HEALTH ASPECTS OF CELLULAR MOBILE TELEPHONES

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INTRODUCTION

Cellular mobile telephones are one of the main topics among health aspects of electromagnetic fields. In many countries, the number of people opposing communication towers is on the rise. Lawsuits against telecommunication and power line companies have been filed. All this makes people doubt the safety of electromagnetic fields.

With respect to cellular phones, there are two scenarios:

☆ Exposure of the operators of hand-held terminals (HHT).

☆ Exposure of the general public from base stations (BS).

In the first case, the transmit antenna of the HHT is very close to the human body. For normal operation, the distance will roughly be 2 - 3 cm. The transmitter power of the HHT is comparatively low, but there is a considerable fraction of the radiated electromagnetic energy penetrating the tissue. Considering the second case, BS transmitter powers are by a factor of 100 - 1000 higher, but the distance between antenna and the human body is by a factor of 1000 - 100000 greater, as far as areas of unrestricted public access are concerned. As the power density of an electromagnetic wave decreases inversely proportional to the square of the distance, exposure of the public is always significantly (by many orders of magnitude) lower than exposure of operators of HHTs.

Some well-known interaction mechanisms of microwave radiation with the human body have been very well-established today. In some other areas, there is still a need for further research. This paper summarizes present knowledge on human safety with mobile telephone systems.

TECHNICAL CHARACTERISTICS OF CELLULAR MOBILE TELEPHONE SYSTEMS

Cellular mobile telephone systems can be categorized with respect to several parameters: Digital or analogue modulation, carrier frequencies, transmitter power, etc. Table 1 shows a survey about the technical characteristics of some selected, important systems used around the world today. We find that

- both analogue and digital systems are used today, but the trend clearly goes towards digital systems. With respect to biological effects, the key difference between the two kinds of modulation is that analogue systems use continuous transmission, while digital systems use pulsed transmission.
- Transmitter frequencies of HHTs are in the ranges of 441-456 MHz, 810-849 MHz, 872-915 MHz, 1.429-1.453 GHz, and 1.710-1.785 GHz. With respect to biological effects, a different carrier frequency makes a difference in the amount of energy absorbed in the tissue (see chapter about the heating effect below).
- Mean transmitter powers of HHTs never exceed 1 W, for most digital systems it is below 0.6 W. Moreover, most systems operate at even reduced power when the transmission channel is sufficiently good.

The data given in Table 1 summarizes the key characteristics of cellular telephones with respect to health aspects.

RELEVANT BIOLOGICAL EFFECTS

Based on present knowledge, the following biological effects can be considered relevant for human exposure to electromagnetic radiation from mobile telephone systems:

Local heating of tissue due to absorption of electromagnetic energy:

This effect occurs while using hand-held terminals. Results of scientific investigations will be discussed below. The effect does not occur with exposure of the general public by the electromagnetic radiation from base stations, as far as areas of unrestricted public access are concerned.

Interference of the electromagnetic field from hand-held terminals with electronic medical implants such as cardiac pacemakers or defibrillators:

The results of scientific investigations will be discussed below. Interference caused by the electromagnetic radiation from base stations does not occur, as far as areas of unrestricted public access are concerned.

Other effects that are known from in-vivo or from in-vitro experiments seem not to be relevant or have not been sufficiently well established yet to allow a conclusion to be made.

Changes in human EEG:

One researcher (1) reported a five-fold increase in the power density of the 10.7 Hz (α) - spectrum of the human EEG. Changes were observed during and after exposure with 217 Hz - modulated radiofrequency fields of a power density of less than 0.1 $\mu W/cm^2$. The carrier frequency was 150 MHz, the duration of the square-wave pulses were 100 μs. We have repeated the experiments described in (1), the same was done at several other research

