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Work-Related Factors Associated with Occupational Exposure to Static Magnetic Stray Fields from MRI Scanners

Kristel Schaap,[1] Yvette Christopher-De Vries,[1] Évelyne Cambron-Goulet,[2] and Hans Kromhout[1]*

Purpose: This study aims to identify work-related and personal factors associated with workers' exposure to static magnetic fields (SMF) and motion-induced time-varying magnetic fields (TVMF) from MRI scanners.
Methods: Measurements of personal exposure to SMF and TVMF were performed among MRI staff during 439 work shifts at 14 different workplaces using portable magnetic field dosimeters. These data were coupled with contextual workplace and worker information. After data cleanup, 324 remaining observations were used to develop linear mixed effects models for various measures of peak and time-weighted average (TWA) exposure.
Results: Exposure levels near whole-body closed-bore scanners increased by 30% to 76% for each additional tesla of scanner strength, depending on exposure metric. Small-bore animal scanners, on the other hand, showed a reversed association with scanner strength. Measures of peak and TWA exposure were differently associated with specific tasks and scan procedures. In addition, body height of the worker was negatively associated with measured exposure levels.
Conclusion: The study revealed workplace characteristics, scan activities, and personal characteristics associated with SMF and TVMF exposure levels of MRI staff and was able to quantify the unique contribution of each of these factors while adjusting for the presence of others. **Magn Reson Med 75:2141–2155, 2016. © 2015 Wiley Periodicals, Inc.**

Key words: static magnetic fields; time-varying magnetic fields; occupational exposure; MRI staff; exposure determinants

INTRODUCTION

The past decade has seen increasing interest in work-related exposures and their health aspects among MRI personnel. As the magnets used for MRI became stronger, it became clear that MRI workers might experience acute transient symptoms such as vertigo, nausea, and metallic taste while working near MRI scanners (1–4). These symptoms are associated with exposure to very strong static magnetic fields (SMF) and motion-induced time-varying magnetic fields (TVMF) to which workers are exposed when moving through the spatial gradients of the static magnetic stray field around an MRI scanner (4–8). Various national and international guidelines have proposed limit values to control occupational exposure to electromagnetic fields, including those fields relevant to MRI staff (9–13). Also, the European Union decided to limit occupational exposure to electromagnetic fields, although the directive states that MRI-related activities are exempt from exposure limits. This derogation is allowed provided that the circumstances justify exceeding the exposure limit values. For example, employers are required to demonstrate that MRI workers are still protected against adverse health effects and against safety risks (14). The presence of exposure-related symptoms and the introduction of exposure guidelines emphasize the relevance of exposure assessment among this group of workers.

Various studies have aimed to measure or estimate SMF and TVMF exposure levels of individual workers at MRI or NMR facilities (15–25). Exposure to static and time-varying magnetic fields was found to be highly variable between different MRI workers, but also exposure levels within the same individuals could differ from day to day (25,26). This can be explained by the fact that the level of personal exposure to these fields is influenced by a range of factors related to the workplace or job performed, such as the scanners used, layout of the MRI facility, or specific tasks performed by an individual worker. In addition to this, personal characteristics such as a worker's movement patterns and velocity near an MRI scanner can play a role. To what extent these factors contribute to personal exposure levels is unknown. For example, it is expected that the nominal magnetic field of the MRI scanner (expressed in tesla (T)) will play a prominent role in the exposure levels of MRI staff. However, it is not entirely clear what the extent of this contribution is or whether this contribution will have equal significance in all workplace scenarios.

The overall aim of our study was to identify to what extent various work-related and personal factors are associated with an MRI worker's exposure to SMF and TVMF. Using portable magnetic field dosimeters, we measured personal shift-based exposure to MRI-related

[1]Institute for Risk Assessment Sciences, Division of Environmental Epidemiology, Utrecht University, Utrecht, the Netherlands.
[2]Département des sciences de la santé communautaire, Université de Sherbrooke, Sherbrooke, Canada
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*Correspondence to: Hans Kromhout, Institute for Risk Assessment Sciences, Utrecht University, P.O. Box 80178, 3508 TD Utrecht, The Netherlands. E-mail: h.kromhout@uu.nl
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SMF and TVMF among MRI staff and other individuals working with or near MRI scanners (researchers, physicians, cleaners, etc.). Simultaneously, auxiliary information was collected at various levels (personal, workplace, and activity) by means of questionnaires and work shift logbooks. Other data from these logbooks (e.g., scanner type and field strength; symptoms reported during shift) have previously been used in a study on MRI-related symptoms among the same study population (4). The SMF and TVMF exposure levels that were measured and their variability within and between workers have previously been reported elsewhere (25). In the current study, information from the questionnaires and logbooks was linked to measured exposure levels and was used to develop empirical statistical models for various metrics of full-shift SMF and TVMF exposure.

METHODS

Workplace Selection and Study Population

From the approximately 150 different MRI facilities in the Netherlands (27), 14 facilities were selected for an exposure survey. MRI facilities were selected to include a large set of potential exposure determinants. The selection included MRI facilities in general hospitals, academic hospitals, and research institutes that scanned humans (either patients or volunteers) or animals—and that employed different types of MRI installations in terms of scanner field strength, scanner design, and shielding. Each facility was visited for 1 or 2 weeks, depending on the size of the MRI department. Employees who worked near the MRI scanner were asked to participate in the study. These were mainly MRI radiographers and MRI researchers but also included clinical, technical, and maintenance staff. The study was approved by the Medical Research Ethics Committee of the Utrecht University Medical Center, Utrecht, The Netherlands, and each participant signed a consent form prior to participation.

Measurement Strategy and Data Collection

Personal shift-long measurements of exposure to static magnetic fields (B, in mT) and motion-induced time-varying magnetic fields (dB/dt, in mT/s) in three orthogonal directions (x, y, z) were collected at a sampling rate of 50 Hz using portable magnetic field dosimeters (Magnetic Field Dosimeter, University of Queensland, St Lucia, QLD, Australia). A more detailed description of the measurement devices can be found in two other publications (18,25). The dosimeter was secured to the chest with an elastic strap, and participants were asked to wear it during at least 1 day. When a participant's work schedule allowed, repeated measurements (i.e., multiple shifts per participant) were obtained in order to assess exposure variability. In cases for whom full-shift measurements were not feasible, for example, when a participant's duties involved departing from the MRI facility, the participant was measured during the time at the MRI facility.

Each participant completed a general questionnaire including questions on job title, gender, age, body height, and number of years working with MRI. Participants were also provided with logbooks, where they registered which tasks were performed during the measurements. This also included questions about the duration of the work shift, the MRI scanners that a person had worked with, the type and number of patients that had been scanned (e.g., sedated patient), the type and number of scan procedures performed, and additional tasks that took place inside the MRI scanner room (e.g., contrast medium administration).

