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ORIGINAL ARTICLE

Comparative international analysis of radiofrequency exposure surveys of mobile communication radio base stations

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This paper presents analyses of data from surveys of radio base stations in 23 countries across five continents from the year 2000 onward and includes over 173,000 individual data points. The research compared the results of the national surveys, investigated chronological trends and compared exposures by technology. The key findings from this data are that irrespective of country, the year and cellular technology, exposures to radio signals at ground level were only a small fraction of the relevant human exposure standards. Importantly, there has been no significant increase in exposure levels since the widespread introduction of 3G mobile services, which should be reassuring for policy makers and negate the need for post-installation measurements at ground level for compliance purposes. There may be areas close to antennas where compliance levels could be exceeded. Future potential work includes extending the study to additional countries, development of cumulative exposure distributions and investigating the possibility of linking exposure measurements to population statistics to assess the distribution of exposure levels relative to population percentiles.

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INTRODUCTION

It is estimated that over 90% of the global population has access to mobile networks and that there were 5.3 billion mobile subscriptions at the end of 2010.[1] Services are provided by a network of radio base stations and it was estimated that there were over 1.4 million installed globally in 2006 (ref. 2) with a 2008 industry analyst report projecting 4.7 million base stations at the end of 2010, with annual growth of about 200,000.[3] In addition to growth in subscribers, there has also been a rapid evolution in mobile radio technology.[4] Risk perception studies show that some communities, members of the general public, academics and politicians have concerns about possible health effects of exposure to radiofrequency (RF) energy transmitted by mobile phones and wireless networks.[5]

In an effort to provide public information and allay community concerns, regulatory agencies and academic institutions have undertaken extensive measurement surveys of the environmental levels of RF energy in locations near the individual transmitter sites of mobile networks and made the results publicly available. The World Health Organization (WHO) also recommends on-going work to characterize population RF exposure and notes that this would be particularly useful for global exposure assessment in view of the upcoming WHO health risk assessment for RF fields.[6] There have been limited efforts to compile and compare survey data between countries[7-9] and each found that RF exposures in publicly accessible areas were typically many thousands of times below the levels recommended in international human exposure guidelines.[10] A recent cumulative distribution analysis of UK measurements (a subset of the same data used in our study) reported a median exposure level of 0.0037 μW/cm^2 with 5th and 95th percentiles of 1.3×10^{-5} μW/cm^2 and 0.11 μW/cm^2, respectively.[11]

The aims of our research project were to build on the earlier analysis and:

(1) Compile a summary of key characteristics of national measurement surveys of public RF exposures from radio base stations in a large sample of countries.
(2) Investigate similarities or differences between the results of various national RF surveys and different technologies or frequency bands (where sufficient information was available).
(3) Investigate any chronological trends in the exposure data where individual national surveys may have been conducted over a number of years.

METHODS

Two primary criteria were applied to the selection of RF measurement surveys for inclusion in this study:

(1) The data had to be accessible, either from published sources (journal or website) or freely supplied on request from the owners of the data. The vast majority of data (over 99.6%) has been sourced from government agencies, universities or independent research institutes.
(2) The survey instrumentation used for the measurements was capable of frequency/service differentiation and the data reported per mobile technology and service band of interest or, at a minimum, the total level across all the mobile phone bands present.

Where possible we asked for the raw measurement data and if this was not available then we asked for summary information (minimum, maximum, mean, standard deviation, number of points and measurement years). It was also important that the data were available as field strength levels rather than as percentage of relevant human exposure standard as

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the specific service frequency was not always available for conversion purposes. We obtained data on the extensive Italian national measurement program,[12] but we do not yet have access to the software needed to analyze nearly 50 million measurement samples and intend to include the results in a future publication. Table 1 summarizes the sources of the surveys for 23 countries, their main characteristics and expands the abbreviated names of the mobile technologies. The US data set was unique in that a majority of the measurements were made on rooftops and buildings within close proximity of the transmitting antennas. All other data sets were primarily ground-based measurements around towers or elevated installations.

There are four general methods of assessing exposure levels to RF fields. These methods include narrowband and broadband measurements,[57] personal RF dosimeters and theoretical calculations. In this study, we have collected and reported only broadband and narrowband measurements. Personal RF dosimeters have been used to assess personal exposure in population samples,[58] however, we did not use data from these measurements because they have limited sensitivity, are affected by coupling with the body of the wearer and assess individual exposure rather than exposure at a location.[59,60] Theoretical calculations have also not been used as they generally over-estimate actual levels because of the use of worst case assumptions.

In brief, broadband instruments, which have frequency responses typically several hundred kilohertz up to several gigahertz, can be used to measure the total RF power across the frequency bands covering FM radio/TV broadcast and radio base stations, but frequency- or channel-specific

Table 1. Countries from which data were sourced, the years over which the surveys were carried out, the number of data points, the measurement method and the types of services measured.

Country	*Code*	*Years of survey data*	*Total number of data points*	*Method of measurement*	*Types of services surveyed*[a]	*Reference*
Australia	AU	2000	13	Narrowband	CDMA800, GSM900/1800, WCDMA	13–15
		2003	663			
Austria	AT	2000	233	Narrowband	GSM900/1800	7, 8, 16, 17
		2006	491	Narrowband	GSM900/1800, WCDMA	
Belgium	BE	2000–2002	380	Narrowband	GSM900/1800	18, 19
		2009–2010	482	Narrowband	GSM900/1800, WCDMA	
Canada	CA	2001/2002 and 2004	686 recovered but many more values measured	Narrowband	AMPS800 and PCS1900	20–22
Egypt	EG	2009	276	Broadband	Broadcast, GSM900/1800, WCDMA	23
France	FR	2001–2007	2000 approx.	Narrowband	GSM900/1800, WCDMA	24, 25
Germany	DE	2003 (Bavaria)	1073	Narrowband	GSM900/1800	26, 27
		2001–2008 (Numerous States)	1867	Narrowband	GSM900/1800, WCDMA	28–30
Ghana	GH	2007–2008	50	Narrowband	GSM900/1800	31
Greece	GR	2003–2009	174	Narrowband	GSM900/1800, WCDMA	32
Hungary	HU	2000	80	Narrowband	GSM900/1800	7
Ireland	IE	2003–2009	15,048	Narrowband	GSM900/1800, WCDMA	33
Japan	JP	2008[b]	40 averages analyzed but many more data points measured	Narrowband	CDMA and WCDMA	34, 35
Malaysia	MY	2005 and	128	Narrowband	GSM900/1800, WCDMA	36
		2009–2010	9	Narrowband		37
Netherlands	NL	2009–2010	273	Narrowband	GSM900/1800, WCDMA	19
New Zealand	NZ	2003–2009	214	Broadband	Broadcast, GSM900/1800, WCDMA	38, 39
Peru	PE	2007	75	Narrowband	GSM1900	40
South Korea	KR	2007–2009	9755	Narrowband	Broadcast, GSM900, PCS1900, WCDMA	41, 42
Spain	ES	2002–2008	4827	Narrowband	GSM900	43
Sweden	SE	2000	31	Narrowband	Broadcast, NMT, GSM900/	7
		2000–2007			1800, WCDMA	44
Switzerland	CH	2004–2006–2008	29	Broadband and Narrowband	Broadcast, GSM900/1800, WCDMA	45–51
Thailand	TH	2005	12,770	Narrowband	GSM900/1800	52–54
		2007	956	Broadband	GSM900/1800	
United Kingdom	UK	2001–2010	135,536	Narrowband	ETACS, GSM900/1800, WCDMA	55
United States of America[c,d]	US	2003–2009	1127	Broadband	Broadcast, AMPS800, CDMA800 and PCS1900	56

