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Radiofrequency electromagnetic fields; male infertility and sex ratio of offspring

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Abstract Concern is growing about exposure to electromagnetic fields and male reproductive health. The authors performed a cross-sectional study among military men employed in the Royal Norwegian Navy, including information about work close to equipment emitting radiofrequency electromagnetic fields, one-year infertility, children and sex of the offspring. Among 10,497 respondents, 22% had worked close to high-frequency aerials to a "high" or "very high" degree. Infertility increased significantly along with increasing self-reported exposure to radiofrequency electromagnetic fields. In a logistic regression, odds ratio (OR) for infertility among those who had worked closer than 10 m from high-frequency aerials to a "very high" degree relative to those who reported no work near high-frequency aerials was 1.86 (95% confidence interval (CI): 1.46–2.37), adjusted for age, smoking habits, alcohol consumption and exposure to organic solvents, welding and lead. Similar adjusted OR for those exposed to a "high", "some" and "low" degree were 1.93 (95% CI: 1.55–2.40), 1.52 (95% CI: 1.25–1.84), and 1.39 (95% CI: 1.15–1.68), respectively. In all age groups there were significant linear trends with higher prevalence of involuntary childlessness with higher self-reported exposure to radiofrequency fields. However, the degree of exposure to radiofrequency radiation and the number of children were not associated. For self-reported exposure both to high-frequency aerials and communication equipment there were significant linear trends with lower ratio of boys to girls at birth when the father reported a higher degree of radiofrequency electromagnetic exposure.

Keywords Electromagnetic fields · Infertility · Occupational exposure · Offspring sex ratio · Male infertility · Radiofrequency electromagnetic fields

Abbreviations
CI Confidence interval
OR Odds ratio

In recent decades, concern and discussion has been growing about decreasing fecundity and fertility in many countries [1, 2]. The reasons for this possible decreasing fertility are complex, as both social and behavioral changes in societies contribute in addition to biological mechanisms. However, several studies indicate that semen quality may have decreased in the past half century [3–5] and that reduced semen quality is associated with reduced fertility [6]. Various types of environmental and occupational exposure have been suggested as possible causes for the reduced semen quality [1, 7], but few factors have been consistently identified. One of the exposures have been non-ionizing electromagnetic fields and in special radiofrequency electromagnetic fields [8].

Non-ionizing electromagnetic fields are usually divided into groups according to frequency bands ranging from 50 Hz to several gigahertz, including extremely low-frequency electromagnetic fields emitted by electric equipment and radiofrequency fields emitted by radio communication and navigation equipment, mobile phones and radar.

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Many Royal Norwegian Navy employees are exposed to non-ionizing radiation. Employees use technical equipment creating electromagnetic fields both onshore and especially on board the ships. Navy personnel are exposed to fields in the whole range of frequencies but differ from other parts of the population because they are frequently exposed to radiofrequency electromagnetic fields during work. All ships have radar, transmitters and antennas causing exposure to radiofrequency fields. On several ships the distance between the personnel on deck and the antennas and the radars is short, and the personnel use this equipment whenever the ships are sailing. One study [9] has indicated adverse reproductive health outcome in a subgroup of employees in the Royal Norwegian Navy and suggested that this was related to electromagnetic radiation from the electronic equipment on board.

Little is known about exposure to non-ionizing electromagnetic fields and male reproductive health. Some studies on semen quality have reported that exposure to radiofrequency radiation has adverse reproductive effects [10–13], whereas others have not found such an effect [14, 15]. Recent studies have shown that using mobile phones negatively affects semen motility [16–18] and sperm concentration [17]. The sex ratio of offspring is important as an indicator of reproductive hazard [19], and there have been reported decreased sex ratio among fathers after exposure to radiofrequency electromagnetic fields [20–23] but only one was significant [22].

We investigated the association between men's self-reported occupational exposure to radiofrequency electromagnetic fields in the Navy and infertility and sex ratio of the offspring.

