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A discussion of potential exposure metrics for use in epidemiological studies on human exposure to radiowaves from mobile phone base stations[1]

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There is currently a high level of concern in many countries that exposure to radiowaves from mobile phone base stations may be hazardous to health. When investigating such suggested risks, epidemiologists need to define an exposure metric that can reliably discriminate between exposed and unexposed groups of people. We conducted a feasibility study to investigate if either short-term measurements of electric field strength, calculations of electric field strength, or distance from nearby mobile phone base stations could be used to develop a metric reflecting an individual's exposure to radiowaves. With electric field strengths in the range of 0.012–0.343 V/m, radiowaves from mobile phone base stations were found to give a material contribution to total exposure; however, stronger signals were frequently measured from other sources such as broadcast radio and television transmitters. Theoretical considerations and the measurements made during this work demonstrated that studies at the population level on suggested adverse effects of radiowaves from mobile phone base stations are not feasible since no valid metric for estimating historical exposures is currently available. The pace of radio infrastructure development is also such that today's measurements are unlikely to be good proxies for either past or future exposures. The complex propagation characteristics affecting the beams from base station antennas include shielding effects and multiple reflections from house walls and other buildings. These factors, combined with the presence of other environmental sources of radiowaves, cause distance from a base station to be a poor proxy for exposure to radiowaves indoors. It may be possible to adapt computer models developed by network providers to predict network coverage for epidemiological purposes; however, this has yet to be investigated. Furthermore, there is little evidence that presently justifies epidemiological studies being restricted to adverse effects of radiowaves from mobile phone base stations while neglecting radiowaves at other frequencies produced by different transmitters. *Journal of Exposure Analysis and Environmental Epidemiology* (2000) **10,** 600–605.

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Introduction

In many countries, including Germany, people have expressed concern that exposure to radiofrequency electromagnetic fields (RF-EMF) from mobile phone base stations could lead to adverse health consequences. Moreover, the putative risk is perceived as being high, because the technology is unfamiliar. At many base station locations, residents were not consulted when the equipment was installed and they therefore tend to consider the involuntary exposure as unacceptable. Several local pressure groups have been founded with the aim of removing base stations, and successful protests have been reported from Australia (Chapman and Wutzke, 1997; Jong and Armstrong, 1997). Local initiatives sometimes gain significant attention by questioning the basis of protection guidelines (ICNIRP, 1998a,b) and by claiming that radiowaves are not only associated with thermal effects but also with diseases like cancer. In view of people's concerns, there is pressure on scientists and the government to conduct research on other possible effects from RF-EMF emitted from mobile phone base stations. The point is often made that, because of the rapid deployment of new installations, even small risks may have significant public health consequences. Against this background, we performed a feasibility study in Germany to investigate whether an exposure metric for epidemiological purposes could be defined that reflects an individual's exposure to RF-EMF from mobile phone base stations. The study also investigated whether exposure to RF-EMF from mobile phone base stations could be included in an international case–control study on brain cancer and the use of mobile phones (Cardis and Kilkenny, 1999).

Methods

Current Situation

There are currently four network operators providing five mobile telephone systems in Germany. One of the

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networks is analogue (C net), operating at 450 MHz, and the remaining four networks are digital (GSM) (Steele and Hanzo, 1999), two of them operating in the 900 MHz band (D net: 890–915 MHz uplink, 935–960 MHz downlink) and two of them operating in the 1800 MHz band (E net: 1710–1785 MHz, uplink; 1805–1880 MHz, downlink). The C net system was introduced in 1985, but never had more than a million users and now plays only a minor role in German mobile phone communications. The GSM systems have operated since late 1992 and there were more than 20 million users of mobile phones (24% of the German population) by summer 1999. At the same time, there were 29,000 base station sites, with one third of these sites used by more than one network operator. Each GSM base station antenna transmits on one to four carrier frequencies with eight time slots available per carrier. The first carrier contains the broadcast control channel (BCCH) in its first time slot and this is used to set up connections for phone calls in the remaining and 7, 15, 23 or 31 traffic channels (TCH). The maximum radiated power per carrier frequency is about 4–10 W and the carrier containing the BCCH is transmitted quasi-continuously at full power, even when no calls are being handled (quasi-continuously means that the power envelope shows transient dips between timeslots where the power envelope ramps down at the end of one timeslot before rising again for the next timeslot). The remaining carriers are only transmitted when calls are present and can minimise the power radiated in each timeslot so that communication is just maintained with each phone user (see Figure 1). These power considerations imply that the power radiated by a base station with the potential to emit four 10 W carriers could vary between 10 and 40 W depending upon the call traffic at a given time. If it is assumed that the maximum power is radiated from all of

