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Real-world cell phone radiofrequency electromagnetic field exposures

Stephen Wall[a,*,1], Zhong-Min Wang[a,*], Thomas Kendig[a], Dina Dobraca[b], Michael Lipsett[b,1]

[a] Environmental Health Laboratory Branch, California Department of Public Health, 850 Marina Bay Parkway G365/EHLB, Richmond, CA, USA
[b] Environmental Health Investigations Branch, California Department of Public Health, Richmond, CA, USA

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ABSTRACT

In 2011 the International Agency for Research on Cancer classified radiofrequency electromagnetic fields (RF EMF) from cell phones as possibly carcinogenic to humans. The National Toxicology Program and the Ramazzini Institute have both reported that RF EMF exposures significantly increase gliomas and Schwannomas of the heart in rodent studies. Recent studies indicate that RF EMF exposures from cell phones have negative impacts on animal cells and cognitive and/or behavioral development in children. Case-control epidemiological studies have found evidence for cell phone use and increased risk for glioma and localization of the glioma associated with the consistent exposure site of regular cell phone use. Understanding the exposure level, or power density, from RF EMF emitted by cell phones under real-world usage and signal reception conditions, as distinct from the published measurements of maximum Specific Absorption Rate values, may help cell phone users decide whether to take behavioral steps to reduce RF EMF exposure. Exposure measurements were conducted on phone models from four major mobile network operators (MNOs) in the USA for calls received under strong and weak reception signal conditions, near the phone face and at several distances up to 48 cm. RF EMF exposure from all phones was found to be greater under weak (1–2 display bars) than under strong (4–5 display bars) reception signal conditions by up to four orders of magnitude. Notably, RF EMF exposure levels under weak reception signal conditions at a distance of 48 cm from the phone were similar to or greater than those detected under strong reception signal conditions at a distance of 4 cm. Under weak reception signal conditions, power density reductions of up to 90% occurred at 16 cm typical for speaker phone or texting over the 4 cm near-ear exposure. The results of this investigation of second-generation (2G) technology suggest that reduced and precautionary use of cell phones under weak signal conditions could lower a user's RF EMF exposure by up to several orders of magnitude. Bluetooth headset power density exposures were 10–400 times lower than those of the cell phones to which they were connected and dependent on the headset rather than the connected phone. The results of this study informed the development of public health guidance regarding cell phone use.

1. Introduction

Worldwide cell phone usage has increased sharply in recent years. The number of wireless phone accounts in the United States increased from 33.8 million in 1995 to near 400 million in 2017 (CTIA, 2017). At the end of 2019, the number of cell phone accounts worldwide is expected to exceed five billion (Sawers, 2017). The substantial increase in cell phone usage has raised concerns about potential adverse health effects from long-term radiofrequency electromagnetic fields (RF EMF) exposures. There continues to be evidence that RF EMF exposure from cell phones has negative impacts on animal cells and cognitive and/or behavioral development in children (Zalata et al., 2015; Calvente et al., 2016). In 2011 the International Agency for Research on Cancer (IARC) classified RF EMF from cell phones as possibly carcinogenic to humans (IARC, 2011). The National Toxicology Program (2018) and the Ramazzini Institute (Falcioni et al., 2018) have reported that both near-field and far-field RF EMF exposures significantly increase gliomas and Schwannomas of the heart in rodent studies. Case-control epidemiological studies have found evidence for cell phone use and increased risk for glioma (Coureau et al., 2014), as well as for glioma localization associated with the consistent exposure site of regular cell phone use (Grell et al., 2016). The IARC classification was based on limited evidence of carcinogenicity from the results of several epidemiological studies associating long-term cell phone use with increased risks of glioma, a malignant brain tumor, and of acoustic neuroma, a benign tumor of the acoustic nerve (IARC, 2011; Baan et al., 2011). Also,

* Corresponding authors.
E-mail addresses: drstephenwall@comcast.net (S. Wall), zhong-min.wang@cdph.ca.gov (Z.-M. Wang).
[1] Stephen Wall and Michael Lipsett are currently retired from CDPH.

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Table 1
FCC MPE Limits for the general population. Power density limits between 300 and 1500 MHz, dependent on operating frequency.

MPE Limits: General Population/Uncontrolled Exposure		
Frequency Range (MHz)	Power Density (mW/cm^2)	Averaging Time (min)
300–1500	Frequency/1500	30
1500–100,000	1.0	30

Federal Communications Commission, OET Bulletin 65 Supplement C Appendix A, p. 26.

several governmental agencies and public health organizations, in the U.S. and elsewhere, have issued official public health guidance on cell phone use to minimize RF EMF exposure (Health Canada, 2015; President's Cancer Panel, 2010; NHS, 2016; WHO, 2014).

In the U.S. the Federal Communications Commission (FCC) regulates RF intensity of exposure using Maximum Permissible Exposure (MPE) limits, as measured by power density in milliwatts per square centimeter (mW/cm^2). General population MPE limits as given in Table 1 are based on measurements and standards developed by the National Council on Radiation Protection and Measurements (NCRP) and the Institute of Electrical and Electronics Engineers (IEEE) (Means and Chan, 2001). Maximum EMF from RF devices used in close proximity to the body (principally cell phones) is regulated using the Specific Absorption Rate (SAR), a measure of the rate of RF energy absorption by the body. The FCC MPE limits, and the NCRP and American National Standards Institute (ANSI)/IEEE limits on which they are based, are derived from exposure criteria quantified in terms of SARs. Measurements of SARs require a complex model laboratory system to simulate peak energy absorption at the *highest cell phone exposure power density level*. Peak SAR limits in watts per kilogram (W/kg) are determined for cell phones under maximum emission intensity rather than a range of more typical usage conditions (Table 2). In this study, we measured power density (the basis for the FCC's MPE limits) under different cell phone reception signal strength conditions designed to mimic typical real-world exposures. These measurements represent the fundamental RF EMF environmental exposure levels from the cell phone emission source rather than estimates of energy absorption by the body.

Previous studies have investigated cell phone RF power emissions under real-world use conditions during travel, when power control causes the transmitted level to vary in response to changes in signal strength received from the cell tower. European studies considering the Global System Mobile (GSM) transmission technology used in California also found the same power control inverse relationship between cell phone transmission level and the cell tower reception signal strength (Gati et al., 2009; Kuhn and Kuster, 2013; Wiart et al., 2000). This cell phone power control produces a temporary peak in transmission power at call initiation or cell tower handover during travel.

Previous measurements in the San Francisco Bay Area for MNOs using a number of second generation digital phones (2G) with GSM and CDMA cell phone technology reported a similar power control effect, with increasing cell phone transmission power when traveling due to reductions in reception signal strength (Kelsh et al., 2010).

Unlike these previous studies, this investigation was designed to examine power output of a variety of phones under stationary conditions, providing laboratory-based comparisons of cell phone RF power densities that can be absorbed by the body under different reception signal strength conditions typical of normal use, without the power control changes associated with travel between cell towers. Unlike the SAR, which is a measure of the RF EMF interaction with laboratory surrogates for human tissue, power density represents an environmental measurement of the RF EMF exposure from the cell phone emission source (Usman et al., 2009).