Methods

Design and data collection

The study population comprised all current and former male military employees in the Royal Norwegian Navy, defined by the military employment list. The data were collected during two time periods depending on whether they were currently or formerly employed. All military employees currently employed in September 2002 ($n = 2{,}497$) received a postal questionnaire during autumn 2002. The response rate was 62% ($n = 1{,}550$). Former military employees were defined as those employed in the Royal Norwegian Navy for more than 16 months from 1950 to September 2002. Sixteen month was chosen to exclude conscripts. A total of 15,259 received a questionnaire at the end of 2004 and 9,666 of them responded (63%). Among the respondents, 719 men were excluded because they answered that they had been employed less then 1 year or had only worked as a civilian in the Navy, leaving 8,947 formerly employed military men.

The employees were identified by both name and personal identification number, and their current address was found by using the National Population Registry. In both surveys we sent two reminders to nonrespondents. We finally included 10,497 currently and formerly employed military men in the analysis.

Questionnaires

The questionnaire sent to the current employees was 20 pages long including various topics related to work and health. The questionnaire sent to the former employees contained only a subset of these questions. This study only used questions that were identical in the two surveys.

The questionnaire included three questions on exposure to radiofrequency electromagnetic fields: work closer than 10 m from high-frequency aerials, work closer than 3 m from communication equipment and work closer than 5 m from radar. Further questions asked about exposure to organic solvents or paint, welding or torch-cutting or working with the hull and lead. These types of exposure were considered because of the possible effects on reproductive health [24–28]. Each of these six work exposure items was asked separately for exposure in the Navy and for exposure at other workplaces or at leisure. They were formulated as "Have you ever worked with…" with response categories "not at all", "low", "some", "high", "very high" or "do not know". We combined the exposure in the Navy and exposure at other workplaces or at leisure separately for each exposure, such that the new combined exposure variables were given the highest exposure of these two. If the answer was missing or the response was "do not know" for exposure both in the Navy and outside the Navy, the combined variable was set to "missing".

Infertility was determined by a single question: "Have you and your partner ever tried to become pregnant without success for more than 1 year?" The response categories were "yes", "no" and "do not know". The analysis only included those who answered "yes" or "no" ($n = 9{,}925$, 95%).

We also asked whether the participants had biological children, and how many. For each of the children the participants should give the year of birth and gender of the child. In the analyses of sex ratio only children born the year after first employment in the Navy was included.

Some participants had probably not started their reproductive career. Two new variables were therefore defined as a combination of infertility and whether they had children. (1) Fertility problems: reported infertility and had children. (2) Involuntary childlessness: reported infertility and had no children. For both variables, we used the respondents who had not reported infertility and had

children as the reference group. For these two variables, we excluded those who did not answer the question on infertility or answered "do not know" and those who reported no problems with infertility and did not have children. Analyses including this people into the reference group did not change the results.

We also asked the participants about current smoking habits, which was categorized into ever-smokers (current smokers, former smokers and sometime smokers) or never-smokers. We dichotomized information on current alcohol consumption into >13 and ≤13 alcohol units of 4 cl. per week [29]. We obtained information on the dates employment in the Navy started and stopped from the military employment list. Age was divided into 10-years age groups, which reflect birth cohorts.

Statistics

We performed tests for linear trend between radiofrequency electromagnetic fields and infertility by Mantel–Haenszel chi-square analysis. We used logistic regression to estimate the effect of radiofrequency electromagnetic fields on infertility and whether they had biological children in two separate analyses. The estimated odds ratios (OR) with 95% confidence interval (CI) were adjusted for smoking habits, alcohol consumption and exposure to organic solvents, welding and lead. To investigate which of the three exposure variables of radiofrequency electromagnetic fields most strongly affected infertility, we included each of the radiofrequency variables and exposure to organic solvents, welding and lead, and age as continuous variables in addition to smoking habits and alcohol consumption in a backwards stepwise logistic regression.

