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Very high radiofrequency radiation at Skeppsbron in Stockholm, Sweden from mobile phone base station antennas positioned close to pedestrians' heads

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ABSTRACT

In urban environment there is a constant increase of public exposure to radiofrequency electromagnetic fields from mobile phone base stations. With the placement of mobile phone base station antennas radiofrequency hotspots emerge. This study investigates an area at Skeppsbron street in Stockholm, Sweden with an aggregation of base station antennas placed at low level close to pedestrians' heads. Detailed spatial distribution measurements were performed with 1) a radiofrequency broadband analyzer and 2) a portable exposimeter. The results display a greatly uneven distribution of the radiofrequency field with hotspots. The highest spatial average across all quadrat cells was 12.1 V m^{-1} (388 mW m^{-2}), whereas the maximum recorded reading from the entire area was 31.6 V m^{-1} (2648 mW m^{-2}). Exposimeter measurements show that the majority of exposure is due to mobile phone downlink bands. Most dominant are 2600 and 2100 MHz bands used by 4G and 3G mobile phone services, respectively. The average radiofrequency radiation values from the earlier studies show that the level of ambient RF radiation exposure in Stockholm is increasing. This study concluded that mobile phone base station antennas at Skeppsbron, Stockholm are examples of poor radiofrequency infrastructure design which brings upon highly elevated exposure levels to popular seaside promenade and a busy traffic street.

1. Introduction

Electromagnetic fields are known physical risk factors. When mobile phone base station antennas are installed, the immediate physical environment, including the public and the living spaces can be greatly affected by microwaves.

Measuring public exposure to radiofrequency fields is significant from public health perspective, but also for future epidemiological studies. Given the rapid development of mobile communication technologies, the radiofrequency landscape is continuously diversifying and intensifying: more frequencies are introduced to provide novel mobile phone and data services; more base station antennas are constantly installed to facilitate the increasing need for data amounts, pushed through the networks. Meanwhile, public exposure also increases.

In previous publications we have reported environmental exposure to radiofrequency (RF) electromagnetic (EMF) radiation at certain places in Stockholm in Sweden such as the Central Railway Station (Hardell et al., 2016), the Old Town (Hardell et al., 2017), with special attention to Järntorget in the Old Town (Hardell et al., 2019), and Stockholm city (Carlberg et al., 2019). Of special interest was to measure RF radiation in one Stockholm apartment with two groups of base station antennas nearby (Hardell et al., 2018). That apartment was further examined using a RF broadband analyzer and the results were compared with another Stockholm apartment with substantially much lower RF radiation but equally good wireless communication possibility (Koppel et al., 2019).

Earlier studies done in Europe show constant increase of public exposure, especially in urban environment. The increase is attributed to new mobile phone base stations installed, but also to the increased usage of corresponding mobile services. Sánchez-Montero et al. (2017) monitored urban exposure in Alcalá de Henares (Spain) for ten years and reported city mean field increase from 0.277 (203 μW m^{-2}) in 2006 to 0.395 V m^{-1} (414 μW m^{-2}) in 2015. Sánchez-Montero et al. (2017) admit that during the ten years of monitoring the number of mobile phone base

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station has doubled, but also conclude that the probability of being exposed to a high value of 14 V m^{-1} (519 mWm^{-2}) is less than 0.01% and the probability of being exposed by 28 V m^{-1} (2079 mWm^{-2}) is negligible (Sánchez-Montero et al., 2017).

It is expected, that wherever mobile phone base station antennas are installed, high exposure areas might be encountered. Although these highly exposed areas constitute a minor part of the urban environment, these should be carefully studied for the sake of the people who work and live there.

Urbinello et al. (2014) emphasized "A continuous monitoring is needed to identify high exposure areas and to anticipate critical development of RF-EMF exposure at public places", while they informed a steep RF radiation growth in public places within one year. The growth of RF radiation has been substantial in many countries, also in Sweden as exemplified in this study.

Sagar et al. (2018) conducted a literature review, looking at studies in between 2000 and 2013 of radiofrequency electromagnetic exposure in microenvironments in Europe. For outdoor microenvironments they report the mean total RF exposure to be 0.54 V m^{-1} for spot measurements. Typical exposure levels were around 0.5 V m^{-1} and rarely over 1 V m^{-1}. They report downlink contributing the most to the total RF exposure in outdoor microenvironments in all studies except one.

An updated review by Jalilian et al. (2019) on European microenvironments' studies from 2015 to 2018 found mean outdoor exposure ranging from 0.07 to 1.27 V m^{-1}. Mobile phone base stations' downlink signals were the most relevant contributor to total exposure. The review concluded a tendency for RF levels to increase with increasing urbanity. Also, the review found that all different types of studies reported mean exposure levels of less than 1 V m^{-1}; different types included spot measurement, fixed site monitoring, and personal measurement with volunteers.