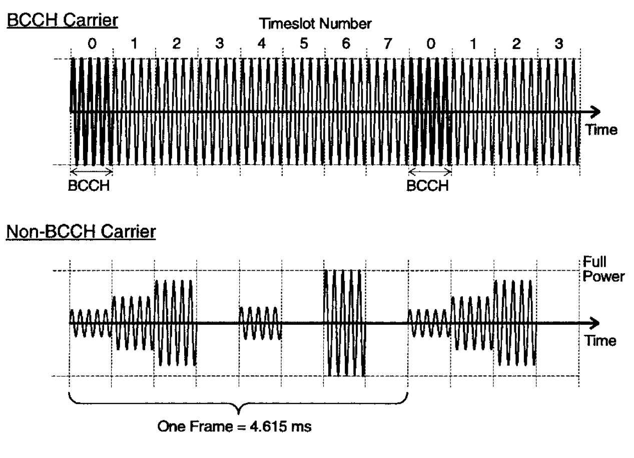

Figure 1. Illustration of the mode of operation of a GSM base station.

the antennas at a site shared by four network operators, the total radiated power into a given cell (or sector) may theoretically exceed 100 W.

Sample Measurements

Research focusing specifically on RF-EMF from mobile phone base stations is only justified if biological effects from this kind of field differ from effects caused by other radiowaves, possibly because:

(a) the power modulation on the non-BCCH carriers from mobile phone base stations (217 Hz) causes biological effects; or if
(b) radiowaves produce biological effects only within certain frequency ranges and the mobile communication frequencies belong to such frequency "windows".Alternatively, specific research could be justified if:
(c) the emitted fields from mobile phone base stations dominate people's total exposure to RF-EMF.

While there is little evidence in support of the first two hypotheses (ICNIRP, 1996), the third hypothesis can be tested through measurements of the RF-EMF.

During the feasibility study and within the context of the international case–control study on tumours of the brain, head and neck (Cardis and Kilkenny, 1999), we evaluated various aspects of the feasibility of such a study. One important task was to test the efficacy of the questionnaire and, while investigating this, we interviewed about 50 patients and a comparable number of controls. These controls were selected as a random sample from the telephone books of Bielefeld, Heidelberg, Mainz, and some rural areas. Nine of the controls lived in Mainz and at their current residences, we were able to conduct outdoor measurements of RF-EMF over the frequency range from 100 kHz to 2.9 GHz. It should be noted that the nine measurement locations were randomly sampled and were not selected because they were close to any base station. The measurements were performed by the German Regulatory Authority for Telecommunications and Posts, which is a governmental institution that issues certificates of safety for all radio transmitters operating in Germany (the department that conducts the measurements is also situated in Mainz and that is why they agreed to conduct some sample measurements in Mainz). The maximum signal strength was recorded by spot measurements using an antenna that was moved to detect horizontally as well as vertically polarised fields arriving from all directions and at heights between 2 and 10 m above the ground. All signals with electric field strengths above 100 μV/m (equivalent to a power density of 25 pW/m^2) were recorded.

Results

Measurements

Table 1 shows the results of the measurements at the nine random locations in Mainz. The range of fields emitted from mobile phone base stations was 0.012–0.343 V/m and this is considerably below guidelines published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) (ICNIRP, 1998a,b). For members of the public, ICNIRP advises reference levels of approximately 41 V/m for the D net (900 MHz) and 58 V/m for the E net (1800 MHz). At six out of the nine measurement locations, base stations produced at least one of the three strongest signals. Other sources of strong signals included radio broadcast antenna towers and air traffic communication transmitters (peak electric field strengths; average field strengths are considerably lower). In particular, one single AM radio broadcast tower emitted fields that were above 0.1 V/m at six out of nine measurement locations. Three locations were within 1 km of each other (lines 3, 5 and 6 of Table 1); however, the measured signal strengths at these locations were markedly different. The measured signal strengths produced exposures that were between 240 and 750 times below the ICNIRP reference level (ICNIRP, 1998a), as indicated in the last column of Table 1 (in terms of power density, the measured exposure is many thousands to millions below the reference level since, in the far field of transmitters, the power density equals the square of the electrical field strength divided by 377 Ω [=intrinsic impedance of free space]).

