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Greater prevalence of symptoms associated with higher exposures to mobile phone base stations in a hilly, densely populated city in Mizoram, India

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ABSTRACT

Members of the scientific community and the general public are raising concerns about the potential health and environmental effects of radio-frequency electromagnetic fields (RF-EMF) for those living nearby mobile phone base stations (MPBS). This study examined the impact of RF-EMF (900–1900 MHz) on symptoms spanning four health categories: mood-energy, cognitive-sensory, inflammatory, and anatomical issues. A questionnaire identifying health symptoms within these categories, was given to 183 highly exposed and 126 reference residents, matched on demographics. While years of residing near the MPBS influenced the prevalence of some symptoms, proximity to the base station and higher levels of exposure (measured using power density) influenced the prevalence of many of the symptoms. A higher proportion of symptoms was found in residents who were either living within 50 meters of a MPBS or who were exposed to power densities of 5–8 mW/m^2, for all four health categories. This relationship between exposure level and symptom prevalence was further influenced by age, daily mobile phone use (over 5 h per day), and lifestyle factors, for certain symptoms. Hierarchical regression analysis revealed that level of exposure (power density) was the only factor contributing to the number of symptoms experienced by residents, for all four health categories. An unexpected finding was that among the more highly exposed residents, the younger individuals (under 40 years) reported more inflammation related issues than older individuals. These results underscore the need to inform policymakers regarding the benefits of adopting a precautionary approach to potential risks associated with RF-EMF exposures from MPBS.

PLAIN LANGUAGE SUMMARY

Investigating the health effects of man-made electromagnetic fields (RF-EMF) created by telecommunications signals from mobile phone base stations is relevant to people living in cities across the world today. The study was conducted in a hilly, highly populated city in Mizoram, India, where many people live close to and in line of sight of the masts on telecommunications towers. A survey was given to residents in their homes, asking about what health symptoms they were experiencing across a range of health categories (mood-energy, cognitive-sensory, inflammatory, and anatomical). At the same time, the level of RF-EMF in their lounge room was measured. The symptoms reported by people living closer to mobile phone base stations (less than 300 m) were compared with those from people living further away (more than 400 m). More people who lived closer to base stations reported health symptoms in all of the health categories investigated. Relatively fewer people who lived further away reported symptoms. Other factors such as age, high mobile phone use (more than 5 h/day) and smoking and drinking also influenced this outcome, for some of the symptoms. The most significant contributor to the number of symptoms reported by residents was the strength of RF-EMF to which they were exposed in their home. A surprising result was that younger people up to 40 years old showed more inflammatory conditions that were related to higher exposures than older people (such as headache, allergy and chest pain). These health effects of RF-EMF should be heeded by those responsible for the installation of mobile phone base stations in cities.

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Radio-frequency electromagnetic fields (RF-EMF); mobile phone base stations (MPBS); power density; exposure; health symptoms

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Introduction

The increasing deployment of mobile and wireless technologies has significantly elevated man-made radiofrequency electromagnetic frequency (RF-EMF) background levels over time (Bandara and Carpenter 2018). Due to this technological development, mobile phones and their accompanying infrastructure known as mobile phone base stations (MPBS), have become ubiquitous. In India, telecommunication companies are in strong competition with each other and are continually installing new MPBS and upgrading their wireless internet services to enhance RF-EMF signal coverage across the country. MPBS transmit signals in the form of radio-frequency electromagnetic radiation (RF-EMR), which are then received by mobile phones to establish wireless communications. MPBS typically operate from 900 MHz to 1900 MHz (Levitt and Lai 2010) but are also expanding into higher GHz radio frequencies to support new generations of mobile telephony (e.g., UMTS 2100 MHz and LTE 2300 MHz and higher frequencies for fifth generation (5 G) telecommunication). The installation of an MPBS typically comprises clusters of antennas that emit signals in close proximity to residential and commercial areas.

MPBS constantly emit signals which are complex, pulsed and modulated, and their long-term effects are not well understood (Kim et al. 2019). Consequently, there is growing concern amongst the scientific community regarding the negative impacts of RF-EMF from MPBS on the public and the environment, because the emission of RF-EMR results in a constant whole-body exposure (BioInitiative Working Group, Sage, and Carpenter 2012; Nyberg et al. 2023; Zothansiama et al. 2017). Although RF-EMF is designated as a non-ionizing form of radiation, continuous exposure to RF-EMF can lead to the activation of free radical processes and the excessive production of reactive oxygen species (ROS) in living cells (Yakymenko et al. 2016). Additionally, exposure to RF-EMF from MPBS is capable of inducing non-thermal biological effects (Belpomme et al. 2018) and has the potential to pose health risks to humans and animals, because this form of radiation can be absorbed by biological tissues (Dong et al. 2022). Furthermore, the human body is an efficient conductor of electricity; therefore, RF-EMF can influence the electrical activity in excitable tissues of the human body, which can lead to cell perturbations (Imran et al. 2023). The impact of RF-EMF on physiological systems may vary depending on the frequency, intensity, morphology, and measured power density (Hu et al. 2021; Panagopoulos et al. 2002).

Following the installation of a MPBS, individuals have reported experiencing various forms of physical or mental ailments (Vijay and Choudhary 2017). Over time, individuals residing near MPBS have developed symptoms such as headaches, memory deficiencies, sleep disturbances, tremors, dizziness, depressed mood, increased irritability, decreased appetite, nausea, difficulties in concentration, and visual disturbances (Abdel-Rassoul et al. 2007; Alazawi 2011. The prevalence of negative health symptoms has been found to be greater in individuals residing in close proximity to MPBS compared to those residing further away (López et al. 2021; Premlal and Eldhose 2017; Singh et al. 2016). In addition, Ali et al. (2021) observed that there was a notable correlation between health issues (such as skin disorders, hair loss, sleeping difficulties, and fertility issues) and proximity to MPBS. The prevalence of these symptoms is notable, in that approximately half of the individuals residing near MPBS have been found to report sleep disruptions, headaches or dizziness, alterations in mood, anxiety, and depression (Shariful Islam 2014).

A questionnaire-based evaluation among adolescent students and middle-aged individuals from many schools and offices in Ujjain, a city crowded by large numbers of MPBS, revealed a significant correlation between distance of base stations and a range of health symptoms, including fatigue, sleep disruption, dizziness, decreased cognitive focus, memory impairment, headache, earache, rapid heart rate, impaired vision, and anxiety (Saxena and Kumawat 2018). Preliminary research conducted in Aizawl, Mizoram on the Mizo population revealed a higher occurrence of fatigue, headache, and dizziness among individuals residing in the close vicinity of MPBS (Pachuau et al. 2015). Sleep disturbances, fatigue, headaches, depression, and dizziness, were among the most common problems that residents close to MPBS experienced (Gandhi et al. 2015; Premlal and Eldhose 2017; Vijay and Choudhary 2017). In a cross-sectional study on individuals residing in close proximity to MPBS, Alazawi (2011) found that individuals living within 300 m of a base station experienced significantly higher levels of discomfort, irritability, nausea, headache, dizziness, nervousness, depression, sleep disturbance, and memory loss compared to those living more than 300 m away from the MPBS. The authors recommended that MPBS should be sited at a minimum distance of 300 m from human populations so as to reduce exposures.

In an investigation of biological effects related to MPBS, Zothansiama et al. (2017) showed that individuals living in close proximity to the base stations exhibited a considerably elevated frequency of micronuclei (MN) and a reduction in antioxidant levels. Higher mobile phone usage has also been long

associated with negative health effects (Choi et al. 2020; Wacks and Weinstein 2021). Nittby et al. (2008) observed changes in the memory function of rats, following prolonged exposure to RF-EMF from mobile phones.

The collection of health symptoms such as headache, fatigue, nausea, lack of concentration, loss of appetite, visual disturbance, irritability, depression, and insomnia, has previously been associated with microwave sickness (Carpenter 2015; Johnson Liakouris 1998). This collection of symptoms has been found to be significantly higher in populations living close (within 100 m) to MBPS as compared to those living further away (Abdel-Rassoul et al. 2007; Bortkiewicz et al. 2012; Hutter et al. 2006; Santini et al. 2002, 2003).

