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Measured radiofrequency exposure during various mobile-phone use scenarios

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Epidemiologic studies of mobile phone users have relied on self reporting or billing records to assess exposure. Herein, we report quantitative measurements of mobile-phone power output as a function of phone technology, environmental terrain, and handset design. Radiofrequency (RF) output data were collected using software-modified phones that recorded power control settings, coupled with a mobile system that recorded and analyzed RF fields measured in a phantom head placed in a vehicle. Data collected from three distinct routes (urban, suburban, and rural) were summarized as averages of peak levels and overall averages of RF power output, and were analyzed using analysis of variance methods. Technology was the strongest predictor of RF power output. The older analog technology produced the highest RF levels, whereas CDMA had the lowest, with GSM and TDMA showing similar intermediate levels. We observed generally higher RF power output in rural areas. There was good correlation between average power control settings in the software-modified phones and power measurements in the phantoms. Our findings suggest that phone technology, and to a lesser extent, degree of urbanization, are the two stronger influences on RF power output. Software-modified phones should be useful for improving epidemiologic exposure assessment.

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Introduction

Most radiofrequency (RF) exposure assessments of mobile phone users for epidemiologic purposes have used subscriber billing records, questionnaires, and interviews to characterize temporal features of mobile phone usage (Funch et al., 1996; Rothman et al., 1996; Berg et al., 2005; Cardis et al., 2007). These methods have assumed that exposure duration and measures of repetition are valid surrogates for RF energy absorbed from mobile phone handsets; however, technical features of mobile phone handset design, the service provider technology and coverage, and other factors may have a significant impact on the intensity of RF exposure, which would affect the absorbed dose (Andersen and Pedersen, 1997; Hillert et al., 2006).

The original analog mobile phone system (AMPS) used only two RF channels to control communication. Various digital techniques have been used to enhance the efficiency of RF spectrum use and the capacity and reliability of the wireless communication system. These digital techniques are: (1) TDMA (time-division multiple access) technology, which is now obsolete and was used principally in the United States; (2) the GSM (Global System for Mobile Communication) technology, originally adopted in Europe and now found globally, which also employs TDMA; and (3) CDMA (Code-Division Multiple Access) technology, first used widely in the United States and later more universally. These digital technologies are in use in several frequency bands (spectral regions) that currently exist between 824 and 1910 MHz. The frequency of operation can also be a significant factor in the RF power output. In addition to the various encoding techniques, conservation of battery power and efficient use of the spectrum without sacrificing communications quality require moment-to-moment adjustments in handset power output that create an additional source of amplitude variation. Epidemiologic research to date, and the exposure assessment study presented here, address only models that were either first-generation (1G) analog devices or second-generation (2G) digital phones.

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The power control (PWC) settings used in current GSM mobile phones can be stored and retrieved for analysis as a potential tool for RF exposure assessment. Special phones have been developed through software modification to store PWC information stamped with the date and time of calls (software-modified phones, SMPs). Hardware-modified phones have been designed to capture real-time information on power output and record the position of the phone with respect to the user's head. These data are useful for personalized dosimetry and can be recorded when the mobile phone is in normal use (Inyang et al., 2007; Morrissey, 2007). Personal dosimeters have also been developed to assess RF exposures from mobile-phone base stations (Radon et al., 2006; Breckenkamp et al., 2008).

A few previously published environmental studies investigated PWC settings from GSM phones. Wiart et al. (2000) studied the influence of PWC and discontinuous transmission of SMPs on RF exposure in Paris (Wiart et al., 2000). They found that the major effect on emitted power was base station handovers, during which the power is set to a maximum level for a brief period. These authors found that the dense concentrations of base stations caused more frequent switching, and therefore, mean power increased (Wiart et al., 2000). A more recent study reported that the handovers are dominant in today's GSM networks; and therefore the peak spatial-specific absorption rate (SAR) at maximum power is a good proxy for the average exposures of GSM users (Kuehn et al., 2009).

Morrissey (2007) studied volunteers in different geographic locations using SMPs and found that the highest average transmit power was observed in Malaysia and Europe, and the lowest average transmit power in the United States (Morrissey, 2007). In another study that issued SMPs, exposure variability was observed across different geographic locations, by use while stationary *versus* moving, by indoor *versus* outdoor use, and due to the use of hands-free devices (Erdreich et al., 2007).

Based on GSM base station records, Lonn et al. (2004) reported that average transmit power was highest in rural locations compared with denser urban locations, which they concluded was due to the lower density of base stations in rural areas (Lonn et al., 2004). However, a small urban area had a lower proportion of call time at the maximum power level than the city area, indicating that factors other than base-station density (for example, density of buildings) may influence handset power output.

Balzano (1999) estimated the range of variation of exposure to a user for several exposure parameters based on engineering principles, rather than "real-world" measurements (Balzano, 1999). He concluded that by far the most influential exposure parameter is RF power level, (estimated change in exposure in the range of 100:1), followed by phone model, (range of 20:1), then position (range of 10:1) and finally anatomical features (range of 2:1) (Balzano, 1999). The dependence of RF exposure on device design, position at head, head shape, internal anatomy, and metallic accessories such as glasses, jewelry, and metallic implants, has been summarized (Burkhardt and Kuster, 1999; Kuster, 2000, 2001). For a given antenna input power, device design and device position relative to the head appear to have the largest impact on the strength and distribution of the induced fields. Metallic accessories can be neglected for spatial peak SAR in the brain, but may significantly influence exposures in nearby tissues and those in contact with the handset.

Only recently have epidemiologic studies attempted to characterize exposure through methods that estimate SAR values for regions of the brain where a tumor is located (Takebayashi et al., 2008; Gosselin et al., 2009). Such exposure estimates might provide for a more accurate and less biased assessment of the potential health risks potentially attributable to mobile phone use.