In conclusion, radiowaves from mobile phone base stations contribute materially to the overall environmental exposure to RF-EMF, at least in urban areas; however, this contribution is not great enough to justify research neglecting other environmental radio signals. Exposure misclassification would be a problem for any study focusing purely on signals from base stations, as subjects not exposed to radiowaves from mobile phone base stations but exposed to radiowaves from other sources would be falsely classified as unexposed. Under these circumstances, the misclassification would be random (non-differential), i.e. spread equally between the groups defined as cases and controls. This would compromise the statistical power of the study and lead to an inability to identify any effect that might have been present (dos Santos Silva, 1999).

Exposure Metrics

Strictly speaking, there are no people who are completely unexposed to radiowaves because radiowaves travel great distances and transmitters are spread throughout the environment. Everyone who lives where calls can be made with mobile phones is exposed to a background power density of around 0.001–10 μW/m^2 at mobile phone frequencies, and the German network operators have indicated that coverage is 99% of Germany. What is necessary for epidemiological purposes is an exposure metric that can reliably discriminate between subjects exposed at background level and subjects having substantially higher exposure to radiowaves. Potential candidates for exposure metrics are field measurements, field estimations and distance measurements (proximity to a base station).

Measurements Measurements permit exposure to be assessed over the entire RF-EMF range, from which the exposure component arising from mobile phone base stations can be extracted. Aside from the practical problem that spectral measurements can take several hours to perform, there are other disadvantages with this technique. First of all, the measurements are point-in-time measurements that are unlikely to be good proxies for average

Table 1. Electric field strength measurements in the range of 100 kHz–2.9 GHz at nine randomly selected measurement points in Mainz, Germany.

Strongest signal (total RF range; (100 kHz–2.9 GHz)		Strongest signal from mobile phone base stations		Rank of strongest signal from base station within total RF range	Factor below guidelines[c]
[V/m]	Type (f [MHz])[a]	[V/m]	Net[b]		
0.248	FM radio broadcast (90)	0.035	D	17	460
0.112	AM radio broadcast (0.9)	0.045	E	6	460
0.309	E net base station antenna (1800)	0.309	E	1	450
0.191	E net base station antenna (1800)	0.191	E	1	500
0.331	air traffic communication (1300)	0.243	D	3	330
0.479	air traffic communication (1300)	0.107	E	3	750
0.343	D net base station antenna (900)	0.343	D	1	240
0.108	AM radio broadcast (0.9)	0.012	E	9	630
0.120	AM radio broadcast (0.9)	0.078	E	3	320

[a]Frequencies are rounded to avoid identification of particular transmitters.
[b]Mobile telephone system: D net: 890–915 MHz, uplink; 935–960 MHz, downlink; E net: 1.710–1.785 MHz, uplink; 1805–1880 MHz, downlink.
[c]Total exposure compared to the electric field strength reference levels advised by the ICNIRP for the general public.

exposure. Since the radiated power from base stations depends on the varying call traffic, the radiated power is time-dependent. Secondly, the number of base stations has increased rapidly over recent years, meaning that today's measurements would not be good proxies for past exposures. This is particularly the case in respect of cancer studies because of the expected long latency period. Thirdly, residential measurements do not take into account the individual's exposure at work, or elsewhere, which might be very different to their exposure level when at home. Moreover, since there is only a poor correlation between indoor and outdoor power density, outdoor measurements may not be used as proxies for exposure levels within houses. This is because house walls provide shielding from outdoor radiowaves and there may be indoor sources of radiowaves that could produce higher exposures than signals from outdoors, e.g. base stations of digital cordless telephones (DECT). One further major disadvantage of RF measurements is that in our feasibility study, they were very costly (about 1,000 Euro per measurement) and time-consuming. No suitable personal dosimeter to record the individual's RF exposure has been developed so far. Body-worn instruments are available that measure exposures at levels comparable with the reference levels, e.g., in industrial environments, but the equipment lacks sensitivity at locations that are not in the immediate vicinity and directly in the beam of base station antennas.