The limits established by the International Commission for Non-ionizing Radiation Protection (ICNIRP) for public exposure to microwave radiofrequency (RF) transmissions are designed specifically to protect individuals from known thermal effects, such as shock and burns, resulting from high intensity exposure (ICNIRP 2020). However, multiple studies (Havas et al. 2010; Pachuau et al. 2015) have found that exposure to RF-EMF at low levels, considerably below the ICNIRP public safety threshold could cause non-thermal effects that may result in adverse biological or physiological consequences.

The possible detrimental effects of RF-EMF from MPBS have been shown to be contingent upon the power density and the proximity of the base stations (Navarro et al. 2003, Sharma and Lamba 2017) as well as signal frequency and morphology (Panagopoulos et al. 2002). Numerous experimental studies have been carried out to examine biological impacts, including those that have investigated potential health implications (Christopher et al. 2020; Singh and Kapoor 2014). However, to date, scientific consensus has not been reached due to conflicting and divergent perspectives held within the scientific field (Nyberg et al. 2023; Weller and McCredden 2024).

The present study aimed to obtain further insight into the link between health symptoms and proximity to MPBS. Similar to past research, this study gathered data on health symptoms experienced by a highly exposed group of participants living very close to a MBPS, compared with symptoms experienced by a less exposed reference group living further away. The study was conducted in a highly populated city, where MPBS are very close to dwellings, and where there is a great deal of telecommunications traffic occurring 24/7. Information regarding demographics, lifestyle choices and mobile phone use was also gathered. If RF-EMF exposure from MPBS is associated with health challenges, then it is expected that the overall health of the highly exposed group will be poorer than that of the reference group. Poorer health is also expected for those who engage in stressful lifestyle choices, or who are heavy users of mobile phones (Kim et al. 2016), regardless of their exposure to RF-EMF from base stations. However, it is expected that a higher exposure to MPBS would continue to have an effect on health symptoms even after taking into account of all of the other stress factors, including the use of mobile phones.

Materials and methods

Mobile phone base stations

The study was carried out in Aizawl city, located at coordinates 23.8789° N and 92.8976° E, during the year 2023–2024. Thirty mobile phone base stations that were installed in densely populated regions of the city were selected for this study. These base stations operate at frequencies of 900 MHz (for a total of 20 base stations) and 1800 MHz (for a total of 10 base stations), as determined by the output of the directional spectrum analyser used to record power density (**see "Power density measurements" section below**). This was necessary as there is no official government map showing tower placement or frequencies for this region of India.

Each base station was equipped with dishes and sectored antennas that were positioned in an equilateral manner (Table 1). This arrangement allowed for complete network coverage in a 360° radius. The city is situated in a hilly area, so that certain residences are horizontally aligned and in line-of-sight with the towers' antennas. RF-EMF exposures in this study were initially delineated by set distances defined at 1–50 m, 51–100 m, and 101–300 m for all residences located on the adjacent slope, regardless of whether the towers are installed on rooftops or on the ground. Figure 1 illustrates the close proximity of base stations to residential areas and their strategic placement on hilly areas.

Selection of participants

The highly exposed group consisted of 183 individuals who were over 18 years old and who lived within 300 m of a mobile phone base station. Similarly, the reference group comprised of 126 individuals who lived at a minimum distance of 400 m away from a mobile phone base station. The distance from each residence to the nearby MPBS was determined using a digital laser tape measure (Bosch, GLM).

Table 1. Composition of base stations and demographic data for the highly exposed group.

Base station	Components		Power density (mW/m^2)	Average age (yr) of volunteers	Gender of volunteers	
	Disc-antenna	Sectored-antenna			Male	Female
1	6	5	2.90–4.56	38.2	4	2
2	8	4	4.31–5.41	36.2	3	3
3	5	9	2.67–4.75	40.7	3	4
4	4	8	2.04–2.15	34.8	3	3
5	8	6	5.68–7.24	43.1	3	3
6	9	6	5.64–6.47	37.4	2	4
7	6	6	2.13–2.47	33.7	3	3
8	5	8	2.64–2.90	38.8	2	4
9	8	3	3.57–5.72	39.1	4	2
10	6	9	2.09–3.87	33.3	3	3
11	4	3	2.17–3.50	42.7	2	4
12	6	6	3.84–5.78	35.4	3	4
13	8	5	4.48–4.94	36.3	3	3
14	5	6	4.90–5.64	37.4	3	3
15	2	4	4.17–6.31	30	3	3
16	4	6	3.19–5.74	26.9	4	2
17	6	8	2.15–3.10	39.8	2	4
18	4	2	3.28–6.41	40.7	2	4
19	1	4	5.40–5.74	40.3	2	4
20	4	6	4.28–5.70	39.7	3	3
21	2	6	2.57–4.29	46.8	3	3
22	5	8	5.70–5.87	47.8	2	4
23	6	9	5.74–6.12	37.5	4	2
24	3	8	2.40–2.64	39.3	2	4
25	6	6	3.14–4.10	35.6	3	4
26	2	4	2.45–3.10	39.2	3	3
27	6	6	2.57–4.29	43.1	3	3
28	6	8	7.14–7.22	42.7	3	3
29	5	6	5.01–5.71	42.7	4	2
30	8	4	2.09–3.87	41.3	2	4
Totals	**158**	**179**			**86**	**97**

The reference individuals were selected so as to match with those in the highly exposed group in terms of age and gender. Additionally, the selection process ensured that none of the participant's residences were located within a 500 m radius of electric transformers, high tension electrical power lines, radio or television broadcast transmitters. This was done purposefully so as to eliminate any potential influence from these other sources of EMFs that could have confounded the results. Participants were also selected so as to ensure that the majority of their exposure came consistently from the local MPBS. Only those who stayed at home during the day due to being home-makers or unemployed were included in the highly exposed group. In addition, control group participants (i.e. living more than 400 metres from the MPBS) were screened to ensure that they were not being highly exposed at work (i.e., any MPBS near to their workplace was also more than 400 metres away). Mobile phone use was included as a variable in the analysis. Wi-Fi modem exposure was not recorded because modems are rarely used in the homes of this population, who rely on their mobile phone for communications, web browsing and social media. Moreover, the small subset of residents who did use them was expected to be scattered evenly across distance from the tower and therefore would not vary systematically with the experimental groups.

Table 1 presents an overview of the distribution of participants across the 30 MPBS. A minimum of six individuals were chosen for sampling around each mobile base station. Participants were recruited by a process of going door-to-door in the vicinity of the towers. The objectives of the study were conveyed to the resident, in a way that gave no indication regarding the expectations of the researchers (e.g., "We are investigating various health symptoms of people in this community. There has been some talk about whether the background signals from the telecommunication towers dotted around the place may be affecting people's health. It is unlikely to be true, and there are different studies showing both positive and negative effects so we



(a) (b)

Figure 1. (a) A base station located within 20 m and in line of site of residences, and (b) The hilly terrain with base station signals travelling directly into some residences.

are checking to see"). The same introduction was given to all residents irrespective of distance from MPBS so that it was less likely that merely mentioning the topic would create a bias towards perceived threat that would influence the results in any systematic way.

Residents were then asked for their voluntary participation. Provided that consent was granted, a questionnaire was used to collect data from each participant.

Administering the questionnaire did not influence the way in which the questions were answered. The research assistants were aware of the distance condition of the participants and of the power density of exposure. Therefore, so as to minimise influence on outcomes, the researchers sat to the side while the resident filled in the questionnaire. Assistants were instructed to abstain from helping the residents with the questionnaire. Only when occasionally asked by the resident they provided additional context to the question.

Questionnaire

The questionnaire collected data on demographics and lifestyle behaviours, including duration of residing near the MPBS, distance of residence from the base station, duration of mobile phone use, average daily mobile phone usage, and lifestyle habits related to smoking, chewing of tobacco, consumption of tobacco-infused water, betel nuts chewing, and alcohol consumption (Table 2).

Information on the different health symptoms were collected, including mood-energy symptoms such as anxiety, agitation, increased irritability, fatigue, sleep problems, dizziness; cognitive-sensory symptoms including concentration problems, memory problems, problem-solving issues, ear problems, visual disruption, skin problems, abnormal sensation; inflammatory symptoms including headache, allergy, increased infections, weight problem, chest pain; and anatomical

Table 2. Demographic and behavioural characteristics of highly exposed and reference groups.