The problem with most of the spot measurement studies is their inability to adequately represent spatial RF field distribution. This is due to two reasons: 1) the measurement sample is too small and does not account for highly exposed areas and/or 2) the spots where the measurements are collected do not coincide with the RF hotspots. RF hotspots occur usually around RF sources such as mobile phone base station antennas. Furthermore, RF hotspots depend on the radiation pattern of the antenna and the surrounding environment, hence the field distribution is uneven. It is not possible to visually identify RF hotspots around the antennas, this can only be done by detailed measurements or computer simulations.

For example, Aerts et al. conducted a detailed RF field mapping in Ghent, Belgium. They performed in total 650 broadband measurements in a city subarea of 1 km^2. The study found five hotspots, with max total electric field ranging from 1.3 to 3.1 V m^{-1} (Aerts et al., 2013). Their study showed, that significantly higher RF exposure levels are likely to occur than those reported by the majority of studies. In addition, they demonstrated that construction of a detailed RF heat map of the investigated area is important to characterize and outline the hotspot area.

1.1. *The aim of the study*

In this study we identified an area in Stockholm with an aggregation of base station antennas placed at low level, close to pedestrians' heads. The aim of this research is to point out highly exposed radiofrequency areas in the city environment and to analyze the sources and the reasons for the high exposure. We performed detailed measurements and constructed a detailed RF heat map. Such conclusions would help to better design the RF infrastructure sites with the aim of minimizing the public exposure. No ethical permission was needed since no test persons were involved.

2. Materials and methods

In this study spatial distribution of RF radiation sources was measured. The RF radiation sources were mobile phone base station antennas located at the Skeppsbron street, Stockholm, Sweden. This area is characterized by dense RF infrastructure as 15 mobile phone base station sectoral antennas from several operators are located on the same building complex, where the elevation from the street level is only few meters.

The site was selected by visually identifying radiofrequency sources, based on the dense packing of mobile phone base station antennas. Also the site is well suited for a scientific study, as it is positioned within the city center, whereas one side of the site is open to the sea where there are no RF sources nearby. The old town with old buildings is located on the other side of the street.

2.1. *Study design*

The measurements were conducted on a business day afternoon (January 14, 2019) with busy traffic which allows to assume higher network traffic. All measurements were done outdoor.

Field distribution was determined covering an area of 60 × 250 m, representing a street strip of old town buildings at one side and the sea (Strömmen) at the other side. The area is composed of the Skeppsbron street with busy traffic and pedestrians represented by a seaside promenade. Seaside promenade is filled with indoor and outdoor cafés, some operating throughout the year. Antennas are installed on top of those cafés. The promenade and the cafés are packed with hundreds of people on a holiday period – many of which at close range to the mobile phone base station antennas.

The area was covered by 3 × 11 quadrats, where each quadrat cell (quad) was measured with RF broadband analyzer by registering RF readings from one end of the quad to another by following North-South axis with a slow pace. For each quad, one moving measurement scan was done. Quads were drawn to both sides of the Skeppsbron street. Each quad measurement was done for about 1 min with average and maximum readings registered. The measurements were taken at the height from 1 to 1.8 m by moving the meter in circular movements along the quad. This allows covering the standing waves and detecting maximum radiation points.

RF broadband analyzer used was Narda NBM-520, with an E-field probe E0391 (Narda-Safety-Test-Solutions GmbH, Pfullingen, Germany). This meter of Narda NBM-series is capable of time and spatial averaging and determining the maximum level during the monitored period. Manufacturer's probe EF0391 is intended for base station measurements with a frequency range from 100 kHz to 3 GHz. This meter and the probe cover a large range of RF sources, including different telecommunications protocols: frequency modulation (FM) radio broadcasting; television (TV) broadcasting; TETRA emergency services (police, rescue, etc.); global system for mobile communications (GSM) second generation mobile communications; universal mobile telecommunications systems (UMTS) third generation mobile communications, 3G; long-term evolution (LTE) fourth generation mobile communications standard, 4G; digital European cordless telecommunications (DECT) cordless telephone systems standard; Wi-Fi wireless local area network protocol, 2.45 GHz; worldwide interoperability for microwave access (WIMAX) wireless communication standard for high speed voice, data and internet.

Later, the measurement readings were entered into vector mapping software 3DFIELD ver. 4.5.2.0 (by Vladimir Galouchko) and field distribution map created (in V m^{-1}). Field distribution map was based on quadrat measurement spatial averages by using kriging, which is a geostatistical calculation method.