Table 1. Selected public cellular mobile telephone systems that use HHTs

System	Countries	Mobile transmitter frequencies [MHz]	Mobile transm. mean rms output power [W] [1])	Modulation	Multiple Access	Analogue / Digital
NMT 450	Scandinavia, Denmark, France, Austria, Switzerl.	441-456 [2])	1	PM speech FSK contr. sign.		A
ETACS	U. K., Italy, Austria, Spain, Malta, Ireland	872-905	0.45 [3])	PM speech FSK contr. sign.	SCPC/ FDMA	A
NTT	Japan	915-940 [2])	1			A
NMT 900	Scandinavia, Denmark, Switzerland	890-915	1	PM speech FSK contr. sign.	FDMA/ TDMA	A
GSM	Europe, Asia, Pacific	880-915	0.25 [4])	GMSK	TDMA	D
CDMA	North America	824-849	0.6	QPSK	DS/CDMA	D
NADC	North America, Asia, Pacific	824-849	0.2	/4 DQPSK	FDMA/ TDMA	D
JDC (PDC)	Japan	810-826	0.3	/4 DQPSK	FDMA/ TDMA	D
JDC (PDC)	Japan	1429-1453	0.3	/4 DQPSK	FDMA/ TDMA	D
DCS 1800	Europe	1710-1785	0.125	GMSK	TDMA	D

[1]) All systems except NMT 450 use mobile power control. Example: GSM in Austria: Power reduction in 2 dB-steps as soon as -94 dBm (÷ 0,4 pW) is reached at the mobile receiver input.

[2]) Summary of frequencies used in different countries or regions, values rounded.

[3]) 0,6 W ERP = standard, approximately 1,5 dB antenna gain assumed.

[4]) Units with 2 W peak power. The standard would allow 5 W for HHTs, but there are no 5 W terminals on the market.

PM .... phase modulation
FSK .... frequency shift keying
GMSK ..... gaussian minimum shift keying
QPSK ...... quadrature phase shift keying
DQPSK ... differential quadrature phase shift keying
FDMA ..... frequency division multiple access
TDMA ..... time division multiple access
DS/CDMA direct sequence code division multiple access
SCPC .... single channel per carrier

laboratories throughout the world. All results were negative, the findings of (1) were not confirmed, e. g. (2). Thus, at present, reactions to the observations reported in (1) would not be justified.

Influences on cell membrane permeability:

The transport of the cations potassium (K^+), sodium (Na^+) and calcium (Ca^{++}) from the interior of the cell to the intercellular space can be increased by amplitude modulated fields (1 - 100 Hz) in the frequency range of 50 MHz - 3 GHz (3, 4, 5). This has overall significance for the general cell function. The effect seems to be restricted to certain „windows" of power density and frequency. It seems to be a true non-thermal effect, as the results have been obtained even at specific absorption rates below 1 mW/kg. So far there has not been any mechanism demonstrated that could explain the phenomenon. Furthermore, the relevance of the effect for human health is totally unclear. Thus, the preliminary results about influences on cell membrane permeability cannot be used to derive conclusions regarding the use of mobile telephone systems at present.

Influences on nerve tissue:

The electrochemical potential of brain- and peripheral nerve cells can be affected by radiofrequency radiation (4, 5). It seems to be impossible to distinguish between thermal and non-thermal effects. The literature available today does not permit any conclusions regarding exposure with mobile telephone systems.

Influences on the immune system:

Several studies show that it has been possible to increase the level of macrophage activity or to inhibit the activity of natural killer cells by exposure to radiofrequency radiation. Effects seem to be mainly due to thermally induced stress when the whole-body temperature is increased by 1 degree Celsius or more. A chain reaction is then initiated from the hypothalamus. Results are not conclusive. At present it is not possible to derive any conclusions regarding mobile telephone systems.

Mutagenic and carcinogenic effects:

It has not been possible to demonstrate independent mutagenic effects (genetic damage) at cellular levels, even under weak hyperthermic conditions. An independent initiation effect on the DNA level with direct DNA damage has not been positively demonstrated after exposure to radiofrequency fields. The activity of the enzyme ornithine decarboxylase and the activity of nonspecific protein kinases can be affected by strong radiofrequency fields. Therefore, such fields cannot be regarded as an initiator of a carciogenic process on the cellular level. A possible promotion has not been proven, but, according to some published, preliminary results of investigations, it cannot be excluded (6). These studies are very controversial. The majority of the studies was done using specific absorption rates higher than those occuring with normal use of mobile telephones. On the basis of data available today it is not possible to derive conclusions regarding mobile telephones.

Most of the data regarding the effects mentioned above are inadequate for drawing any conclusions about possible health effects of cellular telephones. Further investigations will be necessary before judging the relevance of the above mentioned effects.