Data Handling and Exposure Metrics

The original sampling rate of 50 Hz was compressed to 10 measurement values per second. Based on these data, three summary metrics of personal SMF exposure during the work shift were calculated for personal exposure to both B and dB/dt: 1) instantaneous peak exposure (*peak*); 2) time-weighted average (TWA) exposure averaged over the total duration of the shift (*full-shift TWA*); and 3) TWA exposure averaged only over the time that a worker was exposed to a SMF (*SMF-exposed TWA*). This latter metric is representative of the average exposures during the exposed periods and cannot be obtained from a full-shift TWA metric, which is often defined by long unexposed periods. By means of maximum likelihood imputation, measurement files with an exposure value of 0 mT or 0 mT/s (0.5%–7.3% of the files, depending on the exposure metric) were attributed a random value between the lowest nonzero value and a value a factor 10 lower (28). A detailed description of the handling of the exposure measurement has been described in a previous publication (25).

Model Development

The measured exposure data of participants were linked to their complementary contextual information from the logbooks and general questionnaire and analyzed by linear mixed effects models, assuming a compound symmetry covariance structure (using PROC MIXED in SAS 9.4; SAS Institute Inc., Cary, NC). The study includes repeated measurements on the same study participants, with an unequal number of observations per subject (i.e., unbalanced data). Linear mixed effects models are suitable for the analysis of unbalanced datasets with correlated (e.g., repeated) measurements (29). Work practices differ strongly between animal research MRI facilities and human clinical and research MRI facilities. Therefore, separate models were developed for these two groups. The exposure data in our study followed a log-normal distribution; therefore, we log-transformed the exposure data before including them in the models. Linear mixed effects models were developed for each exposure metric, with the natural log-transformed exposure level as the dependent variable, and the MRI facility, job, and subject incorporated as random effects. The equations defining the model structure are provided in the online Supporting Appendix S1.

In the linear mixed effects models, β is the regression coefficient for the natural log-transformed exposure metric. The exponential function $\exp(\beta)$, or e^{β}, gives the effect on the untransformed exposure metric, which is to be interpreted in a multiplicative manner.

When TWA exposure metrics were modeled, the independent variables considered for inclusion in the final models were scanner-related variables; binary variables describing procedures or tasks; ordinal frequency variables that described how often different tasks or procedures were performed; and personal or measurement-related factors such as gender, age, body height, years of work experience, and measurement day. For models with peak exposure as dependent variable, frequency variables were omitted, but an additional variable that described the total number of scan procedures was added. This was to control for the possibility that a higher number of scan procedures might increase the probability of experiencing a high instantaneous peak exposure. When three or fewer different values had been reported for a frequency variable, this resulted in limited contrast in exposure frequencies; therefore, the frequency variable was omitted from analysis. Additionally, when a task or procedure had been reported during less than 10 shifts, the frequency variable was omitted from analysis. Thus, in both cases only the binary variable of the procedure was considered.

The scanner-related variables included scanner type and scanner field strength for models of human MRI applications. Although upright scanners can be considered as a variant of open scanners, both types were considered here as individual and distinct categories. For models of animal research, MRI applications scanner orientation, scanner field strength, and SMF shielding were used. During 10% of all shifts, participants had worked with multiple scanners. To be able to analyze the linear effect of scanner strength, we used a numerical variable that represented the highest field of all scanners that a person had worked with during the monitored shift. The most commonly reported scanner strength (1.5 T for human MRI facilities, 9.4 T for animal research MRI facilities) was chosen as a reference scanner strength value in the linear mixed effects models. This means that the effect estimate of field strength is given as the change in exposure level per tesla increase from 1.5 T or 9.4 T, respectively.

Each model was built up from an original base model that contained only the scanner-related factors. The remaining work-related factors were subsequently added to this base model, and the effect of each factor on the model, as assessed by the P value of the fixed effect and the Akaike Information Criterion (AIC), was noted. The factor with the most significant contribution was included into the model, provided that the following criteria were satisfied: the contribution of the factor to the model was significant on an alpha level of 5% ($P < 0.05$); the model fit improved (AIC reduction of at least 2 points); and the direction of effect for factors already included in the model did not change. Furthermore, some additional rules were used: factors that correlated strongly ($r > 0.6$ or < -0.6) were not jointly included; and the binary and frequency variable of the same exposure determinant were not jointly included. The addition of exposure determinants in this supervised step-by-step selection process was repeated until there were no remaining factors with a statistically significant effect and model improvement of AIC with more than 2 points. After inclusion of the work-related factors, this process was repeated for the personal and measurement-related factors. Model selection was done using the maximum likelihood estimation method for the covariance parameters, and the final models were refit with restricted maximum likelihood.

Given the exploratory nature of this study, we decided to additionally include variables of tasks and procedures that had a relatively large effect on exposure levels, even if they did not reach their statistical significance ($P > 0.05$). Therefore, statistically nonsignificant factors increasing or decreasing exposure levels with a factor 1.5 (50%) or more (i.e., fixed effect regression coefficient (β) for the log-transformed exposure levels must be > 0.41 or < -0.41) were also kept in the final models.

RESULTS

Between March 2011 and February 2012, a total of 439 personal SMF-exposure measurements were collected. Measurement files that were damaged (n = 23), measurements of unexposed shifts (n = 9), and measurement files for which a logbook was unavailable (n = 1) or crucial information on potential exposure affecting factors was missing (n = 66) were excluded from analysis. In addition, exposure measurements were excluded from the analysis when less than 50% of the actual time spent at the MRI facility had been measured (n = 16). This left 324 measurements from 224 subjects (Fig. 1), including repeated measurements from 37% of the participants. Measurement durations varied from 5 minutes to 12.3 hours, with an average of 6.2 hours. Workplaces and participants are described in Table 1. Tables 2 and 3 describe the variables that were considered as determinants in the linear mixed models of the human and animal MRI applications, respectively. The total range and mean of measured exposure levels can be found in Table 4, showing that exposure levels were higher and the range of exposure levels wider at human MRI facilities compared to animal research MRI facilities.

Human MRI Applications

Tables 5.a and 5.b show the linear mixed effects models of B and dB/dt exposure metrics, respectively, for the human clinical and research MRI facilities (n = 275). Confidence intervals (CIs) of 95% for the regression coefficients are included in the online Supporting Tables S1.a and S1.b. The models were able to explain 47% to 76% of the total variability in B exposure and 27% to 40% of the total variability in dB/dt exposure. Furthermore, the models were better able to explain TWA exposure than peak exposure.

