research staff).

For radiographers, between-worker variability in exposure levels was relatively small compared to temporal day-to-day variability. This is most likely due to the fact that radiographers have relatively standardized work protocols and work shifts of similar length, although some exposure variability is still expected between workers since they work with scanners of different magnetic flux densities and perform different scan procedures. For research staff, the variability in average exposures between workers was relatively large. This might be explained by the fact that the work of a researcher near an MRI scanner varies a lot from one individual to another, ranging from scanning patients or animals to testing new coils on imaging phantoms. The overall relatively high levels of exposure variability between workers illustrate that the variation of the total sample cannot be entirely explained by differences between jobs or sectors. Other factors such as local work practice, scanner types, magnetic flux density, and performed tasks may be important contributors to further explain differences in personal MRI-related SMF exposure. Furthermore, individual differences in work practice, including proximity to the scanner bore, presence in the strongest spatial gradients of the magnetic stray field around the scanner, and velocity of movement through the magnetic stray field, are postulated to be important drivers of between-worker variability in exposure levels. A better understanding of the role of these determinants is necessary in order to obtain more accurate estimates of personal exposure when exposure measurements are not available.

Using the GM of our exposure data, we observed peak *B* exposure levels of 531 mT (range 17–2302 mT) among MRI radiographers. These levels are comparable to full-shift peak *B* exposure levels measured at five clinical and research MRI sites in Brisbane, Australia (mean peak *B* = 570 mT) (Fuentes *et al.*, 2008) and among 19 MRI radiographers at four clinical MRI sites in the UK (mean peak *B* per unit 320–553 mT) (Bradley *et al.*, 2007). Also task-based measurements of radiographers' SMF exposure in Japan showed peak *B* values comparable to the values observed in our study (Yamaguchi-Sekino *et al.*, 2014). The average peak dB/dt exposure levels measured among radiographers in the current study (mean = 839 mT s^{-1}; range 13–4052 mT s^{-1}) were lower than the levels measured in the Australian study (mean = 2196 mT s^{-1}; range 560–5980 mT s^{-1}). Also average shift TWA *B* exposure levels in our study were lower than those in the studies by Bradley *et al.* (2007) and Fuentes *et al.* (2008). There must be some caution in the comparison of exposure levels between different countries, since it is known that differences exist between the work content of certain jobs. For example, while the administration of contrast medium belongs to the common tasks of MR radiographers in the Netherlands, in Poland this is often done by special MRI nurses (Karpowicz and Gryz, 2013). In addition, the MRI facilities in the current study were not randomly sampled, but were chosen to include variability in MRI applications. This resulted in underrepresentation of general hospitals and overrepresentation of specific jobs, such as research staff and MRI radiographers, compared to the overall distribution in the Netherlands (Schaap *et al.*, 2013). Therefore, the overall exposure levels reported in this study should not be regarded representative for the entire MRI-exposed population in the Netherlands, although they do provide a good overview of what levels can be expected in the different sectors and jobs. Nevertheless, estimates of exposure levels and exposure variability will be less representative for some job categories for which only few measurements were available (as few as five observations for cleaners).

Up to now, the main focus of MRI-related SMF research has been on acute short-term physiological, sensory, and neurocognitive effects (e.g. Glover *et al.*, 2007; Roberts *et al.*, 2011; Van Nierop *et al.*, 2012; Schaap *et al.*, 2014). The exact mechanisms behind many of these effects are still largely unclear. This makes it difficult to select appropriate metrics to express exposure, especially when these are to be used for epidemiological studies. For acute and short-term effects from SMF exposure, measures of instantaneous exposure levels will most likely be relevant to consider. Therefore, peak exposure is considered. This measure of maximum exposure can also be used for comparison to exposure limit values and action levels (McRobbie, 2012; Directive 2013/35/EU, European Union, 2013). In addition to peak exposure, which is based on a single point in time, this paper considers other metrics which provide more information about the exposure patterns of a worker during the entire shift. The proportion of the shift during which the worker was exposed to the SMF is used as a descriptive metric to give some insight in the differences in the way the work shifts of individuals are arranged and result in different patterns of exposure. The TWA is a measure of central tendency of exposure. Since participants were on average exposed to SMF during only 3.7% of their shift, the full-shift TWA's will be determined to a substantial amount by the unexposed time. To provide a better insight in exposure levels during exposed periods, we therefore also calculated a TWA exposure metric based on exposure levels during the actual time spent near the MRI system, while exposed to SMF: the SMF-exposed TWA. A similar approach was used by Breysse *et al.* (1994), who calculated average magnetic field exposure levels of telephone lineworkers based on task performance time only, excluding breaks and driving time. In occupational epidemiology, the full-shift TWA is often used to assess long-term health effects of occupational exposure to various agents. This exposure metric was calculated because it enables comparison to other studies, which often reported only peak and shift-TWA (or 24-h TWA) exposure, and no other measures of central tendency (e.g. Bradley *et al.*, 2007; Fuentes *et al.*, 2008; De Vocht *et al.*, 2009).