Abbreviations: AMPS, advanced mobile phone system; CDMA, code division multiple access; ETACS, extended total access communications system, a variant of AMPS; GSM, global system for mobile; NMT, nordic mobile telephone; PCS, personal communications services; WCDMA, wideband CDMA.
[a]Broadcast (FM radio and television). The number following the system acronym refers to the frequency band of operation of the system.
[b]The Japanese Ministry of Internal Affairs and Communications has collected data for 2006, 2007 and 2008, but unfortunately the data for 2006 and 2007 does not contain summary tables of data.
[c]Data for San Francisco, California.
[d]The US data set was unique in that a majority of the measurements were made on rooftops and buildings in close proximity of the transmitting antennas. All other data sets were primarily ground-based measurements around towers or elevated installations.

information is often not available or not easily obtained. As a general comment for comparisons purposes such as presented here, broadband measuring instruments have limitations because of their lack of frequency selectivity and also because they are designed to indicate higher levels relative to the various exposure limits and are used closer to RF sources than other measuring techniques such as narrowband instruments. Often, however, the contribution from a specific source can be assessed because a dominant source can be identified through proximity or by switching sources on and off to measure their contribution to the total RF background. Broadband instruments have a sensitivity threshold to electric fields above the equivalent of 0.01 μW/cm^2.[61]

Narrowband or frequency-specific instruments have higher sensitivity and are able to discriminate between the various RF sources. However, it can also be difficult to directly compare narrowband measurements from different surveys as the operational parameters of the spectrum analyzers or frequency selective receivers may be different. For example, differing resolution bandwidths and peak hold or time averaged modes can be selected. The survey techniques can also be different, e.g., is an area scanned and only the peak field reported or are the levels spatially averaged in some manner, are single polarizations or isotropic responses reported? The total RF field from narrowband surveys is found by summing the power density of the exposure across the frequency band of interest. Narrowband instruments can typically detect electric fields 4–5 orders of magnitude below broadband instruments but this is very dependent on the amount of amplification and the signal processing involved in the setup.

There have been significant advances in both broadband and narrowband instrumentation over recent years, which have addressed the issues of size, portability and isotropic response of the instrumentation and the choice between the two types of instrumentation is now one of cost and purpose. For the purpose of demonstrating compliance of a particular installation, broadband measurements may be sufficient. However, measuring particular sources or their contribution to the total background generally requires some means of identifying the various frequencies present and is particularly true of complex sites with multiple transmitters and services, and in urban areas.

RESULTS

In Table 2, the data have been pooled by country, year (where the annual data are available) and by wireless technology (generally only for narrowband measurement surveys). We excluded Ghana and France from the analysis due to incomplete survey information, so analysis was based on 21 countries. The statistical values calculated for each data set are minimum, maximum, mean and standard deviation. Note that data are presented as absolute power density levels in the units of μW/cm^2–the levels are not relative to the respective human exposure limits for RF fields, which vary by frequency.[10] A total of 175,547 data points were collected in this study but due to incomplete information and problems of interpretation only 173,323 points (98.7%) were included in the analysis.

Figure 1 compares the survey results across the 21 countries. We calculated a global average across all measurements, weighted by the number of points per country, as 0.0567 μW/cm^2 as indicated by the lower dotted line in Figure 1. The weighted average was calculated as shown in Eq. (1):

$$\text{global weighted average} = \frac{\text{country weighted average} \times \text{number of points}}{\text{global number of points}} \tag{1}$$

Where the *country-weighted average* was based on the number of measurements for each radio technology relative to the total number of measurements. There was approximately three orders of magnitude difference between the mean values for the country data sets. Two key factors may explain the difference in mean levels. First, the use of broadband *versus* narrowband instruments–not surprisingly the broadband measurements yield the highest average values and the narrowband measurements the lowest average values. Second, the choice of measurement location was not standardized between countries (most were at ground level except the USA which included a large number of rooftops). Measurements in Germany near 11 different GSM (Global System for Mobile Communications–typically refers to 2G or second generation systems) and 3G (third generation) base station types (urban, rural, indoor, outdoor, etc) found that the exposure varied by three orders of magnitude due to choice of measurement location.[62]

In Figure 2, the results of the annual surveys for the UK and the USA are plotted with the annual averages for Spain, Greece and Ireland. These countries were selected because of the number of years surveyed and also to allow a comparison of trends between narrowband (UK, ES, GR, IE) and broadband (US) measurements. The very limited variation year on year between surveys in the same country is striking in Figure 2. During the period of the UK measurements subscribers grew from 42.9 million to 77.5 million (81%) and for the US from 50.9 million to 283.1 million (456%)[63] and 3G technologies were deployed but average exposure measured in the surveys remained largely unchanged. This is probably indicative of the within-country similarities with respect to survey methodology, survey equipment, mobile network structure and the choice of measurement location. The UK averages are 2–3 orders of magnitude lower than those for Spain, Greece and Ireland and we believe this is due to very low reported sensitivity of the UK measurements and differences in proximity to the antennas. The US measurements included many rooftops and other locations around the immediate vicinity of base station antennas. Measurements on rooftops close to the antennas would reveal readings that could be significantly higher, and exceed reference levels for the public directly in front of transmitting antennas.[64] The general survey approach in the US is to spatially average the RF fields over the height of a person, typically taken as 1.8 m. Also in the US, measurements are generally made to identify the contour of the maximum exposure level for the public as it may also apply to workers on the rooftop who have not been trained and not aware of their exposure. Finally, we note that while the mobile technologies are deployed nationally throughout the US, the measurements are for one city only.

Figure 3 compares exposure by technology averaged for 16 countries and all available years from data measured using narrowband survey techniques. It is clear from this graph that, apart from the Mobile 800 MHz band (limited measurements in Canada and the UK only) and the GSM1900 (early deployment in Canada in 2003) and excluding current LTE (Long Term Evolution or 4G–4th generation system) with very limited deployment, all of the technology averages are within about a factor of 10 of 0.1 μW/cm^2.

