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Original Contribution

Modeled and Perceived Exposure to Radiofrequency Electromagnetic Fields From Mobile-Phone Base Stations and the Development of Symptoms Over Time in a General Population Cohort

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We assessed associations between modeled and perceived exposure to radiofrequency electromagnetic fields (RF-EMF) from mobile-phone base stations and the development of nonspecific symptoms and sleep disturbances over time. A population-based Dutch cohort study, the Occupational and Environmental Health Cohort Study (AMIGO) ($n = 14{,}829$; ages 31–65 years), was established in 2011/2012 (T_0), with follow-up of a subgroup ($n = 3{,}992$ invited) in 2013 (T_1; $n = 2{,}228$) and 2014 (T_2; $n = 1{,}740$). We modeled far-field RF-EMF exposure from mobile-phone base stations at the home addresses of the participants using a 3-dimensional geospatial model (NISMap). Perceived exposure (0 = not at all; 6 = very much), nonspecific symptoms, and sleep disturbances were assessed by questionnaire. We performed cross-sectional and longitudinal analyses, including fixed-effects regression. We found small correlations between modeled and perceived exposure in AMIGO participants at baseline ($n = 14{,}309$; $r_{\text{Spearman}} = 0.10$). For 222 follow-up participants, modeled exposure increased substantially (>0.030 mW/m^2) between T_0 and T_1. This increase in modeled exposure was associated with an increase in perceived exposure during the same time period. In contrast to modeled RF-EMF exposure from mobile-phone base stations, perceived exposure was associated with higher symptom reporting scores in both cross-sectional and longitudinal analyses, as well as with sleep disturbances in cross-sectional analyses.

cell phones; geospatial model; mobile-phone base stations; nonspecific symptoms; perceived exposure; prospective cohort studies; radiofrequency electromagnetic fields; sleep disturbances

Abbreviations: AMIGO, Occupational and Environmental Health Cohort Study; CI, confidence interval; 4DSQ-S, somatization scale of the Four-Dimensional Symptom Questionnaire; EMF, electromagnetic field; MOS, Medical Outcomes Study; RF-EMF, radiofrequency electromagnetic fields.

Exposure to radiofrequency electromagnetic fields (RF-EMF) from mobile-phone base stations has increased rapidly in the last several decades. Biological mechanisms responsible for health effects at everyday exposure levels are unknown. Systematic reviews (1–4) have found no consistent associations between modeled RF-EMF exposure and any individual symptoms or groups of symptoms. A part of the general population (1.5%–10%) (5, 6) attributes symptoms such as sleep disturbances, headaches, or dizziness to electromagnetic field (EMF) exposure. It is suspected that there may also be psychosocial mechanisms involved (7–10). People have little control over exposure to RF-EMF from mobile-phone base stations, and in combination with uncertainty about potential health risks, this can lead to concern (11, 12) and increased symptom reporting.

Different types of studies have been applied to evaluate effects of RF-EMF exposure from mobile-phone base stations on symptoms: laboratory studies (13, 14) and observational studies (15, 16). An important limitation of laboratory studies is that only acute effects of short-term exposure can be evaluated. A limitation of observational epidemiologic studies is that exposure assessment is often inaccurate.

Simple proxies have been used for exposure assessment, such as the distance between fixed-site transmitters and the home address (17, 18), but these are not sufficiently accurate (19, 20). Use of a 3-dimensional geospatial model is currently the preferred method for assessing personal exposure to far-field RF-EMF exposure from base stations in large populations (19, 21), but application of these models in epidemiologic studies has so far been limited. In addition, most observational studies have been cross-sectional, limiting causal inference. Longitudinal studies with accurate exposure assessment are needed to resolve uncertainty about the potential association between far-field RF-EMF exposure and health outcomes (22).

