Section 5

Assessment of Radiofrequency Exposure to the General Public

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Summary

- Use of radiofrequency field (RF) emitting devices near the body (in the near-field) increases personal exposures. The highest typical personal exposure to RF is from the use of a mobile phone at the head. The most important contributor to the intensity of this exposure is the type of technology (e.g., Global System for Mobile Communications (GSM) output power levels are several times higher than Code Division Multiple Access (CDMA) levels in the field).

- Additional engineering factors that affect output power levels of mobile phones and other RF emitting devices include adaptive or power control, duty cycle, frequency, and size of antenna.

- Environmental factors that affect the intensity of exposure of mobile phones include location (indoors vs. outdoors, urban vs. rural, presence of buildings/obstacles) and being in transit, particularly in buses and trains.

- Once in the far field of local RF-emitting devices, the exposure levels decrease substantially with increasing distance (inverse square law), but levels are affected by reflections from buildings and other obstacles.

- Ambient exposures, which are natural and man-made environmental exposures the general public may receive even when not directly using RF devices, are several orders of magnitude (up to millions of times) lower than exposures received when using a mobile phone at the head. Exposure from mobile phones and DECT cordless phones (even when not in use), FM broadcasting, and microwave ovens can be important contributors to background exposure to RF.

- Although most studies indicate that personal exposures to RF from individual sources are low (below exposure limits), the increasing number of sources in combination with increasing duration of use may potentially increase total exposures over time, offset to some extent by improvements in technology. Continued assessment of new and emerging technologies, as well as of overall personal exposures to RF sources, will be useful in determining trends over time.

5.1 Introduction

In addition to low levels of exposure to natural sources of RF, principally from sunlight, exposure to electric and magnetic fields from man-made sources of RF such as radio and television transmitters and mobile communications is almost universal. Accurate assessment of exposure is critical in determining exposure-response relationships in epidemiological studies on the health effects of RF. Surrogates of exposure to RF from mobile phone use obtained by surveys are most commonly simple estimates of hours/minutes or number of calls over a specific period of time. These indices are usually obtained by questionnaire or interviews in observational studies. In addition to assessment of time by duration and frequency of occurrence, assessment of intensity (output power in the case of RF) is an important exposure index.

In assessing intensity of exposure, an understanding of possible biological mechanisms informs the exposure assessment strategy. Biological models for how exposure might affect disease outcomes include cumulative, threshold, repetition, and rate of change models. Most epidemiological studies derive exposure assuming a cumulative exposure model (using total duration of calls as a measure of exposure) or a repetition model (number of events of RF exposure). But a criticism of using cumulative or repetition models is that they do not differentiate between low intensity and high intensity exposures. For example, using a cumulative model would not be appropriate when assessing temperature and duration of immersing a hand in water, as health effects would be expected at 100°C for one minute but not at 20°C for five minutes, even though the cumulative exposure would be the same.

Also affecting intensity of exposure is the fact that RF can be reflected, absorbed and transmitted. RF at frequencies used in telecommunications penetrates into the body tissues for a few centimetres. Energy is not deposited uniformly throughout the body and RF becomes less penetrating into body tissues as the frequency increases.[1]

The objective of this section is to compare exposure measurements for various RF emitting devices, describe what factors affect exposure, and determine the typical daily exposures to RF experienced by the general population.

The type of data collected in exposure studies include output power of sources usually in units of watts (W) or decibels in the logarithmic scale referenced to 1 mW (dBm) and electric field strength in units of Volts per meter (V/m) or power density (W/m^2), at specified distances in the far field. Absorption into body tissues is proportional to output power (W), power density is proportional to output power, and electric field strength is proportional to the square root of output power.[2] However, for near field exposures from devices held close to the body like mobile phones or tablet PCs, power density and electric field strength measures do not apply and instead, Specific Absorption Rate (SAR) is calculated in W/kg as a dosimetric measure.

When reviewing the exposure data from these studies, reference can be made to the exposure limits for total exposures and for various RF frequencies (see Section 13).

5.2 Methods

The literature search strategy for the “exposure assessment” of RFs was carried out using the EBSCO, OvidSP, and Embase databases. EBSCO databases were searched first in stages, with each search expanding upon the previous key terms and phrases. The results were then compared to determine whether or not the additional terms aided in the precision of the results. It was found that phrases such as “exposure assessment” and strings of words such as (radiofrequency OR radio-frequency OR “RF” OR electromagnetic fields) proved effective in retrieving relevant results. Once the search terminology was established and a large collection of relevant sources was collected in EBSCO, the searches were essentially replicated in OvidSP and Embase, although little additional material was uncovered. As a final check, World Cat was searched using the broad term "electromagnetic frequency" to scan for additional articles, and a small selection of articles were added.

Suggested search terms:

Exposure assessment	Radiofrequency	RF-emitting devices
"exposure assessment"	radiofrequency OR radio-frequency OR RF OR electromagnetic fields	cell* phone* OR cellular mobile phone* OR wi-fi OR wifi, wireless OR wireless internet OR microwave* OR "smart meter"OR "base stations"

Sixty-four abstracts were originally reviewed. Criteria for inclusion were papers which included measurements of RF sources and/or mention of factors that affected exposure in terms of output power, power density or SAR. Of those 64 abstracts, 22 were deemed relevant and retrieved articles were reviewed in their entirety. Papers were back referenced to identify an additional 15 articles. For the most part, only recent literature published after 2005 was considered.

To enable comparison, we attempted to use the same units to describe output power in Watts (W), power density (mW/cm^2), and SAR (W/kg averaged over 10g[1]). We converted electric field strengths V/m to mW/cm^2 using an RF calculator.[6] We also converted all power density measurements to mW/cm^2 to enable comparisons. For example, 1 mW/m^2 was divided by 10,000 to convert to 0.0001 mW/cm^2. The values in mW/cm^2 can then be compared to Health Canada Safety Code 6 limits (e.g., for microwave frequencies of 2.4 GHz, the limit is 1 mW/cm^2). Where conversions were not possible, we have noted the original units in the table of results (Tables 1 and 2).

[1] In Europe, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) SAR guideline[3] is 2 W/kg averaged over 10 g for localized head and trunk, whereas the Federal Communications Commission (FCC) and Health Canada uses 1.6 W/kg averaged over 1 g for head and trunk.[4,5] As all studies were conducted outside of North America, SAR was often reported as averaged over 10 g.

5.3 Results

The exposure studies were categorized into three major types:

1) **Source measurements in the field.** These studies used either spectrum analyzers or phantom models brought into the field. In the case of mobile phones, occasionally, dose phones (software modified phones) were sometimes used to collect power control levels that serve as surrogates for actual output power levels.

2) **Source measurements in the laboratory.** SAR measurements were ascertained in the laboratory using either real devices or antennas emitting at frequencies that were relevant to RF emitting devices.

3) **Personal exposure or area measurements.** For personal exposure assessment, total RF measurements were obtained by using dosimeters and daily logs to determine probable sources. For area measurements, a spectrum analyzer was placed in different locations to determine ambient exposure.