Scanner type was a significant determinant of all three metrics of B and dB/dt exposure. In comparison to 1.5 T closed-bore scanners, working with extremity scanners of 1.0 or 1.5 T was associated with 73% to 97% lower exposure levels, depending on exposure metric. On the contrary, upright scanners of 0.6 T were associated with 1.26 to 4.18 times higher exposure levels than 1.5 T closed-bore scanners. Even in comparison to 3.0 T closed-bore scanners, exposure levels at 0.6 T upright scanners were higher for all metrics but peak B. Working

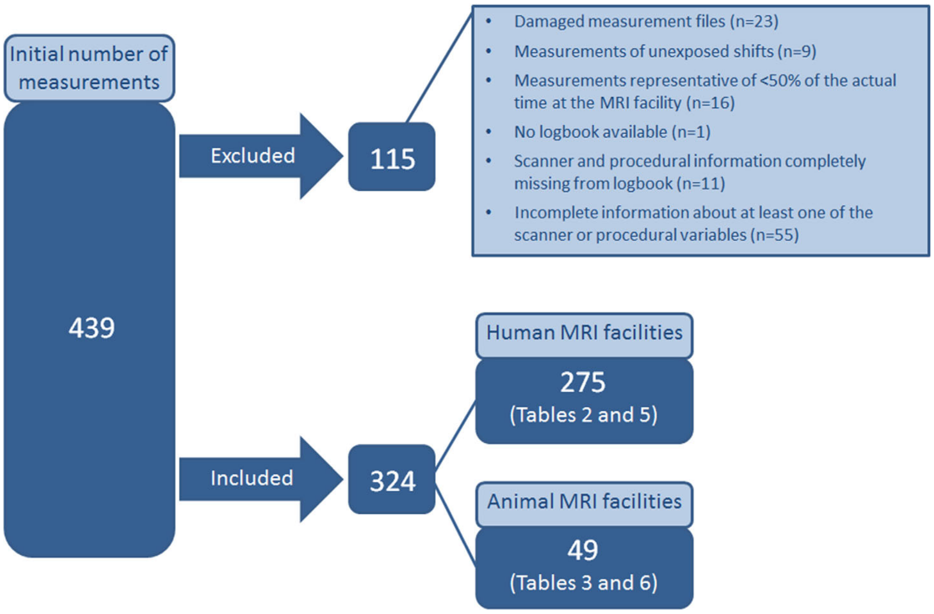

FIG. 1. Overview of number of measurements collected, excluded, and included in the statistical modeling.

with an open-bore scanner did not result in significantly different exposure levels than working with other scanners. Among human MRI facilities, the effect of scanner strength could only be analyzed for closed-bore scanners due to limited variety in scanner strength of other scanner models. There was a strong and statistically significant positive effect of scanner strength on all exposure metrics, with a 30%, 38%, and 61% increase in peak B, SMF-exposed TWA B, and full-shift TWA B, respectively, per tesla increase (from 1.5 T) in scanner strength. For dB/dt, the association with scanner field strength was even stronger, with a 36%, 57%, and 76% increase in exposure per tesla increase (from 1.5 T) in scanner strength, respectively.

There was a 10% increase in full-shift TWA B and dB/dt exposure with each additional human scan procedure. Workers who performed functional MRI (fMRI) scans had a 20% increase in full-shift TWA dB/dt exposure for each fMRI procedure. Furthermore, peak exposures were positively associated with the total number of scan procedures performed (3% and 4% increase in peak B and dB/dt, respectively, per scan procedure).

The influence of specific procedures and tasks on exposure varied considerably per metric. Peak B exposure level was significantly associated with (contrast) medication administration. SMF-exposed and full-shift TWA B, on the other hand, were significantly associated with other procedures and tasks. For example, scanning a high-care patient was positively associated with full-shift TWA B exposure, and the number of IV placements inside the scanner room showed a negative association with SMF-exposed TWA B exposure. Performance of MR-guided interventions had a large significant effect on peak and full-shift TWA dB/dt exposure. This procedure was also positively but not statistically significantly associated with SMF-exposed dB/dt. Both TWA dB/dt exposure metrics increased with every procedure, during which anesthetics and/or associated monitoring was required. Furthermore, administering contrast or medication inside the scanner room was associated with an increase in all metrics of B exposure and full-shift TWA dB/dt. Cleaning the scanner room was significantly associated with a large decrease in exposure for both TWA B metrics.

Table 1
Workplaces and Participants Included in the Analysis

		N
Type of Workplace	General hospital	4
	Academic hospital	4
	Academic children's hospital	1
	Human neuroscientific research institute	1
	Experimental animal research facility	4
	Total	14
Participants' Job Title	Radiographer, radiography student, or intern	103
	Medical doctor or medical specialist (including radiographers)	3
	Anesthesiology staff	17
	Scientist, researcher, research student	90
	Technical staff (medical, maintenance) and medical physicists	3
	Lab assistant or lab technician	3
	Cleaner	5
	Total	224

Table 2
Variables Considered as Determinants for the Linear Mixed Effects Models of MRI Applications Among Human Clinical and Research MRI Facilities

Variable Name	Categories	$N_{nonmiss}$ [a]	N_{bin} [b]	Median (range)	Description
Scanner Variables					
highestfield		275		1.5 (0.5–7.0)	Highest scanner field strength (in tesla [T]) during one work shift. Reference value is 1.5 T.
scanner_closed		275	259		Closed-bore (0.5 T, 1.5 T, 3.0 T, 7.0 T) scanner
scanner_open		275	12		Open-bore (1.0 T) scanner
scanner_extrem		275	4		Extremity (1.0, 1.5 T) scanner
scanner_up		275	10		Upright (0.6 T) scanner
Scan Procedures					
proc_total [c]		275	269	7 (0–18)	Total number of scan procedures performed during shift, irrespective of type
proc_human		275	256	7 (0–18)	Total number of scan procedures on human subjects
proc_anatomic		275	192	6 (0–18)	Standard diagnostic anatomic scans
proc_angio		275	37	0 (0–4)	MR angiography scans
proc_cardiac		275	29	0 (0–10)	Cardiac MRI scans
proc_fmri		275	49	0 (0–8)	Functional MRI scans
proc_imri		275	3	0 (0–5)	MR-guided interventions
proc_brachytherapy		275	3	0 (0–2)	MR-guided brachytherapy
proc_incubator		275	5	0 (0–2)	Scanning newborn in special MRI-adapted incubator
proc_testscan		275	40	0 (0–9)	Test scans on phantom or volunteer for development or optimization of protocols and procedures
proc_specimen		275	3	0 (0–1)	Ex vivo specimen scans
Other Procedures					
preparation		275	199	3 (0–21)	Standard preparation of scanner room for next scan procedure (e.g., replacing coils and bed linen)
pump		275	76	0 (0–8)	Building up, filling, or emptying contrast pump
cleaning_regular		275	70	0 (0–4)	Regular tidying up or cleaning of scanner, scanner bed, or scanner room (e.g., at end of day)
cleaning_thorough		275	3	0 (0–1)	Thorough cleaning of scanner room, including scanner and scanner bore (e.g., at end of week, or after a patient who requires contact isolation)
cleaning_cleaner		275	5	0 (0–3)	Cleaning scanner room by a cleaner
repairs [d]		275	5		Repairs inside scanner room
dressing [d]		275	2		Putting on protective clothing before handling patients who require contact isolation
troubleshoot [d]		275	4		Spending extra time inside scanner room for troubleshooting because of technical failure or defects
Number of Scan Procedures During Which Scanner Room Was Entered to ...					
task_IV		275	85	0 (0–11)	Inject an IV cannula (or assist a colleague doing so)
task_contrast		275	114	0 (0–12)	Administer contrast medium or medication (e.g., by manual injection)
task_monitoring		275	62	0 (0–8)	Attach electrocardiogram, vectorcardiogram, or other monitoring appliances to patient/volunteer
task_anesth		275	22	0 (0–8)	

(Continued)