Additionally to analyze the frequency composition the entire quadrat was in parallel also measured with an exposimeter EME Spy 200 b y Microwave Vision Group, Paris, France. The exposimeter measures 20 predefined frequency bands covering most public RF radiation emitting devices currently used in Sweden. The exposimeter covers frequencies from 88 to 5850 MHz. For FM, TV3, TETRA, TV4&5, Wi-Fi 2.4 GHz and

Wi-Fi 5 GHz the lower detection limit is 0.01 V m^{-1} (0.27 μW m^{-2}); for all other bands the lower detection limit is 0.005 V m^{-1} (0.066 μW m^{-2}). For all bands the upper detection limit is 6 V m^{-1} (95,544 μW m^{-2}; 9.5544 μW cm^{-2}). The sampling rate used in this study was every 4th second which is the fastest possible sampling rate for the given exposimeter when all bands are active. The exposimeter was held at some distance (about 0.4 m) from the body. The unit reports the exposure in a conservative manner since each reported value is the sampling outcome, where many samples are taken and statistically processed including minimum, mean, median and maximum values. The meters had valid calibration.

Based on Cellmapper.net mobile phone operators and their corresponding services, mobile bands and frequencies were determined (Table 1). A large number of base station sector antennas emit a multitude of downlink frequency spans (N = 14) covering 2G, 3G and 4G services. Service providers have their own allocated frequency spans, but some are shared.

2.2. Statistical methods

Broadband RF readings using Narda NBM-520 were collected in Volts per meter (V m^{-1}) based on quadrat measurements covering the entire area. Each quadrat produced a spatial average and maximum reading calculated on the space covered. Based on quadrat cells measurements, two samples were formed: one of spatial averages and the second of spatial maximums. For both samples minimum, quartiles, median and maximum were calculated containing all the spatial measurement values in the area, using MS Excel 2016.

Means in microWatts per square meter (μW m^{-2}) were calculated for all measured frequency bands for measurements using the exposimeter EME Spy 200. Values below the lower detection limit were treated as no (0) exposure. Total exposure was calculated as the sum of all measured frequency bands. Stata/SE 12.1 (Stata/SE 12.1 for Windows; StataCorp., College Station, TX, USA) was used for all calculations.

3. Results

The results display a greatly uneven distribution of the RF fields with hotspots. The close proximity to the RF sources creates highly elevated field levels in the immediate vicinity to the base station. Given the antennas elevation from the ground, people walking on the street are highly exposed when passing or hanging around the area.

Fig. 1 presents a boxplot of spatial RF distribution of the entire investigated area. Both spatial average and maximum readings of RF broadband analyzer are included in the graph. The fields emanated by the base station antennas overlapped at several locations, elevating the exposure to high levels. The highest spatial average across all quadrat cells was 12.1 V m^{-1} (388 mW m^{-2}), whereas the maximum recorded reading over the entire area was 31.6 V m^{-1} (2649 mW m^{-2}). These were far-field measurement results, the meter was not used in the near-field of antennas. The lowest spatial average quadrat was 1.4 V m^{-1} (5.2 mW m^{-2}) which is still relatively high, considering the levels reported by the review studies (Jalilian et al., 2019; Sagar et al., 2018) discussed in the Introduction chapter. This emphasizes that the entire microenvironment

Table 1
Mobile phone operators, their corresponding services and frequencies used at Skeppsbron, information from cellmapper.net.

Operator	Bands	Downlink frequency (MHz)
Telia	4G	806, 1815, 1832, 2660
	3G	2152, 2157
	2G	950
Telenor	4G	936, 1857, 2630, 2680
	3G	2112, 2122
Tele2	4G	936, 1857, 2630, 2680
	3G	2152, 2157, 2162

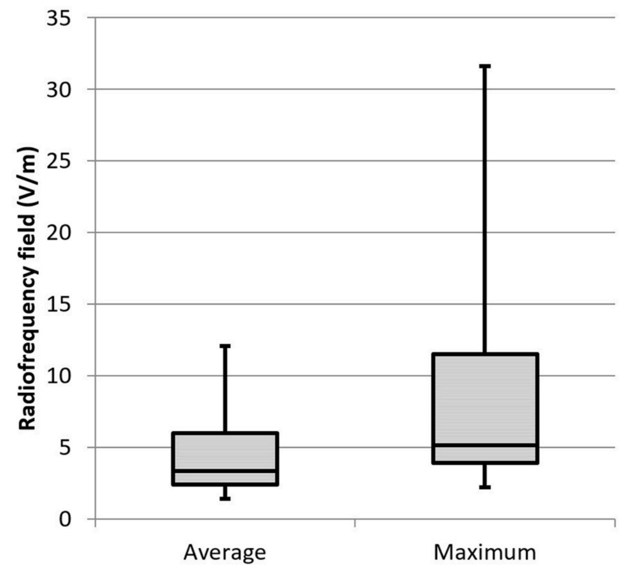

Fig. 1. Boxplot of spatial distribution of the radiofrequency field (V m^{-1}) at Skeppsbron street, based on quadrat measurements covering the entire area; sample is based on spatial averages and maximums of a quadrat cells; boxplot depicts (from bottom up) minimum, first quartile, median, third quartile and maximum of the sample containing all the spatial measurement values in the area.

in Skeppsbron street is covered with relatively high levels of radiofrequency radiation.