In a cross-sectional study (16) carried out among the general population in the Netherlands, over 20% of the participants reported high or extremely high levels of worry about potential health effects from RF-EMF exposure to mobile-phone base stations. This study also found that perceived exposure was associated with a higher number of nonspecific symptoms when accounting for modeled RF-EMF and extremely-low-frequency magnetic field exposure. Numerous other studies found associations between symptom reporting and different perceptions (e.g., perceived exposure, perceived risk, worry, concerns, annoyance, or modern health worries) with regard to EMFs (4, 9, 16, 23–26) but also with regard to other potential environmental risks (27–32), such as perceived infrasound exposure from wind turbines and perceived air quality. However, most of these studies were cross-sectional, and many did not consider actual exposure. One explanation for the association between EMF perceptions and symptom reporting could be a nocebo mechanism, which postulates: The expectation that negative health effects may occur upon exposure can lead to more symptoms. Evidence for this mechanism was seen in provocation studies with sham exposure (9, 26). Conversely, the experience of symptom distress may lead to a search for a cause of these symptoms (33, 34) and increased attention to potential exposures. Attention focusing can amplify the perception of physical signals, a process described as somatosensory amplification (26, 35, 36). Biochemical and psychosocial mechanisms may mutually influence each other (37), and therefore there is added value in considering both modeled and perceived exposure in relation to health outcomes simultaneously and longitudinally.

This is what we set out to do in this prospective cohort study with respect to modeled and perceived exposure to RF-EMF from mobile-phone base stations and self-reported nonspecific symptoms and sleep disturbances. Figure 1 shows a diagram of the possible relationships between the variables of interest. The main research questions that are addressed in this paper are: 1) Is there an association between modeled and perceived exposure to RF-EMF from mobile-phone base stations? and 2) How are modeled and perceived exposure associated with nonspecific symptoms and sleep disturbances over time? We improve upon previous studies by way of our longitudinal design, and by the combination of modeled exposure and self-reported perceived exposure, in a large study sample nested within a community-based cohort that was not recruited specifically for EMF-related questions.

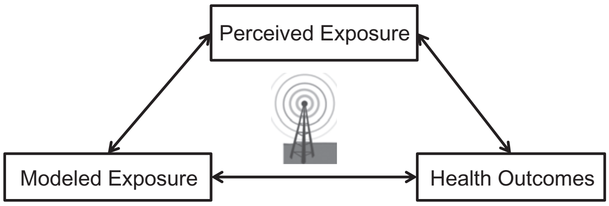

Figure 1. Possible associations between modeled and perceived exposures to far-field radiofrequency electromagnetic fields from mobile-phone base stations and health outcomes (nonspecific symptoms and sleep disturbances).

METHODS

Population

This study was nested in the Occupational and Environmental Health Cohort Study (AMIGO) cohort, which was set up to study environmental and occupational determinants of diseases and symptoms in the Dutch population (participants were aged 31–65 years; see Slottje et al. (38) for a full description). From the full cohort, that is, all participants who were eligible to participate and completed the study questionnaire at baseline (T_0 = 2011/2012; n = 14,829), we invited a subgroup (n = 3,992) to complete 2 follow-up questionnaires (in 2013 (T_1) and 2014 (T_2)). We based the selection criteria for this subgroup on modeled and perceived exposure to RF-EMF from mobile-phone base stations at baseline in order to achieve exposure contrast: a random selection of 1,429 persons with modeled exposure less than 0.0265 mW/m^2 and perceived exposure (on a scale of 0–6) less than 2; all subjects with modeled exposure less than 0.0265 mW/m^2 and perceived exposure greater than 1 (n = 1,272); all subjects with modeled exposure greater than or equal to 0.0265 mW/m^2 and perceived exposure less than 2 (n = 1,069); and all subjects with modeled exposure greater than or equal to 0.0265 mW/m^2 and perceived exposure greater than 1 (n = 222). Only subjects who participated at T_1 (n = 2,228; response rate 56%) were invited to complete the T_2 questionnaire (n = 1,740; response rate 78%).