DISCUSSION

This large-scale international comparative analysis of the results of RF exposure surveys of mobile communications networks has a number of limitations. Caution must be observed in comparing absolute values between countries because of differing measurement instruments (e.g., narrowband spectrum analyzers or broadband survey instruments) and the criteria for selecting the measurement locations was not standardized between countries. In addition, our study does not allow any conclusions in regard to the percentage of the total population exposed to RF signals from base stations though it seems likely that this will have increased over time as networks were expanded to meet coverage obligations in license conditions. However, a number of observations in respect of the types of base stations surveyed and the

Table 2. Summary statistics for the measurement survey data by country, mobile technology and year (where available).

Country Code	*Year*	*Cellular technology*	*No. of points*[a]	*Minimum ($\mu W/cm^2$)*	*Maximum ($\mu W/cm^2$)*	*Average ($\mu W/cm^2$)*	*Standard deviation ($\mu W/cm^2$)*
AU	2000	GSM900	13	5.00E−04	7.20E−02	2.47E−02	2.29E−2
	2003	CDMA	119	3.00E−07	3.72E−02	3.55E−03	6.66E−03
		GSM900	355	4.80E−07	7.03E−01	1.89E−02	5.92E−02
		GSM1800	51	8.01E−06	4.25E−01	1.79E−02	7.22E−02
		WCDMA	138	1.50E−06	7.60E−02	6.16E−03	1.18E−02
		Total	663	4.80E−07	7.03E−01	3.75E−02	1.02E−01
AT	2000	GSM900	197	1.60E−08	1.34E+00	2.86E−02	1.27E−01
		GSM1800	36	4.30E−06	1.35E−01	9.63E−03	2.44E−02
		Total	233	1.60E−08	1.34E+00	2.57E−02	1.17E−01
	2006	GSM900	226	< 1.00E−06	2.14E−01	4.30E−03	1.79E−02
		GSM1800	226	1.00E−06	4.75E−01	4.64E−03	3.54E−02
		WCDMA	39	< 1.00E−06	7.30E−03	5.43E−04	1.51E−03
		Total	491	< 1.00E−06	4.75E−01	9.03E−03	4.11E−02
BE	2000	GSM900/1800	178	5.61E−04	4.06E+00	2.40E−02	5.84E−01
	2001	GSM900/1800	132	8.59E−05	4.24E+01	6.43E−01	4.04E+00
	2002	GSM900/1800	70	3.21E−03	1.03E+02	2.54E−01	1.30E+01
	2000–2002	Total	380	8.59E−05	1.03E+02	2.69E−01	6.12E+00
	2009–2010	GSM900	180	1.17E−04	3.93E+00	2.27E−01	5.25E−01
		GSM1800	160	1.57E−05	1.22E+00	3.66E−02	1.21E−01
		WCDMA	142	3.82E−05	1.23E−01	8.31E−03	1.93E−02
		Total	482	1.57E−05	3.93E+00	9.94E−02	NA
CA	2003	AMPS	143	1.11E−04	6.42E−02	7.59E−03	1.27E−02
		PCS1900	143	1.63E−05	2.54E−02	1.61E−03	2.68E−03
		Total	286	1.63E−05	6.42E−02	4.60E−03	9.67E−03
	2004	AMPS	200	4.47E−05	3.80E−02	1.79E−03	4.73E−03
		PCS1900	200	2.69E−04	3.02E−02	7.73E−04	2.50E−03
		Total	400	4.47E−05	3.80E−02	1.28E−03	3.81E−03
EG	2009	GSM900/1800	276	3.00E−02	1.15E+00	4.12E−01	2.15E−01
FR	2001–2004[b]	GSM900	NA	NA	NA	9.23E−02	NA
		GSM1800	NA	NA	NA	9.23E−02	NA
		WCDMA	NA	NA	NA	1.30E−03	NA
	2004–2007	GSM900	NA	NA	NA	1.12E−01	NA
		GSM1800	NA	NA	NA	4.68E−02	NA
		WCDMA	NA	NA	NA	1.40E−02	NA
		Total 01-07	~2000	–	–	–	–
DE	2003	GSM900	517	3.06E−07	1.51E−01	3.91E−03	1.34E−02
		GSM1800	556	1.62E−07	5.59E−01	2.49E−03	2.53E−02
		Total	1073	1.62E−07	5.59E−01	3.17E−03	2.04E−02
	2002–2008	GSM900/1800	1867	2.7E−07	7.15E+01	7.33E−01	NA
		WCDMA	464	2.40E−06	2.79E+01	3.59E−01	NA
GH	2007	GSM900	50	1.00E−06	1.00E−03	NA	NA
		GSM1800	50	1.00E−06	1.00E−02	NA	NA
GR	2003–2005	GSM900	26	3.74E−05	1.86E+00	2.27E−01	5.35E−01
		GSM1800 and WCDMA	26	2.45E−05	2.76E+00	3.22E−01	6.79E−01
		Total	52	1.77E−04	3.78E+00	5.49E−01	1.12E+00
	2006	GSM900	32	1.29E−05	1.85E+00	1.34E−01	3.51E−01
		GSM1800and WCDMA	32	6.88E−05	6.60E−01	1.15E−01	1.72E−01
		Total	64	8.17E−05	1.90E+00	2.49E−01	3.89E−01
	2007	GSM900	38	3.16E−05	1.85E+00	1.43E−01	3.56E−01
		GSM1800 and WCDMA	38	1.61E−03	1.08E+00	1.59E−01	2.76E−01
		Total	76	1.64E−03	2.18E+00	3.02E−01	5.34E−01
	2008	GSM900	39	6.20E−05	5.19E+00	2.52E−01	9.21E−01
		GSM1800 and WCDMA	39	2.86E−04	1.92E+00	2.31E−01	4.33E−01
		Total	78	3.48E−04	6.87E+00	4.83E−01	1.23E+00
	2009	GSM900	39	2.19E−04	1.25E−01	1.73E−02	2.93E−02

Table 2. (Continued)