EXPOSURE OF OPERATORS OF HAND-HELD TERMINALS

Heating effect

Hand-held terminals are operated at distances between antenna and biological tissue of approximately 5 - 30 mm. The parts of the tissue (head) that are located close to the antenna absorb a significant amount of electromagnetic energy. This absorption of energy leads to a temperature rise in the tissue. Supply of energy and cooling by blood flow can compensate, if a certain amount of power per mass (specific absorption rate, in watts per kilogram) is not exceeded, and if the rate of blood flow (volume per time, in liters per minute) is sufficiently high. This criterion will be fulfilled for very low power transmitters (numerical values will be given below) and tissue with a high rate of blood flow. An example for this is the brain, which has a metabolism that is eight times the body average. The criterion might not be fulfilled for tissue with a low rate of blood flow such as the eye. Another relevant criterion is the sensitivity of the organ that is irradiated. Critical organs could be

- the eye (located at the body surface; high absorption due to protein; no blood flow);
- the inner ear (located very close to the antenna of the hand-held terminal; no absorbing tissue (only bone) between antenna and cochlear; high absorption in the liquid of the cochlear, which contains the hair cells; thermally isolated location in bone with only minimal blood flow);
- the hypothalamus (well-cooled by blood flow, surrounded by brain tissue with a high rate of blood flow; possibly critical organ because it controls a variety of functions in the body, e. g. circulation of blood, breathing, etc.);
- pineal gland (well-cooled by blood flow; possibly critical organ because it produces the tumor-inhibiting hormone melatonin).

Due to the heterogenity of the human head, the field distribution in the tissue is very complex. Today, complicated numerical techniques are used to calculate local specific absorption rate (SAR) and local temperature rise. Furthermore, results of measurements of electric field-strength and temperature rise in homogeneous and heterogeneous phantoms are available. The following, simple equations are used to determine SAR, once the field-strength has been calculated:

$$SAR = \frac{\sigma|E|^2}{\rho} = c\frac{dT}{dt}$$

where

$|E|$ ...... absolute value of electric field-strength in the tissue

σ .... conductivity of the tissue; typical values of σ at 900 MHz are between 0.2 S/m (cortical bone) and 2 S/m (aqueous humour)

ρ .... density of the tissue; for tissue with high water content, $\rho \approx 1$

c .... heat capacity of the exposed part of the body; for tissue with high water content, $c \approx 4.0\text{-}4.2\ J.kg^{-1}.°C^{-1}$

dT/dt .. time derivative of tissue temperature.

Published *results about SAR* are sufficiently consistent to draw reliable conclusions: The SARs in various kinds of tissue have been experimentally determined in phantom materials (7), see Figure 1. There is a strong frequency-dependence. The values in Figure 1 are valid for a typical separation distance of 2,5 cm between antenna and body (normal operation of a HHT) and irradiation from a half-wave dipole.

Tissues:

- ● muscle
- ■ brain
- ○ fat
- □ eye

Irradiation with half-wave dipole,
25 mm from phantom surface
7 W transmitter power

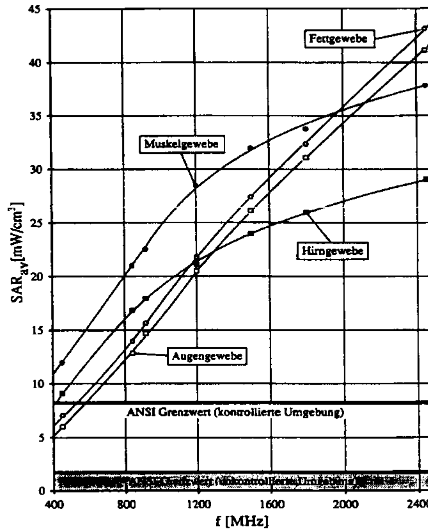


Figure 1: Specific absorption rates in various kinds of tissue, averaged over 1 g (7)

The *distribution of SAR in the head* has been studied by several authors. Figure 2 shows histograms of the SAR-distribution in a horizontal plane through the eyes at 800 MHz (8). The calculation was done using the finite-difference time-domain (FDTD) method. The model of the head consisted of 126.000 cubic cells with a side length of 3,2 mm each. The head is irradiated by a plane wave from the front. Maximum absorption occurs in the eyes. Another local maximum occurs in the center of the head. For the adult (Fig. 2a), the SAR in the center of the head is lower than the SAR in the eyes. For the child (Fig. 2b), the SAR in the center of the head is approximately the same as the SAR in the eyes. When the dipole is located in front of one eye, maximum absorption also occurs in this eye. The maximum in the center of the head disappeares at this near-field exposure. At higher frequencies, the fraction of power penetrating the head is less than at lower frequencies, absorption primarily occurs at the surface and within the first few centimeters of tissue.