In our study, we measured the RF power output level of various phones used in a variety of scenarios, with the expectation that these data could be translated into a measure of dose for RF exposure, the SAR (Lonn et al., 2004; Inyang et al., 2007). We used two types of mobile RF data collection systems to evaluate various exposure variability questions — a software-modified phone technology, and a mobile phantom-head data collection system. It was our objective to evaluate various factors that could affect RF output such as: provider technology, environmental region (proxy for base-station density), mobile phone design, and use while moving *versus* use while stationary. If practical, these factors could be incorporated into future exposure assessment protocols of epidemiological studies and may be useful in the interpretation of current epidemiological research.

Methods

Instrumentation

Two types of data collection systems were used in our field studies. Software-modified phones were developed by Motorola Labs by adapting Motorola Timeport P7379 GSM mobile phones to capture time- and date-stamped power control settings every 2.5 s for up to 3 hours (Morrissey, 2007). The stored information was then downloaded to a laptop computer using custom software.

The second system integrated a phantom head, in which an RF power probe was located along with a computer-based system for data recording and analysis (System Network and Hand-set Analyzer (SYNEHA), Schmid & Partner Engineering AG, Zurich, Switzerland). This system, described in Kuehn et al. (2009), was developed to measure the RF energy output performance of mobile phones under real-life conditions. In our study, the measurement system was driven in a van through various environments. The system included three phantom heads filled with a sucrose-based fluid having dielectric properties that simulate the human brain. Each phantom had a pair of dipole electric probes fixed in positions near each ear. The probes were 10, 14, or 30 mm long, in order to be sensitive across a suitable mobile telephone frequency range. The SYNEHA system was able to measure RF power radiated into the phantom head for up to four mobile phones (two phantoms, two phones per phantom), but because of crosstalk between signals at each probe within a phantom head, data collection was conducted with only one phone per phantom. During data collection, the system was subject to the effects of changing distances to base stations, different topographic and building environments, and various traffic speeds. For accurate positional tracking, the system recorded time-stamped latitude and longitude from a GPS receiver simultaneously with the RF power data.

The deviation from linearity of the SYNEHA system power sensors is <0.2 dB. The uncertainty of the average power SYNEHA measurements depends on whether the measured signal was always above the detection threshold. The system has a dynamic range of >33 dB, which indicates that for the AMPS, GSM, and TDMA systems the measurement uncertainty will be determined only by uncertainty due to deviations from field sensor linearity. For CDMA, which has much greater dynamic range, at times the phones may have operated below the systems detection threshold and the SYNEHA system would have sampled noise instead of the actual signal from the phone. We estimated the overall effect on mean signal levels from these assumptions: mean power of 0 dBm in CDMA and the sensitivity level at -15 dBm, and actual signal power of -65 dBm for 50% of the time. In this example, the resulting error in average power made by sampling noise instead of the actual signal is <0.15 dB and comparable with uncertainty from non-linearity. Therefore if the mean of average power is sufficiently great than the noise level (as was the case in our study), the overall SYNEHA uncertainty is relatively small, approximately 0.4 dB. Additional uncertainties are introduced due to the power instability of individual phones (typically <0.4 dB) and due to vibrations when driving (typically <0.2 dB). Thus, uncertainty in average power from all sources is less than ± 1 dB (± 25% in power).

Data collection and processing were performed in three steps. First, the electromagnetic fields measured by the E-field probe were sampled every 256 μs by an EASY4 (Schmid and Partner Engineering AG, Zürich, Switzerland) measurement server. These data were then transferred to a PC running the SYNEHA software for processing of the power values. The SYNEHA display shows intermediate data in a numerical and/or graphical presentation. Because of the large amount of data, intermediate data were displayed in graphical form to monitor data collection and system performance.

Mobile Phones

Eight different models of phones from two manufacturers were used in this study (Table 1). Motorola StarTAC models were obtained for use with AMPS (analog), CDMA, and TDMA; Motorola V60 models for CDMA, GSM, and TDMA; Nokia 5165 models functioned on CDMA and TDMA; and Nokia 8290 and 2128i were GSM only models. The CDMA and TDMA handsets supported the AMPS 800-MHz band. No single model supported all four technologies. These phone models represented a mix of flip and candy-bar phones. In addition, we purchased Motorola Timeport software-modified phones (candy-bar style) that operated on the GSM 1900-MHz band and, therefore, were tested only in this band.

The above popular models were selected through discussions with major manufacturers and retailers of mobile

Table 1. Models, technologies, and frequency bands of mobile telephones used in SYNEHA Data Collection System.

Model	Technology	Provider	No. of phones	Shape of Phone (candy bar/flip)	Frequency band (MHz)[a]
Motorola StarTAC	TDMA	Cingular	3	Flip	800/1900
Motorola StarTAC	CDMA	Verizon	2	Flip	800/1900
Motorola StarTAC	Analog	Cingular	2	Flip	800
Motorola V120	TDMA	Cingular	2	Flip	800/1900
Motorola V120	CDMA	Verizon	2	Flip	800/1900
Motorola V60	TDMA	Cingular	2	Flip	800/1900
Motorola V60	CDMA	Verizon	1	Flip	800/1900
Motorola V60	GSM	Cingular	1	Flip	1900
Motorola Timeport	GSM	Cingular	2	Candy bar	1900
Nokia 5165	TDMA	Cingular	2	Candy bar	800/1900
Nokia 5165	CDMA	Verizon	1	Candy bar	800/1900
Nokia 5190	GSM	Cingular	1	Candy bar	1900
Nokia 8290	GSM	Cingular	1	Candy bar	1900
Nokia 2128i	GSM	Cingular	1	Candy bar	800/1900

Although some models were capable of operation in the 800- and 1900-MHz bands, during the test period, the GSM system operated only in the 1900-MHz band, and all others operated only in the 800-MHz band.

phones, as well as technical staff from the Cellular Telephone and Internet Association (CTIA), and by reviewing analysts' reports (Lehman Brothers, personal communication) and lists of phone models from the 1990s and early 2000s. Phones were selected based on sales volume, duration of use by the general public, and availability for purchase for the study. We located at least two samples of each model selected for purchase and testing (Table 1).