Table 2
FCC SAR Limits for the general population. Partial-Body SAR is the main limit discussed when considering cell phones.

SAR Limits: General Population/Uncontrolled Exposure (W/kg)		
Whole-Body	Partial-Body	Hands, Wrists, Feet and Ankles
0.08	1.6	4.0

Federal Communications Commission, OET Bulletin 65 Supplement C Appendix A, p. 27.

2. Materials and methods

2.1. Cell phones tested

In this study, we tested twenty-two cell phones spanning seventeen models, six manufacturers, supported by four different Mobile Network Operators (MNOs) with different contract service plans, ranging from Go Phones (pay as you go) to data-capable plans. The phones included devices using second generation wireless mobile telecommunications GSM and CDMA technology during the period 2011–2013, representing RF EMF exposure before the widespread deployment of 3G and 4G technology. The MNOs are referred to in this report as MNOs A, B, C, and D. The majority of test phones were from MNOs A (n = 7) and B (n = 10), both of which had nearly equivalent numbers of subscribers, and substantially more than MNOs C (n = 3) and D (n = 2) (Dano, 2013). For comparison, the SAR value, body style, antenna type, and broadcast technology for each cell phone employed in the study is provided in Table 3.

2.2. Measurement instrument and test stand

Cell phone measurements were made using the EMR 300 Radiation Meter (Narda Safety Test Solutions, Hauppauge, NY, USA) with probe type 18 (100 kHz–3 GHz). The three-axis isotropic probe continuously cycles through all three orthogonal axes and displays an electric field value (E) in volts per meter (V/m) by integrating the values from all three axes. The typical measurement range is from 0.2 to 320 V/m, although the specific probe utilized provided reproducible levels as low as 0.1 V/m. The fundamental electric field measurements are then converted to power density (S) in milliwatts per square centimeter (mW/cm^2), using Eq. (1) (Ulcek and Cleveland, 1997):

$$S = \frac{E^2}{377x10} \tag{1}$$

where the impedance of free space constant (377 Ω) is multiplied by ten to yield mW/cm^2.

Cell phone EMF measurements were made with a test stand shown in Fig. 1, which utilized a non-conductive rail system made of fiberglass channel (Harrington Plastics: Aickinstrut, Chino, CA, USA), thereby avoiding measurement artifacts due to RF-induced electric fields within metal components. The rail system incorporated a cradle to elevate the EMR 300 in a fixed position so that the probe orientation toward the test cell phone would always be the same. Each phone was mounted in a universal cradle (iGrip, Pforzheim, Germany) designed to hold it in an orientation typical of use during calls. For each measurement the cradle elevation was adjusted to align the EMR fixed probe directly in line with the usual ear listening position on the cell phone face. Measurements at different distances between the cell phone and the EMR probe were made by moving the phone cradle horizontally along the rail system while maintaining the vertical alignment. Accurate measurements of the separation of the probe and cell phone under test provided for a high degree of position reproducibility in the power density measurements as a function of distance from the cell phone face.

Table 3
Phone details including SAR value, body style, antenna type, and technology.

Phone Code	SAR Value (W/kg)	Body Style	Antenna Type	Technology
A 1	1.14	Flip	Internal	CDMA: 850, 1900 MHz
A 2	1.46	Candy Bar	Internal	CDMA: 850, 1900 MHz
A 3	1.27	Flip	Internal	CDMA: 850, 1900 MHz
A 4	1.31	Candy Bar/Flip	Internal	CDMA: 850, 1900 MHz
A 5	0.78	Flip	Internal	CDMA: 850, 1900 MHz
A 6	1.31	Slider	Internal	CDMA: 850, 1900 MHz
A 7	1.14	Flip	Internal	CDMA: 850, 1900 MHz
B 1	1.14	Flip	External	GSM: 850, 1900 MHz
B 2	0.85	Candy Bar	Internal	GSM: 850, 1900 MHz
B 3	0.85	Candy Bar	Internal	GSM: 850, 1900 MHz
B 4	0.85	Candy Bar	Internal	GSM: 850, 1900 MHz
B 5	0.74	Flip	Internal	GSM: 850, 1900 MHz
B 6	1.47	Flip	Internal	GSM: 850, 1900 MHz
B 7	1.26	Slider	Internal	GSM: 850, 1900 MHz
B 8	1.29	Candy Bar	Internal	GSM: 850, 1900 MHz
B 9	1.29	Candy Bar	Internal	GSM: 850, 1900 MHz
B 10	0.95	Candy Bar	Internal	GSM: 850, 1900 MHz
C 1	0.54	Flip	Internal	GSM: 1700, 1900 MHz
C 2	0.49	Candy Bar/Slider	Internal	GSM: 1700, 1900 MHz
C 3	1.55	Candy Bar	Internal	GSM: 1700, 1900 MHz
D 1	1.43	Candy Bar	Internal	CDMA: 800, 1900 MHz
D 2	1.43	Candy Bar	Internal	CDMA: 800, 1900 MHz

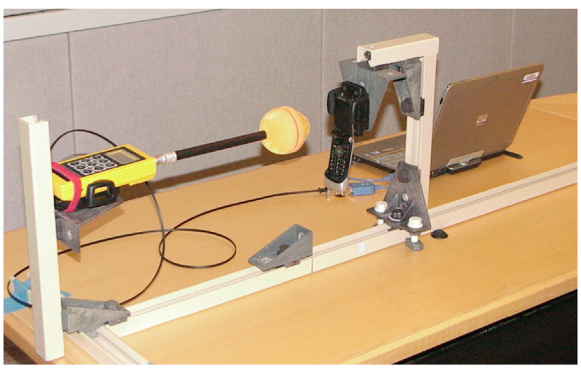

Fig. 1. Rail measurement system for cell phone and Bluetooth headset power density determinations. EMR 300 probe is held stationary while the cradle holding the device to be tested is positioned in height and distance. (As a potential RF EMF source, the laptop computer was moved away during measurements.).

2.3. Frequency analysis and far-field distance

An important consideration in determining cell phone power density is the near-field region around the source, where the RF EMF is nonuniform and is therefore difficult to measure. Conversely, farther from the source (far field), the RF EMF is homogeneous. In the current measurement application, the minimum distance away from the cell phone antenna for far-field measurements was calculated by Eq. (2), where d is the distance to the far field and λ is wavelength of the broadcast e-field. (WHO IPCS, 1993)

$$d = \frac{\lambda}{2\pi} \tag{2}$$

The operating frequencies in both strong and weak reception signal locations for cell phones from each MNO are given in Table 4, as determined using the frequency spectrum capability of the SRM 3006 Selective Radiation Meter (Narda Safety Test Solutions, Hauppauge, NY, USA). The technologies used by all four MNOs have the capability of operating on multiple frequency bands, as indicated in Table 4, with MNOs B and D operating on separate frequency bands under strong and weak signal conditions. Some MNOs utilize a shift to a lower frequency band in weak reception areas, since in general lower frequencies allow carriers to provide coverage over a larger area, while higher frequencies allow carriers to provide service to more customers in a smaller area. From Eq. (2), the minimum far-field distances for the measured frequencies of 835 MHz and 1865 MHz were 5.7 cm and 2.6 cm, respectively. Although the far-field distance varies somewhat with frequency, we used a distance of 4 cm from the cell phone surface normally placed against the ear to the probe forward surface for all measurements, to provide uniformity in data interpretation, as well as a basis for comparison of cell phone power density exposure under reproducible conditions. This is also consistent with the distance between the on-ear cell phone emission source and the exposure target organs, which are further away than the 3.5 cm length of the typical adult ear canal. We also used the SRM-3006 to verify the cell phone transmission frequency and the stability of the power density during the call, which permitted us to rely on the simplicity of operation afforded by the EMR 300 broadband instrument for cell phone transmission level measurements. EMR 300 measurements of cell phones under weak signal conditions were within five percent of the more sensitive SRM 3006 spectrometer.

