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ABSTRACT

The recent expansion of personal telecommunications has led to a rapid increase in the exposure of people to the radio-frequency (RF) radiation. Although the mobile phones are low power devices, the antenna is so close to the head that the local exposure may slightly exceed 2 W/kg, the current exposure limit for the local specific absorption rate SAR for the general public. The increase in the temperature is, however, too small to have any physiological significance. On the basis of experiments with cell cultures it is possible that other biological effects caused by some unknown non-thermal mechanism exist, but thus far there is no conclusive biological or epidemiological evidence to suggest any diseases or adverse physiological changes below the thermal threshold.

The use of a mobile phone by a person wearing a pace-maker, is not recommended, if the immunity of the pace-maker has not been assured.

The exposure caused by the base stations is in all practical cases well below the power density limits for general public.

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Avainsanat matkapuhelimet, radiotaajuinen säteily, mikroaallot, ominaisabsorptionopeus, terveyshaitat

TIIVISTELMÄ

Henkilökohtaisten matkapuhelimien viimeaikainen yleistyminen on lisännyt merkittävästi väestön altistumista radiotaajuiselle säteilylle. Vaikkakin matkapuhelimien säteilyteho on suhteellisen pieni, antenni on niin lähellä päätä, että koko väestöön sovellettava paikallisen ominaisabsorptionopeuden SAR:n raja 2 W/kg voi joissakin tapauksissa hieman ylittyä. Säteilyn aiheuttama lämpötilan nousu päässä on kuitenkin niin pieni, että sillä ei ole mitään fysiologista merkitystä. Soluviljelmillä tehdyt kokeet viittaavat siihen, että myös muita kuin lämmöstä johtuvia vaikutuksia voisi esiintyä, mutta toistaiseksi ei ole minkäänlaisia vakuuttavia todisteita siitä, että lämmitystason alapuolella radiotaajuinen säteily aiheuttaisi sairauksia tai haitallisia fysiologisia muutoksia elimistössä.

Sähkömagneettisen häiriön johdosta matkapuhelimen käyttöä ei suositella sydämentahdistimen kantajalle, jos tahdistimen häiriösietoisuutta ei ole varmistettu.

Väestön altistuminen tukiasemien säteilylle jää lähes aina huomattavasti väestöä koskevien tehotiheysrajojen alapuolelle.

CONTENTS

REFERENCES

1 INTRODUCTION

Handheld mobile phones emit radio waves most commonly in the frequency range from 100 to 2,000 MHz. More than half of the radiated energy may be absorbed into the user's head. As a result of this, the temperature of the skin and outer layers of the brain may increase slightly. See Figure 1. Although, the increase of tissue temperature is too small to have any physiological significance, it is possible, in theory, that the electric field may, by some unknown non-thermal mechanism, disturb the normal cell function. Mobile phones may also interfere with cardiac pacemakers.

The first mobile phone systems became operational in Finland at the beginning of the 1970's. It was only at the end of the 1980's and the beginning of the 1990's, when the number and usage of mobile phones started to increase rapidly, as a consequence of reduced prices and technical development that transformed the mobile phones into the pocket sized devices they are today. At the same time, the exposure levels increased slightly because in today's small mobile phones the antenna is located closer to the user's head than in the older, larger, models. Finnish mobile phone networks had slightly more than 2 million subscribers by the end of 1997.

The first dosimetric measurements performed with the new type of mobile phones (Cleveland and Athey 1989) indicated that, on the contrary to the previous beliefs, the absorption levels in the user's head caused by the radiation power of 1 W may exceed the international safety recommendations for the General Public (CENELEC 1995, ICNIRP 1996). This has been confirmed in the later studies (Dimbylow and Mann 1994, Meier et al. 1994, Kuster and Balzano 1996). At the same time, it has become clear, that exposure limits for workers which are based on biological studies are not exceeded (IEEE 1992, ICNIRP1998).

Although, research on biological effects of radio-frequency (RF) radiation has not produced alarming results (ICNIRP 1996, WHO 1993), the interest on possible health effects caused by the mobile phones is justified. An ever increasing proportion of the population will be exposed to the radiation emitted by mobile phones, the level of exposure is relatively close to the threshold value of thermal effects and non-thermal effects cannot be excluded. Moreover, it should be noted that the mobile phone industry is an important part of the Finnish national economy. Therefore, the potential health risks related to the products of that industry have to be well understood, so that they may be prevented in advance when developing new technologies.

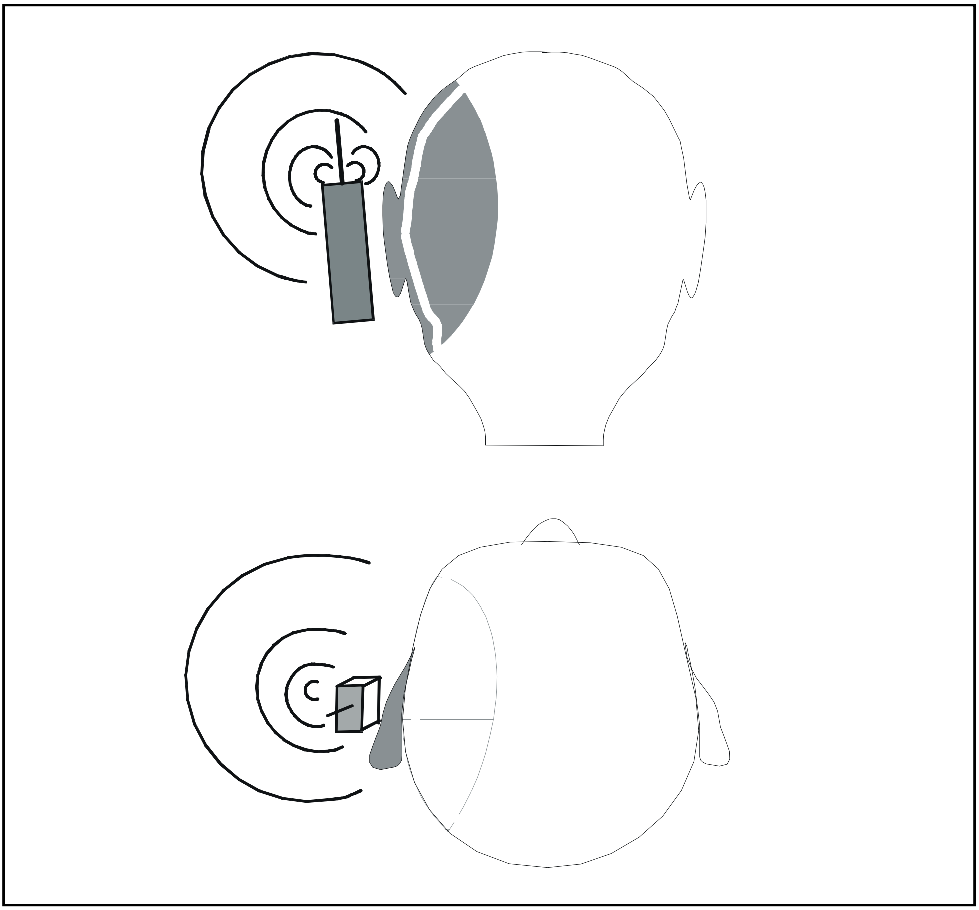

Figure 1. *A schematic of the absorption of energy radiated by a mobile phone into the user's head.*

The scope of this report is to examine and evaluate the most essential studies on absorption of RF radiation to the head and its biological effects that have been published during the last 10 years. A Finnish research program, "Biological effects of electromagnetic fields", which was related to the European COST 244 research program was completed at the same time as this report. The results of that program have been taken into consideration as much as possible in this report.

Special attention is given to the research results that suggest that there is a possibility of central nervous system cancer, eye damage or disruption of brain activity, even if the exposure levels do not cause significant increase in the tissue temperature. The possible special effects caused by pulse and amplitude modulated radiation are covered because of the digital mobile phone systems. On the basis of the biological review and international recommendations (CENELEC 1995, CENELEC 1997, ICNIRP 1996) guidelines for the radiation safety of mobile phones are given. Other topics cover the mobile phone interference with cardiac pacemakers and radiation safety of base stations.

2 MOBILE PHONE TECHNOLOGY AND APPLICATIONS

2.1 Mobile phone networks

The first mobile phone network in Finland, the Auto Radio Puhelin (ARP) (Car Radio Telephone) became operational in 1971. It was manually operated. The number of subscribers increased slowly passing the 10,000 mark in 1976. 20,000 subscribers were reached in 1980 and 30,000 in 1982. Today, the network is called Mobinet and it covers the whole Finland with its 322 base stations and 800 radio channels. The number of subscribers was at its largest (36,000) in 1986. Later this number decreased because the subscribers started to use more advanced systems.

The Nordic Mobile Telephone (NMT) system started operation in the frequency range of 450 MHz in 1982. The capacity of NMT450 (180 channels) became insufficient in urban areas within a couple of years. The number of subscribers in the NMT450 system increased steadily until 1995 totaling 200,000 subscribers. The NMT450 network covers all but some sparsely populated areas of Finland.

The NMT900 network was founded in 1986 to increase the capacity in the densely populated areas where the capacity of the NMT450 system had become insufficient. The number of subscribers increased rapidly at the beginning of the 1990's. There were roughly 440,000 subscribers in 1995. The number has not increased significantly after that. The coverage of the NMT900 network is not so extensive as the coverage of the NMT450 network.

The Global System for Mobile communications (GSM) started operation in 1992. The purpose of the GSM network was to provide new service in the densely populated areas where the capacity of the other networks had been exceeded. The number of subscribers has increased more rapidly in the GSM network than in other networks since 1994, and it is still increasing. There were 1,500,000 subscribers at the end of the year 1997.

The present networks may have occasionally become overloaded in the densely populated areas because of the tremendous popularity of mobile phones. Therefore, new GSM1800 networks were introduced in the year 1997. The introduction of GSM1800 was possible because the frequency range needed for the new networks was no longer used for radio-links. Frequency range, modulation and output power of the handheld phones used in the mobile systems currently operational in Finland are shown in Table I. Development in the number of subscribers in the mobile phone systems in Finland during 1970–1997 is shown in Figure 2. At the end of 1997, there were more than 2 million mobile phone users in Finland. In other words, there were 40 mobile phone subscriptions for every 100 inhabitants. The mobile phone penetration in Finland was the world's largest at the end of 1997. According to the information received from the network operators the average duration of a mobile phone call is 1–2 minutes. However, the duration of the calls and the number of calls per individual may increase in the future when the mobile phones will replace the fixed line phones.

Table I. *Technical information on the mobile phone systems currently operational in Finland.*

System	ARP/ Mobinet	NMT450	NMT900	GSM900	GSM1800
Frequency range (MHz)					
Phone	152.9–154.9	453–457.5	890–915	890–915	1,710–1,785
Base station	147.9–149.9	463–467.5	935–960	935–960	1,805–1,880
Modulation method	Analog	Analog	Analog	Digital	Digital
Peak output power of the handheld phone[1] (W)	5	1.5	1	2	1
Maximum mean (rms) output power of the handheld phone (W)	5	1.5	1	0.25	0.125

[1] Pulse power in the case of the GSM mobile phone systems

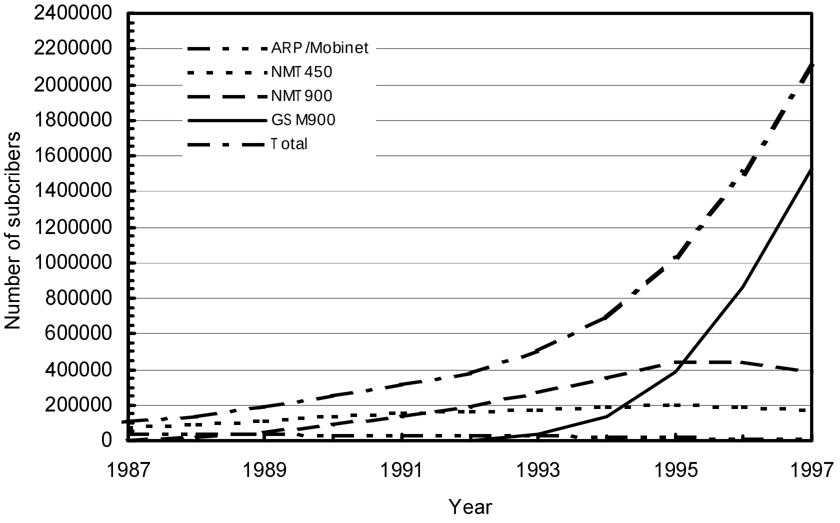

Figure 2. *The development of number of subscribers in the mobile phone systems in Finland in 1987–1997.*

2.2 Mobile phone designs and types

Older NMT networks use analog and newer GSM networks digital modulation. In the analog modulation the speech is transformed into an analog signal in the microphone of the phone. This analog signal is used to modulate the frequency (ARP/Mobinet) or phase (NMT) of the RF carrier wave. During speech the phone transmits a continuous signal of constant amplitude.

In the digital modulation, the analog signal generated by the microphone will be sampled 8,000 times per second. Each sample consists of 13 bytes (zeros or ones). The digital signal is then condensed in the speech coder. After this the error correction codes are added to it. The carrier wave is modulated with the modified bitstream so that a zero-byte will phase shift the signal by -90° and one-byte by +90° (Minimum Shift Keying, MSK). The carrier wave amplitude is not changed at this stage. The modulated signal passes through a filter (so-called Gaussian filter) to reduce the bandwidth. The mobile phone transmits modulated bits in short bursts, that have a duration of 0.577 ms (1 time slot) and repetition rate of 4.615 ms (8 time slots). The transmitted power of a GSM phone as a function of time is shown in Figure 3. The maximum average power is approximately 1/8 of the pulse power. During a GSM900 phone communication the maximum average power is approximately 0.23 W during the speech and minimum average power 0.03 W in the DTX (Discontinuous transmission) mode during the listening periods. In the standby mode, mobile phones establish a short connection called “location update” to the nearest base station once in a certain time interval (typically, in order of 1 hour in the case of GSM900) or when moving from one location area to another.