Set-Up of SYNEHA System

The SYNEHA system was used to obtain contemporaneous data from two mobile phones placed in fixed positions on the exterior sides of two phantom heads, with the speakers aligned with the ears. In addition to collecting data from the two phantom heads, a third phantom had one or two software-modified phones (Motorola Timeport P7389) that simultaneously captured PWC data. Data from the software-modified phones were compared with measurements from the SYNEHA system to assess the correlation between software-modified phone power control settings and the SYNEHA recorded power output. To address the effect of voice-activated discontinuous transmission (DTX), which reduces output power when there is no speech, all phones were subjected to continuous rock music to generate a high proportion of sound to the phones. This could have caused a relatively higher average output power than what would be observed with normal conversation on a mobile phone.

Reference Values of SYNEHA System

The SYNEHA system was used to determine the output power relative to the maximum output power. Therefore, the sensor reading at the maximum output power had to be determined first. This determination of the reference values was performed by simply placing the phone at the head and setting the device at the highest output power (Table 2). Three methods were applied. (1) For AMPS 800 MHz, a base-station simulator (Anritsu MT8802A, Japan) was used. (2) An RF-sealed metal box was used into which the head and phone were placed and the cover slowly closed until the link was interrupted. The maximum reading of the sensor was assumed to represent the phone's maximum output power. (3) The maximum reading during the test drive was compared with the reference values determined by the other methods.

Table 2. Minimum and maximum power output values of each technology of mobile phones used as input values for SYNEHA analysis software.

Technology	Communication system minimum (dBm)	Communication system maximum (dBm)
AMPS	+8	+28
GSM	0	+30 to +33
TDMA (IS-136)	+8	+28
CDMA (IS-95)	−30	+24

Although many handsets were able to operate in two bands (for example, GSM 800/1900 MHz), the operating band was not a factor throughout this study, because at the time of testing, GSM service in the study area was exclusively in the GMS 1900-MHz band, and all other technologies operated only in the 800-MHz band. The SYNEHA-recorded power levels measured during the study represent relative levels among the different handset models, types, technologies, etc., rather than absolute power levels.

Driving Routes

Base-station density maps of the San Francisco Bay Area were provided by the two largest local networks — Cingular/AT&T and Verizon. Cingular/AT&T provided service for all TDMA, GSM, and Analog mobile phones, whereas Verizon provided service for all CDMA phones. From the base-station density maps, three routes were designed to represent a dense urban environment, a suburban environment, and a rural environment, corresponding with decreasing base-station density. The dense urban route was the San Francisco downtown financial district, the suburban route of surface streets and highways was in Menlo Park, and the rural route followed a road approximately 100 miles south of San Francisco near Morgan Hill, California. All driving routes could be completed in 20–30 min. The urban route went through an area of numerous tall buildings, whereas the suburban route was mostly residential neighborhoods with some commercial areas. Several sections of the suburban route had substantial tree foliage. The rural route was primarily open agricultural land, with mixed farming and ranching activities, characterized by rolling hills not exceeding 1000 feet in elevation.

Data Collection

Power control data (software-modified phones) and RF output power data (SYNEHA system) were collected primarily while mobile phones were located in the van while driving over the pre-established routes. Additional PWC data were obtained from stationary locations or by the technician in the van who was not driving. These additional PWC data were used to assess factors such as time of day and to compare software-modified phone PWC to the SYNEHA system RF power output data. Using the SYNEHA system, RF power data were collected over 17 days: (1) rural route, 6 days between October and December 2005 and in March 2006; (2) suburban route, 7 days in March 2006; and (3) urban route, 3 days in May 2005. RF power measurements were collected while the van was driven along each route and at stationary locations for 2 to 6 min during the drive (stationary locations were consistent for each route) (Table 3). Two stops lasting 3 min each were incorporated into the rural and suburban routes, but not in the urban route due to

Table 3. Number of routes completed by technology and type of route for measurements of RF fields in phantoms by SYNEHA Data Collection System[a].

Route	Analog	CDMA	GSM	TDMA	Total
Rural	11	31	17	13	72
Suburban	5	46	43	2	96
Urban	6	15	8	11	40
Total	22	92	68	26	208

[a] Data collected from 19 May 2005 to 2 March 2006.

difficulty in finding a consistent location to stop and park. GPS data were collected simultaneously with SYNEHA data.

The 14-mm dipole phantom heads were used for GSM, Analog, and TDMA mobile phones (with the exception of the TDMA V60, which was run on the 30-mm dipole head), and the 30-mm dipole phantom head was used for CDMA phones. The 10-mm dipole phantom head was not sensitive enough for any of the phones used in this study; therefore, it was used in the front passenger seat only for software-modified phones. The 14- and 30-mm phantom heads were placed in the middle row of seats, and the SYNEHA unit and laptop computer were placed in the rear of the van.

Software-modified phone data were collected under three different protocols: (1) attached to a front-seat phantom, but without SYNEHA system running ($n = 39$ days); (2) attached to a second-row phantom with the SYNEHA system recording RF output data from other phones ($n = 10$ days, 34 separate route runs), and (3) handheld or in a custom hat holder without a phantom, in a variety of outdoor and indoor locations for 3–4 min at each location.

