Exposure to Static Magnetic Fields and Risk of Accidents among a Cohort of Workers from a Medical Imaging Device Manufacturing Facility

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Purpose: To study the association between occupational MRI-related static magnetic fields (SMF) exposure and the occurrence of accidents.
Methods: Recent and career SMF exposure was assessed by linking a retrospective job exposure matrix to payroll based job histories, for a cohort of (former) workers of an imaging device manufacturing facility in the Netherlands. Occurrence of accidents was collected through an online questionnaire. Self-reported injuries due to accidents in the past 12 months, and the first (near) traffic accident while commuting to work and from work were analyzed with logistic regression and discrete-time survival analyses, respectively.
Results: High recent SMF exposure was associated with an increased risk of accidents leading to injuries [odds ratio (OR) 4.16]. For high recent and career SMF exposure, an increased risk was observed for accidents resulting in physician-treated injuries (OR 5.78 and 2.79, respectively) and an increased lifetime risk of (near) accidents during commute to work (hazard ratios 2.49 and 2.45, respectively), but not from work.
Conclusion: We found an association between MRI-related occupational SMF exposure and an increased risk of accidents leading to injury, and for commute-related (near) accidents during the commute from home to work. Further research into health effects of (long-term) SMF exposure is warranted to corroborate our findings. **Magn Reson Med 75:2165–2174, 2016. © 2015 Wiley Periodicals, Inc.**

Key words: accidents; epidemiology; magnetic resonance imaging; occupational exposure; static magnetic fields

INTRODUCTION

The question whether there are health risks associated with exposure to MRI related electromagnetic fields (EMF), including static magnetic fields (SMF), continues to be topical. Acute symptoms and neurocognitive effects have been reported to be associated with exposure to MRI-related SMF and time-varying magnetic fields, mainly among workers in MRI-production, and to a limited extent, among imaging workers in healthcare (1–6). Hardly any data are available on effects of long-term occupational exposure to SMF (7,8), but considering the nature of reported acute effects on balance (6), visual perception and hand–eye coordination (4), the question was raised whether long-term SMF exposure may lead to increased risk of work-related accidents, commute-related (near) accidents, and accidents in general.

The largest groups of SMF-exposed workers are found in clinical and research settings where MRI techniques are being applied (9). However, workers developing and producing MRI systems are presumed to be more frequently and higher exposed (10), because they generally spend more time near and in MRI systems, which are factors considered to be major determinants of exposure to SMF (11–13).

A retrospective occupational cohort study was initiated to study the potential effects of (long-term) occupational exposure to MRI-related EMF, and in particular, SMF among former and current employees of a medical imaging device manufacturing facility, some of whom have been exposed to SMF for up to 25 years. One of the outcomes of interest was risk of accidents, given anecdotal case reports and studies indicating acute effects of exposure such as vertigo (5), disturbed visual perception and hand–eye coordination (4), and disturbed balance (6). While the mechanisms through which long-term exposure may lead to an increased risk of accidents are unknown, and may not be the same as the mechanisms for acute effects, the potential consequences of the reported acute effects warrant an assessment of accident risk. We aimed to assess whether workers occupationally exposed to SMF may be at higher risk of being involved in an accident leading to injury, or being involved in a (near) accident during commute to and from work.

METHODS

Study Population

Base Cohort

For this retrospective occupational cohort study, both exposed and nonexposed former and current employees of a medical imaging device manufacturing facility (hereafter: the manufacturing facility) in the Netherlands were selected using historical company records. The base cohort was defined as all employees who had been employed at the manufacturing facility, for at least one year (365 days) between 1984 and 2010, in one or both of the business units, MR and X-ray. Employees who

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during their employment of at least 1 year had volunteered to undergo an image acquisition procedure [voluntary MRI scan, from here on referred to as a scan (procedure)] as part of the design and manufacturing process were also included in the base cohort. These groups were not mutually exclusive; part of the eligible workers had worked in both business units, and MR volunteers worked in these two or other business units of the manufacturing facility.

In the MR business unit, MRI systems have been designed, developed and produced since 1984. X-ray business unit employees were included in the cohort as a nonexposed comparison group. The MR and X-ray business units design and produce (medical) imaging instruments, are at the same plant location, and require workers of similar educational background and skills. Working conditions like workload, safety training and work related stress were considered comparable between business units.

The historical company records comprised (i) information from the salary administration, including name and address and employment status (job titles over time), gender, year of birth, and (ii) records kept at the occupational health service on workers who had received one or more voluntary MRI scans (MR volunteers). Data were made available to the researchers without names and addresses. The base cohort consisted of 5173 employees who had ever worked at the MR (n = 1205), X-ray (n = 3202), or at both (n = 569) business units. It also included 968 workers who had ever been scanned as an MR volunteer (of whom n = 197 had not been employed at MR or XR business unit).

Questionnaire Cohort

All base cohort members were considered eligible to be invited for our online questionnaire if a full address was available in company records and if the company records did not indicate that the person was deceased (in total 5002 eligible current and former employees). Invitations were sent to the eligible cohort members in November 2010, including one personalized letter from the manufacturing facility and another (anonymous) letter attached to it from the researchers, which contained login codes for the online questionnaire. Nonrespondents received a reminder in November 2011. By mistake, a subgroup of n = 277 workers was omitted in the November 2010 mailing. They were invited in 2011 and received a reminder letter three weeks later. The online questionnaire was accessible until mid-January 2012. A paper version of the questionnaire was provided upon request (n = 13) The online questionnaire took on average one hour to complete and contained questions on the following topics: demographics, educational level, current employment, detailed work history, MR volunteer status, occurrence of accidents, lifestyle including alcohol consumption, and general health status.