Characteristics	Category	Highly exposed		Reference		*t*	χ^2	p
		N (%)	M ± SEM	N (%)	M ± SEM			
Age (yr)	18–40	101 (55.2)	40.3 ± 0.9	69 (54.8)	38.6 ± 1.1	1.3		0.20
	41–60	82 (44.8)		57 (45.2)				
Gender	Male	86 (46.9)		60 (47.6)			0.01	0.91
	Female	97 (53.1)		66 (52.4)				
Alcohol consumption	Yes	33 (81.9)		23 (18.3)			0.00	0.96
	No	150 (18.1)		103 (81.7)				
Smoking habit	Yes	53 (29)		38 (30.2)			0.05	0.82
	No	130 (71)		88 (69.8)				
Tobacco chewing	Yes	42 (22.9)		28 (22.2)			0.02	0.88
	No	141 (77.1)		98 (77.8)				
Tobacco infused water consumption	Yes	10 (5.5)		9 (7.1)			0.36	0.55
	No	173 (94.5)		117 (92.9)				
Betel nut chewing	Yes	119 (65)		83 (65.9)			0.02	0.88
	No	64 (35)		43 (34.1)				
Daily mobile phone use (hr)	≤5	58 (31.7)	5.3 ± 0.3	36 (28.6)	5.2 ± 0.3	0.2		0.83
	>5	125 (68.3)		90 (71.4)				
Distance from base station (m)	1–50	94 (51.4)	103 ± 12		539.3 ± 19.6	−19.1		0.00
	51–300	89 (48.6)						
Power density (mW/m^2)	Range	2.0–7.2	4.8 ± 0.1	0.01–1.2	0.7 ± 0.1	21.3		0.00
Years residing near base station	≤8	95 (51.91)	12.5 ± 2.1					
	>8	88 (48.1)						

symptoms including joint pain, muscle problems, nerve pain, digestive problems, loss of appetite, nausea and irregular heartbeat. Initially, participants were asked to rate whether they experienced these symptoms using a 1 to 4 scale (never, sometimes, often, always). However, early on in the study, it became apparent that most participants were unable to give a definitive rating for their symptoms. Instead, they were only able to say whether they experienced them or not. Thenceforth participants were only asked to answer 'yes' or 'no' to the symptom items on the questionnaire. This is further confirmation that the research assistants did not try to influence results. Assistants could have helped the residents to choose their ratings when asked, so as to ensure coherent ratings data, but they abstained.

Power density measurements

Radio-frequency power density measurements were conducted in 103 households, specifically in the living room. The trained assistant measuring the power density asked participants to ensure that all mobile phones and other electronic devices were turned off while measurements were being taken. All RF measurements were conducted using an Aaronia HF-60105V4 spectrum analyser (Germany) using an initial sweep to determine the frequency range for the nearby tower (e.g. 900 MHz) then a pan around the room for a couple of minutes with the analyser zoomed in on that frequency. The average peak value across several sweeps of this frequency range was recorded. The average peak value across several sweeps of this frequency range (max average) was then displayed on the screen as power density [W/m^2]. The highest reported power density was 7.24 mW/m^2 (Table 1).

The guidelines of the Department of Telecommunications, Ministry of Communications, Government of India, New Delhi set the safety limits for public exposure from mobile phone base stations at 0.45 W/m^2 (450 mW/m^2) for 900 MHz and 0.90 W/m^2 (900 mW/m^2) for 1800 MHz (Department of Telecommunications 2013). Thus, all recorded power density levels were situated well below the official limits.

Statistical analysis

Pearson`s correlation was used to verify whether there was a relationship between power density of exposure and the distance of residences from the base stations. Due to participant limitations in responding (described above), all responses to health symptom items were rated on a binary scale (yes, no). Any responses that had been rated 'sometimes', 'often' or 'always' were rescored as 'yes' and all responses rated 'never' were rescored as 'no'. Subsequently, only binary data was available for symptom scoring and analysis rather than the ordinal data that was originally planned.

The number of participants answering yes or no to each symptom item was collated for each demographic variable and each exposure variable (Supplementary Data1). Chi-squared tests were conducted to ascertain whether the proportions of 'yes' and 'no' responses for each symptom were different for the highly exposed versus reference groups, within each level of the demographic variables and across the levels of the exposure variables (Table 4).

The health symptoms indicated by responses to each of the questionnaire items were grouped into four health symptom categories: Mood-Energy, Cognitive-Sensory, Inflammatory and Anatomical (Tables 3 and 4). For each participant, their total numbers of symptoms within each of these four categories were used for graphical summaries and for further analysis. Hierarchical linear regression was then used to investigate the extent to which exposures from MPBS were able to predict the level of each of the four health categories, over and above the variance contributed by the demographic and behavioural characteristics and from mobile phone exposures (treated as covariates in the hierarchical linear regression). A p-value of less than 0.05 was considered statistically significant.

Unfortunately, data for years of residing near MPBS was not collected for the reference group, so this variable could only be analysed for the highly exposed group that had a range of 5 to 18 years for years of residing near MPBS. Initial screening showed that the data was skewed towards the lower range, so the median value (8 years) was used rather than the mean so as to separate the years of residing data into two groups for further analysis (5–8 years and 9–18 years).

Results

Demographic and behavioural characteristics of the study groups

The demographic and behavioural characteristics of the highly exposed and reference groups are shown in Table 2.

All demographic and behavioural characteristics (including gender, age, habit of alcohol consumption, smoking, tobacco chewing, consumption of tobacco-infused water, betel nut chewing, and average daily use of a mobile phone). For all of these variables, there was no statistical difference between the highly exposed and reference groups, indicating that the two groups were adequately matched.

The average distance of households from the mobile base station was significantly lower for the highly exposed group (103 ± 12 m) than for the reference group (539 ± 20 m), as expected. Similarly, the average RF power density of the highly exposed group living within a perimeter of 300 m (2.1–7.2 mW/m^2; average 4.8 ± 0.1 mW/m^2) was significantly higher than the reference group living at least 400 m away from mobile phone base stations (0.01–1.2 mW/m^2; average 0.7 ± 0.1 mW/m^2).

The power density and the distance from the base station were found to be significantly negatively correlated (r_p= −0.90, $p < 0.001$), indicating that the intensity of exposures experienced by inhabitants decreased as their distance from the base station increased. A scatterplot of this relationship (Figure 2) showed that the distance data was subsequently divided into three groups (1–50 m, 51–300 m, over 400 m) which corresponded approximately to three main power density groupings (5.1–8.0 mW/m^2, 3.1–5.0 mW/m^2, 0.0–3.0 mW/m^2). This grouping decision still left 33 participants in the reference group with power densities readings as high as some of those in the highly exposed group (residing 51–300 m from the MPBS). This is because a clean linear drop off in power density with distance was not observed, illustrating that distance information is not a perfect proxy for exposure levels. The overlap can be explained by the hilly terrain and the tall buildings; with some residences at more than 400 m of MPBS having clear line of sight of the masts, while some residences situated less than 300 m from a MPBS being either partially or fully obscured by other buildings (Figure 1).

The consequence of the overlap was that some of the reference group had higher exposure levels than those designated to the highly exposed group. While this creates noise in the data, it does not create a confounding factor, because the overlap in power density works against finding any differences in health symptoms between the exposed and reference groups. If differences are found in spite of this noise, the effects of exposure on health symptoms can be considered to be strong. Table 4 shows that significant differences were indeed found between the highly exposed and reference groups.

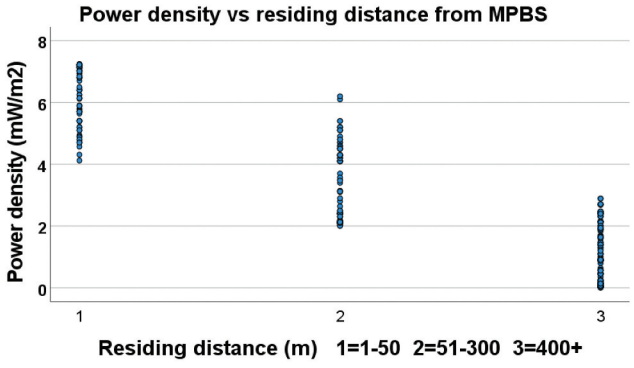


Figure 2. Scatterplot of distance residing from MPBS versus power density from MPBS exposures as measured in each participant's living room.