In analyzing associations between working near high-frequency aerials and fertility problems and involuntary childlessness, we adjusted the OR for smoking habits and alcohol consumption. Adjustment for exposure to organic solvents, welding and lead did not change the estimates in the analysis of infertility, and since the number of cases with infertility problems or involuntary childlessness was relatively low we did not adjust for this exposure in analyzing these two variables.

The dose response association between exposure for radiofrequency electromagnetic fields and offspring sex ratio was analyzed by Mantel–Haenszel chi-square and the OR were estimated from an unadjusted logistic regression.

We calculated Pearson bivariate correlation coefficients to quantify the associations between the exposure variables.

To test the differences in the number of children between personnel with different exposure levels, we performed linear regression adjusted for alcohol consumption and smoking habits.

Because reproductive history depends on age, we stratified the analysis by age groups according to the respondents' age when answering the questionnaire: <29, 30–39, 40–49 and ≥50 years. Statistical significance was set at $P < 0.05$.

Results

The mean age among the 10,497 respondents was 49 years. They had joined the Navy at a mean age of 20 years and had worked in the Navy on average 11 years (Table 1). Sixty percent were ever-smokers, and 6% drank more than 13 standard alcoholic drinks per week. Among those younger then 30 years, 17% reported that they had experienced infertility, 18% of those 30–39 years old, 19% of those 40–49 years old and 12% of those 50 years or older (Table 1). The percentages refer to the study population after excluding those who did not answer the question on infertility or answered "do not know" and those who reported no problems with infertility and did not have children.

A total of 22% reported that they had been working closer than 10 m from high-frequency aerials to a "high" degree or "very high" degree; 19% worked closer than 3 m from communication equipment and 21% worked closer than 5 m from radar (Fig. 1). Exposure to lead was slightly lower, and exposure to organic solvents or paint and welding, torch-cutting or working with the hull was considerably lower. In each of the three radiofrequency exposure groups, about one fourth of the respondents reported that they had never worked close to the specific exposure.

When analyzing the relation between the exposure and infertility in the whole study population, all three radiofrequency exposure variables gave significant linear trends, with higher reported levels of exposure related to more reported infertility. The OR for infertility among those who had worked to a "low" degree closer than 10 m from high-frequency aerials relative to those who reported no work near high-frequency aerials was 1.39 (95% CI: 1.15–1.68), adjusted for age, smoking habits, alcohol consumption and exposure to organic solvents, welding and lead. The OR for "some", "high" and "very high" exposure to high-frequency aerials were 1.52 (1.25–1.84), 1.93 (1.55–2.40) and 1.86 (1.46–2.37), respectively (data not shown).

When dividing the analysis into four age groups, all three radiofrequency exposure variables showed a significant linear trend in all age groups, except for those younger than 30 years and exposed to communication equipment (Table 2). Those who reported exposure to a "high" or "very high" degree showed significantly more infertility for all three radiofrequency exposure variables in all age

Table 1 Descriptive data from all participants in two cross-sectional studies of infertility among current (2002) and former (1950–2002) employed in the Royal Norwegian Navy

				First time in Navy	Duration in Navy	Smoking		More than 13 standard alcoholic drinks per week		Infertility	
Age group	*n*	%	Mean age (years)	Mean age	Mean year	Yes	%	Yes	%	Yes	%
−29	960	9.1	25.6	19.6	5.3	377	39.4	163	17.1	30	17.3
30–39	2,276	21.7	34.9	20.0	7.7	989	43.5	96	4.3	305	17.8
40–49	2,319	22.1	44.3	19.8	12.4	1,277	55.1	113	4.9	380	18.6
50+	4,940	47.1	62.9	20.3	13.7	3,668	74.3	313	6.6	516	11.7
Total	10,495	100.0	49.3	20.0	11.4	6,313	60.1	685	6.5	1,231	14.7
Missing	2			176.0	143.0	19		242		2,151[a]	

[a] Those who did not answer the question on infertility or answered "do not know" and those who reported no problems with infertility and did not have children