Accidents

The questionnaire included the following items regarding accidents: (i) Involvement in an accident or an event that resulted in physical injury (hereafter referred to as "an accident") in the past 12 months (yes or no), and how often this had occurred in the past 12 months. For the most recent accident, the severity of injury was estimated by asking whether this injury had been treated by a physician (hereafter referred to as "doctor treated injury (DTI)"); whether this accident took place at the workplace; and what caused the injury (e.g., a fall from stairs or a height, cut by a sharp object). Only the most recent accident was singled out for more in detail questioning to minimize recall bias and participant burden considering the length of the questionnaire. (ii) Involvement in a traffic accident or near collision (hereafter referred to as a "commute-related (near) accident") while driving a vehicle either from home to work, or from work to home or to another destination; and if so, in which calendar year this event happened. In the case of multiple commuting accidents, the number of commuting-related (near) accidents per commute direction and years in which the first and most recent event took place were requested. From these data, year of first commute accident in either direction was used in the statistical analysis.

Exposure Assessment

Occupational SMF exposure

Historical company records from the salary administration documented employment and job mobility of employees between 1938 and 2011 within the manufacturing facility. These records were supplemented with self-reported job histories from the questionnaire when specific information on job title was missing (n = 809). Job histories were used to estimate occupational SMF exposure and total employment duration at the facility. Exposure to SMF was assessed by linking job history data (job title per year from pay-roll records) to a retrospective job exposure matrix (JEM) with SMF exposure levels per job title per year between 1984 and 2011, which was specifically developed for this purpose (11). The former MRI Safety Expert of the manufacturing facility was involved in recoding of the historical job titles to match them with the job titles of the applied JEM. Several knowledgeable contact persons at the production facility were consulted when clarification of a job description was needed.

Individual SMF exposure was modeled for each year between 1984 and 2011 and was expressed in Tesla minutes (T-min) per year. Based on these annual (12-month period) exposure values, two occupational SMF exposure measures were estimated: recent exposure (i.e., exposure in the 12-month period of the calendar year of interest), and cumulative career exposure. For the analyses of accidents in the past 12 months, recent exposure was the SMF exposure in the calendar year X, and career exposure was the sum of all modeled exposure values per calendar year up to and including year X, where year X is the calendar year in which the questionnaire was accessed (2010 or 2011). The 66th percentiles of recent and career exposure distributions were used to distinguish between low and high exposure categories.

For the discrete-time survival analyses of commute-related (near) accidents, recent exposure was the SMF

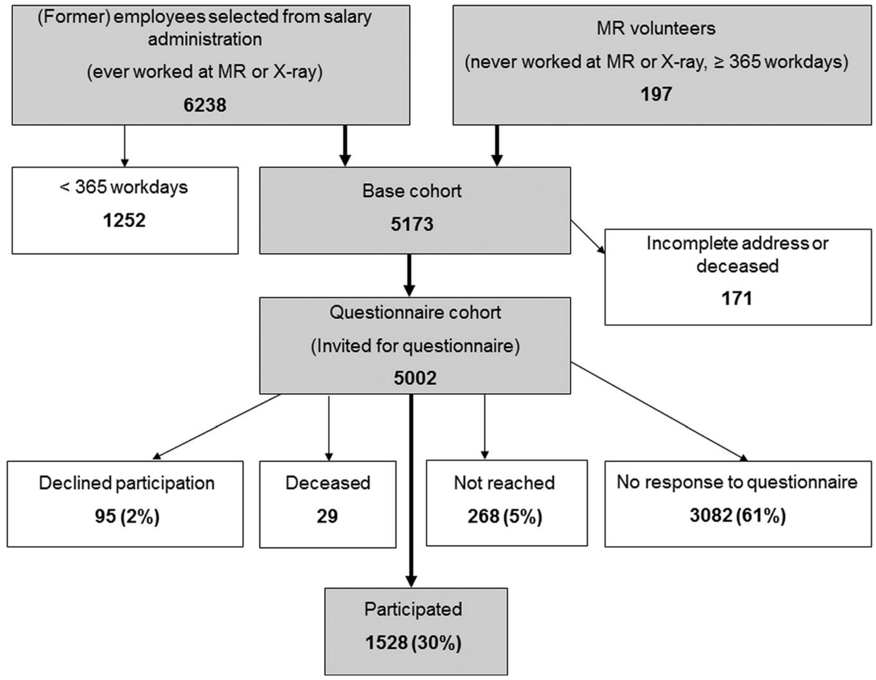

FIG. 1. Flowchart of base cohort, questionnaire cohort and the questionnaire participation rates. The base cohort was formed by selecting MR and X-ray workers and MR volunteers with employment duration ≥1 year at the manufacturing facility between 1984 and 2010.

exposure in year Y, and career exposure was the sum of all modeled exposure values per calendar year up to and including year Y, where year Y was each individual year between 1941 and 2010/2011 a (former) employee was part of the discrete-time survival analyses. The studied time period of 1941–2011 was based on the age inclusion criteria (see description of statistical analyses for details) and the last year in which the questionnaire could be initiated. Employees were grouped by age for each year they contributed to the analyses. Per age group the 66th percentiles of recent and career exposure distributions were used to distinguish between low and high exposure categories.