Data Analysis

SYNEHA generated data points every 256 μs, but the output data for GSM, TDMA, and analog data were averaged over intervals of 120 ms duration. CDMA data, which can vary more rapidly, were averaged at 1.2 ms intervals and thus were more likely to capture short-lived peaks and the rapid changes of CDMA power control.

The stepwise software-modified phone power control settings were converted to the corresponding power levels over the range 0.001 W (step 15) to 1.0 W (step 0) (Table 4). Descriptive statistics (mean, minimum, maximum, s.d.) were generated for the factors of technology, moving *versus* stationary, different models of GSM phones, and type of route (urban, suburban, rural). Power-level averages were obtained with appropriate consideration of the logarithmic nature of the decibel scale.

Moving and stationary data were separated by identifying each stop location from the simultaneously recorded GPS data. Although there were minor fluctuations in the GPS coordinates, the data could be used together with the recorded time of each stop to confirm whether data were from the moving *versus* the stationary series. Using analysis of variance procedures (ANOVA) that accounted for the unbalanced design, we evaluated the contribution of RF output by the study factors: technology and route. The RF power data from the SYNEHA system and the PWC data from software-modified phones could be compared only for the GSM technology, because the software-modified phones were exclusively GSM. Two types of output power averages were calculated for the SYNEHA data: overall average, and the average of peak levels within each 120-ms or 1.2-ms interval and compared with the average PWC levels.

Table 4. Power control settings (PWC) and corresponding power levels in software-modified phones.

Power step	Power (dBm)	Power (W)
0	30	1
1	28	0.6
2	26	0.4
3	24	0.25
4	22	0.16
5	20	0.1
6	18	0.06
7	16	0.04
8	14	0.025
9	12	0.016
10	10	0.01
11	8	0.006
12	6	0.004
13	4	0.0025
14	2	0.0016
15	1	0.001

Results

Of the 208 route samples collected, 72 routes were driven in rural, 96 in suburban, and 40 in urban locations (Table 3). By technology type, more data were collected for the CDMA (44%) and GSM (33%) technologies. We had fewer data for the TDMA and analog technologies (12 and 10%, respectively), in part due to the rapid phase out of these technologies. For the four technologies we examined, on average, analog mobile phones operated with the highest power output, whereas CDMA technology operated, on average, at the lowest power output levels (Figure 1). (Power in dBm is relative to the specific level of 1 mW, such that on a logarithmic scale, negative values indicate a power below 1 mW.) Mean TDMA and GSM power output values were 18.2 and 14.1 dBm, respectively. The CDMA and GSM technologies showed the most variation in RF output levels, as reflected by their range and standard deviation (Table 5). ANOVA results indicated that technology type accounted for the greatest proportion of the

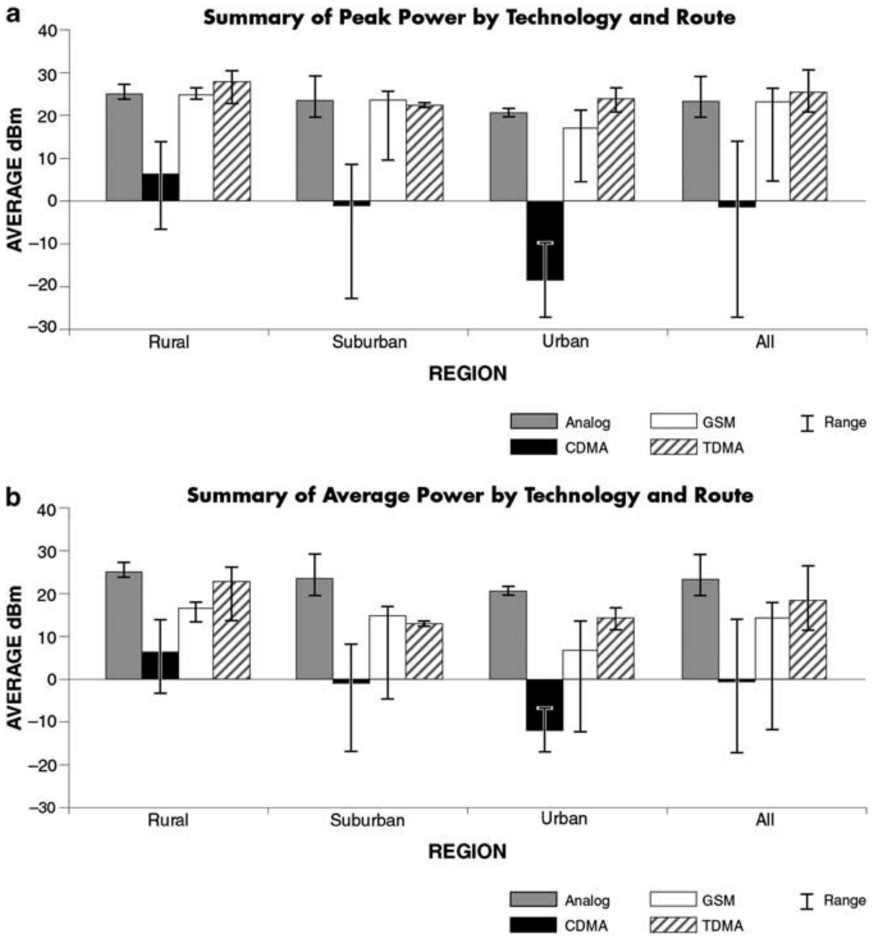


Figure 1. (a) Summary of average peak power levels (dBm) by mobile phone service technology and data collection area (rural, suburban, or urban). (b) Summary of average power levels (dBm) by mobile phone service technology and data collection area (rural, suburban, and urban).