TABLE 2. *Continued*

Variable Name	Categories	$N_{nonmiss}$ [a]	N_{bin} [b]	Median (range)	Description
					Apply anesthetics and/or associated monitoring appliances to patient/volunteer
task_rectalgel		275	6	0 (0–5)	Apply rectal gel to patient/volunteer
task_rectalcoil		275	6	0 (0–2)	Place a rectal coil
task_bloodsample		275	2	0 (0–2)	Collect a blood sample from patient/volunteer
task_salivasample		275	2	0 (0–1)	Collect a saliva sample (swab) from patient/volunteer
task_equipment		275	29	0 (0–8)	Attach peripheral equipment for experimental applications (e.g., button box, eye tracking device, camera, tactile stimulus, etc).
Specific Patient Types					
pt_anesth		275	27	0 (0–8)	Anesthetized patients
pt_sedated		275	7	0 (0–1)	Sedated patients
pt_highcare		275	78	0 (0–7)	Patients who needed extra care, attention, or instructions (e.g., immobile, young, or anxious patients)
Personal Information					
gender	Female		162		
gender	Male		113		
age		266		33.1 (19.1–62.2)	Age (in years)
agecat	1		133		Age 18–33 years
agecat	2		102		Age 33–49 years
agecat	3		31		Age 49–65 years
bodyheight		266		174 (153–200)	Body height (in cm)
MRItotalyears		236		3.9 (0–30.1)	Years of MRI experience since start of MRI work
MRIcumyears		236		3.5 (0–30.1)	Cumulative years of MRI experience, excluding periods of non-MRI work
Other					
dosimeter		275			ID of dosimeter that was used for measurement
dosimeter_moved		275	6		The dosimeter had moved/slid down while inside scanner room
Weekend		275	17		Measurement during weekend

[a]$N_{nonmiss}$ = total number of measurements for which information about variable was available.
[b]N_{bin} = number of measurements for which binary variant of variable was positive (i.e., shifts during which specific task, procedure, or characteristic occurred).
[c]Total number of scan procedures was included as potential exposure modifier in models for peak exposure only. Was 0 for all five cleaners and for one radiographer who had only prepared scanner room but was not involved in any scan procedures.
[d]Only binary variant of variable available

Animal Research MRI Applications

Tables 6.a and 6.b show the linear mixed effects models for the animal research MRI facilities (n = 49). Confidence intervals of 95% for the regression coefficients are included in the online Supporting Tables S2.a and S2.b. Job title was excluded from the random effects because the models showed no exposure variation between jobs. The models were able to explain 29% to 43% of the total variability in B exposure and 2% to 52% of the total variability in dB/dt exposure. With only 9.9% and 1.5% of the total exposure variability explained, peak and SMF-exposed TWA dB/dt exposure variability could hardly be predicted by the information in the models.

The field strength of the scanners had a negative association with all exposure metrics but SMF-exposed TWA B. Exposure levels were reduced by 16% to 41% for each tesla increase in scanner strength (from 9.4 T). Working with a scanner that was not actively shielded increased the peak B, SMF-exposed TWA B, and full-shift TWA dB/dt exposure. Full-shift TWA B exposure increased with the number of times the coils were tuned and the number of times the scanner was cleaned, whereas full-shift TWA dB/dt exposure increased with the number of times a sample was prepared. Unlike the models for human MRI applications, no associations were found between peak exposure metrics and total number of scan procedures per shift. Furthermore, preparation of the scanner was positively associated with peak B, peak dB/dt, and full-shift TWA B. Positioning of the sample/animal was associated with increased levels

Table 3
Variables Considered as Determinants for Linear Mixed Effects Models of MRI Applications Among MRI facilities for Experimental Animal Research

Variable Name	Categories	$N_{nonmiss}$ [a]	N_{bin} [b]	Median (range)	Description
Scanner Variables					
orientation_horizontal		49	39		Scanner bore is horizontally oriented
orientation_vertical		49	10		Scanner bore is vertically oriented
unshielded		49	27		At least one of scanners participant worked with during this shift had a magnet that was not actively shielded off.
highestfield		49		9.4 (4.7–11.7)	Highest scanner field strength (in tesla [T]) during one work shift. Reference value is 9.4 T.
Scan Procedures					
proc_total [c]		49	47	1 (0–10)	Total number of samples that were scanned
proc_invivo		49	33	1 (0–10)	Scans on live animal (mouse or rat)
proc_exvivo		49	16	0 (0–3)	Scans on ex vivo sample (e.g., postmortem animal, animal organ, or phantom)
Other Procedures Performed Inside Scanner Room					
preparation_scanner		49	37	1 (0–10)	Preparation of scanner before start of scan procedure
preparation_material		49	31	1 (0–8)	Preparation of materials that will be used during scan procedure (e.g., tubes, probes, measurement devices, syringes)
preparation_ sample		49	34	1 (0–10)	Preparation of sample and positioning of sample on tray outside scanner
positioning_sample		49	37	2 (0–12)	Sample positioning into bore
removal_sample		49	34		Sample removal from bore
attach_monitoring		49	27	1 (0–10)	Attaching monitoring devices to sample
adjust_monitoring		49	16	0 (0–26)	Adjust monitoring parameters such as ventilation or anesthesia
tuning		49	37	2 (0–10)	Tuning radiofrequency coils
injection		49	14	0 (0–11)	Injecting contrast medium or other substance
cleaning_scanner		49	11	0 (0–3)	Cleaning scanner and tray on which sample is placed
cleaning_surroundings		49	23	0 (0–5)	Cleaning surroundings of scanner or material that was used
fillcryogen		49	2	0 (0–1)	Refill liquid cryogenic substances
repairs		49	2	0 (0–4)	Repairs inside scanner room
surgery		49	3	0 (0–2)	Surgery inside scanner room
hands_in_bore		49	19	0 (0–10)	Subject reported to have put hands inside scanner bore
Personal Information					
gender	Female	16			
gender	Male	33			
age		49		31.5 (24.8–64.8)	Age (in years)
agecat	1	33			Age 18–33 years
agecat	2	14			Age 33–49 years
agecat	3	2			Age 49–65 years
bodyheight		49		179 (158–197)	Body height (in cm)
MRItotalyears		43		3.6 (0.5–21.0)	Years of MRI experience since start of MRI work
Other					
dosimeter		49			ID of dosimeter used for measurement
dosimeter_moved		49	0		The dosimeter had moved/slid down while inside scanner room
weekend		49	0		Measurement during weekend

[a] $N_{nonmiss}$ = total number of measurements for which information about variable was available.
[b] N_{bin} = number of measurements for which binary variant of variable was positive (i.e., shifts during which specific task, procedure, or characteristic occurred).
[c] Total number of scan procedures was included as potential exposure modifier in models for peak exposure only. Was 0 for a researcher who only refilled cryogenic fluid and for a researcher who performed surgery on an animal inside scanner room.