Fig. 2 displays a spatial distribution of the RF field at the Skeppsbron street. Exposure readings are based on spatial average of a given quadrat cell. High field levels are encountered close to the base station antennas, whereas the highest levels were not detected below the antenna, but at 26 m distance, directly on the line of the direction of sector antenna. The field decreases with increasing distance from the base station array, but is still significantly elevated at the entire 250 m length of the studied street area.

Highest field levels as registered across the street, may also refer to confounding action of building walls, as some building materials may reflect the incident waves, hence giving rise to resultant exposure level (Koppel et al., 2017a). Also the weather can play a role in microwave propagation as wet walls may increase building material microwave reflection properties (Koppel et al., 2017b).

Exposimeter measurements (mean of sample) showed that the majority of exposure was due to mobile phone downlink bands. Most dominant were 2600 and 2100 MHz bands used by 4G and 3G mobile phone services, respectively. Also 800, 900 and 1800 MHz bands were clearly elevated in the frequency spectrum, which fits the 4G profile (Table 2). The exposimeter was unable to register the highest exposure levels as the upper detection limit was exceeded repeatedly. Therefore, FM, as well as 1800 MHz, 2100 MHz, and 2600 MHz downlinks were not properly evaluated by the exposimeter measurements. Meanwhile, broadband meter measurements were able to register also the highest levels.

Table 3 compares public exposure to radiofrequency fields in Stockholm, based on authors' studies – comparing this study at Skeppsbron street to previous measurements. Comparison is done based only on exposimeter (EME Spy 200) measurements, excluding broadband meter measurements. RF field comparison reveals that Skeppsbron street is one of the highest public exposure areas in Stockholm so far measured with the maximum field level exceeding upper detection limit of the exposimeter.

Figs. 3 and 4 are photographs of the street view with some of the mobile phone base station antennas pointed out. The antennas are placed quite low, near the street level, where microwaves irradiate

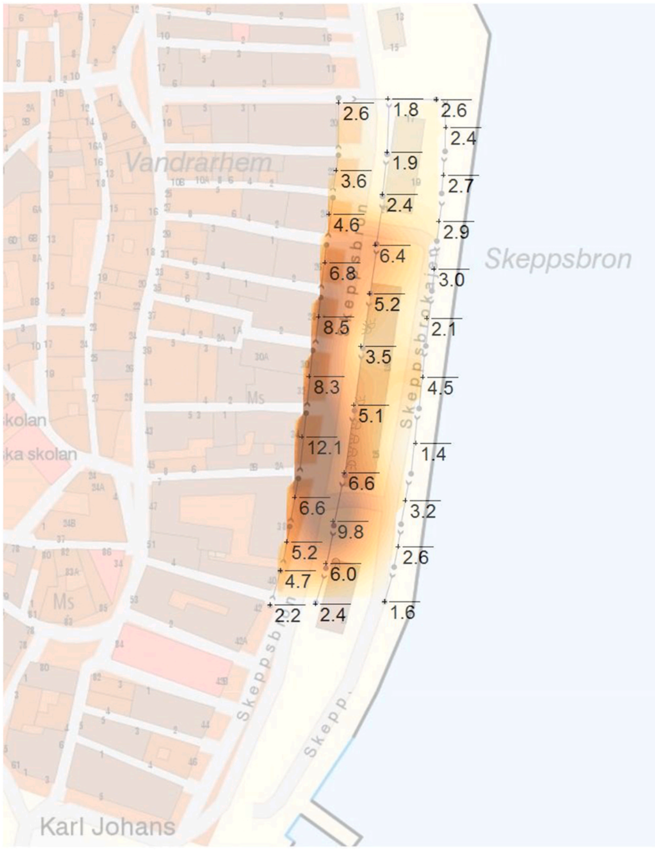

Fig. 2. Spatial distribution of the radiofrequency field (values in V m $^{-1}$) at Skeppsbron street, based on spatial average of a given quadrat cell; hotspots are displayed in darker red where pedestrians are exposed at close range or rays overlap from several mobile phone base station antennas; the investigated area measures about 250 m North to South; map by Lantmäteriet, Sweden. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Exposimeter measurements of the radiofrequency field at Skeppsbron street, analysis of all data (μW m^{-2}) treating values at detection limit as 0. (Note: Exposimeter's highest detection limit (95,522.5 μW m^{-2} was constantly exceeded, therefore Max-values are likely to be much higher, as also confirmed by broadband measurements.) Total (n = 915).