Effects of exposure types on health symptoms

Table 3 provides an overview of the results, showing where there were higher percentages of health symptoms for those in the exposed group dependent on the number of years of residing near the base stations and the distance of residence from the base stations (for both the highly exposed and reference groups).

The percentage of the highly exposed group reporting health symptoms was influenced by the years of residing near the base stations, for some of the symptoms only. A significantly greater percentage of those who had resided near the MPBS for 9 to 18 years compared to those residing 5 to 8 years reported agitation, sleep problems, skin problems, abnormal sensations, allergies, and loss of appetite. Moreover, some of the symptoms were highly prevalent irrespective of years of residing (e.g. anxiety, concentration, memory, problem solving, and headache). It could be that any length of time residing near the MPBS facilitates such symptoms. However, there were no participants in the sample who had resided for less than 5 years, and so it was not possible to ascertain whether the frequency of these symptoms would be less when participants had only resided there for one or two years.

The percentage of the highly exposed group reporting health symptoms was strongly moderated by distance to the MPBS. There was a significant association between distance of residing and every health item except for weight problems. Greater proportions of symptoms were reported by those residing less than 50 m from the MPBS. Similarly, the percentage of the highly exposed group reporting health symptoms was moderated by the power density of exposure. For every health symptom, the proportion of reported symptoms varied significantly with exposure level, with greater proportions of symptoms reported by those most highly exposed with a power density of 5.1 to 8 mW/m^2.

For each of the four health categories used to summarize symptom groups, there was a positive relationship between proximity to the MPBS and the average number of symptoms (Figure 3a). The overlap due to hilly terrain resulted in some residents in the reference group experiencing exposure

Table 3. Percentages of the highly exposed group reporting health symptoms according to years of residing, and percentages of exposed and reference groups reporting health symptoms according to residing distance from MPBS and power density of exposure.

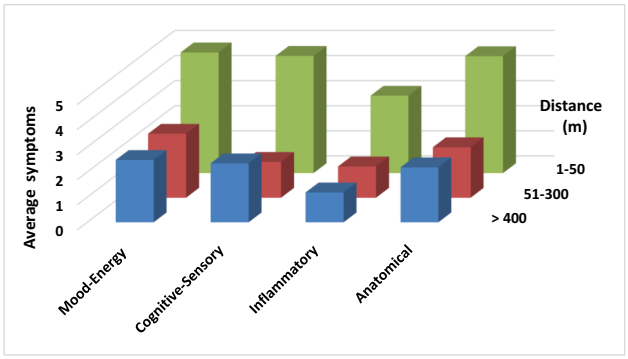
	Exposed group		Exposed and reference groups					
	Years of residing near MPBS % reporting symptom		Distance from the MPBS (m) % reporting symptom			Power density (mW/m^2) % reporting symptom		
	5–8 *N=95*	9–18 *N=88*	1–50 *N=94*	51–300 N=89	400 + *N=126*	0–3 *N=43*	3–5 *N=49*	5–8 *N=91*
Mood-Energy								
Anxiety	75.2 (71)	78.6 (69)	93.6*** (88)	58.4 (52)	42.1 (53)	32.5 (14)	83.7 (41)	93.4*** (85)
Agitation	14.2 (14)	37.1*** (33)	39.4*** (37)	5.6 (5)	4.0 (5)	3.0 (1)	18.4 (9)	36.3*** (33)
Increased Irritability	77.0 (73)	78.6 (69)	96.8*** (91)	57.3 (51)	39.7 (50)	39.6 (17)	79.6 (39)	94.5*** (86)
Fatigue	75.2 (71)	85.7 (75)	100.0** (94)	57.3 (51)	78.6 (99)	69.2 (30)	79.6 (39)	96.7*** (88)
Sleep problems	60.2 (57)	77.1* (68)	93.6*** (88)	38.2 (34)	59.5 (75)	50.3 (22)	59.2 (29)	91.2*** (83)
Dizziness	43.4 (41)	55.7 (49)	57.4*** (54)	38.2 (34)	24.6 (31)	24.3 (10)	44.9 (22)	61.5*** (56)
Cognitive-Sensory								
Concentration problem	56.6 (54)	61.4 (54)	90.4*** (85)	24.7 (22)	39.7 (50)	4.7 (2)	51.0 (25)	87.9*** (80)
Memory problems	61.1 (58)	72.9 (64)	95.7*** (90)	33.7 (30)	54.8 (69)	16.3 (7)	59.2 (29)	92.3*** (84)
Problem solving issues	54.0 (52)	64.3 (57)	89.4*** (84)	24.7 (22)	58.7 (74)	4.7 (2)	53.0 (26)	85.7*** (78)
Ear problems	12.4 (12)	17.1 (15)	17.0* (16)	11.2 (10)	5.6 (7)	2.3 (1)	16.3 (8)	18.7* (17)
Visual disruption	39.8 (38)	50.0 (44)	59.6*** (56)	27.0 (24)	40,5 (51)	14.0 (6)	28.6 (14)	65.9*** (60)
Skin problems	30.1 (29)	61.4*** (54)	63.8*** (60)	19.1 (17)	29.4 (37)	11.6 (5)	30.6 (15)	62.6** (57)
Abnormal sensations	20.4 (19)	38.6** (34)	51.1*** (48)	2.2 (2)	6.3 (8)	2.3 (1)	10.2 (5)	48.4** (44)
Inflammatory								
Headache	77.9 (74)	82.9 (73)	94.7*** (89)	64.0 (57)	64.3 (81)	44.1 (19)	81.6 (40)	95.6*** (87)
Allergy	38.9 (37)	64.3*** (57)	69.1*** (65)	27.0 (24)	18.3 (23)	20.9 (9)	34.7 (17)	69.2*** (63)
Increased infections	49.6 (47)	64.3 (57)	85.1*** (80)	23.6 (21)	41.1 (52)	4.7 (2)	50.0 (24)	82.4*** (75)
Weight problems	6.2 (5)	2.9 (2)	7.4 (7)	2.2 (2)	10.3 (13)	0.0 (0)	2.0 (1)	8.8** (8)
Chest pain	30.1 (29)	31.4 (28)	52.1*** (49)	7.9 (7)	5.6 (7)	4.7 (2)	14.3 (7)	51.6** (47)
Irregular Heartbeat	9.7 (9)	7.1 (7)	12.8** (12)	4.5 (4)	1.6 (2)	2.32 (1)	6.1 (3)	14.3* (13)
Anatomical								
Joint pain	38.9 (37)	38.6 (34)	55.3*** (52)	21.3 (19)	22.2 (28)	7.0 (3)	28.6 (14)	58.2** (53)
Muscle problems	49.6 (47)	65.7* (58)	80.9*** (76)	29.2 (26)	31.0 (39)	14.0 (6)	42.7 (21)	81.3** (74)
Nerve pain	39.8 (37)	44.3 (39)	56.4*** (53)	25.8 (23)	28.6 (36)	14.0 (6)	32.7 (16)	59.3** (54)
Digestive problems	67.3 (64)	74.3 (65)	92.6*** (87)	46.1 (41)	38.9 (49)	25.6 (11)	77.6 (38)	86.8** (79)
Loss of appetite	61.9 (58)	78.6* (69)	93.6*** (88)	41.6 (41)	56.3 (71)	30.3 (13)	57.1 (28)	92.3*** (84)
Nausea	53.1 (51)	64.3 (57)	80.9*** (76)	32.6 (29)	40.5 (51)	16.2 (7)	51.0 (25)	78.0** (71)

The cells indicate the results of the 2 x 2 chi-squared tests conducted for symptoms versus years of residing (yes/no x 5–8/9–18 years), the 2 x 3 chi-squared tests conducted for symptoms versus distance (yes/no x 0–50 m/51–300 m/400+ m) and the 2 x 3 chi-squared tests conducted for symptoms versus power density (yes/no x 0–3.0 mW/m2/3.1–5.0 mW/m2/5.1–8.0 mW/m2).Significant effects are indicated in the column representing the level of the variable that had the highest values. Significance of Chi-squared tests: *$p < 0.05$ **$p < 0.01$ ***$p < 0.001$.