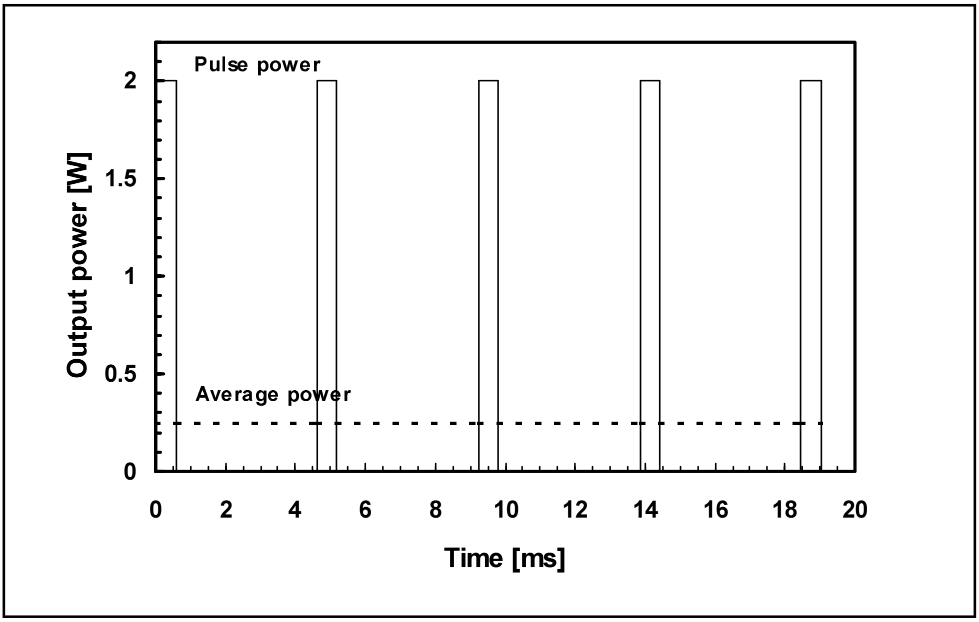

Figure 3. *Transmit power of a GSM phone as a function of time.*

Mobile phones can be divided into handheld phones, vehicle-mounted phones and portable phones depending on their construction. In a handheld phone, the microphone, earphone and antenna are all in the same casing. Usually the handheld-phone antenna is located a few centimeters away from the user's head when the phone is used. Sometimes the antenna may even touch the earlobe. In the case of a portable phone the microphone and earphone are located in a separate part that is connected via a cord to the transmitter/receiver. The distance of the user from the transmitter/receiver can be more than 0.5 meters because of the cord. A vehicle-mounted phone is a portable phone that is fixed to the vehicle. It uses a separate antenna that is placed outside the vehicle.

The most common handheld phone antenna is a whip, whose length is typically $\lambda/4$, $3\lambda/8$ or $\lambda/2$ (where λ is the wavelength). A whip antenna is cheap and easy to manufacture. It has a wide bandwidth and a suitable radiation pattern for mobile-phone use. Some examples of whip antennas for 900 MHz are shown in Figure 4. The current distribution of the antenna changes so that the current maximum moves from the base of the antenna towards the center point of the antenna when the antenna is made longer. The current maximum of a $\lambda/4$ antenna is located closest to the user's head. Relatively strong electrical currents may also be induced on the casing of the phone because the casing acts as a ground plane for the antenna. In the case of $3\lambda/8$ and $\lambda/2$ antennas the currents are weaker, and the current maximum of the antenna is located farther away from the user's head.

In addition to whip antennas helical antennas are also used in handheld phones. A helical antenna consists of a wire that is wound in the shape of a helix. The advantage of the helical design is its small size. The height of a whip antenna for 900 MHz is 100 mm whereas the height of a $\lambda/4$ helical antenna is only 26 mm. A dual antenna design including both a whip and a helical antenna is used in more recent phone models. The whip is used only when the antenna is fully extended. Otherwise, the helical antenna, which is located at the base of the whip, is used. However, the whip and helical antennas will break easily if the phone is mishandled by dropping it, for example. Therefore, also integrated planar antennas such as planar inverted F antenna (PIFA), dual L antenna and microstrip antenna (Haapala 1998) have been developed. These antennas are suitable to be used in the 1,800 MHz range, especially, since the high frequency allows them to be made small enough and they can be attached to the phone casing without protruding parts.

At the turn of the century, ground-based networks will be accompanied by satellite-based networks. Phones that will be used in the mobile satellite communications may use same or slightly higher output power than the phones of the current ground-based mobile systems.

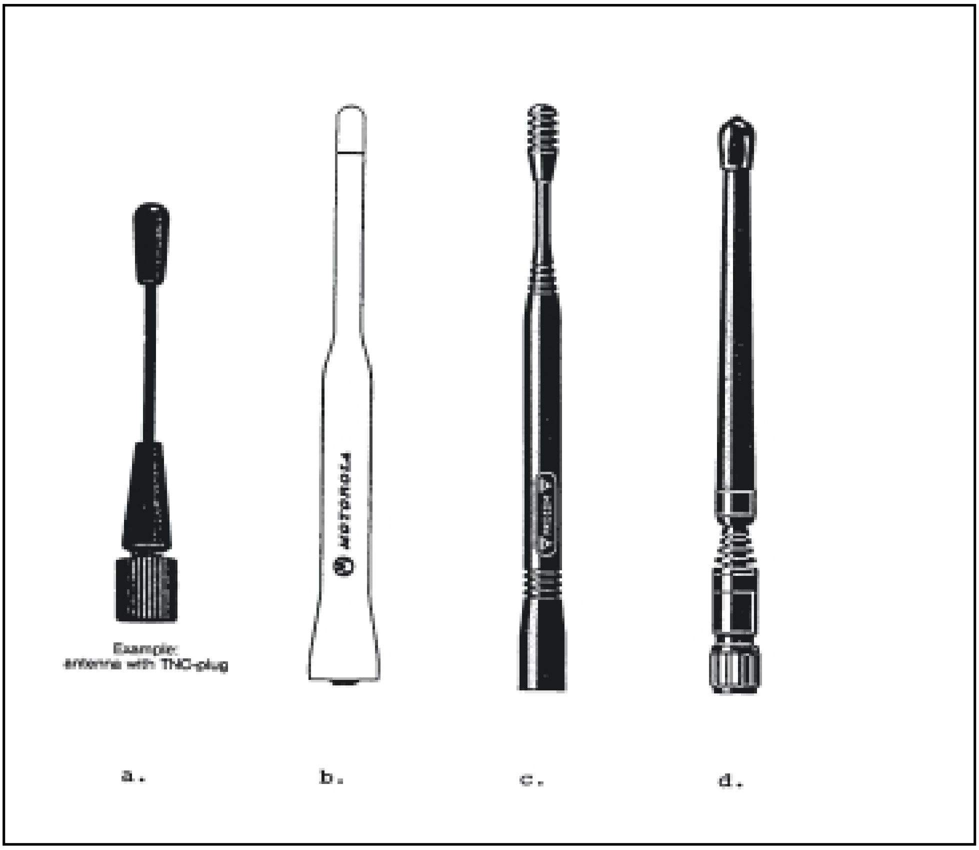

Figure 4. *Examples of whip antennas for 900 MHz. a) λ/4 antenna, height 100 mm, b) 3λ/8 antenna, height 150 mm, c) λ/2 antenna with an elevated feed point, height 210 mm, d) Top fed λ/2 antenna, height 200 mm (Laukkanen 1993.)*

3 ABSORPTION OF RADIATION INTO THE HEAD

3.1 Specific Absorption Rate of Electromagnetic Energy, SAR

Radio-frequency electrical currents in the antenna and in the casing of a hand-held mobile phone will induce RF electric fields in tissue. As a result of this a part of the radiated energy will be absorbed into tissue causing an increase in the tissue temperature. The absorption is caused by the power loss involved with dielectric polarization. Vibrations of water molecules, movements of free ions and movements of bound charges attached to macro-molecules contribute most to the dielectric polarization in biological material in radio frequencies.

Power loss is defined by SAR (Specific Absorption Rate) which determines the power absorbed per unit mass. Local SAR is given by

$$SAR = \frac{\sigma E^2}{\rho} \qquad (1)$$

where σ is the electric conductivity and ρ the mass density. The (root mean square) rms value of the electric field strength in the x, y, z point, E is defined by

$$E = \sqrt{E_x^2 + E_y^2 + E_z^2} \qquad (2)$$

where the E_x, E_y and E_z are the rms values of the x, y, and z components of the electric field. In practice SAR is always determined as an average value in the finite tissue volume. The whole body average, $\mathrm{SAR}_{\mathrm{wba}}$ simply gives the power absorbed into the whole human body divided by the mass of the body.

It can be seen from Equation (1) that SAR is directly related to the conductivity of tissue. The conductivity, on the other hand, increases when the water content of tissue increases. Therefore, the temperature in tissue types with high water content such as muscle, blood, skin and nerve tissue increases more than the temperature in dryer tissue types such as fat and bone. The conductivity of the most important tissue types in mobile frequencies is shown in Table II (Gabriel et al. 1996).

SAR is the dosimetric unit of biological effects associated with the temperature increase in tissue. However, also the electric field strength can be used as a dosimetric unit particularly when effects of other type are concerned. According to equation (1), 1 W/kg relates to the electric field strength of roughly 30 V/m at the mobile phone frequencies. The conductivity is approximately 1 S/m (Table II) and tissue density 1,000 kg/m^3, the density of water, which is a good approximation for the most tissue types excluding bone tissue where the density is considerably greater.

Table II. *Typical conductivity values of certain tissue types in different frequencies.*

	Conductivity (S/m)			
Tissue type	150 MHz	450 MHz	900 MHz	1,800 MHz
Muscle	0.73	0.81	0.94	1.3
Skin (wet)	0.56	0.69	0.85	1.2
Blood	1.2	1.4	1.5	2.0
Grey brain matter	0.60	0.76	0.94	1.4
White brain matter	0.35	0.46	0.59	0.92
Fat	0.07	0.083	0.11	0.19
Bone	0.070	0.096	0.14	0.28
Liver	0.53	0.68	0.86	1.3

3.2 Determining SAR

SAR caused by a handheld mobile phone can be determined accurately only by directly measuring or calculating the E-field induced in the tissue or the accompanied temperature rise. Dosimetric assessments that are based on E- and H-fields radiated to free space by the device under test can be used only for simple screening tests to exempt a low power device from direct SAR tests.

The most commonly used method for SAR analysis is the Finite Difference Time Domain (FDTD) method. The numerical models that are needed in FDTD calculations are usually derived from MRI images (Magnetic Resonance Imaging) or figures of anatomic cross-sections. The resolution of FDTD models is 2 mm at its best. Improving the resolution is difficult because of insufficient anatomic data, limited amount of computer memory (RAM) and excessive increase of calculation time.

Phantoms that simulate the anatomy and electrical properties of the human head and upper torso are used in the dosimetric measurements. SAR is most commonly determined by measuring the E-field in tissue (Equation (1)). However, also a method based on measuring the temperature is possible, at least in principle (Chapter 4.2), but usually it is limited to the calibrations of SAR probes (Jokela et al. 1998). Heterogeneous phantoms are composed of semi-solid materials whereas in homogeneous phantoms liquid solution may be used, see Figure 5. The phantoms composed of liquid have a major advantage, because they allow freedom of movement for the probe measuring the absorption. In the case of heterogeneous phantoms the measurements have to be performed in fixed holes that distort the E-field. Theoretical analyses indicate that maximum SAR in homogeneous phantoms may be equal (Watanabe et al. 1996, Hombach et al. 1996) or at the most 1.5 times higher (Lazzi and Gandhi 1996) than the maximum SAR in heterogeneous phantoms. It is likely that the standardized SAR tests will be based on measurements performed with homogeneous liquid phantoms. Calculations verified with measurements are a possible option, as well (CENELEC 1997, FCC 1996).

If SAR values are to be compared with the exposure limits given in radiation safety standards they must be averaged over a cubical mass of either 1 gram (IEEE 1992, FCC 1996) or 10 grams (CENELEC 1995, 1997), which smoothens peak values. In a homogeneous phantom, the side length of the cube is 1 and 2.2 cm, for the 1 g and 10 g masses, respectively. Tissue must fill up the cube, which means that the center point of the cube must be located at least half a side-length distance from the skin. Currently, it is unclear how the earlobes and the cavities of the head should be taken into consideration. There is no final agreement on the shape of the averaging volume either. Instead of a cube the use of a sphere of flat sheet has been suggested.

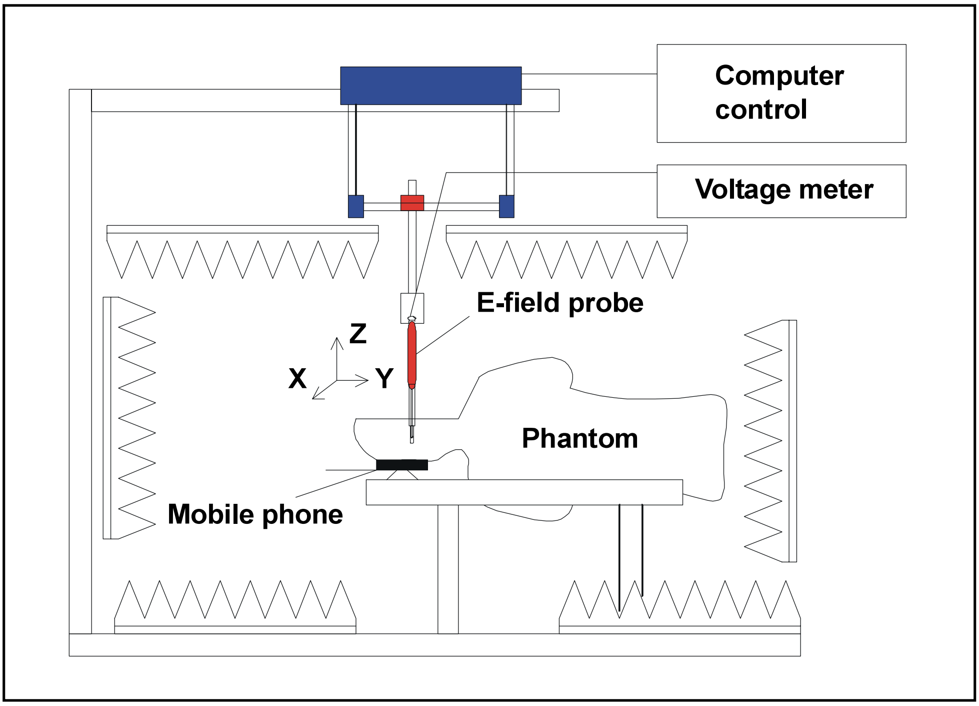

Figure 5. *The SAR measurement system developed by STUK in the COST 244 project (Puranen et al. 1997). SAR values are determined by measuring the electric field strength in a realistically shaped homogeneous liquid phantom with a small, moving, isotropic E-field probe (SPEAG ET 3DV5). The movement of the probe is controlled by a computer.*

3.3 Results of dosimetric studies

The power absorption in the head caused by a handheld mobile phone depends on many factors. The distance from the antenna, radiated power and frequency are the most important ones. However, also the type of the antenna, the shape and material of the casing, the alignment of the phone, the anatomy of the head and the electrical properties of tissue all significantly affect the absorption. Moreover, the head influences radiation properties of the phone by changing the antenna impedance and radiation pattern.