Table 4
Geometric Mean and Range of Measured Exposure Levels for Six Different Exposure Metrics

Exposure Metric	Human Clinical and Research MRI Facilities (n = 275)	MRI Facilities for Experimental Animal Research (n = 49)
Peak B (mT)	523.32 (13.00–2661.10)	133.41 (5.58–604.50)
Peak dB/dt (mT/s)	787.47 (0.48–5015.92)	143.28 (0.43–1280.67)
Full-shift TWA B (mT)	3.25 (0.02–39.90)	1.03 (0.04–26.90)
Full-shift TWA dB/dt (mT/s)	0.61 (0.00–12.72)	0.09 (0.00–3.80)
SMF-exposed TWA B (mT)	69.06 (5.00–956.00)	28.76 (1.35–158.00)
SMF-exposed TWA dB/dt (mT/s)	12.68 (0.06–258.40)	2.02 (0.04–95.80)

SMF, static magnetic field; TWA, time-weighted average.

of SMF-exposed TWA B. Tuning the coils was associated with higher full-shift TWA dB/dt.

Personal and Measurement-Related Factors

Measurement-related factors (dosimeter, movement of dosimeter, weekend) were not associated with measured exposure levels in any of the models. Because information on personal characteristics (body height, age, gender, MRI experience) was not available for all 224 individuals, we analyzed the effect of personal characteristics in a subset of participants with this information available. For human MRI facilities, the effect of body height was statistically significant in the models for peak B and SMF-exposed TWA B and dB/dt, with an approximate 1% decrease in exposure for each cm of body height. In the models for animal MRI facilities, body height was significantly associated with a 3% to 7% decrease per cm in all exposure metrics but full-shift TWA B. The resulting models, based on the observations for which body height data was available, can be found in the online Supporting Tables S3 and S4, and the associated 95% CIs for the regression coefficients are can be found in the online Supporting Tables S5 and S6.

DISCUSSION

This study assessed how personal and work-related factors relate to shift-based exposures to static magnetic fields and motion-induced low-frequency time-varying magnetic fields at clinical and research MRI facilities. Previous studies that measured or estimated magnetic field exposure levels of clinical and research MRI staff found that the strength of a scanner was sometimes insufficient to predict exposure ranking, and that exposure levels were additionally determined by work practices such as the number or type of tasks performed (16,18,23,30). The current study was able to quantify the unique contribution of several of these factors at the same time under real work conditions, while adjusting for the presence of other factors related to exposure. The selection of exposure metrics was based on several considerations. Research on (health) effects of MRI-related static magnetic fields has mainly focused on acute short-term physiological, sensory, and neurocognitive effects (4–6,31,32). Peak exposure might be a relevant exposure metric for acute health effects from SMF exposure. This metric is based on an instantaneous exposure level during a single point in time, and is therefore sensitive to infrequently occurring high-exposure situations such as a single bending motion into a magnet bore. The time-weighted average of all exposure events during a shift will provide insight into the overall exposure level of a worker during an entire shift. This SMF-exposed TWA metric is determined by the intensity as well as the duration and frequency of exposure events. The full-shift TWA, on the other hand, is additionally determined by the duration of nonexposure events during a shift. Despite the fact that each exposure metric is sensitive to different exposure patterns, a previous study on the same exposure measurement data (25) revealed that all three metrics are considerably correlated for shift-based measurements of B (Pearson $r = 0.69–0.71$) as well as dB/dt (Pearson $r = 0.70–0.78$). Nevertheless, in the models presented here, associations of several work-related factors with exposure values behaved differently for the different metrics.

Human MRI Applications

The design of an MRI scanner, as well as the flux density of its magnet (here referred to as the *scanner strength*) characterize an MRI worker's exposure levels. The low exposure levels associated with extremity scanners can be explained by their small bore diameter and effective containment of their magnetic stray fields. Working with upright human scanners, on the other hand, requires radiographers to stand right between the magnet coils while placing the patient in the scanner, resulting in the higher exposure levels observed with these 0.6 T scanners compared with 1.5 T or even 3.0 T closed-bore scanners. The effect of scanner strength could be examined for closed-bore scanners only, due to the limited variety in scanner strength of other scanner models within human clinical and research MRI departments.

Following the current trend of replacing 1.5 T closed-bore scanners by a 3.0 T version, the results of this study suggest that workers' peak B and dB/dt exposure levels would increase approximately by a factor 1.5, and that TWA exposure levels would increase with a factor of up to almost 2.5. Switching from 3.0 to 7.0 T would even result in TWA exposure levels that are almost a factor 10 higher.

In addition to the scanner characteristics, exposure levels were associated with how often a worker entered a scanner room: The total number of human subjects scanned was a main factor associated with full-shift TWA exposures. This number was different for radiographers, who perform routine scans and scanned on average nine subjects per day compared to research staff,

Table 5.a
Linear Mixed Effects Models of SMF (B) Exposure for MRI Applications Among Human Clinical and Research MRI Facilities (n = 275)

Exposure Metric			Peak B			SMF-Exposed TWA B			Full-Shift TWA B		
Model Variables (fixed effects)	Type[a]	N[b]	β	exp(β)	*P* Value	β	exp(β)	*P* Value	β	exp(β)	*P* Value
Intercept			**4.783**	**119.49**	**<0.01**	**3.778**	**43.74**	**<0.01**	−0.376	0.69	0.40
Scanner											
Variables											
scanner_closed	bin	259	**0.626**	**1.87**	**<0.05**	0.003	1.00	0.99	0.113	1.12	0.74
scanner_open	bin	12	−0.016	0.98	0.94	−0.213	0.81	0.23	−0.261	0.77	0.36
scanner_extrem	bin	4	**−1.131**	**0.32**	**<0.01**	**−1.316**	**0.27**	**<0.01**	**−2.512**	**0.08**	**<0.01**
scanner_up	bin	10	**0.854**	**2.35**	**<0.01**	**0.696**	**2.01**	**<0.01**	**1.270**	**3.56**	**<0.01**
highestfield * scanner_closed [c]	con*bin interaction	259	**0.265**	**1.30**	**<0.01**	**0.320**	**1.38**	**<0.01**	**0.473**	**1.61**	**<0.01**
Scan Procedures											
proc_total	freq	269	**0.030**	**1.03**	**<0.05**						
proc_human	freq	256							**0.098**	**1.10**	**<0.01**
proc_brachytherapy	bin	3				**−0.987**	**0.37**	**<0.01**	−0.450	0.64	0.39
proc_testscan	bin	40				**0.250**	**1.28**	**<0.05**			
proc_specimen	bin	3				−0.504	0.60	0.07	−0.452	0.64	0.31
Other Procedures											
cleaning_thorough	bin	3	0.406	1.50	0.22						
cleaning_cleaner	bin	5	−1.326	0.27	0.08	**−1.623**	**0.20**	**<0.01**	**−2.707**	**0.07**	**<0.01**
Tasks in Scanner Room											
task_IV	freq	85				**−0.051**	**0.95**	**<0.05**			
task_contrast	bin	114	**0.185**	**1.20**	**<0.05**	**0.261**	**1.30**	**<0.01**	**0.343**	**1.41**	**<0.01**
task_rectalgel	bin	6							0.613	1.85	0.05
task_rectalcoil	bin	6				**−0.687**	**0.50**	**<0.01**	**−0.798**	**0.45**	**<0.05**
task_bloodsample	bin	2							0.825	2.28	0.19
task_salivasample	bin	2							**1.279**	**3.59**	**<0.05**
Specific Patient Types											
pt_highcare	bin	78							**0.262**	**1.30**	**<0.05**
Variance Components of Random Effects			Empty Model[d]	Full Model[e]	%[f]	Empty Model[d]	Full Model[e]	%[f]	Empty Model[d]	Full Model[e]	%[f]
Between facilities			0.04	0.00	97.4%	0.05	0.01	85.2%	0.11	0.00	99.6%
Between jobs			0.82	0.38	53.3%	0.77	0.15	80.4%	2.27	0.15	93.4%
Between subjects			0.23	0.16	28.0%	0.26	0.09	65.8%	0.68	0.39	43.3%
Residual (day-to-day)			0.29	0.19	36.3%	0.23	0.14	38.9%	0.59	0.32	45.2%
Total			**1.38**	**0.73**	**46.9%**	**1.32**	**0.39**	**70.4%**	**3.65**	**0.86**	**76.4%**