Modeled exposure

RF-EMF exposure to mobile-phone base stations at the participant's geocoded home address was modeled with the 3-dimensional geospatial model NISMap (39, 40). The applicability of this model for epidemiologic studies has been described in a number of previous studies (21, 39–43). The model uses detailed information about 3-dimensional building data, topography, home coordinates, bedroom elevation (exposure measured 1.5 m above floor height), antenna location, antenna characteristics, and radiation patterns to compute the field strength of GSM900 (Global System for Mobile Communications; European Telecommunications Standards Institute, Sophia-Antipolis, France), GSM1800, and UMTS (Universal Mobile Telecommunications System; 3rd Generation Partnership Project) mobile-phone frequencies. Antenna locations and characteristics were not available for the year 2014, and therefore the exposure estimate changed in comparison with 2013 only in the case of a different home address or bedroom elevation. Therefore, analyses with modeled exposure as the predictor of interest were carried out only for T_0, T_1, and the time interval T_0–T_1. We calculated the total modeled downlink exposure in mW/m^2 by summing GSM 900, GSM 1800, and UMTS modeled values (i.e., at the time of the study, LTE (Long Term Evolution; European Telecommunications Standards Institute) communication was not available in the Netherlands). We did not model exposure at work, because subjects in general spend less than 30% of their time at work, and because exact locations at work are uncertain, particularly for professions that are not bound to one location (e.g., drivers or builders).

Perceived exposure

Perceived exposure was measured at all time points (T_0, T_1, and T_2) with the question: "To what extent are you exposed to (electromagnetic fields/radiation from) base stations for mobile phones, radio, or television (on a scale of 0–6, where 0 = not at all and 6 = very much)?" Although we did not model exposure to base stations for radio and television, we expected that participants might not be able to distinguish between different types of RF-EMF-emitting base stations, and therefore we included all types of emitters in the perceived exposure question.

Health outcomes

We assessed 2 self-reported health outcomes at T_0, T_1, and T_2: nonspecific symptoms and sleep disturbances. Similar to another study on EMFs and symptoms (44), we used the total symptom score from the somatization scale of the Four-Dimensional Symptom Questionnaire (4DSQ-S) (45), which consists of 16 nonspecific somatic symptoms (e.g., headaches, low back pain, and dizziness) commonly reported in general medical practices. According to the Four-Dimensional Symptom Questionnaire manual (45), participants indicated for each symptom whether they had been bothered by it during the previous week on a 5-point scale (ranging from "no" to "constantly"). The scores per symptom were trichotomized and then summed over the symptoms to obtain a total score (no = 0; sometimes = 1; regularly/often/constantly = 2). Sleep disturbances were measured using the Sleep Scale of the Medical Outcomes Study (MOS). Based on the responses to 6 sleep items, a scale score (Sleep Problems Index 1: 0–100) was calculated following the instructions described by Spritzer and Hays (46). Higher scores indicate more sleep disturbances or lower sleep quality.

Covariates

General information about age, sex, and education was gathered by questionnaire at baseline. We gathered information about neighborhood income (percentage of income earners with a low income in the neighborhood) as an indication of neighborhood socioeconomic status and information about degree of urbanization from the Dutch Central Bureau of Statistics in 2012 (key figures neighborhoods).

Statistical analysis

To answer the first research question, we computed the Spearman correlation coefficient for the correlation between modeled and perceived exposure in the full AMIGO cohort. Secondly, we applied linear regression in the subgroup to examine whether participants with an increase in modeled exposure of at least 0.030 mW/m^2 between T_0 and T_1 (the cutoff point based on the 90th percentile of the distribution of absolute change in modeled RF-EMF exposure to mobile-phone base stations) experienced a different change in perceived exposure than the reference group (no change in modeled exposure).