Table III summarizes spatial peak SAR values that have been measured or calculated in different laboratories. These values have been normalized to the radiated power of 1 W. Since the shape of the casing, type of the antenna, measurement position and phantom vary in different studies, the results are not entirely comparable. The shown SAR values are the spatial peak values on the surface of the experimental or numerical phantom. These values may be slightly higher than the SAR on the surface of the brain but slightly lower than the SAR in the skin.

As can be seen in Table III, the SAR values determined by different research groups vary considerably. There are real differences in the handheld phones used in the studies but variation is also caused by the uncertainty of SAR determination methods, not sufficiently standardized. Comparison tests, in which different laboratories determine SAR values in a homogeneous sphere and cube placed in the field of a simple radiator (a dipole) by measurements and calculations, have been done in the COST 244 project. The results of the comparison measurements are not yet available. However, the preliminary results of the calculations indicate that the spatial peak value of SAR at 900 MHz can vary even by a factor of four. The calculated SAR values are notably higher in the recent studies than in the past. This may be a result of an improved resolution. The most reliable calculation results are achieved by using the resolution of better than 3 mm.

As much as 50% of the radiation power emitted by a handheld mobile phone can be absorbed in the user’s head and the hand holding the phone. The absorption is at its greatest in the hand, skin of the head, earlobe and on the surface of the brain (Figure 1 and Figure 6). Bone tissue absorbs radiation poorly, because of its low conductivity (Table II). Kuster and Balzano (1992) have shown that the maximum absorption occurs at the point where the handheld phone is closest to the head and the surface current density at its maximum. The maximum absorption can be often, but not always, found at the feed point of the antenna. Antennas, which are small compared to the wavelength, can cause significant surface currents to the phone casing. In that case, the point of the maximum absorption may be found at close proximity of the phone casing. On the other hand, if the electrical length of the antenna is more than $\lambda/2$, the current maximum may move up from the feed point. In most of the cases, SAR is directly proportional to $1/d^p$ where d is the distance between the antenna and the head and p varies from 1.5–2 (Watanabe et al. 1996, Kuster and Balzano 1992).

Cleveland and Athey (1989) measured the absorption caused by a handheld phone in the heterogeneous phantom that was composed of three different materials simulating brain, muscle and eye tissues. Two analog phones operating at 900 MHz were tested. The spatial peak value of SAR, which was measured in the normal operating position of the phone, was 3.5 W/kg averaged over the mass of approximately 1 g. When the antenna was placed directly in front of the eye, SAR was 3.5 W/kg in the eye.

Anderson and Joyner (1995) used similar type of phantoms as Cleveland and Athey. Three different phones operating at 900 MHz range were measured. When the phones were in the normal operating position the greatest SAR measured on the surface of the brain was 1.4 W/kg and in the eye 0.35 W/kg. These values are close to the 1 g averaged values. Therefore, absorption in the eye is relatively small when the phone is used in a normal operating position.

Dimbylow and Mann (1994) calculated absorption in the infant’s head at 900 and 1,800 MHz. A high-resolution (2 mm) anatomic model segmented on the basis of MRI images was used. The largest values of SAR in the normal operating position were 4.7 W/kg (1 g) and 3.1 W/kg (10 g) at 900 MHz. The corresponding values at 1,800 MHz were 6.7 W/kg (1 g) and 4.6 W/kg (10 g), which indicate the increase of the surface absorption and decrease of the skin depth when the frequency increases. It can be seen by examining graphical SAR distributions published by these authors that higher SAR values than previously expected can exist in a small area of few square millimeters. SAR values of 14 W/kg were calculated in the earlobe and 4–8 W/kg on the surface of the brain at 900 MHz, for example. Absorption in the eye was very small when the normal operating position was used. However, when the antenna was placed directly in the front of the eye the average SAR in the eye was in the same range as the standard SAR (averaging masses varying from 1 to 10 g) in normal operating position.

Table III. *Local spatial peak SAR values at 900 MHz determined for the analog handheld phones in different studies. The radiation power has been normalized to 1 W.*

Reference	SAR [W/kg] 1 g	SAR [W/kg] 10 g	Distance[1] [cm]	Notes
Cleveland & Athey	3.5	-	1.0	Measured, λ/2[2], device 1
Cleveland & Athey	1.7	1.0	-	Measured, λ/2, device 2
Dimbylow & Mann	4.7	3.1	1.4	Calculated, λ/4,
Anderson & Joyner	1.4	-	1.5	Measured, λ/2, device 1
Anderson & Joyner	1.1	-	3.3	Measured, λ/4, device 2
Anderson & Joyner	0.7	-	3.0	Measured, λ/4, device 3
Meier et al.	4.0	2.7	-	Measured[3]
Meier et al.	10	5.0	-	Measured[4]
Hombach et al.	8.0	6.3	1.5	Calculated, λ/2[5]
Watanabe et al.	4.3	-	3.0	Calculated, λ/4
Watanabe et al.	2.0	-	3.0	Calculated, λ/2
Jensen et al.	2.0	-	2.0	Calculated, λ/2
Jensen et al.	1.3	-	2.0	Calculated, PIFA[6]
Jensen et al.	3.8	-	2.0	Calculated, PIFA[7]
Gandhi & Lazzi	4.8	-	≈3.0	Calculated, λ/4
Gandhi & Lazzi	2.7	-	≈3.0	Calculated, 3λ/8
Balzano et al.	1.2	-	-	Measured[8], λ/2
Balzano et al.	2.1	-	-	Measured[8], helical antenna
Pitkäaho et al.	4.0	2.5	1.5	Calculated, λ/4, vertical
Pitkäaho et al.	2.6	1.7	1.5	Calculated, λ/4, horizontal

[1] The distance between the antenna and the head (mostly measured from the antenna feed point).
[2] The length of the antenna in wavelengths
[3] The peak value in the normal operational position in the group of nine different handheld phones
[4] The peak value in the worst possible position in the group of nine different handheld phones
[5] A dipole antenna
[6] Antenna on the backside of the phone
[7] Antenna on the side of the phone
[8] Average value measured for different types of analog handheld phones in different positions

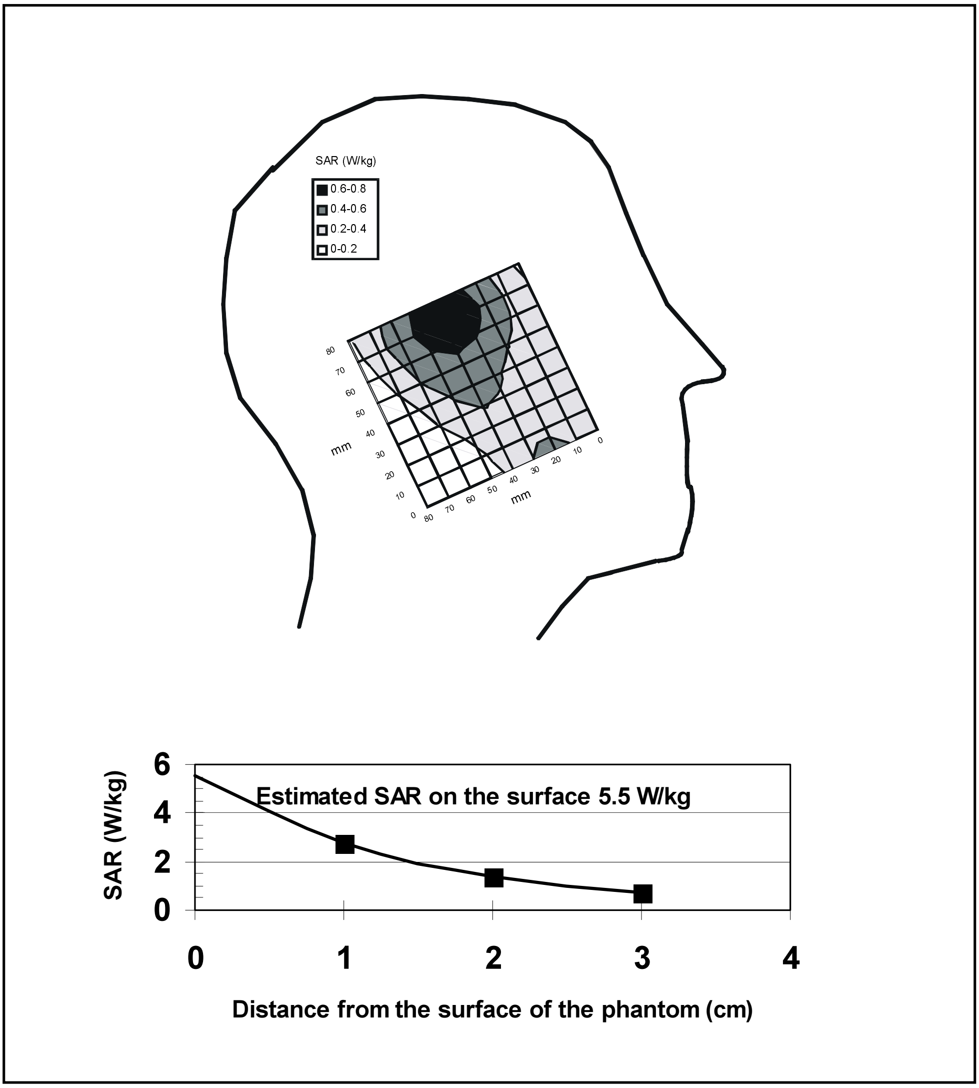

Figure 6. *The specific absorption rate caused by an NMT900 phone a) in the depth of 3 cm from on the inner surface of the phantom, b) at the point of maximum as a function of the distance from the inner surface. Measurements were performed with the SAR measurement system of STUK (Puranen* et al. *1997).*

Hombach et al. (1996) exposed several experimental and numerical phantoms to the radiation emitted by a horizontal half-wave dipole at 900 MHz. The highest spatial peak SAR value was 8 W/kg (1 g) and 6.3 W/kg (10 g) in the most complex numerical phantom. However, the spatial peak SAR was 12 W/kg in the skin and on the surface of the brain when a resolution of few millimeters was used.

Meier et al. (1995) measured nine different types of 900 MHz handheld phones in the normal operational position and in a worst case position that produced maximal SAR. A homogeneous liquid phantom was used in the tests. The local peak SAR of the worst device was 4 W/kg (1 g) and 2.7 W/kg (10 g) in the normal operating position; the values showed an almost twofold increase in the worst case position. In the case of the best device the 1 g SAR was less than 0.4 W/kg in the normal operating position and less than 1 W/kg in the worst case position.

Watanabe et al. (1996) studied theoretically the effects of the distance, antenna length, ears and hands to the absorption at 900 MHz and 1,500 MHz. The RF exposure of the phones having a half-wave antenna was approximately half of that of the phones with a quarter-wave antenna. This decrease is the result of the current maximum moving further away from the head in the case of the half-wave antennas. Adding the earlobes to the model increase the absorption by 20–60% depending on the antenna type. In this case the peak SAR is most often found in the earlobe. The hand does not have a significant effect to the absorption in the head. However, the peak SAR values in the hand can be higher than the values in the head as was shown in the study of Okoniewski and Stuchly (1996). At 1,500 MHz the peak SAR in the head is 2–3 times as high as at 900 MHz.

Gandhi and Lazzi (1996) used a high-resolution model to study how the absorption caused by a handheld phone depends on the frequency and characteristics of the anatomic model. The normalized SAR at 835 MHz varied from 2.7 to 4.8 W/kg as shown in Table III. These results can be compared to the SAR values at 1,900 MHz. The surface SAR (1 g) was 9 W/kg for the λ/4 antenna and 5.5 W/kg for the 3λ/8 antenna at 1,900 MHz. The peak value in the brain was only 20% of the value in the skin at 1,900 MHz whereas at the lower frequency it increased to 40%. When the size of the skull decreases, the radiation penetrates deeper into the brain and the local peak SAR slightly increases. The spatial peak absorption in the infant’s head was 1.5 times the absorption in the adult’s head.

Balzano et al. (1995) have measured a large number of handheld phones using a homogeneous phantom. Two average values of the measurements are shown in Table III. The phone type used in the measurements was an American analog phone resembling an NMT900 phone. The output power of the phone (0.6 W) has been scaled to 1 W in Table III in order to make the comparison easier. In the extended position the antenna functions as a λ/2 radiator and in the retracted position as a helical radiator. It can be seen from Table III that the RF exposure near the helical antenna is higher than that near the λ/2 antenna. This is a result of the magnetic field strength being relatively high in the close vicinity of the helical antenna. The exposure from the retracted antennas varied between 1.5–3 W/kg and the exposure from the extended antennas between 1–1.3 W/kg. It is interesting to compare the latter results to the exposure of older mobile phone types (0.3–0.7 W/kg) measured in the same study. Antennas of the first handheld mobile phones were located considerably farther away from the user's head than the antennas of modern phones because of the larger casing. This should be taken into consideration in epidemiological studies.

Pitkäaho et al. (1997) have performed numerical SAR calculations as a part of the COST 244 project in the Technical Research Center of Finland (VTT). Commercial software called XFDTD (Remcom, inc., Pennsylvania) was used in the calculations. XFDTD simulates the human being with the model based on MRI scans. Also a more accurate model called "Visible man" is include in XFDTD. The spatial peak SAR for a whip-antenna in a horizontal and vertical position calculated with the "Visible man" model are shown in Table III. The calculated SAR values that have been averaged over 1 g are smaller by a factor of 2.3 (vertical) and 2.9 (horizontal) than the peak value calculated in the 3 mm cell. The results of VTT agree well with the results of the other research groups.

On the basis of Table III following conclusions can be made on the exposure from 900 MHz hand-held mobile phones: The 10 g averaged spatial peak exposure from NMT900 phones exceeds commonly 2 W/kg but not 10 W/kg. If the averaging mass decreases to 1 g SAR increases by the factor of 1.5 but most likely it will not exceed 10 W/kg in the normal position. Local peak SAR may be even 10 W/kg up to a few millimeters from the surface of the brain. Since the average radiated power of GSM phones is only 25% of the power radiated by the NMT phones, the peak SAR value induced by the GSM phones is also smaller – in the most cases less than 2 W/kg. There is a considerable difference depending on the antenna type. Some of the new PIFA antennas (Jensen and Rahmat-Samii 1995) seem to induce lower SAR values than the λ/2–λ/4 antennas.

The local peak SAR induced by a 1,800 MHz phone can be up to two times as high as the SAR induced by a 900 MHz phone, if the radiated power is the same. This means that in a small volume of few cubic millimeters the GSM1800 devices can induce peak SAR values which equal those of GSM900 devices despite of smaller output power, see Table I. However, at higher frequencies the attenuation increases, which reduces the averaged SAR values. According to the measurements (Kuster and Balzano 1996), the SAR induced by the GSM1800 phones is at its maximum only 1 W/kg for 10 g averaging and 2 W/kg for 1 g averaging.