Table 4
Operating frequencies, resulting wavelengths, and technology for each MNO under both strong and weak signal conditions.

MNO	Operating Frequency (MHz)		Wavelength (λ) (cm)		Technology
	Strong Signal	Weak Signal	Strong Signal	Weak Signal	
A	835	835	35.9	35.9	CDMA
B	1865	835	16.1	35.9	GSM
C	1890	1890	16.1	16.1	GSM
D	1850	835	16.1	35.1	CDMA

2.4. Cell phone power density with source distance

Power density levels were determined as a function of distance from test cell phones in both strong and weak reception signal conditions, using the non-conductive rail system shown in Fig. 1. Measurements were made at the minimum of 4 cm from the cell phone face to the probe forward surface, and at increasing distances up to a maximum of 48 cm. At every distance, three measurements consisting of 75 data points each (obtained during contiguous 0.4 s intervals, for a total of 30 s) were completed for each cell phone during the incoming call connected mode. To account for other detectable sources of RF EMF,

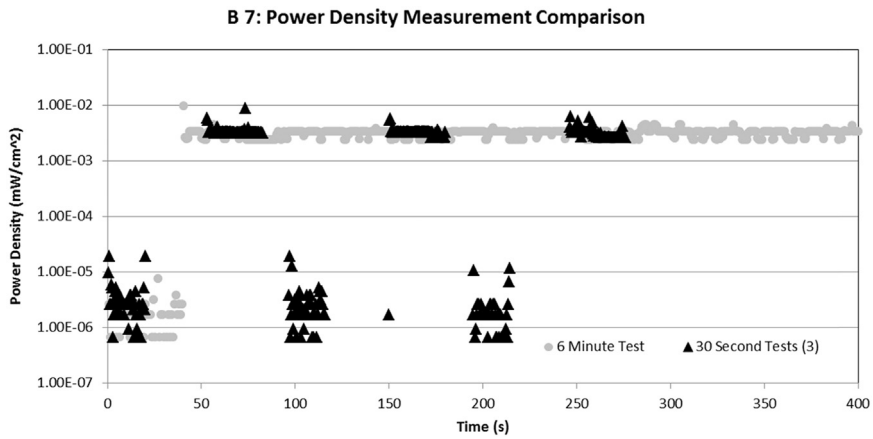

Fig. 2. Comparison of phone B 7 when measured over a six minute period and 30 s periods.

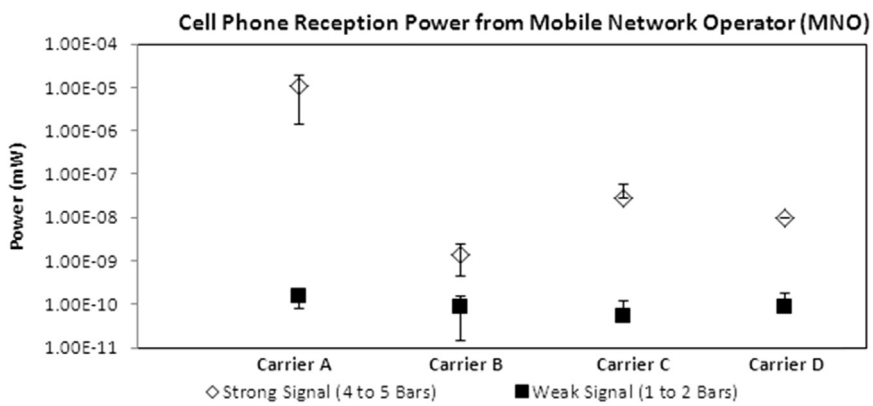

Fig. 3. Comparison of reception signal power associated with cell phone signal strength bar indicator display for different Mobile Network Operators.

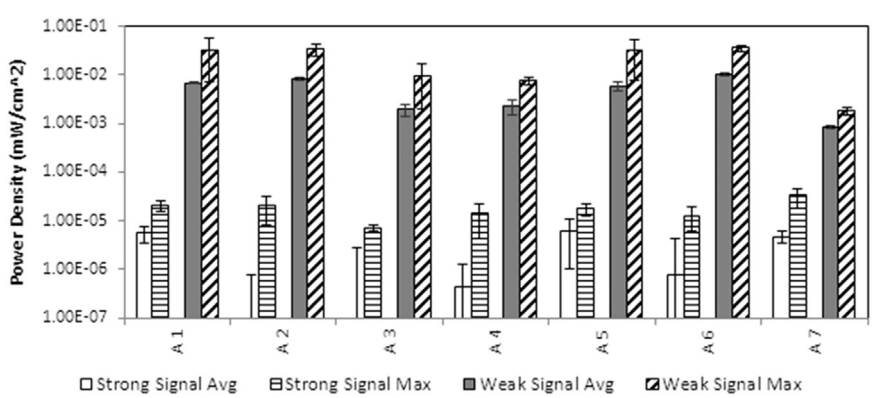

Fig. 4. Mobile Network Operator A cell phones. Comparison of average and maximum power density measured 4 cm from the typical cell phone ear position, under strong (4–5 display bars) and weak (1–2 display bars) signal reception conditions.

baseline power density levels prior to each call consisted of 50 data points obtained over 20 s. For each measurement distance, the consistently low baseline level before the call was subtracted from the measurement during the call to yield adjusted average and adjusted maximum power density levels.

An example of measurement details is provided in Fig. 2, where clock time duration of the entire three measurement sequence (non-call emissions [baseline], call connection spike, and call connected levels used to characterize the phone emission) is shown superimposed on a greater than 6 min measurement conducted on the same MNO phone. This example demonstrates that, after the initial connection spike, the on-call transmission level was constant and the calculated mean level and standard deviation for the 30 s segmented measurements and the continuous 6 min measurements were nearly identical. Power control is essential when the reception signal varies (e.g., while traveling), requiring adjustments in the cell phone transmission power, but for a static measurement the power control is primarily used to reduce the power density from call initiation levels to a steady state within seconds.