The data from all questionnaires (T_0, T_1, and T_2) were then combined and analyzed using mixed-effects regression models (unstructured covariance structure), clustered at the subject level, with a fixed effect for year to adjust for temporal population trends in health outcomes. Four type of models were used in the subgroup to assess cross-sectional and longitudinal associations between perceived and/or modeled exposure with health outcomes: 1) cross-sectional analyses, 2) cohort analyses, 3) change analyses, and 4) fixed-effects analyses. The cross-sectional analyses were also conducted in the full cohort at baseline. In the cohort analyses, we assessed the association between exposure and change in symptoms during the subsequent year. In the change analyses, we examined whether change in exposure over a 1-year period was associated with change in health outcome over the same time period. Perceived exposure and health outcomes were analyzed as continuous variables. Change scores were calculated by subtracting the score between 2 consecutive years (i.e., $T_1 - T_0$ and $T_2 - T_1$). Because of the skewed distribution of modeled exposure, it was analyzed dichotomously in the cross-sectional, cohort, and fixed-effects analyses. The cutoff point was based on the distribution of modeled total downlink exposure at baseline in the full cohort (low: <90th percentile; high: 90th–100th percentiles; cutoff point: 0.050 mW/m^2). For the change analyses, we created a variable with 3 categories of modeled exposure based on the distribution of the absolute change in modeled exposure between T_0 and T_1. We compared the study participants with the 10% largest decrease (upper cutoff point: -4.571×10^{-4} mW/m^2) and the 10% largest increase (lower cutoff point: 0.030 mW/m^2) with the remaining 80% (reference group) for the time interval $T_1 - T_0$. All models included adjustment for sex, age, education, urbanization, and neighborhood income at baseline, with or without additional adjustment for exposure (i.e., perceived exposure adjusted for modeled exposure and vice versa).

Finally, we applied fixed-effects regression models (47) (outcome variables 4DSQ-S score and MOS sleep index, respectively) with the predictors perceived exposure (continuous) and modeled exposure (dichotomous). An advantage of this model is that it controls for all stable characteristics of an individual, regardless of whether they are measured or not. However, there is a potential disadvantage for the estimation of the effect of a change in modeled exposure, as an increase in modeled exposure is assumed to have the exact opposite effect of a decrease in modeled exposure, which is not necessarily true.

Missing values (full cohort: ≤4%; subgroup: <1%) were replaced with the most common category (categorical variables) or with the mean value (continuous variables). Analyses were carried out using SAS (SAS Institute, Inc., Cary, North Carolina).

RESULTS

Table 1 lists the baseline characteristics of the full cohort (n = 14,829) and the subgroup (n = 3,992) at baseline. Demographic characteristics were similar in the full cohort and the subgroup. Exposure and health characteristics at baseline and follow-up are shown in Table 2. Perceived and modeled exposure were higher in the subgroup than in the full cohort as a consequence of the selection method we applied to increase exposure contrast. There were no significant differences for mean modeled exposure (t test: $t = 0.16$, $P = 0.88$) or perceived exposure (t test: $t = 1.80$, $P = 0.07$) at baseline between subgroup participants who completed all follow-up questionnaires and participants who did not complete both follow-up questionnaires. The distribution of change scores from perceived exposure, 4DSQ-S, and MOS sleep index are shown in Web Figure 1 (available at https://academic.oup.com/aje).

We found small correlations between modeled and perceived exposure in the full cohort at baseline ($r_{\text{Spearman}} = 0.10$). We compared participants with an increase in modeled exposure between T_0 and T_1 (absolute change >0.030 mW/m^2; n = 222) with the reference group (10th–90th percentiles of the absolute change in modeled exposure; n = 1,779) and found a positive association with change in perceived exposure in the same time period (increase in β_{modeled} = 0.31 (95% confidence interval (CI): 0.11, 0.50), $P < 0.01$). For most of these participants with an increase in modeled exposure, this change was due to changes in antennas in the vicinity of their home address; only 15 (7%) of these participants had moved to a new address.