Figure 3 shows the maximum values of SAR, averaged over 10 g of tissue, as a function of distance between antenna feed-point and the body (10). At a distance of 2 cm (realistic worst-case for normal operation) and a position of the HHT at the side of the head, the maximum is about 3 W/kg per W for 900 MHz and 4 W/kg at 1.8 GHz. A larger averaging volume results in lower SAR-values, a smaller volume results in higher SAR-values. According to another study, averaging over the eye in an exposure situation where the transmitter is held in front of this eye results in a maximum of approximately 6 W/kg/W at 900 MHz and 11 W/kg/W (adult) to 18 W/kg/W (child) at 1,8 GHz (9). From Table 1 we can see, that transmitter power is less than 1 W for all systems except NMT and NTT. Therefore, in particular for the digital systems, SAR will be lower than the values mentioned above. For, e. g., a GSM handy with 0.25 W average power, worst-case SAR in the eye will be 1,5 W/kg for 2 cm distance. If the antenna is brought even closer to the head, SARs will be higher: For a distance of 3,2 mm and averaging over 1 g of tissue, a local SAR as high as 30.4 W/kg per W has been calculated (9). Such a position of the HHT at the head anyway does not correspond to normal operation.

A more difficult task than the calculation of local SAR is the *calculation of local temperature rise*. Only very few results are available at present. In a recent study (11), the basic relation between SAR, temperature change and transmitter power has been shown, see Figure 4. The graph is valid after 30 seconds of exposure. For such short exposure time, temperature rises linearly with energy deposited in the tissue. Later, thermal equilibrium will be reached. The final amount of temperature rise will depend on a variety of parameters such as the kind of tissue, environmental temperature, cooling by blood flow, etc. In another study (12), the spatial SARs, averaged over one cm^3, were calculated for the human eye, and then the heat conduction equation was solved using the implicit alternating-direction (IAD) algorithm. Irradiation from a half-wave dipole at frequencies of 840 MHz, 915 MHz, 1500 MHz and 1800 MHz led to temperature rises as shown in Figure 5a. For a continuous transmitter power of approximately 0,7 W and a distance of 2 cm between antenna and surface of the eye, maximum temperature differentials reach approximately 0.2° C at 840 MHz, 0.25° C at 915 MHz, 0.6° C at 1500 MHz and 0.65° C at 1800 MHz. For a distance of 6.5 mm and a CW transmitter power of approximately 0.8 W, maximum temperature elevation reaches approximately 1° C at 840 and 915 MHz and approximately 2.2° C at 1500 and 1800 MHz. A maximum absolute temperature of 39° C at 1500 MHz was calculated in the posterior region of

a) Head of an adult b) Head of a child

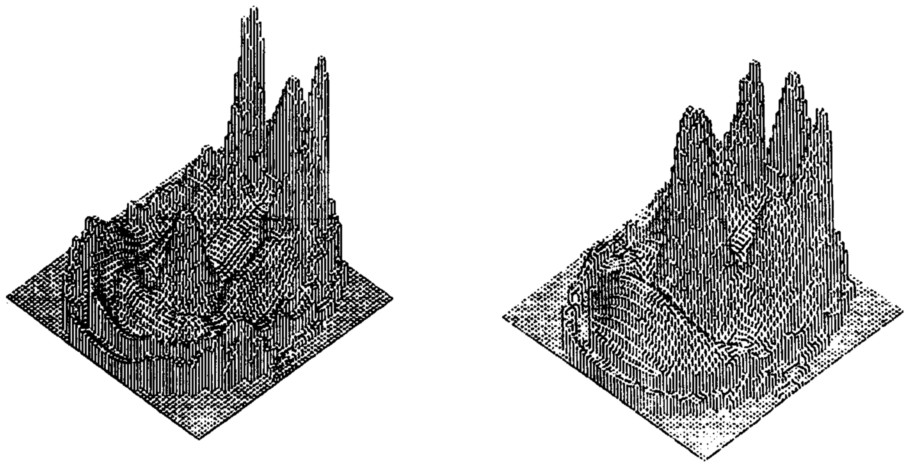
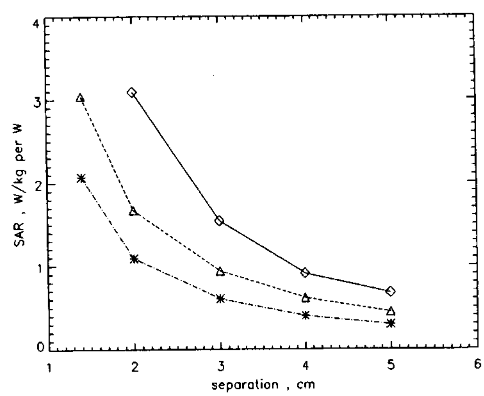