Table 5. Statistical characterization of the distribution of overall and peak RF power output (dBm) by technology collected in SYNEHA data collection system.

	Analog		CDMA		GSM		TDMA	
	Overall	Peak	Overall	Peak	Overall	Peak	Overall	Peak
N (trips)	22	22	92	92	68	68	26	26
Mean	22.34	23.38	−0.38	−1.27	14.11	23.18	18.23	25.63
Median	24.10	24.13	2.36	2.9	15.36	24.39	16.10	24.31
Std Dev.	3.02	3	8.24	10.48	5.40	3.93	5.37	3.23
Minimum	19.35	19.42	−17.26	−26.98	−12.41	4.63	11.22	20.83
Maximum	29.01	29.03	13.43	13.74	17.66	26.31	25.88	30.62

variation, and that geographic area (urban, suburban, and rural) accounted for a lesser, but significant, amount of variation (Table 6). The interaction term of technology type and route also gave a statistically significant result.

Technology type remained the major distinguishing factor for RF power levels within each of the three routes, with relative RF power output showing similar trends in the urban, suburban, and rural locations, and corresponding to the overall trend described above (Figure 1). In all regions, CDMA was the lowest and analog the highest. GSM and TDMA technologies were intermediate in all three regions. GSM power levels were significantly lower than TDMA on the urban route, similar to TDMA on the suburban route, and lower, though not statistically different from TDMA, on the rural route (Figure 1a and b).

Sample traces of RF output for the four technologies (Analog, TDMA, GSM, and CDMA) provide more detailed views of the RF power output variation that can be masked in summary measures (Figure 2). GSM traces were dominated by RF output spikes that likely reflect base-station handovers. CDMA traces showed frequent changes in power output (dark area below −10 dbM), far lower than for other technologies. The analog technology reflected the least power control, with RF power remaining constant for longer periods of time. TDMA technology looks somewhat similar to the analog traces with respect to step function type changes in power levels; however, more changes in levels were observed in the sample TDMA trace compared with the variation for the analog phone.

Table 6. Technology and route contributions to RF power output variation: ANOVA results: unbalanced design.

	d.f.	Total sum of squares	Mean sum of squares	F value	*P*-value
Technology[a]	3	738.7	246.2	195.7	<0.0001
Route[b]	2	126.3	63.1	50.2	<0.0001
Technology*route	6	43.5	7.3	5.8	<0.0001

The "*" designates multiplication—it is a way to represent the interaction term in our ANOCA model for Technology and route variables.

[a] Refers to different mobile phone technologies: CDMA, TDMA, GSM and Analog.

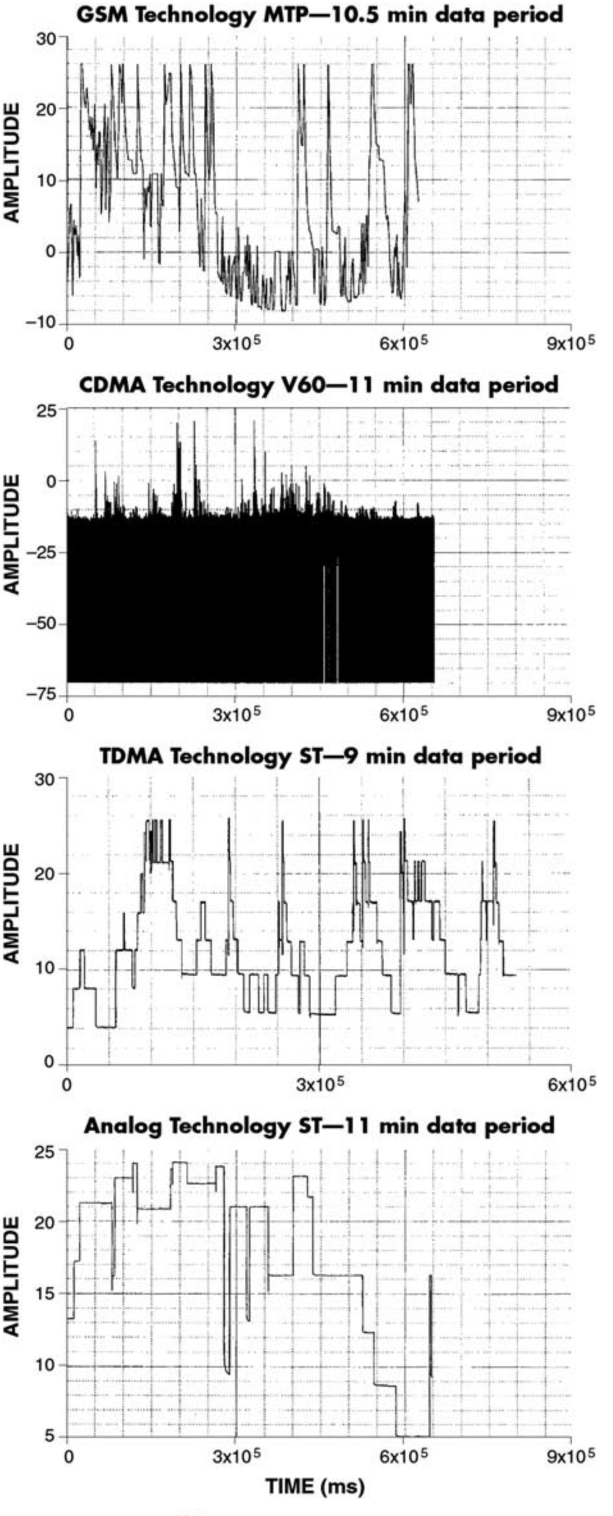
[b] Refers to type of driving routes where data were collected: rural, suburban, urban.