The cross-sectional analyses conducted in the full cohort at T_0 (Table 3) and in the subgroup (Table 4) showed that perceived exposure but not modeled exposure was significantly positively associated with both nonspecific symptoms and sleep disturbances. In the cohort analyses, we found no associations between either modeled or perceived exposure and change in nonspecific symptoms or sleep disturbances 1 year later (Table 4). In the longitudinal change analyses in the subgroup (Table 4), an increase in perceived exposure but not modeled exposure was associated with an increase in nonspecific symptoms but not sleep disturbances over the same time interval. These results were consistent with the

Table 1. Baseline Characteristics (T_0) of the AMIGO Cohort, Including a Subgroup Also Invited to Complete 2 Additional Follow-Up Questionnaires (T_1 and T_2), in a Study of Modeled and Perceived Radiofrequency Electromagnetic Field Exposure From Mobile-Phone Base Stations in Relation to Nonspecific Symptoms and Sleep Disturbances, the Netherlands, 2011/2012

	Full Cohort (n = 14,829)			Subgroup (n = 3,992)		
	No. of Persons	**%**	**Mean (SD)**	**No. of Persons**	**%**	**Mean (SD)**
Sex						
Male	6,561	44.2		1,755	44.0	
Female	8,268	55.8		2,237	56.0	
Age, years			50.6 (9.4)			50.2 (9.5)
Education[a]						
Low	4,546	30.7		1,123	28.1	
Middle	4,627	31.2		1,239	31.0	
High	5,656	38.1		1,630	40.8	
Neighborhood SES			39.4 (6.9)			39.5 (7.4)
Urbanization[b]						
Very high	1,263	8.5		516	12.9	
High	3,307	22.3		1,236	31.0	
Moderate	3,228	21.8		972	24.3	
Low	3,615	24.4		867	21.7	
Very low	3,416	23.0		401	10.0	

Abbreviations: AMIGO, Occupational and Environmental Health Cohort Study; SD, standard deviation; SES, socioeconomic status.

[a] Low = primary school/vocational education/community college; intermediate = vocational education/high school; high = college/university or higher.

[b] Very high = average of >2,500 addresses/km^2; high = average of 1,500–2,500 addresses/km^2; moderate = average of 1,000–<1,500 addresses/km^2; low = average of 500–<1,000 addresses/km^2; very low = average of <500 addresses/km^2.

Table 2. Modeled and Perceived Exposure to Radiofrequency Electromagnetic Fields From Mobile-Phone Base Stations and Symptom Characteristics in the Full AMIGO Cohort (T_0) and a Selected Subgroup Invited to Complete 2 Follow-Up Questionnaires (T_1 and T_2), the Netherlands, 2011–2014

Variable	Full Cohort (T_0) ($n = 14{,}829$)		Subgroup					
			T_0 ($n = 3{,}992$)		T_1 ($n = 2{,}228$)		T_2 ($n = 1{,}740$)[a]	
	Exposure, mW/m^2	Mean (SD)	Exposure, mW/m^2	Mean (SD)	Exposure, mW/m^2	Mean (SD)	Exposure, mW/m^2	Mean (SD)
Modeled RF-EMF exposure								
Percentile 10	0.000		0.000		0.000		0.000	
Percentile 25	0.000		0.001		0.001		0.001	
Percentile 50	0.001		0.007		0.009		0.009	
Percentile 75	0.013		0.040		0.051		0.050	
Percentile 90	0.050[b]		0.121		0.146		0.137	
Perceived exposure[c]		1.0 (1.2)		1.8 (1.6)		1.9 (1.6)		1.8 (1.6)
4DSQ-S score		5.9 (5.2)		6.4 (5.5)		6.2 (5.2)		6.1 (5.1)
MOS sleep index score		27.4 (14.8)		28.3 (15.3)		28.2 (14.7)		27.1 (14.3)

Abbreviations: AMIGO, Occupational and Environmental Health Cohort Study; 4DSQ-S, somatization scale of the Four-Dimensional Symptom Questionnaire; MOS, Medical Outcomes Study; RF-EMF, radiofrequency electromagnetic field; SD, standard deviation.

[a] Transmitter locations and characteristics were not available in 2014; therefore, transmitter data from 2013 were used.

[b] Cutoff point for cross-sectional and cohort analyses.