Cell phones were tested under both strong and weak reception signal conditions. A strong reception signal, when a phone has the best communication, was considered to be represented by 4–5 bars in the cell phone signal display, while a weak reception signal, when a phone has poor communication, was represented by 1–2 display bars. Signal display bars were selected as the most accessible indication of the reception signal strength for the general public, with the relationship

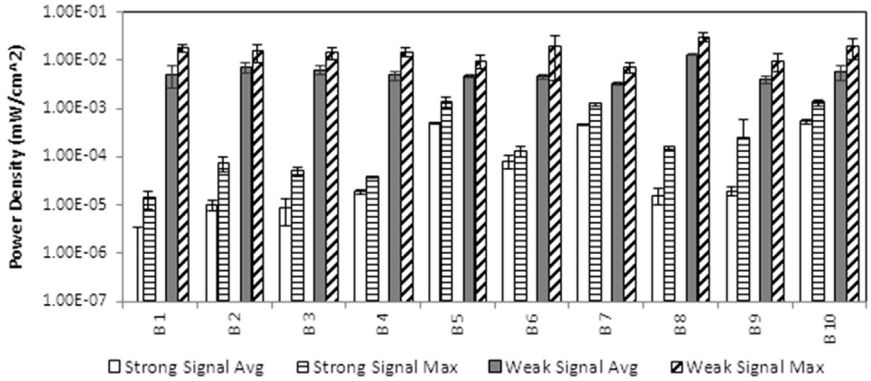

Fig. 5. Mobile Network Operator B cell phones. Comparison of average and maximum power density measured 4 cm from the typical cell phone ear position, under strong (4–5 display bars) and weak (1–2 display bars) signal reception conditions.

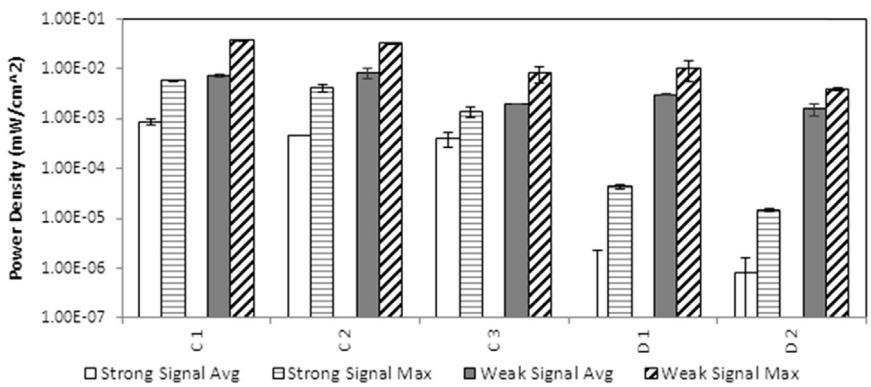

Fig. 6. Mobile Network Operators C and D cell phones. Comparison of average and maximum power density measured 4 cm from the typical cell phone ear position, under strong (4–5 display bars) and weak (1–2 display bars) signal reception conditions.

between display bars and reception signal strength power level discussed in the results section. Different unoccupied conference rooms at the California Department of Public Health (CDPH) campus in Richmond, California, were chosen to provide strong and weak reception signal environments. All strong reception signal condition measurements were performed in the same conference room, which provided a 4–5 bar signal strength environment for all phone models. Weak reception signal condition measurements for MNOs A and D were performed in a different conference room than those for MNOs B and C, to ensure that all phones could operate in a 1–2 signal display bar environment.

2.5. Bluetooth headsets

Use of Bluetooth headsets is one approach to reducing RF EMF exposure from cell phones. To investigate the magnitude of this potential reduction, power density measurements were conducted on nine different Bluetooth headsets, using the same experimental set-up shown in Fig. 1, with the associated cell phone operating under weak reception signal conditions. Each headset was positioned in the cradle and the power density measured. Bluetooth headset measurements were performed using the same experimental protocol, in the same conference rooms utilized for the weak reception signal cell phone measurements.

After establishing equivalence with the results obtained from the EMR 300 instrument, used for all cell phone measurements, the updated model, NBM 550 Broadband Field Meter (Narda Safety Test Solutions, Hauppauge, NY, USA) with probe type EF 0691 (100 kHz–6 GHz, 0.35–650 V/m), was employed for power density measurements on all the Bluetooth headsets tested. Bluetooth headsets operate in the frequency band between 2400 and 2480 MHz (as verified using the SRM-3006 spectrometer), which is the upper frequency range of the EMR 300 and middle of the NBM 550 range. The equivalency of the measurements from the newer NBM-550 and the older EMR-300 provided a quality assurance validation of the EMR-300 cell phone measurements.

Bluetooth headset power density measurements were conducted while connected to one cell phone model each from MNOs A and B with the cell phones connected to a call under weak signal conditions. To ensure the power density measurement was only attributable to the headsets, the connected cell phones were placed 4–5 m behind and away from the measurement probe. Power density measurements were made at a 6 cm distance from the typical ear location on the headset, to ensure the probe RF EMF sensing region was well within the far-field region. Power density measurements for the two cell phones, used to connect with the Bluetooth headsets, were also conducted separately at 6 cm distance from the typical ear location using the NBM 550 Broadband Field Meter. As with the cell phone measurements, baseline power density was measured before activation of the Bluetooth-connected call, and this typically small correction was applied to all power density measurements.

3. Results

3.1. Cell phone power density and signal strength

In order to compare the reception signal strength represented by the cell phone display bars for the different MNOs, the reception power was determined by using the field test mode function available for most phone models (wpsantennas.com, 2017). In the field test mode, activated by a combination of key strokes, the signal power received was indicated on the cell phone display in dB_m, the standard measurement unit for power based on a one milliwatt (mW) reference signal (dBm =