Bold font in the upper part of this table represents statistically significant effects ($p < 0.01$ and $p < 0.05$).
SMF, static magnetic field; T, tesla; TWA, time-weighted average.
[a]Variable type: bin = binary, freq = frequency, con = continuous.
[b]Number of shifts during which factor was reported.
[c]Effect per tesla difference from 1.5 T.
[d]Model with only random effects.
[e]Model with fixed and random effects.
[f]Percentage of variance explained by fixed effects in final model.

Table 5.b
Linear Mixed Effects Models of TVMF (dB/dt) Exposure for MRI Applications Among Human Clinical and Research MRI Facilities (n = 275)

Exposure Metric			Peak dB/dt			SMF-Exposed TWA dB/dt			Full-Shift TWA dB/dt		
Model Variables (fixed effects)	Type[a]	N[b]	β	exp(β)	P Value	β	exp(β)	P Value	β	exp(β)	P Value
Intercept			**4.730**	**113.29**	**<0.01**	0.640	1.90	0.36	**−3.521**	**0.03**	**<0.05**
Scanner Variables											
scanner_closed	bin	259	**0.667**	**1.95**	**<0.05**	0.664	1.94	0.07	0.722	2.06	0.07
scanner_open	bin	12	−0.071	0.93	0.80	−0.332	0.72	0.30	−0.313	0.73	0.35
scanner_extrem	bin	4	**−1.237**	**0.29**	**<0.01**	**−1.763**	**0.17**	**<0.01**	**−2.642**	**0.07**	**<0.01**
scanner_up	bin	10	**1.217**	**3.38**	**<0.01**	**1.654**	**5.23**	**<0.01**	**2.153**	**8.61**	**<0.01**
highestfield * scanner_closed [c]	con*bin interaction	259	**0.305**	**1.36**	**<0.01**	**0.450**	**1.57**	**<0.01**	**0.564**	**1.76**	**<0.01**
Scan Procedures											
proc_total	freq	269	**0.037**	**1.04**	**<0.05**						
proc_human	freq	256							**0.098**	**1.10**	**<0.01**
proc_fmri	freq	49							**0.185**	**1.20**	**<0.05**
proc_imri	bin	3	**1.007**	**2.74**	**<0.05**	0.459	1.58	0.36	**1.379**	**3.97**	**<0.01**
proc_brachytherapy	bin	3	−0.710	0.49	0.15	**−1.472**	**0.23**	**<0.05**	−0.469	0.63	0.47
Other Procedures											
preparation	bin	199	**0.296**	**1.34**	**<0.05**						
cleaning_cleaner	bin	5	−0.413	0.66	0.70				−1.856	0.16	0.26
dressing	bin	2				−0.436	0.65	0.45	−0.440	0.64	0.47
Tasks in Scanner Room											
task_contrast	bin	114							**0.355**	**1.43**	**<0.05**
task_anesth	freq	22				**0.177**	**1.19**	**<0.05**	**0.237**	**1.27**	**<0.05**
task_rectalcoil	bin	6				−0.783	0.46	0.08	−0.624	0.54	0.20
task_bloodsample	bin	2				**−2.020**	**0.13**	**<0.01**	−0.752	0.47	0.34
task_salivasample	bin	2	0.634	1.89	0.26	0.483	1.62	0.47	1.417	4.12	0.06
Variance Components of Random Effects			Empty Model[d]	Full Model[e]	%[f]	Empty Model[d]	Full Model[e]	%[f]	Empty Model[d]	Full Model[e]	%[f]
Between facilities			0.09	0.01	91.8%	0.14	0.05	66.4%	0.19	0.03	81.1%
Between jobs			0.99	0.79	20.0%	1.85	1.45	22.0%	2.89	1.98	31.3%
Between subjects			0.25	0.12	50.8%	0.78	0.42	45.8%	1.14	0.61	46.5%
Residual (day-to-day)			0.57	0.46	18.1%	0.58	0.39	32.1%	0.79	0.39	50.3%
Total			**1.90**	**1.39**	**26.8%**	**3.35**	**2.31**	**31.1%**	**5.00**	**3.02**	**39.6%**

Bold font in the upper part of this table represents statistically significant effects ($p < 0.01$ and $p < 0.05$).
SMF, static magnetic field; T, tesla; TWA, time-weighted average.
[a]Variable type: bin = binary, freq = frequency, con = continuous.
[b]Number of shifts during which factor was reported.
[c]Effect per tesla difference from 1.5 T.;
[d]Model with only random effects.
[e]Model with fixed and random effects.
[f]Percentage of variance explained by fixed effects in final model.

Table 6.a
Linear Mixed Effects Models of SMF (B) Exposure for MRI Applications Among MRI Facilities for Experimental Animal Research (n = 49)

Exposure Metric			Peak B			SMF-Exposed TWA B			Full-Shift TWA B		
Model Variables (fixed effects)	Type[a]	N[b]	β	exp(β)	P-value	β	exp(β)	P-value	β	exp(β)	P-value
Intercept			**4.107**	**60.77**	**<0.05**	2.278	9.76	0.06	−1.383	0.25	0.12
Scanner Variables											
orientation_vertical	bin	10	−1.607	0.20	0.14	−1.433	0.24	0.21	−1.213	0.30	0.24
unshielded	bin	27	**0.787**	**2.20**	**<0.05**	**1.300**	**3.67**	**<0.01**	0.238	1.27	0.56
highestfield [c]	con	49	**−0.212**	**0.81**	**<0.05**	−0.173	0.84	0.09	**−0.377**	**0.69**	**<0.01**
Procedures Performed Inside Scanner Room											
preparation_scanner	bin	37	**0.718**	**2.05**	**<0.01**				**0.829**	**2.29**	**<0.01**
positioning_sample	bin	37				**0.801**	**2.23**	**<0.05**			
tuning	freq	37							**0.161**	**1.17**	**<0.01**
cleaning_scanner	freq	11							**0.384**	**1.47**	**<0.01**
fillcryogen	bin	2	**−0.754**	**0.47**	**<0.05**	−0.526	0.59	0.15			
repairs	bin	2	−0.567	0.57	0.49	−0.751	0.47	0.38	0.687	1.99	0.57
surgery	bin	3				−0.539	0.58	0.19			
Variance Components of Random Effects			Empty Model[d]	Full Model[e]	%[f]	Empty Model[d]	Full Model[e]	%[f]	Empty Model[d]	Full Model[e]	%[f]
Between facilities			0.92	0.64	30.8%	0.66	0.71	−8.7%	0.92	0.45	50.7%
Between subjects			0.85	0.47	44.4%	1.10	0.46	57.6%	1.56	1.10	29.4%
Residual (day-to-day)			0.19	0.10	44.9%	0.12	0.15	−18.2%	0.41	0.10	75.2%
Total			**1.96**	**1.21**	**38.1%**	**1.88**	**1.32**	**29.4%**	**2.89**	**1.66**	**42.7%**

