Measurements of radiofrequency electromagnetic fields, including 5G, in the city of Columbia, SC, USA

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Abstract. The present study aimed to characterize the wireless infrastructure and public exposure to radiofrequency (RF) electromagnetic fields, including the sub-millimeter wave 5G, in the city center of Columbia, SC, USA. A downtown measurement route was designed to cover popular outdoor areas, including business, recreational and shopping areas. The route was measured five times during different days and times. An exposimeter, was used to cover all the main civilian wireless broadcasting and downlink sources in frequencies 88-5,850 MHz. The measurement route at the streets and squares calculated 1.240 V/m as a mean exposure (total as a sum of all frequency bands) and 6.867 V/m as all times maximum. The most common contributors to the exposure budget were bands FM US, 14DL, 27DL, 25DL and 66DL - mainly indicating 4G. The exposure levels were found to be 12-16% lower during weekends as compared to business hours ($P<0.001$). The spatial analysis of the field distribution revealed 15-20 hotspot areas. A number of hotspots were found where cell phone base station antennas were mounted on top of the utility poles and therefore positioned at low levels, close to street level. On the whole, the findings of the present study suggest that cell phone base station antennas should be distinct and noticeable, as this would assist individuals who need to limit their exposure by distancing themselves from RF sources.

Introduction

The city of Columbia is the capital of the US state of South Carolina with a population of 131 thousand individuals (2019 estimate) (1). South Carolina is a southern state located in South East US, at the coast of Atlantic Ocean. The city has a well-developed wireless connectivity infrastructure with services provided by all major cell phone service providers. As a central hub for the state, the city of Columbia entails offices for large corporations and small businesses, government and city municipality departments. The city is also home to a number of colleges, including the University of South Carolina, Benedict College, Columbia College, Columbia International University, Fortis College, South University, Allen University and Lutheran Theological Southern seminary.

In previous studies, the authors investigated public and occupational radiofrequency (RF) exposure in European cities, including both outdoor and indoor exposure. For example, in June and August, 2017, RF level measurements were conducted in city center of Stockholm, Sweden. That study is analogous to the present study as it covered a central city area, including business district, shopping and tourist areas, together with popular leisure streets and squares. In Stockholm the total (of all frequency bands) mean exposure level was 5,494 μW/m^2 (1.439 V/m), whereas the major contributions were downlinks from LTE 800 (4G), GSM + UMTS 900 (3G), GSM 1800 (2G), UMTS 2100 (3G) and LTE 2600 (4G) (2). In another detailed investigation into RF exposure levels in Stockholm, the authors performed a spatial exposure map of Järntorget square, where the mean exposure value was 5.2 V/m (median, 5.0 V/m; range, 1.2-11.6 V/m), indicating one of the highest exposure areas in the old town (3). The previous Stockholm Old Town measurement in 2016, covering six different areas, including squares and streets determined that the mean level of the total RF radiation was 4,293 μW/m^2 (1.27 V/m) and max 173,302 μW/m^2 (8.08 V/m) (4).

In recent studies, the authors compared indoor living places in the city of Stockholm, where a maximum exposure at 6 V/m was encountered at the attic apartment, located at the same elevation and only some 6 m away from the base station antennas (5). In another indoor exposure study, the authors conducted exposimeter measurements in Swedish schools. The mean exposure to RF radiation ranged from 1.1 to 66.1 μW/m^2 (0.02 to 0.16 V/m), whereas the highest mean level was 396.6 μW/m^2 (0.39 V/m) and maximum peaks reached 82,857 μW/m^2 (5.59 V/m) (6). In another densely packed indoor area, Stockholm central railway station, the mean total RF radiation level varied between 2,817 to 4,891 μW/m^2 (1.03 to 1.36 V/m) for different measurement and maximum

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levels close to a wall mounted cell phone base station yielding >95,544 μW/m^2 (6.0 V/m) (7).

Herein, the findings of other authors in similar studies are briefly discussed below. Jalilian *et al* (8) performed a review of exposure studies across European cities, finding mean outdoor exposure to range from 0.07 to 1.27 V/m for downlink signals, as from mobile phone base stations were highest contributors. Their study concluded that everyday exposure during the pre-5G era, from 2012 to 2018 had not noticeably risen.

Sagar *et al* (9) also conducted a review of RF exposure in 8 European cities. Of note, the majority of studies studies report mean RF EMF exposure values, whereas others report median values (for details, please see each publication in the aforementioned study). For outdoor microenvironments, great variability has been reported, ranging from 0.11 V/m (France) (10) to 1.59 V/m (Sweden) (11).

In another study by Sagar *et al* (12), microenvironments were compared, including outdoor places in several cities in different countries, namely Switzerland, Ethiopia, Nepal, South Africa, Australia and the US. Los Angeles was included from the US where city center mean exposure levels were reported to be 1.24 V/m (12). City centers in other countries reported the following values: Switzerland, 0.48 V/m; Nepal, 0.75 V/m; South Africa, 0.85 V/m; Ethiopia, 1.21 V/m; Australia, 1.46 V/m [please see Table 1 in the aforementioned study by Sagar *et al* (12)].

Thielens *et al* (13) investigated different microenvironments in Melbourne, Australia. They recorded the highest mean total 0.89 V/m RF-EMF exposure in Melbourne's central business district (13) Misek *et al* (14) performed RF EMF exposure anayses and measured 1.07 V/m in the city center, Andrej Hlinka Square, Zilina, Slovakia. Iyare *et al* (15) measured GSM900, GSM1800 and UMTS bands in Leuven, Belgium using spectrum analyzer measurements at 60 locations. They calculated the maximum field value of 2.53 V/m (total exposure), whereas GSM900 was the main contributor (15).

Cansiz *et al* (16) conducted exposimeter measurements in the cities of Diyarbakir and Batikent, Turkey. The highest field level recorded was 7.18 V/m, where the main contributor was the Universal Mobile Telecommunications System (UMTS) band (16). Also in Turkey, in the Altınordu district of Ordu, Kurnaz and Mutlu (17) measured city center RF exposure in 2016 and 2017, and recorded the average level to be 0.79 V/m and the highest 5.86 V/m. Tang *et al* (18). also performed measurements in the densely populated city of Xiamen, China, finding that the integrated electric field intensity ranged from 0.32 to 1.70 V/m, whereas the power density levels of 2G were higher than 3G and 4G.

The aforementioned studies by other authors have followed different methodologies, producing different parameters, which render comparisons difficulties at best. It should be emphasized that there is a need to report all the relevant statistical indicators (mean, median, min, max) and to provide detailed background information on the locations and times the measurements were obtained. The authors have developed a methodology to characterize any city and an example of a city is provided below.