Table 1 provides measurements from recent studies of output power levels or power densities of RF for specific sources. The RF devices include wireless phones and phone technologies, wireless local area networks, Smart Meters, mobile phone base stations and other sources (e.g., microwave ovens, radio/TV broadcasting). The units for output power are consistently given as mW. Power density units are mW/cm^2 unless specified as V/m. Note for all the tables that because the methods of exposure assessment vary somewhat between studies, the values can be compared for different exposure devices within a study, but not between studies.

Table 1. RF output power and power density levels for specific sources of RF*

RF Source	Frequency	Location; Distance	RF Power Output (mW)	RF Power Density (mW/cm^2)	Reference
WIRELESS PHONES					
Mobile phone	900 MHz, 1800 MHz	California; At ear during call		1-5	Electric Power Research Institute (EPRI) (2011)[7]
Analog	850 MHz	California; At ear of phantom	171.4 (overall average)		Kelsh et al. (2011)[8]
TDMA	850 MHz	California; At ear of phantom	66.53 (overall average)		Kelsh et al. (2011)[8]
GSM	1900 MHz	California; At ear of phantom	25.76 (overall average)		Kelsh et al. (2011)[8]

RF Source	Frequency	Location; Distance	RF Power Output (mW)	RF Power Density (mW/cm^2)	Reference
GSM software modified phones	1900 MHz	California; At ear of phantom Rural Suburban Urban	43 (average) 35 (average) 25 (average)		Kelsh et al. (2011)[8]
GSM (ambient, not during use)	900 MHz	Urban (Basel) Rural (Bubendorf)		0.16 V/m (avg, urban) 0.10 V/m (avg, rural)	Burgi et al. (2008)[9]
GSM (ambient, not during use)	1800 MHz	Urban (Basel) Rural (Bubendorf)		0.42V/m (avg, urban) 0.04 V/m (avg, rural)	Burgi et al. (2008)[9]
UMTS (ambient, not during use)		Rural (Bubendorf)		0.02 V/m (avg., rural)	Burgi et al. (2008)[9]
WCDMA (used in UMTS networks in Europe)		Europe; At ear	Big City – 0.2 Small City – 0.4 Buildings – city 1.1 Market Centers – 5 City Driving – 0.15 Highway – 0.3 Outdoor – < 1 Indoor – < 5		Gati et al. (2009)[10]
DECT phones	1.9 GHz	At base station or handset: 1 vs. 6 calls	Station: 10; 60 At Handset: 10; 10 Idle Station: 2.5		Swiss Federal Office of Public Health (FOPH) (2011)[11]
WIRELESS LOCAL AREA NETWORK					
WLAN	2.4-5 GHz	California; 3 feet		0.0002-0.001 0.000005-0.0002	EPRI (2012)[7]
WiFi (laptop)	2.4 GHz	US, France, Germany, Sweden; 1 m		0.004 (maximum time-averaged – integrated power density 70-3000 MHz)	Foster (2007)[12]
WiFi laptops and access points	2.4 GHz	UK; 0.5 to 1.9 m in 10 cm steps	Spherically integrated radiation power (IRP): laptops – 5-17 access points – 3 to 28	Laptops: 0.0022- 0.000013- (max) Access points: 0.0087- 0.00022-	Peyman et al. (2011)[2]
WiFi laptops and access points	5 GHz	UK; 0.5 to 1.9 m in 10 cm steps	Spherically integrated radiation power (IRP): laptops – 1 to 16 access points – 3 to 29		Peyman et al. (2011)[2]

RF Source	Frequency	Location; Distance	RF Power Output (mW)	RF Power Density (mW/cm^2)	Reference
WiFi laptops and access points	2.4 GHz	UK; 1 m	Laptops: 17-57 Access points: 16-229	Laptops: 0.0002-0.0005 Access points: 0.0001-0.0018	Peyman et al. (2011)[2]
WiFi laptops and access points	5 GHz	UK; 1.5 m	Laptops: 5-45 Access points: 17-165	Laptops: 0.00002-0.0002 Access points: 0.0001-0.0006	Peyman et al. (2011)[2]
SMART METERS					
Smart Meters	900 MHz, 2400 MHz	California; 3 feet		0.0001 (250 mW, 1% duty cycle) 0.002 (1 W, 5% duty cycle)	EPRI (2011)[7]
Smart Meters	900 MHz, 2400 MHz	California; 10 feet		0.000009 (250 MW, 1% duty cycle) 0.002 (1 W, 5% duty cycle)	EPRI (2011)[7]
Smart Meters	900 MHz (RF LAN) 2400 MHz (HAN Transmitter) Cell relay 850 MHz Cell relay 1900 MHz	California; Power output at surface (not taking into account duty cycle)	126 (0.5th %ile) 257 (50th %ile) 398 (99.5 %ile) 39.8 (0.5th %ile) to 114.6 (99.5 %ile) 1514 (max, GSM) 326 (max, CDMA) 741 (max, GSM) 305 (max, CDMA)		Tell et al. (2012)[13]
Smart Meters	900 MHz	BC; 30 cm 1 m 3 m (0.07% duty cycle)		0.0032 0.002.02 0.001.17 (one active Smart Meter)	British Columbia Centre for Disease Control (2012)[14]
MOBILE PHONE BASE STATIONS					
Mobile base stations		Germany; Different distances		3x10E-10- 0.07152	Bornkessel (2011)[15]
Mobile phone base station	900 MHz, 1800 MHz	Germany; 10s to a few thousand feet		0.000005-0.002	EPRI (2011)[7]
GSM Mobile phone base station (simulated)	900 MHz	Germany; 49-704 m		3.4x10E-09-0.000783	Bornkessel et al. (2007)[16]
UMTS base station (simulated)	2100 MHz	Germany; 49-704 m		1x10E-08- 0.00693	Bornkessel et al. (2007)[16]

RF Source	Frequency	Location; Distance	RF Power Output (mW)	RF Power Density (mW/cm^2)	Reference
GSM WCDMA WiMAX Base stations	Wideband spectrum 75 MHz– 3 GHz	Saudi Arabia 10 m to peak distance of 39–501 m	60 base stations worst case: 21.96 (wideband)	Most values: GSM900: 1 x10E-8 to 1 x 10E-7: GSM1800 & UMTS: 1 x 10E-9 to 1 x10E-8	Alhekail et al. (2012)[17]
OTHER SOURCES					
Microwave ovens	2450 MHz	California; 2 inches; 2 feet		5 0.05–0.2	EPRI (2011)[7]
Microwave ovens	2450 MHz	<5 cm		New: 0.08 (avg) Old: 50% <0.062, 0.17, 0.41 (avg)	Alhekail (2001)[18]; Matthes (1992)[19]; Thansandote (2000)[20]
Radio/TV broadcast station	Wide spectrum	Far from source (in most cases)		0.001 (highest 1% of population) 0.000005 (50% of population)	EPRI (2011)[7]
FM radio		Urban (Basel) Rural (Bubendorf)		0.03 V/m (avg, urban) 0.02 V/m (avg, rural)	Burgi et al. (2008)[9]
Digital Audio Broadcasting		Urban (Basel) Rural (Bubendorf)		0.00 V/m (avg, urban) 0.00 V/m (avg, rural)	Burgi et al. (2008)[9]
TV		Urban (Basel) Rural (Bubendorf)		0.03 V/m (avg, urban) 0.04 V/m (avg, rural)	Burgi et al. (2008)[9]

5.3.1 Mobile phones

The bulk of the scientific literature on RF exposure assessment has been on mobile phones. The currents and charges on the metal parts of the mobile phone form the reactive near-field (5 cm for 900 MHz, 2.5 cm for 1900 MHz).[21] Cellular networks are designed to operate so that the voice quality of one channel (one frequency) is limited by the interference of other signals using the same frequency in other parts of the cellular systems.[21] For current mobile phones, the network uses power control or adaptive control, which reduces RF power to a minimum level compatible with voice quality for a conversation.[21]

Many factors can change the intensity of exposure including technology, location, transit, and usage of the phone.