We evaluated potential RF output differences for three different GSM models (Motorola V60 (Flip), Motorola Timeport (candy bar), and Nokia 5190 (candy bar), to assess whether phone design or model affected RF output levels. The mean and median RF output levels were similar across the three phones from two manufacturers, although the Nokia model had somewhat higher variability (Table 7). For CDMA technology, the Motorola StarTac had a higher mean value than either the Nokia model or the Motorola V60 model.

RF output levels varied depending on whether the van was stopped or moving. To address this issue, data were collected at a fixed location in the rural and suburban routes (with the van stopped for 3–4 min). We were unable to collect this type of stationary data on the urban route due to difficulties in finding a stopping location that would always be available. Overall, we observed more variability in RF levels when the van was moving than when it was stationary (Table 8). For all technologies, values were slightly higher when the phantom was moving, but these differences were generally modest and were not statistically significant, except for the TDMA technology data collected during a rural route (Table 8). No TDMA data were available for the suburban route.

The comparison of software-modified phones' RF output characteristics and the SYNEHA system data was restricted to GSM technology, because this was the only system for which we had both types of data and for which software-modified phones are currently available. The two average summary measures (overall time-weighted average and average of the peak exposures for each 120-ms period) calculated from SYNEHA systems were roughly an order of magnitude different for GSM phones (Table 9). PWC levels (from software-modified phones) correlated closely with average maximum or peak output power levels calculated from the SYNEHA system (Table 9). The correlation coefficients were almost always statistically significant.

Although the experimental design was not structured to formally examine time-of-day effects, because we did not stratify our data collection efforts by time of day, we did


GSM Technology MTP—10.5 min data period

CDMA Technology V60—11 min data period

TDMA Technology ST—9 min data period

Analog Technology ST—11 min data period

Note:
X-axis major tic marks = 5 min
X-axis minor tic marks = 1 min

Figure 2. Sample SYNHEA RF output data (dB) for GSM, CDMA, TDMA, and Analog mobile phone technologies collected over 9–11 min data collection periods.

Table 7. Average of peak measures of RF power output (dBm) over 120-ms intervals by GSM phone model, and 1.2-ms intervals for CDMS phone models for all types of routes (urban, suburban, and rural)[a].

	GSM Technolgy			CDMA Technology		
	Motorola V60 (flip)	Timeport (software-modified phone) (candy bar)	Nokia 5190	Motorola Startac	Motorola V60	Nokia 5165
N^b	8	41	8	71	19	2
Mean	24.09	23.84	21.94	2.17	−13.12	−11.06
Median	24.32	24.38	24.22	5.34	−10.50	−11.06
Std. Dev.	0.80	1.66	5.35	8.64	7.74	0.44
Minimum	22.26	19.64	9.67	−25.88	−26.98	−11.37
Maximum	24.71	26.31	25.18	13.74	−3.58	−10.75
Interquartile range	0.66	1.25	3.24	8.92	16.35	0.62

[a] The basic datum is the average over each 120-ms measurement period.

[b] Number of routes (approximately 20 minutes of data collection for each route) by technology and phone type.

Table 8. Comparison of maximum power levels (dB): moving *versus* stationary conditions by route and technology.

	Moving max power				Stopped max power			
	Average	Min	Max	SD	Average	Min	Max	SD
Rural								
Analog	23.68	8.00	29.30	4.37	24.46	23.16	26.31	0.77
CDMA	−16.91	−30.00	26.67	18.40	−23.44	−30.00	24.91	13.87
GSM	22.22	0.00	30.08	6.50	19.63	0.00	30.03	3.41
TDMA	27.11	8.00	35.66	6.35	19.20	11.00	33.13	4.80
Suburban								
Analog	18.32	8.00	24.02	4.28	20.41	8.00	21.12	2.23
CDMA	−23.18	−30.00	26.59	14.34	−23.37	−30.00	22.57	13.84
GSM	17.96	0.00	31.90	8.93	22.35	13.45	30.01	5.79

collect data across the morning, afternoon, and evening periods that allowed us to evaluate potential differences (Figure 3a–c). Our available data suggest higher levels in the morning (0800–0900 hours) in urban and suburban areas, and higher evening levels in the suburban location. Only limited data were collected during the evening (only suburban), and for rural areas, there were no morning or evening data.

Discussion

This study is one of the first of its kind to compare power levels emitted from mobile phones of various model types and technologies (Kuehn et al., 2009). Most exposure assessment research conducted to date has evaluated only the GSM mobile phone technology. We examined four different technologies that have commonly been used in the United States; however, as this research was completed, both TDMA and analog technologies were essentially discontinued, making future evaluations in “normal use” settings not possible. This also posed a challenge to this research effort, because phones that would operate using primarily analog or TDMA were difficult to purchase, and special arrangements had to be made with service providers to set up accounts that would work using these technologies. In fact, TDMA was phased out in the San Francisco Bay Area while this study was being conducted, and final field sampling was conducted without the mobile phones that used TDMA technology. Although no longer in common use, historically, analog and TDMA technologies were more prevalent among US mobile phone users. For epidemiologic purposes, it is also important to compare these historical technologies to current CDMA and GSM services.

We observed that technology was the most important factor determining the levels and variability in RF power output in the mobile phantom heads. Consistent with their technical designs, average and peak power radiated into the phantoms were highest for analog phones and lowest for CDMA phones. We identified the variation in RF output for GSM phones that is apparently attributable to base-station switching as reported earlier (Wiart et al., 2000). We also observed that the highest power levels were observed in rural locations and the lowest in dense urban locations. A similar finding was reported in Swedish communities for GSM technology (Lonn et al., 2004). This result may be due to the lower density of base stations in a rural location *versus* urban locations. Although base-station density of the system is likely not the only source of mobile-phone power output variations. Traffic on the system and high concentrations of tall buildings may also affect the frequency of handovers on GSM systems and affect overall RF power output (Lonn et al., 2004).