The present study was performed to physically characterize the wireless infrastructure and determine public exposure to RF electromagnetic fields, including the sub-millimeter wave 5G, in the city environment of Columbia, SC, USA. The present study is particularly applicable to the emergence of 5G cell phone systems and the installment of corresponding base station antennas by the cell phone service operators.

This study is part of ongoing measurements of RF fields in public places. The aim was to provide reliable measurement data, characterizing the RF exposure levels on the dawn of the 5G mobile communications era, using high-quality measurement devices and following rigorous scientific methods. The results also provide the means of comparing public exposure to other cities worldwide. The findings of the present study may hence prove to be meaningful for public health and safety discourse. From the perspective of public RF exposure, Apart from the study by Sagar *et al* (12), no such public exposure surveys have been performed in the US for three decades, at least to the best of our knowledge. The authors aim to continue with further studies investigating other US cities.

Materials and methods

Characterizing the exposure of a city downtown area. A measurement route was planned in the downtown area of Columbia, taking into account central locations for various activities, such as business, shopping, dining and recreation. The authors have previously measured several European cities and have developed a method to characterize public exposure to RF electromagnetic fields (2-5,7). By this method, four types of common places are included in the city environment where the public comes into contact with these physical fields: i) City streets, including downtown business district(s), shopping areas, recreational hotspots with cafes and other outdoor recreational places, and historic and tourist locations; ii) city squares; iii) green areas, such as parks, promenades or others, depending on the geographical placement of the city; and iv) public transport hubs, such as railways station, bus stations or others, depending on the infrastructure of the given city. By accounting the aforementioned locations, typical exposure levels for any city can be confidently registered and displayed.

Measurements were conducted at least five times, following the same measurement route; however, they were conducted on different days, including business days and weekends, and at different times of day, from morning to evening. The temporal distribution allows for the identification of the times at which the exposure is the highest.

Measurement route in the city of Columbia, SC. The route represents the downtown area of the city of Columbia. The route was designed to cover the popular public areas, including recreational and commonly visited areas. The route was designed to include major public hotspots; hence, the route is representative of public exposure in this city.

The measurement route for city streets and squares consisted of 12 markers, designating the different street strips or squares included in the measured public objects. The route includes the three main downtown streets of the city: i) Assembly Street, a business street where several offices reside. This is one of the busiest streets, the arterial road of the city; ii) Main Street which is a popular shopping street, with a number of pedestrians either walking, sitting in cafes or shopping (Fig. 1); iii) Gervais Street; iv) Greene Street; and v) Lincoln Street. Gervais Street represents a typical area

Table I. Frequency bands present and measured in Columbia, SC, USA.

Band	Transmitted by	Bandwidth (MHz)	Frequency span (MHz)
FM US	Radio broadcasting	20	88-108
TV UHF	Television broadcasting	145	470-615
71 DL	4G, 5G base station	35	617-652
12 DL	4G base station	17	729-746
17 DL	4G base station	12	734-746
13 DL	4G base station	10	746-756
14 DL	4G base station	10	758-768
27 DL	4G base station	17	852-869
26 DL	3G, 4G base station	35	859-894
ISM	Short range applications	26	902-928
DECT 6	Cordless phones	10	1920-1930
25 DL	4G base station	65	1930-1995
66 DL	4G base station	90	2110-2200
30 DL	4G base station	100	2305-2405
W 2G	Public or private WLAN	10	2437-2447
41TDD	4G, 5G base station/cell phone	194	2496-2690
7 DL	4G base station	70	2620-2690
22 DL	4G, 5G base station	80	3510-3590
43 TDD	4G, 5G base station/cell phone	200	3600-3800
W 5G	Public or private WLAN	700	5150-5850

DL, cellular download band; TDD, cellular band servicing both upload and download traffic; ISM, industrial, scientific, and medical frequency bands; DECT, digital European cordless telecommunications.

Figure 1. Main Street (Columia, SC, USA): A popular shopping and leisure area with several cafes and small shops.

comprised of small shops and businesses. The area is also popular with small cafes, bars and diners. The buildings in this area are mostly one- and two-story buildings, no high-rise buildings are present at the strip included in the measurements. The Gervais Street area represents the oldest business district part of Columbia, as several of the buildings were built 100 years ago. The route also accounts for Pendleton, Sumter and Laurel Streets, along the Main Street; the route accounts detailed measurements from Boyd plaza. Lincoln Street contains both old historic buildings and relatively modern buildings, constructed over the past few decades. Lincoln Street in the proximity of Gervais Street contains a historical