There are no SAR test data available on the handheld NMT450 phones so far. However, due to the lower surface absorption, it is highly likely that the peak SAR values are smaller than the values of the NMT900 phones. On the other hand, the absorption in the inner parts of the brain is increased because the skin depth increases at lower frequencies.

The RF exposure from the handheld phones is not likely to increase in the future, because the manufacturers, who are being pressured by safety standards and demands of markets, strive to design antennas and phone casings in a such way that exposure limits will not be exceeded. The design aim, in developing new antenna structures, such as PIFA antennas, is to reduce the power absorbed into the head. This is also technically advantageous since the radiated power increases. Also, a smaller output power will be used in the handheld phones as the number of base stations increase. Some of the handheld phones that will be used in the future personal satellite communication systems may have a slightly higher output power than existing handheld phones. However, with the proper antenna design the additional power can be radiated towards the sky without increasing the exposure of the user.

4 BIOLOGICAL EFFECTS

4.1 General

The biological effects of radio-frequency (RF) radiation can be divided into thermal, isothermal and non-thermal effects. The normal systemic and/or local thermoregulation mechanisms of tissues are activated by thermal energy absorbed from the RF field. The purpose of thermoregulation is to maintain the temperature of subcutaneous tissue especially in the head and trunk as close to 37°C as possible, in order to prevent any damage to tissue. The normal physiological range is around ±1°C, but in exhausting physical exercise a temperature rise of two degrees is quite common (Adair 1994). Excessive thermal energy is dissipated from the body through increased sweating and peripheral circulation. When the local temperature exceeds 40°C, even the blood vessels in the inner part of the body become dilated, making the cooling of local hot spots more effective. Cells are damaged when the temperature reaches around 42°C (Sapareto et al. 1982).

In the power ranges where thermal conduction mechanisms effectively prevent significant temperature rises of individual cells, perceptible side effects linked to changes in thermoregulation can still be generated by the RF exposure. These side effects come under the category of isothermal effects, which are entirely physiological in character and not directly connected with any health risk. However, long-term exposure can create mild physical stress of an unspecific nature. Only in a sufficiently low power range (SAR < 0.4 W/kg) with no activation of thermoregulation systems can any effects be considered specific non-thermal effects independent of thermal conduction. However, the presence of such effects in humans or test animals has not been demonstrated conclusively.

4.2 Increase in head temperature and its physiological effects

A local rise in temperature resulting from RF radiation can be estimated approximately using the well-known Pennes bio-heat equation (Bowman 1982). The equation for brain tissue can be presented in simple form (Lyons et al. 1989, Samulski et al. 1989) as follows:

$$\frac{dT'}{dt} = \frac{SAR}{c} - \lambda_{T'} \qquad (3)$$

where T' is the rise in temperature, t is time, SAR is the local specific absorption rate (average of around 10 g tissue mass), c is the specific heat at the brain tissue (3.64 kJ/kg °C) and λ is the effective heat sink rate constant representing the local cooling capability of the tissue. At a temperature rise of less than 3°C, λ can be assumed to remain constant, which enables the following analytical solution for equation (3):

$$T' = \frac{SAR}{\lambda c}(1 - e^{-\lambda t}) \tag{4}$$

On the basis of microwave hyperthermia experiments made on dogs (Samulski et al. 1989, Lyons et al. 1989) it can be concluded that the heat sink rate constant in the brain is approximately 0.4 l/min, i.e. the exponential thermal time constant ($1/\lambda$) is around 2.5 minutes.

The derivation of equation (3) is based on the assumption that the local hot spot is large enough to allow time for blood to reach the tissue temperature. According to NRPB (1993), this requirement is valid if the hot spot has distributed over the mass of at least 10 g. Blood circulation smoothens thermal peaks so that in a volume of less than 1 cm^3, the maximum temperature variation is probably not greater than 1°C. The thermal model based on equation (4) is an approximation which, however, is reasonably accurate provided that the cooling due to blood convection is at least as effective as the cooling due to the thermal conduction.

Figure 7 shows the rise in temperature at SAR levels of 2 W/kg and 10 W/kg, as calculated with equation (4). The former is the SAR limit applied to the general population and the latter applies to occupationally exposed people working in controlled conditions. In practice, the highest possible local SAR for an NMT phone with a frequency of 900 MHz and radiated power of 1 W is less than 5 W/kg.

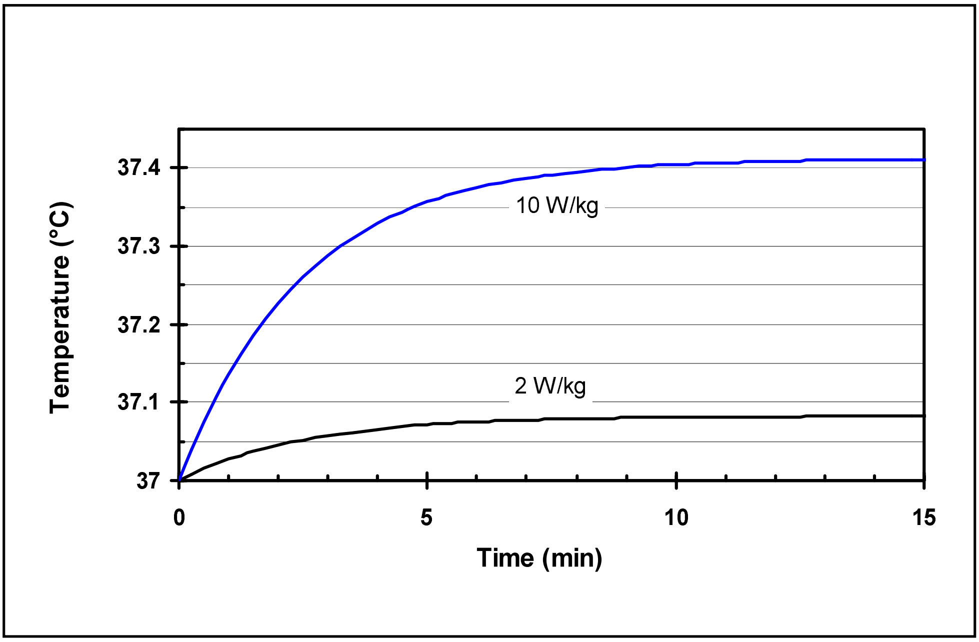

Figure 7. *Calculated rise in brain temperature caused by RF radiation.*

The maximum rise in temperature as calculated with this model is approximately 0.4°C when the local SAR is 10 W/kg and λ is 0.4 l/min (Anderson and Joyner 1995). The NRPB report (1993) presents similar conclusions: the temperature of a local hot spot in the brain rises by up to 0.6°C if the SAR is 10 W/kg. Within about six minutes the temperature will reach 90% of its maximum value. Up to 40°C the maximal temperature rise is linearly proportional to the SAR. At higher temperatures the model becomes non-linear; thermal convection will first become more efficient as blood vessels dilate, but may later become weaker if the rise in temperature causes damage to the blood vessels. It is clear from the foregoing discussion that with a local SAR of approx. 50 W/kg, a temperature rise of three degrees is possible, which probably does not cause any thermal damage. Local dilation of blood vessels will prevent any dangerous heating. Cell damage is possible if exposure reaches 100 W/kg. Assuming that the highest possible SAR in the brain caused by a 1 W NMT900 phone is 5 W/kg as a 10 g average (Meier et al. 1995, Kuster and Balzano 1996), the maximum rise in brain temperature would be 0.2–0.3°C. Radiated power of more than 10 W would be needed before local brain temperature would reach physiologically significant levels.

As the lens of the eye contains no blood vessels with cooling effect, it is somewhat more sensitive to heat than other tissues. Besides, the lens has no capability to replace the damaged cells, and even the slightest damage in the lens may cumulate in the long run. The thermal conduction as a cooling mechanism is more important for the eye than for a tissue containing blood. When estimated with a numerical model (Scott 1988) that accurately predicts thermal conduction, the maximum rise in the eye temperature is about 1°C when the average SAR in the eye is 10 W/kg (Anderson and Joyner 1995).

4.3 Effects on the central nervous system in vivo

A microwave pulse with an energy density of more than 100 mJ/m^2 and a duration of less than 30 μs causes an auditory sensation when reaching the head (Puranen and Jokela 1996). It is probably caused by a very slight but rapid rise in local temperature. The sudden thermal expansion of microscopic proportions related to this phenomenon causes mechanical vibrations which travels directly to the inner ear and creates irritation in the auditory receptor cells. Even a very small number of individual pulses can create an auditory sensation, and the pulse frequency itself is of little importance. The average power density can actually be very low, less than 1 W/m^2. The auditory sensation as such is not particularly harmful, but can still cause stress. It can also be taken as a sign of a thermoelastic process in the tissue, which could also explain other phenomena discovered with experiments on pulsed radiation. However, in the pulse signal of a digital mobile phone, the duration of the pulse is too long (577 μs) to cause any auditory sensation.

Experiments have shown that pulsed radiation in particular can affect the central nervous system at subthermal exposure levels in a number of ways. Lai et al. (1987, 1988, 1989a, 1989b, 1991) have made extensive tests on the effects of 2,450 MHz radiation on rat brain. Most experiments have been made using pulsed radiation with a pulse duration of 2 μs and a pulse frequency of 500 Hz, which gives a duty factor of 1/1000. In most cases, the average whole-body SAR measured calorimetrically has been 0.6 W/kg. The lowest SAR value producing a response has been 0.45 W/kg.

The parameters studied are connected with cholinergic nervous activity in the brain. The cholinergic system in the brain is believed to play an important role when an animal adapts its behaviour to environmental changes.

Exposure to radiation caused changes in choline uptake especially in the hippocampus area of the brain, but also in the frontal cortex. A single exposure of 20 minutes caused an increase in choline uptake, whereas an exposure of 45 minutes caused a decrease. The changes were fairly small (approx. 30%). The response remained the same, even when the effect was increased to 1.2 W/kg.

It was possible to prevent the effect in the hippocampus by giving a dose of naltrexone before exposure. Naltrexone is an inhibitor of the body's own opiates (morphine-like substances). This demonstrates that the effect of radiation was mediated by these substances. The decrease in choline uptake in the hippocampus, seen after an exposure of 45 minutes, was subject to development of tolerance: if the exposure was repeated on 10 successive days, no response was detected after the 11th exposure. However, no tolerance developed to the opposite response of shorter exposure, namely an increase in choline uptake.

After repeated exposure, it was also established that there had been a compensatory change in the number of cholinergic nervous receptors in the tissue. For example, in the hippocampus, a 45-minute exposure repeated on 10 successive days resulted in an increased number of receptors. This effect could be prevented with naltrexone.

The response in the frontal cortex was partly similar and partly dissimilar to the response in the hippocampus. Continuous-wave (CW) radiation at a frequency of 2,450 MHz and with an average SAR of 0.6 W/kg (whole-body) lead to a decrease in choline uptake in the frontal cortex. On the other hand, no such effect could be detected in the hippocampus. Also, naltrexon had no effect on this response. In general, effects detected in the frontal cortex could not be prevented with naltrexon, in contrast to the effects in the hippocampus.

Lai et al. (1989a; 1994) also studied the effects of pulsed exposure on the short-term memory of rats. The experiments were carried out in a cage with 12 branches, each with food at the end. The rat had to remember which branch it had already probed and which of them may still contain food. The number of unnecessary probes was registered. During a test series of 10 days the rat learned to remember the right branches and a substantial drop in the number of unnecessary probes was observed. When the tests were performed after irradiation of 45 minutes, performance was below the levels achieved without irradiation from the first day onwards, and day-to-day learning was also distinctly slower. However, this effect could be completely prevented both with naltrexon and with physostigmine, which is an anticholinergic drug.

When the same test was conducted after an exposure of only 20 minutes, it produced different results. During the first two days, the post-exposure performance was somewhat better than performance without exposure, but the ten-day learning curve was slightly flatter. In all, there were no significant effects on learning.

Responses in different parts of the brain show that this is not local damage, but a physiological response to systemic exposure. The same research group has reported similar effects on the cholinergic system of the brain caused, for example, by noise (Lai 1987, Lai et al. 1989c). A noise level of 100 dB lasting for 45 minutes caused similar effects in the hippocampus to a 45-minute exposure to pulsed RF radiation. The response to noise could also be prevented with naltrexon. In contrast, a noise of 70 dB had the opposite effect, i.e. an increase in choline uptake. Restraint stress in rats prevented from moving by tying their legs caused a decrease in choline uptake after 45 minutes in both the hippocampus and frontal cortex (Lai et al. 1986). The effect in the hippocampus could be prevented with naltrexon, but this was not the case in the frontal lobe.

Another study reported that restraint stress in rats resulted in an increase in choline uptake in the hippocampus after 10 minutes, but that after two hours the uptake decreased (Finkelstein et al. 1985). The response was thus biphasic. This is consistent with Lai's observation that, after being tied, the rat struggles for a few minutes, but then calms down and remains still.

All these observations suggest that the decline in cholinergic activity in the hippocampus, mediated by endogenous opiates, is connected with the body's general adaptation to stressful situations.

Lai's research group also detected changes in the number of benzodiazepine receptors after similar exposure to pulsed radiation (Lai et al. 1992). A single exposure of 45 minutes lead to a 13% increase in the number of receptors in the cortex but not in the hippocampus or cerebellum. However, when the exposure was repeated on 10 successive days, no increase could be detected. In other words, adaptation had occurred. It has also been shown that other kinds of stress, such as a noise of 100 dB or a swim in cold water, can cause a similar increase in the number of receptors (Lai and Carino 1990). In fact, benzodiazepines play an important role as mediators of the body's response to stress.

The effects on the brain described above indicate that pulsed RF radiation at a level not causing significant increase in body temperature can trigger off a mild physiological stress response. Stress in animals could be triggered by an auditory sensation caused by the pulse. In this case, the effects on health would be limited to effects of unspecific stress similar to the effect of repeated noise. These effects are probably of little practical significance, unless the exposure is frequent or of very long duration.

According to the results obtained by Lai's group, CW radiation has more limited and unspecific effects, and its cause and significance remain unclear. It may be a question of a minimal isothermal effect related to thermoregulation.