5.3.1.1 Technology

The type of technology appears to be the most important variable in explaining differences in intensity of exposure of mobile phones. In the early 1980s, first generation (1G) analog phones were introduced using a FDMA (frequency division multiplexing access) where frequency was modulated to communicate between the mobile phone and base station. Second generation (2G) phones were introduced in the 1990s with TDMA (time division multiple access) or CDMA (code division multiple access) technology. In TDMA technology, the channel can be shared by establishing time slots assigned to each user. Global System for Mobile Communications (GSM, based on TDMA technology) uses eight slots. The assignment of one slot per user gives rise to the pulsed nature of the wave; for example, a GSM phone will only be transmitting for 1/8th of the transmission time (1/8th duty cycle).[11] CDMA uses a different code to allow for multiple users to use the same channel, and therefore the transmission is continuous.

Third generation phones (3G) include Universal Mobile Telecommunications System (UMTS) wide-band CDMA (WCDMA) and High Speed Downlink Packet Access (HSDPA). Many of the phones in use today are considered 3.5 G, meaning the phones have additional data streaming features but use a 3G network (e.g., smartphones).[22] Some networks have started converting over to 4th generation (4G) networks which will allow 4G phones to be better able to stream more data faster, providing a mobile broadband version of a laptop computer. The 4G technologies include Long Term Evolution (LTE), and WiMAX (Worldwide Interoperability for Microwave Access), which are based on FDMA-type technologies

The output power of mobile phones is described as peak output power, maximum output power, or actual output power. Peak output power is the phone's maximum possible power level, whereas maximum output power is the phone's maximum power level within a network. For instance, the peak output power of GSM can be 1W or 2W, but because GSM only transmits for ⅛th of the call time and every 26th pulse is omitted, the maximum output power is 120 mW or 240 mW.[11] For CDMA and UMTS technologies, the transmission is continuous, and therefore the peak and maximum output power are the same at 250 mW.

Actual output power is usually lower than maximum output power due to adaptive or power control (which reduces RF power of mobile phones to a minimum level compatible with voice quality for a conversation).[21] Some studies report that adaptive control for GSM phones can decrease RF output by 50% of the maximum output power levels.[23,24] In the German Mobile Telecommunication Programme study, GSM operation produced average output power levels between 10 and 70% of maximum output power and maximum output power was only reached during 5 to 30% of the call time.[15] Discontinuous transmission (DTX) in GSM technology, which allows for transmission only during speaking, can also decrease output power levels by 30%.[23,24] Similarly, with

CDMA or WCDMA technology, when the user is not speaking, the mobile phone runs at ½ or ⅛ of maximum output power.[25]

Mobile phones using different technologies and frequency bands have different peak output power. For instance, in a study of 1G and 2G phones, the phones that were used had a range of nominal peak output power levels ranging from 250 mW to 2 W, but in real-world scenarios, the average power levels were much lower (Table 1, Figure 1).[8] In this study, analog technology produced the highest average power levels, followed by TDMA, GSM, and CDMA. CDMA produces RF up to hundreds of times lower than the other technologies.[8] The output power of UMTS 3G mobile phones was a hundred times lower than that of GSM phones in one study.[26]

The reason analogue phones (which are no longer in use) produced the highest RF output power levels is related to the fact that no power control was available and they were always operating at maximum power. The 2G and newer technologies all utilize power control. GSM has some unique features that make it different from the other technologies in that the phone transmits at peak power each time there is a handover of the signal from one base station to another ("hard" handover); as a result, the more handovers there are (such as might be experienced by driving or moving quickly), the higher total number of peaks and average power.[15] Due to this handover phenomenon for GSM phones, very short calls can produce higher average output power levels because the first connection to the base station occurs at maximum power before dropping to a lower power level.[27]

CDMA technology was originally developed by the US military to transmit near background levels of RF.[28] Therefore in real-world scenarios, it transmits the lowest level of power of the 1G and 2G technologies.[8] CDMA in Canadian systems has a power control of 800 times per second.[29] WCDMA (3G) technology used in UMTS networks in Europe uses even faster power control at a rate of 1500 Hz instead of GSM which varies at a rate of 16.6 Hz (once every 60 ms). This faster power control means that WCDMA and CDMA devices can connect with more than one base station at a time during a handover ("soft" handover) so they can avoid maximum power emissions when handover occurs.[10]

5.3.1.2 Hands-free kits

Hands free kits, such as wired headsets, are effective in reducing exposure to RF. For example, SAR at the head when using a headset was found to be 8–20 times lower than when making calls holding the phone to the ear.[30] Kuhn et al. confirmed the findings but notes the possibility of localized exposure enhancement due to EMF from the electrical part of the device in the ear.[31]

5.3.1.3 Location

Study location is an important predictor of exposure.[24,32] Studies have shown that output power levels of mobile phones used in rural areas are higher than in urban areas, likely due to lower base station densities in rural locations.[8,10] Presence of obstacles such as buildings impact RF.[9] Average emitted power is usually greater indoors compared to outdoors as building features interfere with signals.[10,33]

5.3.1.4 Transit

For GSM mobile phones, being in motion while in a car or other mode of transportation tends to increase average output power as handovers are characterized by maximum peaks.[8,34] CDMA phones utilize soft handovers and therefore movement does not influence the output power of CDMA as much (as long as base stations are available for handovers).[8] However, for UMTS phones, moving was observed to increase output power.[11,26] Some studies show that being in transit (particularly in trains or buses) produces the highest total ambient field exposures,[33] which is likely due to the GSM handover phenomenon, but may also be due to the high use of wireless devices on trains and buses.