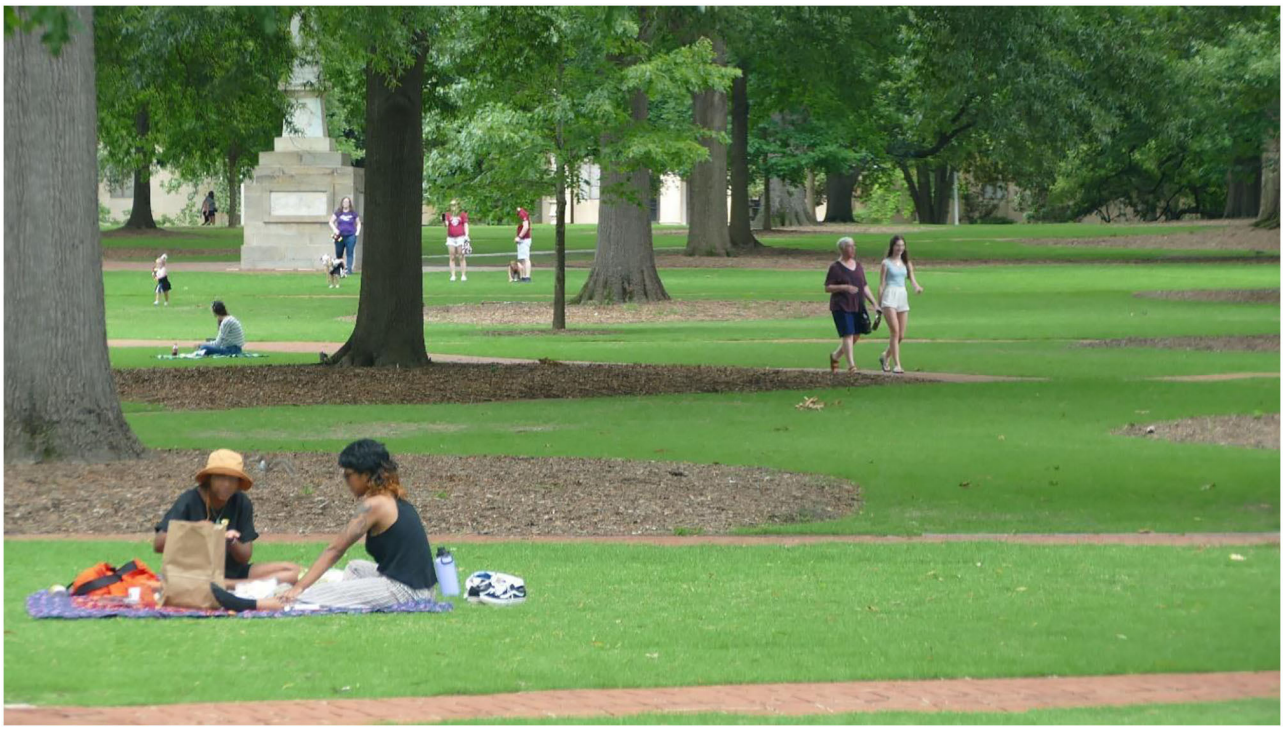

Figure 2. Horseshoe Park (Columia, SC, USA) located at the heart of the campus; this park is popular amongst students.

leisure area with popular bars and pubs in the construction style of the beginning of the last century. The southern part of Lincoln Street includes the city's main free time locations, including a conference center, arena and other features.

The route starts and ends at the University of South Carolina campus and continues along the city center, passing several central buildings, including FedEx, Wells Fargo Bank, Optus bank, Synovus bank, South Carolina Secretary of State, State House, Supreme Court, Sheraton Columbia Downtown, Marriott Columbia, Columbia Museum of Art, Columbia City Hall, US Social Security Administration, Federal building, Courthouse, United States Postal Service, Richland county main library, the South Carolina Department of Transportation, Colonial Life Arena and the Carolina Coliseum.

In additional to the street route, the present study measured RF levels at Columbia's train street (850 Pulaski Street, Columbia). Public parks included i) State House Park, Assembly Street; ii) Horseshoe Park, Sumter Street (Fig. 2); and iii) Finlay Park, 930 Laurel Street. For the parks and the train station, only one measurement round was conducted. All aforementioned locations are presented in Fig. 3.

Additionally, another measurement route was planned for parks and the railway station, which was conducted independently from the aforementioned route.

The meter was held at arm's length which is ~50 cm from the body, to minimize the shielding effect of the operator's body. The measurement was activated and a preset route was followed for each measurement round. All the measurement rounds were conducted at a steady pace, maintaining a constant speed. The city squares were measured using a spiral movement pattern, covering the square by evenly distributed layout; this allows for spatial representation and the calculation of the mean exposure level.

Spatial distribution of the field. Other series of measurements were conducted to analyze the spatial distribution of the radiofrequency field exposure. An area of 0.89x1.0 miles (1.4x1.60 km) was selected, where all streets were measured using the grid mapping method. The spatial measurement was performed once, unlike the aforementioned representative route measurements which were performed five times. An exposimeter (EME SPY Evolution; MVG) was used for the measurements together with a GPS logger for obtaining geographical coordinates from GPS. During the measurements, the GPS accuracy was 1-3 meters, allowing for good spatial accuracy to prepare a field distribution vector map. Vector mapping 3D Field software ver. 4.6.1.0 was used to conduct the calculations, where the kriging method 'Natural neighbors II' was applied and the number of gradients set to 20. To clearly illustrate the elevated exposure areas i.e., hotspots, the highest gradient was set at 2.0 V/m, whereas all the values above that were treated at the same color (dark red). Spot measurement data were fed to the contour map software 3DFIELD ver. 4.5.2.0 (by Vladimir Galouchko) and spatial field distribution maps were drawn.

Measurement device. The EME SPY Evolution was used, a latest model exposimeter (MVG). EME Spy Evolution is a selective, isotropic and portable electromagnetic field meter for measuring various communication standards between 80 MHz and 6 GHz, such as (frequency modulation) radio broadcasting; television (TV) broadcasting; Terrestrial Trunked Radio (formerly known as the Trans-European Trunked Radio; 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

