Health Council of the Netherlands

Influence of radiofrequency telecommunication signals on children's brains

Gezondheidsraad
Health Council of the Netherlands

To the State Secretary of Infrastructure and the Environment

Subject	: presentation of advisory report *Influence of radiofrequency telecommunication signals on children's brains*
Our reference	: U-6780/EvR/bp/673
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Dear State Secretary,

I have the pleasure of presenting you with the advisory report *Influence of radiofrequency telecommunication signals on children's brains*. It has been drafted by the Electromagnetic Fields Committee and reviewed by the Standing Committee on Radiation and health.

The use of mobile telephones is still increasing, and ever more other applications of wireless communication appear, especially wireless use of internet through Wi-Fi connections. As a result of this the exposure of people to the electromagnetic fields generated by this equipment increases. This worries people. These concerns often focus at exposure of children, since they are still developing and because of that may be more sensitive to possibly negative effects of such exposure. In relation to the use of mobile phones, in particular the development and functioning of the brain is relevant. For several years now focused research has been performed into this matter. The Committee has evaluated the results of this research and of animal studies. It concludes that no evidence has been found that exposure to radiofrequency electromagnetic fields has a negative influence on the development and functioning of children's brains, not even if this exposure is frequent. Because of a lack of data, the Committee cannot make any statements on possible other, long term effects in children, such as the development of brain tumors. The studies on this subject in adults are currently being evaluated by the Committee. The Health Council will publish an advisory report on this later.

Kind regards,

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Influence of radiofrequency telecommunication signals on children's brains

to:

the State Secretary of Infrastructure and the Environment

the Minister of Economic Affairs, Agriculture and Innovation

the Minister of Health, Welfare and Sport

No. 2011/20E, The Hague, October 18, 2011

The Health Council of the Netherlands, established in 1902, is an independent scientific advisory body. Its remit is “to advise the government and Parliament on the current level of knowledge with respect to public health issues and health (services) research...” (Section 22, Health Act).

The Health Council receives most requests for advice from the Ministers of Health, Welfare & Sport, Infrastructure & the Environment, Social Affairs & Employment, Economic Affairs, Agriculture & Innovation, and Education, Culture & Science. The Council can publish advisory reports on its own initiative. It usually does this in order to ask attention for developments or trends that are thought to be relevant to government policy.

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Contents

Executive summary

Does mobile telephone use lead to health damage in children? In previous advisory reports, the Health Council of the Netherlands determined there were no indications for this. An important caveat was the very limited amount of available data. Since then, new studies have been performed. Based on these recent data, the Electromagnetic Fields Committee of the Health Council issues a new advisory report on this topic. In concrete terms, it examines the effects of exposure to radiofrequency electromagnetic fields, such as those generated by mobile telephones, mobile telecommunications antennas or Wi-Fi facilities, on the development and function of the brains of children aged 0 to 16 years. Additionally, the Committee answers the question of whether there is reason to use different exposure limits for children than for adults.

Sources

The pattern and level of exposure differs for different sources. When using a mobile phone the exposure is local and temporary. Exposure to radio waves from antennas and Wi-Fi equipment is over the entire body and protracted. The levels, however, are orders of magnitude lower than when using a mobile phone. Effects of heating, the basic for the exposure limits, do not occur in either case. Research is therefore focussed on non-thermal effects.

Research into effects

The Committee included both animal studies and studies with children in its analysis. The studies look only at short-term effects and examine various aspects, such as effects on brain function, behaviour and cognition, the blood-brain barrier (which prevents proteins in the blood from reaching brain tissue), and physiological functions (such as blood pressure, heart rate, respiratory rate). In some cases, only animal studies are available, sometimes only small-scale human trials. Available data therefore remains limited and is inconsistent.

Available research does not provide any evidence for harmful effects of exposure to electromagnetic fields on children's brain function. Radio waves appear not to have any demonstrable negative effects on behaviour and cognition. Data on potential effects on the blood-brain barrier are only available from animal studies. In these studies, exposures even far beyond the limits did not lead to any effects. Radio waves also do not appear to have any harmful physiological effects on children.

Long-term effects

In May 2011, The *International Agency for Research on Cancer* (IARC) of the World Health Organisation classified radiofrequency electromagnetic fields as ‘possibly carcinogenic to humans’, primarily based on results of various epidemiological studies of the relationship between mobile phone use and the incidence of brain tumours in adults. Recently published results of a study on children aged 9-17 year were equivocal. Epidemiological research into the relationship between mobile phone use and brain tumours in children is currently still underway in various countries. Therefore, no conclusions may yet be drawn regarding long-term effects in children. The Committee has conducted a systematic analysis of all data currently available from epidemiological research into these effects. It will publish a separate advisory report on that subject.

Exposure

The unit used to determine exposure from radio waves is the ‘specific absorption rate’ (SAR), a measure for energy absorption in tissue that can lead to the development of heat. Because the SAR cannot be measured in practice, it has been translated to so-called reference levels, expressed as the strength of the electrical field at the exposure site. Reference levels depend on frequency. A broad margin was used to determine the limits, because scientific data often display uncertainties and there are differences in sensitivity between population groups. The limit is therefore fifty times lower than the level above which health effects may occur.

In order to determine what level of exposure mobile telephones or laptop antennas generate and determine whether such exposure remains within the limits, dosimetric research is done. This research shows that there are differences between adults and children in terms of patterns and degree of energy absorption. The average SAR for the entire head is the same, but the peak SAR may be higher in children, and the location in the head where it occurs may also vary. This is due to anatomic differences between adults and children. The type of telephone and the way in which it is held also determine the extent and location of the peak SAR. Dosimetric research data does not lead to the conclusion that mobile telephone use or the use of Wi-Fi equipment leads to higher risks for children than for adults.

Limits

The Committee concludes there is no reason to recommend different exposure limits for children. The broad uncertainty margins in the current limits take the potential additional sensitivity of children into account. However, reference levels for frequencies around 2 GHz do need to be adjusted, as new scientific insights have shown that their derivation from the SAR is no longer correct. This lowering has few practical consequences, as there are no publicly accessible areas in The Netherlands with field strengths greater than the new reference levels.

Conclusion

In summary, the Committee concludes that there is no cause for concern based on the knowledge about short-term effects outlined in this advisory report. Available data do not indicate that exposure to radiofrequency electromagnetic fields affect brain development or health in children. However, such effects cannot be ruled out. The number of studies remains limited, and is focused almost exclusively on children aged 10 years and older. In order to make better substantiated claims, more research is needed, particularly in young children. Further research into long-term effects is also desirable.

Chapter 1

Introduction

1.1 Why this advisory report?

The Health Council has examined the potential health effects of exposure to radiofrequency electromagnetic fields generated by mobile telephones in various advisory reports and Annual Updates. Radiofrequency electromagnetic fields are part of the electromagnetic spectrum (see Figure 1).

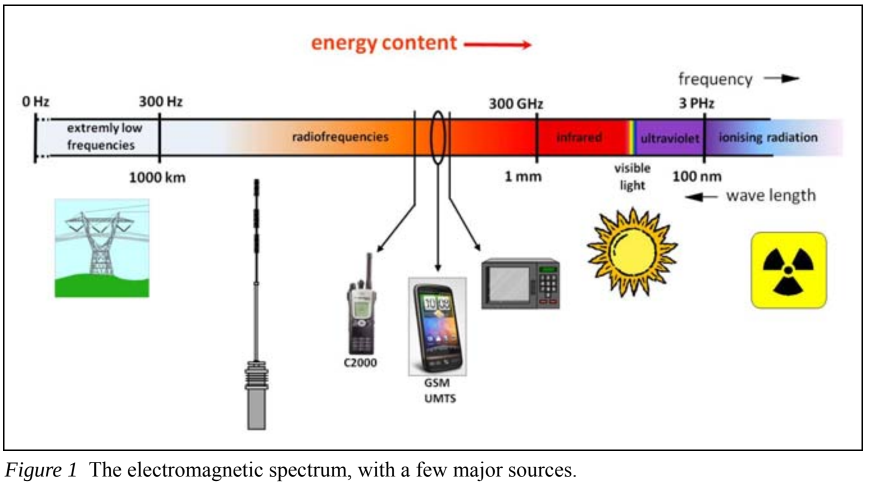

Figure 1 The electromagnetic spectrum, with a few major sources.

Electromagnetic fields are characterised by the frequency with which they oscillate from positive to negative, expressed in Hertz (Hz). The higher the frequency, the greater the energy content of the fields. At frequencies above 3 petahertz (PHz: 3.10^{15} Hz), the energy content is great enough to break molecular bonds. This process is known as ionisation, and electromagnetic fields with frequencies above 3 PHz are also referred to as ionising radiation. All frequencies below 3 PHz are collectively referred to as non-ionising electromagnetic fields. For electromagnetic fields with frequencies in the radiofrequency spectrum, as is also the case for infrared radiation, heat development is the only scientifically established effect that can lead to health problems.

In previous advisory reports, the Health Council concluded that negative health effects have not been demonstrated, with the exception of heat-related effects that can occur at high exposure levels.[1] Excessive warming can lead to dehydration and exacerbate existing cardiovascular problems, for example. To date, no other mechanisms of action have been demonstrated that might explain potential health effects (non-heat related, or non-thermal effects).[2] Despite this, potential health effects of exposure to electromagnetic fields remain a topic of public debate, which is one of the reasons why the Health Council regularly reports on scientific developments in this field.

A topic that has gathered a great deal of public interest is whether the use of cell phones poses a health risk particularly in children. The Health Council reported on this in its 2002 advisory report *Mobile telephones*[3] and a 2005 advisory letter.[4] The limited concrete data available at the time did not lead to, as was the case for others[5], recommendations to limit mobile telephone use by children.