5.3.1.5 Other factors

One study showed that for data transfer there is up to a four times increase in output power than for voice for wCDMA technology. However, while the output power increases during data transfer, distancing of the phone from the body (e.g.,10 cm away from the head) attenuates the exposure.[10] Other research on UMTS phones has shown that data upload can produce output power levels that are about 30 times higher than a stationary call (and about 14 times higher than a moving call). Also, mobile phones continue to transmit when on, but not in active use. GSM phones transmit once every 12–240 minutes and UMTS once every 5–720 minutes.[11]

Different models of phones using the same technology do not show substantial differences in output power, particularly in comparison to technology or urban/city differences.[8,24]

5.3.1.6 Specific Absorption Rates (SAR) of mobile phones

Dosimetry is used to evaluate the induced electric fields in the body from exposure to near-field RF sources through either experimental modelling or numerical calculation of SAR in Watts per kilogram. For frequencies higher than 100 kHz, such as RF from mobile phones, the SAR links the strength of exposure of an external RF field (power density) to the effect of a temperature rise inside the body due to vibration of molecules.[1] Before mobile phone models are permitted for sale, SAR testing is required by agencies like International Commission on Non-Ionizing Radiation Protection (ICNIRP) in Europe and Federal Communications Commission (FCC) in the US to ensure that phones do not expose the general public to levels above safety guidelines. SAR measured for compliance consists of forcing phones to maximum output power and measuring the SAR in phantom heads (models of human heads with similar dielectric properties of the human head). When CDMA phones are forced to maximum output power, the SAR surpasses GSM and TDMA phones.[26] However, in the field CDMA transmits power on average hundreds of times lower than the nominal maximum output power level.[8] Therefore compliance testing evaluates the worst-case exposures from mobile phones, which can be substantially lower in real-world scenarios.

Some of the studies that were reviewed measured SAR by simulating maximum output power levels in specific frequency bands (representing RF devices but not using the actual devices in the studies) at the head or body. In these worst-case scenarios, SAR levels were often above current standards.[35,36] However, several studies have attempted to evaluate more realistic SAR using phantom heads and whole body models in the laboratory, and several factors have been shown to influence SAR. Distance of the RF source from the head is an important factor to consider. The absorbed power for a mobile phone placed 10 cm from the head decreases more than 10 times than when it is held close to the ear. At 40 cm from the head, the maximum SAR over 10g is close to 1% of the SAR obtained by touching the phone to the head [10]

Lower frequency RF tends to penetrate more deeply into brain tissue. A study by Kuhn et al. (2009) showed that average peak SAR of phones from the FCC database at 1900 MHz were lower than those at 850 MHz.[26] Another study by Togashi et al. (2008) showed that a fetus averaged SAR and fetal brain averaged SAR exposed to mobile radio terminal RF at 900 MHz were more than five times higher than those at 2 GHz.[38] However, there are two resonance frequency ranges where more absorption in tissue occurs: between 2100–2400 MHz there is greater RF absorption at the skin, whereas at a lower resonance frequency of ~100 MHz, RF is absorbed more in the muscle and fat, resulting in higher SAR values in these regions.[37]

Whole body exposure at frequencies in the range of 80 to 180 MHz and 1–4 GHz to ICNIRP reference exposure levels may expose children and small persons (shorter than 1.3 m) to above acceptable ICNIRP SAR levels.[15] A 2010 study by Christ et al. on GSM phones did not find differences for peak spatial SAR (defined as the maximum value of SAR averaged over 10 g) between an adult head model and children models (3, 6, and 11 year old).[39] However, local SAR (without spatial 10 g averaging) for children showed higher exposure of some tissues and organs such as sub-regions of the brain (cortex, hippocampus and hypothalamus) and in the eye due to closer distance to the phone, whereas other head regions were lower than adults. A large increase in induced fields for children's bone marrow was attributed to its higher conductivity compared with that of adults.[39]

In Table 2, representative SAR values are given for wireless phones, WLAN and other sources of RF. The assessment of SAR depends on the performance of the electric field probe, the phantom dimensions, the dielectric properties of the tissue used and the exposure conditions. Typically, a 30% expanded uncertainty is reported for mobile phone SAR measurements.[1] Values found are not directly comparable between studies due to differences in methodology, including type of antenna used and characteristics of the phantom model.

Table 2. SAR values for specific source of RF

RF Source	Frequency	Distance	Description	SAR (10 g W/kg)	Reference
WIRELESS PHONES					
Smart phones & mobile phones	GSM 900, GSM 1800, UMTS		140 phones Left and right ear of head model	0.168–1.61 Median: 0.817	Bornkessel (2011)[15]
Simulated mobile phones systems	900 MHz at 1 W	40 mm & 10 mm	half-wave dipole antennas & planar inverted F antenna	Fetus 1.2–1.4, Fetal brain 1.8–2.9 Mother 0.8–1.1 (estimates from graph)	Togashi et al. (2009)[38]
Simulated mobile phones systems	2 GHz at 1 W	40 mm & 10 mm	half-wave dipole antennas & planar inverted F antenna	Fetus 0.1–0.25, Fetal brain 0.05–1.5 Mother 0.2–1.0 (estimates from graph)	Togashi et al. (2009)[38]
Simulated mobile phone	1850 MHz	125 mW, at head	10-year old child phantom and adult	Child: 0.596 (10g); 0.885 (1g) Adult: 0.362 (10 g 0.527 (1 g)	De Salles et al. (2006)[35]
Simulated mobile phone	850 MHz	600 mW, at head	10-year old child phantom and adult	Child: 2.05 (10 g); 2.89 (1 g) Adult: 1.7 (10 g); 1.8 (1 g)	De Salles et al. (2006)[35]
Cordless phones (DECT)	1880–1900 MHz		4 handsets	0.01 to 0.05	FOPH (2011)[11]
WIRELESS LOCAL AREA NETWORK					
WLAN	2, 4 GHz	Worst case	Using maximum output power and data rate; Using ISEE 802.11g	Access point: 0.27 PC card: 0.11	Kuhn cited in FOPH (2011)
WiFi (laptop)	2.4 GHz	34 cm	Using inverted F antenna operating at peak power of 100 mW, duty factor of 1, highest localized SAR at head	0.0057 head	Findlay et al. (2010)[36]

RF Source	Frequency	Distance	Description	SAR (10 g W/kg)	Reference
OTHER SOURCES					
Microwave ovens	2450 MHz	<0.1 cm 5 cm 30 cm	With microwave oven emitting at maximum permitted leakage level (5 mW/cm^2 at a distance of 5 cm)	< 0.1 cm: 7.95 5 cm: 0.256 30 cm: 0.0056	Bangay and Zombolas (2003)[40]
Baby monitors	446 MHz	Worse case	Devices at 500 mW peak power continuously	0.08	FOPH (2011)[11]
	863	Worst case	10 mW peak power continuously	0.01	FOPH (2011)[11]
Simulated Portable radio terminal	900 and 2000 MHz			0.007 and 0.0004 (peak fetus 10 g SAR, right arm, −60°)	Akimoto et al. (2010)[41]

*values estimated from bar chart (Figure 8)[38]

5.3.2 Cordless phones

Cordless phones are wireless handsets that communicate with a base station connected to a fixed telephone line. Multiple frequency bands exist, with the most common in North America being 900 MHz, 1900 MHz, 2.4 GHz, and 5.8 GHz. Digital Enhanced Cordless Telecommunications (DECT) phones, which utilize the 1900 MHz band, are most commonly used in Europe and are also used in North America. As most of the RF exposure literature originates in Europe, only data for DECT cordless phones are reported here.