Figure 2. Histograms of the SAR in an anatomical model of the human head that is irradiated by a plane wave from the front at 800 MHz, horizontal cross-section through the eyes (8).



Asterisks: HHT and antenna horizontally beside the left ear (chassis at front, antenna at back of the head)
Diamonds: HHT and antenna vertically in front of the left eye (antenna up)
Triangles: HHT and antenna vertically in front of the left ear (antenna up)

Figure 3. Maximum values of SAR, averaged over 10 g of tissue (10)

the eye for 6.25 mm distance. Lower transmitter power will result in lower temperature rise and lower absolute temperature, see Fig. 5b: For 2 cm distance and 1500 MHz, temperature rise for a peak transmitter power of 0.7 W and a duty cycle of 1:8 (GSM) is only about 0.04 °C, where it has been about 0,6 °C for 0.8 W CW. Thus we can estimate that the maximum temperature rise in the eye for, e. g., a 2 W - GSM handy with 0.25 W average power at 2 cm distance will not exceed 0.1 to 0.2 °C.

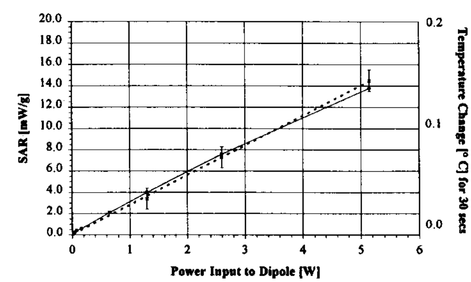
Induction of cataracts in the eye has been shown to occur at temperatures of 41° C or more. Considering the worst-case data given above (12), there seems to be a sufficient safety factor between temperatures occuring with the use of HHTs and temperatures that must be regarded hazardous for the eye.

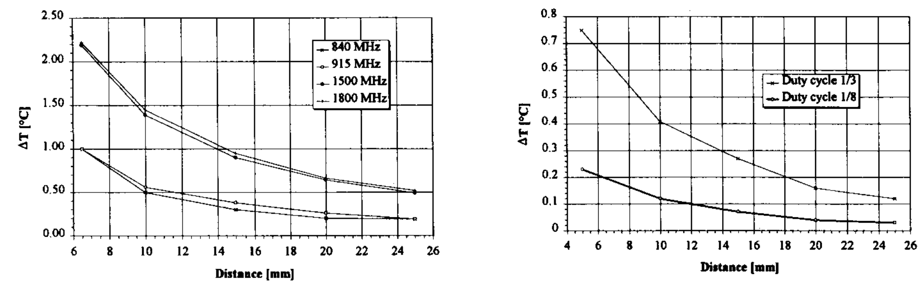
Temperature elevations in other, possibly critical organs, such as the inner ear, the hypothalamus, etc., have not yet been precisely calculated. This is an important, remaining task that should be carried through, before final judgements about thermal effects, exposure limits, or restrictions on transmitter power can be made.