[c] Perceived exposure was measured on a scale of 0–6, where 0 = not at all and 6 = very much.

results of the fixed-effects models for both nonspecific symptoms ($\beta_{\text{perceived}} = 0.13$ (95% CI: 0.05, 0.21), $P < 0.01$; $\beta_{\text{modeled}} = 0.20$ (95% CI: −0.35, 0.75), $P = 0.47$) and sleep disturbances ($\beta_{\text{perceived}} = 0.09$ (95% CI: −0.14, 0.32), $P = 0.48$; $\beta_{\text{modeled}} = -0.32$ (95% CI: −1.97, 1.33), $P = 0.70$).

DISCUSSION

In this prospective cohort study, we investigated the association between modeled and perceived exposure to RF-EMF from mobile-phone base stations and self-reported health outcomes, that is, nonspecific symptoms and sleep disturbances. The small correlation between modeled and perceived exposures enabled the investigation of these 2 measures as conceptually separate predictors for health outcomes. Our results gave no indication that modeled RF-EMF exposure from mobile-phone base stations was associated with health outcomes. On the contrary, perceived exposure was associated with higher nonspecific symptom scores as well as more reported sleep disturbances.

Interpretation of findings

The lack of an association between low modeled RF-EMF exposure levels from mobile-phone base stations in the home environment and health outcomes in both the cross-sectional and the longitudinal analyses is in line with most recent previous studies (15, 16, 48). However, modeled exposure may be associated with certain symptoms but not with the total symptom score. We therefore explored this in secondary cross-sectional logistic regression analyses, for each of the symptoms in the 4DSQ-S scale separately in the full cohort (Web Table 1). Two symptoms (dizziness and pressure or tightness in the chest) were slightly more likely to be reported by exposed participants than by nonexposed participants, but not significantly after adjustment for multiple testing.

Visible exposure sources such as antennas may influence to some extent whether participants think they are exposed, resulting in a weak correlation between modeled and perceived exposure in this study. Interestingly, a substantial increase in modeled exposure during a 1-year period was associated with a change in perceived exposure, suggesting that some participants were aware of changes in their environment such as the placement of new antennas.

Perceived exposure was associated with worse health outcomes in both cross-sectional analyses (4DSQ-S and MOS sleep index) and longitudinal-change and fixed-effects analyses (4DSQ-S scores only). Perceived exposure may be influenced by visual cues related to actual exposure, although other factors such as affective reactions to the environment could be more important. Previous studies (49, 50) found that most people have little knowledge about RF-EMF exposure, which can explain the small correlation between modeled and perceived exposures. Not only the perception of being exposed but also the belief that exposure may be harmful, the extent to which someone feels concerned about exposures or symptoms, and a number of social and personal factors are probably important in determining whether someone develops and/or reports symptoms (10, 26, 51, 52). Higher symptom scores

Table 3. Associations of Modeled and Perceived Exposure to Radiofrequency Electromagnetic Fields From Mobile-Phone Base Stations With Nonspecific Symptoms and Sleep Disturbances (Linear Regression Analyses) in the Full AMIGO Cohort ($n = 14,829$) at Baseline, the Netherlands, 2011/2012

Predictor	Outcome											
	4DSQ-S Score						MOS Sleep Index					
	Adjusted[a] β	95% CI	*P* Value	Unadjusted[b] β	95% CI	*P* Value	Adjusted[a] β	95% CI	*P* Value	Unadjusted[b] β	95% CI	*P* Value
Perceived exposure (0–6)	0.54	0.47, 0.61	<0.0001	0.54	0.47, 0.61	<0.0001	1.27	1.08, 1.46	<0.0001	1.28	1.09, 1.47	<0.0001
Modeled exposure (dichotomous)	0.19	−0.07, 0.45	0.1610	0.37	0.10, 0.64	0.0075	0.56	−0.21, 1.33	0.1539	0.98	0.21, 1.75	0.0129

Abbreviations: 4DSQ-S, somatization scale of the Four-Dimensional Symptom Questionnaire; CI, confidence interval; MOS, Medical Outcomes Study.