Bold font in the upper part of this table represents statistically significant effects ($p < 0.01$ and $p < 0.05$).
SMF, static magnetic field; T, tesla; TWA, time-weighted average.
[a]Variable type: bin = binary, freq = frequency, con = continuous.
[b]Number of shifts during which factor was reported.
[c]Effect per tesla difference from 9.4 T.
[d]Model with only random effects.
[e]Model with fixed and random effects.
[f]Percentage of variance explained by fixed effects in final model.

Table 6.b
Linear Mixed Effects Models of TVMF (dB/dt) Exposure for MRI Applications Among MRI Facilities for Experimental Animal Research (n = 49)

Exposure Metric			Peak dB/dt			SMF-Exposed TWA dB/dt			Full-Shift TWA dB/dt		
Model Variables (fixed effects)	Type[a]	N[b]	β	exp(β)	P-value	β	exp(β)	P-value	β	exp(β)	P-value
Intercept			3.571	35.56	0.06	0.125	1.13	0.92	**−3.913**	**0.02**	**<0.05**
Scanner Variables											
orientation_vertical	bin	10	−1.007	0.37	0.58	−1.730	0.18	0.41	−2.051	0.13	0.13
unshielded	bin	27	0.327	1.39	0.57	1.277	3.59	0.09	**1.162**	**3.20**	**<0.05**
highestfield [c]	con	49	**−0.533**	**0.59**	**<0.05**	**−0.423**	**0.65**	**<0.05**	**−0.298**	**0.74**	**<0.05**
Procedures Performed Inside Scanner Room											
preparation_scanner	bin	37	**1.219**	**3.39**	**<0.01**	0.795	2.22	0.08			
preparation_ sample	freq	34							**0.200**	**1.22**	**<0.01**
adjust_monitoring	bin	16				−0.801	0.45	0.29			
tuning	bin	37							**1.106**	**3.02**	**<0.01**
injection	bin	14				−0.594	0.55	.16			
fillcryogen	bin	2	−0.621	0.54	0.14	−0.632	0.53	0.32			
repairs	bin	2	−1.188	0.30	0.56				0.777	2.17	0.45
hands_in_bore	bin	19				−0.686	0.50	0.16	−0.601	0.55	0.10
Variance Components of Random Effects			Empty Model[d]	Full Model[e]	%[f]	Empty Model[d]	Full Model[e]	%[f]	Empty Model[d]	Full Model[e]	%[f]
Between facilities			1.01	1.67	−66.1%	1.16	2.56	−121.4%	1.32	0.98	25.4%
Between subjects			4.25	3.18	25.2%	2.82	1.39	50.8%	2.25	0.68	69.9%
Residual (day-to-day)			0.33	0.19	43.6%	0.51	0.47	7.7%	0.36	0.22	38.0%
Total			**5.59**	**5.04**	**9.9%**	**4.49**	**4.42**	**1.5%**	**3.93**	**1.88**	**52.0%**

Bold font in the upper part of this table represents statistically significant effects ($p < 0.01$ and $p < 0.05$).
SMF, static magnetic field; T, tesla; TWA, time-weighted average.
[a]Variable type: bin = binary, freq = frequency, con = continuous.
[b]Number of shifts during which factor was reported.
[c]Effect per tesla difference from 9.4 T.
[d]Model with only random effects.
[e]Model with fixed and random effects.
[f]Percentage of variance explained by fixed effects in final model.

who scanned on average only two human subjects per day. In addition, the total number of scan procedures, irrespective of the type of scan or subject, was positively associated with peak exposure. We hypothesize that this is a direct effect of increased probability of a single high exposure event with each additional scan procedure.

The negative association that was observed between the number of IV placements inside the scanner room and SMF-exposed TWA B exposure might have to do with the fact that, in MRI departments in the Netherlands, two radiographers are involved with each patient. Possibly, the radiographer placing the IV is less involved in tasks that take place nearer to the bore, such as placing the radiofrequency coils. The considerably lower exposure levels associated with general cleaning of scanner rooms are possibly due to focus of the cleaning staffs' activities on the floor and waste bins at a certain distance from the scanner bore. Also, cleaning staff's activities within a scanner room usually lasted only a few minutes per day, resulting in very low full-shift TWA exposure levels.

Animal Research MRI Applications

Different effects were observed near small-bore scanners at animal research MRI facilities. A striking result was that field strength of the scanners was negatively associated with five exposure metrics and showed similar negative but statistically nonsignificant trends for the remaining metric, even when scanner shielding and orientation were taken into account. We are unable to explain this association, but it possibly suggests that local work practice and design of the MRI facility play a more important role.

General Discussion

Depending on exposure metric, 2% to 76% of the exposure variability could be explained by a limited amount of information about scanners, scan procedures, and tasks. Overall, the collected information was better able to account for exposure variability among human-oriented MRI facilities than among animal research MRI facilities. This is possibly determined by the following observations: First, as depicted in Table 4, the range of exposure levels at animal MRI facilities was smaller compared to human MRI facilities. Second, animal research facilities were very different from one another with respect to the work organization (e.g., number of workers sharing tasks), the physical settings of the MRI scanner rooms (e.g., size of the room, distance of control panels from the scanner bore, access to the coils), and the equipment used (presence or absence of a tray to install the animal before introducing it into the scanner vs. preparation outside of the room). The distance from the scanner bore that is necessary to perform specific tasks, as well as the duration of these tasks, are to a large extent explained by local organization parameters that are difficult to measure. This is confirmed by a larger contribution of between-facility variance to the overall exposure variability and a lower percentage of between-facility variance that was explained by the fixed effects, as compared to the models for human clinical and research MRI facilities.

The fact that SMF (B) exposure variability could be better explained than TVMF (dB/dt) exposure variability was expected; dB/dt exposure is more sensitive to differences in personal behavior such as movement patterns around MRI scanners. Not all exposure variability could be explained by the factors in our models. Unexplained variability can be attributed to multiple factors. First of all, with the questionnaire and logbook, we were unable to assess differences in personal behavior, movement patterns, and speed of movement. Second, not all work practices have been included in our data collection and model development. For example, we could have differentiated between contrast administration procedures requiring different distances from the scanner bore. Third, residual variability can be attributed to measurement error due to the quality of the exposure measurements or the validity of the responses in the logbook and questionnaire.