DECT phones produce pulsed emissions. A 10 millisecond frame is divided into 24 time slots. When a call is in progress, a handset transmits during one of these slots and receives a signal from the base station during a timeslot 5 milliseconds later. The base station can communicate with up to six handsets at a time. When no calls are in progress, the base station transmits a brief pulse every 10 milliseconds. In certain models, the base station never transmits when the handset is placed in the cradle.[11] The peak output power for DECT phones is 250 mW, but because the transmission is pulsed, the average output power is lower, typically 2 mW. Cordless phones (DECT) do not usually implement power control like most modern mobile phones, although some energy-efficient models regulate power so that output power decreases when the connection is good.[11] For this reason, SAR from cordless DECT phones can be higher than SAR from UMTS phones (but can be up to five times lower than GSM phones).[42] In a study of six telephone calls, the power at the DECT base was 60 mW and at the handset was 10 mW. In the idle state, the power at the base was 2.5 mW and 0 mW at the handset (Table 1, Figure 1).[11] SAR measurements for four handsets ranged from 0.01 to 0.05 W/kg (Table 2).[11]

5.3.3 Mobile phone base stations

The mobile phone network is divided into "cells," each with its own macrocell base station typically mounted on a rooftop to send and receive radio signals. Output powers are typically of tens of watts and macrocells cover distances from 1 to 10 km. Microcells have output power of up to a few watts and cover several hundred meters. Picocells are used in dense areas such as airport terminals and shopping centers and have output powers of up to 100 mW. Public exposure from mobile phone base stations is much lower than that from mobile phone use. One of the largest studies of GSM and UMTS base stations was performed in Bavaria in Germany, and showed that the median level was at 1.2% of the ICNIRP guidelines with the maximum emission being 0.072 mW/cm^2 (corresponding to 7.8% of the ICNIRP guidelines).[15] Studies have shown that using distance from a base station as a surrogate of exposure is inaccurate. As the antenna does not radiate uniformly, there is a main lobe with side lobes of RF and null areas. As many base stations are located well above ground level, the areas immediately adjacent to the base station may be in null areas, such as the case with a study where the lowest power density levels from a base station installed 30 m above ground were at 80 m and highest levels of power density were at 230 m from the station.[15] Better predictors of exposure are orientation of the main lobe and line-of-sight conditions.[16]

5.3.4 Wireless Local Area Networks (WLAN)

WLAN allows devices to connect wirelessly with a central hub. WLAN has a maximum transmission power between 100–200 mW and primarily operates at 2.4–2.4835 GHz, although some operate at 5.15–5.825 GHz. "Terminals" consist of laptop computers and other devices and the point of entry to the wired network is an "access point" usually located within tens of meters of the terminals in the same building.[2] Wireless Fidelity (WiFi) networks, which are types of WLAN, transmit bursts or "pulses" of RF.[12] Worldwide Interoperability for Microwave Access communication technology (WiMAX) is essentially a larger version of a WiFi network. Through the use of orthogonal frequency division multiple access (OFDMA), it operates on a larger scale with multiple overlapping access points and has a range of many square miles.

With the small size of antennas inside laptops and other WiFi devices the distance to the far field (where exposure attenuates rapidly) is relatively short.[2] For example, if the antennas are 5–10 cm in size, radiating near field extends to no more than 16 cm at 2.4 GHz and 33 cm for 5 GHz.[2]

Although, WLAN antennas would ideally radiate omnidirectionally, often they radiate in certain directions with nulls in others. Therefore, the extent to which the radiated power is directed toward a user is useful for understanding exposure. One study showed that antennas in laptops are oriented such that most of the RF irradiates along the screen and up away from the body.[2] Most WiFi devices have several antennas which allow for switching of individual bursts to the appropriate antenna for optimal performance. Due to the different locations of antenna in the device, the radiation pattern can change depending on which antenna is in use.[2]

For WLAN devices, the duty cycle increases when data are transmitted and depends on the rate of data transmission.[2] Even when no data are being transmitted, the access point transmits a signal (beacon) lasting 0.5 ms every 100 ms to allow devices to synchronize with it.[11] For transmission of a beacon, the average output power is 0.5 mW, but for a large amount of data, the mean output power can be up to 70 mW.[11] For the same data rate, however, a higher order of modulation (more bits encoded per symbol) reduces the duty cycle, leading to lower exposure. In addition, maximum data rates can be achieved when WiFi devices are close to the access point, but rates fall with increasing distance, being affected by reflections from surrounding objects and network congestion.[2]

Field strengths are higher from access points compared to terminal devices. In the Peyman et al. study (2011),[2] the field strength of the access points was almost double that of the laptops. In a study of SAR for access points and PC,[11] values were 0.27 and 0.11 W/kg, respectively, using the Institute of Electrical and Electronics Engineers (IEEE) WLAN g standard (the most common WLAN standard used today).[43]

WLAN hotspots are areas where internet access is available, such as in airports or stations. Access points are usually mounted in ceilings or walls and rarely in floors. The energy emitted from these hotspots has been measured to be much lower than ICNIRP's recommended maximum level of 61 V/m (1 mW/cm^2).[11]

5.3.5 Smart Meters

Smart Meters record consumption of electricity, water, and natural gas and transmit information wirelessly to the utility company for billing purposes.[44] A number of different wireless technologies can be used, including CDMA, LTE and WiFi.[1] There are different types of Smart Meters. Most transmit in the 900 and 2.4 GHz frequency bands and communicate with a utility access point that can be located on transmission line poles that are high above ground or, in the case of a mesh network, at a central residence.[13,44] Smart Meters transmit data several times a day for milliseconds at a time,[13,44] therefore the duty cycles are quite low (0.07% to a peak of 4%).[7,14,44] A number of studies have been conducted measuring the power density of Smart Meters utilizing different assumptions of duty cycle and output power (Tables 1 & 2).

One recent study measured the output power of Smart Meters in a mesh network, which consisted of 500 and 750 residences through which data was transmitted to a single residence collection point that then relayed the network data to the utility. Three different types of transmitters were evaluated: 1) RF Local Area Network (LAN) at 900 MHz which interconnects residences, 2) Home Area Network (HAN) at 2.4–2.5 GHz which interacts with devices and equipment within a residence, and 3) a cell relay (GSM 900 MHz or CDMA 1900 MHz) that serves as the mesh network's collection point, which relays data to the utility.[13] The study differed from previous studies on Smart Meters in that the output power immediately at the surface of the meter was ascertained and no duty cycle was assumed. The authors indicated that readings at the meter surface brought the probe's protective shell into contact with the meter within the reactive near field of the meter antenna which may have led to inaccurate high readings. Even if measurements were inaccurately high, the 99.5th percentile of measurements at the face of the Smart Meters were lower compared to the nominal peak output power of mobile phones (398 mW vs. 2W for GSM at 900 MHz and 115 mW vs. 250 mW for CDMA at 1900 MHz).[13] At 20 cm from the meter, the levels dropped by about 10-fold in most cases.[13] Most other studies conducted their measurements at various distances from the meter and assumed various duty cycles.[7,14,44]