Country Code	Year	Cellular technology	No. of points[a]	Minimum (μW/cm²)	Maximum (μW/cm²)	Average (μW/cm²)	Standard deviation (μW/cm²)
		GSM1800 and WCDMA	39	9.46E−04	1.02E+00	7.49E−02	1.73E−01
		Total	78	1.99E−03	1.03E+00	9.23E−02	1.82E−01
	2003-2009	GSM900	174	1.29E−05	5.19E+00	1.50E−01	5.33E−01
		GSM1800 and WCDMA	174	2.45E−05	2.76E+00	1.73E−01	3.78E−01
		Total	348	8.17E−05	6.87E+00	3.23E−01	7.95E−01
HU	2000	GSM900	57	5.78E−03	1.28E+00	1.37E−01	2.39E−01
		GSM1800	9	1.08E−02	1.31E−01	4.19E−02	4.62E−02
		Total	66	5.78E−03	1.28E+00	1.24E−01	2.25E−01
IE	2003-2004	GSM900	6670	1.00E−07	4.93E+00	4.05E−02	1.59E−01
		GSM1800	6139	9.01E−08	4.55E+00	2.35E−02	1.79E−01
		WCDMA	3	1.23E−05	4.54E−05	2.74E−05	1.67E−05
		Total	12,812	9.01E−08	4.93E+00	3.23E−02	1.69E−01
	2005-2006[c]	GSM900	79	1.06E−06	1.82E+00	1.43E−01	2.91E−01
		GSM1800	79	4.24E−08	5.30E+00	1.91E−01	7.43E−01
		WCDMA	72	1.30E−07	5.07E−01	1.57E−02	6.54E−02
		Total	230	4.24E−08	5.3E+00	1.19E−01	4.73E−01
	2007[c,d]	GSM900	230	4.48E−07	5.27E+00	8.87E−02	5.08E−01
		GSM1800	146	9.55E−08	6.29E−02	5.11E−03	1.05E−02
		WCDMA	187	9.58E−07	3.56E−01	1.70E−02	4.49E−02
		Total	563	9.55E−08	5.27E+00	4.32E−02	3.28E−01
	2008	GSM900	235	2.39E−06	1.88E+01	2.26E−01	1.29E+00
		GSM1800	139	1.06E−06	8.53E+00	1.54E−01	9.98E−01
		WCDMA	194	3.42E−06	4.86E+00	9.57E−02	4.40E−01
		Total	568	1.06E−06	1.88E+01	1.64E−01	1.00E+00
	2009	GSM900	279	3.14E−06	1.66E+01	2.76E−01	1.24E+00
		GSM1800	173	1.01E−05	3.50E+00	8.14E−02	3.03E−01
		WCDMA	269	2.47E−06	1.17E−01	5.14E−03	1.36E−02
		Total	721	2.47E−06	1.66E+01	1.28E−01	7.91E−01
	2003-2009[e]	GSM900	7548	1.00E−07	1.88E+01	6.29E−02	4.23E−01
		GSM1800	6725	4.24E−08	1.63E+01	3.17E−02	3.14E−01
		WCDMA	775	6.63E−08	1.41E+01	6.20E−02	6.28E−01
		Total	15,048	4.24E−08	1.88E−01	4.89E−02	3.92E−01
JP	2008	CDMA800	20	1.02E−06	2.37E−03	3.49E−04	5.85E−04
		WCDMA	20	1.38E−07	7.41E−04	1.59E−04	2.10E−04
		Total	40	1.38E−07	2.37E−03	2.54E−04	4.44E−04
MY	2005	All mobile frequencies	9	9.16E−02	2.10E+00	4.88E−01	6.59E−01
	2009-2010	All mobile frequencies	128	2.00E−07	2.00E−01	9.30E−03	NA
	Total	All mobile frequencies	137	2.00E−07	2.10E+00	4.08E−02	NA
NL	2009-2010	GSM900	101	4.53E−05	9.42E−01	3.93E−02	1.14E−01
		GSM1800	97	1.41E−05	6.40E−01	2.10E−02	6.95E−02
		WCDMA	75	2.98E−05	1.49E−01	8.25E−03	2.11E−02
		Total	273	1.41E−05	9.42E−01	2.43E−02	NA
NZ	2003-2004[f]	All mobile frequencies	57	4.00E−02	3.60E+01	1.58E+00	4.79E+00
	2005[f]	All mobile frequencies	58	1.00E−02	2.15E+01	1.46E+00	3.08E+00
	2006[f]	All mobile frequencies	45	3.00E−02	7.17E+00	1.62E+00	1.71E+00
	2007[f]	All mobile frequencies	40	7.00E−02	1.70E+01	2.15E+00	3.72E+00
	2008[f]	All mobile frequencies	14	7.00E−02	1.82E+00	6.78E−01	5.34E−01
	2003-2008[f]	All mobile frequencies	214	1.00E−02	3.60E+01	1.6E+00	3.44E+00
PE	2001-2004	GSM810-GSM900	295	6.68E−11	1.57E+01	5.56E−01	1.75E+00
		PCS1900	75	2.15E−05	6.12E+00	1.01E+00	1.16E+00
		Total	370	6.68E−11	1.57E+01	5.38E−01	1.65E+00
KR	2007	TRS[g]	57	1.06E−06	1.73E+00	1.67E−01	3.27E−01
		CDMA	158	2.65E−07	5.39E+01	1.30E+00	5.79E+00
		GSM1800	969	9.55E−06	4.95E+00	3.90E−01	7.14E−01
		WCDMA	4	2.65E−07	2.65E−07	2.65E−07	0.00E+00
		Total	1188	2.65E−07	5.39E+01	4.99E−01	2.23E+00

Table 2. (Continued)