The impact of mobile phone radiation on the EEG of voluntary, fully awake test subjects has recently been studied in Finland (Hietanen et al. 1997); no effects were observed. German researchers have also reached a similar conclusion (Röschke and Mann 1997). However, they did detect slight though significant effects on the sleep pattern of healthy test subjects (Mann and Röschke 1996). A 900 MHz digital mobile phone with a pulse width of 580 µs and frequency 217 Hz was used as the exposure source. On average, the test subjects fell asleep 2.5 minutes sooner, and the proportion of REM of the total sleep fell from 17 to 14%. In the opinion of the authors, a hypothesis stating that the exposure makes it easier to fall asleep and causes a drop in REM sleep can be constructed on the basis of these results.

4.4 Effects on the eye

The RF exposure in the eye created by ordinary mobile phones is normally much smaller than the exposure on the brain surface close to the ear. If the device is held in front of the eye, as is often the case with professional radiotelephones, the SAR in the eye can be significant. If the exposure is high enough to cause a significant rise in lens temperature, the lens may become opaque, resulting in cataract. Tests have shown that the threshold value for local SAR causing cataract is above 100 W/kg for CW radiation. The threshold for pulsed radiation can be lower. In tests carried out *in vitro* at a normal, fixed temperature, a time-averaged SAR of 10 W/kg was enough to damage the lens of a rat exposed to pulse-radar radiation; the pulse had a duration of 20 µs and the exposure lasted one hour (Stewart-DeHaan et al. 1985).

Temporary damage has been detected in other parts of the eye following exposure levels below those mentioned above. Recent tests on monkeys, whose eyes are similar to those of humans, carried out by Kues et al. (1985, 1992) have provoked a lively debate. The monkeys, which were anaesthetized, were exposed to 2.45 GHz radiation of CW or pulsed form. The pulse duration was 10 µs and pulse frequency 100 Hz. Each period of exposure lasted four hours. The irradiation resulted in hole-like defects in the cell layer (endothelium) on the inner surface of the cornea. The defects were at their most evident 24 hours after exposure. After about four days the defects were no longer visible. With CW radiation and one single exposure, the power density threshold value for damage to occur was 300 W/m^2, corresponding to an approximate SAR value of 7.8 W/kg in the eye. Weekly repetition of the exposure did not lower the threshold. However, when the exposure was repeated on four successive days, the threshold decreased to 200 W/m^2 and 5.2 W/kg. Exposure of this kind increased the temperature in the anterior chamber of the eye by 0.77°C.

With pulsed radiation, the power density threshold was lower. A clear response was detected after a four-hour exposure to pulsed radiation with an average power density of 100 W/m^2 and the corresponding local SAR in the eye amounting to 2.6 W/kg. The energy density of a single pulse was then 1 J/m^2 and the specific absorption (SA) 26 mJ/kg. The response was especially clear when the exposure was repeated on four successive days.

The same experimental set-up was also used to show that pulsed radiation can influence the permeability of the blood vessels in the iris. Fluorescent marker substance leaked to the anterior chamber, demonstrating increased permeability of blood vessels. For a four-hour exposure repeated on three successive days, this effect was evident after reaching a threshold value for average power density of 100 W/m^2 (2.6 W/kg). The damage could be detected immediately following the exposure, but one week later it was no longer discernible.

When pulsed radiation was combined with therapeutic doses of timolol or pilocarpine, two drugs used as eyedrops for treating glaucoma, both of these effects (i.e. damage to the corneal endothelium and leakage through the wall of the iris blood vessels) intensified and the threshold value dropped. When radiation was combined with timolol, the threshold value actually went below 10 W/m^2 or 0.26 W/kg.

The authors of these studies suggest that both effects might be linked to the formation of free radicals, which, according to the authors, might be further strengthened by the drugs referred to.

Another research group (Kamimura et al. 1994) attempted to repeat the experiment with CW radiation and studied the effects on the corneal endothelium. In their experiment, the monkeys were fully awake, which better simulates real exposure conditions. The exposure lasted for four hours but was not repeated on successive days. The highest exposure level applied was 430 W/m^2, corresponding to 11 W/kg in the eye. No damage was detected, however.

This negative result has often been cited as proof of the unreliability of Kues's results. However, it should be borne in mind that Kues obtained a threshold value of 7.8 W/kg with a similar experimental set-up (single exposure to CW radiation). In other words, the difference is not very great and it could well be explained by the fact that in Kamimura's experiment the monkeys were awake, which may have led to improved cooling through open eyes or by blinking.

Kues's group has also studied the effects of pulsed microwave radiation on monkey retina. However, preliminary results reported as conference abstracts have not yet been published in scientific journals (Kues et al. 1990 and 1991). With an SAR level of 3.5–4.0 W/kg, a four-hour exposure repeated seven times resulted in changes in the electroretinogram (frequency, pulse duration, pulse frequency and SA were 1.25 GHz, 0.5 µs, 16 Hz and 250 mJ/kg, respectively). One week after the exposure the changes were no longer discernible. Although preliminary information concerning other effects on the retina at lower exposure levels were presented at the 1990 annual meeting of the Bioelectromagnetics Society, these results have not yet been published in scientific journals either.

Since the changes detected in the eye have been of a short-term nature, they probably do not indicate any major health effect, unless the exposure is extremely long and frequent. However, the threshold value for effects with pulsed radiation, especially when combined with medication for glaucoma, is remarkably low.

Results produced with very narrow pulses should not be generalized and applied to exposure caused by digital mobile phones. The duration of the pulse in mobile phones is typically at least ten times greater. For the same average SAR, then, the peak SAR is correspondingly no more than one tenth of the peak SAR used in the biological pulse experiments referred to above.

4.5 The *in vitro* effects of microwave radiation on cell membrane physiology

4.5.1 General considerations

The cell membrane plays a crucial role in transduction of external signals into the cell interior and between cells. The cell membrane, composed of lipids, proteins and carbohydrates, is a fluid structure whose components may alter their localization and interactions with other molecules in response to external and internal signals. This, in turn, may alter the steady state of the cell and the normal pattern of response to the external/internal signals. Microwave radiation has been suggested to influence cell membrane fluidity and the normal interaction between the cell membrane components.

The causal factors involved in the microwave radiation effect on cell membrane are not yet clear. It has been postulated that the observed microwave-induced effects might be mediated either by thermal (increased oscillation of water molecules) or non-thermal (e.g. changes in distribution of charged molecules, generation of the reactive oxygen species) effects, or by both simultaneously. Neither can the possibility be excluded that the low-SAR irradiation may cause thermal effects, because it is not possible to determine the temperature within the sub-mobile compartments. Thus, even in the experiments conducted with a rigorously controlled temperature there may occur a physiologically relevant temperature rise within some organelle(s). Such a “compartmentalized” temperature increase might be potent enough to alter cell physiology. However, independently of the cause of the microwave effect on cell membrane (thermal and/or non-thermal), the microwaves appear to be able to alter the properties of cell membrane, which may have physiologically significant consequences both *in vitro* and *in vivo*.

The mechanisms leading to cell membrane injury following microwave irradiation depend on the dose and mode of irradiations. Thus, it is well known that high-intensity microwaves (more than 100–150 W/m^2) exert direct and indirect thermal effects. At intensities below 100 W/m^2 non-thermal effects become crucial. Already from the mid 1970’s observations have been presented indicating that amplitude modulated radiation can influence all membrane. Some changes in membrane functions (i.e. cation transport and membrane permeability, ligand binding, signal transduction and cell communication) occur upon weak, low-frequency (below 100 Hz) modulated irradiation, but continuous fields of the same intensity do not cause any effects on cells. These changes in membrane function may be explained by a specific interaction between the weak low-frequency modulated electromagnetic fields and the charged groups of membranes as well as the potential profile of membranes. In a very strong field, cell membranes become electrically non-linear structures. This enables them to function as detectors of the field, which means that they filter the low frequency components from the radio-frequency field. Thus, there may be a connection between effects of amplitude modulated radio-frequency fields and low-frequency electric and magnetic fields. However, non-linearity phenomenons at exposure levels encountered in practice have thus far not been established.

Some of the effects of microwave radiation on cell membrane structure and physiology have been determined. It has been found that exposure of a cell to microwaves may alter: (i) membrane fluidity and permeability, (ii) activity of enzymes, (iii) cytoplasmic signal transduction pathways and (iv) changes in cell morphology. These alterations in cell membrane physiology may impair the normal functioning of tissues/organs as well as exert some tumor-promoting effects on cells that acquired mutation(s). However, as shown below, the results obtained in different laboratories, using different experimental set-ups and models are often discordant and require further clarification. Also, many studies lack experiments that would determine whether the observed microwave effects on cell components are indeed able to alter the overall cell/tissue physiology.

4.5.2 Ion channels

Na^+/K^+-ATP-ase is the most common model used to study the effects of microwaves on cation permeability and enzymatic activity. Tsong & Astumian (1988) have reported that the pumping of Na^+ out of the cell can be induced by exposure to a 1-MHz field (2 kV/m). On the other hand, exposure to fields with higher frequencies (2.45 GHz; SAR = 6 W/kg) was shown to inhibit the activity of Na^+/K^+-ATP-ase in an experimental system where the activity of other ATP-ases was inhibited by ouabain. However, although significant (over 30%) inhibition of enzymatic activity was observed, it took place at a non-physiological temperature of $+25^{\circ}$C. Thus, the physiological significance of this observation is unclear.

Calcium ion transport was also shown to be affected by microwave exposure. Dutta et al. (1989) reported that a 147-MHz field, at amplitude modulation ranges of 13–16 Hz and 57.5–60 Hz (SAR = 0.05–0.005 W/kg) caused an efflux of Ca^{++} from human neuroblastoma cells. Similar increase in Ca^{++} efflux with a 915-MHz field, amplitude-modulated at 16 Hz, was earlier reported by this research group (Dutta et al. 1984). Finally, stimulation of Ca^{++} efflux from the nervous cells seems to be a general phenomenon as it was also reported for the normal (non-transformed) avian and feline brain cells (Bawin et al. 1978, Blackman et al. 1981). Because Ca^{++} ions are required for normal functioning of brain tissue, the above studies suggest that perturbations in Ca^{++} efflux in brain cells, if taking place *in vivo*, might affect normal brain physiology.

Ca^{++} ions also play a crucial role in the normal physiology of heart muscle. Schwartz et al. (1990) have reported that in frog heart, exposure to a microwave field of 240 MHz, amplitude-modulated at 16 Hz, causes an increase of 18–21% (at SAR = 0.3–0.15 mW/kg) in Ca^{++}. However, exposures to a continuous-wave field or to a field amplitude-modulated at 0.5 Hz (approx. the beating frequency of a frogs heart) had no effect on Ca^{++} efflux. In a subsequent study, Schwartz & Mealing (1993) reported lack of effect of a 1-GHz field (SAR from 3.2 μW/kg to 1.6 W/kg), either continuous wave or amplitude-modulated at 0.5 and 16 Hz, on the Ca^{++} efflux and on the contractility of atrial strips from frog heart. As with brain tissue, alterations in Ca^{++} efflux observed in heart muscle may cause perturbations in the normal functioning of this organ.

4.5.3 Permeability for molecules

Lange et al. (1993) examined the effect of 2.45 GHz microwaves (continuous wave, power density 800 W/m^2; exposure period 30 min.; SAR = 72 W/kg) or a matched radiant-energy thermal load (both raised rat rectal temperature by 3°C) on the permeability of rat liver canalicular membrane for tritium-labelled sucrose and mannitol. The microwave-induced decrease in membrane permeability for sucrose was found to be due to the thermal effect. However, the decline in permeability for mannitol was specific to the microwave radiation, as the thermal radiation alone did not induce a matching effect.

4.5.4 Cell membrane fluidity/charge

The decline in membrane permeability induced by microwave radiation observed by Lange et al. (1993) is to some extent supported by the study of Phelan et al. (1992). They found that exposure of B-16 melanocyte cell line to non-thermal microwave energy (SAR = 0.2 W/kg, power density 100 W/m^2, 100 pulses/s) caused cell membrane rigidification. Because the effect was diminished in the presence of superoxide dismutase, the oxygenated free radicals were suggested to be responsible for the rigidification effect. However, the authors did not postulate that microwave radiation causes increase in generation of free radicals but suggested that irradiation causes some “perturbations” in normal degradation of free radicals. In contradiction with the above “rigidification-effect”, microwaves were also reported to increase cell membrane fluidity and consequently to change the charge of the cell surface. Ismailov (1978) demonstrated that microwave radiation causes a higher electrophoretic mobility of erythrocytes 30 min. after exposure at SAR greater than 10 W/kg. The probable reason for this was the increased negative charge of the cell membrane. Similarly, in the study by Somosy et al. (1991) it was observed that the binding of cationized ferritin to the cell surface changed upon exposure to low-frequency modulated microwave irradiation (24 W/kg) but it was not altered by a continuous microwave field.

4.5.5 Changes in cell shape/morphology

Chang (1989) found that a short exposure to low-intensity microwave *in vitro* at 100 W/m^2 (SAR = 0.2418 W/kg) caused marked changes in the fine structure of liver cells. Somosy et al. (1991) found similar ultrastructural changes following irradiation by continuous waves in the same intensity range. However, the modulated microwave fields were more effective. The cells that were exposed to the low-frequency modulated microwave irradiation (24 mW/kg) underwent cell ruffling and partial detachment from the substratum. Continuous microwave fields did not cause such shape alterations. However, both continuous and modulated microwave fields caused similar morphological changes in the cell organelles (dilation of rough endoplasmic reticulum cisternae and Golgi apparatus cisternae, increase of lysosomes and autophagic vacuoles, disruption of internal mitochondrial membrane, appearance of vacuoles with myelinated figures and amorphous material and deep intendations appearing in nuclei). The physiological significance of these morphological changes requires further clarification.

4.6 Activity and/or expression of enzymes

4.6.1 Cholinesterase/acetylcholinesterase

ChE/AChE is a common model for studies of the effect of microwaves on enzymatic activity. Early studies by Nikogosyan (1962), Revutsky & Edelman (1964) and Baranski (1972) suggested that microwave exposure can alter the activity of ChE. However, there were discrepancies between these studies. Nikogosyan (1962) observed increase in ChE activity in blood after exposure to 3 GHz radiation at 400 W/m^2 for 1.5 h. A similar observation was reported by Revutsky & Edelman (1964) for the 2.45 GHz radiation. However, Baranski (1972) observed species-dependent alterations in ChE activity following microwave irradiation. In this study, exposure of the brains of guinea pigs and rabbits over 3-months period (1 h/day) to pulsed fields of 250 W/m^2 caused changes in ChE activity. In the same study it was also observed that exposure of guinea pig brain for 3 h to 2.45–GHz fields at 35 W/m^2 and 250 W/m^2 caused a field-power-density-dependent decrease in ChE activity. It was also suggested that the pulsed exposures were more effective than the continuous-wave exposures.