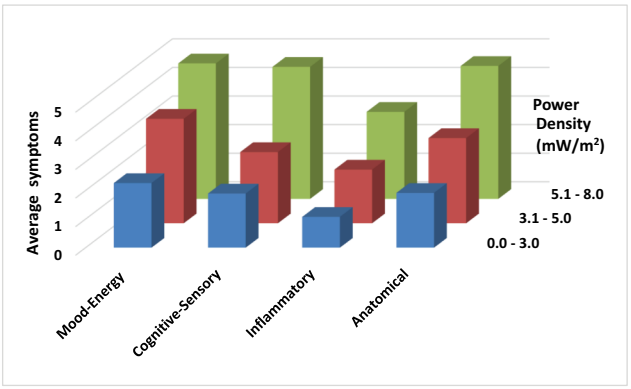
Table 4. Heat map showing significant differences between the proportions of highly exposed and reference groups reporting symptoms, according to demographics and behavioural characteristics. Also shown are where differences occurred between the two categories of the demographic or behavioural variables within either the highly exposed or the reference group.

	All	Gender		Age (yrs)		Daily Mobile Phone usage (hrs)		Alcohol		Smoking		Tobacco chewing		Tobacco infused water		Betelnut chewing	
		M	F	18-40	41-60	< 5	> 5	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Mood-Energy																	
Anxiety							*										
Agitation		*						*									
Increased Irritability																	
Fatigue																	
Sleep problem																	
Dizziness		**						*		**				*			
Cognitive-Sensory																	
Concentration problem		*						*									
Memory problem							*										
Problem solving							*										
Ear problem					*												
Visual disruption					*		*										
Skin problem																	
Abnormal sensation		**					*	*		**							
Inflammatory																	
Headache																	
Allergy																	
Increased infections																	
Weight problem																	
Chest pain		*			*					**							
Anatomical																	
Joint pain					**												
Muscle problem		*						*		*							
Nerve pain					*												
Digestive problem														*			
Loss of appetite		**						**									
Nausea		**								*							
Irregular Heartbeat					*												

Significant difference found between the highly exposed and reference groups, **using a 2x2 Chi-squared test.**		Significant difference found between the two levels of the demographic, using **a 2x2 Chi-squared test**.
	($p<0.05$)	* ($p < 0.05$) ** ($p < 0.01$)
	($p < 0.01$)	Note: Significant differences are always indicated in the column representing the category of the demographic that had the higher values.
	No significant difference	



(a)



(b)

Figure 3. Relationship for average number of symptoms in each health category with (a) residing distance from MPBS, and (b) power density of exposure.

levels higher than those in the exposed groups. This explains why the average health symptoms at 400 m or more are equal or higher than average symptoms at 51 to 300 m. The relationship between increasing power density and increasing average number of symptoms gives a clearer picture of the effect of levels of exposure on health symptoms (Figure 3b). Those living with the highest power density of exposure experienced significantly more symptoms in all four health categories and more total symptoms overall compared to those living with the lowest exposures. The underlying data and statistical tests for these relationships are shown in Supplementary Data2.

Effects of MPBS exposure, demographics and behavioural on health symptoms

An overview of the various health symptoms that differed significantly between the highly exposed and reference groups for each of the demographic and behavioural characteristics examined is provided in Table 4. Each cell depicts the results of a 2 × 2chi-squared test for symptoms versus each demographic variable (yes/no x level1/level2 of demographic).

Table 3 shows that there was a set of various health symptoms that showed proportionally greater levels in the highly exposed group compared to the reference group, as follows: (1) **Mood-Energy**: anxiety, agitation, increased irritability, **fatigue**, dizziness; (2) **Cognitive-Sensory**: concentration problems, memory problems, **problem-solving issues**, ear problems, skin problems, abnormal sensations; (3) **Inflammatory**: headache, allergy, increased infections, weight problems, chest pain, irregular heart beat; (4) **Anatomical**: joint pain, muscle problems, nerve pain, digestive problems, loss of appetite, nausea. This pattern of results is termed "the overall pattern of exposure results" in the sections below.

The effects of exposure on fatigue and weight problems were not moderated by any of the demographic variables. Therefore, these two items have been omitted from the following discussion of how the overall pattern of exposure results varied with the demographic variables

The above overall pattern of exposure results for the four health categories was not altered by gender, but it was moderated by age. That is, for those older than 40 years, proportionally more of the highly exposed group than the reference group indicated that they suffered from all of the problems listed in the overall pattern of exposure results above, and also from sleep problems in the Mood-Energy category. However, those younger than 40 years in the highly exposed group suffered more than the reference group only from agitation, abnormal sensations, muscle and digestive problems, as well as all of the symptoms in the inflammatory health category.

Regardless of exposure level, the older age group reported proportionally more ear and visual problems, chest, joint and nerve pain, and irregular heartbeat. That is, the pattern of results for age was different from the pattern of results for exposure level, indicating that the greater proportion of symptoms reported by the highly exposed group was not due to aging alone.

The overall pattern of results was also moderated by the amount of daily mobile phone use. Those who used a mobile phone for more than 5 hr per day reported the above overall pattern of exposure results across the four health categories. However, those who used a mobile phone for less than 5 hr per day did not show a greater proportion of agitation, dizziness, memory problems or chest pain in the highly exposed compared to the reference groups. In both the highly exposed and reference groups, proportionally more of those who used a mobile phone for more than 5 hr per day reported anxiety, memory problems, problem solving issues, visual disruption, and abnormal sensation. Therefore, there

seems to be an interaction between level of mobile phone use and exposure from MPBS for the cognitive-sensory symptoms.

Alcohol drinkers and non-drinkers showed different results from the overall pattern of exposure results within the anatomical health category, where, for the non-drinkers only, proportionally more in the highly exposed group reported nerve pain, loss of appetite, nausea and irregular heartbeat than the reference group. Thus, MPBS exposure seemed to interact with alcohol consumption for some of the symptoms.

For both smokers and non-smokers, proportionally more of the highly exposed group than the reference group reported all of the health symptoms except for memory problems. The exceptions were that only the smokers reported visual disturbances more often for the highly exposed compared to the reference group and only the non-smokers reported irregular heartbeat and loss of appetite more often in the highly exposed compared to the reference group. Thus, smoking seemed to interact with exposure to MPBS in different ways for some of the health symptoms.

The overall pattern of exposure results was not moderated by use of betel nut or tobacco chewing. All differences between levels of the demographics are shown in Table 4, where a higher proportion of a range of health symptoms were reported by the males, the older age group, those with greater mobile phone use, the alcohol drinkers, smokers, and to a small extent those using tobacco infused water.

Together the results in Tables 3 and 4 suggest that higher, chronic exposures to RF-EMF have a significant impact on a range of health symptoms spanning mood-energy, cognitive-sensory, inflammatory and anatomical issues. Furthermore, increases in the prevalence of these health symptoms are due to a combination of higher exposures to MPBS, heavier mobile phone use and some lifestyle choices. The categories used for determining years of residing were probably too limited for determining affects from years of exposure.

Relative contribution of study variables to non-specific health symptoms

In order to ascertain the relative contribution of the demographic, behavioural and exposure variable sets to the level of symptoms experienced by the participants for each health category, a set of hierarchical multiple linear regression analyses were conducted. The demographic variables from Tables 3 and 4 that were shown to be indicative of differences between the highly exposed and reference groups, were used as the possible predictor variables, and summary health symptom scores were used as outcome variables. Summary scores were allocated using the total number of symptoms each person experienced for each of the mood-energy, cognitive-sensory, inflammatory, and anatomical categories.

The results from Tables 3 and 4 described above suggested that gender, use of betel nut, tobacco infused water and tobacco chewing had little influence on the outcomes, while age, smoking and alcohol consumption, seemed to have greater effects on outcomes. Thus, these two sets of variables were entered first and second into the regression equation (Models 1 and 2). Next, given that high level of mobile phone moderated the outcomes (Table 3), the mobile phone use variable was entered next (Model 3). Then, years of residing near MPBS was added (Model 4) since this variable had been shown to effect some of the symptoms (Table 3), even though data was only available for the highly exposed group. Finally, level of exposure to mobile phone base stations in terms of power density (mW/m^2) was added as a continuous variable (Model 5). This order of entering variable sets was used so as to ascertain whether mobile phone use, years of residing near the MPBS, or exposure to MPBS added a significant amount of variance to the number of symptoms experienced, over and above the variance contributed by the behavioural and demographic variables.