5.3.6 Microwave ovens

Microwave ovens work in the 2.4 GHz band at an output power of between 500–2000 W. A study on 60 new appliances measured an average leakage of 0.08 mW/cm^2. For used appliances, the leakage from three studies (with a total of 339 appliances ranging in age from 0.1 to 23 years) was < 0.062 (for 50% of ovens), 0.17 (average), and 0.41(average) mW/cm^2.[18-20] Worn or dirty door seals, or work door or catch were the more likely causes of leakage RF. In one study of SAR, researchers prepared the microwave oven to leak at the maximum permitted level and measured SAR at 30 cm (whole body exposure) and 5 cm (equivalent to head exposure). The levels were 0.0056 W/kg and 0.256 W/kg, respectively. The only time that ICNIRP recommended levels were exceeded was when the body made direct contact with the operational microwave with doors closed (7.95 W/kg).[40]

5.3.7 Bluetooth

Bluetooth allows for high-frequency (2.4 GHz) voice and data transfers over short distances. For example, it can connect a headset wirelessly to a mobile phone or a laptop to a printer. Bluetooth devices are categorized into three power classes. Most of the Bluetooth devices that come in contact with the body are Class 2 and 3, which are weak and limited in range. Some Bluetooth transmitters are in Class 1, which allows access to the internet and can produce power levels similar to mobile phones. The maximum transmission power of Class 1 is 76 mW compared to 1.9 and 0.8 mW for Class 2 and 3, respectively.[11]

When Bluetooth devices with the same communication profile are in the same area, they automatically communicate with each other. Up to eight devices can link in what is known as a piconet. There is one device that is known as the master (which takes the lead and organizes the data transfer) and the other devices are "slaves." Time slots are assigned to devices, but if several time slots are combined, then the pulse frequency drops to 533 Hz (for three time slots) and 320 Hz (for five time slots). If no data transfer is occurring, the slaves do not transmit but receive a beacon from the master periodically. Since Bluetooth devices switch on and off, they only consume power when transferring data. This produces low frequency magnetic fields of about 1 Hz (beacon) up to several thousand.[11]

Blue tooth devices which transmit in the frequency band of 2.4–2.5 GHz emit RF at a hundred times lower than mobile phones.[42] SAR was measured for two different Bluetooth Universal Serial Bus (USB) plug-in antennas in Class 1 and 2 at maximum data rate and maximum output power, one Class 2 personal digital assistant (PDA), and two different hands-free headsets. SAR levels ranged from 0.00117 to 0.466 W/kg (Table 2).[11] At 20 cm, the electrical field decreased rapidly to about 20–150 times lower than ICNIRP standards (1 mW/cm^2).[11]

5.3.8 Broadcasting

Analogue FM radio and TV broadcasting antennas operate at frequencies from 80 to 800 MHz, and the antennas have output power of 10 to 50 kW. The total power of the newer digital video (DVB) and audio (DAB) broadcasting systems is lower than that for analogue broadcasts. The highest power DVB-T transmitter has an average effective radiated power (ERP) of 200 kW per multiplex, as opposed to the analogue version with 1000 kW ERP per service. While the DAB channel transmitter has an ERP of up to 10 kW, the main VHF FM transmitter ERP is 250 kW per service.

5.3.9 Other RF sources

Wireless mice and keyboards of PCs operate at 20–40 MHz frequency range, lower than other wireless systems; RF is emitted when moving, clicking or typing with the devices.

Baby monitoring systems consist of a baby unit and one or two parent units and operate at a variety of different frequency bands (between 27 to 2400 MHz), which correspond to power and range. Parent units are primarily receivers, but some can transmit and receive. Certain systems have a video monitor, which requires transmission at 2400 MHz. Most baby monitors do not transmit continuously but only when certain sound levels are reached. Some systems test that the parent unit is within range by sending out test signals every few seconds. The SAR for two baby monitors at frequencies of 863 MHz and 446 MHz transmitting at 10 mW and 500 mW were 0.01 and 0.08 W/kg, respectively (Table 2).[11]

Radio-controlled toys such as cars and gliders operate at different frequencies and output powers vary widely. Similarly, RF identification technology such as road tolling and security cards range in frequencies up to 5.8 GHz.[1]

Other personal effects such as metal accessories (including jewellery) can also affect conductivity of RF waves, but based on engineering principles the effect is small.[21]

Natural sources of exposure to RF include the sun, which emits low power densities of less than 0.001 mW/cm^2.[45] Our own bodies emit RF fields from approximately 30 to 300 GHz at 0.0003 mW/cm^2.[46]

5.3.10 Area exposure measurements

Joseph et al. (2012)[47] conducted 30-minute area measurements in 311 locations in three European countries (Belgium, The Netherlands, and Sweden) using a narrowband spectrum analyzer. The average electric field strength for all sources was low at 0.71 V/m (equivalent to 0.000134 mW/cm^2) with GSM 900 and GSM 1800 sources dominating (0.49 and 0.24 V/m, respectively). Higher total values were obtained outdoors compared to indoors because field strengths of mobile phones were not assessed in the study. LTE, UMTS with High Speed Packet Access (HSPA) and DECT and FM were comparable (0.017, 0.16, 0.15, and 0.15 V/m, respectively). In indoor environments, even though DECT results are the second highest (after GSM 900), authors caution that exposures to DECT were overestimated as uplink (mobile phone to base station) traffic was also measured at this frequency band. Average electric field strength for WMAX, which was only available in a few cities in Belgium and The Netherlands, was 0.07 V/m compared to 0.03 V/m for WLAN. LTE and WiMAX are relatively new and not as common as GSM.[47]

5.3.11 Personal Exposure Measurements (PEM)

Real-life exposure measurements from multiple sources have been attempted using personal exposure meters for frequency selective exposure assessment. One study measured source exposures and personal exposures using exposimeters on 166 participants in Basel, Switzerland.[48,49] The mean weekly personal exposure to all RF sources was 0.013 mW/cm^2 when measurements during personal phones calls were excluded and 0.015 mW/cm^2 when they were included.[49] The greatest contributors were mobile phone base stations, mobile phones, and DECT cordless telephones. Mean values were highest in trains, airports, and tramways or buses, and higher in the day than at night.[48]

Viel et al. (2009)[50] conducted personal exposure measurements (PEM) of 377 people in France for 24 hours. The total field mean value was 0.201 V/m (equivalent to 0.0000107 mW/cm^2) with the greatest contributor being FM sources (0.044 V/m), followed by similar readings for WiFi, UMTS mobile phones and cordless phones. Levels were higher in the daytime for GSM uplink (communication from mobile phone to base station) and Digital Cellular Service (also known as GSM 1800) downlink (base station to mobile phone), whereas levels for Tetrapol (walkie-talkies), TV and UMTS were higher during the sleeping hours. The total field was higher outdoors than indoors, which was due to transportation contributing most to the total PEM.[50]