Country Code	Year	Cellular technology	No. of points[a]	Minimum ($\mu W/cm^2$)	Maximum ($\mu W/cm^2$)	Average ($\mu W/cm^2$)	Standard deviation ($\mu W/cm^2$)
	2008	TRS[g]	82	2.65E−07	1.61E+00	3.40E−01	4.02E−01
		CDMA	542	9.55E−06	8.37E+00	4.54E−01	9.71E−01
		GSM1800	875	1.30E−05	7.37E+00	2.74E−01	6.00E−01
		WCDMA	2285	1.70E−05	8.86E+01	2.45E−01	1.96E+00
		Total	3784	2.65E−07	8.86E+01	2.84E−01	1.59E+00
	2009	TRS[g]	118	2.65E−07	1.80E+00	3.03E−01	3.31E−01
		CDMA	348	1.30E−05	4.57E+00	3.86E−01	7.07E−02
		GSM1800	682	1.70E−05	1.38E+01	3.64E−01	8.77E−01
		WCDMA	3635	6.63E−06	2.25E+01	3.46E−01	8.29E−01
		Total	4783	2.65E−07	2.25E+01	3.51E−01	8.19E−01
	2007–2009	TRS[g]	257	2.65E−07	1.80E+00	2.85E−01	3.59E−01
		CDMA	1048	2.65E−07	5.39E+01	5.59E−01	2.40E+00
		GSM1800	2526	9.55E−06	1.38E+01	3.43E−01	7.28E−01
		WCDMA	5924	2.65E−07	8.86E+01	3.07E−01	1.38E+00
		Total	9755	2.65E−07	8.86E+01	3.43E−01	1.39E+00
ES	2002[h]	GSM900	3818	8.10E−03	1.18E+00	1.02E−01	1.73E−01
	2003[h]	GSM900	264	6.00E−03	5.35E+00	6.05E−01	9.40E−01
	2004[h]	GSM900	149	1.00E−03	6.01E+00	6.47E−01	1.09E+00
	2005[h]	GSM900	149	1.50E−02	3.35E+00	6.96E−01	8.40E−01
	2006[h]	GSM900	149	1.00E−03	3.44E+00	6.36E−01	8.59E−01
	2007[h]	GSM900	149	5.00E−03	3.55E+00	5.29E−01	8.24E−01
	2008[h]	GSM900	149	5.00E−03	5.61E+00	6.47E−01	1.17E+00
	2002–2008	GSM900	4827	1.00E−03	6.01E+00	5.37E−01	9.11E−01
SE	2000	GSM900	31	1.00E−07	2.74E−01	2.27E−02	5.64E−02
	2001–2004	GSM900	68	1.59E−04	5.03E+00	2.57E−01	8.66E−01
		GSM1800	61	8.02E−05	2.57E−01	2.42E−02	4.64E−02
		WCDMA	34	1.30E−04	1.38E+01	4.63E−01	2.36E+00
		Total	163	8.02E−05	1.38E+01	2.13E−01	1.21E+00
	2005–2007	GSM900	91	3.51E−06	1.49E+01	3.58E−01	2.02E+00
		GSM1800	87	1.57E−07	1.19E+01	2.02E−01	1.30E+00
		WCDMA	89	1.25E−06	8.67E−01	2.74E−02	1.04E−01
		Total	267	1.57E−07	1.49E+01	1.97E−01	1.40E+00
	2001–2007	GSM900	159	3.51E−06	1.49E+01	3.14E−01	1.63E+00
		GSM1800	148	1.57E−07	1.19E+01	1.29E−01	9.98E−01
		WCDMA	123	1.25E−06	1.38E+01	1.48E−01	1.25E+00
		Total	430	1.57E−07	1.49E+01	2.03E−01	1.33E+00
	2009–2010	GSM900	30	1.00E−03	1.16E+00	1.91E−01	2.93E−01
		GSM1800	30	2.03E−04	1.13E+00	1.26E−01	2.29E−01
		WCDMA	30	1.80E−03	5.27E−01	1.06E−01	1.53E−01
		Total	90	2.03E−04	1.16E+00	1.41E−01	NA
CH	2004	GSM900/1800/ WCDMA	18	5.97E−03	4.41E−01	9.69E−02	1.14E−01
	2006	GSM900/1800/ WCDMA	20	1.17E−02	4.83E−01	1.50E−01	1.25E−01
	2008	GSM900/1800/ WCDMA	20	2.23E−02	5.27E−01	1.60E−01	1.28E−01
	2004–2006	GSM900/1800/ WCDMA	58	5.97E−03	5.27E−01	1.37E−01	1.24E−01
TH	2005	GSM900	6385	4.07E−04	3.02E−01	4.72E−03	1.28E−02
		GSM1800	6385	8.91E−04	1.38E+00	1.42E−02	3.56E−02
		Total	12,770	4.07E−04	1.38E+00	9.45E−03	2.72E−02
	2007	GSM900 and GSM1800	906	1.00E−02	9.12E+00	1.20E−01[i]	8.9E−02[i]
UK	2001	ETACS[j]	6250	3.29E−11	8.81E−02	3.91E−05	1.50E−03
		GSM900	6310	1.21E−10	6.36E−01	2.05E−03	1.89E−02
		GSM1800	6370	5.16E−09	7.48E−01	5.74E−03	3.18E−02
		Total	18930	3.29E−11	7.48E−01	2.63E−03	2.16E−02
	2002	GSM900	7320	4.32E−10	1.59E−01	6.49E−04	5.04E−03
		GSM1800	14,638	8.32E−10	1.10E+00	1.08E−03	1.26E−02
		Total	21,958	4.32E−10	1.10E+00	9.39E−04	1.07E−02

Table 2. (Continued)

Country Code	Year	Cellular technology	No. of points[a]	Minimum ($\mu W/cm^2$)	Maximum ($\mu W/cm^2$)	Average ($\mu W/cm^2$)	Standard deviation ($\mu W/cm^2$)
	2003	GSM900	6400	1.33E−09	2.25E−01	6.55E−04	6.15E−03
		GSM1800	12,800	7.43E−10	6.25E−01	9.63E−04	9.70E−03
		Total	19,200	7.43E−10	6.25E−01	8.60E−04	8.68E−03
	2004	GSM900	3960	5.55E−10	2.35E−01	1.12E−03	7.29E−03
		GSM1800	7900	8.58E−10	4.96E−01	1.30E−03	1.22E−02
		Total	11,860	5.55E−10	4.96E−01	1.24E−03	1.08E−02
	2005	GSM900	4789	2.65E−13	2.38E−01	1.00E−03	5.68E−03
		GSM1800	7910	1.22E−09	3.52E−01	9.44E−04	6.51E−03
		WCDMA	1540	5.66E−06	1.68E−02	1.07E−04	7.36E−04
		Total	14,239	2.65E−13	3.52E−01	8.73E−04	5.88E−03
	2006	GSM900	1659	3.16E−07	1.51E−01	4.52E−04	4.48E−03
		GSM1800	1657	6.81E−07	5.15E−02	3.99E−04	2.32E−03
		WCDMA	1659	7.21E−06	3.32E−02	2.21E−04	1.56E−03
		Total	4975	3.16E−07	1.51E−01	3.57E−04	3.05E−03
	2007	GSM900	2340	1.36E−10	2.22E−01	1.09E−03	8.37E−03
		GSM1800	2340	5.92E−11	1.32E−02	1.21E−04	7.31E−04
		WCDMA	2338	2.37E−10	1.22E−02	8.29E−05	5.57E−04
		Total	7018	5.92E−11	2.22E−01	4.30E−04	4.89E−03
	2008	GSM900	3160	1.29E−10	7.25E−02	3.03E−04	2.24E−03
		GSM1800	3200	5.80E−11	6.22E−02	1.45E−04	1.37E−03
		WCDMA	3070	2.51E−10	3.11E−02	1.46E−04	1.10E−03
		Total	9430	5.80E−11	7.25E−02	1.99E−04	1.65E−03
	2009	GSM900	4070	3.21E−07	9.91E−02	5.91E−04	3.33E−03
		GSM1800	4150	5.86E−07	6.22E−02	1.90E−04	1.40E−03
		WCDMA	4070	5.41E−06	3.23E−02	1.49E−04	8.73E−04
		Total	12,290	3.21E−07	9.91E−02	3.09E−04	2.15E−03
	2001–2009	ETACS	6250	3.29E−11	8.81E−02	3.91E−05	1.50E−03
		GSM900	40,008	2.65E−13	6.36E−01	9.43E−04	9.09E−03
		GSM1800	60,965	5.80E−11	1.10E+00	1.39E−03	1.38E−02
		WCDMA	12,677	2.37E−10	3.32E−02	1.40E−04	9.90E−04
		Total	119,900	2.65E−13	1.10E+00	1.04E−03	1.12E−02
US	2003	All mobile signals	196	2.00E−02	1.00E+01	7.00E−01	1.33E+00
	2004	All mobile signals	67	6.60E−02	1.20E+01	9.29E−01	1.83E+00
	2005	All mobile signals	159	3.60E−02	2.80E+01	7.75E−01	2.42E+00
	2006	All mobile signals	189	1.90E−02	5.60E+01	2.32E+00	7.10E+00
	2007	All mobile signals	279	1.90E−02	7.00E+01	1.40E+00	5.51E+00
	2008	All mobile signals	138	1.90E−02	3.00E+01	1.87E+00	4.85E+00
	2009	All mobile signals	99	2.20E−02	3.00E+01	1.25E+00	3.28E+00
	2003–2009	All mobile signals	1127	1.90E−02	7.00E+01	1.36E+00	4.26E+00