Interference to Medical Implants

Electromagnetic fields can interfere with electronic apparatus. We have studied 9 scientific publications and symposium contributions about experiments with cardiac pacemakers and defibrillators, e. g. (13, 14, 15, 16). In these studies, a total of 363 tests have been carried out using actual implants in phantoms. In 116 cases interferences occured, this corresponds to 32 %. Among these, 40 (11 %) caused inhibition, 33 (9 %) caused asynchronous pacing, 36 (10 %) caused synchronization, and 7 (2 %) caused combinations of the three effects. All tests were done at very small distances between HHT and surface of the phantom, i. e. representing a HHT held close

Figure 4. Typical values of specific absorption rate and temperature change versus transmitter power, measured in a phantom irradiated by a half-wave dipole at 840 MHz (11)





a) 4 different frequencies, peak transmitter power approximately 0.8 W

b) 2 different duty cycles at 1500 MHz, peak transmitter power approximately 0.7 W

Figure 5. Maximum temperature differentials in a model of the human eye for various distances between a dipole antenna and the body surface (12)

to the chest. The above mentioned statistics do not mean that one third of all pacemaker patients have to expect interferences when using a mobile telephone. Most of the tests were carried out in-vitro, and worst-case configurations were used. Enlargement of the separation between HHT and the pacemaker eliminated the interference in all cases. Recommendations for the safety distance range between 10 cm and 40 cm.

Interference to a pacemaker can mean a severe health hazard to the patient:

- Switching to the asynchroneous mode during normal heart activity can trigger vertricular fibrillation, if the impulses appear within the vulnerable phase of the heart. This certainly indicates serious danger.
- Synchronization can lead to wrong stimulation of ventricles. This can make patients feel unwell and effects of weakness and fainting can be expected.
- Inhibition would also result in weakness and fainting.

A major reason for the interferences is the amplitude-modulation of the mobile telephone signals. Therefore, the majority of interferences were found with digital systems. The most dangerous pulse repetition rates are 2 - 8 Hz. Pacemakers can interprete such signals as signals from the heart, whereas they usually filter out components at, e. g., 217 Hz, the normal pulse repetition rate of GSM. Frequency components at 2 - 8 Hz occur during signaling or for instance in the DTX-mode of GSM (discontinuous transmission). In this mode, the number of frames is reduced as long as the user is silent. Also the ringing phase poses a risk to the pacemaker patient. As analogue systems also use digital signaling, interferences are not restricted to digital systems. For analogue systems, the dialing phase appeared to be most critical.

Different kinds of pacemakers show very different reactions to exposure to mobile telephone signals. It is very important that pacemaker patients receive detailed information about possible interferences. Keeping the HHT away from the chest and not carrying it in the breast pocket could be a general safety recommendation for pacemaker patients. Moreover, doctors responsible for implantations should give recommendations for measures to be taken in case of undesired exposure.

EXPOSURE OF THE GENERAL PUBLIC

Cellular nets use cell sizes of typically 1 - 10 km in diameter. The trend goes towards smaller size cells, a higher number of base stations, and consequently lower transmitter powers at both HHT and BS. Antennas of BSs are located on masts on the top of high buildings in order to ensure good transmission. Antennas are constructed so that their directivity enables maximum radiation in the horizontal plane and minimum radiation towards the ground. The surrounding of such an antenna must be an obstruction-free space for at least several tens of meters. Thus, exposure in areas with public access can never be in the main beam of the antenna.

General public exposure to radiation from BSs is very comparable to exposure from television (TV) stations. The highest-frequency TV channels in Europe are at 860 MHz, which is within the frequency range used for cellular phones as well. Figure 6 shows electric field-strengths measured in a typical urban environment (Vienna, 4th district). FM radio stations, TV stations and cellular telephone signals typically range between 60 and 100 dBµV/m, corresponding to 0,01 - 0,1 V/m. Local maximum values can reach 1 V/m. The public has been exposed to such signals for decades. Looking at the ambient frequency spectrum shown in Figure 6 we can see that signals from cellular telephones are an additional contribution to the total exposure, but they appearently add just a very small percentage.

Let us try to evaluate the SAR for this exposure situation. For far-field exposure at 900 MHz, a field-strength of 0,1 V/m causes a whole-body averaged SAR of approximately 10^{-7} W/kg. In the frequency range of 30 MHz to approximately 300 MHz, a field-strength of 0,1 V/m causes approximately 10^{-6} W/kg. If we were to add up 1000 radiofrequency signals, total SAR would still be below 1 mW/kg, whereas the present, well-agreed limit value for the general public is 80 mW/kg. Thus it is evident, that there is a large safety factor between actual signal levels and recommended safety limits.

Also, TV transmitters have been well-accepted through the years and there were no diseases or health hazards reported.