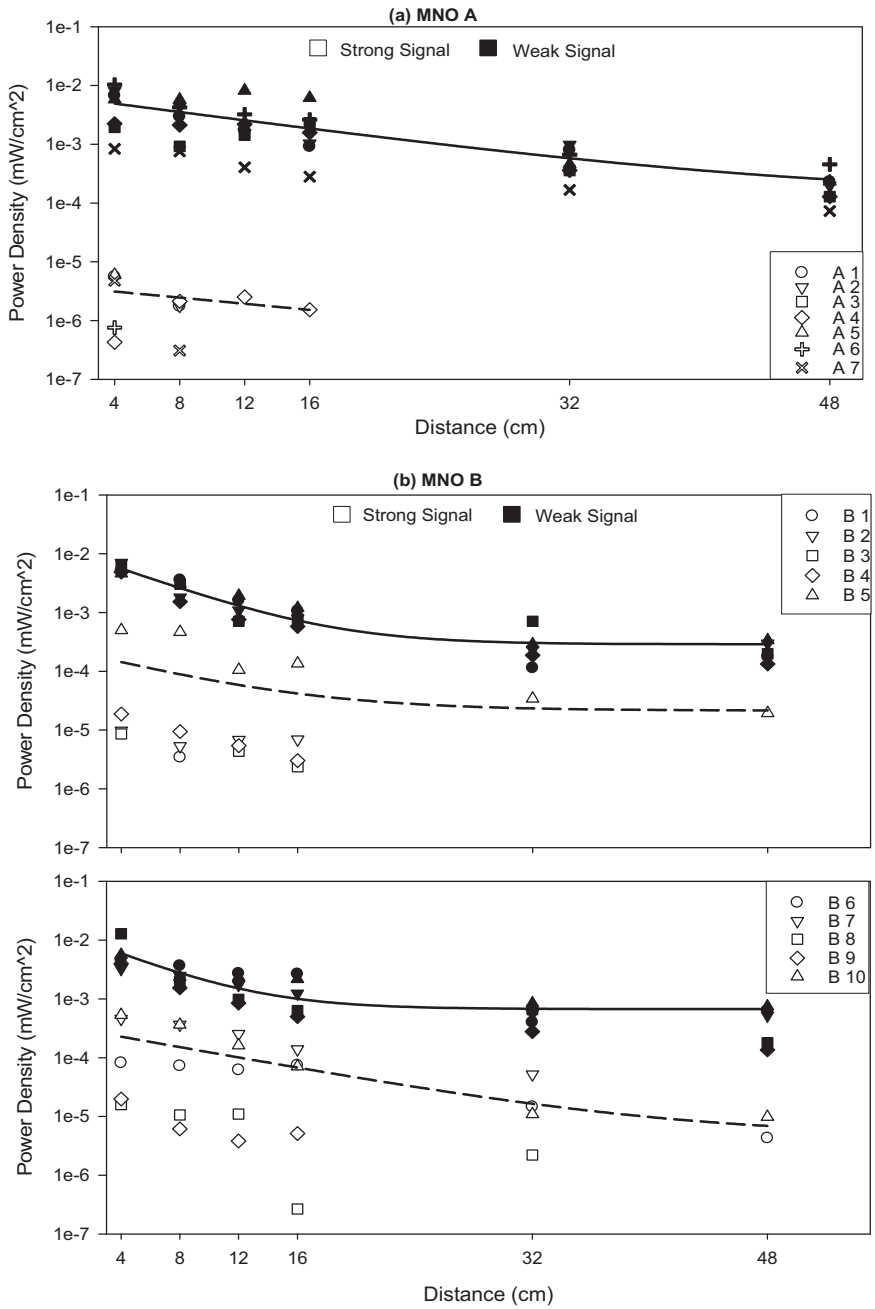

Fig. 7. Comparison of measured power density with distance for cell phone models under strong and weak reception conditions for (a) Mobile Network (MNO) A and (b) Mobile Network (MNO) B.

$\log_{10}$ Signal Power / 0.001 W), which was converted to mW and determined for each of the four MNOs studied under both strong and weak reception conditions.

As shown in Fig. 3, for the strong reception signal environment, the power received by phones from the different MNOs varied by several orders of magnitude. In contrast, all four MNOs were found to have a similar relationship between weak reception signals based on the 1–2 bar display and the actual reception power. Display bars were used as indicators of reception signal strength in this study, since this metric is readily available to all cell phone users.

Comparisons of the power density measurements for cell phone models tested under different reception signal conditions at the closest distance of 4 cm for the two larger MNOs, A and B, are given in Figs. 4 and 5, respectively. All seven MNO A cell phones tested under strong reception signal conditions (4–5 display bars) produced power density measurements very close to baseline levels. Power density levels from two MNO A phones (A2 and A3) were so low they could not be reliably distinguished from the baseline. The other five MNO A cell phones power density levels were in a range between 4.3×10^{-7} and 6.0×10^{-6} mW/cm^2 averaged over the measurement duration. A maximum power density level recorded during each measurement interval was well above baseline for all seven MNO A phones and ranged from 7.0×10^{-6} to 3.2×10^{-5} mW/cm^2, but represented only 1.3% of the measurement time interval.

Under weak reception signal conditions, power density from all MNO A cell phones were well above baseline, and orders of magnitude higher than under strong reception signal conditions. Power density levels ranged over more than an order of magnitude from 8.3×10^{-4} to 1.0×10^{-2} mW/cm^2 averaged over the measurement duration, while maximum power density levels ranged from 1.81×10^{-3} to

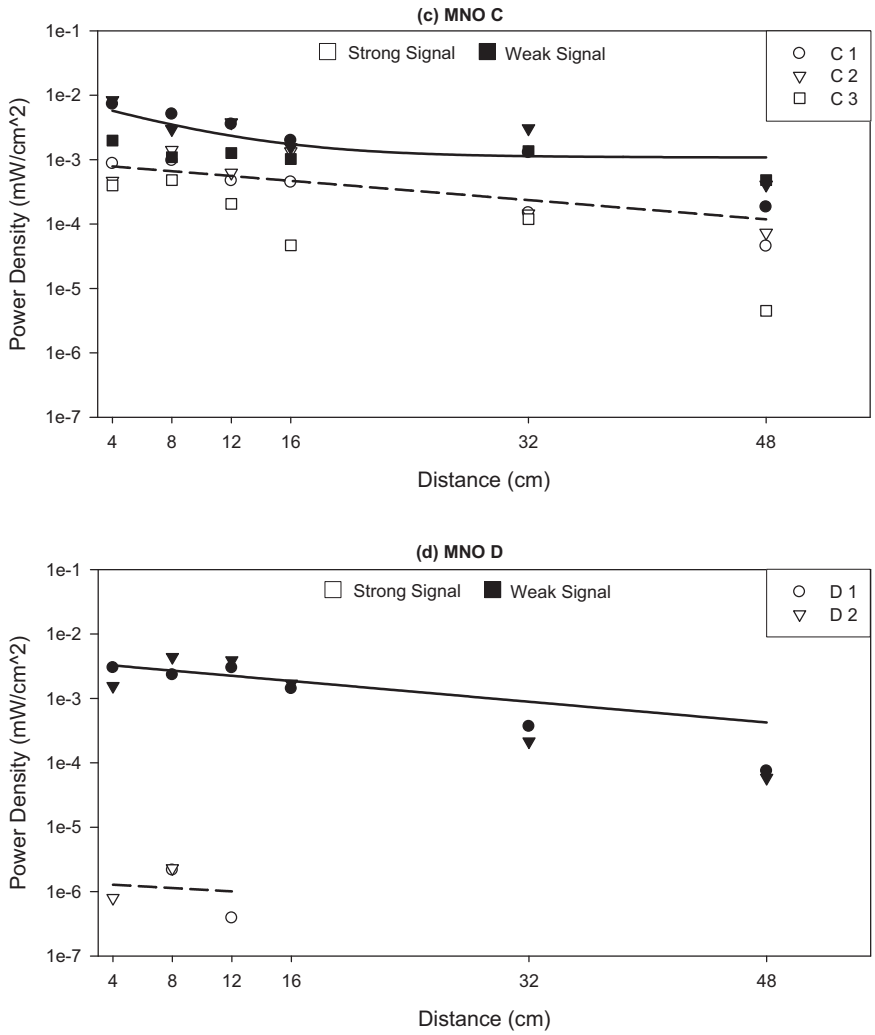

Fig. 8. Comparison of measured power density with distance for cell phone models under strong and weak reception conditions for (a) Mobile Network C and (b) Mobile Network D.

3.48×10^{-2} mW/cm^2.