The scarcity of research data has lead to calls by, among others, the Health Council[6,7] and the World Health Organisation (WHO)[8,9] to conduct more focused research into potential effects in children. This call has been answered in various countries, and more and more scientific publications on the topic are appearing. The increased amount of information justifies a renewed analysis, presented in this advisory report.

Other than worries about potential harmful effects of mobile telephone use for children, there are sometimes also concerns regarding the presence of antennas for mobile telecommunication in children's living environments, for example on or near schools, or about Wi-Fi facilities (wireless internet) at schools. Only very limited research is available on this subject. These studies are also discussed in this advisory report.

Sources

The pattern and level of exposure differs for different sources. When using a mobile phone the exposure is local and temporary. Exposure to radio waves from antennas and Wi-Fi equipment is over the entire body and protracted. The levels, however, are orders of magnitude lower than when using a mobile phone. Effects of heating, the basic for the exposure limits, do not occur in either case. Research is therefore focussed on non-thermal effects.

1.2 Scope of this report

This advisory report examines short-term effects caused by exposure to radiofrequency electromagnetic fields. It does not address potential long-term effects. The Committee is drafting a separate advisory report on that subject, but almost no data are available on such effects on children. In May 2011, The International Agency for Research on Cancer (IARC) of the World Health Organisation classified radiofrequency electromagnetic fields as 'possibly carcinogenic to humans', primarily based on results of various epidemiological studies of the relationship between mobile phone use and the incidence of brain tumours in adults. Recently published results of a study in children aged 9-17 years were equivocal. Epidemiological research into the relationship between mobile phone use and brain tumours in children is currently still underway in various countries. Therefore, no conclusions may yet be drawn regarding long-term effects in children. The Committee has conducted a systematic analysis of all data currently available from epidemiological research into these effects; these are used as the basis for its advisory report.

This advisory report also does not examine the potential influence on cognitive development or behaviour in children by other factors, such as the degree or manner of mobile phone use. These factors change over time and with age. It is illustrative, however, to provide some information on this topic.

Various studies have shown that mobile phone use among children is extremely widespread.[10-16] Even among primary school children, the percentage of users is significant.[14,15] A 2009 study among 5416 Dutch young people aged 8 through 18, showed that about 25% of 8 year-olds has a mobile phone, and that this percentage increases linearly to about 100% at the age of 13.[16] Usage also changes with age: text messaging becomes more common and frequent than calling. A study from the USA found that the percentage of children with a mobile phone increased in all age groups between 2004 and 2009: among 8-10 year-olds from 21% to 31%, among 11-14 year-olds from 36% to 69%, and among 15-18 year-olds from 56% to 89%.[15] On average, the youngest age group spends 10 minutes per day talking via mobile phone, the middle group spends 36 minutes, and the oldest group spends 43 minutes. The time spent text messaging is higher: 1 hour and 13 minutes in the middle group and 1 hour and 51 minutes in the highest age group. The 8-10 year-olds barely text at all, a finding confirmed by Dutch research.[16] During texting, the exposure of the head to radiofrequency fields is significantly lower than while talking on the phone.

In Annex B, the Committee provides a brief overview of the rapid growth of mobile telephony.

This advisory report thus only examines the potential short-term effect of exposure to radiofrequency electromagnetic fields. It attempts to answer the following questions:

- Does the use of mobile telephones or presence of antennas for mobile telecommunications or Wi-Fi facilities in the living environment lead to an increased risk of harmful health effects in children in the short term due to exposure to the electromagnetic fields emitted by these devices?
- Is there reason to set different exposure limits for children than for adults?

For the purposes of this report, ‘children’ includes young people until the age of 16 years.

1.3 Exposure limits

As health effects are possible beyond a certain level of exposure to electromagnetic fields, various organisations have proposed exposure limits. In many countries, including The Netherlands, the limits defined by the International Commission for Non-Ionizing Radiation Protection (ICNIRP) are observed.[17] In North America, the limits defined by the IEEE (previously the Institute of Electrical and Electronics Engineers) are used.[18,19]

Both ICNIRP and IEEE limits are based on short-term effects. Both organisations are of the opinion that long-term effects are insufficiently established to be used to set exposure limits. The limits for high and low frequencies are based on different effects; for low frequencies, electrical stimulation of central and peripheral nervous systems is important; for high frequencies (the area covered by this advisory report) it is the generation of heat. The limits are formulated using different units. For low frequencies, the strength of the induced internal electrical field is used, and for high frequencies the

Specific Absorption Rate (SAR), a measure for energy absorption and therefore heat development in tissue.

ICNIRP and IEEE call these units *basic restrictions*. A problem with these units is that in practice they cannot be measured in the body. Therefore, values for measurable units have been derived from the basic restrictions: the strength of the undisrupted electrical and magnetic field at the site of exposure, which correspond respectively with the electrical field strength and SAR generated in the body. These units are referred to as *reference levels* by ICNIRP and *maximum permissible exposures* (MPEs) by IEEE. At the time, they were derived from the basic restrictions in such a way as to ensure that not exceeding the reference levels also means not exceeding the basic restrictions. This means that the reference levels can be used as a relatively easy way to determine whether exposure limits are met. In practice, the strength of the electrical field is usually used.

In establishing the basic restrictions, a certain margin of uncertainty was used, which takes into account the uncertainty inherent in the scientific data on the one hand, and the differences in sensitivity between various population groups on the other. For example, young children, the elderly and the sick are often less capable of dealing with heating of the body by external factors. The margin of uncertainty for the general population is a factor of 50. This means that the limits are set 50 times lower than the levels above which health effects may occur (see Figure 2).

In practice, the reference levels are used as exposure limits for radio-frequency electromagnetic fields. An exception is the situation in which a mobile telephone is held against the head. In this case, the distance between the source of exposure, the telephone, and the body is so small that reference levels do not apply. In such cases, the basic restriction must be used, which in this case is the SAR. For most mobile phones, the documentation lists the SAR value; this is the maximum SAR that can be reached in the head.

This advisory report uses the terms ‘reference level’ and ‘SAR limit’ for exposure limits.

1.4 Structure of this report

This advisory report has been drafted by the Electromagnetic Fields Committee of the Health Council. Committee membership is listed in Annex A.

The report begins with a brief summary of certain relevant aspects of human brain development. Annex C to this introduction provides more background information on the electro-encephalogram (EEG).

The Committee conducted an extensive literature search into the current state of knowledge regarding the possible influence of regular or long-term exposure to electromagnetic fields with frequencies between 10 MHz to 300 GHz on the development of the brain and brain function in children; this search is described in Annex D.

The main body of this advisory report includes a summary and conclusions based on the available data. An extensive description of the studies found is included in Annex E. Finally, in Annex F, the Committee provides an overview of current exposure limits and proposes partial adjustments.

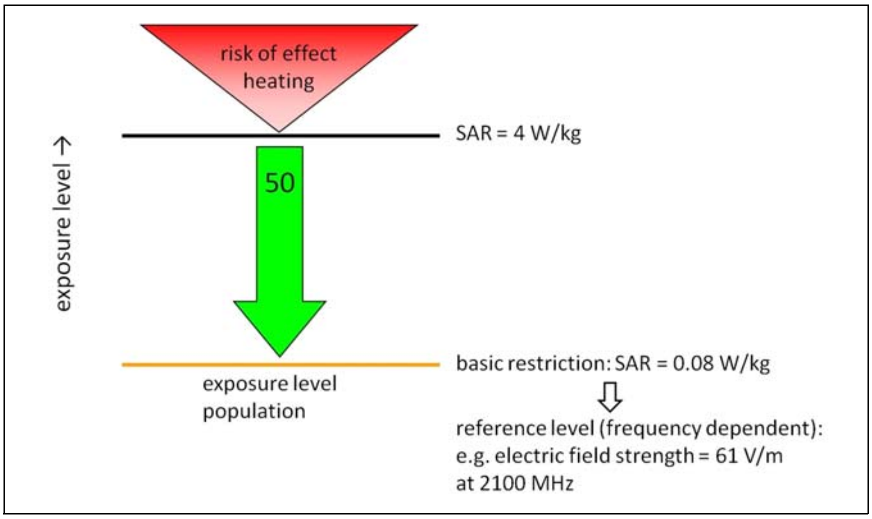

Figure 2 Above a certain level of exposure, for example an SAR of 4 W/kg for whole-body exposure, a health effect may occur, for example excessive and therefore harmful warming. Exposure for the general population has been set 50 times lower, at an SAR of 0.08 W/kg. This is the basic restriction. Reference levels have been derived from the basic restrictions; these are frequency dependent.

Chapter 2

Human brain development

The development of the brain in humans is a long and extremely complex process, which continues after birth into adulthood.

2.1 Myelinisation

From the perspective of penetration of electromagnetic fields into brain tissue, water content and myelinisation are of particular importance. Myelinisation is the process through which nerve fibres are surrounded by an isolating layer, myelin, formed by the fatty cell membranes of the so-called Schwann cells. This allows electrical impulses to be conducted along nerve fibres. Increased myelinisation and the associated decrease in water content leads to a decrease in electrical conductivity of brain tissue.[20,21] In turn, this results in changes to the penetration of electromagnetic fields into brain tissue. Myelinisation begins before birth, and is fastest during that period and in the first two years of life. The process then plateaus rapidly. At the age of about two years, myelinisation of nerve fibres has almost reached adult level.[20,21] This may mean that electrical conductivity of brain tissue will not change significantly after that age, but there are no data available on this.