Frequency band	Mean	Median	Min	Max
FM	1304.0	19.6	0.0	95,522.5
TV3	7.2	0.0	0.0	1601.4
TETRA I	0.0	0.0	0.0	1.0
TETRA II	0.0	0.0	0.0	4.7
TETRA III	2.3	0.0	0.0	403.4
TV4&5	17.4	0.6	0.0	2434.4
800 (DL)	751.3	164.5	0.7	12,978.6
800 (UL)	0.0	0.0	0.0	6.6
900 (UL)	0.0	0.0	0.0	8.6
900 (DL)	2545.3	926.5	0.4	35,473.9
1800 (UL)	71.0	8.3	0.0	3291.8
1800 (DL)	3466.6	714.5	3.6	95,522.5
DECT	367.6	0.0	0.0	36,548.9
2100 (UL)	0.1	0.0	0.0	45.5
2100 (DL)	6558.8	1237.4	1.7	95,522.5
WIFI 2G	0.4	0.0	0.0	61.3
2600 (UL)	689.5	154.1	0.0	17,275.1
2600 (DL)	11,338.3	3483.6	1.7	95,522.5
WIMax	0.2	0.0	0.0	58.9
WIFI 5G	0.4	0.0	0.0	93.8
Total	27,120.5	10,481.5	24.4	373,381.0

Table 3
Public exposure to radiofrequency field in Stockholm – this study compared authors' previous studies; exposimeter EME Spy 200 measurements; analysis of all data (μW m^{-2}) treating values at detection limit as 0.

Study	Total (n)	Mean	Median	Min	Max
Stockholm, Central Station (Hardell et al., 2016)	1669	3860.2	920.6	5.8	9206.3
Stockholm, Old Town (Hardell et al., 2017)	10,437	4292.7	534.0	0.0	173,301.8
Stockholm, City (Carlberg et al., 2019)	11,482	5494.2	3346.0	36.6	205,154.8
Stockholm, Järntorget, Old Town (Hardell et al., 2019)	792	21,354.9	12,655.3	381.7	178,928.2
Stockholm, Skeppsbron (current study)	915	27,120.5	10,481.5	24.4	373,381.0

Fig. 3. Street view on the Skeppsbron street with some of the mobile phone base station antennas pointed out with a circle; note the low placement of the antennas, where microwaves irradiate the pedestrian at close range.

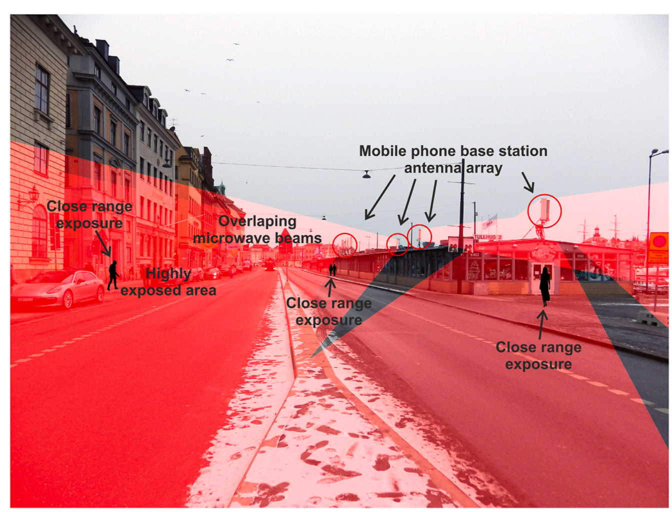

Fig. 4. Problem context of mobile phone base station antennas created high exposure at Skeppsbron street; altogether 15 antenna panels could be counted on that building, all positioned at low elevation close to the street level; the maximum RF exposure was at 31.6 V m^{-1}, registered at close range to the antennas.