The hierarchical regression results are summarized in Table 5. The results showed strong effects of power density of exposure on all health categories, as follows: **(1) Mood-energy issues**: All of the factors together explain 58% of the variance in mood-energy issues, with power density contributing a significant proportion towards this (48%). While gender, (being female) initially predicted mood-energy issues, this variable lost significance when power density was included into the prediction equation. **(2) Cognitive-Sensory issues**: All of the factors together explain 46% of the variance in cognitive-sensory, with power density contributing a significant proportion towards this (37%). While gender initially predicted cognitive-sensory issues, this variable lost significance when power density was included into the prediction equation. **(3) Inflammatory issues**: All of the factors together explain 54% of the variance for inflammatory issues with power density contributing a significant proportion towards this (51%). None of the demographic variables contributed towards inflammatory issues initially; however, in the final model when power density was included, age (being younger) also contributed significantly towards inflammatory issues. **(4) Anatomical issues**: All of the factors together explain 53% of the variance in anatomical issues with

Table 5. Hierarchical linear regression for the prediction of health symptoms from demographics, mobile phone usage, years of residing and power density of exposure from MPBS.

		Standardized Beta coefficients					
	Predictor	Model-1	Model-2	Model-3	Model-4	Model-5	Tolerance
MOOD-ENERGY ISSUES	Tobacco chewing	-.01	-.04	-.04	-.03	-.02	.83
	Tobacco infused water	-.07	-.06	-.06	-.05	-.03	.97
	Betel nut chewing	.14	.12	.12	.10	.07	.89
	Gender	.19*	.26**	.26**	.24**	.14	.71
	Alcohol consumption		.06	.06	.04	.01	.85
	Smoking		.10	.10	.09	.09	.74
	Age		.11	.11	.10	-.03	.88
	Daily mobile phone use (hr)			.04	.02	.03	.98
	Years Residing				.16	.06	.91
	Power density					.72***	.92
	R^2	0.05	0.08	0.08	0.10	0.58	Durbin Watson=1.9
	R^2 change	0.05*	0.03	0.001	0.02	0.48***	
		Standardized Beta coefficients					
	Predictor	Model-1	Model-2	Model-3	Model-4	Model-5	Tolerance
COGNITIVE-SENSORY ISSUES	Tobacco chewing	.11	.08	.08	.09	.10	.83
	Tobacco infused water	-.03	-.03	-.02	-.02	.002	.97
	Betel nut chewing	.07	.08	.08	.06	.03	.89
	Gender	.15	.18*	.18*	.16	.07	.71
	Alcohol consumption		.06	.06	.04	.02	.85
	Smoking		.02	.02	.01	.004	.74
	Age		.12	.12	.11	-.002	.88
	Daily mobile phone usage (hr)			.01	.02	.03	.98
	Years Residing				.13	.04	.91
	Power density					.64***	0.87
	R^2	0.05	0.07	0.08	0.08	0.46	Durbin Watson=1.8
	R^2 change	0.05	0.02	0.001	0.02	0.37***	
		Standardized Beta coefficients					
	Predictor	Model-1	Model-2	Model-3	Model-4	Model-5	Tolerance
INFLAMMATORY ISSUES	Tobacco chewing	-.05	-.05	-.05	-.04	-.0	.83
	Tobacco infused water	-.01	-.01	-.01	-.001	.02	.97
	Betel nut chewing	.06	.07	.07	.05	.01	.89
	Gender	.12	.10	.10	.08	-.02	.71
	Alcohol consumption		-.004	-.004	-.02	-.05	.85
	Smoking		-.04	-.04	-.05	-.05	.74
	Age		-.03	-.02	-.04	-.17**	.88
	Daily mobile phone usage (hr)			.04	.03	.04	.98
	Years Residing				.14	.03	.91
	Power density					0.74***	.92
	R^2	0.02	0.02	0.03	0.04	0.54	Durbin Watson=1.7
	R^2 change	0.02	0.00	0.002	0.02	0.51***	

(*Continued*)

Table 5. (Continued).

		Standardized Beta coefficients					
	Predictor	Model-1	Model-2	Model-3	Model-4	Model-5	Tolerance
ANATOMICAL ISSUES	Tobacco chewing	.05	-.02	-.02	-.02	-.01	.83
	Tobacco infused water	-.01	-.01	-.01	-.01	.02	.97
	Betel nut chewing	.07	.09	.09	.08	.05	.89
	Gender	.16*	.18*	.18*	.18*	.08	.71
	Alcohol consumption		.003	.003	-.004	-.03	.85
	Smoking		.03	.03	.03	.02	.74
	Age		.27***	.27***	.26***	.14*	.88
	Daily mobile phone usage (hr)			.01	.01	.01	.98
	Years Residing				.07	-.02	.91
	Power density					.67***	.92
	R^2	0.04	0.10	0.10	0.11	0.53	Durbin Watson=1.8
	R^2 change	0.04	0.07	0.00	0.01	0.42***	

Key: *p <0.05; **p <0.01; ***p <0.001.
Tolerance indicates a suitable lack of multicollinearity between independent variables.
Tolerance > 0.02 is healthy.
Durban Watson tests for autocorrelation (when the residuals are not independent from each other); Durban Watson of 1.5–2.5 is healthy.

power density contributing a significant proportion towards this (42%). While gender and age predicted anatomical issues initially, gender lost significance when power density was included. In the final model both age (being older) and power density together contributed significantly towards anatomical issues.

Years of residing close to MPBS did not contribute significantly to any of the health issues. However, the range from 1 to 4 years residency was not covered by our sample, and the years of residing data was not taken for those in the reference group (> 300m). Therefore, our data do not allow final conclusions on the importance of time as a component of the exposure dose.

Two-way ANOVA was used to further explore possible interactions between age and level of exposure on health outcomes, with age categorized into <40 yr and >40 yr, and the three power density categories above used to represent level of exposure. The results (Figure 4) show that for all four health categories, the number of symptoms reported by residents was higher for the highly exposed groups (power density: 3.1–5.0 0 mW/m^2 and 5.1–8.0 mW/m^2), and lowest for the lowest exposed group **(power density: 0.0–3.0 mW/m^2)**. In all cases however, those exposed to the highest power densities (5.1–8.0 mW/m^2) reported more symptoms.

There was no significant interaction between age and **exposure** from MPBS for any health category, except for inflammatory issues (Figure 4c), where for the exposed groups it was the younger people (<40 yrs) who had more symptoms that the older group for the two highest exposure groups (3.1–5.0 mW/m^2 and 5.1–8.0 mW/m^2).

Further exploration was conducted into the results shown in Figure 4c, so as to ascertain which particular inflammatory conditions were contributing towards the age group differences. Table 6 presents the breakdown of inflammatory issues for the <40 yrs and >40 yrs age groups, for the two higher exposure groups. The results show that for the mid-exposure range (3.1–5.0 mW/m^2) the <40 yrs age group were experiencing proportionally more allergies and increased infections than the >40 yrs age group, while both age groups had a high proportion of headaches. For the highest exposure range (5.1–8.0 mW/m^2) the <40 yrs age group was experiencing proportionally more increased infections than the >40 yrs age group, while both age groups had a high proportion of headaches.

Figure 4 shows that for anatomical health issues, there was a simple main effect of age for the reference group living further way, with the lowest power density (0.0 mW/m^2 –3.0 mW/m^2), where the older people had more anatomical issues, which is an expected effect of aging. These results corroborate and illustrate the results of the hierarchical regression showing effects of both age and level of exposure (as power density), with age effects moving in opposite directions in the inflammatory versus the anatomical health categories. These opposing results are explored further in the discussion.