The functional development of the brain runs partially parallel to the myelinisation, because the latter process occurs as nerve cells (neurons) are activated. However, the formation of synapses – the connections between neurons that allow them to communicate with each other – is also of great importance for functional development. Synapses are formed primarily in the early years of life, creating an excess. Synapses that are not necessary subsequently disappear. This process continues until the end of puberty. It is likely designed for fine-tuning the neuronal network, which allows information processing to better adapt to environmental requirements. The time course is different for different parts of the brain, which is mirrored by the differences in the development of brain function (see Figure 3).[22]

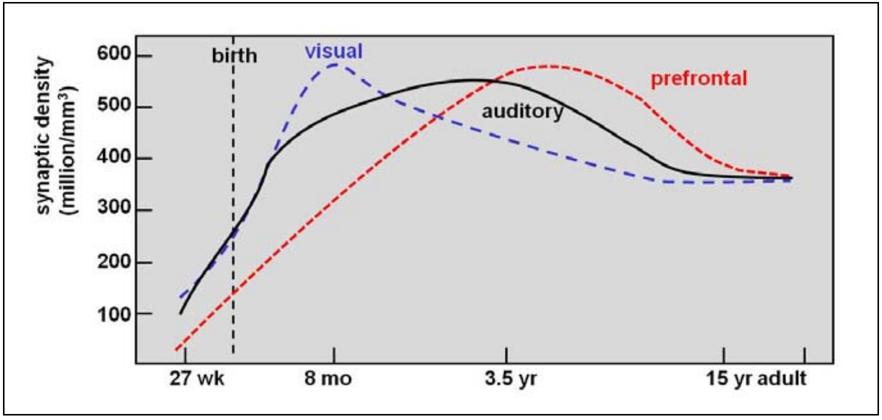

Figure 3 Development of the number of synapses in various parts of the cerebral cortex.[22]

During adulthood, there is a balance between processes of formation and disappearance of synapses, influenced among other things by learning and memory processes.

Disappearance of synapses occurs under the influence of electrical activity, stemming also from the senses. The question therefore arises of whether exposure to external electromagnetic fields, which can create an electrical field in the brain, can affect this process. Should this be the case, than this means that exposing the brain to external electromagnetic fields influences development of the brain, and thus of the organism. It is therefore of great importance to gather more information on this, for example from research into changes in brain function following exposure during early stages of life.

2.2 Cell division and cell growth

One of the reasons why children are often assumed to be more sensitive to the effects of external factors than adults is that there is a lot of cell division in their bodies as they grow. Cell division is a process during which damage caused by exposure to, for example, external factors may not be able to be repaired sufficiently, which may lead to errors in genetic material. These errors can subsequently lead to diseases or abnormalities. The increase in the number of cells in the brain in humans primarily takes place in the early years of life.

In newborns, the head accounts for about a quarter of body length; in adults this is about 10%. The growth of the head occurs primarily during the first decade of life. Subsequently, particularly during puberty, the rest of the body grows, changing the proportion between body and head. The circumference of a one year-old's head is about 83% of that of an adult (Figure 4). This figure is about 93% for a 7 year-old.[23] This growth occurs primarily in the skull and brains. Structures such as the internal parts of the auditory organ and eyes do not continue growing after birth.[24]

The thickness of skull bones increases almost linearly during the first twelve years after birth, after which growth drops off significantly, practically coming to a halt at the age of approximately 18 years.[25] The water and ion content of skull bones, and therefore their conductivity, decreases during this period. Because of this, and the increase in thickness, the barrier effect of skull bones increases. The growth of the brain during the first year of life is due to an increase in both the number and weight of brain cells.[26] Later in life, only the weight of the cells increases.

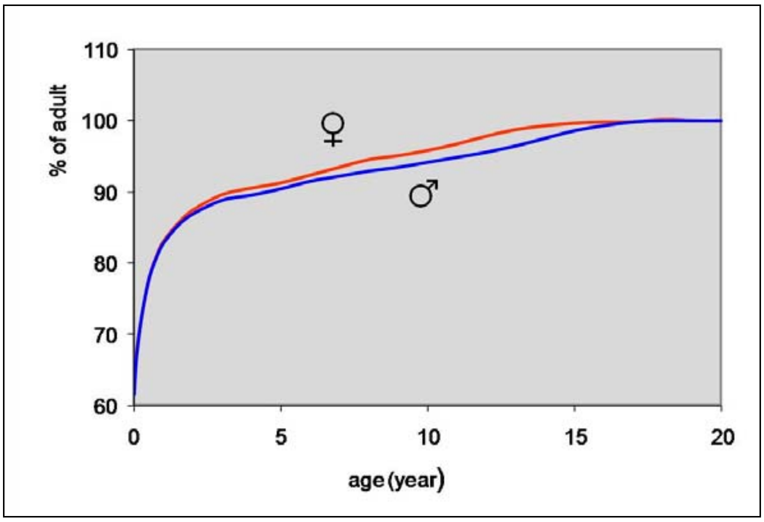

Figure 4 Skull circumference as percentage of adult dimensions, for boys and girls in Flanders.[23]

Chapter **3**

Effects of radiofrequency fields on children's brains

Only a limited number of scientific studies on the effects of radiofrequency fields on the development and functioning of children's brains have been published. In the following sections, the Committee provides general conclusions on the various topics studied. A more extensive description of the studies underlying these conclusions and an overview table may be found in Annex E. In this report, the Committee limits itself to exposure after birth, as it feels this situation is most relevant to the question of whether mobile telephone use, or exposure to radiofrequency electromagnetic fields generated by antennas or Wi-Fi systems, can lead to health problems in children.

When interpreting experimental studies, it is important to keep in mind that extrapolation of animal studies to humans is difficult, among other things because in experimental animals, particularly rodents like mice and rats that are mostly used for such research, the entire brain is exposed, so the distribution of electromagnetic fields over the brain is different from that in humans. Additionally, there are major differences in brain architecture and development between rodents on the one hand, and monkeys (used in some studies) and humans on the other. Therefore, the Committee feels that rodents are a poor model for most research into the effect of radiofrequency electromagnetic fields on early human brain development. For the sake of completeness, rodent studies are discussed, however.

This Chapter begins with a brief overview of relevant research using cultured cells (in vitro research). This type of research is useful and necessary in order to study effects at cellular and molecular levels. Because the cells are kept in an artificial environment, without the normal regulatory mechanisms and interactions that occur in an intact organism, any changes observed cannot simply be extrapolated to health effects in an organism, such as a human being.

In the subsequent sections, available animal studies are first discussed, followed by studies done with children.

3.1 In vitro studies with brain cells

In vitro, varied effects have been observed in freshly isolated nerve cells, generally at exposure levels higher than the SAR limit value of 2 W/kg applicable to exposure of the head while using a mobile telephone.[27-31] The variation in cell lines and endpoints makes it difficult to obtain a clear picture. Studies on supporting cells from brain tissue provide contradictory results: on the one hand, one study found an effect on an enzyme important to cell growth and differentiation at exposure slightly below the SAR limit[32], on the other hand, another study found no effect at exposure more than 10x higher than the SAR limit.[33]

The data from the in vitro studies do not allow the Committee to draw any conclusions about whether the observed effects have any health relevance.

3.2 Effects on brain development and function

The electrical activity of the brain can be measured by attaching electrodes to the head and recording the electrical signals. This is called an electro-encephalogram (EEG). Appendix C includes a more detailed explanation of the EEG, and information about the meaning of the various brain waves.

3.2.1 Animal studies

A study using rats found no effect of exposure to radiofrequency fields on the spontaneous EEG and on electrical activity induced by a light stimulus.[34] Exposure to radiofrequency fields occurred at levels of 20% and 100% of the SAR limit for exposure of the head in humans. Another study using rats[35,36] also found no effect of exposure to radiofrequency fields on electrical activity triggered by a sound stimulus; in rabbits, however, an effect was found.[37-39] Unfortunately, these studies are difficult to interpret due to a lack of adequate exposure data.

In some animal studies, changes were also found in several cell types in brain tissue following exposure to radiofrequency fields, for example in the rat[40-42] (exposure to 2.3% or 100% of the SAR limit in humans) and gerbils (exposure level not stated).[43] In other studies with rats and in a study with squirrel monkeys (exposure to up to 7x the SAR limits for humans), no such effects were found.[44-47]

3.2.2 Children

In its 2008 Annual Update, the Committee concluded that exposure to radiofrequency electromagnetic fields generated by mobile telephones can lead to subtle changes in brain activity in adults.[48] Three studies in children[49-51] also found subtle, but different changes in the so-called alpha band of the EEG (natural frequencies of 8-13 Hz). However, it is unknown what these variations in alpha band activity mean. There are no signs that they affect the development of the brain or health. These studies were limited in terms of number of subjects, and the findings could also be due to chance. In two other studies, one of which with a large number of subjects, no effects were found.[52,53]

3.2.3 Conclusion

The Committee feels that consistent effects of exposure to radiofrequency electromagnetic fields on brain function in children have not been demonstrated. Insofar as effects were observed, they are temporary and minor and there are no signs that they can influence health. Animal studies also fail to demonstrate effects on brain function.

3.3 Effects on behaviour and cognition

Cognitive functions such as memory and reaction time are very important for proper functioning in the living environment. Changes to these functions can mean worsening, but also improvement. Variations in cognitive function between individuals are significant.

3.3.1 Animal studies

In one study, long-term exposure of young rats (a few hours per day for several weeks) to levels of 15% and 150% of the 2 W/kg SAR limit for exposure of the head in humans resulted in improved learning capacity and memory.[46] In another study long-term exposure to 318% of the reference level (an electrical field strength of 61 V/m at 2450 MHz) resulted in lower endurance.[54] In four other studies in young rats, no effects were found on behaviour or memory following exposure to, respectively, 1.5-7% of the SAR limit [55], 2.3% of the SAR limit[42], 225% and 318% of the reference level (an electrical field strength of 61 V/m at 2450 MHz)[34] and 160% of the reference level (an electrical field strength of 42 V/m at 925 MHz).[56]

3.3.2 Children

In children, laboratory testing did not unequivocally demonstrate that short-term exposure to radiofrequency electromagnetic fields generated by mobile phones leads to changes in cognitive functions.[51,57-59] A recent study among 13-15 year-olds in which memory tasks were tailored to individual capacities found signs for decreased precision in one test.[51]

In an observational study among children around the age of 13, differences were found in the group of daily mobile phone users compared with the group of children who rarely used the telephone. However, these differences are likely not related to electromagnetic fields emitted by the telephone, but to handling and using the telephone (particularly skill in operating keys when text messaging).[60] This study only reported on observations made of an existing situation; exposure could not be verified and was not determined; only the number of calls per week was recorded. Such research is therefore of limited value within the context of this report.