From Fig. 5, of the ten MNO B cell phones measured at 4 cm under strong reception signal conditions, nine produced power density levels above baseline, while all ten were well above baseline under weak reception signal conditions. Average and maximum power density levels for strong reception spanned two orders of magnitude, with the average level range from 8.6×10^{-6} to 5.3×10^{-4} mW/cm^2, while maximum levels were higher in a range from 1.4×10^{-5} to 1.4×10^{-3} mW/cm^2. Under weak reception conditions much higher levels were measured, with average weak signal levels from 3.3×10^{-3} to 1.3×10^{-2} mW/cm^2 and maximum levels from 6.9×10^{-3} to 3.0×10^{-2} mW/cm^2.

The results of power density measurements at 4 cm for MNOs C and D cell phones are given in Fig. 6. Under strong reception signal conditions all three MNO C phones and one of two MNO D phones had power density levels above baseline, while all five cell phones for both MNOs were well above baseline under weak reception signal conditions. MNO C average and maximum power density levels for strong reception signal conditions spanned less than one order of magnitude, with an average range of 4.0×10^{-4} to 8.7×10^{-4} mW/cm^2 and maximum range of 1.4×10^{-3} to 4.3×10^{-3} mW/cm^2, while the one MNO D phone with power density above baseline had average and maximum strong signal emission levels of 8.0×10^{-7} and 1.5×10^{-5} mW/cm^2, respectively. Power density for weak cell tower reception signal levels spanned one order of magnitude or less for both MNOs, with a MNO C average range of 2.0×10^{-3} to 8.3×10^{-3} mW/cm^2 and MNO D range from 1.6×10^{-3} to 3.0×10^{-3} mW/cm^2. MNOs C and D had maximum power density ranges of 8.0×10^{-3} to 3.6×10^{-2} and 3.9×10^{-3} to 9.7×10^{-3} mW/cm^2, respectively.

3.2. Cell phone power density with distance

Power density measurements were also performed at distances greater than 4 cm from the typical cell phone ear position to determine the effect of distance on measured power density. Measurements of power density were made at six distances between 4 and 48 cm under both strong and weak cell phone reception signal conditions. A comparison between measured power density levels under strong and weak reception signal conditions at all distances is given in Fig. 7 for MNOs A and B and in Fig. 8 for MNOs C and D. At distances greater than 16 cm under strong reception signal conditions, most measured power density levels were not distinguishable from baseline levels.

For cell phones supported by MNOs A and D, power density levels under weak reception signal conditions were between two and three orders of magnitude greater than under strong reception signal conditions at every distance investigated. However, cell phones using MNOs B and C displayed less of a difference, with power density measurements for weak reception signal conditions exceeding measurements under strong reception signal conditions by one to two orders of magnitude. For almost all MNO cell phones, the measured power density at the furthest distance of 48 cm under weak reception signal conditions

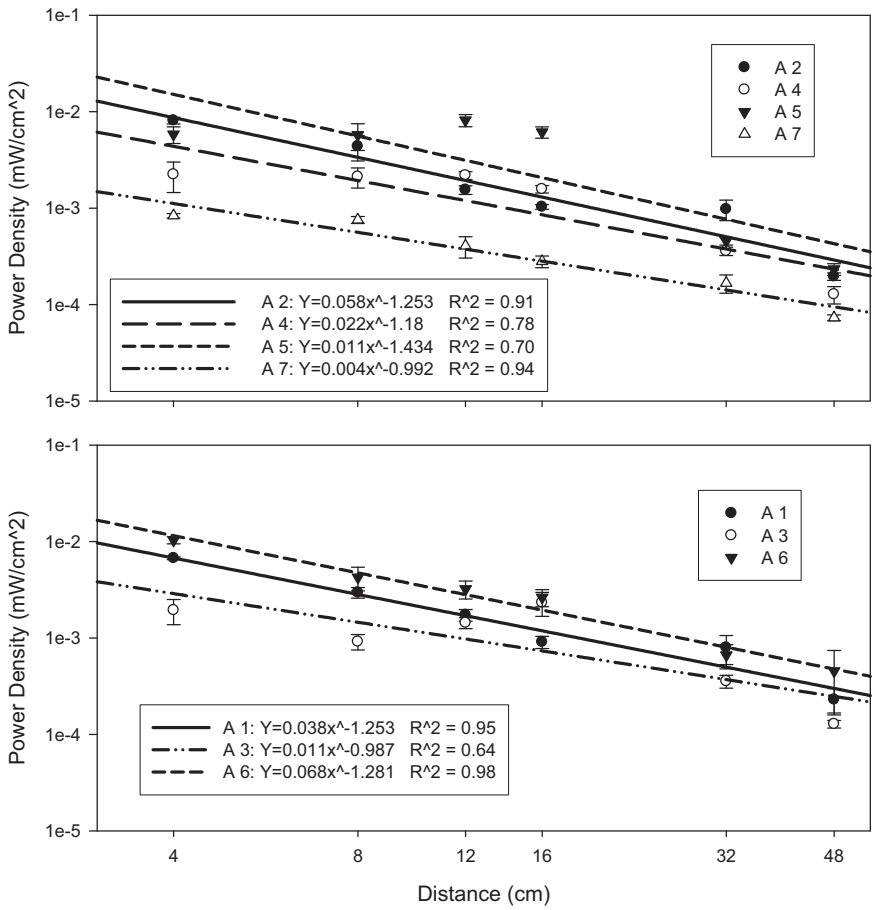

Fig. 9. Mobile Network Operator A power density as a function of distance from cell phone face under weak reception signal conditions. Power curve fit yields well behaved regression line to allow prediction of power density levels at intervening distances.

was equal to or greater than the power density measured at the nearest distance of 4 cm under strong reception signal conditions.

To further investigate cell phone higher power density levels under weak reception signal conditions, the levels for phones using MNOs A and B were fitted with a power curve regression in Figs. 9 and 10, respectively. Regression line fits for the majority of cell phones and associated MNOs were determined to have a coefficient of determination, R^2, greater than 0.9, indicating that the power curve fit can be used to estimate power density cell phone levels at distances between measurements. There is a variation in the dependence of the power density with distance between cell phone models with different MNOs, yielding a power curve of $1/X^n$ with n between 0.81 and 1.634. This was a much less rapid drop in power density than the expected decrease proportional to the inverse square of the distance, which is consistent with a complex design for cell phone antennas intended to extend the range of the RF EMF transmission. The consistent relationship between power density and distance, down to the closest measurement at 4 cm, confirmed that the instrument readings were performed in the far-field region, where RF EMFs are well formed.

3.3. Bluetooth headset power density

Measurements of power density for all nine Bluetooth headsets, while connected to each of two cell phone models supported by MNOs A and B under weak signal conditions, are given in Fig. 11a and b. Each Bluetooth headset was found to have minimal difference in the measured power density between call connections with the MNO A and B phones. Conversely, there was a wide variation in power density between the different Bluetooth models, regardless of which call-connected MNO phone was used. For comparison with cell phone exposure level without a Bluetooth headset, power density readings from the headsets were at least an order of magnitude lower for the measurement period average, and nearly two orders lower than the maximum level. When connected to the MNO A cell phone, the different Bluetooth headset average emission ranged from 1.2×10^{-5} to 2.1×10^{-4} mW/cm^2, compared to the direct cell phone power density measured at the same 6 cm distance of 1.8×10^{-3} mW/cm^2. For the MNO B cell phone, different Bluetooth headset average emissions ranged from 5.1×10^{-6} to 2.2×10^{-4} mW/cm^2, compared to the direct cell phone emission measured at the same 6 cm distance of 2.2×10^{-3} mW/cm^2.