Joseph et al. (2008)[33] conducted PEM for five hours for each of 28 different realistic exposure scenarios (combinations of outdoors/indoors, rural/urban, standstill/moving, night/day) in Ghent, Belgium. The highest outdoor exposures were due to downlink signals of GSM and DCS (up to 0.52 V/m or 0.0000717 mW/cm^2). The authors noted that high indoor exposure can occur from WiFi (up to 0.58 V/m) and DECT (up to 0.33 V/m). Outdoor scenarios with highest maximum values were GSM DL (downlink) and indoors were lower as the signals had to penetrate through building materials. The highest total exposure occurred for train and bus scenarios due to GSM UL (uplink) (up to 1.90 V/m or 0.000959 mW/cm^2) and DCS UL (uplink) (up to 0.44 V/m) exposures, particularly at night. The higher number of handovers from GSM and DCS and higher concentration of people likely meant that more uplink communication was occurring. During the day (outdoors), mostly FM, GSM DL, and DCS DL were present. At night, GSM UL, DCS UL, and DECT were much lower while WiFi was present both day and night with the highest levels at night. FM, TV/DAB, TV, and GSM DL did not differ much when comparing day and night in a fixed location. Fewer RF sources were available in rural Belgium (e.g., UMTS was not yet deployed), therefore exposures were generally lower for the investigated scenarios. Joseph et al. calculated whole body SAR using the PEM data; for instance, for an electric field value of 0.26 V/m, they calculated the higher limit, p95 (SAR), to be 2.08 μW/kg and for 0.36 V/m they calculated it to be 3.88 μW/kg, which are close to one hundred thousand times below exposure limits.[33]

A 24-hour RF exposure profile was collected of 3022 children and adolescents in four Bavarian cities in Germany.[51] Half of the children and nearly all of the adolescents owned mobile phones which were used for short durations during the day only. The data were expressed as a mean percentage of the ICNIRP standards; the overall exposure was very low and ranged from a mean of 0.13% to 0.92% of the ICNIRP reference level per second during waking hours.[51] Authors did not report levels separately for each of the different frequency ranges that were covered (GSM 900 and 1800 up and downlink; and WLAN).

One study by Joseph et al. (2010)[52] attempted to compare PEM across countries in Europe—Belgium, Switzerland, Slovenia, Hungary, and the Netherlands—using the same personal exposure meters. The highest exposure occurred in transportation vehicles (trains, cars, buses), particularly during uplink of mobile phones with three frequency bands of 880–915 MHz, 1710–1985, and 1920–1980 MHz (range of 0.0000239 to 0.000101 mW/cm^2). DECT phone measurements were much lower than for mobile phones but were greatest in office and urban homes (primarily in the range of 0.000 to 0.000006mW/cm^2). FM measurements ranged up to 0.0000096 mW/cm^2 and were higher than for TV/Digital Audio Broadcasting and WLAN. WLAN measurements were highest in the office and urban home (0.000 to 0.0000018 mW/cm^2). Tetrapol, WLAN and TV/Digital Audio Broadcasting (DAB) were considered minor sources of RF.

A recent study by Bolte and Eikelboom (2012)[53] in the Netherlands was able to discern through the additional use of a GPS logger, the spatial and temporal differences in RF exposure for 98 people (excluding their own phone calling) over 24-hour exposure periods. The mean power density was 0.000018 mW/cm^2, with evening exposure being about four times higher than nighttime and twice as high as daytime. The main contributor to exposure was other people in the vicinity making calls from mobile phones and DECT phones. The activities contributing most to exposure included ones occurring in places with a high density of people, such as travelling using public transportation, and at social events, pubs and shopping malls. The highest peak exposure in the WiFi band was 0.0265 mW/cm^2 from use of a microwave for a short period of time.

5.4 Discussion

The public is exposed to RF from several sources on a daily basis. For the most part, exposure assessment studies have found all RF levels from sources to be below current exposure limits (the limits are provided in Section 13). The highest exposures result from being in the near-field of active RF devices, with personal use of a mobile phone at the head contributing most to total RF exposure. Because cordless phones do not exhibit power control like mobile phones, they can potentially emit more RF than UMTS mobile phones, although they do emit less than GSM mobile phones. WLAN devices emit far less RF than mobile phones and cordless phones but may be used for longer periods of time. Power densities near WLAN access points are greater than WLAN terminals. In general, being in the far-field of sources, such as the case with base stations and broadcast stations results in far lower exposures than using RF-emitting devices in the near field.

Personal Exposure Measurement (PEM) data are often dominated by RF from mobile phones, DECT phones, and WLAN, but surprisingly FM has been found to contribute substantially to far-field exposures.[50] Overall, exposures are higher in the daytime due to higher usage of mobile phones and cordless phones; however, WiFi sources are prevalent both day and night.[47] Being in transit produces higher exposures with personal use of GSM mobile phones (which produce maximum output power upon each handover). Also, in mass transit, such as in buses or trains, other passenger use of wireless devices contributes to personal exposure.[52] However, ambient exposure from others' use of WiFi and mobile phones contributes much less to exposure than personal usage of a RF device.

Total PEM tend to be higher in rural locations, likely due to a lower density of mobile phone base stations. Although intuitively, one may assume that an increase in base stations means higher ambient exposure, mobile phones do not need to use as much power (due to adaptive control) to communicate with the base stations due to shorter distances. As a good connection translates into lower output power levels, urban centres with higher base station densities often experience lower RF than rural centres.

The nominal peak output power levels of WLAN and Smart Meters are comparable to some mobile phones (e.g., 250 mW), but the duty cycle of these systems are low, meaning that these systems do not transmit often or for extended periods of time. In addition, these devices are not meant to be used in the near field (at the head or body) and therefore exposure decreases with distance from the source.

Although mobile phones and wireless communication systems contribute most to overall personal exposure, with each generation of mobile phones, the RF that is emitted is lower due to changing technologies and higher base station densities. Although 3G technologies like UMTS produce lower output power levels than previous generations, GSM (2G), which has unique features that result in higher output power levels, is still being used in current 3G and 4G model phones that have the capability of switching from one technology or frequency to another. For instance, new mobile phones using LTE or WiMax technologies will fall back to GSM or CDMA networks when 4G networks are unavailable.[54] Therefore, knowledge of output power characteristics of 2G technologies remains important for understanding contributions to current personal exposure.

5.4.1 Limitations

There are many new and emerging sources of RF for which very little exposure information is available. One study of area measurements evaluated LTE and WiMax, but indicated the difficulties with exposure assessment given that these networks were not well established in these areas.[47] In addition, other uses of RF such as for aesthetic purposes (e.g., RF facials) have been documented in the literature, but as of yet, no exposure studies have been conducted.

In reviewing exposure data from various studies, it is not possible to directly compare study exposure measurements to each other as study parameters differ substantially. Studies are conducted in different locations and use different sampling techniques, sampling intervals, sampling equipment, distances, and models of RF-emitting devices. Even within the same study, output power can vary substantially depending on location of study centres and network operators.[24,32] However, comparisons of different devices within each study can be used to determine relative output power. Measurement of power density, electric fields, and SAR are all subject to limitations in measurement accuracy.