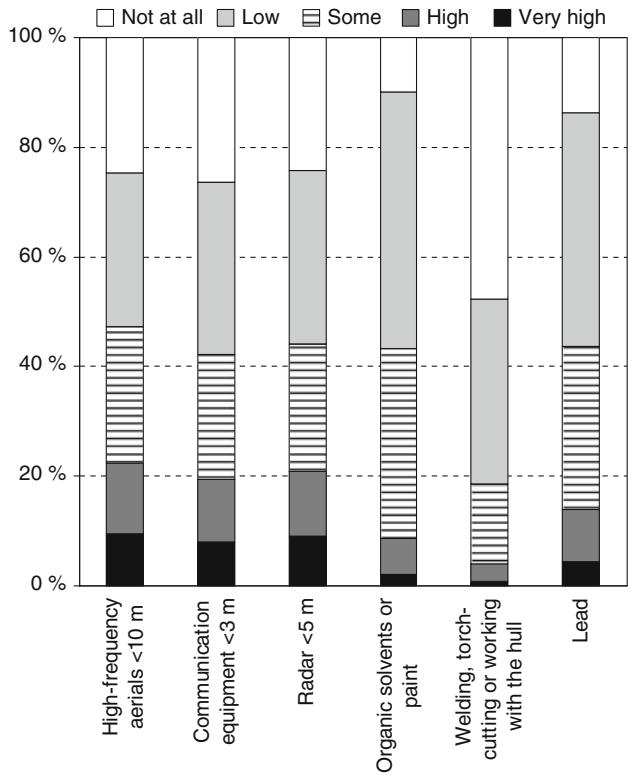

Fig. 1 Distribution of male military Navy workers working close to radiofrequency equipment, organic solvents, welding and lead in the Navy, at other workplaces or at leisure

groups, except for those younger than 30 years and exposed to communication equipment. The greatest and most significant effect was for high-frequency aerials in the two oldest age groups. Among those 40–49 years old, those reporting a "high" degree of working closer than 10 m from high-frequency aerials had an OR of 1.82 of infertility relative to "not at all", and the OR was 1.90 for "very high" relative to "not at all". The associations were similar among those 50 years or older.

The correlation coefficients between the three electromagnetic field exposure variables varied between 0.70 and 0.78. The other correlation coefficients between the six exposure variables ranged from 0.06 to 0.22, except for organic solvents and welding (0.48).

We performed stepwise backward logistic regression analysis including all three radiofrequency exposure variables as continuous variables in addition to exposure to organic solvents, welding, lead, age, smoking and alcohol consumption. The last step of this model included as significant variables working with high-frequency aerials, working with communication equipment and smoking habits. This model showed that high-frequency aerials had the strongest and most significant effect on infertility, and each step of increase in degree of self-reported exposure for high-frequency aerials increased the risk of infertility by 10% (OR = 1.10, 95% CI: 1.01–1.19).

Self-reported exposure to high-frequency aerials was also significantly related to the two constructed variables fertility problems and involuntary childlessness (Table 3). There was a significant linear trend with more fertility problems with higher exposure to high-frequency aerials in the two oldest age groups, and there was a significant linear trend between exposure to high-frequency aerials and involuntary childlessness for all age groups. Generally, the OR was higher for involuntary childlessness than for fertility problems. OR for involuntary childlessness among those who had worked closer than 10 m from high-frequency aerials to a "very high" degree relative to "not at all" were 3.14 among those 40–49 years old and 3.16 among those ≥50 years old.

Analysis of how working near communication equipment and working near radar influenced fertility problems and involuntary childlessness gave similar associations as for working near high-frequency aerials (results not given).