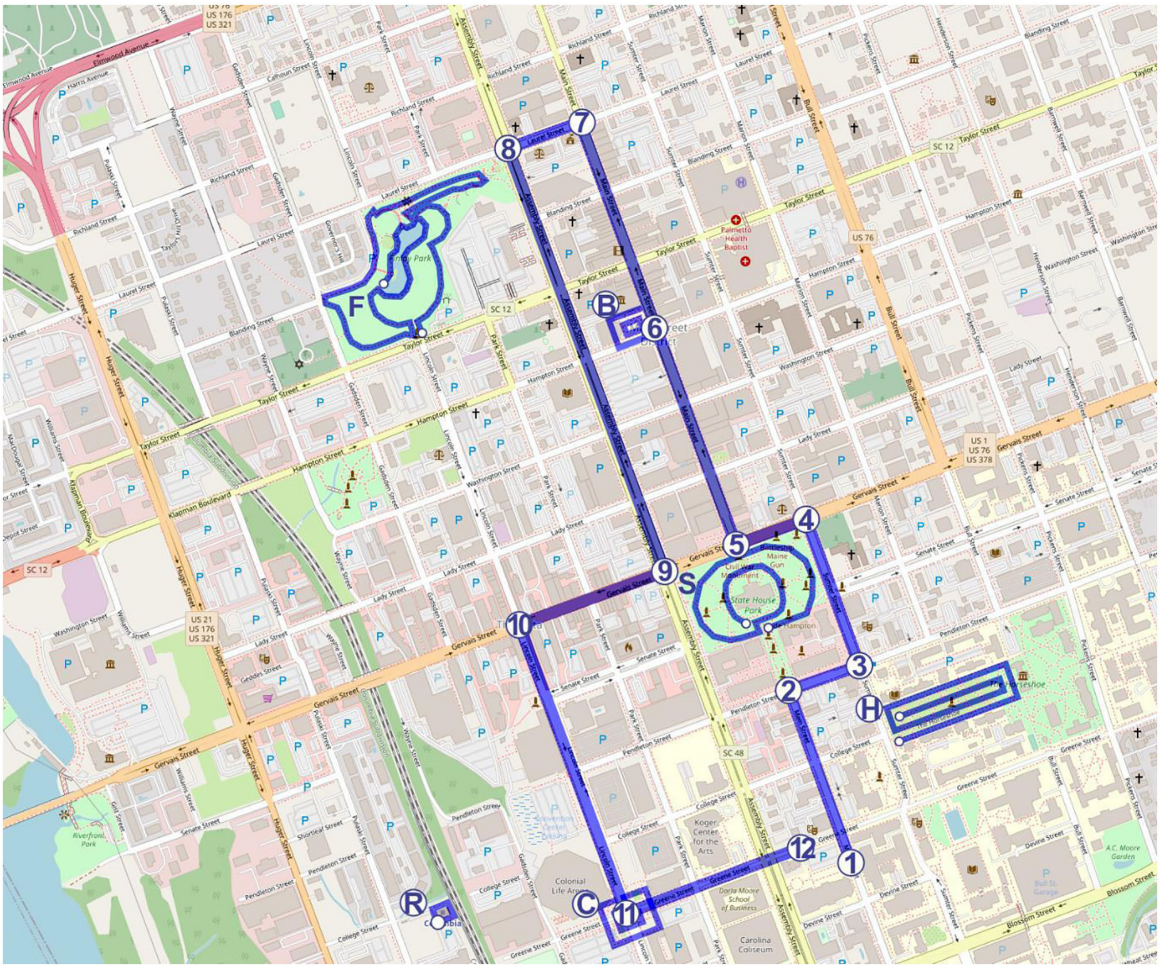

Figure 3. Measurement routes (Columia, SC, USA) characterizing public exposure to radiofrequency in the downtown area. H, Horseshoe Park; F, Finlay Park; B, Boyd Plaza; C, Colonial Life area square; R, railway station; S, State House Park. © OpenStreetMap contributors, the data are available under the Open Database License; base map and data were from OpenStreetMap and OpenStreetMap Foundation (openstreetmap.org).

communications standard, 4G; digital European cordless telecommunications (DECT) cordless telephone systems standard; Wi-Fi wireless local area network protocol. EME Spy Evolution allows for the recording of field levels with a user set period and recording duration. The lower detection limit of the meter is 0.05 V/m (2.7-6 GHz) and 0.02 V/m (0.08-2.7 GHz). The upper detection limit is 6 V/m for all bands. The meter can store 166,000 measurement samples for 20 band scenarios. For each band, the meter monitors the frequency bandwidth for a specific time and registers (records) either an average or median depending on the band (signal type).

For this measurement task, EME SPY Evolution was configured to measure the maximum number of frequency bands and at sampling rate of 6 sec (shortest for the given number of bands).

Frequency bands. EME SPY Evolution software includes 85 preset frequency bands covering all European, American and Asian cellphone bands, as well as other civilian RF sources. Prior to the measurements, a configuration must be set to select desired bands. The device was configured to measure mostly download (DL) bands, as the interest of the study was to characterize the exposure from cell phone base station antennas. Cellular bands are designated as b1 … b79 and can be duplex bands, meaning one for upload and the other for download, e.g. b26UL and b26DL. Some cellular bands have both the upload and download traffic within the same band, meaning sharing the same frequencies e.g., 5G band b41.

Other, non-cellular exposure sources were also included, constituting for the entire civilian RF infrastructure, including TV, radio, industrial, scientific, and medical frequency bands (ISM), DECT and TETRA. The frequencies used in the US were preconfigured and set to the meter. USA TETRA is permitted in the 450-470 MHz and 809-824/854-869 MHz business/industrial land transportation (B/ILT) band (19). TETRA is a standardized trunked radio system (20). TETRA is used by a number of professional services, including government, emergency, police, rescue, ambulance and railway services. The Federal Communications Commission (FCC) has set regulations for permitting intentional radiators in the 902-928 MHz ISM band; ISM bands near 900 MHz and 2.4 GHz are allowed to be used in the US (21). The preparatory measurements did not detect any transmitters at 450-470 MHz; thus, this was omitted from the frequency table. In the US and Canada, DECT is permitted at frequencies 1,920-1,930 MHz (22). DECT (23) is most often familiar by cordless telephones, baby monitors, but is also used for door opener remotes and traffic.

Table II. Radiofrequency levels at specific areas in Columbia, SC, USA.

Location	Map marker	Length of measured strip (ft/m)	n	Mean (V/m)	Median (V/m)	Min (V/m)	Maximum (V/m)
Gervais Street (west)	9-10	1,048/319	64	1.750	0.870	0.150	6.867
Main Street (middle)	5-6	1,664/507	80	1.624	1.096	0.261	5.903
Pendleton Street	2-3	537/163	21	1.568	1.368	0.566	3.728
Greene Street	11-12	1,294/394	59	1.548	1.319	0.228	4.917
Sumter Street	3-4	1,084/330	41	1.280	1.158	0.548	2.880
Assembly Street	8-9	3,125/953	127	1.243	0.928	0.116	3.772
Main Street (south)	1-2	1,239/378	77	1.072	0.984	0.089	2.444
Boyd plaza	B	1,023/312	48	0.997	0.809	0.197	2.195
Lincoln Street	10-11	2,107/642	78	0.956	0.654	0.250	5.490
Laurel Street	7-8	506/154	26	0.923	0.548	0.240	2.849
Main Street (north)	6-7	1,476/450	64	0.871	0.544	0.168	3.164
Colonial Life Arena square	C	1,685/513	82	0.858	0.680	0.242	2.771
Gervais Street (east)	4-5	553/168	28	0.785	0.669	0.381	3.275
State House Park	S	3,788/1,150	223	0.740	0.581	0.174	2.093
Finlay Park	F	5,233/1,600	267	0.688	0.614	0.187	1.409
Horseshoe Park	H	3,989/1,220	232	0.475	0.410	0.212	1.210
Railway Street	R	395/120	39	0.341	0.260	0.143	0.755
Streets and squares altogether	-	14,626/4,458[a]	795	1.240	0.859	0.089	6.867
Parks altogether	-	NA	722	0.645	0.530	0.174	2.093

The total exposure of all measured frequency bands and the analysis of all data (V/m) across all measurement rounds is shown, treating values at lower detection limit as 0. [a]Length of measured strip TOTAL (m/ft) is calculated by adding street strip lengths, excluding squares, parks and Railway Street; n, number of measurement points per each strip, average across all measurement rounds; maximum indicates highest of all measurement rounds; NA, data not available or computable.

Prior to the measurements, a literature search was conducted, accounting for the public sources revealing the cellular bands used in the corresponding city or area. In addition, multiple measurement test runs were conducted in the area to identify and confirm the cellular bands used in the city. The aim was to cover all relevant sources of public exposure from the civilian RF infrastructure, including GSM 2G, 3G, LTE 4G and 5G submillimeter wave bands (<6 GHz). The selected bands do not include most cell phone upload bands, as this level is highly dependent to the proximity of people using cell phones and was not within the scope of this study.