In adults, some experimental studies did find effects on cognitive function, but these effects were always minor and reversible, and generally indicated improvement in performance.[61-72] Studies with larger numbers of adult subjects generally showed no effect.[59,73-83]

3.3.3 Conclusion

Exposure to radiofrequency electromagnetic fields appears not to have a clear effect on behaviour and cognition in children. Animal studies only used rats, and are therefore less relevant in the eyes of the Committee. A general problem in both studies with children and animal studies is the limited number of studies and, with one exception[60], the small number of human subjects or animals per study.

3.4 Effects on the blood-brain barrier

The blood-brain barrier ensures that large molecules such as proteins cannot pass from the blood into the brain tissue. If this were the case, this might affect brain function and general health. Research into the effects of exposure to radiofrequency fields on the blood-brain barrier is therefore important.

In multiple studies, long-term exposure of young rats to mobile telephone signals or other radiofrequency electromagnetic fields, at levels far exceeding the exposure limit (SAR up to 6 W/kg, the limit being 2 W/kg) did not lead to changes in the blood-brain barrier.[46,84,85] Two recent reviews indicate that there is no convincing evidence of effects on the blood-brain barrier in adult animals either.[86,87]

3.5 Physiological effects

Changes in physiological functions may affect health if they fall outside the normal variation and cannot be compensated sufficiently. If the homeostatic balance of an organism is disrupted, the organism can become sick.

3.5.1 Animal studies

Various physiological changes have been observed in young rats following exposure to radiofrequency electromagnetic fields, such as variable effects on growth hormone levels[88,89] (exposure to 20% of the 2 W/kg SAR limit for exposure of the head in humans), an increase in DNA damage[90,91] (exposure to 5.5 to 100% of the SAR limit), increases and decreases in various brain enzyme activities[92-94] (exposure to 4% or 5.5% of the SAR limit) and variable effects on pain sensation (exposure to 20% of the SAR limit).[95]

The animal studies that found DNA damage in brain cells must be viewed within the context of all data on this subject. In a recent review, Verschaeve *et al.* concluded that the available data do not provide conclusive evidence for genetic effects in experimental animals.[96]

3.5.2 Children

A study in children examined many physiological parameters, however without indicating the natural variation.[97] In male, but not female teens, a decrease in electrical conductivity of the skin was found following exposure to a mobile telephone signal; effects on blood pressure, heart rate or respiratory rate were not found in either gender.

3.5.3 Conclusion

The available data generally do not indicate that exposure to radiofrequency electromagnetic fields below the exposure limits can lead to physiological changes that are harmful to health. However, study findings should be replicated in order to allow more solid conclusions to be drawn.

3.6 Epidemiological research

Epidemiological studies cannot demonstrate a direct causal link between exposure to electromagnetic fields and health effects, but they can provide indications for such a relationship.

In a study among German youths aged 8-12 and 13-17 years, exposure was measured over a 24 hour period. An increase in behavioural, but not other emotional problems – based on self-reporting – was found in the most exposed group.[98] No relationship was found between exposure and chronic complaints.[99]

A case-control study (Cephalo) was conducted in Denmark, Norway, Sweden and Switzerland, examining the relationship between mobile telephone use and the incidence of brain tumours in children aged 7-19 years.[100,101] The authors conclude that no increased brain tumour risk was demonstrated, but the problems with interpreting this study are comparable to those in similar studies in adults. The Committee is currently drafting a report on this that will include a discussion of the results from the Cephalo study.

Additionally, in 2010, a large case-control study (MOBI-KIDS) was launched in 13 countries – including The Netherlands – examining the relationship between mobile telephone use and the incidence of brain tumours in children aged 10-24 years (see http://www.mbkds.net/).

As indicated in Chapter 1, first use of mobile telephones by children is shifting towards increasingly younger age groups, and usage is increasing in all age groups. Younger children call more than they text, but this pattern reverses with increasing age. Research into effects in children, particularly long-term effects, is lagging behind these developments. The results of the ongoing studies will not be available for a number of years. Therefore, no conclusions may yet be drawn regarding long-term effects in children.

Chapter 4

Dosimetry and exposure limits

4.1 Computer models

ICNIRP used simple mathematical models to derive reference levels from the basic restrictions.[17] Over the past decades, computer models for accurately calculating internal field strength and SAR, using anatomical models, have undergone substantial development. These models have been created using full-body MRI scans, which were subsequently divided into blocks of a few cubic millimetres (voxels). Each voxel is assigned the electromagnetic properties of the tissue it corresponds with in the model. This allows calculation of how an electromagnetic field from outside the body spreads in the body, along with the resulting current density, electrical field strength or SAR. The smaller the voxels, the more accurate the model (but the longer the computing time).*

* ICNIRP formulates the SAR as the SAR averaged over the whole body (total-body SAR). Additionally, ICNIRP gives values for the local SAR (for example for the head or limbs), which are values averaged over 10 g of tissue (SAR_{10g}). IEEE uses a similar approach, but in an older and still frequently used version of the recommendations, IEEE averaged the local SAR over 1 g of tissue (SAR_{1g}). In dosimetric research, the location and size of the maximum SAR (peak SAR) are often determined. Whether this is the SAR in 1 voxel, the SAR_{10g} or the SAR_{1g} is not always indicated.

4.2 Development and application of specific models

Such models are currently commonly used to determine the relationship between exposure to an external electromagnetic field and the internal field strength generated by it. These types of calculations are important for two reasons. First, in order to determine exposure caused by, for example, mobile telephones or laptop antennas, and whether exposure limits are met. Second, to investigate whether exposure to reference levels does not exceed basic restrictions under all circumstances. In both cases, it is important to not only use models of adults, but also models of children of various ages, as differences in anatomy between children and adults may be considerable. Furthermore, it is important to consider the anatomic variation in both men and women. To these ends, various models have been developed in recent years.[102-107] A series of models of women in various stages of pregnancy has also been developed.[108-112] The latest developments are models that can be placed in various positions (seated, arms raised, etc.).[113]

Initially, linearly scaled models of adults were used to model children.[104,114,115] However, because all kinds of anatomical changes occur during growth, this scaling leads to inaccuracies, particularly in skin thickness and the proportion of the head and brain.[107] Furthermore, for transitions between tissues with major differences in electromagnetic properties, linear downscaling can negatively affect the accuracy of the SAR determination.[116] Therefore, later studies also take into account the changing proportions relating to growth in children.[102,107,117] In the meanwhile, anatomically correct models have been developed based on MRI scans of children.[103,118,119]

4.3 SAR calculations using specific models

The studies with advanced models showed that the SAR averaged over the entire head for adults and children is practically is the same, but the peak SAR may be higher in children, and the location of the peak SAR in children can also be different from that in adults. This is due to differences in size and proportions of the head between adults and children. The size and location of the peak SAR also appears to be very strongly influenced by the location of the antenna relative to the head.[103,118,120] In a mobile phone, the location of the antenna in the telephone is important, as is the way the telephone is held next to the head. The degree to which the pinna is compressed also has an effect.[121]

In the relatively few available models of both adults and children, a large variation was found in calculated SAR values.[107,118,119,122] This means that variation within the population will likely be even greater.

4.4 Exceeding SAR

One important finding from the studies is that the reference levels provided by ICNIRP for the frequency area around 2 GHz are too high for children: with exposure at the reference level, the basic restrictions are exceeded by a small amount.[102,104-107,113,115,119,122-126] This situation only applies to exposure in the so-called far field, meaning at a certain distance from the source. This problem does not occur for calls made with a mobile telephone, because the distance to the head is minimal. In practice, there are very rarely situations in which exposure approaches the reference level. Also, a minor exceeding of the basic restrictions will not lead to a situation that threatens health, because the basic restrictions include a safety and uncertainty margin. However, the reference values do need to be revised in order to obtain correct values.

Based on current insights, use of mobile telephones by children may lead to a slightly higher peak SAR in the head than for adults. Mobile telephones are required to be designed so that the SAR they cause in the head does not exceed a value of 2 W/kg. This also applies to the use of a telephone by children. The method for determining the maximum SAR is such that it cannot be ruled out entirely that exceptional situations will occur in which the maximum value will be exceeded. The odds of this occurring are slightly higher for children than for adults. However, because the maximum SAR is generally considerably lower than 2 W/kg[127], the odds that the limit will be exceeded in practice are likely extremely low for both adults and children.

Calculations of the SAR for realistic exposure situations for electromagnetic fields generated by a Wi-Fi access point or laptop[128] show that the ICNIRP limits are not exceeded.

Chapter 5

Conclusions and recommendations

The development of the human brain is a complex process. On the one hand, young brains have greater capacity for repair than adult brains, so that negative effects may be more easily compensated for; on the other hand, exposure to external factors such as electromagnetic fields may affect brain development in such a way that it may lead to negative effects.

5.1 Have health effects been found?

The first question the Committee wanted to answer in this advisory report is:

Does the use of mobile telephones or presence of antennas for mobile telecommunications or Wi-Fi facilities in the living environment lead to an increased risk of harmful health effects in children in the short term due to exposure to the electromagnetic fields emitted by these devices?

The answer to this question is: based on currently available knowledge this is not the case, but this knowledge is still limited in a number of areas and available data are inconsistent.