For both the analyses of accidents in the past 12 months as well as the discrete-time survival analyses of traffic-related (near) accidents, the 33rd and 66th percentile were chosen as a cut-off points to create exposure categories for low, medium and high exposure. The categories for low and medium exposure were consequently combined into one because of small numbers or no events in these categories.

Low and high occupational (cumulative) SMF exposure categories were compared with the group of nonexposed workers (from MR and X-ray business units and nonexposed MR-volunteers from other business units). For analyses with recent exposure an additional exposure group of "past exposure" was created. This exposure group consisted of occupationally SMF exposed workers with no exposure in the relevant calendar year, but who had been exposed previously.

MR Volunteer Scan Exposure

The focus of this study was on the association between occupational exposure to MRI-related SMF and accident risk, but the additional exposure to EMF as an MR volunteer could not be ignored. We included MR volunteer status in our analyses to account for this additional exposure to radiofrequency fields (RF) and switched gradient fields (SGF) emitted during a scan procedure in the study population.

EMF exposure from a scan procedure as an MR volunteer was regarded as a different type of EMF exposure than occupational exposure to SMF (which was supposed to be also a proxy for exposure to low-frequency time-varying magnetic fields (TVMF) from movement through the static magnetic stray field around a scanner). MR volunteers, however, hardly move during a scan procedure (except very shortly when moving to and from the MRI system) and are in a homogenous SMF in the bore of the MRI scanner. As a consequence exposure to TVMF while being scanned will be minimal and directly related to the number of scans (an exposure measure used in the statistical analyses). The main MR volunteer exposure to TVMF will take place during movement to and from an MRI-system before and after a scan procedure and when an MR-volunteer is positioned inside the bore. The duration of MR volunteer movement is considered very brief and the contribution of TVMF to the total of MR-volunteer-related EMF exposure is small compared with the exposure to RF and SGF during a scan procedure.

In addition to a high SMF field in the bore of the MRI scanner, a volunteer will be exposed to RF and SGF emitted during a scan procedure. Company safety guidelines instruct workers to minimize exposure to RF and SGF by leaving the scanner room during a scan procedure. Consequently the EMF exposure of an MR volunteer was treated as a different exposure than the occupational exposure of an MR worker.

A company protocol for the MR volunteer program required that each voluntary scan procedure from 1984

Table 1
Characteristics of Current and Former Employees from the Base Cohort and Questionnaire Participants

	Ever occupationally SMF exposed		Never occupationally SMF exposed					
	SMF exposed MR workers[a]		SMF non-exposed MR workers		X-ray workers[b]		non-MR and non-X-ray MR volunteers[c]	
	Base cohort (n = 479)	Questionnaire participants (n = 212)	Base cohort (n = 1295)	Questionnaire participants (n = 408)	Base cohort (n = 3,202)	Questionnaire participants (n = 811)	Base cohort (n = 197)	Questionnaire participants (n = 97)
MR volunteers[d], N°	219 (46%)	116 (55%)*	314 (24%)	147 (36%)**	238 (7%)	121 (15%)**	197 (100%)	97 (100%)
Participation rate		44%		36%		25%		49%
MR volunteers only		53%		47%		51%		49%
Duration of employment, mean (range)	13.5 (1.0-32.3)	14.9 (1.0-31.9)**	11.5 (1.0-37.6)	14.0 (1.0-36.3)**	11.2 (1.0-40.4)	12.9 (1.0-40.4)**	11.1 (1-35.7)	12.7 (1-35.6)*
MR volunteers only	14.7 (1.3-31.9)	16.2 (2.3-31.9)*	14.2 (1.1-34.3)	15.5 (1.1-31.3)*	16.1 (2.0-35.5)	16.4 (2.0-35.5)	11.1 (1-35.7)	12.7 (1-35.6)*
Employed at facility, N° (%)	335 (70%)	141 (67%)	495 (38%)	174 (43%)	1608 (50%)	408 (50%)	86 (44%)	47 (48%)
MR volunteers only	161 (74%)	85 (73%)	161 (51%)	77 (52%)	136 (57%)	65 (54%)	86 (44%)	47 (48%)
Age, mean years (range)	47.2 (24-80)	50.2 (26-80)**	51.9 (18-87)	55.3 (23-83)**	50.8 (19-86)	53.3 (23-85)**	50.9 (27-79)	52.9 (31-79)*
MR volunteers only	47.3 (24-75)	49.4 (31-75)**	51.9 (26-75)	54.5 (26-7)**	52.6 (31-76)	53.8 (31-76)	50.9 (27-79)	52.9 (31-79)*
Male, N° (%)	433 (90%)	193 (91%)	1089 (84%)	350 (86%)	2699 (84%)	705 (87%)*	156 (79%)	79 (81%)
MR volunteers only	190 (87%)	101 (87%)	269 (86%)	124 (84%)	205 (86%)	107 (88%)	156 (79%)	79 (81%)
Career occupational SMF exposure (T-min median (range)) [a]	4719 (4-179,911)	3755 (8-179,911)						
MR volunteers only	4199 (8-148,888)	3121 (8-125,357)						

*$P < 0.05$, 2 sided, non-response analyses of the original cohort-subgroup (SMF exposed MR workers, SMF non-exposed MR workers, X-ray workers or non-MR and non-X-ray MR volunteers) and questionnaire participants of corresponding sub-group.