Possible interactions between mobile phone usage and exposure levels (power density categories) were also further explored using two-way ANOVA, so as

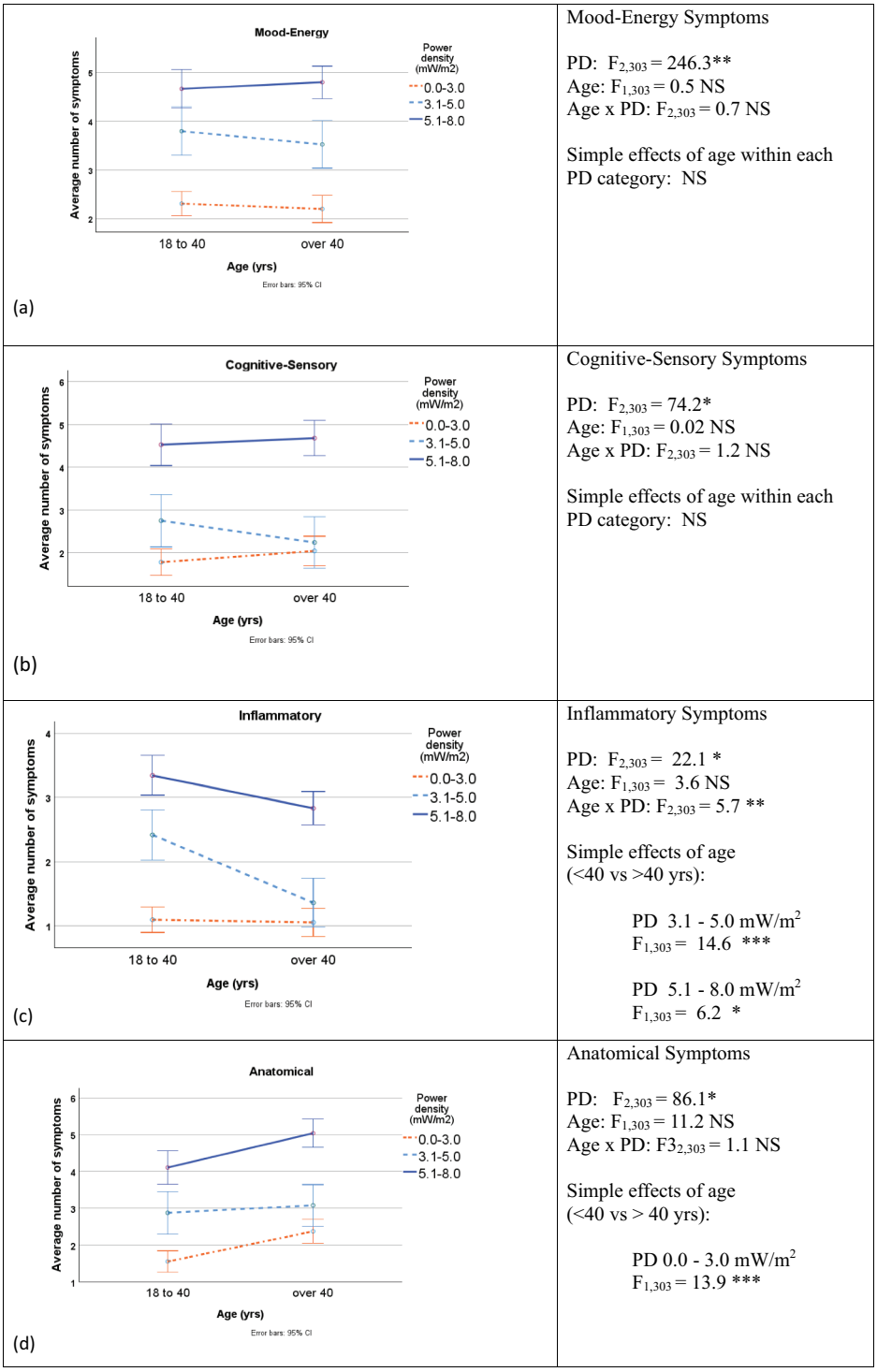


Figure 4. Effects of age and exposure from MPBS on number of symptoms in the four health categories. PD=power density; *$p < .05$; **$p < .01$; ***$p < .001$; NS = not significant.

to understand the combined influence of these factors on each of the four health categories. Once again, more symptoms were reported by those with higher MPBS exposures. However, there was no main effect of mobile phone use and no interaction between mobile phone usage and distance from base station for any of the health categories (see Supplementary Data 3).

Table 6. Percentage of residents in the two highest exposure groups reporting each inflammatory condition, according to age group.

Exposure	PD 3.1–5.0 mW/m^2 % (N)		PD: 5.1–8.0 mW/m^2 % (N)	
Inflammatory Factor	<40 years $N = 24$	>40 years $N = 25$	<40 years $N = 38$	>40 years $N = 53$
Headache	88% (21)	84% (21)	94% (36)	90% (48)
Allergies	54% (13) **	16% (4)	79% (30)	62% (33)
Increased Infections	75% (18) ***	20% (5)	92% (35) *	75% (40)
Weight Problems	4% (1)	0% (0)	21% (8)	0% (0)
Chest Pain	21% (5)	8% (2)	47% (18)	55% (29)

2 × 2Chi-squared tests were conducted within each exposure level, for each condition. The results of these test showed whether the <40 yrs group reporting the condition was significantly different from the proportion in the >40 yrs group reporting that condition. Any significant differences are shown in the cell of the group with the highest proportion PD=Power density * $p < .05$; ** $p < .01$; *** $p < .001$.

Discussion

While RF-EMF holds potential for numerous unforeseen applications with beneficial aspects, widespread uncontrolled chronic exposures may lead to major adverse impacts on population health and the wider environment (Cucurachi et al. 2013; Levitt et al. 2022). The current study investigated whether a range of health symptoms were more prevalent in individuals living closer to MPBS (within 300 m), and whether these effects were separate from other stress factors such as demographics, lifestyle choices and mobile phone use. The results showed that while there was significant variation in the type of health issues faced by individuals, the overall prevalence of most symptoms was shown to increase significantly with increasing levels of exposure (measured using power density). This result builds on the earlier work of Navarro et al. (2003) who found an association between the reported intensity of symptoms and the observed power density.

The prevalence of symptoms also increased approximately with closer proximity to the MPBS. Past studies have related symptoms to distance from towers; e.g., Santini et al. (2002, 2003). However, the data collected for this study has shown that distance information is not a perfect proxy for exposure level, as noted by Neubauer et al. (2007). In hilly terrains or built-up areas, power density is a more accurate independent variable for ascertaining health effects. This awareness may assist town planning in terms of understanding exposure levels at different locations. It may also inform future research when selecting exposed versus reference groups, rather than merely replicating the 300 m cut-off for the reference group that is often chosen (e.g. Alazawi 2011; Santini et al. 2002).

The symptoms found to be more prevalent in the highly exposed group spanned a wide range of health categories; i.e. mood-energy (anxiety, agitation, increased irritability, dizziness), cognitive-sensory (concentration problems, memory problems, ear problems, skin problems, abnormal sensations), inflammatory (headache, allergy, increased infections, chest pain, irregular heartbeat) and anatomical (joint pain, muscular problems, nerve pain, digestive problem, and nausea). Most demographic and behavioural variables (except for age) did not have a significant influence on any of these health categories, when considered in isolation. However, residents with greater exposures to MPBS experienced more mood-energy, cognitive-sensory, inflammatory and anatomical issues. In particular, individuals living within a distance of less than 50 m from the base stations had a higher occurrence of all symptoms. These results are in accordance with prior studies on MPBS and the RF-EMF emitted (Alazawi 2011; Jayaraju et al. 2023; Nilsson and Hardell 2023).

While the results and conclusions from the current study are based on epidemiological data, they corroborate the results of studies that have examined blood parameters that have found genetic damage in people of people living in close proximity to MPBS (Gulati et al. 2024; Zothansiama et al. 2017) indicating the induction of oxidative stress, leading to inflammatory issues and chronic disease.

RF-EMF may induce a variety of physiological changes, including thermoregulatory responses, alterations in various biological systems, such as neurological, immunological, endocrine, cardiovascular, dermal, ophthalmological, as well as reproductive and behavioural responses (Eskander et al. 2012; Maluin et al. 2021; Narayanan et al. 2010; Singh et al. 2023; Verma et al. 2019). The health issues found in this study are known to be symptoms of these negative physiological changes. Irregular heartbeat and chest discomfort has been previously reported among inhabitants living close to MPBS, and these symptoms were viewed as an indication of the activation of the "fight or flight" response, indicating physiological stress (Havas 2013). Concentration problems and problem-solving issues associated with exposure to RF-EMF have also been reported in prior studies (Abdel-Rassoul et al. 2007; Singh et al. 2016).