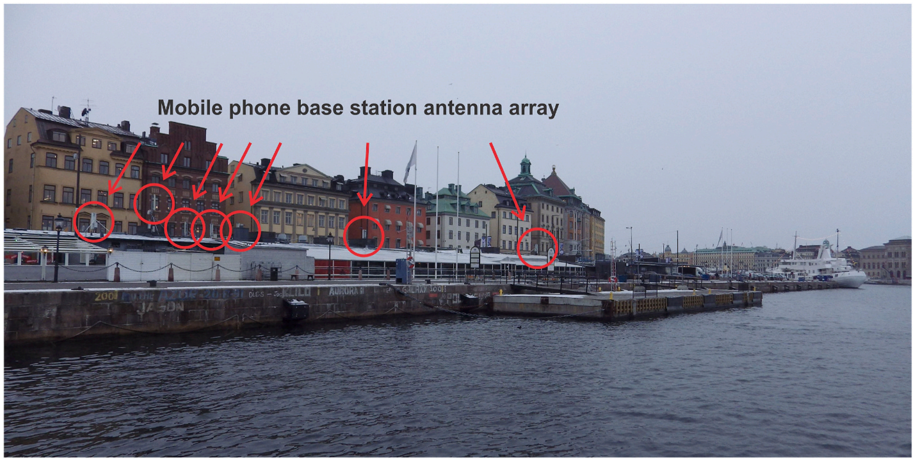

Fig. 5. The antennas are mostly facing the buildings, as the operators want to force the wave into the old town through the narrow streets. Considering the low placement of antennas and pushing all this power - creates very high exposure levels nearby.

pedestrians at close range. Fig. 5 depicts the context – very low placement of the antennas, most of which are targeting the buildings in order to push the microwave into the narrow streets and further into the old town.

4. Discussion

This study, and our previous ones, have recorded the exposure to RF radiation which will provide means for historic comparison for both public and occupational exposure. It is clear from our current study and the previous ones that the level of ambient RF radiation exposure is increasing, see Table 3. Public exposure in different places around the globe is shown in Table 4. Our average and peak RF measurement results are much higher than many of those measurements in that table, indicating a rather recent and rapid increase in radiofrequency radiation levels in city centers. To provide comparison, Bergqvist et al. (2001) measured 0,18 mW m^{-2} highest average levels in Stockholm city center in 2001 (Bergqvist et al., 2001). Swedish radiation protection authorities pointed out recently highest average levels like 720 mW m^{-2} at Järntorget (Esternberg, 2020) and 690 mW m^{-2} at Skeppsbron area (Umeå kommun 2019) in Stockholm. One possible reason for our high RF readings in 2019 was the upgrade of 4G (LTE) base stations with new antenna panels including more antenna elements for the forthcoming 5G (which started officially in Stockholm in 2020).With the development of mobile communications technologies and the widespread use of wireless services the exposure will continue to increase with substantially higher exposure levels and also ever increasing frequency bands, even though several research reports indicate health risks. These risks are relevant to those people working or living in the highly exposed places – in this study they are 1) people living in the apartments across the street from the antennas, 2) workers of the shops across the street and beneath the antennas.

This research identified an increased RF exposure risk area in the center of Stockholm city. Clearly we measured high RF radiation levels of the same magnitude at a square (Järntorget) in the old town (Hardell et al., 2019). These results may be compared with the Ramazzini Institute rat study on far field exposure to 1.8 GHz RF radiation of 0, 5, 25, 50 V m^{-1} with a whole-body exposure for 19 h/day similar to that from base stations (Falcioni et al., 2018). Increased incidence of glioma and heart tumours of the Scwannoma type were found, i.e. similar tumour types as found among people using wireless phones. A statistically significant increase in the incidence of malignant Schwannoma in the heart was found in male rats at the highest dose, 50 V m^{-1} corresponding to whole-body SAR of 0.1 W/kg. Increased non-significant incidence of heart Schwann cells hyperplasia was observed in exposed male and female rats at the highest dose. In irradiated female rats at the highest dose (50 V m^{-1}) the incidence of malignant glial tumours was increased, although not statistically significant. In the current study maximum exposure level of 31.6 V m^{-1} was measured. Thus, there is no reasonable safety limit comparing with the animal study.

Table 4
Public exposure to radiofrequency fields at different places.