In our population 80% had biological children, varying from 17% among those younger than 30 years when answering the questionnaire to 92% among those 50 years

Table 2 Risk of infertility by exposure to self-reported radiofrequency electromagnetic fields in four age groups

		Work closer than 10 m from high-frequency aerials					Work closer than 3 m from communication equipment					Work closer than 5 m from radar				
		Total	Infertility				Total	Infertility				Total	Infertility			
Age (years)[a]	Degree of exposure level		%	OR[b]	95% CI[c]	*P*[d]		%	OR[b]	95% CI[c]	*P*[d]		%	OR[b]	95% CI[c]	*P*[d]
−29	Not at all	197	2.0	1.00			256	1.6	1.00			258	1.9	1.00		
	Low	256	2.3	1.10	0.30–4.07		292	2.7	1.86	0.54–6.40		318	1.9	0.87	0.25–2.99	
	Some	202	1.5	0.71	0.15–3.34	**0.013**	171	5.3	**3.56**	**1.05–12.08**	0.077	155	4.5	2.13	0.64–7.06	**0.001**
	High	114	7.0	**3.84**	**1.09–13.52**		86	4.7	3.50	0.83–14.78		88	2.3	1.11	0.20–6.00	
	Very high	144	5.6	2.70	0.76–9.53		105	3.8	2.49	0.60–10.42		93	9.7	**5.09**	**1.59–16.30**	
30–39	Not at all	368	10.9	1.00			439	9.3	1.00			411	10.0	1.00		
	Low	621	12.9	1.24	0.83–1.87		736	13.6	**1.53**	**1.04–2.26**		758	14.1	1.46	0.99–2.15	
	Some	576	14.2	1.36	0.90–2.04	**0.011**	491	16.7	**1.88**	**1.25–2.82**	**0.007**	494	13.2	1.32	0.87–2.02	**0.005**
	High	332	15.7	1.51	0.97–2.37		286	15.4	**1.76**	**1.11–2.80**		287	16.7	**1.79**	**1.14–2.82**	
	Very high	270	17.0	**1.72**	**1.08–2.74**		218	15.6	**1.80**	**1.10–2.96**		233	17.6	**1.91**	**1.19–3.07**	
40–49	Not at all	464	11.6	1.00			488	13.7	1.00			463	13.0	1.00		
	Low	684	17.4	**1.46**	**1.03–2.07**		755	15.8	1.04	0.75–1.45		755	17.2	1.22	0.87–1.71	
	Some	553	17.9	1.43	0.99–2.07	**<0.001**	534	19.3	1.28	0.91–1.81	**<0.001**	528	17.8	1.24	0.87–1.79	**0.002**
	High	286	20.6	**1.82**	**1.21–2.75**		244	19.7	1.37	0.91–2.08		247	20.6	**1.59**	**1.05–2.41**	
	Very high	184	22.8	**1.90**	**1.20–3.01**		155	25.2	**1.86**	**1.18–2.94**		195	21.5	1.50	0.95–2.35	
50+	Not at all	1312	8.5	1.00			1330	9.8	1.00			1203	9.5	1.00		
	Low	1123	10.5	1.28	0.96–1.69		1242	9.8	1.02	0.78–1.34		1249	10.2	1.11	0.84–1.46	
	Some	1042	12.6	**1.59**	**1.20–2.11**	**<0.001**	992	12.5	1.31	0.99–1.73	**<0.001**	1059	13.4	**1.58**	**1.20–2.09**	**0.001**
	High	505	15.4	**2.02**	**1.45–2.81**		463	15.1	**1.71**	**1.23–2.37**		518	12.7	1.39	0.98–1.97	
	Very high	305	15.4	**1.84**	**1.23–2.74**		293	16.0	**1.71**	**1.16–2.53**		349	13.8	**1.50**	**1.01–2.23**	

[a] Age when answering questionnaire

[b] Adjusted for smoking habits, alcohol consumption, organic solvents or paint, welding, torch-cutting or working with hull and lead. OR, Odds ratios

[c] CI, Confidence interval

[d] Test for linear trend (Mantel–Haenszel chi-square)

Statistically significant results are in bold

or older. The exposure was not linearly associated with whether they had biological children (chi-square). Nor were exposure and number of children significantly associated (linear regression). This analysis was stratified by age groups and adjusted for alcohol use and smoking habits.