Entering the near-zone of a BS antenna by, e. g., climbing an antenna mast, requires seperate safety considerations. Here, field-strengths can exceed the safety limits. Careful operation is required as is the case at any radio transmitter or at any industrial location where electromagnetic fields are applied. In areas of unrestricted public access, such situations should not occur.

From the above considerations we can conclude that, based on present knowledge, exposure of the public to the electromagnetic radiation from base stations appears to be no health risk.

88-108 MHz: FM radio stations
170-230 MHz: TV channels
470-860 MHz: TV channels

120 dBµV/m ÷ 1 V/m

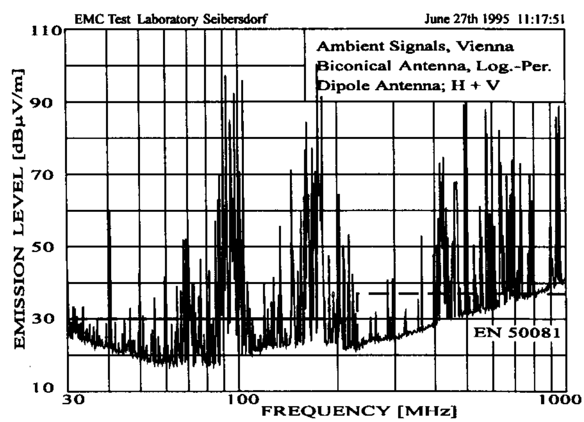


Figure 6. Ambient signals measured in Vienna, 4th district

SUMMARY AND CONCLUSIONS

The maximum, localized specific absorption rate in the head of a user of a modern cellular telephone reaches 6 W/kg per W transmitter power with normal use (hand-held terminal in a position at the head, where one can speak into the microphone and listen to the loudspeaker; distance between antenna and body surface not less than 2 cm). The strongest hand-held terminals available on the market today use 1 W average transmitter power, most types use less. For a typical GSM handy, e. g., maximum specific absorption rate is 1.5 W/kg in such an exposure situation. The maximum local temperature rise in possibly critical organs in the head, such as the inner ear, the hypothalamus, etc, associated with a certain specific absorption rate cannot be precisely specified yet. Results of scientific investigations are available for the eye. Here, for a distance of 6.25 mm (worst-case), a maximum absolute temperature of 39 °C has been numerically calculated for a continuous transmitter power of 0.7 W at the highest frequencies used in cellular mobile communications today (calculation for 1500 MHz, data at 1800 MHz are almost identical). This maximum occured in the posterior region of the lens. Cataracts are known to occur at temperatures of 41 °C or more, thus there seems to be a sufficient safety factor. The temperature actually occuring with normal use of cellular telephones is well within a range that the human body is frequently exposed to. A healthy body is able to properly react by thermoregulation. Based on today's knowledge, there is no indication of hazard when hand-held terminals are used in a normal way.

As a precaution, a warning should be expressed regarding a possible exposure situation such as the antenna of a hand-held terminal being pressed against the eye or another part of the head for several minutes or longer. In this case, specific absorption rates can reach 30 W/kg per W or more, which could mean a hazard due to excessive, local heating. This should anyway be treated as a special case of misuse.

A number of further biological effects of microwave radiation has been observed during in-vitro and in-vivo experiments. The relevance of these effects for human safety is totally unclear at present, thus these effects cannot be used to derive safety criteria. The studies are very controversial, clear indications of hazards have not been demonstrated. As a precaution, such effects should however be investigated further. If reliable results become available and they have an impact on human health, they must be accounted for in relevant safety guidelines and standards.

An explicit warning must be expressed to any person with electronic, medical implants. For switched-on hand held terminals a safety distance between antenna and implant should always be kept, as long as immunity of the device has not been clearly demonstrated. The required safety distance should be specified for each type of pacemaker, defibrillator, etc. Typically, it is of the order of 10 - 40 cm. Patients should avoid carrying a hand-held terminal in their breast pocket. Operation at the ear (normal use of the telephone) has been demonstrated to be safe for most types of pacemakers.

Public exposure to radiation from base stations does not cause any hazard. The level of exposure is far below the threshold for well-established effects. Moreover, the public has been exposed to very similar electromagnetic fields (broadcast radio and television) for decades and no adverse effects have been reported.

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