Study	Investigated locations	Exposure (mean)
Joseph et al. (2010)	Europe, outdoor	372–569 $\mu W\ m^{-2}$
Bolte et al. (2011)	Netherlands, railway stations	304–354 $\mu W\ m^{-2}$
Bolte and Eikelboom (2012)	Netherlands, outdoor activities	208 $\mu W\ m^{-2}$
Rowley and Joyner (2012)	23 countries	730 $\mu W\ m^{-2}$
Urbinello et al. (2014)	Europe, Basel, Ghent, Brussels	271–892 $\mu W\ m^{-2}$
Verloock et al. (2014)	Belgium, public places	1020 $\mu W\ m^{-2}$
Estenberg and Augustsson (2014)	Stockholm city, Sweden	6700 $\mu W\ m^{-2}$
	Sweden, urban	1500 $\mu W\ m^{-2}$
	Sweden, rural	230 $\mu W\ m^{-2}$
Calvente et al. (2015)	Spain, Granada	799 $\mu W\ m^{-2}$
Gonzalez-Rubio et al. (2016)	Spain, Albecete	4,2–2102 $\mu W\ m^{-2}$
Choudhary and Vijay (2017)	India, Kota city residential	5452–77,840 $\mu W\ m^{-2}$
	industrial, commercial	2386–68,769 $\mu W\ m^{-2}$
	agricultural	2378–68,724 $\mu W\ m^{-2}$
	rural	1878–68,724 $\mu W\ m^{-2}$
Sánchez-Montero et al. (2017)	Spain, Alcalá de Henares	2006: 0.278 V m^{-1} (205 $\mu W\ m^{-2}$) 2010: 0.407 V m^{-1} (439 $\mu W\ m^{-2}$) 2015: 0.396 V m^{-1} (416 $\mu W\ m^{-2}$)
Thielens et al. (2018)	Australia, Melbourne	0.05–0.89 V m^{-1} (6–2101 $\mu W\ m^{-2}$)
Misek et al. (2018)	Ziina city, center	1.072 V m^{-1} (3048 $\mu W\ m^{-2}$)
	residential	1.852 V m^{-1} (9097 $\mu W\ m^{-2}$)
	rural	0.510 V m^{-1} (690 $\mu W\ m^{-2}$)
	Visnove, rural	0.093 V m^{-1} (23 $\mu W\ m^{-2}$)
Eeftens et al. (2018)	Europe, 5 countries	150–160 $\mu W\ m^{-2}$
Zeleke et al. (2018)	Australia, Melbourne	0.233 V m^{-1} (144 $\mu W\ m^{-2}$)
Christopoulou and Karabetsos (2019)	Greece, urban	0.244 V m^{-1} (158 $\mu W\ m^{-2}$)
	Greece, suburban	0.229 V m^{-1} (139 $\mu W\ m^{-2}$)

Electromagnetic fields are a physical risk factor. However, current legislation does not require the mobile phone services operator to ask for approval from neighboring inhabitants, when installing RF sources. Nevertheless, when mobile phone base station antennas are installed, the immediate physical environment, including the neighborhood living environment is greatly altered by the microwaves.

Studies from recent decades have shown elevated health risk under long term exposure to such highly elevated radiofrequency fields.

A review by Khurana et al. (2010) found in 80% of the available studies neurobehavioral symptoms or cancer in populations living at distances <500 m from base stations (Khurana et al., 2010). In another review exposure from base stations and other antenna arrays showed changes in immunological and reproductive systems as well as DNA double strand breaks, influence on calcium movement in the heart and increased proliferation rates in human astrocytoma cancer cells (Levitt and Lai, 2010).

When a GSM 900 MHz base station was installed in the village Rimbach in Germany it had an influence on the neurotransmitters adrenaline, noradrenaline, dopamine and phenyletylamine (Buchner and Eger, 2011). Influence on cortisol and thyroid hormones in people living near base stations was shown in other studies (Augner et al., 2010; Eskander et al., 2012).

Dode et al. (2011 compared base station (BS) clusters and cases of deaths by neoplasia in the Belo Horizonte municipality, Minas Gerais state, Brazil, from 1996 to 2006. In their study largest electric field was 12.4 V m^{-1} and the smallest was 0.4 V m^{-1}. They found cancer-related death rates be higher close to base stations. This finding confirmed earlier findings by Eger (Eger et al., 2004).

In a study from India, genetic damage using the single cell gel electrophoresis (comet) assay was assessed in peripheral blood leukocytes of individuals residing in the vicinity of a mobile phone base station and comparing it to that in healthy controls. Genetic damage parameters of DNA migration length, damage frequency, and damage index were significantly ($p < 0.001$) elevated in the sample group compared to respective values in healthy controls (Gandhi et al., 2014).

The effect of RF radiation among 20 subjects living close to mobile phone base station compared with 20 subjects living with a distance of about 1 km was studied (Singh et al., 2016). The authors concluded that: "*It was unveiled that a majority of the subjects who were residing near the mobile base station complained of sleep disturbances, headache, dizziness, irritability, concentration difficulties, and hypertension. A majority of the study subjects had significantly lesser stimulated salivary secretion (p < 0.01) as compared to the control subjects*."

Zothansiama et al. (2017) in India inspected DNA damage and antioxidant status in cultured human peripheral blood lymphocytes (HPBLs) of individuals residing in the vicinity of mobile phone base stations and compared it with healthy controls living further away. The analyses of data from the exposed group ($n = 40$), residing within a perimeter of 80 m of mobile base stations, showed statistically significantly ($p < 0.0001$) higher frequency of micronuclei when compared to the control group, residing 300 m away from the mobile base stations.