4. Discussion

4.1. Comparison with previous studies

The primary purpose of this study was to determine real-world power density as a measure of exposure for a number of cell phone models registered with different mobile network operators, under both weak and strong reception signal conditions. Unlike many previous investigations, the measurements of power density were made under stationary conditions for both GSM and CDMA technology. At the Richmond study site in the San Francisco Bay Area, some mobile network operators (MNO) were found to utilize different frequency bands depending on the reception signal strength. Measurements reported in other studies under mobile conditions are subject to continuous variations in the cell phone transmission level due to the power control adjustments in response to the reception signal strength. This was

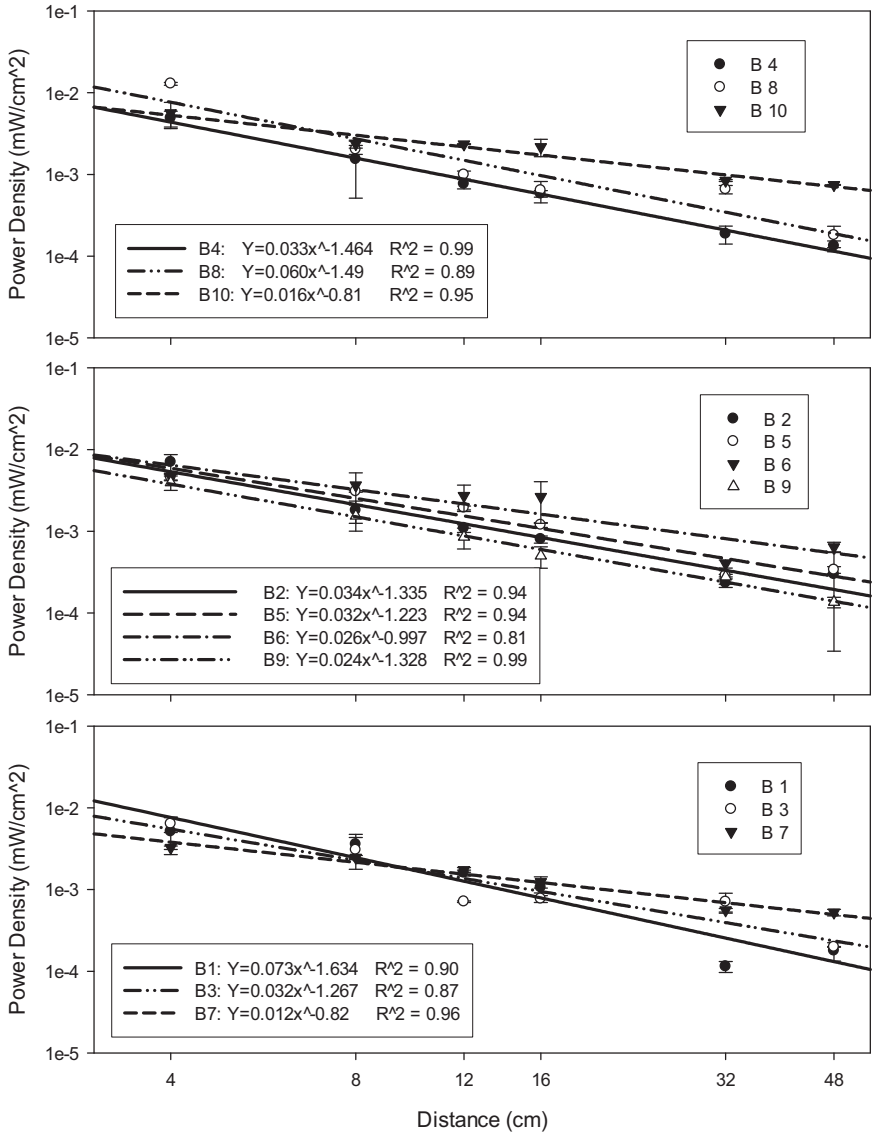

Fig. 10. Mobile Network Operator B power density as a function of distance from cell phone face under weak reception signal conditions. Power curve fit yields well behaved regression line to allow prediction of power density levels at intervening distances.

evident in European studies, which identified increases in cell phone transmission power in response to reduced reception strength, with the principal effect occurring during cell tower handover (Gati et al., 2009; Kuhn and Kuster, 2013; Wiart et al., 2000). Previous measurements in the San Francisco Bay Area for MNOs using GSM and CDMA cell phone technology reported a similar power control effect with increasing cell phone transmission power when moving due to reductions in reception signal strength (Kelsh et al., 2010).

4.2. Signal reception environments

In this study, the finding of significantly higher cell phone RF EMF power density exposure measured in weak signal reception environments, noted for emission power in previous studies, (Gati et al., 2009; Kuhn and Kuster, 2013; Wiart et al., 2000; Kelsh et al., 2010; Hardell et al., 2006; Hillert et al., 2006) was extended to include a large variety of commonly used cell phones employing different MNO services. All 22 cell phones had power density levels between one and four orders of magnitude higher when operating under weak signal conditions. The difference between weak and strong reception signal environments was at least two orders of magnitude higher for 73% of the phones tested. In contrast, under strong reception signal conditions, the measured power density from some phones was so low as to be indistinguishable from the baseline RF EMF. Based on the 2G technology investigated, reduced and precautionary use of cell phones under weak signal conditions could lower a user's RF EMF exposure by up to several orders of magnitude.

4.3. Effect of exposure distance

Measurement of power density at increasing distances from the cell phone indicated the same trend, with measured power density orders of magnitude higher for weak rather than strong reception signal environments at each distance. Under both weak and strong reception signal conditions, the power density decreased by up to two orders of magnitude as the distance from the phone increased up to 48 cm. The RF EMF power density for some phones at 48 cm under weak reception signal conditions was equal to or greater than the power density at 4 cm under strong reception signal conditions. Under weak reception signal conditions, power density reductions of up to 90% occurred at 16 cm (a typical distance for speaker phone or texting) compared to the 4 cm near-ear exposure. Depending on the Bluetooth headset model,