As there has been public concern over pulsed modulated waves, a research gap is an absence of assessment of pulsed modulation. Some studies compared devices with pulse modulation to those without and one study conducted measurements at intervals that were sufficiently small to capture the pulsing of GSM phones.[8] Most studies assumed a cumulative exposure model in devising their sampling strategies for comparison with current standards, but this biological model may not be appropriate. A reasonable alternative is a rate of change model which assumes that the frequency of RF oscillates from higher intensity to lower intensity in a particular RF event. When undertaking exposure assessment studies, researchers must ensure that their sampling protocol is sufficient to capture the salient features of the chosen model (for instance, ensuring that the sampling interval is sufficiently short to capture any peaks, so that peaks are not averaged out in a long sampling period when applying a repetition model).

In order to determine exposure from all sources, some knowledge of the individual contributions of sources must be considered. However, it is difficult to assess exposure from multiple sources that emit at similar frequencies (e.g., microwave oven and WLAN), and for PEM, researchers must rely on accurate activity logs to distinguish one source from another.

Also, PEM indicates a field value close to the human experience but the user's exposure is dependent on how the device is used. For instance, a mobile phone can be used at the head or with a headset with the phone in a pocket or purse. Since the monitors are usually hung at the waist, they do not capture actual exposures from sources held close to the body at different locations.[50] In addition, PEMs are appropriate for capturing far-field exposures, but are inappropriate for measuring near-field exposure. As a result, PEMs may underestimate true exposure.

5.4.2 Future implications

As with mobile phones, we expect that each generation of new technologies of RF-emitting devices will become more energy-efficient and therefore produce lower average output power. However, there is a growing demand that new technologies handle more data and transmit it more quickly, thereby possibly increasing the power necessary to handle the demand. LTE and similar technologies enabling high data rate applications will increase; these new and emerging technologies will create new exposure scenarios that will require assessment.[15]

In addition, the duration of exposure to sources of RF is increasing with time, so future exposure assessment studies must consider the duration as well as type of use of various devices. Average ambient exposure levels to RF measured in urban areas of the US in 1975 were 0.005 mW/cm^2; in 1998 the exposure levels were 0.05 mW/cm^2 in Sweden, and in 2009 the averaged power density in Greece urban areas was 0.39 mW/cm^2. Differences in methodology and location affect direct comparison, but the trend of increasing exposure to RF is evident. In 1975 the principal sources of RF were from broadcast band signals, whereas more than 60% of RF exposure is presently attributed to wireless telecommunication devices.[55]

Although ideally it would be preferable to capture personal exposure information in future studies, PEM studies that collect total field measurements from all RF sources for all subjects can be resource-intensive, therefore some researchers have investigated methods for predicting field exposures without doing PEM. A modest correlation (R^2 of 0.56) was shown between PEM and questionnaire data coupled with RF measurements from fixed site transmitters to predict personal RF exposure.[48] Also, another study evaluated the correlation between measured source data and modelled data for a city and rural area and found good correlation for different types of sources including mobile phones and broadcast stations.[9] Dose phones (software modified phones) have been used consistently to measure GSM power control levels which can be proxies for actual output power levels. These dose phones have shown good correlation with GSM source measurements[8]; therefore, there may be potential in creating dose phones using newer generation models of phones that could easily be used by participants in future studies.

In future studies, it may be important to measure the pulse power density in addition to the average power density. More research is needed to determine a biologic marker of exposure.

As for SAR compliance testing, a recent study showed that peak temperature increase was a better metric for detecting localized heating effects of RF and suggests that peak temperature increase for a specific duration of exposure be used instead of the current restrictions based on SAR 10 g or 1 g.[56]

5.5 Conclusion

Due to the widespread use of RF devices, average exposure of the general public above natural background levels is increasing but remains much lower than internationally accepted guidelines. The greatest contributor to personal exposure to RF is use of mobile phones at the head. The output power levels in the near field of RF devices are hundreds to millions of times higher than ambient field levels. Although the intensity of exposure for most RF emitting devices is below any current exposure limits and becoming lower over time for mobile phones, there are also more sources for which we have very little exposure measurement information. Also, duration of exposure is increasing to the many different sources of RF; therefore, it continues to be necessary to assess individual sources of exposures and total exposures over time.

Summary of Factors that Affect RF Power Density

1. **Technology.** The type of technology contributes the most to power variation of mobile phones. Mobile phones using CDMA technology emit the least RF. There is little research yet on 4G phone technologies.

2. **Antenna configurations.** Often RF antennas do not radiate omnidirectionally, but instead radiate in certain directions with nulls in others.[2] Knowing the direction of the main lobe will help inform the general public of placement of RF-emitting devices or in locating mobile phone base stations.

3. **Adaptive control.** For most mobile phones, the network exercises power control or adaptive control, which reduces RF power of each roaming unit to a minimum level compatible with voice quality for a conversation.[21] Therefore, mobile phones usually transmit at less than maximum power.

4. **Duty cycle.** The duty cycle is the ratio of pulse duration to the pulse repetition period and applies to technologies that pulse, such as with GSM or WiFi. Depending on the duty cycle, the average output power levels will differ (e.g., average powers will be much higher with duty cycles of 100% vs. 1%).

5. **Distance.** In the far field, power density is inversely proportional to the square of the distance. However in the near field, close to the RF-emitting device, this relationship does not apply. Also, shorter distances between a receiver and access point or base station reduces the output power necessary to communicate. For instance, a higher density of mobile phone base stations means that the output power levels of mobile phones will be lower than for lower density areas.

6. **Frequency.** Radio waves penetrate less into body tissues as frequency increases[2]; therefore, people will absorb less RF from devices using higher frequency bands.

7. **Data rates and signal quality**. Data transfer causes higher output power than voice.[10] Good signal quality reduces output power.

8. **Location.** Whether an RF device is being used indoor vs. outdoors or in a rural vs. urban location will affect exposure.

9. **Transit**. Being in a moving vehicle tends to increase average output power levels. Much of the increase can be attributed to GSM mobile phones switching base stations, but for mass transit, it can also be attributed to the number of wireless devices being used by passengers.

10. **Size.** A larger antenna will increase the size of the near-field. Also, size of the person being exposed will affect exposure. For the same emitted power, children and fetuses experience higher SAR.

11. **Models of RF devices.** Different models of RF devices produce different output power levels and can be affected by size of antenna, antenna placement, packaging, etc. However, the differences between models of mobile phones are small compared to differences between technologies.[8,24]

12. **Tissue type.** The amount of reflection, absorption and transmission from specific RF frequencies varies with the type of material and its thickness. RF at telecommunication frequencies generally tend to be absorbed and may penetrate into the body tissues for a few centimetres.[1]

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5.7 Appendices

Appendix A: Equations Related to Exposure

1. dBm – referenced to 1 mW
2. dBm = 10 log [Signal (mW)/1mW]
3. Power (mW)=10^dBm/10
4. $\lambda = c/f$; where λ is the wavelength, c is speed of light 3x10E8 m/s, and f is the frequency in Hz (cycles/second)
5. Reactive near field = $\lambda/2\pi$; where λ=wavelength
6. Boundary between near and far field: $d = 2\ L^2/\lambda$; where d=distance; L=length of antenna; λ =wavelength
7. **To convert mW/m² to mW/cm² divide by 10,000**
8. **To convert mW/cm2 to W/m2 multiply by 10**