[a] Adjusted for modeled exposure and perceived exposure, respectively. In addition, all analyses adjusted for baseline values of sex, age, education, neighborhood socioeconomic status, and urbanization.

[b] Adjusted only for baseline values of sex, age, education, neighborhood socioeconomic status, and urbanization.

are associated with lower health-related quality of life and increased use of health-care services (53, 54). Adequate risk communication can improve understanding of EMF exposure in the general population (50) and may prevent the development and/or increased reporting of symptoms, in part. However, the pathways between perceived exposure and symptoms may be bidirectional, or perhaps experiencing symptoms typically precedes concern about environmental exposures (33, 34). This may partly explain why our longitudinal cohort analyses did not show temporal precedence of perceived exposure before an increase in symptoms. Other explanations for this effect may be a shorter lag period or ceiling effects. Subjects with higher perceived exposure already had higher symptom scores at baseline and were therefore less likely to report even higher symptom scores in the following questionnaire.

Despite our finding that modeled RF-EMF exposure from mobile-phone base stations was not associated with health outcomes, it remains important to consider the role of both RF-EMF exposure sources in the environment and perceived exposure. Our results suggest that especially a change in the presence of antennas in the home environment may increase perceived exposure, and possibly also indirectly influence symptom scores in individuals. Complicated relationships between exposure sources, actual exposure, perception, and the development of symptoms also exist for other environmental exposures. For noise exposure, prior studies found that the association between modeled exposure to noise from road traffic and symptom score was mediated by noise annoyance (55, 56). There is a need for more multidisciplinary studies that consider the role of both actual environmental exposures and perception in relation to self-reported health outcomes.

Strengths

Our study design had several strengths, allowing for robust conclusions regarding potential effects of perceived and modeled exposure to mobile-phone base stations on the experience of nonspecific symptoms and sleep disturbances. The main strength of our study was the prospective design. Secondly, the study sample was large, and we oversampled highly exposed subjects, which produced adequate statistical power for assessment of potential health effects of RF-EMF from mobile-phone base stations in the general population. Thirdly, the AMIGO cohort (38) was set up with the broad purpose of studying occupational and environmental exposures in relation to health outcomes in the general population. Therefore, the participants were not aware of the focus on EMFs. Finally, we used the NISMap model, with detailed input data (home coordinates, bedroom elevation, antenna characteristics), to estimate RF-EMF exposure to mobile phones in the bedroom at the home address. NISMap is able to meaningfully rank participants on modeled exposure (21, 40, 41, 43), although there can be substantial misclassification.

Table 4. Associations of Modeled and Perceived Exposure to Radiofrequency Electromagnetic Fields From Mobile-Phone Base Stations With Nonspecific Symptoms and Sleep Disturbances (Mixed Models) in the AMIGO Subgroup Invited to Complete 2 Follow-Up Questionnaires (T_0: $n = 3{,}992$; T_1: $n = 2{,}228$; T_2: $n = 1{,}740$), the Netherlands, 2011–2014