A total of 18,625 children were born after the fathers have had occupation in the Navy. For both self-reported exposure to work closer then 10 m from high-frequency aerials and 3 m from communication equipment there were a significant linear trend with lower sex ratio (boys to girls births) with higher degree of exposure (Table 4). A similar, but weaker and not significant trend was seen for father's exposure to radar.

Discussion

Self-reported exposure to radiofrequency electromagnetic fields among Navy personnel was significantly and linearly associated with 1 year infertility. This applied to work close to high-frequency aerials, communication equipment and radar both for the whole population and for all age groups (except personnel younger than 30 years working close to communication equipment). The correlation with infertility was even stronger among those who were involuntarily childless. In addition there was a decrease in the offspring sex ratio, boys to girls, when the fathers reported that they had worked with a higher degree of exposure to radiofrequency fields.

Our findings on infertility are in accordance with previously findings where semen quality was reduced after occupational exposure to electromagnetic fields. In a study of 365 infertile couples, Irgens et al. found that among men occupationally exposed to electromagnetic fields (worked as welders, cooks or electricians) had reduced semen quality [10]. Another study among 31 men with long-term occupational exposure to microwaves (10,000–

Table 3 Fertility problems and involuntary childlessness by degree of self-reported exposure to high-frequency aerials in four age groups

Age (years)	Work closer than 10 m from high-frequency aerials	Total	Fertility problems[a]				Involuntary childlessness[b]			
			n	OR[c]	95% CI[d]	*P*[e]	*n*	OR[c]	95% CI[d]	*P*[e]
≤29	Not at all	47	1	1.00			3	1.00		
	Low	43	6	6.24	0.71–55.03		0	–	–	
	Some	29	1	1.41	0.08–23.93	.065	2	1.15	0.18–7.42	**0.010**
	High	24	1	2.54	0.15–43.60		7	**7.21**	**1.62–32.09**	
	Very high	26	5	**10.92**	**1.17–101.71**		3	2.23	0.40–12.40	
30–39	Not at all	278	28	1.00			12	1.00		
	Low	488	60	1.28	0.79–2.06		20	1.01	0.49–2.11	
	Some	450	54	1.23	0.76–2.00	0.194	28	1.48	0.74–2.99	**0.011**
	High	257	33	1.35	0.79–2.31		19	1.90	0.90–4.01	
	Very high	216	29	1.45	0.83–2.53		17	2.08	0.96–4.48	
40–49	Not at all	426	47	1.00			7	1.00		
	Low	628	91	1.36	0.93–1.98		28	**2.84**	**1.23–6.59**	
	Some	517	71	1.26	0.84–1.87	**0.003**	28	**3.40**	**1.46–7.91**	**0.007**
	High	266	46	**1.73**	**1.11–2.70**		13	**3.22**	**1.26–8.21**	
	Very high	169	33	**1.99**	**1.22–3.26**		9	**3.14**	**1.11–8.86**	
≥50	Not at all	1259	81	1.00			31	1.00		
	Low	1090	82	1.20	0.87–1.66		36	1.42	0.87–2.32	
	Some	1009	90	**1.40**	**1.02–1.93**	**<0.001**	41	**1.78**	**1.10–2.87**	**<0.001**
	High	487	58	**2.06**	**1.44–2.96**		20	**1.90**	**1.07–3.39**	
	Very high	290	25	1.45	0.90–2.34		22	**3.16**	**1.76–5.68**	

[a] Had children and reported infertility for 1 year

[b] No children and reported infertility for 1 year

[c] OR relative to those who have had children and reported no infertility. Adjusted for smoking habits and alcohol consumption. OR, Odds ratio

[d] CI, Confidence interval

[e] Test for linear trend (Mantel–Haenszel chi-square)

Statistically significant results are in bold. The analysis excludes those who did not answer the question on infertility or answered "do not know" and those who reported no problems with infertility and did not have children

3,600 MHz) also reported significantly reduced sperm quality compared with 30 controls [11].