The more recent studies by Olcerst & Rabinowitz (1978) and Galvin et al. (1981) reported a complete lack of effect of microwaves on ChE/AChE. Olecrest & Rabinovitz (1978) reported that temperature-controlled exposure of purified enzyme and enzyme present in defibrinated rabbit blood to 2.45-GHz fields with power density 100–1,000 W/m^2 had no effect on ChE activity. Only exposure without temperature control to a power density of 1,250 W/m^2 lead to a decline in enzyme activity, which was probably caused by the thermal denaturation of the enzyme. Using purified AChE and creatine phosphokinase, Galvin et al. (1981) also observed no change in the enzymatic activity following exposures to 2.45-GHz fields with SAR of 1–100 W/kg. Dutta et al. (1992) reported that in neuroblastoma cells (NG108) exposure to 147-MHz fields, amplitude-modulated at 16 Hz, causes an increase in enzyme activity that can be observed at a time-window of 7 h to 7.5 h after exposure. None of the above-cited studies was able conclusively to resolve the controversy over whether ChE/AChE activity is affected by microwaves or not.

4.6.2 ß-galactosidase

Saffer & Profenno (1992) examined the effect of microwaves at different frequencies (2–4 GHz) but at constant SAR (10 W/kg) on the expression/activity of ß-galactosidase in *E. coli*. They observed an increase in enzyme expression/activity that was independent of microwave frequency, thus suggesting that heat is a causal factor. However, because the bulk-heating did not cause an increase in the activity of ß-galactosidase, the authors suggested that a thermal gradient might be responsible for the observed microwave effect.

4.6.3 Ornithine decarboxylase

Buys et al. (1988) have examined the effect of microwaves on ornithine decarboxylase (ODC), an enzyme that regulates synthesis of polyamines that are necessary for DNA synthesis during the S-phase of the cell cycle. Thus, any disturbances in ODC activity may have a direct effect on cell cycle progression and cell proliferation. Buys et al. reported that the exposure of various tumor cell lines (Reuber H35 hepatoma, CHO, 294T melanoma) to the 450-MHz field with amplitude-modulated frequencies between 10 and 20 Hz lead to an increase of up to 50% in ODC activity (peak response at 16 Hz). An amplitude modulation of 20–100 Hz had no effect on the ODC activity. Furthermore, the exposure of cells to a 450-MHz field, amplitude-modulated at 16 Hz, followed by phorbol ester treatment (TPA, 1.6 uM), showed an additive effect. However, the physiological significance of the rise in ODC activity remains unclear, as it was not associated with any changes in DNA synthesis (^{3}H-thymidine incorporation). A similar potentiating effect of microwaves on ODC activity was reported by Litovitz et al. (1993). The ODC activity was doubled 8 h after exposure to 915-MHz field (SAR = 2.5 W/kg) with amplitude modulation at 55, 60 and 65 Hz. The possible physiological consequences of ODC activation were not tested in the study.

4.7 The possible role of microwave radiation in carcinogenesis

4.7.1 Genotoxic effects

Most of the public concern over the use of mobile phones is connected with the uncertainty about whether the phones can induce or affect the development of cancer. Cancer development is a multistage process consisting of initiation, promotion and progression. Genotoxic tests can be used for assessing the possible effects of mobile phone radiation on cancer initiation.

An exposure agent that is capable of damaging the cell genotype is in principle also capable of causing cancer (‘initiator carcinogen’) or hereditary damage. There are various genotoxic tests for describing genotype damage. Some of these measure DNA disintegration (e.g. breaks of one or both DNA strands; chromosome damage) while others measure changes in DNA base sequence (e.g. one more or one less base pair as a result of repair; depurination). In some genotoxic tests, the actual mechanism may be unknown and the change to be measured may be a result of both genotoxic and non-genotoxic processes (change in the number of chromosomes, sperm malformation, cell transformation).

It is generally believed that RF radiation or even microwave radiation of more than 1 GHz cannot cause any direct gene damage. This is because the radiation energy is far too weak to be able to break chemical bonds (Léonard et al. 1983). When the absorption of RF radiation by tissue is high enough to cause a discernible rise in temperature (cf. microwave oven), changes such as protein denaturation start taking place in the cell structure. In some exposure situations, RF radiation might produce indirect genotoxic effects either through thermal effects or as effects resulting from changes in the permeability characteristics of the cell membrane.

The summary on genotoxicity of RF radiation by Brusick (1995; 1995/96), which looks at 105 different studies, is the most comprehensive work produced on this subject. So far, it has only been presented in international meetings and thus no comprehensive literary survey of all these studies is available. The range of research material evaluated by Brusick's group was very wide, and comparison of the studies is difficult because they are based on different frequencies, radiation sources and exposure conditions and have used different testing systems. Only some of the studies are concerned with mobile phone frequencies. In many cases, relatively high exposure levels have been used and, consequently thermal effects cannot be excluded. When interpreting the results of genotoxic tests, it should be kept in mind that *in vitro* tests especially are relatively sensitive and that tests with chemical substances also produce sporadic positive results. In these cases sporadic marginal effects also occur in non-mutagens. Under *in vitro* conditions, a false positive result of this kind may arise from, for example, pH changes or changes in osmotic conditions. Marginal responses in both *in vitro* and *in vivo* conditions can also be caused by an abnormal control result or the small size of the sample. Depending on the test system, the proportion of sporadic positive results can vary from just a few per cent to a major share of the total. Table IV shows the summary compiled by Brusick's group on the basis of 105 genotoxicity studies.

Depending on the mechanism, damage to the genome has been divided into three categories: DNA disintegration (55 studies), nucleotide change and/or recombination (43 studies) and unknown mechanisms (7 studies). A total of 73 studies produced a negative and 32 a positive result. When mechanisms were examined, almost all of the tests based on nucleotide change (point mutation) and recombination produced a negative result, whereas nearly half of the studies examining DNA disintegration were positive. This may be partly explained by a thermal effect which could be expected to cause DNA breaks rather than base changes. Brusick summarizes the 105 studies by suggesting that RF radiation is not directly mutagenic and that the harmful effects observed with high frequencies and in powerful fields are the result of a thermal effect. However, it is possible that some exposure conditions can produce indirect effects on gene replication and transcription.

Table IV. *Results of genotoxic effects of RF radiation as produced by different studies.*

		Research result		
Mechanism	Type of damage	Studies	Negative	Positive
DNA disintegration				
	DNA breaks	14	9	5*
	Micronuclei	5	0	5
	Chromosome damage	30	17	13
	Dominating lethal mutation	6	3	3
Nucleotide substitution and recombination				
	Genemutation	26	25	1
	SCE	17	15	2
Unknown				
	Loss of chromosome	2	2	0
	Sperm malformations	2	1	1
	Cell transformation	3	1	2

[*] All *in vivo*

Studies where the RF radiation was so low that the possibility of a thermal effect can be excluded are especially noteworthy. Lai and Singh (1995) exposed rats to 2,450-MHz microwave radiation for two hours and examined the number of DNA breaks in rat brain cells using the single cell electrophoresis method ('Comet assay'). The number of DNA breaks in brain cells subjected to electrophoresis immediately after pulsed radiation (pulse duration 2 µs, 500 pulses/second) was comparable to the control level, but the number of DNA breaks increased substantially four hours after exposure (SAR = 1.2 W/kg). Following 2,450 MHz of CW radiation, a growth in the number of DNA breaks was discernible both immediately after the exposure and four hours later (SAR = 1.2 W/kg). These findings were, however, not confirmed by Malyapa et al (1998). Instead they noticed that the results from the comet assay were strongly influenced by the method used to kill the rats after exposure. When using CO_2 to cause asphyxia, the results varied heavily depending on the time between starting CO_2 treatment and cooling down the dissected brain. A delay of a couple of minutes caused DNA damage of the same magnitude as 2 Gy of ionizing radiation when measured by the comet assay. On the other hand, rapid decapitation by guillotine followed by immediate dissection and cooling of the brain gave consistent results with small standard deviations. None of the experiments showed any indication of an effect of 2 h CW microwave exposure (2,450 MHz, SAR 1.2 W/kg) neither immediately after exposure, nor 4 hours later. As Lai et al had used a combination of CO_2 asphyxia and decapitation to kill the rats, confounding caused by the killing procedure is a likely explanation of their results.

Sarkar et al. (1994) exposed mice to 2,450 MHz radiation with a power density of 10 W/m^2 (SAR = 1.2 W/kg) for two hours daily for 120, 150 and 200 days. DNA samples of the brains and testicles of the exposed and control animals were dissected using restriction enzymes and hybridized together with a synthetic oligonucleotide probe with a repetitive sequence. Compared with the control animals, the length of the DNA base sequences of the exposed animals had changed in the region of 7–8 kb. As this 7.7 kb *Hin*f I fragment was not evident in the DNA of the control animals but appeared in the DNA of exposed animals, the authors assumed that the copy number of the marker of the non-exposed animals was so low that it did not show up in electrophoresis. Microwave exposure could cause these repeated base sequences to be copied. It is not yet known whether genotoxic substances can cause mutations in repetitive sequence DNA. It is known, however, that stress can cause extra copying of DNA sequences in repetitive DNA in non-coding (outside genes) areas (Ramel 1989).

The lack of direct DNA effects does not exclude the possibility that under certain conditions DNA could be damaged as a result of indirect mechanisms. Especially in recent years, a number of studies have examined the possibility that electromagnetic fields can make cells sensitive to the effects of chemical mutagens and carcinogens. Research on these combined effects has produced varied results; some indicate that combined effects exist, whereas others have failed to detect them (Rosenthal et al. 1989, Kerbacher et al. 1990, Ciaravino et al. 1991, Scarfi et al. 1991, Hintenlang 1993, Damiani et al. 1995, Maes et al. 1996). Not all these studies have been concerned with RF radiation, and only Damiani et al. (1995) and Maes et al. (1996) have focused on mobile phone frequencies. The latter group discovered that exposure to the 954-MHz field of a GSM base station antenna increased the genotoxic effect of mitomycin C in cell cultures. They suggested that the mechanism for this sensitizing could be either an increased permeability of the cell membrane or an opening of the chromatine structure, which would make it easier for chemical mutagens to reach the DNA.

4.7.2 Effects on cell proliferation and tumor promotion in vitro

The above described (Chapters 4.5. and 4.6.) effects of microwave radiation on cell membrane physiology and on the activity of enzymes may have a potentiating effect on tumor promotion and progression by regulating cell proliferation and/or cell death. Several studies addressed the question of cell transformation and regulation of cell proliferation by microwave radiation alone or in concert with other factors. Balcer-Kubiczek & Harrison (1985, 1989, 1991) have examined the effect of microwave radiation on transformation of C3H/10T$^1/_2$ mouse embryo fibroblasts. The first study (Balcer-Kubiczek & Harrison 1985), using microwave radiation of 2.45 GHz (SAR = 4.4 W/kg), demonstrated that exposure to microwaves reduced cell-plating efficiency by 50%, and that the microwaves, neither alone nor in combination with benzopyrene and X-rays, did not transform the cells. However, the microwave exposure followed by phorbol ester treatment (at non-transforming concentration) led to a statistically significant 3.5-fold increase in cell transformation. A similar effect of combined treatment of microwave radiation and phorbol ester was reported in a subsequent study (Balcer-Kubiczek & Harrison 1989). However, in this study the authors did not detect any effect of microwaves on cell-plating efficiency, which contradicts the findings of their first report (Balcer-Kubiczek & Harrison 1985).

The same authors (Balcer-Kubiczek & Harrison 1991) have also reported that a microwave field of 2.45 GHz, pulse-modulated at 120 Hz (SAR = 0.1, 1 and 4.4 W/kg), in combination with subsequent phorbol ester treatment, had a transforming effect on the C3H/10T$^1/_2$ cells. The three studies cited above, in spite of some discrepancies in the results, suggest that although microwaves alone may not be potent enough to induce cell transformation, in combination with a cell-transforming factor and/or stimulator of cell proliferation they may have an *in vitro* carcinogenic effect on cell cultures. Whether this also applies to the *in vivo* conditions remains to be determined.

4.7.3 Animal tests carried out to study induction of cancer in vivo

In recent years, animal experiments have focused on the possible cancer promoting effects of RF radiation, i.e. its ability to promote cancerous growth. A Polish research group (Szmigielski et al. 1982) looked into the promoting effect in mice using three different cancer models: 1) sarcoma cells were transferred from one mouse to another in such numbers that between one and four cancerous foci would normally be expected to appear after two weeks; 2) during a five-month period, the skin of a mouse was treated with benzopyrene, which causes skin cancer in most mice; 3) tests were carried out with a mouse strain in which 80% of the females spontaneously develop breast cancer within a year. CW radiation of 2,450 MHz with a power density of 50 or 150 W/m^2 was used for exposure. The equivalent whole-body SAR is 2–3 W/kg or 6–8 W/kg. The exposure time was two hours per day for six days a week. For comparison, other groups of mice were kept in very small cages for weeks or months, which caused chronic stress syndrome and aggressive behaviour.

All three tests produced similar results. Exposure to RF radiation caused the cancer to develop significantly earlier, as did the chronic stress caused by captivity. The lower SAR-level (2–3 W/kg) created effects similar in magnitude to captivity; the higher SAR-level clearly had a greater effect.

The results are, in themselves, convincing. However, because of shortcomings and inconsistencies in the reporting, the interpretation must be somewhat cautious. The results suggest that even though exposure did not cause any measurable increase in rectal temperature, the effect is nevertheless a result of unspecific physical stress related to thermal load. According to the authors, a rate of 2 W/kg is already well above the energy production of the basal metabolism in mice. In their earlier projects (Roszkowski et al. 1980), the same authors concluded that an absorption of 18 W/kg caused a discernible rise in temperature in mice (rectal temperature 41.5 ± 0.5°C). However, other studies (Gordon 1982) suggest that mice have a higher basal metabolic rate and that only a rate in excess of 20 W/kg could cause clearly discernible thermal stress in mice.

Another group (Santini et al. 1988) exposed mice to both pulsed radiation and CW radiation with a frequency of 2,450 MHz so that the average whole-body SAR was 1.2 W/kg. Even a daily exposure lasting for several months had no discernible effect on the development of melanoma transplanted in the mice.

In a recent annual meeting of the Bioelectromagnetics Society, Adey et al. (1996) reported a study in which rat foetuses had been given a small dose of ethylnitrosurea, which causes tumours in the nervous system. The rats were then exposed to pulse-modulated radiation imitating mobile phone exposure for two hours a day, four days a week. The average whole-body SAR was 0.3–0.75 W/kg, depending on the size of the rat. No effect on initiation or promotion of central nervous system tumours were detected; in fact, there were fewer tumours in the irradiated group than in the sham-irradiated control group, and they were of smaller size.