**$P < 0.001$, 2 sided, non-response analyses of the original cohort-subgroup (SMF exposed MR workers, SMF non-exposed MR workers, X-ray workers or non-MR and non-X-ray MR volunteers) and questionnaire participants of corresponding sub-group.

[a]SMF exposure based on company records of individual job histories and estimated with the use of a historical JEM developed for this study(11). 15% of the company record based job histories were supplemented with data from self-reported job histories.

[b]Does not include X-ray workers who have also ever worked at MR business unit (n=569); they are included in the SMF exposed and SMF non-exposed under MR workers.

[c]MR volunteers who were never employed at MR and X-ray business units, but who have been exposed to EMF related to one or more scan procedures.

[d]All subgroups of MR workers and X-ray workers contain MR volunteers, who have been exposed to EMF related to one or more scan procedures.

Table 2
Absolute Numbers and Crude Rates of Self-Reported Accidents with Injury in the Past 12 Months

	Occupationally SMF exposed[a]		Never occupationally SMF exposed			
	Recent SMF exposed MR workers	Ever SMF exposed MR workers	SMF non-exposed MR workers	X-ray workers[b]	non-MR and non-X-ray MR volunteers[c]	Total of never occupationally SMF exposed
Number of respondents						
All, N°	50	200	363	714	89	1166
Men, N°	42	181	312	624	72	1008
MR volunteers only [d], N°	28	111	133	101	89	323
At least one accident with injury in the past 12 months						
All, N° (%)	4 (8%)	13 (7%)	14 (4%)	34 (5%)	5 (6%)	53 (5%)
Men, N° (%)	4 (10%)	12 (7%)	11 (4%)	28 (4%)	3 (4%)	42 (4%)
MR volunteers only[d], N° (%)	1 (4%)	4 (4%)	5 (4%)	5 (5%)	5 (6%)	15 (5%)
Injury of most recent accident in past 12 months treated by doctor *(DTI)*						
All, N° (%)	4 (8%)	11 (6%)	13 (4%)	23 (3%)	4 (5%)	40 (3%)
Men, N° (%)	4 (10%)	10 (6%)	10 (3%)	20 (3%)	2 (3%)	32 (3%)
MR volunteers only[d], N° (%)	1 (4%)	4 (4%)	5 (4%)	4 (4%)	4 (5%)	13 (4%)

[a]SMF exposure based on company records of individual job histories and estimated with the use of a historical JEM developed for this study(11).
[b]Does not include X-ray workers who have also ever worked at MR business unit, which are included in the SMF exposed and SMF non-exposed groups under MR workers.
[c]MR volunteers who were never employed at MR and X-ray business units, but who have been exposed to EMF related to one or more scan procedures.
[d]All subgroups of MR workers and X-ray workers contain MR volunteers, who have been exposed to EMF related to one or more scan procedures.

onward was recorded, including for each volunteer the actual date of the scan procedure, MRI scanner type and strength, and scan duration for each procedure. The manufacturing company provided all records from 1984 until the end of 2010, without identifying information. The majority of scan procedures was completed with an MRI system with a magnet of 1.5 Tesla (T) or less and lasted on average between 55 and 65 min. Information on magnet strength was missing for 8.4% of data entries and no data was available on the strength of the RF and gradient systems, the driving factors behind the main source of EMF exposure for MR volunteers. Based on this information, scan frequency per year and cumulative number of scans was considered a crude, but acceptable proxy for MR volunteer MRI-EMF exposure (TVMF, RF, and SGF). MR volunteers received on average 4 scans annually during the years they volunteered, and the median cumulative number of scans was 15. Volunteer scans were included either as a categorical variable (0, 1–15, and >15, to distinguish between high (above median) and low number of undergone scans) in the analysis of accidents in the past 12 months, or as a dichotomous variable (ever versus never) in the analysis of commute-related (near) accidents.

Alcohol Use

Recent excessive and age-specific alcohol use was assessed by asking subjects if they had ever consumed alcoholic beverages on a regular basis (at least once a month), and if yes, at what age they started and, if applicable, stopped doing so. They were also asked how many units of alcoholic beverages they consumed on average per week at specific age periods (≤19, 20–39, 40–59, and ≥60). Subjects were asked to count a glass of wine or other alcoholic beverage as one unit, a bottle of beer as 1.5 units, and a bottle of alcopop as one unit, and were also asked to include glasses of alcoholic beverages consumed during meals, as an appetizer or desert (e.g., dessert or port wine, eggnog) in their count. For each of these age categories, age-specific alcohol use was categorized into four groups (no alcohol consumption, and using 33rd and 66th percentiles as cut off points for low, medium and high alcohol consumption). To assess recent excessive (binge) drinking, subjects were asked on how many days they consumed six or more glasses of alcoholic beverages in the past 6 months, and consuming six or more glasses on at least 1 day per month was scored as "recent excessive alcohol use".