Statistical analysis. The mean, median, minimum and maximum values in V/m were calculated to characterize the following: i) Amplitudes of different frequency bands; ii) total exposure at different downtown areas; and iii) total exposure across different weekdays and times of day. The means were calculated as quadratic means. Total exposure was calculated as the sum of all measured frequency bands. Readings at the lower detection limit were treated as zero level (0.00 V/m) exposure. One-way analysis of variance (ANOVA) was conducted to assess whether there was a statistically significant difference in RF public exposure when measured at different weekdays and times. Tukey's test for multiple comparisons was used for post hoc tests of all pairwise combinations of measurement times. Statistical analyses were performed using IBM SPSS software (ver. 26) (IBM Corp.). A value of $P<0.05$ was considered to indicate a statistically significant difference.

Results

Measurements. The measurements in the present study were conducted in the city of Columbia, SC, USA in the period of June 6 to 13, 2021. The measurement route length was calculated 2.8 M (4.5 km), with the average duration of a measurement being 1 h and 10 min. On the whole, 3,943 single measurements were conducted all over the downtown area, distributed over five measurement days; each measurement entailed an amplitude analysis of 20 frequency bands (see Table I).

The highest exposure readings were registered close to cell phone base station antennas that were placed at a low level near the street level. These were cylinders mounted on top of utility poles, street lamps, traffic lights or other arbitrary posts. The antennas were surrounded by a cylindrical cover rendering these unnoticeable for the bystanders.

Analysis of different downtown areas. The area-specific results of the RF exposure measurements averaged across all five measurement rounds are presented in Table II. For parks and the railway, only one measurement round was conducted. The exposure is presented as a total of the 2.8 M (4.5 km) route and also as route legs representing exposure at each measured

Table III. Band specific radiofrequency exposure levels based on all five measurement rounds in the city streets and squares in Columbia, SC, USA.

Band	Mean (V/m)	Median (V/m)	Min (V/m)	Maximum (V/m)
FM US	**0.687**	0.355	0.000	**3.242**
TV UHF	0.021	0.000	0.000	0.165
71 DL	0.101	0.026	0.000	0.895
12 DL	0.000	0.000	0.000	0.000
17 DL	0.000	0.000	0.000	0.000
13 DL	0.191	0.052	0.000	1.867
14 DL	**0.293**	0.082	0.000	**2.653**
27 DL	**0.216**	0.053	0.000	**3.037**
26 DL	0.076	0.000	0.000	0.916
ISM	0.036	0.000	0.000	0.451
DECT 6	0.024	0.000	0.000	0.286
25 DL	**0.513**	0.260	0.021	**5.196**
66 DL	**0.781**	0.388	0.000	**6.001**
30 DL	0.062	0.000	0.000	0.478
W 2G	0.013	0.000	0.000	0.193
41TDD	0.031	0.000	0.000	0.470
7 DL	0.027	0.000	0.000	0.338
22 DL	0.001	0.000	0.000	0.033
43 TDD	0.002	0.000	0.000	0.052
W 5G	0.006	0.000	0.000	0.104

The analysis of all data (V/m) was performed treating values at the detection limit as 0. Values in bold font indicate the highest values. DL, cellular download band; TDD, cellular band servicing both upload and download traffic; ISM, industrial, scientific, and medical frequency bands; DECT, digital European cordless telecommunications.

street strip. The presentation of street strip data helps to identify highly exposed areas in the city, as well as areas with lower exposure levels. In Table II, the column labeled 'Length of measured strip' presents the length of each measured street strip in feet and meters. In squares and parks, the strip length indicates the total length of a spiral-like route pattern which was taken at each area. 'Nr of measurement points' indicates how many measurement points (single measurements) were taken in each corresponding street strip or area.

Based on the measurements collected at locations around the city, the analysis of the means indicates the highest exposure areas (beginning from the highest) at Gervais Street (west), Main Street (middle) and Pendleton Street and Greene Street. The upper detection limit of the meter was repeatedly exceeded at Gervais Street, where also the maximum exposure level of all rounds was registered.

Analysis of frequency bands. Frequency analysis (Table III) revealed that the majority of contributors to the exposure budget were bands 'FM US', '14DL', '27DL', '25DL' and '66DL', whereas the latter two had the highest single measurements recorded throughout the city and over all the measurement bands. The highest exposure places for the bands were accordingly: 1.243 V/m 'FM US' at Main Street (middle); 0.734 V/m '14DL' at Greene Street; 0.616 V/m '27DL' at Laurel Street; 0.847 '25DL' at Pendleton Street; and 1.422 V/m '66DL' at Gervais Street (west); the values indicate the mean exposure of several measurement points at the location, and averaged over all five measurement rounds.

Table IV. Pairwise post hoc comparisons between all measurement times.

Comparison between different times[a]	Mean difference (V/m)	P-value[b]
2106091700 vs. 2106061329	0.18	<0.001
2106101550 vs. 2106061329	0.11	0.01
2106112010 vs. 2106061329	0.02	0.98
2106121340 vs. 2106061329	0.05	0.51
2106101550 vs. 2106091700	-0.07	0.19
2106112010 vs. 2106091700	-0.16	<0.001
2106121340 vs. 2106091700	-0.13	0.002
2106112010 vs. 2106101550	-0.09	0.04
2106121340 vs. 2106101550	-0.06	0.44
2106121340 vs. 2106112010	0.04	0.83

[a]The times are in the format of year/month/day/time (hhmm). [b]P-values were obtained using Tukey's test for multiple comparisons following ANOVA.

Comparing total exposure across different days. The measurements, following the same route, were conducted on five different weekdays: 2106061329, 2106091700, 2106101550, 2106112010 and 2106121340 [the format year/month/day/time (hhmm) designates the end time of a measurement round]. In Fig. 4, a boxplot chart is presented, demonstrating the total exposure, indicating temporal fluctuations across different days and times of day. Temporal variations across different weekdays and times of day are minimal in Columbia with respect to public exposure. The mean exposures over the entire route were measured as follows (in descending order) as follows: i) highest 1.149 V/m on 2106091700, Wednesday afternoon; ii) 1.075 V/m on 2106101550, Thursday afternoon; 1.02 V/m on 2106121340, Saturday midday; 0.985 V/m on 2106112010, Friday evening; and the lowest 0.965 V/m on 2106061329, Sunday midday.