Recently, male reproductive health and the use of mobile phones have been studied. In an in vitro study [16], semen samples from each of the 27 men participating were divided in two parts. One part was exposed to an activated 900 MHz cellular phone and the other part was unexposed. The exposed group had significantly decreased sperm motility. A study in Australia found significantly lower sperm motility and sperm concentration among 52 men who carried mobile phone close to the testes compared with those who did not [17]. Another study of 371 men also associated reduced sperm motility with prolonged use of mobile phones, information of use of hands free was not available in this study [18].

In addition, a study among soldiers who had experienced microwave exposure as radar equipment operators (intelligence radar) showed significantly lower sperm counts and a lower percentage of motile sperm than the comparison group [12]. Another military study reported reduced semen quality ($P = 0.07$) among 19 men operating military missile tracing radar compared with other non-military workers [13]. In contrast, soldiers exposed to communication radar in the military had no significantly reduced semen quality [14]. Schrader et al. [14] suggested that the differences in the results were caused by low exposure in their study [14]. However, some of these studies [11, 12, 14] were based on volunteers and may therefore be biased. Grajewski et al. [15] measured several parameters of semen quality and hormone levels among 12 men exposed to non-ionizing radiation and 34 men without such exposure. The groups differed slightly in semen quality and hormone levels, but a low participation rate and multiple testing make the results unreliable.

The effect of radiofrequency electromagnetic exposure on sex ratio of offspring has been debated lately [23, 30]. Several studies have reported a decrease in sex ration of offspring, with less boys borne, but these studies are small [20–23] and only one of these studies has shown significant findings [22]. Opposite to these findings Mjoen et al. [31]

Table 4 Sex ratio of offspring by father's exposure to self-reported radiofrequency electromagnetic fields

Exposure	Degree of exposure level	Children[a]		Boys			
		N	%	%	OR	95% CI	*P*[b]
Work closer then 10 m from high-frequency aerials	Not at all	4595	25.9	52.1	1.00		
	Low	4898	27.6	51.8	0.99	0.91–1.07	
	Some	4528	25.5	52.6	1.02	0.94–1.11	**0.008**
	High	2282	12.8	50.0	0.91	0.83–1.01	
	Very high	1457	8.2	47.6	**0.84**	**0.74–0.94**	
	Total	17760	100.0				
Work closer then 3 m from communication equipment	Not at all	4738	26.5	51.9	1.00		
	Low	5610	31.4	52.2	1.01	0.94–1.09	
	Some	4222	23.7	51.8	0.99	0.92–1.08	**0.031**
	High	1991	11.2	50.2	0.93	0.84–1.04	
	Very high	1286	7.2	48.1	**0.87**	**0.77–0.98**	
	Total	17847	100.0				
Work closer then 5 m from radar	Not at all	4321	24.0	52.2	1.00		
	Low	5612	31.1	51.7	0.98	0.90–1.06	
	Some	4377	24.3	52.0	0.99	0.91–1.08	0.062
	High	2158	12.0	48.8	**0.87**	**0.79–0.97**	
	Very high	1559	8.6	50.9	0.93	0.83–1.05	
	Total	18027	100.0				

[a] Children borne after first occupation in the Navy

[b] Test for linear trend (Mantel–Haenszel chi-square)

Statistically significant results are in bold

reported recently a borderline significant increase in proportion of males borne by fathers possible exposed to radiofrequency electromagnetic fields. This study was a large register study, but the exposure classification was very crude and may have led to misclassification.

Radiofrequency electromagnetic radiation may have both thermal and non-thermal effects. There is no agreement on which might be most important for possible adverse effects on reproductive health. The effects caused by temperature rise are basically understood; this may reduce sperm quality [32]. However, the existence of non-thermal effects is more hotly debated. Foster [33] discussed that radiofrequency electromagnetic radiation could have effects on the cell membrane excitation and breakdown and also direct electrical forces on cells or cell constituents in addition to thermal effects on biological systems. Fejes et al. [18] have formulated two hypotheses on how radiofrequency radiation may affect male fertility. One suggests that the testis is affected by a change in melatonin level. The other hypothesis is that radiofrequency radiation may cause DNA damage in the genital tract.