Distance Distance to a nearby base station or some form of distance code would be attractive surrogates for measurements of RF-EMF exposure. A distance code in an epidemiological study could be a crude categorical scale (e.g. baseline, medium, high exposure) based on the distance between residence and base station and a combination of other factors. These other factors could relate to the base station (e.g. maximum power load, direction of the main beam) and/or the residence (e.g. storey of the apartment, building materials). The main advantage of such an exposure surrogate would be that it would be practicable for large study populations. However, it could only be used if the distance to the base station and the power density were well-correlated. Theoretical considerations and measurements performed in Germany and the UK (Mann et al., 2000) show that this correlation is very poor (the reasons for this are illustrated in Figure 2). Subjects living close to a base station, but not within the main beam of the antenna, tend to be exposed to fields no higher than would be present in the absence of the base station. Subjects located in the direction of the main beam may also be exposed to fields no higher than background levels because walls and other houses between them and the base station act as shields. Conversely, some subjects not living within the main beam might be exposed to higher scattered fields or elements of the main beam reflected from other houses. In summary, using proximity to a base station as an exposure measure would result in a considerable number of misclassified subjects, particularly when unexposed subjects living close to base station would be falsely classified as exposed. This would reduce the specificity of the exposure index. Since this type of misclassification would be non-differential, risk estimates from epidemiological studies would underestimate any potential effect. For factors with a low prevalence of exposure, only a slight reduction of specificity can lead to gross underestimations of potential effects. Assuming a prevalence of high exposure of 5% and a true risk factor of 1.5, with a sensitivity of 100% and a specificity of 90%, the observed risk estimate would be 1.17 (Breslow and Day, 1980). If the prevalence of high exposure were only 1%, the misclassification would lead to an observed risk estimate of 1.05. This shows that, even if exposed subjects could be correctly identified by a distance measure, the expected large number of unexposed subjects that would be classified as exposed is likely to render the results from the study very difficult to interpret in the context of exposure to RF-EMF.

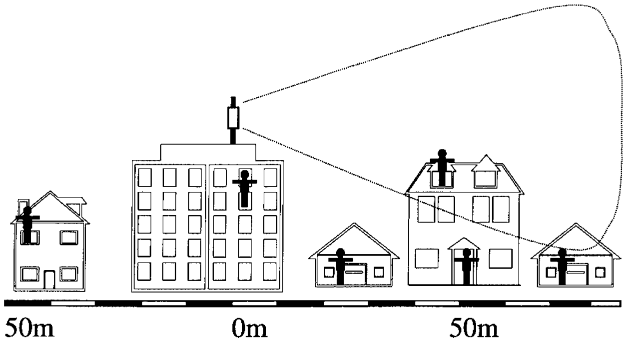

Figure 2. An illustration of how power is radiated from a mobile phone base station antenna (neglecting effects of shielding and reflections by house walls).

Power Density Estimations In Germany, the network operators are developing a computer system that analyses the coverage of mobile phone base stations. This system predicts field strength at a given location on the basis of the position of the base station, the maximum power load, antenna characteristics, and some geographical characteristics. It also takes into account the workload of the base station and estimates the shielding effects of house walls. Therefore, it might be possible that this system could be adapted for epidemiological purposes. However, the prediction model has yet to be validated. Other limitations are that the model cannot predict past exposures and that the assumptions on shielding and reflections are very crude. Sources of radiowaves other than mobile phone base stations are ignored.