The exposure levels in downtown area were 12-16% lower on weekend times as compared to business hours. The results of the statistical analysis using ANOVA revealed a statistically significant difference ($P<0.001$). Pairwise post hoc tests showed statistically significantly different exposure levels for 2106091700 compared to 2106061329 (mean difference, 0.18 V/m; $P<0.001$), for 2106101550 compared to 2106061329 (mean difference 0.11, V/m; $P=0.01$), for 2106112010 compared to 2106091700 (mean difference, -0.16 V/m; $P<0.001$), for 2106121340 compared to 2106091700 (mean difference, -0.13 V/m; $P=0.002$) and for 2106112010 compared to 2106101550 (mean difference, -0.09 V/m; $P=0.04$) (Table IV). The exposure was lower on weekend times (Friday evening through Sunday) as compared to business times. Additionally,

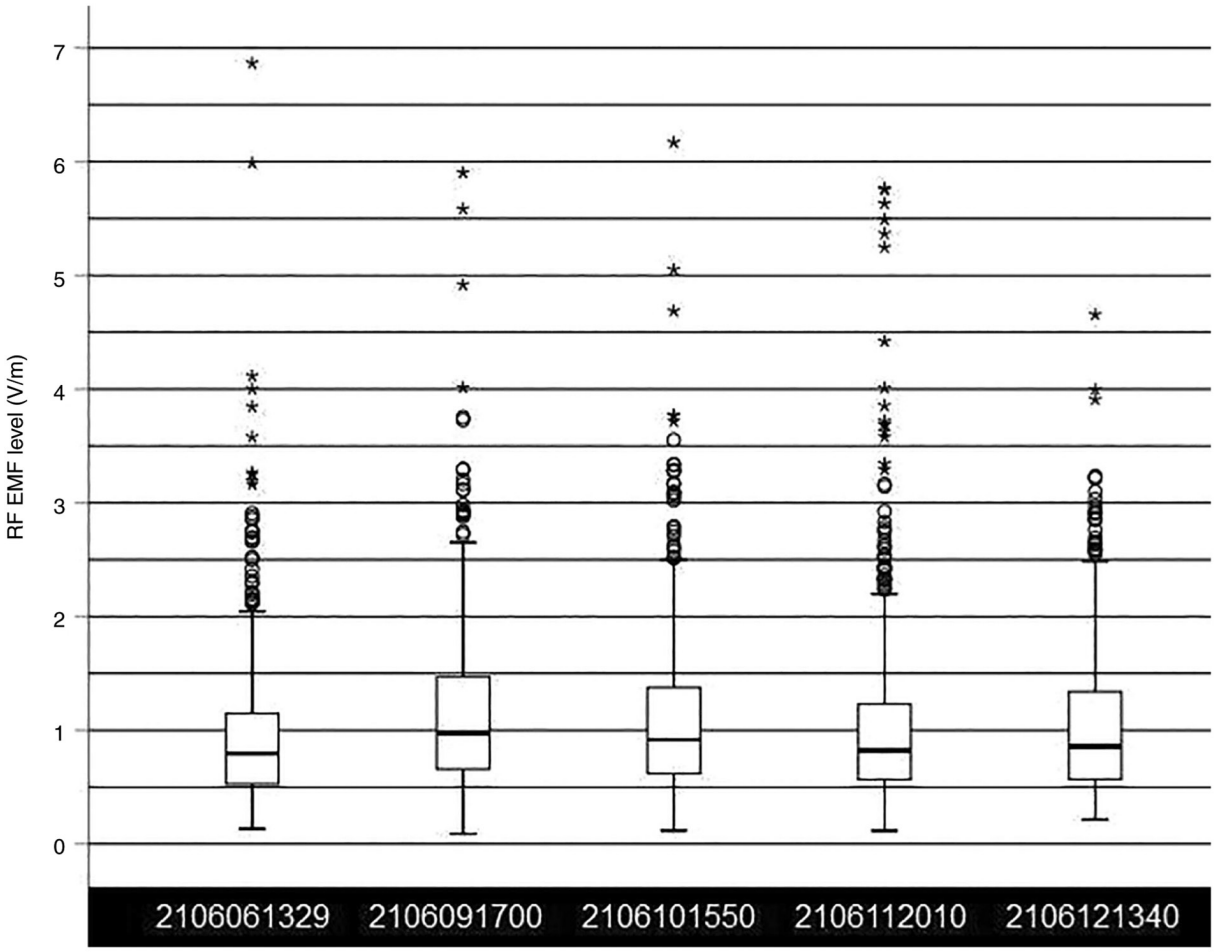

Figure 4. Boxplot of the total exposure on city the streets and squares in V/m. The measurements, following the same route, were conducted on five different weekdays: 2106061329, 2106091700, 2106101550, 2106112010 and 2106121340 [in the format year/month/day/time (hhmm)] in Columbia, SC, USA. The median is indicated by a black line inside each box; the bottom and top of the boxes show first and third quartiles; the end of the whiskers are calculated as the 1.5x interquartile range. Points represent outliers.

the effect size [partial eta squared ($\eta 2p$)] characterized that 0.9% of RF level variability accounted for different measurement times.

Spatial distribution of the field. During the field spatial mapping, 1,448 single measurements were conducted. The total field exposure (sum of all measured frequency bands) at the downtown area was as follows: Mean, 0.879; median, 0.703; min, 0.127; max, 5.507 V/m (meter's upper detection limit was reached). The measurement covered altogether 14.8 miles (23.7 km). The results of spatial field distribution in downtown Columbia, SC are depicted in Fig. 5, where ~15-20 hotspots of elevated exposure could be identified. For example, a number of smaller-scale hotspots could be identified in Gervais Street where cell phone base station antennas are mounted on top of the utility poles and therefore positioned low, close to the street level. However, these are relatively low-powered transmitters, and also due to the low positioning, the elevated field does not reach far. Hotspots that cover larger areas are caused by the transmitters of higher power, which are located on top of the tall buildings. A histogram of the spatial field distribution measurements is depicted in Fig. 6. The highest exposure levels were caused by cell phone base station antennas that were positioned low close to the street level (Figs. 7 and 8).

Discussion

Base stations nearby street level yielded the highest exposure. This is demonstrated by measurements which calculated the highest exposure for Gervais Street, where also the maximum exposure of the entire study was registered. Unlike the other streets measured, Gervais Street can be distinguished by two features: i) New 5G base stations were installed and; ii) the majority of the base station antennas were installed at a low level, close to the street level. Hence, the present study demonstrated that the installment of 5G base station antennas was the reason for the highest exposure areas in the city. The reason for the high exposure levels is the need to bring base stations close to the subscriber devices.

Pedestrians walking on the city streets may notice radio and TV transmitters placed on top of high-rise buildings; however, they are unlikely to suspect that cylindrical objects on top of utility poles, street lamps and traffic lights could be cell phone antennas, particularly considering these are painted the same color as the pole they are mounted on top of. Furthermore, cell phone antennas are not always clearly visible, and thus individuals are unaware of their presence; perhaps this is due to purposes of conforming with any relevant city ordinance, such as aesthetics.