Abbreviations: ETACS, extended total access communications system; NA, not available or not reported; TRS, trunked radio system.
[a]The number of points reported is the number of data points available for analysis and may not be the actual number of data points in the survey given the difficulties of recovering early records.
[b]The French Report lists internal and external measurements but only the external measured values have been reported in this Table.
[c]In 2005, 2006 and half of 2007 the Irish records only contained the maximum signal strength recorded.
[d]In the second half of 2007 the Irish reports included all of the measured signals and it is these values that are recorded in the above Table.
[e]These totals include all measurements including those from the first half of 2007 which is why some of the totals do not match.
[f]These measurements are the maximum measured values.
[g]TRS 851–867 MHz.
[h]The values reported and used in the analysis are the mean values for each of the 52 Provinces of Spain except for 2005 where only the mean values for each of the 19 autonomous communities were reported.
[i]The mean and standard deviation were calculated assuming a normal distribution.
[j]ETACS 917–933 MHz.

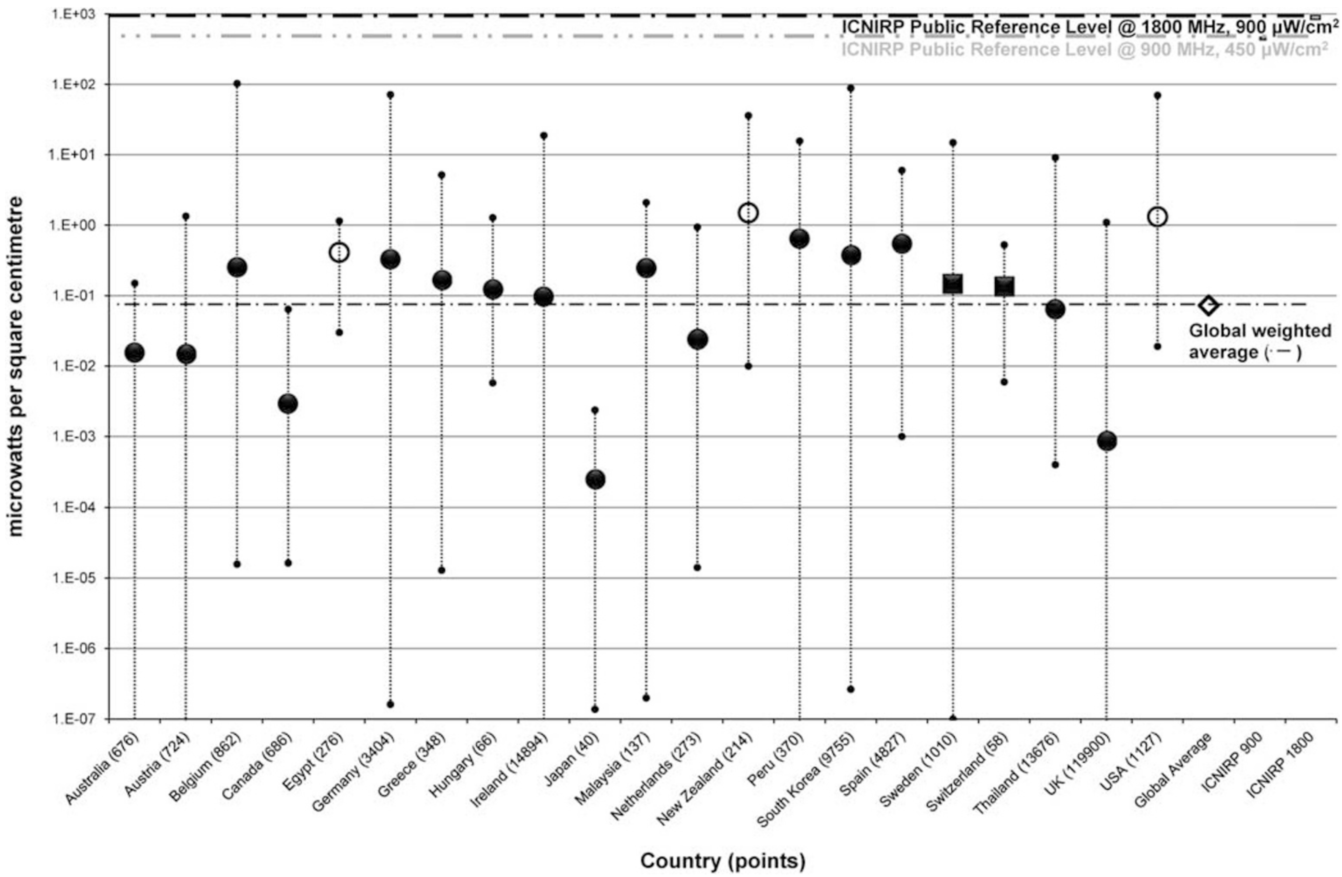

Figure 1. Minimum (●), maximum (●) and narrowband average (●), broadband average (○) or mixed narrowband/broadband average (■) of all survey data for each country with the number of measurement points for the country in brackets. For comparison, the global weighted average marked with dot–dashed line through (◇) and the ICNIRP reference levels for the public at 900 and 1800 MHz are also plotted.

locations at which measurements were made are clear from the results.

Mobile networks comply with RF exposure limits

From an inspection of each of the figures, it can be seen clearly that, irrespective of the year the survey was performed or the country the survey was conducted in, all the survey data complied with the ICNIRP Guidelines[10] and the US Federal Communication Commission Rules[65] by a very large margin irrespective of the service band. The global average in Figure 1 at 0.073 μW/cm^2 is more than 7000 times below the most restrictive ICNIRP reference level for the public relevant to these mobile communication services (400 μW/cm^2 at 800 MHz). It can also be inferred from Figure 1 that the introduction of arbitrary low exposure limits would mean that many base stations would need to be reworked in some way to achieve compliance. In response to the adoption by the Salzburg (Austria) city council of a policy of 0.1 μW/cm^2 in 2001, the Swiss communications regulator commissioned measurements of GSM services and concluded that it would be very difficult to achieve exposure values lower than 10 μW/cm^2 without substantial economic consequences (Coray, Krähenbühl, Riederer, Stoll, Neubauer and Szentkuti, 2002).