In recent years, a growing amount of research has been done into the potential effects of exposure to electromagnetic fields on the health of children and juvenile animals. Compared to the situation of a few years ago, more data are available, but not on effects in young children: the studies were conducted almost exclusively in children over the age of 10 years. At this time, it can only be concluded that the still relatively limited available data do not indicate any effects on the development of the brain or on health if children are exposed to radiofrequency electromagnetic fields such as those generated by mobile telephones, mobile telecommunications antennas or Wi-Fi facilities.

5.2 More research is required

More research, particularly on long-term effects, is required to allow substantiated claims to be made regarding effects of electromagnetic fields on child health. Such research is currently underway. When results are published in a few years, the Committee will perform a new assessment.

In the recently published research agenda for radiofrequency electromagnetic fields[9], the WHO recommends conducting a cohort study examining the relationship between the use of wireless telecommunication devices and the incidence of behavioural and neurological abnormalities as well as cancer in children and adolescents. The Committee supports this recommendation, but also recommends that more experimental research be conducted using various types of signals in children of various ages. However, the Committee realises it is practically impossible to conduct long-term studies in children. Children undergo many and major physical changes in a short time. Additionally, new forms of telecommunication are introduced at a rapid pace, and are quickly embraced by young people in particular. Both issues lead to continuously changing exposure patterns.

Dosimetric research shows that there are differences between adults and children in terms of patterns and degree of energy absorption. Under certain circumstances, the peak SAR may be higher in children than in adults, and the location in the head where the peak SAR occurs may also vary. The SAR averaged over the entire head does not differ for children and adults.

These differences are due to anatomic differences between adults and children. These are greatest in young children and disappear with increasing age. The location of the peak SAR will also shift with increasing age. The type of telephone and the way in which it is held also largely determine the extent and location of the peak SAR. Furthermore, there is significant anatomic variation within the population, greater than can be examined using the limited number of models currently available. Therefore, based on dosimetric data, there is no reason to assume that exposure of children to electromagnetic fields due to use of a mobile telephone leads to greater risks than for adults.

In future research, more calculations should be performed using more models based on MRI scans of children of various ages, particularly using the currently practically non-existent models of children ages 0 to 6 years and over the age of 15 years. The effects of posture should also be examined. Additionally, data should be collected on electromagnetic properties of various tissues in children.

5.3 Are the exposure limits adequate for children?

The second question the Committee wanted to answer was:

Is there reason to propose different exposure limits for children than for adults?

The answer to this question is: no, because the potential additional sensitivity of children and other vulnerable groups was explicitly accounted for in setting the exposure limits. It is one of the reasons why the exposure limits for the general population include an ample uncertainty margin of a factor of 50. Based on the data presented in this report, the Committee sees no reason to recommend different exposure limits for children than for adults.

The Committee would like to make the following remarks, however. The reference levels were defined in such a way, based on available knowledge, that not exceeding these values (in far-field situations, *i.e.* at some distance from the source) means that the basic restrictions are also not exceeded. However, based on the more recent scientific data presented in this report, it turns out that for the frequency area around 2 GHz, the reference levels proposed by ICNIRP[17] are not correct. For young children (and therefore also for small individuals), the reference levels were found to correspond to an SAR value higher than the maximum allowable value. This also applies to the reference levels proposed by the Health Council[129], as they are higher than those of ICNIRP for this frequency range. At the time, it was assumed that the reference levels were determined for the worst-case situations, but this appears not to be the case. Therefore, the reference levels must be corrected downwards. The Committee makes a proposal for such changes in Annex F. It should be noted that the Committee does still adhere to the substantiation of the basic restrictions levels as outlined in the advisory report published in 1997[129], which deviate from those of ICNIRP.*

* In the frequency band between 5 and 300 GHz, the basic restriction is expressed as power density of the electromagnetic field (in units of watt per square meter, W/m2). In its 1997 advisory report, the Health Council selected a power density of 100 W/m2 as a foundation for the basic restrictions, in order to remain in line with exposure limits for infrared frequencies above 300 GHz. The foundation for the ICNIRP basic restrictions is 50 W/m2, which results in a sudden change to a higher value at 300 GHz.

The Committee also notes that in the unlikely event that small individuals are exposed to the reference levels, and the basic restrictions in terms of the SAR are thus slightly exceeded, this does not mean that a situation harmful to health will develop. The maximum SAR value for the general population is no sharp delineation between bad and not bad, but rather, as previously outlined, has been defined with a large uncertainty margin. The maximum allowable value lies 50 times lower than the values above which potential health effects might occur. However, situations should not arise in which the uncertainty margin needs to be used. Therefore, the reference levels must be adjusted.

Based on the current Committee proposal, this means that the reference levels for GSM, UMTS and Wi-Fi applications will be lowered from about 40-70 V/m to 28 V/m. In practice, this has few consequences, as a field strength greater than 28 V/m does not occur in areas in the Netherlands accessible to the general population.

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A The Committee

B The growth of mobile telephony

C The electro-encephalogram

D The search strategy

E Description of studies

F ICNIRP and IEEE limits for the general population

Annexes

Annex **A**

The Committee

The membership of the Electromagnetic Fields Committee consisted of the following individuals at the time this advisory report was drafted:

- Prof. G.C. van Rhoon, *chairman*
  Professor of Physical Aspects of Electromagnetic Fields and Health, Erasmus University Medical Centre Rotterdam
- Prof. A. Aleman
  Professor of Cognitive Neuropsychiatry, Groningen University
- R.M. van der Graaf, *advisor*
  Excutive Director, Knowledge Platform Electromagnetic fields, Bilthoven
- Dr G. Kelfkens, *advisor*
  Physicist, National Institute for Public Health and the Environment, Bilthoven
- Prof. H. Kromhout
  Professor of Occupational Hygiene and Exposure Classification, Institute for Risk Assessment Sciences, Utrecht University
- Prof. E. Lebret, *advisor*
  Professor of Environmental Health Impact Assessment, Institute for Risk Assessment Sciences, Utrecht University, and Chairman Science forum, Knowledge Platform Electromagnetic Fields, Bilthoven

- Prof. F.E. van Leeuwen
  Professor of Cancer Epidemiology, VU University Amsterdam, and Netherlands Cancer Institute, Amsterdam
- Dr H.K. Leonhard, *observer*
  Ministry of Economic Affairs, Agriculture and Innovation, Groningen
- Prof. H.F.J. Savelkoul
  Professor of Cell Biology and Immunology, Wageningen University
- Prof. W.J. Wadman
  Professor of Neurobiology, University of Amsterdam
- D.H.J. van de Weerdt, MD
  Toxicologist and Medical Environmental Scientist, Aid Services Gelderland Midden / GGD, Arnhem
- Prof. A.P.M. Zwamborn
  Professor of Electromagnetic Fields and Health, Eindhoven University of Technology, and TNO, The Hague
- Dr E. van Rongen, *scientific secretary*
  Radiobiologist, Health Council, The Hague

J. Bakker, physicist at the Erasmus University Medical Center Rotterdam, supported the Committee in the area of dosimetry and SAR calculations.

The Health Council and interests

Members of Health Council Committees are appointed in a personal capacity because of their special expertise in the matters to be addressed. Nonetheless, it is precisely because of this expertise that they may also have interests. This in itself does not necessarily present an obstacle for membership of a Health Council Committee. Transparency regarding possible conflicts of interest is nonetheless important, both for the President and members of a Committee and for the President of the Health Council. On being invited to join a Committee, members are asked to submit a form detailing the functions they hold and any other material and immaterial interests which could be relevant for the Committee's work. It is the responsibility of the President of the Health Council to assess whether the interests indicated constitute grounds for non-appointment. An advisorship will then sometimes make it possible to exploit the expertise of the specialist involved. During the inaugural meeting the declarations issued are discussed, so that all members of the Committee are aware of each other's possible interests.

Annex **B**

The growth of mobile telephony

In 2000, in the advisory report on GSM base stations[130], the Committee wrote:

The past years have been characterised by a rapid increase in mobile telecommunications. Public mobile telephony began in 1980 with the first car phone network, ATF-1. 29 base stations serving a total of 2000 car phones provided national coverage. Technical developments have since taken flight, and the introduction of the DCS 1800 system has made mobile telephony available to everyone, in part thanks to the strong commercial proposition for the public. Table 1 provides an overview of developments.

Table 1 Development of mobile telephony in The Netherlands.

launch	network	number of base stations	number of users
1980	ATF-1	29	2.000
1985	ATF-2	126	30.000
1989	ATF-3	363	> 250.000
1994	GSM 900	> 1.000	> 6.000.000
1998	DCS 1800	> 6.000	> 1.000.000

Growth has increased explosively since then. The above data on the number of antennas have been supplemented using data from the Antenna bureau[131] (Figure B1).

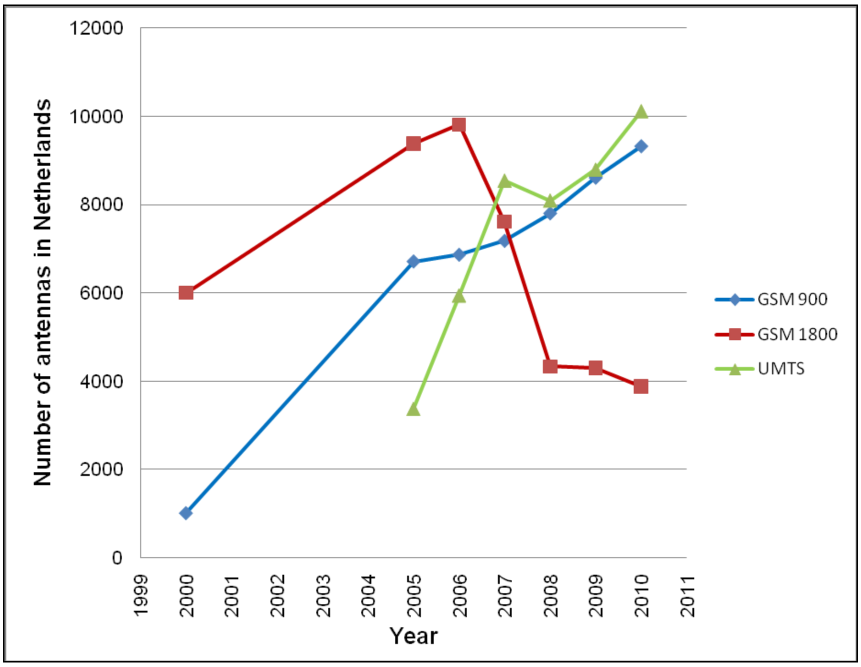

Figure B1 Number of antennas for various mobile telephony systems in The Netherlands. (Source: Antenna bureau.)