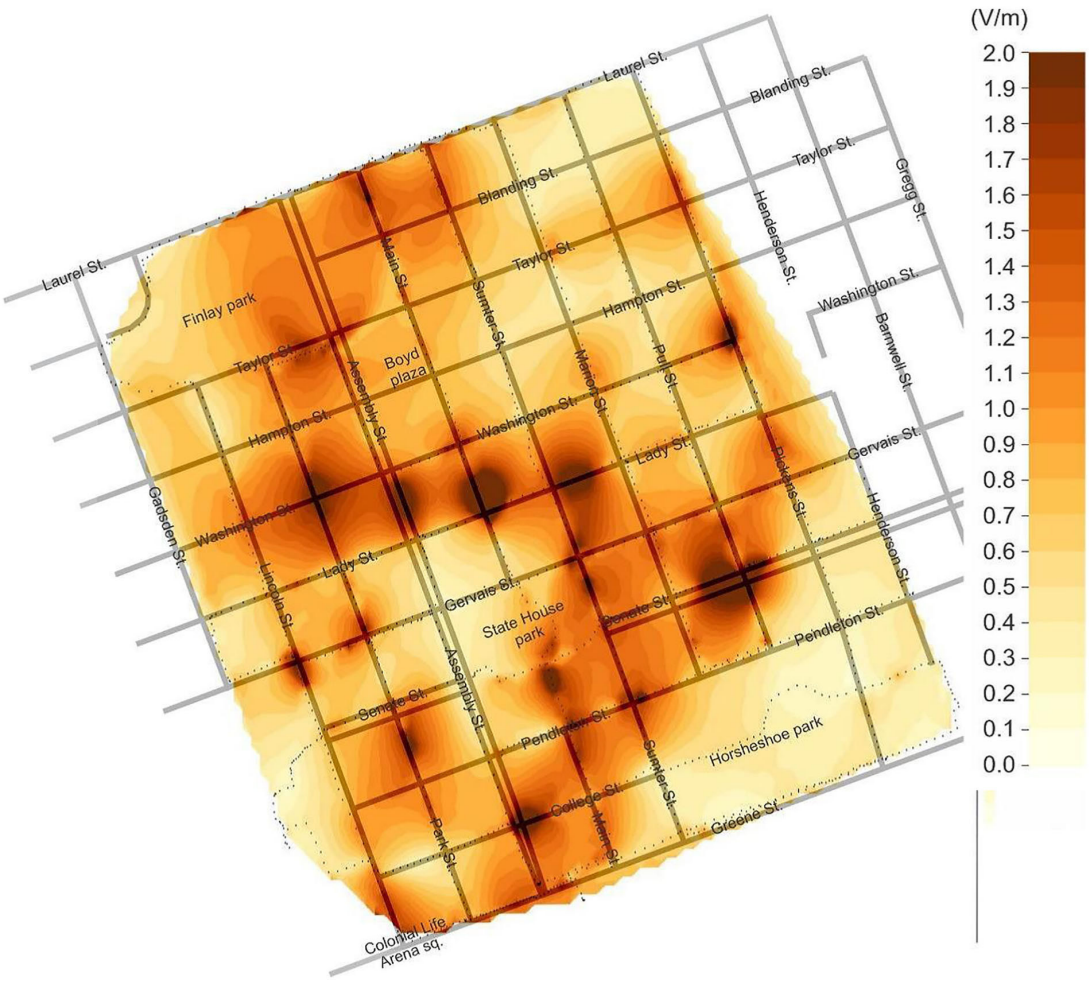

Figure 5. Radiofrequency electromagnetic field (V/m) spatial distribution in the city of Columbia, SC, USA downtown area of 0.89x1.0 miles (north is on the top). Small individual black dots indicate locations of single measurements (n=1,448).

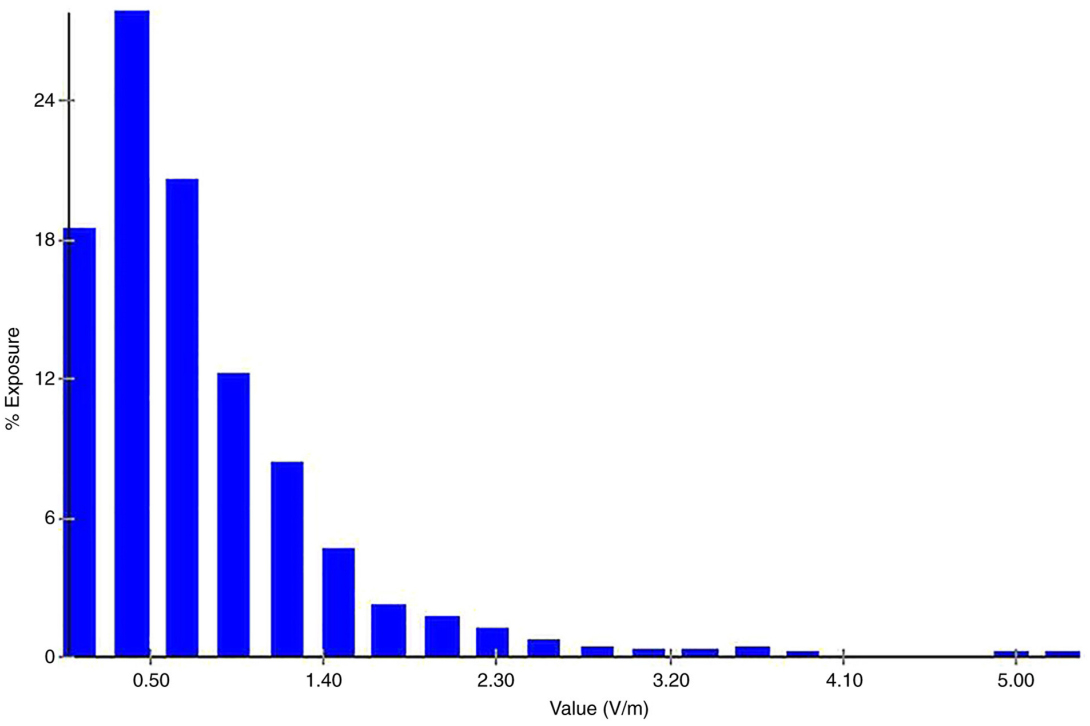

Figure 6. Histogram of spatial field distribution measurements shows that majority of the readings are ~0.5 V/m, whereas high readings of 5 V/m or more were only obtained five times. The histogram characterizes the percentages (%) of exposure values (V/m) in 20 bins.