Broadband measurements are higher than narrowband measurements

For reasons previously discussed, *a priori* it would be expected that broadband measurements would typically yield higher values than narrowband survey measurements. The narrowband measurements are made on a single channel usually a pilot channel, whereas the broadband measurements see all the active traffic channels, as well as other RF sources, within their measurement bandwidth. There are ways to adjust narrowband measurements of single pilot channels to account for the effects of live traffic channels or indeed fully loaded base stations.[33] For GSM signals the relationship is:

$$E_{\max} = E_{\mathrm{BCCH}} \times \sqrt{N_{\mathrm{channels}}} \tag{2}$$

where $E_{\max}$ is the maximum electric field, E_{BCCH} is the GSM broadcast control channel, and N is the number of traffic channels. If N is unknown then it is taken as equal to 4, for a doubling of the E-field (4 times in power density).

For WCDMA (Wideband Code Division Multiple Access–3G) signals the relationship is:

$$E_{\max} = E_{\mathrm{WCDMA}} \times \sqrt{\frac{P_{\max}}{P_{\mathrm{p}} - \mathrm{CPICH}}} \tag{3}$$

where $E_{\max}$ is the maximum electric field, E_{WCDMA} is the WCDMA pilot control channel, $P_{\max}$ is the maximum possible WCDMA power and $P_{\mathrm{P-CPICH}}$ is the power of the pilot channel. Typically, $P_{\mathrm{P-CPICH}}$ transmits with a constant power at 10% of $P_{\max}$, this leads to a threefold increase of the E-field (10 times in power density).

Application to pilot channel measurements of the factors derived from Eqs. 2 and 3 allows extrapolation to the maximum RF exposure level and should improve the agreement between

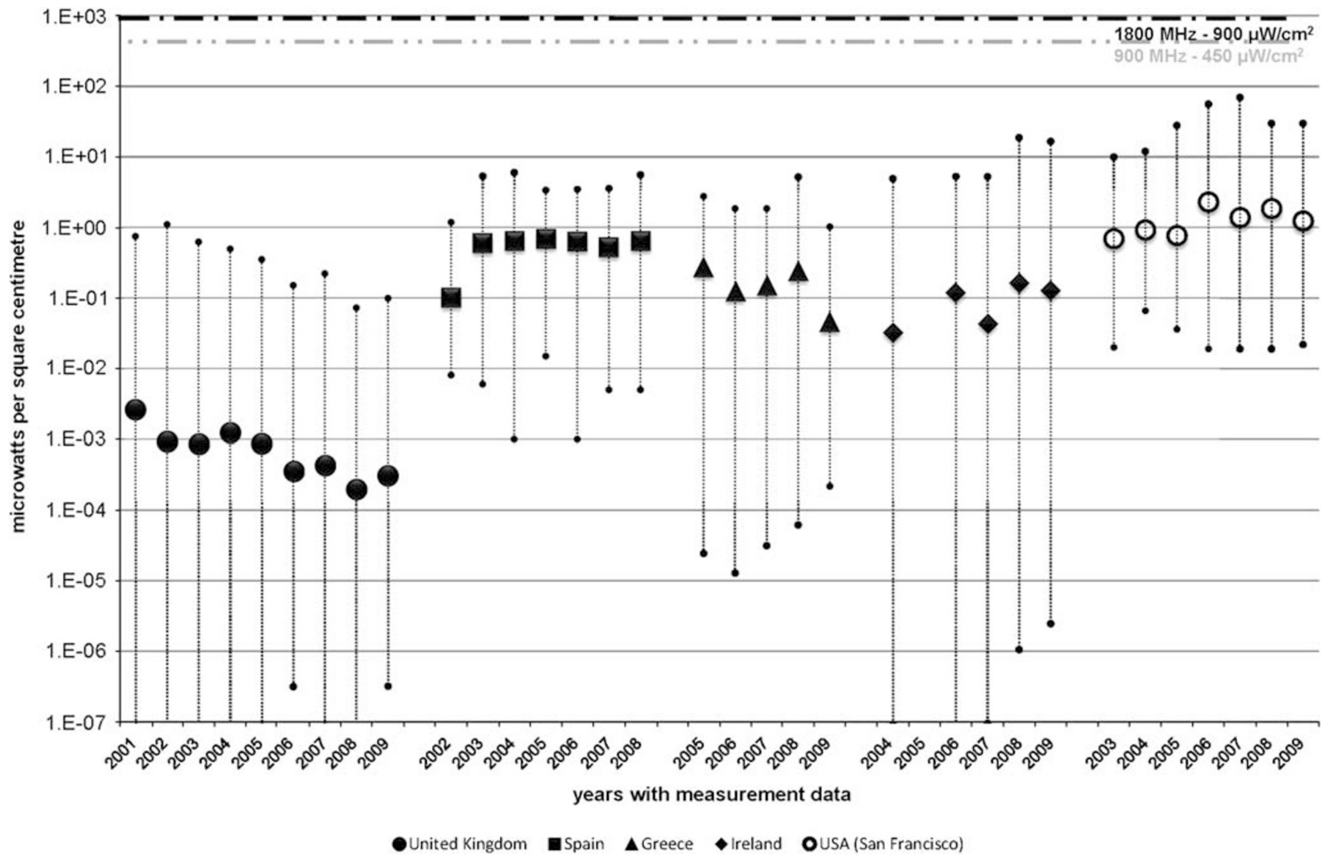

Figure 2. Minimum (●), maximum (●) and average of the narrowband measurements for the UK (●), Spain (■), Greece (▲) and Ireland (◆); and the broadband measurements for the US (○), with the year of measurement data on the horizontal axis. Note that not all years were available in all countries. For comparison, the ICNIRP reference level for the public at 900 MHz and 1800 MHz are included.

narrowband and broadband measurements, provided no other significant RF signals are present. These extrapolation factors explain some of the variation between the narrowband and broadband measurements in Figure 1, but not the large differences for the UK in Figure 2, which we believe are more due to differences in the proximity of the measurement point to the base station and instrumentation with a measurement sensitivity threshold in the region of 10^{-11} μW/cm^2.

Similar mobile technologies mean similar exposure levels

There is a perception among some stakeholders that the installation of more base stations will lead to higher levels of RF in the environment. This is not the case as shown by Figure 2, which demonstrates that despite the increasing number of base stations and deployment of additional mobile technologies, the environmental levels have remained essentially constant. This would be expected as these levels are generally driven by technology needs to provide a certain signal strength to maintain service quality. It should be noted that measurements were generally taken to characterize RF exposure in the vicinity of a specific base station rather than to obtain a profile of exposures either by individuals[58] or geographically.[19] It is reasonable to assume that population exposure to RF exposure from mobile networks has become more ubiquitous as geographic coverage has grown and in-building coverage increased in importance.