A software-modified phone is a type of phone that can replace a person’s usual mobile phone and thus can be used to estimate the user’s RF exposure under “real-life” conditions, and these phones have been used in surveys among volunteer participants (Erdreich et al., 2007; Morrissey, 2007), as well as in several of the INTERPHONE studies (Cardis et al., 2007). The SYNEHA system on the

Table 9. Comparison of software-modified phone power control (PWC) data and SYNEHA RF output data collected simultaneously using SMP and SYNHEA Data Collection System (W).

Route, date	Average power SYNHEA	Average max power SYNHEA	PWC (SMP)
Rural, 10/20/2005	0.027	0.283	0.291
Rural, 11/18/2005	0.054	0.368	0.349
	0.056	0.325	0.323
	0.028	0.250	0.281
Rural, 12/2/2005	0.042	0.261	0.325
	0.030	0.188	0.227
Rural, 3/1/2006	0.054	0.335	0.337
	0.043	0.301	0.304
	0.043	0.304	0.288
	0.049	0.357	0.373
Rural, 6/10/2005	0.030	0.284	0.229
Suburban, 3/2/2006	0.050	0.280	0.285
	0.042	0.258	0.306
	0.017	0.114	0.135
	0.044	0.297	0.330
	0.027	0.183	0.257
	0.034	0.270	0.277
	0.037	0.281	0.301
Suburban, 3/30/2006	0.028	0.263	0.290
Suburban, 3/8/2006	0.035	0.212	0.266
	0.040	0.283	0.304
	0.041	0.264	0.304
	0.026	0.201	0.301
	0.037	0.277	0.301
	0.040	0.270	0.278
	0.033	0.274	0.316
	0.026	0.245	0.261
Urban, 5/26/2005	0.027	0.198	0.112
	0.018	0.171	0.098
	0.026	0.181	0.121
Urban, 5/27/2005	0.028	0.211	0.093
	0.025	0.155	0.063
Summary			
Rural ($n=13$)	0.043	0.307	0.316
Suburban ($n=16$)	0.035	0.252	0.285
Urban ($n=5$)	0.025	0.178	0.090
All ($n=34$)	0.039	0.278	0.292

Results for individual phones and route. Multiple entries for a given date indicate that the route was repeated on that day, for example, for the rural data on18 November 2005 — data were collected three times on the same route.

other hand, requires much more instrumentation to acquire and store data and is not a personal measurement device. Assuming that SYNHEA data are closer to the actual "real-time" RF power output levels from mobile phones, our objective was to determine how well software-modified phone data were correlated to this "gold standard." Our results have shown a strong correlation between average power output level of the software-modified phone and the average of the averages of peak readings from SYNEHA. This correlation was observed despite the different sampling rates (i.e., 2.5 s *versus* 0.256 ms).

We conclude that the software-modified phone may be a feasible tool for exposure assessment in epidemiologic studies. At a minimum, this technology (software-modified phone) or some enhancement of it could be used in validation studies of epidemiology exposure assessment protocols. Currently, the software-modified phone technology is available only for specific models of phones that use the GSM technology and would have to be developed for other technologies (e.g., CDMA, UMTS, 4G, etc.).

Limited data do not permit definitive conclusions on time-of-day effects on power control commands, but they do suggest that, for the GSM system in this region of California, power output control settings were higher in the morning and evening. We observed no significant difference between stationary and moving data for CDMA, GSM, and analog phones, but some differences were observed for the TDMA technology.

Our findings have several implications with respect to epidemiologic research. These findings, in particular the comparison of GSM and CDMA technologies, are mainly relevant to studies of US populations where both of these technologies are present. For other areas, such as Europe, Asia, Australia, Latin America, and Africa, GSM technology predominates, and therefore, the exposure implications of different service technologies would not be relevant. However, the GSM system is slowly being replaced by UMTS in Europe, which is a system similar to CDMA in the United States, with equally low average output power levels during normal use (Kuehn and Kuster, 2009). Under the assumption that the cumulative exposure model of RF power output is the exposure metric of interest, the added technology data would seem likely to modify a cumulative exposure assignment that is based solely on information such as duration of use and number of calls. To the extent feasible, especially in studies conducted in the US, researchers should collect data from network service providers as part of exposure assessment protocols.

The type of location (urban, suburban, rural) where the phone is predominantly used also appears to influence power levels across the different technologies; therefore, such location data would capture additional exposure information that could improve the precision of exposure assessment for epidemiological research. For unexplained reasons, specific geographic regions also appear to modify RF power output levels; this phenomenon has been reported in studies that recruited volunteers to use the SMP technology for their mobile phone communications (Erdreich et al., 2007; Morrissey, 2007). This implies that the epidemiologic study designs should either focus on a geographical area for which homogeneous power output levels can be assumed, or characterize geographic differences in RF power output levels if a study population includes participants from