Statistical Analyses

To assess participation bias, a nonresponse analysis was performed on demographic characteristics, occupational SMF exposure and MR volunteer status. These variables were compared using Student t-test and binomial test for continuous and binomial data, respectively, within subgroups of the base cohort between questionnaire participants and nonparticipants (nonresponders and cohort members not invited to the questionnaire due to being deceased or incomplete address).

Four separate logistic regression models were used to assess the associations between two occupational SMF exposure variables (i.e., recent and career) and two accident outcomes (i.e., the occurrence of accidents in the past 12 months resulting in physical injury and DTI). These logistic regression analyses included volunteer scan

Table 3
Multivariate Logistic Regression of the Association between Exposure and Accidents Leading to Injury[ab] in the Past 12 Months

	Odds ratio	95% Confidence intervals
≥1 Accident with injury in the past 12 months		
Recent SMF exposure		
Non-exposed (no occupational SMF exposure)	1	
Past exposure, but no recent exposure	1.49	0.70 – 3.32
Recent SMF exposure low [>0 - <1796 T-min]	0.76	0.10 – 5.80
Recent SMF exposure high [≥1796 - <11053 T-min]	**4.16**	**1.14 – 15.25***
Cumulative number of scans low [1-15]	1.10	0.56 – 2.06
Cumulative number of scans high [>15]	0.49	0.20 – 1.17
Career SMF exposure		
Non-exposed (no occupational SMF exposure)	1	
Career SMF exposure low [>0 - <24,597 T-min]	1.32	0.57 – 3.03
Career SMF exposure high [≥24,597 - <179,911 T-min]	2.20	0.89 – 5.48
Cumulative number of scans low [1-15]	1.04	0.54 – 1.99
Cumulative number of scans high [>15]	0.47	0.20 – 1.15
Injury of most recent accident in past 12 months treated by doctor (DTI)		
Recent SMF exposure		
Non-exposed (no occupational SMF exposure)	1	
Past exposure, but no recent exposure	1.47	0.63 – 3.42
Recent SMF exposure low [>0 - <1796 T-min]	1.00	0.13 – 7.69
Recent SMF exposure high [≥1796 - <11053 T-min]	**5.78**	**1.57 – 21.32***
Cumulative number of scans low [1-15]	1.27	0.62 – 2.59
Cumulative number of scans high [>15]	0.67	0.27 – 1.66
Career SMF exposure		
No career exposure (no occupational SMF exposure)	1	
Career SMF exposure low [>0 - <24,597 T-min]	1.22	0.46 – 3.23
Career SMF exposure high [≥24,597 - <179,911 T-min]	**2.79**	**1.11 – 7.04***
Cumulative number of scans low [1-15]	1.21	0.59 – 2.48
Cumulative number of scans high [>15]	0.65	0.26 – 1.61

*P <0.05, two-sided
[a]Exposure categories were based on the 66th percentile among those exposed for recent and career SMF exposure and the 50th percentile of number of scans among those with MR volunteer exposure.
[b]The four models (≥1 accident + recent SMF exposure, ≥1 accident + career SMF exposure, DTI + recent SMF exposure, and DTI + career exposure) were adjusted for age, sex and recent excessive alcohol use, and included both SMF exposure and MR volunteer exposure.

exposure (categorical number of scans: 0, 1–15, and >15) and were adjusted for age, gender, and excessive alcohol use.

The associations between (recent and career) SMF exposure and the occurrence of commute-related (near) accidents was based on the year of first commute-related (near) accident to work and from work, respectively, using discrete-time survival analysis (14). This method permits adjusting for the effect of age on accident risk by treating each age year through time as a separate category which gets its own risk estimate. Age groups with less than four exposed employees were not included in the discrete time survival analyses, which resulted in the inclusion of all age groups between 25 and 62, and exclusion of age groups <25 and >62. These discrete-time survival analyses included volunteer scan exposure (ever versus never), and were adjusted for age, gender, and age-specific alcohol use. Analyses were performed with SAS 9.2 (SAS Institute Inc., Cary, NC).

RESULTS

Questionnaire Cohort

Figure 1 shows the participation rate to the questionnaire and the number of employees who could not be reached or declined to fill in the questionnaire. A total of 1479 questionnaire records with complete data on accidents in the past 12 months, and 1393 questionnaire records with complete data on commute-related (near) accidents, were available for analyses.

Table 1 shows participation rates, age and sex and exposure distributions in subgroups of the base cohort and the questionnaire participants up until the end of 2010. The overall participation rate was 30%, ranging from 40% for SMF-exposed MR workers to 25% for X-ray workers. There was a higher participation rate (~50%) among (former) MR volunteers, regardless of their business unit. Employees from the MR and X-ray business units were generally comparable with respect to demographic characteristics. Furthermore, the demographic characteristics were generally similar for employees from the base cohort and the questionnaire participants. Responders were on average only 2.6 years older and had 2.0 years longer employment duration when compared with the base cohort. Among exposed responders, median career SMF exposure appeared to be lower than among those in the base cohort. Both in the base cohort and among the responders, occupationally SMF-exposed employees appeared to be on average slightly younger, yet had longer employment duration at