Levels of B and dB/dt exposure were very strongly correlated for all exposure metrics, with Pearson correlation coefficients ranging between 0.88 and 0.92. Correlations between B and dB/dt were high both when the unexposed duration of a work shift was taken into account (full-shift TWA) and when it was not (SMF-exposed TWA). This implies that the strong positive correlation between B and dB/dt was not just driven by the large unexposed proportion of each shift. The correlation between B and dB/dt will largely be determined by the strength of the main B_0 field of the scanner, which determines both the strength of the static magnetic stray field around the scanner and the size of the spatial gradients of this stray field. The first is a determinant of SMF (B) exposure; the latter of motion-induced dB/dt exposure. However, the strength of the spatial gradients is additionally determined by the scanner model and the shielding of the SMF. Therefore, the correlation between the main B_0 field of the scanner and the size of the spatial gradients is not linear. This was also shown by Capstick *et al.* (2008) who measured and compared the spatial static field gradients of various scanners. The strong correlation of B and dB/dt exposure complicates the disentangling of these two exposure metrics, which would be desirable for epidemiological studies of health effects related to SMF exposure, since SMFs and motion-induced time-varying magnetic fields have different effects on the human body (Glover *et al.*, 2007). Also, from an exposure reduction point of view it can be relevant to disentangle both metrics. When exposure levels of individual jobs are compared, values of B and dB/dt did not always show the same exposure ranking. Technical staff experienced the highest SMF-exposed TWA exposure levels, which were seven times higher than that of cleaners. The SMF-exposed TWA dB/dt exposure of technical staff, however, was only 2.3 times as high as that of cleaners. In addition, cleaners experienced the lowest peak exposures of B, but not the lowest peak exposures of dB/dt. This points to the potential role of differences between jobs in movement patterns around the scanner, including distance and speed.

The different metrics (i.e. peak values and TWAs) that were used to express B and dB/dt exposure were also quite strongly correlated, with correlations ranging between 0.69 and 0.78. The exposure ranking of jobs was similar for the three exposure metrics, with radiographers, researchers, and technical staff representing the highest exposure levels, while cleaners and anaesthesiologists generally experienced the lowest exposure levels. Although these results do not enable us to distinguish clearly between different metrics of magnetic field exposure, it is very well possible that they can be differentiated once other exposure determinants, such as information about specific MRI system characteristics, tasks and procedures, or more detailed information such as velocity and movement patterns, are also taken into account.

Literature has shown acute effects of MRI-related magnetic field exposure on cognitive function, sensory symptoms, balance and vestibular functions (de Vocht, Glover *et al.*, 2007; de Vocht, Stevens *et al.*, 2007; Glover *et al.*, 2007; Roberts *et al.*, 2011; Wilén and de Vocht, 2011; van Nierop *et al.*, 2012; Heinrich *et al.*, 2013; van Nierop *et al.*, 2013). Therefore, the head would be a relevant body part for exposure assessment. In the current study we measured exposure to static and time-varying magnetic fields at the chest. This was as close to the head as possible without having the dosimeter interfere with tasks being performed. Since the head may be moved closer towards the scanner bore, flux densities measured at the chest likely underestimate those experienced at the head. In addition, the head is expected to perform more and different (i.e. more rotational) movements in the static magnetic stray field, and will therefore experience different dB/dt exposure patterns than the chest. We measured magnetic field exposure levels close to the body surface. Laakso *et al.* (2013) showed that motion-induced dB/dt exposure measured on the body surface was proportional to the dB/dt levels inside that body part (in their case the head) and that dB/dt was proportional to the induced electric field (Laakso *et al.*, 2013). This proportionality indicates that the use of an external dB/dt probe for assessment of internal exposure to movement induced fields is suitable.

The European Physical Agents Directive states that MRI staff is exempt from the occupational EMF exposure limit values in this Directive (Directive 2013/35/EU, European Union, 2013). Nevertheless, because the limit values for exposure to SMFs and low-frequency time-varying magnetic fields are aimed to prevent effects such as vertigo, retinal phosphenes, and nerve stimulation, we considered it interesting to compare the measured peak exposure levels to the European Physical Agents Directive limit values. Based on the current exposure measurements, peak exposures during MRI work are expected to exceed 2 T in >5% of the shifts among researchers only. The ELVs for dB/dt exposure are frequency dependant. Because of the complex non-sinusoidal waveforms of motion-induced dB/dt, a perfectly appropriate solution for compliance testing of dB/dt exposure levels to ELVs is currently not available. For non-sinusoidal fields, ICNIRP proposes spectral analysis and application of ELVs to each frequency component (International Commission on Non-Ionizing Radiation Protection (ICNIRP), 2003), but this is thought to result in too conservative restrictions for frequencies <100 kHz (Jokela, 2007). An alternative method for compliance testing of non-sinusoidal complex waveforms is the weighted peak method (Jokela, 2007; McRobbie, 2012), which we applied in the current study for compliance testing of peak dB/dt exposure levels to the associated action levels in the European Directive. However, the non-periodic character of motion-induced fields, e.g. during linear motion across a spatially gradient field, makes it difficult to assign frequency characteristics to these fields. This may result in inaccuracies when comparing measured peak dB/dt levels to peak dB/dt action levels. Therefore, caution should be taken in the interpretation of these results. Nevertheless, we can conclude with relative certainty that the potential for exceeding dB/dt action levels due to motion in the stray field of the scanner is much higher than the chance of exceeding action levels for exposure to SMFs.

Conclusions

In conclusion, we measured levels of static and time-varying magnetic field exposure of MRI staff working in the vicinity of MRI scanners, using portable dosimeters. These dosimeters are relatively new and have not been used on large scale yet. The dosimeters enabled us to provide a realistic representation of everyday variability in exposure levels of various jobs during routine MRI practice. Average and peak *B* and dB/dt exposure levels were highest among technical staff, research staff, and radiographers. Although modest exposure variability between workplaces and occupations was observed, variation between individuals within the same occupation was substantial, especially among research staff. For jobs with large between-worker variation, attributing the job average to an individual worker would not yield a representative estimate of an individual worker's average exposure level. This relatively large variability between workers with the same job suggests that exposure classification based solely on job title may not be an optimal grouping strategy for epidemiological purposes, and that more detailed work-related information, such as the magnetic flux density of the scanner or specific tasks performed, will have to be collected.

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