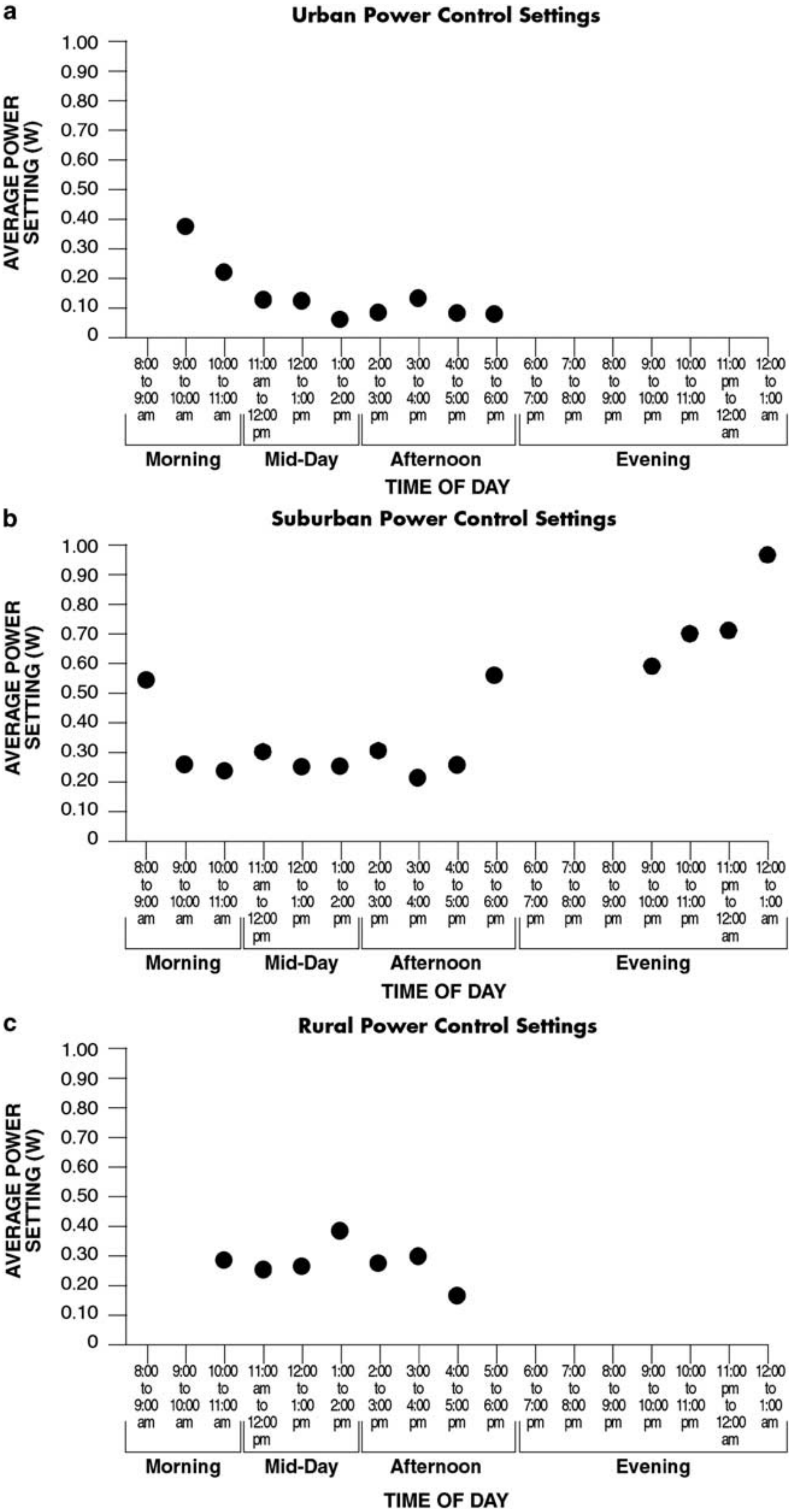


Figure 3. (a) Radiofrequency power output levels (W) collected using software-modified phones by time of call for urban environment data collection area. (b) Radiofrequency power output levels (W) collected using software-modified phones by time of call for suburban environment data collection areas. (c) Radiofrequency power output levels (W) collected using software modified phones by time of call from rural environment data collection area.

different geographical areas. On the other hand, this approach will not be practical for technologies that have been phased out. This is especially true for epidemiologic research on cancer, which typically has long latency periods and will require historical exposure information. In these circumstances, a more generalized modeling approach based on extrapolation from previous studies will be necessary.

Other factors, such as position on the head (tilt or cheek) and side of use, which both likely have significant impacts on local SARs in the brain, could not be evaluated in this study. The development of hardware-modified phones should facilitate collection of these types of data and help to determine variation in RF exposure due to these behavioral differences. An analysis of available Federal Communications Commission (FCC) testing data indicates that the position of the phone relative to one's head is an important exposure predictor, but there are no data available to determine how this varies across mobile phone users (Kuehn et al., in preparation). Also of potential importance in RF exposure assessment is the issue of evaluating tissue-specific exposures. The peak spatial average SAR assessed during compliance testing of mobile phones is potentially misleading when used as proxy for tissue-specic exposure due to the large variability of exposure among different tissues. This suggests that future research should focus on the estimation of brain region-specic exposure based on volumetric SAR measurements in homogeneous media.

Another obvious factor that will affect RF exposures to the head is the use of hands-free technologies, which move the phone device away from the head. As society and technology move toward more uses of mobile phone devices (e.g., text messaging, web browsing, gaming, and video viewing), such uses will affect estimation of RF exposure to the head region and make interpretation of billing records information as a proxy for RF exposure much more difficult.

Our results, and epidemiologic research to date, reflect primarily mobile phone exposures to the head region. Future studies of health and wireless technologies will need to factor in behavioral changes associated with the use of wireless technologies. For historical purposes, our data suggest that additional efforts to obtain information on service technology and regional variation in RF power output will improve exposure classification.

Conflict of interest

This research was conducted through a collaborative research agreement (CRADA) between FDA and CTIA, a non-profit organization of the wireless communications industry. Technical oversight was provided solely by the FDA staff and an independent Scientific Advisory Panel. CTIA funded the work but was not involved in study methodology, data acquisition, analysis, interpretation, or manuscript preparation. Several authors have provided research and consulting services for mobile phone manufacturers, service providers, and governmental bodies on unrelated projects.

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