The Ramazzini Institute findings (Falcioni et al., 2018) are supported by the results in the USNTP study on rats and mice exposed to RF radiation (National Toxicology Program, 2018a, 2018b). A clear evidence of increased incidence of heart Schwannoma and some evidence for glioma and tumours in the adreanal medulla in male rats was found according to the expert panel, for further discussion see Hardell and Carlberg (2019).

4.1. Health risks associated with mobile phone radiation

RF radiation was in 2011 classified as a possible human carcinogen, Group 2B by the International Agency for Research on Cancer (IARC) at the WHO (Baan et al., 2011; IARC Working Group, 2013), After that the evidence on cancer risk has increased so that RF radiation may now be classified as a human carcinogen, Group 1 according to the IARC classification (Carlberg and Hardell, 2017).

By now there is concordance between tumours in human epidemiology (Belpomme et al., 2018; Miller et al., 2018) and animal studies (Falcioni et al., 2018; National Toxicology Program, 2018a, 2018b), that is glioma and Schwann cell tumours. These results are supported by mechanistic studies such as oxidative stress (Yakymenko et al., 2016) and DNA damage from RF radiation (Smith-Roe et al., 2020).

So far personal use of wireless phones, mobile and cordless phones (DECT), have yielded highest RF radiation exposure especially to children and to the brain (Gandhi et al., 2012). However, ambient exposure is of increasing concern and may now be of the same magnitude as for increasing cancer incidence in animal studies. This is exemplified in this study.

The BioInititative Report (2012) defines a target level of 30–60 μW m^{-2}, and for chronic exposure and sensitive people such as children one tenth of this, 3–6 μW m^{-2}, see Chapter 24 of the BioInitiative Report (Sage, and Carpenter, 2012).

Already in 2011 Yakymenko et al. stated that: *It is now becoming increasingly evident that assessment of biological effects of non-ionizing radiation based on physical (thermal) approach used in recommendations of current regulatory bodies, including the International Commission on Non-Ionizing Radiation Protection (ICNIRP) Guidelines, requires urgent reevaluation* (Yakymenko et al., 2011).

This view is supported by 252 EMFscientists from 43 nations www.emfscientist.org:

> "Numerous recent scientific publications have shown that EMF [electromagnetic field] affects living organisms at levels <u>well below most international and national guidelines.</u> Effects include increased cancer risk, cellular stress, increase in harmful free radicals, genetic damages, structural and functional changes of the reproductive system, learning and memory deficits, neurological disorders, and negative impacts on general well-being in humans. Damage goes well beyond the human race, as there is growing evidence of harmful effects to both plant and animal life."

5. Conclusions

This study has pointed out a highly exposed radiofrequency radiation area in the Stockholm city environment and identified the sources and reasons of high exposure. By positioning RF infrastructure to the proximity of the public the risk of health effects is increased since members of the public on the street, also inhabitants in nearby buildings are highly exposed. Mobile phone base station antennas are positioned at the height of second floor levels of adjacent buildings spreading microwaves across the street. Highly elevated exposure levels would likely be encountered in the premises next to the windows facing the mobile phone base station array.

The study concluded that Skeppsbron street mobile phone base station antennas are examples of a poor radiofrequency infrastructure design with mobile phone base station antennas positioned into close range to the general public which brings upon high exposure levels. Given the low placement of the antennas (height from the street floor), the highest exposure was often registered at pedestrian head level. Given that head is one of most vulnerable parts of the body, these placements by mobile telephony service providers put pedestrians into unnecessary risk. Position of these antennas, can pose a health risk to people at close range. This is especially critical for people at particular risk, including persons with medical implants, pregnant women or chronically ill persons.

Based on the latest scientific literature regarding RF exposure and adverse health effects, this study recommends repositioning such base station antennas to areas away from the nearby inhabitants, workers and the general public. Alternatively, very low power antennas may also be considered to reduce the exposure. Occupational exposure of people working close to the antennas should also be considered – shop clerks, restaurant workers are likely to spend considerably longer time under high exposure, compared to the general public.

The following recommendations for radiofrequency infrastructure can be concluded from the current study.

1. Antennas should be positioned as far as possible from the general public, like locations at the high elevations or remote areas, where the antenna targeted area is not regularly/frequently visited by the members of the public.
2. Only low power output mobile phone base station antennas (<15W) should be used in the city environment.
3. To avoid hotspots, created by overlapping arrays, dense packing of many antennas at one site should be avoided.
4. Low power output antennas in the city environment should be positioned into locations where direct beam would not hit members of public closer than 50m.

The conclusions of this study will help to design safer mobile phone base station sites in the city environment, when the aim is to minimize public exposure.

Author contributions

T.K. and M.A. performed the measurements. Conception of the study, design and analyses of the material, writing of the article and approval of the final manuscript was made by all authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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