Predictor	Outcome											
	4DSQ-S Score						MOS Sleep Index					
	Adjusted[a] β	95% CI	*P* Value	Unadjusted[b] β	95% CI	*P* Value	Adjusted[a] β	95% CI	*P* Value	Unadjusted[b] β	95% CI	*P* Value
Cross-sectional analyses												
Perceived exposure	0.28	0.22, 0.35	<0.0001	0.28	0.22, 0.35	<0.0001	0.53	0.34, 0.72	<0.0001	0.53	0.35, 0.72	<0.0001
Modeled exposure	0.06	−0.26, 0.37	0.7170	0.05	−0.27, 0.37	0.7588	−0.49	−1.39, 0.41	0.2858	−0.52	−1.42, 0.39	0.2625
Cohort analyses												
Perceived exposure	−0.03	−0.09, 0.03	0.3508	−0.03	−0.09, 0.03	0.3493	−0.02	−0.2, 0.16	0.8269	−0.02	−0.2, 0.16	0.8268
Modeled exposure	0.10	−0.12, 0.31	0.3900	0.10	−0.12, 0.31	0.3881	0.02	−0.62, 0.66	0.9458	0.02	−0.62, 0.66	0.9456
Change analyses[c]												
Change in perceived exposure	0.14	0.06, 0.22	0.0007	0.14	0.06, 0.23	0.0006	0.08	−0.16, 0.32	0.5005	0.08	−0.16, 0.32	0.4986
Change in modeled exposure[d,e]												
Decrease	−0.33	−0.86, 0.21	0.2271	−0.33	−0.86, 0.21	0.2271	−0.56	−2.18, 1.07	0.5016	−0.57	−2.19, 1.05	0.4908
Increase	0.29	−0.24, 0.83	0.2831	0.29	−0.24, 0.83	0.2823	−0.18	−1.81, 1.45	0.8280	−0.21	−1.84, 1.41	0.7983

Abbreviations: 4DSQ-S, somatization scale of the Four-Dimensional Symptom Questionnaire; CI, confidence interval; MOS, Medical Outcomes Study.

[a] Adjusted parameter estimates were adjusted for modeled exposure and perceived exposure, respectively. In addition, analyses were adjusted for baseline values of sex, age, education, neighborhood socioeconomic status, and urbanization, with a fixed effect for year to adjust for temporal population trends in health outcomes.

[b] Unadjusted parameter estimates were adjusted only for baseline values of sex, age, education, neighborhood socioeconomic status, and urbanization, with a fixed effect for year to adjust for temporal population trends in health outcomes.

[c] The parameter estimates in the change analyses represent the change in 4DSQ-S score and MOS sleep index, respectively.

[d] Estimates and *P* values for the decrease and increase in modeled exposure, respectively, versus the reference group (10th–90th percentiles of the absolute change in modeled exposure: -4.571×10^{-4} mWm^2 to 0.030 mWm^2).

[e] The transmitted data that were required as input data for NISMap model estimation were unavailable at T_2; therefore, regression coefficients for modeled exposure are provided only for T_0 and T_1 and the time interval T_0–T_1.

Limitations

This study had limitations. Importantly, RF-EMF exposure at locations other than the home address was unknown. Secondly, differential recall bias of perceived exposure may occur for participants with high symptom scores, potentially resulting in overestimation of the association between perceived exposure and health outcomes. In contrast to modeled exposure, the measure of perceived exposure also included perceived exposure to RF-EMF from radio and television base stations, because study subjects in general have little knowledge about different types of RF-EMF-emitting base stations (50). Furthermore, we modeled RF-EMF exposure at home, yet subjects reported perceived RF-EMF exposure from base stations in general, which could include base stations they usually came across at work, while commuting, and during leisure time. For these 2 reasons, we may have slightly underestimated the association between modeled and perceived exposure. However, the chance that subjects indeed referred to radio and television base stations was relatively low, given that they are much less abundant than mobile-phone base stations. We did not consider RF-EMF exposure from other sources besides mobile-phone base stations. Therefore, we cannot exclude the possibility that total RF-EMF exposure is associated with symptoms. However, including other exposure sources was not feasible for this particular study, because of the aim to compare effects of modeled and perceived exposure. Correlations between modeled and perceived exposure may be different for other sources. Additionally, the associations of perceived or modeled exposure with health outcomes could be different for other RF-EMF sources.

Conclusion

The results of our nationwide prospective study showed that not modeled exposure but perceived exposure to mobile-phone base stations is a predictor of nonspecific symptoms and sleep disturbances. Awareness of the presence of mobile-phone base stations in the home environment may play an indirect role in symptom reporting, through effects on perceived exposure. Our robust study design adds to the body of evidence that there seems to be no substantial adverse effect of everyday residential exposure to RF-EMF from mobile-phone base stations on the development of nonspecific symptoms and sleep disturbances in the general public.

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