Exposures from mobile networks are similar to broadcast services

The average exposure at ground level from mobile communication technologies seen in Figure 3 is similar to that reported for broadcast services in a narrowband measurement survey of mobile communications and broadcast services in three European countries (Belgium, the Netherlands and Sweden) involving 311 locations spread over 35 areas[19] and a 200 person dosimeter survey in Eastern France.[60] From an historical perspective, measurements of VHF and UHF broadcast services from 486 locations distributed throughout 15 large cities in the USA, which collectively represented ~14,000 individual measurements, reported a median exposure level of 0.005 μW/cm^2.[66]

New surveys confirm existing exposure information

As is evidenced by Figures 1–3, exposures at ground level in public areas are a small fraction of the exposure limits and the levels vary little between countries, technologies and over time. Some countries have established fixed area RF monitoring systems,[67] but we argue based on our data that such schemes provide little new information to stakeholders in comparison to targeted surveys of a sample of existing base stations. It could be further argued that post-installation surveys provide limited new information in relation to typical exposure levels. A more efficient approach to demonstrating compliance to local governments and impacted communities would be for the network operator to provide a numerical assessment before obtaining permit for the installation of the base station.

CONCLUSION

Our analysis of base station RF exposure surveys is based on over 173,000 data points from 2000 onward, across 23 countries (21

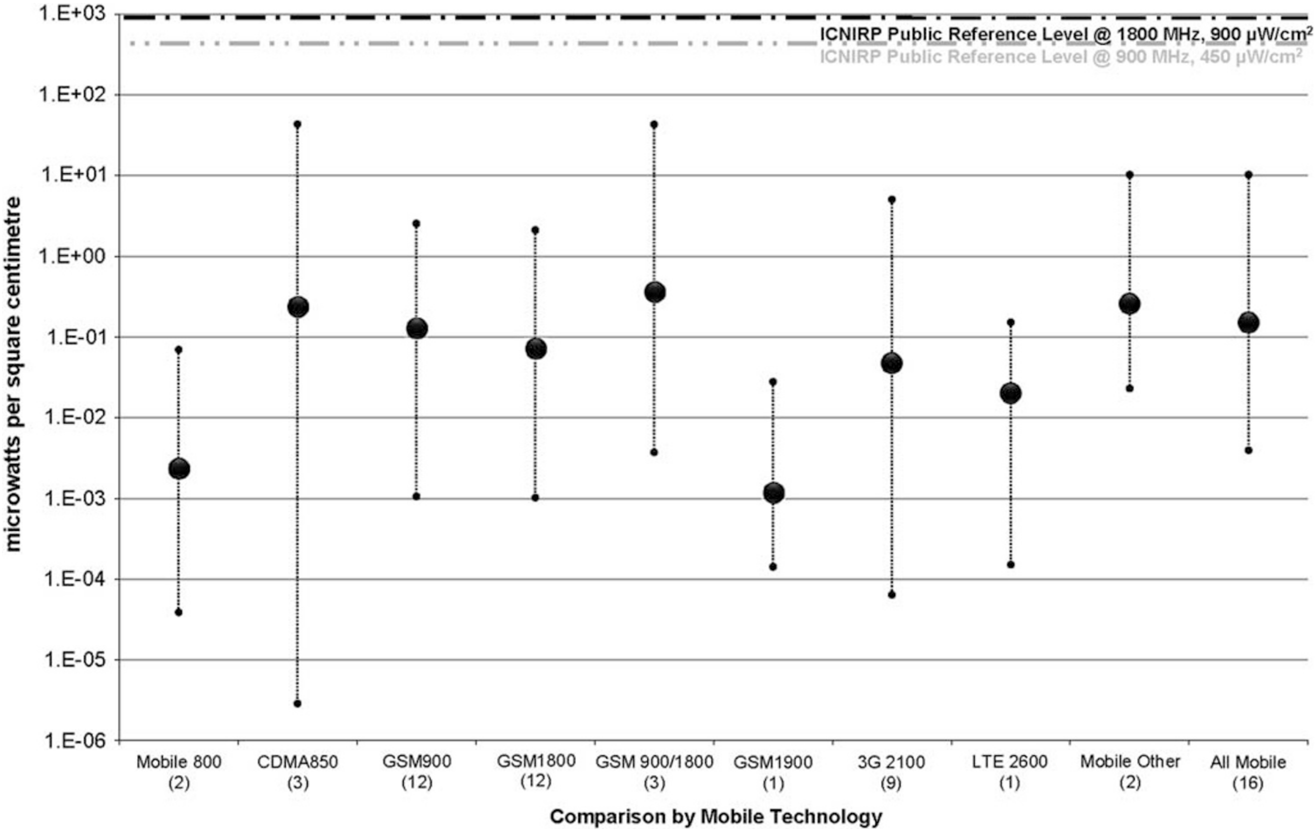

Figure 3. Minimum (●), maximum (●) and average (●) for each wireless technology. For comparison, ICNIRP reference levels for the public at 900 and 1800 MHz are also plotted. *Mobile Other* refers to mobile technologies either not identified in the source survey or not included (e.g., PDC) in one of the other mobile technologies categories. *All Mobile* is the result of averaging over all mobile technologies. Only narrowband measurements (from 16 countries) could be used. The weighted averages for all available measurement years for each country were then averaged over the number of countries with measurements for each mobile technology. The figure in brackets on the horizontal axis label is the number of countries for which measurements were available for each technology.

included in the analysis) and five continents. Across all countries, years and technologies RF exposures at ground level were only a small fraction of human RF exposure standards. Importantly, there has been no significant increase in the RF exposures at ground level in public areas near base stations since the widespread introduction of 3G services, which had 940 million subscribers at the end of 2010, out of a total of 5.3 billion subscribers.[1] Flat projections for voice traffic, the exponential growth in data and regulatory decisions allowing 2G spectrum to be reused for 3G services may see replacement of GSM with WCDMA. Figure 2 suggests that average exposure will not change and policy makers should be reassured by these results. Based on the existing data set it seems unlikely that further measurement surveys will provide substantially different exposure data. In addition, for the locations and types of installations in the original surveys post-installation measurements at ground level for compliance purposes are unnecessary. There may be areas on rooftops and immediately in front of base station antennas where compliance levels could be exceeded and such areas need assessment.[64] Although the average exposure at ground level is low, the wide variation (nine orders of magnitude) between the lowest and highest measured levels provides warning against the adoption of arbitrary RF exposure limits, which could adversely affect provision of mobile communication services.

A challenge for this type of analysis is differing measurement equipment, criteria for selection of the measurement location, settings of measurement equipment and survey methodology. Development of uniform guidance based on technical measurement standards would improve comparability of the results. Where the raw data are available, potential future analysis could include calculation of cumulative exposure distributions and investigation of the ability to combine exposure distributions with geographical and population density data to assess the distribution of exposure levels relative to population percentiles. We plan to conduct additional comparative analyses for those countries in our current data set that provide information on the RF exposures from other radio services such as broadcast television and radio. We intend to continue this work with the addition of the results of RF surveys from other countries, with data for additional years and for new mobile technologies.[68] We would welcome opportunities to cooperate with other researchers.

CONFLICT OF INTEREST

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DISCLAIMER

The views are solely those of the authors.

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