The growth in the number of users is displayed in Figure B2, based on data from the International Telecommunication Union (ITU).[132]

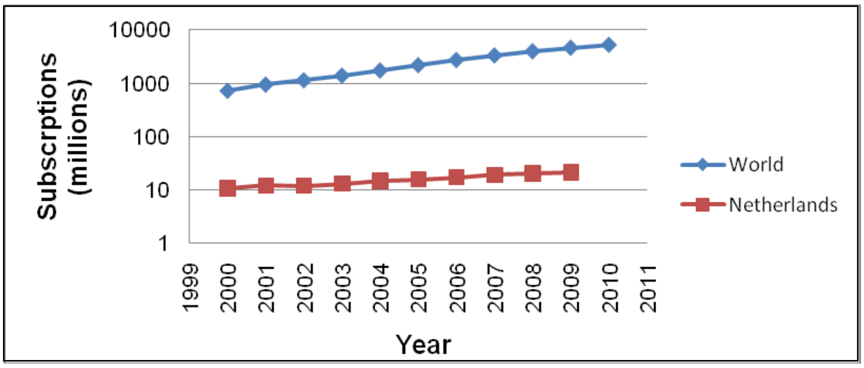

Figure B2 Increase in the number of mobile telephone owners worldwide and in The Netherlands. (Source: International Telecommunication Union.)

With regard to mobile telephone ownership per 100 inhabitants, The Netherlands held the 38th position in 2009 (topping the list are the United Arab Emirates with 232 mobile telephones per 100 inhabitants); Figure B3 displays developments in the past decade.[132]

Phone use is subject to continuous change, and differs between population groups. Young people text and – increasingly – use wireless internet via smartphones. The number of smartphones in the Netherlands is growing very rapidly: by late 2010, the number of smartphone users was expected to reach 3.3 million, representing about 15% of the total number of mobile telephone users.[133]

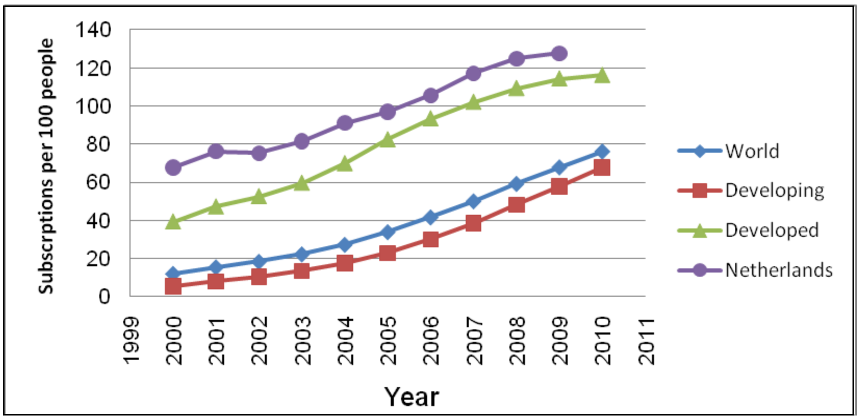

Figure B3 Increase in mobile telephone ownership per 100 persons. (Source: International Telecommunication Union.)

Annex **C**

The electro-encephalogram

An electro-encephalogram (EEG) is a recording of the electrical activity of the brain. The EEG does not provide a detailed image of brain activity, but is a representation of synchronous activity of relatively large numbers of nerve cells in the cortex, the outer layer of the brain. Brain activity is continuous, even at rest. However, there are clear differences in EEG patterns during sleep and while awake.

The waking EEG is generally divided into a number of frequency areas. The amount of activity in each of these areas depends on the individual's psychological state and cognitive activity; there are large inter-individual differences. As frequency areas are not always consistently defined, certain frequencies may be assigned to different frequency areas in some studies. The most common classification of frequency areas is:

- delta (δ): < 4 Hz
- theta (θ): 4-8 Hz
- alpha (α): 8-13 Hz
- beta (β): 13-30 Hz
- gamma (γ): > 30 Hz.

There is only limited knowledge on the functional meaning of various parts of the normal waking EEG. Delta waves are related to slow wave sleep, but also occur during the day, for example while performing continuous attention tasks and during meditation; they do not indicate a negative effect. Theta waves are related to drowsiness and inhibiting a response, a normal brain task. Alpha waves are related to relaxation and reflection. Beta waves are associated with alertness and performing a task. Gamma waves occur when memory is accessed and during performance of tasks requiring mental effort as well as during task integration.

If signals from mobile telecommunication systems appear to affect certain parts of the EEG, this indicates a biological effect, but it is almost impossible to indicate whether such an effect also leads to health problems. An additional complicating factor is the significant inter-individual variation in waking EEGs.

The latter is less true of sleep EEGs. Well-characterised patterns can be identified; these patterns are used to characterise various stages of sleep that a healthy individual undergoes during the night. Inter-individual variations are found primarily in superficial sleep stages. There are usually clear differences between normal EEGs and EEGs associated with certain conditions, such as epilepsy.

Annex **D**

The search strategy

An initial search was conducted in the research database of the WHO International EMF Project (http://www.who.int/peh-emf/research/database/en/index.html) using the following criteria: Freq Range=100 kHz - 300 GHz (radio frequency/MW/mmW), KeyWord=children,Status=All. This database was updated up to 22 May 2009.

Subsequently, a PubMed search using the following search terms was performed: (microwaves[MeSH Terms] OR extremely high frequency radio waves[MeSH Terms] OR radio waves[MeSH Terms] OR cellular phone[MeSH Terms] OR telephone, cellular[MeSH Terms] OR electromagnetic fields[MeSH Terms] OR electromagnetic radiation, nonionizing[MeSH Terms] OR electromagnetic radiation, non-ionizing[MeSH Terms] OR radiation, nonionizing[MeSH Terms] OR base station OR (antenna AND radiofrequency) OR mobile phone) AND (child OR children OR infant OR infants OR Animals, Newborn[MeSH Terms] OR aging[MeSH Terms] OR Brain/embryology[MeSH Terms] OR Fetus/radiation effects[MeSH Terms] OR (development AND brain)) NOT (DNA/analysis OR light OR ultraviolet OR epidemiology OR (extremely low) OR ELF OR psychology OR food OR (text message) OR (text messaging) OR cohort OR (magnetic resonance) OR (low frequency) OR dermatitis OR epilepsy OR static OR geomagnetic OR therapy OR (Social Behavior) OR fertility OR cameras OR email OR e-mail OR interference OR Remote Consultation/instrumentation*[MeSH Terms] OR care OR diabetes OR sms OR cartilage OR electroporation OR egg OR power line OR power lines OR (50 Hz) OR immunostaining). ‘Related articles’ for key publications were subsequently examined.

This provided a total of 147 articles. Of these, 90 related to exposure after birth, or exposure of cultured cells; these were used for this report. Another 35 articles pertained to exposure before birth, 14 were reviews and 9 articles addressed general subjects; these articles were not included in this report.

The literature review was completed on 5 July 2011.

Annex **E**

Description of studies

E.1 In vitro studies with brain cells

Functional effects in nerve cells

Ning *et al.* (2007)[27] exposed primary nerve cells from the hippocampus to a GSM 1800 signal for 15 minutes per day for 6 days. At an SAR of 2.4 W/kg, they found effects of exposure on dendrite formation; this was not the case for an SAR of 0.8 W/kg.

Xu *et al.* (2006)[28] exposed primary rat neurons to a GSM 1800 signal with an SAR of 2.4 W/kg for 15 minutes per day for 8 days. They observed a decrease of intensity of certain synaptic activity (only signals generated by α-amino-3-hydroxy-5-methyl-4-soxazol propionic acid (AMPA) receptors, not by N-methyl-D-aspartate (NMDA) receptors).

Wang *et al.* (2004)[29] exposed neurons from the cerebral cortex of newborn rats to a continuous 900 MHz signal, with an SAR of 3.2 W/kg, for 2 hours per day for 4-5 days or for 12 consecutive hours. Both treatments resulted in a decrease in activity of the enzyme cytochrome C oxidase, which is important for the cell's energy metabolism.

In a follow-up experiment, Wang *et al.* (2005)[30] exposed neurons from the cerebral cortex of newborn rats to a 900 MHz continuous signal with an SAR of 1.1, 2.2 or 3.2 W/kg, for 2 hours per day for 4 or 6 days, or to an SAR of 3.2 W/kg for 12 consecutive hours. Both treatments resulted in a dose-dependent decrease in the receptor protein GluR2 and a rise in intracellular calcium. Wang *et al.* (2005)[134] also noted changes in the expression of GABA receptors*; a not further specified window effect occurred**. The effects found in both studies may affect signal transmission. (These publications were in Chinese language, the Committee was only able to obtain data from the English language summary).

Functional effects in supporting cells

Astrocytes are supporting cells in the brain that ensure proper neuron function. Microglia cells are specific to the brain's immune system. Changes in the function of both cell types may affect brain function.