Figure 7. Gervais Street: Cell phone base station antenna placed close to street level and causing high exposure to pedestrians and nearby café visitors (exposure scenario illustration). The antenna appears camouflaged and seemingly part of a utility pole. The measurer only discovered the antenna due to the high radiofrequency levels in the vicinity.

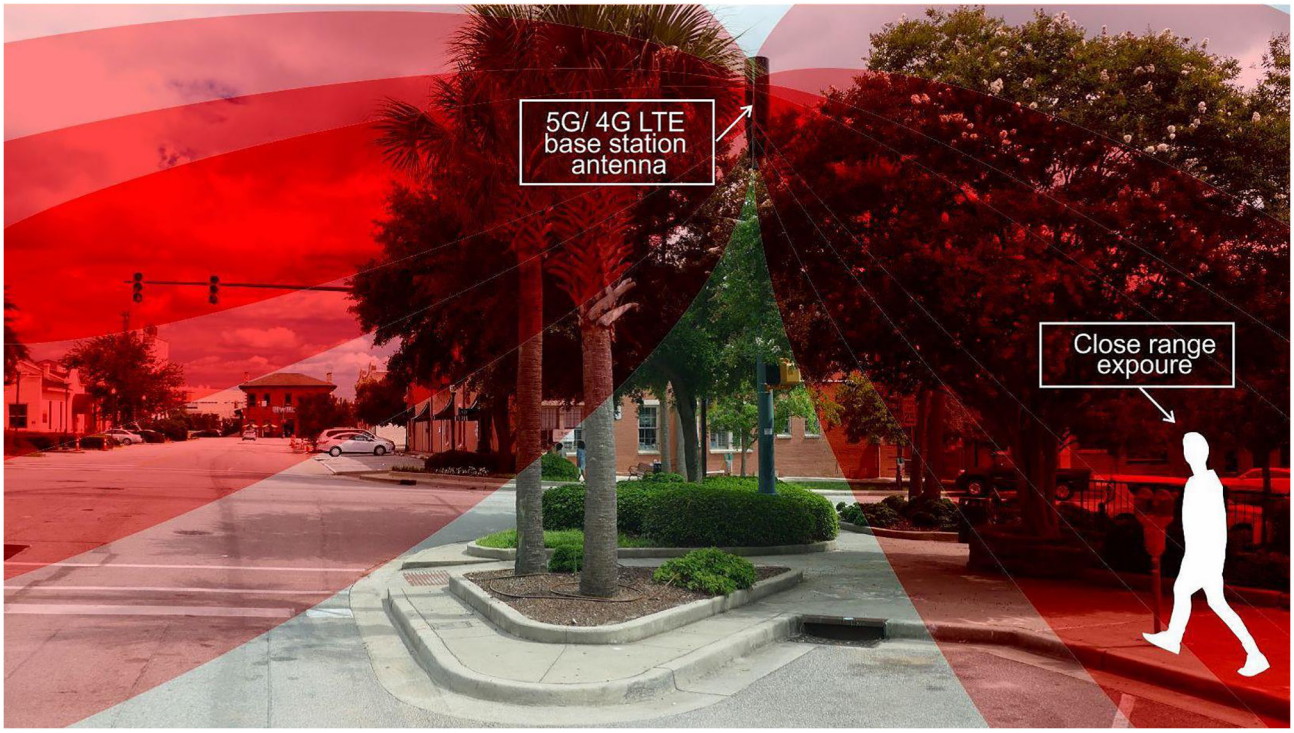

Figure 8. Gervais Street: Another cell phone base station antenna close to street level and causing high exposure to pedestrians (exposure scenario illustration). Note the antenna appears undistinguishable from the utility pole an unnoticeable between the trees.

Temporal analysis revealed that there was a statistically significant difference in exposure levels in the downtown area when comparing total exposure across different days and times. The public exposure varied during different times and days.

In the present study we conducted different assessment methods to characterize city center exposure levels by i) repetitive route measurements (mean 1,240 V/m) compared to ii) grid measurement (mean 0.879 V/m). The difference of means can be expected due to the following reasons: i) the grid measurement covers a wider city center area, including areas of a lower population density; ii) the route approach focuses more at the city center area, where there are more RF

EMF sources. Therefore, the city center route method results in ~30% higher mean than the grid measurement method. In addition, the temporal variation of 16% between means from different days needs to be accounted for. When comparing mean exposures from different cities, higher exposure levels may be obtained, if these differ by ≥2-fold.

The present study measured RF exposure levels in Columbia. In Columbia, SC, the measurement route, which was conducted five times, calculated at the streets and squares 1,240 V/m as a mean exposure (total as a sum of all frequency bands) and 6.867 V/m as all times maximum (Table II).

The majority of previous studies discussed above in the 'Introduction' reported similar results in European cities. An analogous study by the authors in Stockholm, Sweden, following the same method, calculated 1,439 V/m as the mean exposure (2). The highest exposure levels that were measured in a detailed measurements in Stockholm, Järntorget square, resulted in 11.6 V/m as the maximum (3).

Jalilian *et al* (8), in their review article, reported the mean outdoor exposure level of European cities to range from 0.07 to 1.27 V/m. This together with the readings from Stockholm places the mean of Columbia city (1,240 V/m) on top of the European scale.

In conclusion, in the city of Columbia, SC, USA, the present study determined that the highest exposure areas were due to two reasons: i) Cell phone base station antennas on top of high-rise buildings provide good cell coverage reaching far away, but creating elevated public exposure to the RF RMFs at the immediate vicinity; and ii) cell phone base station antennas installed on top of the utility poles have placed the radiation source closer to humans walking on the street level.

RF exposure levels from mobile phone base station antennas near the street level reached high levels. It is thus recommended, that all such close proximity transmitters should be labeled with relevant signs to warn of high RF exposure in the area (24). Cell phone base station antennas should be distinct and noticeable so that people who need to limit their exposure, have been given a chance to do so by distancing themselves from the RF sources. Considering the current trend of cell phone service providers expanding their 5G network, more utility pole base station antennas are expected. Consequently, the public exposure is also likely to increase in the coming years.

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Availability of data and materials

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Authors' contributions

TK performed the measurements. The conception of the study, the design and analyses of the material, the writing of the article and the approval of the final manuscript was made by both authors (TK and LH). Both authors confirm the authenticity of all the raw data. Both authors have read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable.

Patient consent for publication

Not applicable.

Competing interests

LH is an Editorial Advisor of the journal, but had no personal involvement in the reviewing process, or any influence in terms of adjudicating on the final decision, for this article. The author TK declares that he has no competing interests.

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