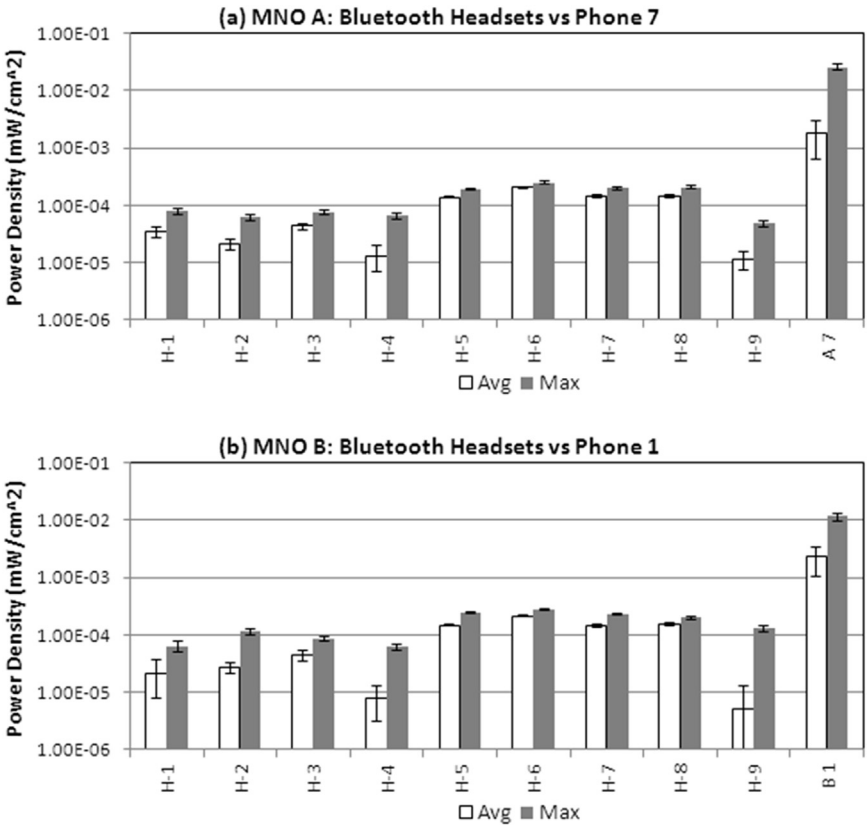

Fig. 11. Comparison of power density levels emitted by a number of Bluetooth headsets (H 1–9) during calls when connected to (a) a cell phone served by Mobile Network Operator (MNO) A (A 7) and (b) a cell phone served by Mobile Network Operator (MNO) B (B 1). Headsets and cell phones were both measured at a distance of 6 cm from the typical ear listening position.

exposures were 10–400 times lower than direct near-ear exposure from the phones to which they were connected.

4.4. Exposure effects

Cell phone RF EMF exposure may cause both thermal and nonthermal tissue effects. The FCC power density MPE limits, and the NCRP and ANSI/IEEE limits on which they are based, are derived from exposure criteria quantified in terms of SARs. The FCC's SAR standard is based on a 1986 U.S. Air Force study that estimated “safe” exposure levels for thermal effects. Evidence for both thermal and nonthermal effects was evaluated, but only the thermal effects were considered scientifically established as a basis for setting exposure limits. Accordingly, the SAR was based on thermal effects for a healthy adult male, with disclaimers that the results would differ for a person of a different size, age, or general health condition (Durney et al., 2013). Recent research indicates that exposure at the level of the current SAR may result in energy deposition in children's heads and bone marrow twice and ten times, respectively, higher than in adults (Gandhi et al., 2012). Significant increases in gliomas and Schwannomas of the heart in rodent studies have been reported for both near-field and far-field RF EMF exposure by the National Toxicology Program (2018) and the Ramazzini Institute (Falcioni et al., 2018). Several epidemiological studies of cell phone use and intracranial malignancy, in which the investigators examined potential impacts of longer latency ipsilateral use (i.e., holding the phone next to the same side of the head where the tumor developed), have reported significantly increased risks of total malignant brain tumors, mainly gliomas (Hardell et al., 2006, 2011; INTERPHONE Study Group, 2010). A population-based case-control study conducted in France (CERENAT) reported significantly increased risks of glioma among heavy phone users compared with non-regular users. These risks showed positive exposure-response relationships with self-reported average calling time per month and cumulative hours of use, and were higher among those with occupational exposures, with tumors of the temporal vs frontal lobe, and with ipsilateral vs contralateral tumors (Coureau et al., 2014). Also, an analysis of tumor localization data from the INTERPHONE study found an association between intracranial distribution of gliomas and self-reported preferred side of the head for cell phone use (Grell et al., 2016).

Evidence of nonthermal effects associated with RF EMF exposure from cell phones is mixed. Changes in the brain from exposure to cell phone electromagnetic fields below levels associated with thermal changes were reported in a study of 47 healthy people during a 50-min cell phone call (Volkow et al., 2011). Exposure to RF EMF from cell phones has been associated with effects on gene and protein expression (Hardell et al., 2013; Baan et al., 2011; Megha et al., 2015) and oxidation (Friedman et al., 2007; Yakymenko et al., 2016). These studies demonstrate the potential existence of biological changes at nonthermal RF EMF exposure levels, but the relationship of these changes to long-term health effects is unknown.

4.5. Classification of exposure risk

In 2011, the International Agency for Research on Cancer (IARC) classified RF EMF as possibly carcinogenic to humans (Group 2B) (IARC, 2011; IARC Working Group on the Evaluation of Carcinogenic Risk to Humans, 2013). This classification was based on limited evidence from epidemiological studies of a possible increased risk of gliomas and acoustic neuromas associated with cell phone RF EMF exposure (Baan et al., 2011; IARC, 2011). Major technological changes in the cell phone RF EMF emission signal characteristics over the past decade may affect the applicability of earlier health effects studies to current exposures. However, the marked increase of cell phone users, the high frequency of typical cell phone use, and the classification of RF EMF as a possible carcinogen have prompted interest in measures to reduce exposure to cell phone RF EMF emission levels under normal use conditions.

Although the levels of cell phone power density measured in this

study were orders of magnitude below the FCC MPE limits for the general population, those limits were derived from exposure criteria quantified in terms of SARs for constant exposures. The FCC has reported that laboratory-derived SAR values do not provide sufficient information to compare RF exposure levels between cell phone models under typical usage conditions (FCC, 2017). Other research indicates that exposures at SAR levels are likely to produce much greater energy deposition in children than adults (IARC Working Group on the Evaluation of Carcinogenic Risk to Humans, 2013).

5. Conclusion

The results of this study, based on typical strong (4–5 display bars) and weak (1–2 display bars) cell phone reception signal environments, suggest a number of potential self-protective measures to reduce RF EMF exposure. Due to the higher emission levels for cell phones operating in weak reception signal environments, avoiding or limiting cell phone use under these conditions is the most obvious measure to reduce exposure. Since this may often be impractical, using the cell phone at a moderate distance by employing speaker-phone mode, wired headset, or by texting rather than talking can reduce RF EMF exposure by up to two orders of magnitude in weak reception signal areas. Bluetooth headsets allow a greater separation from the cell phone during conversations and, although these headsets do emit RF EMF, the power densities measured in this study were as much as 400-fold lower than those from the cell phone itself. Using a cell phone for internet browsing, email or streaming audio or video will generally increase the distance between the phone and the body; however, the exposure characteristics of the associated data signals are different from those of telephonic voice signals. The effects of prolonged exposures to such data signals have not been investigated and may potentially affect other organ systems. Further research is also needed to assess exposures resulting from more current cell phone technology, as well as exposures to individuals in close proximity to a cell phone user, which would require measurements of RF EMF power density from the back and sides of the phone. Based in part on the results of this study, the California Department of Public Health published “How to Reduce Exposure to Radiofrequency Energy from Cell Phones” (CDPH, 2017). Cell phones have become an integral part of the fabric of modern life; additional research is needed to delineate how best to use these devices to ensure protection of public health.

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