Höytö *et al.* (2007)[32] exposed primary astrocytes and two neuroblastoma cell lines to 872 MHz continuous or GSM-modulated electromagnetic fields for 2, 8 or 24 hours at SAR levels of 1.5, 2.5 and 6.0 W/kg. They determined the activity of the enzyme ornithine decarboxylase (ODC), which is important to cell growth and differentiation; high ODC levels can stimulate the development of tumours from pre-malignant cells. At SARs of 1.5 and 6.0 W/kg, a decrease of ODC was found in astrocytes for both continuous and GSM-modulated fields (the SAR of 2.5 W/kg was not tested in this cell line) when all data were pooled. Analysis of separate exposure times did not yield a time-dependent response. No effects were found in other cell lines.

Thorlin *et al.* (2006)[33] exposed primary cultures of astrocytes and microglial cells to continuous 900 MHz electromagnetic fields at an SAR of 27 W/kg for 24 hours, or to GSM-modulated fields at an SAR of 3 W/kg for 4, 8 and 24 hours. The temperature was kept constant at 37 °C. Various parameters indicative for the reaction of these cells to external stimuli were measured, but in no case was a response found.

Gene expression

Zhao *et al.* (2006)[31] exposed primary neurons from the cortex and hippocampus of newborn rats to an 1800 MHz GSM-like signal at an SAR of 2 W/kg for 24 hours, in a 5 minutes on, 10 minutes off schedule. The activity of 34 out of 1200

* Gamma amino buteric acid (GABA) is a key neurotransmitter.
** A window effect means the effect only occurs under specific circumstances, for example in a certain frequency band and not at higher or lower frequencies.

genes potentially affected was found to be increased or decreased. Further analysis of one gene, coding for microtubule associated protein 2 (Map2), found increased expression. This indicates an increase in the production of this protein, which has a function in maintaining the neuron skeleton and the formation of processes, therefore influencing cell function. (This article was published in Chinese, the Committee was only able to obtain data from the English language summary.)

E.2 Development of brain tissue and brain function

Animal studies

Various researchers examined the effects of postnatal exposure to electromagnetic fields on the development of parts of the brain in animal studies. In some cases, exposure also occurred during pregnancy.

In a number of studies, the animals were exposed to an SAR higher than the limit value of 2 W/kg that ICNIRP gives for exposure of the head. This means that in these cases, effects due to heating cannot be ruled out. This applies even more to animals receiving total body exposure to such high SARs. Additionally, there is the question of whether heat regulation in very young animals is the same as in adult animals. If this is not the case, an SAR of 2 W/kg may already lead to a rise in body temperature in young animals, which could explain observed effects.

Research on tissues

Albert *et al.* (1981a,b)[40,44] studied the number of Purkinje cells in the cerebellum after exposure to 2450 MHz radiofrequency fields in rats and squirrel monkeys.

Six day-old rats underwent whole body exposure to 100 W/m^2 (= 194 V/m) for 7 hours per day, for 5 days, resulting in an average whole-body SAR of 2 W/kg. Directly following exposure, a significantly lower number of Purkinje cells were observed compared to sham exposure, but this difference was no longer present 40 days later.

The squirrel monkeys were exposed to 100 W/m^2 (= 194 V/m) for three hours per day during the entire pregnancy and for 9.5 months after birth, resulting in an average whole-body SAR of 3.4 W/kg. There was no difference in density and number of Purkinje cells between exposed and control animals.

In a follow-up study, Albert *et al.* (1988)[41] examined the cerebellum in rats after exposure to 2450 MHz radiofrequency fields. One day-old and six day-old rats were exposed to 100 W/m^2 (= 194 V/m) for 7 hours per day for 5 days, resulting in an mean whole-body SAR of 2 W/kg. They found twice as many cells with piknotic nuclei in the cerebellums of exposed animals than in those of sham exposed control animals. The authors suggest that this indicates that exposure to radiofrequency fields may affect the early development of microneurons in the cerebellum and change the metabolic state of Purkinje cells. According to the authors, this effect may be reversible.

Inouye *et al.* (1983)[45] exposed rats to 2450 MHz radiofrequency fields of 100 W/m^2 (= 194 V/m) from the 4th day of pregnancy until 40 days after birth for 3 hours per day. They calculated that due to the growth of the animals the SAR for the brain during the exposure period decreased from 13.9 to 9.5 W/kg. They found no qualitative or quantitative differences for the examined histological parameters between exposed and control (sham exposed) animals.

In these four experiments, heating effects due to relatively high SARs cannot be ruled out.

Cobb *et al.* (2000)[42] exposed rats before and up to 10 days after birth to a pulsed ultra-wideband electromagnetic field. The peak field strength was 55 kV/m, with a rise time of 300 picoseconds and a pulse width of 1.8 nanoseconds; the whole-body SAR was 45 mW/kg. The only effect they found was that the relationship between medial and lateral length of the hippocampus was larger in the exposed than in sham exposed animals.

Hoffman *et al.* (2001)[43] exposed 'young adult' gerbils to 35.53 kHz radiofrequency fields, modulated with frequencies of 1, 8, 12, 29 or 50 Hz. Modulation with 1, 29 or 50 Hz resulted in a decrease in the increase of the number of cells in brain tissue compared with sham exposure, while such an effect was not observed for modulation with 8 or 12 Hz. Because the authors did not provide any data such as duration and degree of exposure, these results cannot be interpreted.

Kumlin *et al.* (2007)[46] exposed 24 day-old rats 2 hours a day, 5 days a week for 5 weeks to a 900 MHz mobile telephone signal. There were two levels of exposure, resulting in a whole-body SAR of 0.3 or 3.0 W/kg; at the highest SAR value, heating cannot be ruled out. Neither of the SAR values resulted in degenerative changes to brain tissue or neuronal death.

Ragbetli *et al.* (2009)[47] studied the number of pyramidal cells in the hippocampus of mice exposed to a mobile telephone signal during the entire pregnancy and for 21 days after birth. During the exposure period of 12 hours per day, the telephone was alternately set to standby for 1 hour and 45 minutes and in talk mode for 15 minutes. Exposure for the animals was not determined, nor was the strength of the emitted signal. Because the telephone was placed in the middle under the cage, there will have been significant variation in exposure. The authors found no differences between the number of pyramidal cells in exposed and non-exposed animals, but this study cannot be interpreted due to a lack of exposure data.

EEG and ERP

A measure of brain activity that is closely related to the EEG is the evoked or evoked-related potential, ERP. An ERP is a signal generated in a certain brain area by an external stimulus (for example a flash of light or a sound) or a motor activity (for example pressing a button). ERPs are determined by measuring the EEG in relation to the stimulus provided and by subsequently summing and averaging certain parts of the EEG at a fixed point in time after the stimulus. The electrical signal obtained is a representation of brain activity related to the specific stimulus. ERPs are used to investigate the function of neural systems responsible for processing sensory, cognitive and motor stimuli. The interpretation of ERPs is far from simple, however, as changes to arousal and attention in the examined individual can strongly affect the results of such tests.

Rosenstein (reported in McRee *et al.,* 1979)[34] exposed rats to 425 MHz radiofrequency fields, 100 W/m^2 (=194 V/m), from the 12th day after fertilisation and to 2450 MHz fields, 50 W/m^2 (=137 V/m) from the 6th day after fertilisation. In both cases, exposure continued after birth until the age of 92 days. At the age of 140 days, the spontaneous EEG and visual evoked responses were determined. The researchers found no differences between exposed and control animals.

Hearing

Kizilay *et al.* (2003)[35] exposed adult and newborn rats (from an age of 2 days) to electromagnetic fields from a mobile telephone for 30 days for 1 hour per day. They subsequently measured auditory function (via so-called distortion product otoacoustic emission, DPOAEs). The authors indicated that with exposure to chemicals, the most sensitive period for developing auditory damage lies between 11 and 20 days after birth.[135] The radiofrequency exposure of the animals was not determined, nor was the strength of the emitted signal. They found no effect of exposure on the DPOAE on either adult or young animals, but this study cannot be interpreted due to a lack of exposure data.

Kayabasoglu *et al.* (2011)[36] exposed 20 newborn and 20 adult rats to a mobile telephone signal for 30 days and 6 hours per day. They measured the

DPOAE before and after the exposure period, but found no effect of exposure in either young or adult animals. These results also cannot be interpreted due to a lack of exposure data.

Budak *et al*. (2009)[37] exposed 1 month-old and adult rabbits to a 1800 MHz GSM-like signal for 7 days, 15 minutes per day. The DPOAEs in the exposed group were higher than in the controls. In the adult animals, this difference was greater than in the young animals. These results cannot be interpreted due to a lack of exposure data.

In another experiment, Budak *et al.* (2009)[38] exposed 1 month-old male rabbits to a 1800 MHz GSM-like signal for 14 days, 15 minutes per day. Another group was exposed in utero between the 15th and 22nd day of pregnancy (7 days, 15 minutes per day). A third group received both treatments. Depending on the frequency used for the DPOAE, differences were found between various groups, however there was no clear pattern present (Table E1).

The researchers state that in utero, the water content in the middle and inner ear and amniotic fluid may play a protective role. Also in this case, the results cannot be interpreted due to a lack of exposure data.

In a third publication, Budak *et al.* (2009)[39] obtained different results in female rabbits using the same study method (Table E1).