Sex ratio at birth is related to a number of different mechanisms, among them changes in hormone profile [34]. A lowered ratio of testosterone/gonadotrophin in male has been suggested to be causally associated with lower sex ratio in offspring [30]. The lowered hormone ratio is also reported among men exposed to radiofrequency radiation [15].

We focused on non-ionizing radiation, but the workers may have been exposed to other factors as well. A study in Germany [35] described ionizing radiation related to three types of radar in Germany's army. However, the Norwegian Navy has not used any of these types of radar [36], and we have no knowledge about exposure to ionizing radiation in our population.

Our study participants reported exposure both at work and outside work, which is a strength. However, the exposure was rather roughly described and includes no objective measures so the relevance of the findings for similar exposure in civilian setting is difficult. The three different sources of exposure to radiofrequency radiation were highly correlated and seem to coexist to a high degree. This makes them difficult to separate. Further, exposure to non-ionizing electromagnetic fields at lower frequencies may have been present. No information on the duration of the exposure was obtained nor whether the specific exposure had taken place before planning a pregnancy or whether they were exposed at the time they tried to achieve pregnancy. However, we can assume that the participants had been exposed to radiofrequency radiation

before they started family planning, as most of the exposure was reported from their work in the Navy and the vast majority began in the Navy (mean age 20 years) before they started their reproductive career.

Duty on board a ship often means long journeys away from home. Sailing time was not measured and might have been a confounding factor since such long journeys could be related to reduced possibility of conceiving, and since we assume that the exposure was highest on board ships. Nevertheless, since exposure to all three electromagnetic field variables was likely associated with time on board ships, adjusting for one of the electromagnetic field variables might therefore be considered as a proxy adjustment for being on board a ship. The effect of high-frequency aerials was not reduced when adjusted for exposure to communication equipment. This indicates that our findings are unlikely to be an effect of long periods away from home.

The response rate was 63%, but the prevalence of infertility of 15% among the responders was in accordance with other studies of infertility [37, 38] and does not indicate that those with infertility problems were over-represented in our study.

In a cross-sectional survey, there are several potential sources for bias. The information about exposure and outcome was self-reported and obtained from the same questionnaire. Common method bias was therefore possible: a person reporting high exposure might tend to over report the outcome. In addition, there may have been recall bias: a person with a negative outcome might remember exposure better. However, since the exposure was classified from not at all to a very high degree and the results showed significant linear trends for all age groups, ascribing all the results to bias is less likely. Further, the fact that the effect of exposure to high-frequency aerials did not change when adjusted for other types of radiofrequency exposure indicates that common method bias cannot explain all the results. Finally the effect on the sex ratio cannot be ascribed common method bias or recall bias and it has been clamed that offspring's sex ratio for this reason has an advantage as a monitor of reproductive hazard [19].

Although infertility increased among men exposed to radiofrequency electromagnetic fields, the degree of exposure was not related to the proportion of respondents reporting having children. Further, the mean number of children was the same in the exposure subgroups. However, the number of children is not solely a biological issue. Today it is also a social decision, due to family planning, and the number of children is therefore not an optimal measure of fertility as a health parameter. Also, an effect of occupational factors might be temporary. One study has reported that, among men with long-term occupational microwave exposure, two thirds had improved spermatogenesis after 3 months without the exposure [11].

In conclusion, increasing self-reported work near equipment emitting radiofrequency electromagnetic fields among Navy personnel was significantly linearly associated with more reported infertility. Among those who had no children, the association was even stronger. The offspring's sex ratio showed a significant linear trends with lower ratio of boys to girls at birth when the father reported a higher degree of exposure to high-frequency aerials and communication equipment.

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