Although the model outcomes reveal which work-related factors are associated with—and therefore might be potentially driving—workers' exposure levels, the results do not necessarily imply a causal relation because effects may be based on unmeasured confounders. For example, in contrast to scanners of lower field strength, most work at 7.0 T closed-bore scanners was done by researchers, and scan procedures performed at these scanners were different because they included procedures related to research and development. In addition, 7.0 T closed-bore scanners were passively shielded, whereas the other closed-bore scanners were actively shielded. As a consequence, one should be aware that the effect estimates of scanner field strength may not be determined purely by flux density of the magnet but also by confounding work practice and shielding. For this reason, extrapolation of modeling results outside the range and combination of variables included in our models, for example, scanners with magnets >7.0 T, is not advised. Similarly, generalization of the model estimates to other countries should be done with caution. Comparable studies are needed to assess similarities and differences in MRI exposure determinants across countries. On the other hand, variability in average exposures between MRI facilities was close to zero among human clinical and research MRI facilities. This suggests that our models could be applied to other human clinical and research MRI facilities in the Netherlands.

The body height of the MR worker showed a negative association with exposure for multiple metrics in both types of MRI departments. Although the effect of body height was not statistically significant for all exposure metrics, the effect size was similar for each metric. In this study, the dosimeter was placed at the participants' chest. The results suggest that the chest of the taller workers is further away from the strong SMF and spatial field gradients just outside the edges of the scanner bore. Consequently, in order to estimate workers' exposure for the upper body or head by means of information about the work performed, the height of the worker should be taken into account. The reported effect estimates of body height are driven by the closed-bore scanners among human clinical and research MRI facilities and by horizontal small-bore scanners among animal research MRI facilities because these scanner types comprise the largest groups. Although one can assume that the effect of body height on exposure levels will depend on scanner design, the numbers of observations were too small to separately analyze the effect of body height for each specific scanner type.

Because the present amount of available literature on determinants of occupational exposure to MRI-related SMF and TVMF is almost nonexistent, this study was used to explore general trends and identify potentially influential factors. Therefore, factors that were strongly but not statistically significantly associated with one or more of the exposure metrics were also included in the model results tables. Some factors, such as scanner characteristics and cleaning of the scanner room, were statistically significantly associated with several metrics yet additionally showed a nonsignificant but similar effect size for the remaining metrics. In addition, occasionally reported tasks and procedures, such as taking a saliva ($n = 2$) or blood sample ($n = 2$), administering a rectal coil ($n = 6$) or rectal gel ($n = 6$), performing brachytherapy ($n = 3$) or MR-guided interventions ($n = 3$), and cleaning the scanner bore ($n = 3$) were associated with strong increases or decreases in one or more exposure metrics when human subjects were scanned. However, not all of these associations were statistically significant. At animal research facilities, performing repairs inside a scanner room ($n = 2$), injecting contrast medium or other substances ($n = 14$), performing surgery inside a scanner room ($n = 3$), and filling cryogenics ($n = 2$) all had strong positive or negative associations with one or more exposure metrics, but not all of these associations were statistically significant. Caution should be taken when interpreting these statistically nonsignificant model parameters. However, the large effect sizes of these factors make them interesting for further study because these infrequently occurring tasks are potentially influential factors and might become more frequent in the future. For example, MR-guided interventions ($n = 3$), which have included prostate and breast biopsies in our study sample, were significantly associated with strongly increased peak and full-shift TWA dB/dt exposure levels. A statistically nonsignificant but strong positive association with SMF-exposed TWA dB/dt was also observed. These results suggest that MR-guided interventions require a lot of movements near the patient who lies on the scanner table.

To get a better impression of the impact of infrequent procedures on the models, we performed sensitivity tests by running the models without variables for which less than 10 observations were available (results not shown), and we observed that changes in regression coefficients and standard errors for the remaining fixed factors were minimal.

Further task-based exposure measurements will be needed to confirm exposure levels of individual procedures and tasks emerging as potential exposure determinants, especially those occurring infrequently. Close observations of these activities are required to determine how exactly they affect exposure patterns: Do some of these procedures occur at close proximity to the scanner bore? Do they require additional movements or relatively higher movement speeds? Do they increase the time spent near the scanner? Getting answers to these questions will allow for better identification of the factors that contribute to higher exposure levels. This might eventually aid the development of guidance to reduce peak and average exposure for workers working with and around MRI-scanners.

CONCLUSION

This study quantifies and compares the combined associations of scanner characteristics, work practices, and personal characteristics with exposure to static magnetic fields and motion-induced low-frequency time-varying magnetic fields of clinical and research MRI staff and others working in these environments. The models highlight specific MRI workplace characteristics and scan activities that are associated with higher exposure levels of individuals working with and around MRI scanners, and reveal that levels of personal exposure at animal research MRI facilities are associated with different factors than at human clinical and research MRI facilities. Despite high correlations between the exposure metrics (25), the measures of peak and time-weighted average exposure were differently associated with specific tasks and scan procedures. In addition, the variability of some exposure metrics could be better explained than others. This knowledge can be used as a starting point for designing exposure assessment strategies for studies on health effects associated with these exposures among MRI radiographers and other jobs requiring presence in the neighborhood of MRI scanners.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article.

Appendix S1: Model structure of the linear mixed effects models

Table S1.a: 95% Confidence Intervals for the model estimates of SMF (B) exposure for MRI applications among human clinical and research MRI facilities (n=275)

Table S1.b: 95% Confidence Intervals for the model estimates of TVMF (dB/dt) exposure for MRI applications among human clinical and research MRI facilities (n=275)

Table S2.a: 95% Confidence Intervals for the model estimates of SMF (B) exposure for MRI applications among MRI facilities for experimental animal research (n=49)

Table S2.b: 95% Confidence Intervals for the model estimates of TVMF (dB/dt) exposure for MRI applications among MRI facilities for experimental animal research (n=49)

Table S3.a: Linear mixed effects models of SMF (B) exposure for MRI applications among human clinical and research MRI facilities, including body height (n=266)

Table S3.b: Linear mixed effects models of TVMF (dB/dt) exposure for MRI applications among human clinical and research MRI facilities, including body height (n=266)

Table S4.a: Linear mixed effects models of SMF (B) exposure for MRI applications among MRI facilities for experimental animal research, including body height (n=49)

Table S4.b: Linear mixed effects models of TVMF (dB/dt) exposure for MRI applications among MRI facilities for experimental animal research, including body height (n=49)

Table S5.a: 95% Confidence Intervals for the model estimates of SMF (B) exposure for MRI applications among human clinical and research MRI facilities, including body height (n=266)

Table S5.b: 95% Confidence Intervals for the model estimates of TVMF (dB/dt) exposure for MRI applications among human clinical and research MRI facilities, including body height (n=266)

Table S6.a: 95% Confidence Intervals for the model estimates of SMF (B) exposure for MRI applications among MRI facilities for experimental animal research, including body height (n=49)

Table S6.b: 95% Confidence Intervals for the model estimates of TVMF (dB/dt) exposure for MRI applications among MRI facilities for experimental animal research, including body height (n=49)