A study connected with the European COST 244 research program is also under way in Finland. The purpose of the study is to examine the possible effect of mobile phone radiation on the development of cancer (promoting effect) in mice (Heikkinen et al. 1997). Ionizing radiation was used as the initiating factor for the cancer. When using CW radiation, the average whole-body SAR values were 1.2–1.5 W/kg and with pulsed GSM radiation 0.3–0.4 W/kg. According to the available results, RF radiation has no clear cancer-promoting effect. However, the other exposure conditions, which were identical for exposed and sham-exposed animals (spending 1.5 hours a day and five days a week in a cramped space for the entire duration of the test period), were connected with a noticeable delay in weight gain in the mice tested. Only a histopathological study of the samples taken from the mice would show whether there has been any increase in organ-specific cancer risk.

The effect of radar-type pulsed radiation on rat health has been studied by Chou et al. (1992), who exposed rats on a life-long, almost round-the-clock basis. The frequency used was 2,450 MHz, duration of the pulse 10 µs, pulse frequency

800 Hz and the average whole-body SAR 0.15–0.4 W/kg. The effect on the blood count and a number of other health indicators was negligible and there was no discernible effect on life expectancy or the total number of tumours. However, the number of primary malignant tumours was higher in the exposed group (18) than in the control group (5). No individual tumour type, though, had a higher incidence in the exposed rats than is usual in this rat strain. Therefore the authors were not convinced that this difference is of any biological significance.

Repacholi et al. (1997) have looked into the effect of pulsed radiation imitating mobile phone exposure on mice which had received a lymphoma-promoting tumour gene. Frequency was 900 MHz, pulse width 600 ms and pulse frequency 217 Hz. The mice were exposed for 30 minutes twice a day (at 12-hour intervals) for 18 months. During the exposure, the animals could roam freely in their cages. Depending on the location and size of the mouse, the whole-body SAR was estimated to vary between 0.008 and 4.2 W/kg. It can be assumed that each mouse was exposed to at least several W/kg at some point. Of the 101 exposed mice, 43 contracted lymphoma, and of the 100 sham-exposed animals, 22 contracted the disease. The study proved convincingly that exposure contributed to the development of lymphoma in mice carrying the tumour gene. However, because the experimental conditions allowed a great variation in exposure, it is not possible to determine at which level the cancer-promoting effect came into existence. The highest SAR values may have caused slight changes in the thermoregulation system without any real rise in temperature (isothermal effect). In itself, the study lends support to the positive results already referred to.

Most of the animal experiments concerning the possible cancer-promoting effect of weak RF radiation have, however, produced negative results. Thus, in general, exposure well below the level causing an increased thermal load clearly cannot have any strong, specific cancer effect.

4.8 Epidemiological studies

Little epidemiological research has been made on the health effects of RF radiation, and all the studies have had shortcomings (Bergqvist 1997). Mostly exposure assessment has been based only on whether or not an individual belongs to a particular occupational group, and no direct measurements of real exposure have been made. Besides, there are usually no data on other exposure agents, such as chemicals, and on other confounding factors. Many of the studies have produced totally negative results, and the few positive results have not usually been repeated in other studies. In its report, the WHO (WHO 1993) stated that epidemiological studies have provided no clear indication that exposure to RF radiation might have harmful effects on human health.

A Polish study (Szmigielski et al. 1996) looked into the cancer rate among military personnel some of whom are exposed to pulsed or CW RF radiation at work. The subjects were divided into exposed and unexposed persons according to their work tasks. Power density measurements were made at the work locations of exposed persons, but no other individual estimate of the level or duration of the exposure was made.

The study showed that a number of cancer types were significantly more common among the exposed than among the unexposed persons. The total cancer rate among the exposed persons was more than twice that of the unexposed persons. However, it remains unclear how the data on exposure were gathered, and it is possible that knowledge of the cancer diagnosis has come to influence the exposure classification. Besides, the report does not state whether the exposure situation concerns the year the cancer diagnosis was made or previous years. The report does not examine the exposure to other cancer-causing substances either, and thus, the sources of errors cannot be assessed with certainty.

Epidemiological studies on the health risks of mobile phones have been initiated, but no final results are yet available. A study based on private registers of mobile phone subscribers is under way in the USA. The cohort comprises 250,000 persons. As far as possible, a distinction is made between users of hand-held phones and car phones. The exposure caused by the latter type is minimal. The first partial results have already been published (Rothman et al. 1996) and deal with the total mortality during one year (1994). Mortality among the users of mobile phones was well below the mortality in the population as a whole, which is probably connected with the higher socio-economic status of the phone users. No difference was found between users of hand-held phones and car phones.

This provisional result shows only that in the short run, exposure has no substantial effect on total mortality. However, it does not provide us with any answers concerning other factors, such as the possible risk of brain tumour.

When assessing the possible health risks connected with the use of mobile phones, results of epidemiological studies so far published are of little value. Because of their limitations, they cannot yet be used as a basis for any conclusions.

5 RADIATION SAFETY STANDARDS

5.1 Introduction

To prevent RF radiation hazards international and national standards and recommendations have been developed during the recent years. The most important ones, as far as the handheld mobile phones are concerned, are the standards limiting the exposure of the user. Also, technical documents and standards that harmonize testing methods have a significant effect on exposure.

Usually, the radiation of commercially available handheld mobile phones is regulated by the safety limits limiting the exposure of the General Public in “uncontrolled” environment. The radiation from equipment used in professional radio networks is regulated by safety limits for occupational exposure in the “controlled” environment.

The basic exposure limit for RF radiation is 0.4 W/kg which is the SAR averaged over any 6-minute time and over the whole body in the controlled environment (IEEE 1982, IEEE 1992, CENELEC 1995, ICNIRP 1998). In the uncontrolled environment, the SAR averaged over the whole body shall be less than 0.08 W/kg. The SAR can be higher than the above-mentioned values for a short period of time as long as the six-minute average does not exceed the given limits.

The 0.4 W/kg limit has been set in order to avoid the loading of the thermoregulatory system of the body. Animal tests made with primates suggest that the smallest SAR level causing detectable effects in the thermoregulatory system is about 1 W/kg (Adair 1994). For comparison, metabolic heating power per mass unit generated by a human body is 1–1.4 W/kg in rest and even more than 10 W/kg in an extreme physical exercise.

The whole body average SAR limit for the general public 0.08 W/kg, may be exceeded in theory, if the weight of the handheld phone user is less than 10 kg. In practice, it is unlikely that persons weighting so little would use mobile phones. The main problem is the local SAR in the user’s head induced by a handheld phone that must be limited to prevent the local temperature increase of the head.

5.2 Exposure limits

Exposure limits for the local maximum SAR values are shown in Table V. The values shown in the table are used for the head and torso. The local maximum SAR in the limbs can be twice these levels. As can be seen, the maximum SAR in a controlled environment varies between 8–10 W/kg. According to the international and European recommendations (CENELEC 1995, ICNIRP 1996, ICNIRP 1998), the SAR averaged over 10 g shall not exceed 2 W/kg in the uncontrolled environment. As far as Finland is concerned, this is the most important international safety recommendation limiting the radiation emitted by mobile phones. Slightly stricter limits are applied in the United States: The exposure limit is 1.6 W/kg averaged over 1 g in the uncontrolled environment.

Field strength or equivalent power density levels derived from the SAR limits can be applied when the radiating device or antenna is located far enough (see Table VI). Radiation safety of portable phones, car phones, and base stations, for example, can be tested by using these levels. The minimum operating distance that allows the use of field-strength limits is 20 cm according to FCC (1996).

The exposure is commonly defined as a SAR or power density averaged over any six-minute time interval. This means, in the case of mobile phones, that the SAR is averaged only over the pulse-repetition period (GSM) or carrier-wave period (NMT), because limiting the operating time is not practical.

5.2.1 IRPA and ICNIRP

In 1988, the International Non-Ionizing Radiation Commission (INIRC) of the International Radiation Protection Association (IRPA) issued recommendations for the exposure to RF radiation in the frequency range above 100 kHz (IRPA/INIRC 1988). In 1998 the successor of IRPA/INIRC, the International Commission on Non-Ionizing Radiation (ICNIRP) published new safety guidelines that cover all electric and magnetic fields in the frequency range from 1 Hz to 300 GHz. The most significant change from the 1998 recommendations, as far as the radiation safety of the handheld mobile telephones is concerned, was the adoption of 2 W/kg limit for the General Public, which was not included in the old guidelines. The power density levels in the mobile frequency bands will be the same as in the present guidelines.

Table V. *Exposure limits for local SAR.*

Organization	**Year**	**Status**	**Specific absorption rate (SAR)[a] [W/kg]**		**Averaging**		**Frequenc**
			General Public	Controlled environment	Time (min)	Mass (g)	
IRPA	1988	Recommendation	-	10	6	100	10 MHz–3
STM	1990	National regulation	-	10	6	-	10 MHz–3
IEEE	1992	National standard	1.6[b]	8[c]	-	1	100 kHz–6
CEC	1994	Directive proposal	-	10	6	100	100 kHz–3
CENELEC	1995	Standard	2	10	6	10	10 kHz–30
ICNIRP	1996	Statement	2	10	6	10	not availa
FCC	1996	National regulation	1.6[d]	8	-	1	not availa
ICNIRP	1998	Recommendation	2	10	6	10	100 kHz–1

IRPA: International Radiation Protection Association
STM: Ministry of Social Affairs and Health, Finland
IEEE: Institute of Electrical and Electronics Engineers, USA
CEC: Commission of the European Communities
CENELEC: European Committee for Electrotechnical Standardization
ICNIRP: International Commission on Non-Ionizing Radiation Protection
FCC: Federal Communications Commission, USA

[a] twofold SAR allowed in hands and legs
[b] averaged over any 30 minutes in 3–3000 MHz
[c] averaged over any 6 minutes
[d] averaged over the pulse period

Table VI. *Derived reference levels for power density in mobile frequencies.*

	Power density (W/m^2)								
	General Public					Controlled environment			
	150 MHz	450 MHz	900 MHz	1,800 MHz	Averaging time (min)	150 MHz	450 MHz	900 MHz	1,800 MHz
IRPA	2	2.3	4.5	9	6	10	11.3	22.5	45
STM	2	2.3	4.5	9	6	10	11.3	22.5	45
IEEE	2	3	6	12	30	10	15	30	60
CEC[a)]	-	-	-	-	-	10	11.3	22.5	45
CENELEC	2	2.3	4.5	9	6	10	11.3	22.5	45
FCC	2	3	6	12	30	10	15	30	60
ICNIRP	2	2.3	4.5	9	6	10	11.3	22.5	45

[a)] Action levels

5.2.2 CENELEC

European Committee for Electrotechnical Standardization has issued a European prestandard ENV 501662-2: “Human exposure to electromagnetic fields: High frequency” (CENELEC 1995). There is no significant difference between the ENV-standard and the new ICNIRP guidelines in the frequencies above 100 kHz. The prestandard is effective for three years. After that it will be revised and a decision will be made whether it could be approved as a European standard. The ENV-standard has been approved as a national standard, albeit not a binding one, in Finland.

A working group of CENELEC, commissioned by the Commission of European Communities, has prepared a technical report on the radiation safety of mobile phones in the frequency range from 30 MHz to 6 GHz (CENELEC 1998). The purpose of the report is to harmonize European radiation-safety testing methods of mobile telecommunication equipment. Although this report is only a technical document, it may be converted to a standard-like document called “European Specifications”. According to the document, SAR testing can be performed either by measurements or computations, but in either case, the validity of the method must be carefully verified. An anatomically shaped phantom filled with homogeneous liquid can be used in the measurements. Handheld phones are tested in a standard position (intended use position) and three additional positions that are well specified. The power and antenna settings of the phone under test must be set so that the SAR is in maximum. This method allows a testing practice that is less restrictive than the testing in the unrealistic worst case position. Portable mobile phones are tested at the minimum operating distance recommended by the manufacturer, or at the distance of 5 cm. SAR testing is not needed if the average output power of the phone is below 20 mW.

5.2.3 Commission of the European Communities (CEC)

The Commission of the European Communities has prepared a directive proposal on physical agents in work (CEC 1994). The exposure limits for the electromagnetic fields do not differ significantly from the values recommended by ICNIRP (1998). It is probable that the national regulations in most European countries will be based on the ICNIRP recommendations and Physical Agent directive. Therefore, it is likely that the ENV standard will not be approved as a European standard in its present form, but the exposure limits must be harmonized with the limits proposed by CEC. Currently, CEC has also prepared a proposal for a council recommendation that recommends to limit the electromagnetic field exposure of the General Public below the new ICNIRP guidelines.

5.2.4 FCC

For evaluating the environmental effects of radio-frequency radiation, the Federal Communications Commission (FCC), USA, has issued guidelines where the mobile phones are divided into portable and handheld devices. A mobile phone is to be considered portable if the distance of the user from the antenna is not smaller than 20 cm in normal use. In practice, this means that the earphone and microphone are separated from the transmitter. The power density shall not exceed the reference levels (Table VI) recommended by NRCP (National Council on Radiation Protection and Measurements) in 1986. It should be noted that although the averaging time of power density is 30 minutes, FCC recommends, in parallel with the European recommendations, that, for the mobile phones used by the general public, the averaging time should be equal to the pulse repetition period.

According to the FCC, SAR induced by a handheld phone shall not exceed the local peak SAR of 1.6 W/kg averaged over 1 g. The only information given on the testing procedure is that SAR should be determined in the intended use position either by numerical simulations or measurements. FCC regulations appear stricter than the CENELEC recommendations because of the lower SAR limit and smaller averaging mass. However, the difference may actually be smaller than it appears. The SAR-testing positions are defined more accurately in the mobile phone document of CENELEC than in the FCC regulations. Therefore, it is possible that in CENELEC tests the SAR maximum is determined in some unusual operating position resulting in higher SAR than in the FCC tests.

5.2.5 Ministry of Social Affairs and Health, Finland

In Finland the limits for the exposure to non-ionizing radiation have been decreed by the Ministry of Social Affairs and Health (STMp 1474/91). As far as RF radiation is concerned, the limits comply with the old guidelines of IRPA (1988) which do not include the basic restriction of 2 W/kg for the general public (Tables V and VI). STUK is currently preparing a new proposal for the national regulations that will follow the new ICNIRP guidelines, including the 2 W/kg limit.