Table 4
Self-Reported Occurrence and Crude Rates of Reporting at Least One Commute-Related (Near) Accident During Commute

	Ever occupationally SMF-exposed	Never occupationally SMF-exposed			
	SMF exposed MR workers[a]	SMF non-exposed MR workers	X-ray workers[b]	Non-MR and non-X-ray MR volunteers[c]	Total of never occupationally SMF exposed
Number of respondents with complete data on commute accidents					
All, N°	202	366	718	89	1173
Men, N°	182	315	626	72	1013
MR volunteers only [d], N°	112	135	102	89	326
At least one (near) accident commute from home to work					
All, N°	38 (19%)[e]	68 (19%)	133 (19%)	21 (24%)	222 (19%)
Men only, N° (%)	35 (19%)	61 (19%)	123 (20%)	19 (26%)	203 (20%)
MR volunteers only[d], N° (%)	15 (13%)	25 (19%)	13 (13%)	21 (24%)	59 (18%)
At least one (near) accident commute from work to other location					
All, N°	42 (21%)[f]	68 (19%)	144 (20%)	15 (17%)	227 (19%)
Men only, N° (%)	39 (21%)	63 (20%)	129 (21%)	11 (15%)	203 (20%)
MR volunteers only[d], N° (%)	17 (15%)	20 (15%)	19 (19%)	15 (17%)	54 (17%)

[a]SMF exposure based on company records of individual job histories and estimated with the use of a historical JEM developed for this study(11).
[b]Does not include X-ray workers who have also ever worked at MR business unit, which are included in the SMF exposed and SMF non-exposed groups under MR workers.
[c]MR volunteers who were never employed at MR and X-ray business units, but who have been exposed to EMF related to one or more scan procedures.
[d]All subgroups of MR workers and X-ray workers contain MR volunteers, who have been exposed to EMF related to one or more scan procedures.
[e]14 of these workers reporting at least one (near) accident had recent SMF exposure and 26 had accumulated career SMF exposure in the year of the first reported (near) accident, which was used in the survival analysis.
[f]10 of these workers reporting at least one (near) accident had recent SMF exposure and 28 had accumulated career SMF exposure in the year of the first reported (near) accident, which was used in the survival analysis.

the manufacturing facility and were more likely to be still employed at the manufacturing facility than occupationally nonexposed employees.

Risk of Accidents

On average 1.2 accidents (range, 1–4 accidents) were reported by those reporting at least one accident ($n = 66$; 4%). Participants could indicate one or more causes of their most recent accident. Five of those accidents were reported to have occurred at the workplace, of which none occurred at the MR business unit. Fourteen accidents leading to injury were traffic-related, 28 were attributed to tripping or falling, 7 to sport activities, and 23 to other causes. Crude accident and DTI rates were higher in SMF exposed (Table 2).

Recent high SMF exposure was associated with an increased risk of self-reported accidents resulting in injury [odds ratio (OR) 4.16], and with more serious injuries, i.e., DTI (OR 5.78) (Table 3). In addition, the group with high career SMF exposure showed a significantly increased risk of more serious injuries which were treated by a physician (OR 2.79).

While excessive alcohol use was associated with an increased risk of accidents resulting in injury (OR 2.24, 95% confidence interval 1.26–3.99) and DTI (OR 2.02, 95% CI 1.04–3.92), it was not associated with occupational SMF exposure and therefore did not confound the OR for exposure. While the models were also corrected for the potential confounding effects of age and gender on accident risk, these two factors were not found to be associated with increased or decreased accident risk.

Table 4 shows the crude rates of reporting at least one commute-related (near) accident. The discrete-time survival analysis indicated a statistically significant increased risk of a commute-related (near) accident toward work associated with recent and to a lesser extent, with career SMF exposure (Table 5). A similar, but nonsignificant association with career exposure was seen for accidents during commute from work to home or another destination. MR volunteer scan exposure (ever or never) was not associated with an increased risk of commute-related (near) accidents (Table 5). In addition, the number of volunteer scan procedures did not affect the accident risk regardless of commute direction (see Supporting Table S1, which is available online).

Figure 2 shows the model-based estimated chance of remaining free of commute-related (near) accidents, which was smallest for individuals with high recent exposure commuting to work.

DISCUSSION

While effects of acute MRI-related EMF exposure have been studied in the manufacturing environments as well as in clinical settings (5,15,16), and among human

Table 5
Multivariate Discrete-Time Survival Analysis of the Association between SMF Exposure and Self-Reported Year of First (Near) Accident during Commute[ab]

	Hazard ratio	95% Confidence interval
Commuting from home to work		
recent SMF exposure in year of event		
Non-exposed	1	
Past SMF exposure, no SMF exposure in year of event	1.08	0.59 – 1.97
recent SMF exposure low	1.02	0.47 – 2.22
recent SMF exposure high	**2.49**	**1.14 – 5.43***
Ever scanned as MR volunteer	1.03	0.69 – 1.53
Career SMF exposure		
Non-exposed	1	
Career SMF exposure low	0.85	0.48 – 1.50
Career SMF exposure high	**2.45**	**1.40 – 4.30****
Ever scanned as MR volunteer	1.01	0.68 – 1.49
Commuting from work to other location		
recent SMF exposure in year of event		
Non-exposed	1	
Past SMF exposure, no SMF exposure in year of event	1.60	0.95 – 2.69
recent SMF exposure low	0.78	0.32 – 1.91
recent SMF exposure high	1.29	0.47 – 3.53
Ever scanned as MR volunteer	0.99	0.67 – 1.46
Career SMF exposure		
Non-exposed	1	
Career SMF exposure low	1.49	0.93 – 2.40
Career SMF exposure high	0.94	0.44 – 2.01
Ever scanned as MR volunteer	0.99	0.67 – 1.47