Discussion

Many epidemiological studies have investigated effects of environmental electromagnetic fields; however, most studies have considered power–frequency fields (50/60 Hz), particularly in respect of childhood cancer (Portier and Wolfe, 1998). Exposure has been assessed in many different ways, but residential measurements have become the preferred method (Linet et al., 1997; Michaelis et al., 1998; Dockerty et al., 1999; McBride et al., 1999; UKCCSI, 1999). Magnetic field estimations based on the power load of power lines were used in Scandinavian studies, but due to country-specific characteristics of electricity distribution, they are not applicable everywhere (Ahlbom et al., 1993). Ecological studies in the vicinity of TV/radio transmission antennas compared cancer incidence in areas closest to the transmission towers to expected numbers. Exposure was assessed from proximity to these towers (Maskarinec et al., 1994; Hocking et al., 1996; Dolk et al., 1997a,b) or from calculated signal strength (Hocking et al., 1996; McKenzie et al., 1998). In view of this, we decided to evaluate if studies based on these assessment techniques would be feasible for radiowaves emitted from mobile phone base stations.

In the power–frequency range, magnetic fields have been shown to be comparably stable over time (Dovan et al., 1993) and spot measurements in residences were found to be fairly well correlated with measurements from personal dosimetry (Friedman et al., 1996). Neither of these conditions is likely to be satisfied in the mobile phone frequency range, since the rate of installation of new transmitters has been so rapid and RF-EMF is strongly affected by its surroundings (radiowaves are reflected by walls, etc., whereas magnetic fields are able to pass through unaffected). The instability over time prevents the feasibility of cancer studies; however, in the field of acute disorders, e.g. sleep disturbances, spot measurements may be meaningful for estimating exposure.

Even today's spot measurements of RF-EMF should be interpreted with care, because performing measurements over a range of frequencies and within a practical timeframe only allows a short time interval to be recorded at each frequency. Since the radiated power from mobile phone base stations depends on the number of calls at a given time, short-term measurements may be inadequate to estimate exposure over time. The contribution to total exposure arising from signals from intermittently transmitting sources other than base stations may also be overemphasised or neglected completely depending upon whether the signals are present or not during the recording interval.

A categorical exposure scale based on the distance between a residence and a nearby mobile phone base station would be a convenient exposure index, since it could be easily applied to large populations and would be calculable without contacting study participants. Distance measures have been used in cancer studies in the vicinity of broadcast towers. However, these antennas radiate power in the range of hundreds of kilowatts and are therefore likely to be the dominant signal source in their vicinity (Maskarinec et al., 1994; Hocking et al., 1996; Dolk et al., 1997a,b; McKenzie et al., 1998; Schüz and Michaelis, 1999). This is not the case with mobile phone base stations as the powers are very much lower. At typical distances where the public is exposed to RF-EMF from base stations, the fields emitted are much lower and comparable with those of other environmental signals. This makes it very difficult to identify people whose RF-EMF exposure is above the population average. Distance between a residence and a base station is a poor proxy for the total power density within the residence because of:

(a) the directional characteristics of the main beam from base station antennas;
(b) scattering, shielding and reflection of the radiated fields by house walls; and
(c) power density contributions from other sources, such as the base stations of digital cordless telephones.

Therefore, proximity to a nearby mobile phone base station cannot be used as a surrogate for exposure to RF-EMF. Exposure misclassification, particularly classifying unexposed subjects as exposed, would be likely to mask any effect present.

Computer models being developed by German network providers to predict network coverage may be adapted for epidemiological purposes; however, further work will be required in order to validate the models.

In summary, despite extensive epidemiological research in other areas of exposure to EMF, none of the exposure metrics used in previous studies is presently appropriate for studies investigating health effects of RF-EMF from mobile phone base stations. With some further work, measurements may be able to assist investigations of acute effects, e.g. sleep disturbances, but they would not assist investigations of chronic conditions, such as cancer, cardiovascular diseases or neurodegenerative diseases.

Conclusions

The conclusions of our feasibility study are the following.

It would be inappropriate to conduct epidemiological investigations based on proximity to mobile phone base stations since this exposure metric is a poor surrogate for an individual's exposure to radiowaves.

Exposure to radiowaves from mobile phone base stations should not be included as a potential risk factor in a planned

multicentric study on mobile phone use and tumours of the brain and neck. There is no appropriate metric currently available and spot measurements would be inappropriate to assess exposure in cancer studies because today's measurements would be poor proxies for former exposures.

Further studies should be carried out to evaluate if the analysis systems used to predict mobile phone network coverage can be adapted for epidemiological purposes; in particular, to evaluate whether the software tools used can reliably discriminate between levels of exposure in the direction of the main beam from mobile phone base stations.

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