The hippocampus of the brain has been reported to be highly vulnerable to RF-EMF (Mumtaz et al. 2022). This may account for the notably greater occurrence of anxiety, as well as the difficulties with memory, concentration, and problem-solving that were observed in the present study among those exposed to greater power densities. Multiple researchers have emphasised the strong correlation between the occurrence of health problems such as

allergies, abnormal sensations (dysesthesia and paraesthesia), increased irritability, headaches, nausea and digestive issues such as loss of appetite, and RF-EMF exposure (Johansson 2009; Mat et al. 2010; Stein and Udasin 2020).

The collections of health symptoms found in previous studies as well as those observed in the present study have been listed by WHO as symptoms associated with Electro-hypersensitivity Syndrome (EHS) (2005). The WHO has stated that there are currently no definitive diagnostic criteria for EHS. Nevertheless, there is sufficient evidence from clinical, biological, and radiological data to support the recognition of EHS as a distinct, objectively identifiable, and well-characterized neuro-physiological illness (Belpomme and Irigaray 2022; McCredden et al. 2022). In the present study, individuals exposed to a power density of more than 3 mW/m^2had higher levels of fatigue, dizziness, headache, loss of appetite, and nausea compared with those exposed to less than 3 mW/m^2 at their residence. These are all symptoms of EHS, as noted by Havas (2013).

The results of the regression and ANOVA analyses also revealed differential age effects. As expected, effects of age on symptoms occurred independent of exposure levels. Age has been shown to impact various non-specific health symptoms (Havas 2013; Redmayne and Johansson 2015). For example, Navarro et al. (2003) found walking difficulties and hearing loss correlated with age, separate from the effects of exposure. Thus, it is not surprising that the older age group reported more symptoms in the mood-energy, cognitive-sensory and anatomical categories. In particular, the proportions of ear problems, visual disruption, chest pain, irregular heartbeat, joint pain and nerve pain were higher for those older than 40 years in both the highly exposed and reference groups. However, age also interacted with level of exposure from MPBS, in different ways for different health categories. The residents over 40 years in the reference group reported more anatomical issues, showing the typical effects of aging in the general population. Surprisingly, for those in the highly exposed group, it was the younger residents (under 40 years old) who reported more inflammatory issues; in particular, increased infections and allergies. This result partly corroborates the findings of Röösli et al. (2004) who found a higher frequency of headache, concentration difficulties and fatigue in those under 40 years old in the EHS group. The finding that living closer to towers may be a promoter of inflammatory issues for people under 40 years; is of concern and needs further investigation.

Study limitations

The different hours of daily mobile phone usage made no significant contribution to any of the health category issues for those living close to towers. However, this result may have been an artefact of the way in which the data was recorded. It is likely that categorizing 'low' mobile phone use as 1–5 hours is too broad to find any significant differences between low (1–5 hr) and high (>5 hr) mobile phone usage. Past research has shown that the high-risk category for mobile phone use is approximately one hour per day for 10 years (Hardell et al. 2006). Future research should record mobile phone use as a continuous variable making it more possible for a relationship with health outcomes to be found.

Moreover, data on Wi-Fi modem use (time and distance) should be included in future studies. Even though Wi-Fi modems are rarely used in this population, and usage was not expected to vary systematically with the experimental groups, this assumption needs to be tested against future data.

While there was not enough variance in the years of residing data to find an effect on numbers of symptoms reported in any of the health categories (as there was no data for 1 to 4 years), there is a benefit to the range of the data collected (5 to 18 yrs). Cross sectional studies often have the limitation that both power density and symptoms are measured at the same time, so that when a significant relationship is found between the two, it is uncertain whether exposure level is causal. Given that the residents in this study had all been living in their dwellings for at least 5 years, their exposures to higher power densities, potentially increasing over time, had been going on for all of this time before health effects were investigated in the study. This provides greater certainty that the observed higher prevalence of health effects associated with higher power density of exposures from MPBS can be interpreted as a causal relationship.

The research assistants taking the data were aware of the distances of residences from the local tower. This could be seen as a source of bias in the data collection. However, there are several factors that made this less likely. First, the results were not cleanly related to distance, and were more correlated with power density; however, the research assistants taking the data were not aware of the power density measures taken by the assistant engineer, nor were they trained to understand the meaning of power dentistry values. Furthermore, the number of items involved in the questionnaire created a great deal of complexity so that it would have been hard to inject bias into the responses in any systematic manner. Also, the higher prevalence of

inflammatory symptoms for the under 40 years age group was not anticipated and so could not have been due to bias.

Study implications

The maximum recorded power density measured at any dwelling was 7.2 mW/m^2. Most of the measurements taken in dwellings close to the base stations (Table 1) exceeded the safety limits suggested by the Bioinitiative Report 2012. However, all measured values were significantly lower than both the current ICNIRP whole body exposure public limits of 4500 mW/m^2 (900 MHz) to 10,000 mW/m^2 (2000 MHz and higher frequencies) as well as the present Indian Standard of 450 mW/m^2 (Saravanamuttu et al. 2015). These standards for public RF-EMF exposures are predominantly focused on the mitigation of "known" harmful thermal effects, but do not comprehensively cover a range of biological consequences that are intrinsically linked to non-thermal biological responses and health, especially for those who are continuously being exposed to this man-made radiation without choice or informed consent. In this context, the ALARA principle (As Low As Reasonably Achievable), which has widely been used with ionising radiation, has been recommended (Leach and Bromwich 2018).

Table 3 reveals that symptom prevalence was associated with duration of exposure. In toxicology research, the dose of a toxicant is understood to incorporate both intensity and duration of exposure (Tsatsakis et al. 2018).

The ICNIRP guidelines set safety limits based on exposure intensity, averaged over 6 or 30 minutes. Therefore, they do not factor in cumulative doses occurring over time in the real world. Laboratory studies are mostly restricted to timescales of minutes to weeks. Within studies using the longer of these timescales, biphasic effects have been observed (where effects are positive in the short term but then return to baseline as exposure duration increases and become negative with even longer exposure times) suggesting very short -term protective effects such as immune system priming, but detrimental effects after longer exposures (e.g., Fesenko et al. 1999). While adaptive responses have been suggested for long term exposures (Vijayalaxmi et al. 2014), the longer timescales of laboratory experiments show more negative effects. However, there are very few long-term laboratory studies.

Epidemiological data, such as that presented in this study, measures exposures over years and thus has been more able to reveal detrimental, cumulative effects that occur over time. Epidemiological research and intensity x time calculations need to be factored in when setting safety limits for populations who are continuously exposed over a lifetime.

While this study sampled only a moderate sized population from the city of Aizawl, the results can be used to inform public policy on this matter. Our results add to the understanding of health effects related to chronic exposure to RF-Fields emitted from MPBS. Risk management does not require definitive conclusions. Early warnings such as the results of this study provide adequate evidence for policy makers to act, including requiring industry to seek solutions (Gee 2009; Leach et al. 2024). The study results indicate that exposure to RF-EMF at levels lower than the Government recommended general public "safety" threshold can still lead to significant health challenges. The study revealed that the level of MPBS RF-EMF exposure was a primary contributor to the elevated prevalence of a range of health symptoms observed among residents in close proximity to MPBS. Concerning results that have revealed more inflammatory symptoms in resident younger than 40 years living close to MPBS require follow up.

Following these important findings, it is crucial to critically reassess current public RF exposure safety limits in order to include the growing evidence of non-thermal biological impacts of RF-EMF emitted by MPBS over years. The study results emphasize the importance of establishing exposure limits that are based on biological factors, other than heating, to minimize exposure and address the long-term potential for serious health consequences; i.e., "An independent re-evaluation of RFR exposure limits based on the scientific knowledge gained over the past 25 years is needed and is long overdue" (Belyaev et al. 2022).

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Data availability statement

The article contains all the data necessary to understand the conclusions of this investigation.

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