*$P < 0.05$, 2 sided
**$P < 0.01$, 2 sided
[a]The 4 models (home to work + recent SMF exposure, home to work + career exposure, from work + recent exposure, and from work + career exposure) were adjusted for age, sex and alcohol use (categorical units per week per age group), and included both SMF exposure and MR volunteer exposure.
[b]Exposure categories were based on the 66th percentile among those exposed for recent and career SMF exposure.

volunteers (1,3,4,6,17), no studies have been published on the effects of long-term occupational exposure to SMF. Our study is unique as it focusses on risk of accidents associated with both long-term and recent exposure of workers in MRI-systems manufacturing. Acute symptoms of headache and vertigo that were reported by employees when working in SMF and in the bore of MRI systems in cross-sectional studies (1,5) were paramount for the hypothesis of an association between MRI-related SMF exposure at the workplace and risk of accidents. For this reason, we collected self-reported data on occurrence of accidents in the past among exposed and nonexposed (former) employees of an MRI device manufacturing facility.

The results of our study indicate that recent and to a somewhat lesser extent career SMF exposure are associated in an exposure depending manner with risk of self-reported accidents leading to (physician treated) injuries. Recent and career SMF exposure appeared also to be associated with an increased life-time risk of (near) accidents during commute to work, but, contrary to our a priori expectations based on known acute effects of SMF exposure, less so from work to home or elsewhere. We included self-reported near-accidents in our study as we hypothesized that previously reported acute effects on visual perception and hand–eye coordination might not automatically lead to an increased risk of actual traffic accidents, but may influence driving; an effect which may not be observed when focusing on only actual traffic accidents during commute.

Limitations of our study include the retrospective self-reported data on occurrence of [traffic-related (near)] accidents and the relatively low participation rate. With respect to potential response bias, we were able to compare SMF exposure, general demographic characteristics and MR volunteer status between questionnaire participants and the remainder of the base cohort in a nonresponse analysis. Based on these results we argue that the questionnaire participants were a representative sample from our base cohort and the low participation rates are not the driving force behind our findings.

Another limitation of the low participation rate is the low number of reported accidents. Due to the small number of worksite related accidents that were reported, it was not possible to investigate the association of these accidents with MRI-related exposure. The low absolute number of reported accidents in general may have resulted in loss of statistical power and require that our results are interpreted with some caution.

A general limitation of the study is that we rely on self-reported accident data, and hence rely on recall. Our questionnaire participants were aware of the study's focus on effects of MRI-related exposure and most likely knew whether they were occupationally exposed to