6 RADIATION SAFETY OF BASE STATIONS

6.1 Placement of base stations

In rural areas, the base station antennas used in mobile phone networks are usually mounted at the height of several tens of meters on the top of a tower. In urban areas, antennas are mounted on 2–4 meter high masts, which are placed on the roofs of the buildings. In this case the distance of the antenna from the ground varies from 20 to 45 m. Antennas can be placed on the walls of the buildings, as well. In that case the distance of the antenna from the ground varies from 10 to 35 m. An example of the rooftop mounted base station antenna mast is shown in Figure 8. Transmitting antennas are usually placed on the mast and receiving antennas in the ends of the horizontal beam. Antennas are placed so that there is a free space of at least 30 m in the direction of the main beam. Typically, this space extends up to several hundreds of meters to ensure the proper functioning of the mobile network. Base station antennas are also installed indoors. They can be placed on walls or on roofs as long as they are located at least 2 meters above the floor. Normally, they are placed so that people are not working or staying closer than 3 meters to the antenna. Usually, directive antennas consist of few horizontal dipoles and a reflector behind them. Omni-directional antennas are vertical dipole or monopole antennas.

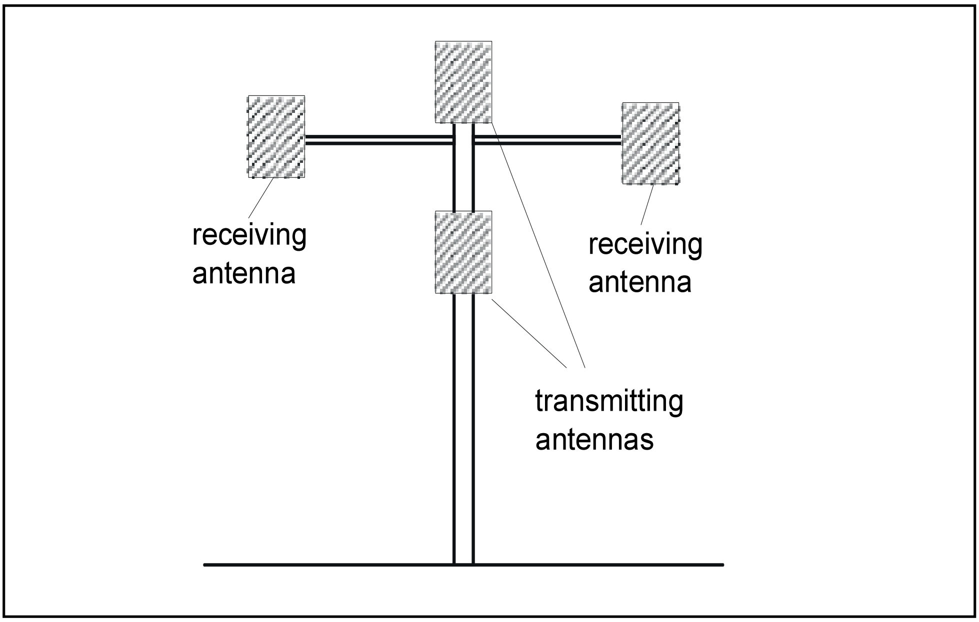

Figure 8. *A roof-top mounted base station antenna mast.*

6.2 Safety distances

The power density generated by a base station antenna depends on several factors: the distance and direction from the antenna, antenna gain, number and output power of the transmitters, number of channels in use, and losses from the cables and components between the antenna and the transmitter. The power density S in the direction of the main beam can be calculated as a function of distance r from

$$S = \frac{NP \cdot 10^{\frac{G-L}{10}}}{4\pi r^2} \tag{5}$$

where N is the number of the transmitters, P is the output power of a single transmitter, G is the gain of the antenna, and L is the combined loss from the cable, power splitter, etc., in decibels. By substituting the power density in the equation (5) with the reference value S_{max} from the exposure standards and solving for r we get the safety distance r_{saf}

$$r_{saf} = \sqrt{\frac{NP \cdot 10^{\frac{G-L}{10}}}{4\pi S_{\max}}} \tag{6}$$

The safety distances for Finnish base station antennas, have been calculated on the basis of the technical information given by the network operators (Table VII). Also, the national exposure limits for the power density in the controlled environment and for the general public at frequencies of 450, 900 and 1,800 MHz, according to the order STMp 1474/91 by the Ministry of Social Affairs and Health, are shown in Table VII. The power density levels for the general public are not exceeded at the distance greater than 10 m from the antenna even in the direction of the main beam. The main beam of the antennas used outdoors is usually very narrow in the vertical plane. For this reason, the safety distances are very small in the directions away from the main beam, being in the case of NMT900 and GSM900 base stations about 1 m or less and in the case of NMT450 base stations a few meters. According to the measurements performed by STUK in the 900 MHz frequency band, the safety distances in all directions, except in the direction of the main beam, were in maximum 1 m for the general public and 0.5 m for the controlled environment, when the antenna gain exceeded 10 dB.

Table VII. *Calculated safety distances for typical Finnish base stations.*

Base station type				Controlled environment			General public		
					Main beam	Side-lobe		Main beam	Side-lobe
	P_{max} [W]	G [dB]	L_{min} [dB]	S_{max} [W/m^2]	r_{saf} [m]	r_{saf} [m]	S_{max} [W/m^2]	r_{saf} [m]	r_{saf} [m]
NMT450	320	11	3	11.3	3.8	1.4	2.3	8.5	3
NMT900									
outdoors	64	18.5	2	22.5	3.2	<0.6	4.5	7.2	1.1
indoors	10	10	2	22.5	<0.6	<0.6	4.5	1.1	<0.6
GSM900									
outdoors	80	18.5	5	22.5	2.6	<0.6	4.5	5.7	0.9
indoors	30	5.5	5	22.5	0.4	<0.3	4.5	0.8	0.6
GSM1800									
outdoors	50	18	5	45	1.4	<0.3	9	3	0.5
indoors	30	5.5	5	45	0.3	<0.3	9	0.6	0.4

P_{max} = The combined peak output power of the transmitters feeding the common antenna
G = The antenna gain
L_{min} = The minimum loss between the antenna and the transmitter
S_{max} = Derived reference levels for power density
r_{saf} = The safety distance, e.g. the greatest distance at which the reference level is exceeded

7 INTERFERENCE OF CARDIAC PACEMAKERS

The only well established health-hazard associated with the electromagnetic radiation from a mobile phone is the interference of the cardiac pacemaker. There are no known cases of death due to the interference, but this possibility cannot be excluded. In the literature, there is at least one reference to a person suffering from the Kearns-Sayre symptom who, while using a GSM phone, lost consciousness for 6.5 seconds because of a complete heart block (Murat et al. 1995).

Approximately 10,000 people in Finland are carrying a cardiac pacemaker implanted due to a severe arrhythmia (Toivonen et al. 1991). Pacemakers are usually implanted on the right side of the heart. The stimulating current is led to the heart via electrode leads placed inside the vein. It has been estimated that 14–27 percent of the persons having a cardiac pace maker in Germany actually carry a device that may be interfered by a mobile phone (Irnich et al. 1996, Hofgärtner et al. 1996).

Electromagnetic radiation emitted by a mobile phone is coupled to the cardiac pacemaker most likely via the electrode leads. In most cases the feed-through filters do not filter interfering RF signals sufficiently at the mobile phone frequencies. The signals are rectified in the semiconductors of the input stages producing pulses (GSM) or DC voltages (NMT) directly proportional to the RF power. DC-voltages can disturb the normal operation of the device by changing the bias voltages of semiconductors, but pulsed voltages induced by digital mobile phones are more harmful. The pulse frequencies vary from 2 to 217 Hz for GSM phones.

Several different types of malfunctions can occur in the pacemakers. These malfunctions depend on the type of the pacemaker, the implantation depth, the sensitivity of the electrical activity of the heart monitoring circuit, the strength of the interfering signal and the modulation mode (Barbaro et al. 1995, Irnich et al. 1996, Hofgärtner et al 1996, Smith and Aasen 1992). In the worst case, the pacemaker can be permanently damaged or its program altered. These kinds of incidents, however, are rare. A more common malfunction is the confusing of the interfering pulses with the natural pacemaking signal of the heart, which may cause the artificial pacemaker to shut down. It is also possible that the pacemaker synchronizes itself to the interfering pulses and produces unwanted pulses. In this case there is a danger of a fatal ventricular fibrillation. Low-frequency modulation in the frequencies below 100 Hz is most harmful, because, in that case, the spectrum of the interfering pulses resembles closely the spectrum of the heart stimulating biovoltages from the natural pacemaker of the heart. Particularly in the frequencies below 10 Hz, the pacemaker may confuse the interfering pulses with heart signals. High pulse-frequencies are not as harmful as low ones because the interference detection circuits make the pacemaker assume an asynchronous mode, which means, that the pacemaker neglects the natural heart pulses and generates stimulating pulses at the predetermined frequency. It is worth noting that the pulse frequencies of GSM interference was observed for 43 patients. The sensitivity to the interference increases in parallel with the sensitivity of the electrical activity monitoring circuit. The attenuation of the interfering signal depends on the amount of tissue between the skin and pacemaker. The attenuation increases when the frequency is increased. Bipolar pacemakers are more immune to the interference in the mobile frequencies than unipolar devices (Höfgärtner et al. 1996).

The maximum interference distance of the cardiac pacemakers has been studied by exposing pacemaker patients (*in vivo*) or pacemakers inside a simple phantom emulating human being (*in vitro*) to the radiation emitted by different types of mobile phones. In a German *in vitro* study the interference sensitivity of 231 different pacemaker models was tested by using analog and digital mobile phones (Irnich et al. 1996) The operating frequency of the analog device was 450 MHz and the digital devices 900 MHz (GSM900) and 1,800 MHz (GSM1800). The output power was 2 W at the frequencies of 450 and 900 MHz and 1 W at the frequency of 1,800 MHz. In the case of digital phones, the output power was the peak output power during the pulse. The maximum interference distance was 45 cm in the case of analog phones and 19 cm in the case of GSM900 phones. Interference was detected in 79 pacemakers of different type when the GSM900 phone was used. Seven of the pacemakers had a maximum interference distance of more than 10 cm. None of the pacemakers in the test experienced any interference when a GSM1800 phone was used. The reduced susceptibility to interference was at least partly caused by the lower level of radiation because the attenuation in the tissue increases at higher frequencies, which also explains why the maximum interference distance of the analog phones operating at 450 MHz was relatively high. However, it should be noted that malfunction caused by an analog phone is not as harmful as that of a digital phone. The increase in the maximum interference distance is directly proportional to $p^{1/3}$ (p is the radiated power).

In an *in vivo* study Hofgärtner et al. (1996) exposed 104 voluntary pacemaker patients having 58 different types of implanted pacemakers to radiation from analog and digital mobile phones. The phones used in the test were an analog handheld phone (450 MHz, 0.5 W), a digital handheld phone (900 MHz, 2 W) and a digital portable phone (900 MHz, 8 W). For 43 patient cases, the maximum interference distance was more than 10 cm for 9 patients. The highest maximum interference distance was 120 cm, apparently associated with a portable phone although this was not mentioned specifically. In an Italian study (Barbaro et al. 1995) 26 different kinds of pacemakers in 101 patients were tested with GSM900 phones. The maximum interference distance 10 cm was obtained when the pacemaker was set to the maximum sensitivity.

In conclusion, the susceptibility of cardiac pacemakers to the radiation from mobile phones may be a serious health hazard. The order of susceptibility is: GSM900, NMT450, NMT900 and GSM1800 phones. The maximum interference distance is most likely less than 0.5 meters in the case of handheld GSM900 phones and less than 1 m in the case of portable or vehicle-mounted phones. The most dangerous forms of interference, particularly caused by digitally modulated devices, are the shutdown of the pacemaker and the generation of unwanted pacemaking pulses that may confuse the normal operation of the heart. Normally, there is no serious danger if someone else than the person carrying the pacemaker uses a handheld phone.

8 SUMMARY AND RECOMMENDATIONS

8.1 Summary

The local peak SAR induced by NMT type analog mobile phones, may exceed 2 W/kg, the exposure limit recommended by ICNIRP for the general public. The exposure limit 10 W/kg recommended for the controlled environment is not exceeded. The local peak SAR induced by GSM type digital mobile phones can be 2 W/kg (time average) in maximum.

The radio-frequency energy that is absorbed into tissue increases the temperature of tissue. This increase is not harmful, if the local peak SAR does not exceed 10 W/kg averaged over 10 g. Then, the temperature rise remains below 1 °C in the brain and the eyes.

Exposure from handheld mobile phones may exceed the level above which different biological effects *in vitro* and *in vivo* have been observed. Some of these non-thermal effects may be real, but there is no conclusive evidence of their harmfulness to the human health nor are their biological or physical mechanisms known. In most cases, the effects are temporary and disappear in a short time after the exposure has ended. There is no evidence of permanent tissue damage if the tissue temperature rise does not exceed a few degrees. The biological effectiveness of amplitude and pulse modulated radiation appears to be greater than that of the continuous radiation with equal heating power.

Mobile phones can interfere with cardiac pacemakers if the person having a pacemaker operates the phone. Digital phones are more harmful than the analog ones because pacemakers are most sensitive to the low frequency components of the GSM modulation.

Outdoor base station antennas do not pose a radiation hazard to the general public. Their antennas are normally placed so that in the areas accessible to the public the power density levels are a small fraction of the exposure limits for the general public. For some indoor antennas, the exposure limits may be exceeded at accessible distances.

8.2 Radiation safety recommendations

To avoid excessive exposure from mobile telephones and their base stations following safety measures are recommended:

1. For handheld mobile phones the local peak SAR averaged over 10 g should not exceed 10 W/kg in the controlled environment and 2 W/kg in areas accessible to the general public.

2. For portable mobile phones the equivalent power density should not exceed at a distance of 20 cm the equivalent power density limits given in the order STMp 1474/91 of the Ministry of Social Affairs and Health, Finland. The radiotelephones in occupational use should be in compliance with the power density limits derived for the controlled environment whereas the phones used by the general public should be in compliance with the power density limits derived for the uncontrolled environment. If the device is not in compliance with the limits at a distance of 20 cm, the minimum safe operating distance should be given in the operating manual or the safety of the device should be ensured by SAR assessment at the intended position.

3. Persons equipped with a cardiac pacemaker should not use mobile phones unless the immunity of the pacemaker to the radiation emitted by the type of mobile phone to be used has been assured. In general the user of the pacemaker should be advised to avoid places where the interference of the pacemaker due to electromagnetic fields is possible.

4. The base-station antenna should be installed so that the power density limits for the uncontrolled environment are not exceeded in the places accessible to the general public. In most cases, the safety distances in the direction of the main beam are 2 m for indoor antennas and 10 m for outdoor antennas. It must be ensured that the power density limits for the controlled environment are not exceed when working within the proximity of base station antennas. The safety distance in the proximity of an outdoor antenna is typically two meters except in the front of a directive antenna. A mast-mounted antenna can be passed quickly, but the antenna element must not be touched. A sufficient safety distance for indoor antennas is 1 m in most cases.

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