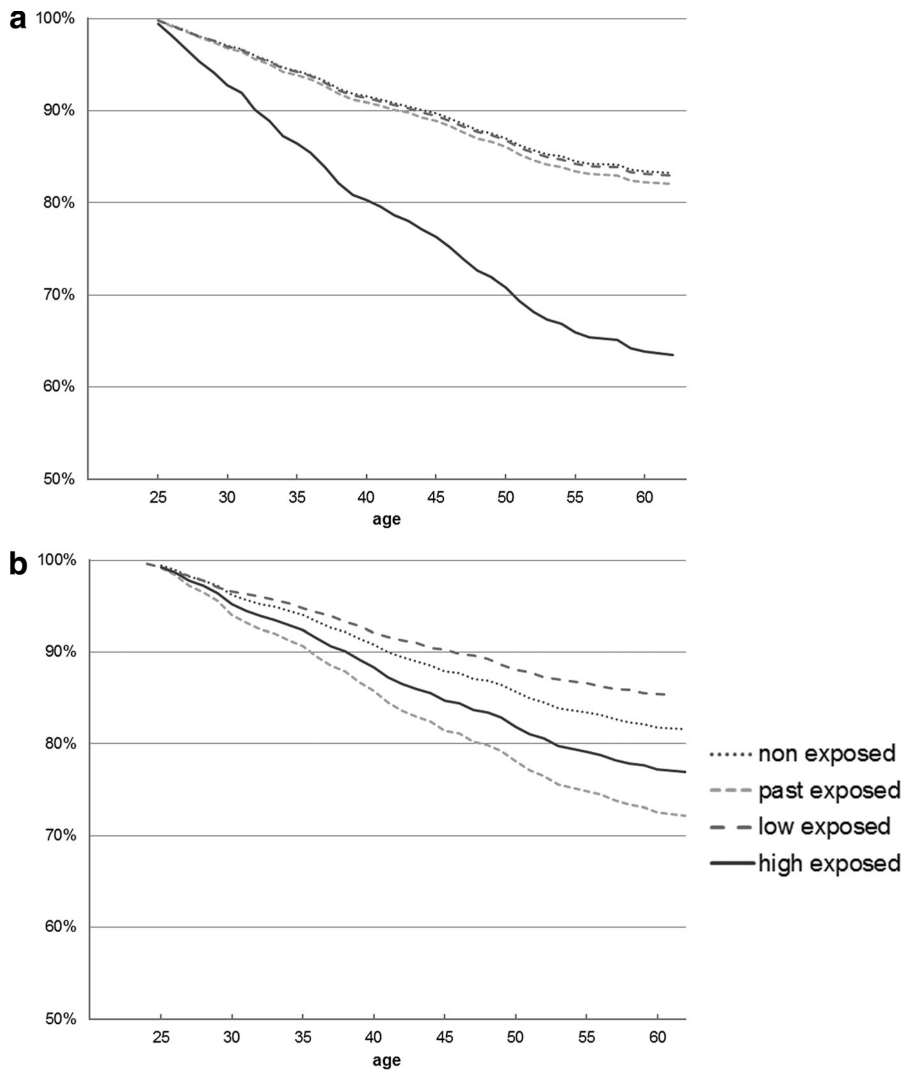

FIG. 2. Model based chance of remaining (near) accident free calculated by discrete-time survival analyses during commute from home to work (**a**) and from work to elsewhere (**b**) in relation to annual SMF exposure. The low exposure categories are defined as the first two tertiles and the high exposure categories are defined as the third tertile of exposed employees per age year. Non-exposed = Never occupationally exposed to SMF and is based on the adjusted baseline hazard; past exposed = SMF exposed before, but no recent exposure in year of accident or reference year. All models are adjusted for sex, age-specific alcohol use (categorical units/week per age category), and being scanned at least once as an MR volunteer (yes versus no).

SMF. However, they could not have been aware of their actual modeled (career) exposure levels which were based on company records. We would have expected such bias to lead to an overestimation of the analyzed accidents increased risks for both commute directions or from work along the lines of our a priori concerns regarding occupational SMF exposure leading to increased accident risk shortly after work.

In addition, no association was found for MR volunteer exposure and accident risk, while it is reasonable to assume MR volunteers were aware whether they participated in few or many volunteer scan procedures. Nevertheless, differential report and recall bias cannot be ruled out completely despite our efforts to minimize their effect.

Presently it is unclear whether the observed associations are causal and, if so, whether the associations are directly due to exposure to SMF or are indirectly by means of other effects such as increased fatigue, disturbed quality of sleep, affected balance, or decreased concentration. Studies on work-related fatigue have suggested an increased risk of accidents during commute after work (18,19), which is not congruent with our findings. Our results may be indicative of a delayed effect through, as of yet, unknown pathways. However, because no clear exposure-response association was shown in our study, further research is a necessity to confirm the presented associations between (high) exposure to SMF and increased accident risks

An important strength is that detailed historical company records facilitated estimation of actual recent exposure between 1984 and 2011 by linkage to a company-specific JEM (11), and allowed for analyses of both recent and career exposure. The main source of occupational EMF exposure for employees is movement through stray SMFs surrounding an MRI system, which have been reported to be related to symptoms, such as vertigo and concentration problems (5). Exposure to other types of electromagnetic fields, such as SGF and RF, were considered to be low and infrequent in this occupational setting (11), with the exception for MR volunteers. The latter were subjected to SGF-EMF and RF-EMF while being scanned in a homogenous SMF within the bore of the magnet. Workers were instructed by company safety guidelines to minimize exposure to RF and SGF by avoiding being in an MRI-room while a test or a scan procedure was in progress, and, therefore, their most notable exposure will have been to SMF when they did not volunteer to be scanned. For this reason, we addressed exposure of MR volunteers while being scanned as another type of SMF exposure in our analyses.

The SMF nonexposed (former) employees from MR and X-ray and MR volunteers from other business units were considered to be an adequate comparison group as they shared similar socioeconomic status influencing aspects, such as educational level and marital status (results not shown), and had similar demographic characteristics (Table 1). Respondents appear to be a representative sample of the cohort despite the relatively low average participation rate of 30%.

Considering all limitations, including reliance on self-reported rare events [accidents leading to injury and commute-related (near) accidents] and the small sample size compared with the original study cohort, caution is needed when interpreting these results to avoid drawing conclusions regarding causation. While it is not possible to rule out the element of chance entirely, the strengths of our study, specifically the study population being a representative sample of the original study cohort and their exposure assessment based on company records, offer reasonable support to our findings.

CONCLUSIONS

We found an association between occupational exposure to SMF from working in an MRI production facility and increased risks of self-reported accidents leading to injury and of commute-related (near) accidents from home to work. The study period comprised the early until recent days in MRI manufacturing (1984–2011). Since then, an increasing number of individuals in MRI manufacturing, clinical and research settings are being exposed to increasingly stronger static magnetic fields. Further research efforts looking into effects of recent and long-term occupational and MRI-related EMF exposure are warranted to corroborate our findings. In particular, because of the increasing numbers of individuals being exposed to increasingly stronger static magnetic fields in their work environments, e.g., during MRI manufacturing and during use of these systems in clinical and research settings.

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SUPPORTING INFORMATION

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

Table S1. Discrete-Time Survival Analysis of Association between MR Volunteer Scan Exposure and Self-Reported Year of First Commute-related (Near) Accident[a]