Table E1 Results of studies by Budak *et al.*

Sound frequency	Effect on male rabbits	Effect on female rabbits
1.0 kHz	No differences	after > controls
1.5 kHz	before > controls before > after before+after > controls before+after > after	after > controls
2.0 kHz	before+after > after	after > controls and before
3.0 kHz	before+after > controls and after	
4.0 kHz	after < controls before+after > controls and after	
6.0 kHz	after < controls; before+after > after	after > controls, before and before+after
8.0 kHz	no differences	after > before and before+after

before: exposure before birth; after: exposure after birth; before+after: exposure before and after birth; controls: no exposure; > effect greater than; < effect less than

Effects on the EEG

Krause's research group from Finland measured electrical activity in children's brains while performing a memory test. The goal was to investigate whether patterns found in adults already occur in children. This provides information about the brain's functional development and is important for allowing interpretation of studies in which exposure of children to electromagnetic fields has taken place – that was not the case in these studies.

In an initial study, Krause *et al.* (2001)[136] compared the EEG of 12 children with an average age of 12 years with that of 12 adults during an auditory memory test. The activity in the theta (4-8 Hz) and alpha bands (8-13 Hz) of the EEG during processing of auditory information was already present in the children examined, but not fully developed compared with adults. Also in a later study in 15 slightly older children (average age of about 13 years), Krause *et al.* (2007)[137] found complex patterns in the theta (4-8 Hz), alpha (8-13 Hz) and beta frequency bands (13-30 Hz) during processing of information during an auditory memory test. The authors suggest that memory systems responsible for remembering may be the last to develop. This makes them potential candidates for being affected by radiofrequency fields of mobile telephones if used by young children.

In a third study among 15 children, Krause *et al.* (2006)[49] therefore examined the EEG during an auditory memory test in 10-14 year-olds while they were exposed to a 902 MHz signal from a mobile telephone. The SAR_{1g} was 1.40 W/kg, the peak SAR was 1.98 W/kg. Exposure was found to generate an effect that differed during various phases of the cognitive process: during the imprinting phase, an effect was seen in the alpha band (8-13 Hz) of the EEG, while during the recognition phase, in addition to the effect on the alpha band, an effect was also seen at 15 Hz, a frequency in the beta band. However, this does not say anything about memory function, a subject addressed below.

A comparable study was performed by Kramarenko and Tan (2003).[50] They exposed 10 children aged 12 to a signal from a 900 MHz GSM telephone. About 10-20 seconds after the beginning of exposure, low-frequency waves (1.0-2.5 Hz, delta band) appeared on the EEG. In the 10 examined adults, exposure also resulted in an increase in EEG activity, but at higher frequencies (2.5-6.0 Hz; delta and theta bands) and only after a longer lag time, 20-40 sec. In both cases, the increased EEG activity disappeared after termination of the exposure. However, the authors do not indicate the intensity of exposure or SAR value for the head. This makes the study difficult to interpret.

Croft *et al.* (2010)[52] examined the waking EEG at rest during exposure to a GSM or UMTS signal in three groups of volunteers, aged 13-15 years, 19-40 years and 55-70 years. The peak SAR_{10g} for the GSM signal was 0.7 W/kg and 1.7 W/kg for the UMTS signal. For the GSM signal, an effect on EEG activity in the alpha band (8-13 Hz) was only seen in the group of 19-40 year-olds, not in children. The UMTS signal did not result in any effect in any age group.

Leung *et al.* (2011)[51] reported on another part of this study, in which the EEG was examined while performing a memory task tailored to individual capacity. Independently of age, a slowing of response was seen in the alpha band for both GSM and UMTS exposure in all three groups.

The findings in young adults are consistent with previous data. In its 2008 Annual Update, the Committee addressed the effects of electromagnetic fields on the EEG in adults:

Various studies have shown that GSM-like signals can affect the spontaneous EEG[50,70,138-147]; however, such effects were not found in other studies.[148-151] A well- conducted, large-scale study in 120 subjects confirmed the findings from a number of smaller studies with regard to an increase in alpha band brain activity (defined as 8-13 Hz in this large study).[152] There may also be effects on brain activity in other frequency bands, but these were not consistently found.

Effects on ERPs

Kwon *et al.* (2009)[53] used EEG analysis in 17 children aged 11-12 years to examine the influence of exposure to a 900 MHz GSM telephone signal on auditory ERPs. Exposure duration was 6 min, maximum SAR_{1g} = 1.14 W/kg, SAR_{10g} = 0.82 W/kg, and the peak SAR = 1.21 W/kg. Exposure did not affect the processing of auditory signals, but the number of subjects was too low to observe subtle differences.

In the 2008 Annual Update, the Committee concluded that studies into the effects on ERPs in adults did not support the results of the EEG studies. Insofar as some studies found minimal effects, these were inconsistent.[139,142,153-161] Other studies found no effect at all.[49,81,155,162-167]

E.3 Behaviour / memory functions

In the 2008 Annual Update, the Committee wrote that research into cognitive effects yield a varied picture. This is due to, among other things, the fact there is little uniformity with regard to the tests used. This has not changed since then.

Most research in humans has been conducted in adults. In the studies done in children, different age groups were examined, with widely varying degrees of mobile telephone use.

Animal studies

Takahashi *et al.* (2010)[55] exposed rats to a 2.14 GHz UMTS-like signal for 20 hours per day from 7 days after fertilisation until 21 days after birth. The whole-body SAR varied from 0.068-0.146 W/kg (high exposure level) or from 0.029-0.067 W/kg (low exposure level). During the post-natal exposure period, no abnormalities in behaviour or memory were found for either exposure level compared with a control group.

Priakhin *et al.* (2007)[56] exposed rats aged 2 and 3.5 months to a pulsed 925 MHz GSM signal with a power density of 1.2 mW/cm^2 (= 67 V/m), for 10 minutes per day for 12 days. Learning and orientation capacity was tested on the 8th day of exposure; no effect of exposure was found. (This study was published in Russian; the English-language summary does not provide any more information than displayed here.)

Kumlin *et al.* (2007)[46] exposed 18 rats from the age of 24 days for 2 hours a day, 5 days a week for 5 weeks to a 900 MHz mobile telephone signal. There were two levels of exposure, resulting in a whole-body SAR of 0.3 or 3.0 W/kg. Neither exposure level led to effects in an open-field test, a maze test or a startle response test. In the water maze test, exposed animals demonstrated significantly improved learning capacity and memory, with the highest level of exposure resulting in the strongest effects. However, at the SAR of 3.0 W/kg, heating effects cannot be ruled out.

Cobb *et al.* (2000)[42] exposed rats before and up to 10 days after birth to a pulsed ultra-wideband electromagnetic field. The peak field strength was 55 kV/m, with a rise time of 300 picoseconds and a pulse width of 1,8 nanoseconds; the whole-body SAR was 45 mW/kg. As indicated above, practically no effects were found on brain structures in this study. The investigators also found no effects on behaviour.

Galvin *et al.* (1986)[54] exposed rats to 2450 MHz radiofrequency fields of 100 W/m^2 (= 194 V/m), 3 hours per day from the 5th to 20th day of pregnancy, and from the 2nd to 20th day after birth. Groups of 11-18 real or sham exposed animals subsequently underwent behavioural testing. At an age of 30 days, the real exposed animals had lower swimming endurance than the sham exposed animals, but this was not the case at the age of 100 days. No other behavioural effects were noted. In a follow-up experiment, the researchers also found decreased swimming endurance at the age of 30-36 days after exposure, and no effect on other behavioural parameters.

Reiter (reported in McRee *et al.,* 1979)[34] exposed rats to 425 MHz radiofrequency fields, 100 W/m^2 (= 194 V/m), from the 12th day after fertilization and to 2450 MHz fields, 50 W/m^2 (= 137 V/m) from the 6th day after fertilization. In both cases, exposure continued after birth until the age of 92 days. They found no differences between exposed and control animals in terms of development of reflexes during the first three weeks of life. There was also no difference between the two groups in terms of spontaneous movement activity at adult ages.

Research with children

Haarala *et al.* (2005)[57] examined various cognitive functions in 32 children aged 10-14 years during exposure to the signal of a GSM mobile telephone, at an SAR_{10g} of 1 W/kg (peak value = 2.07 W/kg), and to sham exposure. They found no effects of exposure on response time or accuracy in various tests.

Preece *et al.* (2005)[58] also looked at cognitive functions in 18 children during exposure to a GSM mobile telephone signal and compared it to sham exposure, in this case in an age group of 10-12 years. Two different exposure levels were applied: an output power of 0.025 or 0.25 W (= full power). The maximum SAR was 0.28 W/kg. They found no effect of exposure on response time at either of the two levels; they had found an effect in previous studies in adults, but then used a different type of (analogue) telephone with a higher output power. During sham exposure – the control situation – response time was longer than measured in adults in the previous experiments.

Riddervold *et al. (*2008)[59] studied various cognitive functions and the occurrence of symptoms in forty 15-16 year-olds following exposure to a 2140 MHz continuous signal for 45 minutes, a 2140 MHz UMTS-modulated signal, a full UMTS base station signal, or sham exposure. Field strength was 1 V/m. None of these signal types affected the cognitive functions tested or the occurrence of symptoms.

Abramson *et al.* (2009)[60] examined cognitive functions in a group of 317 children of about 13 years of age. Memory, response time, accuracy and learning capacity were related to the reported number of weekly telephone calls or text messages. As children made more calls per week, they responded more quickly and less accurately in high-level cognitive tasks. The same was also true for children who sent more text messages. The researchers suggest this effect is primarily related to the frequent handling of a mobile telephone.

Leung *et al.* (2011)[51] studied the effect on two memory tasks of exposure to a GSM or UMTS signal in three groups of volunteers, aged 13-15 years, 19-40 years and 55-70 years. The peak SAR_{10g} for the GSM signal was 0,7 W/kg and 1,7 W/kg for the UMTS signal. The difficulty of memory tests was tailored to individual capacity, in order to increase the comparability of the degree of mental load. During a auditory memory task, no effect of either signal was found in any age group. For an visual memory test, a decrease in precision was found only in the group of 13-15 year-olds following exposure to the UMTS signal. The GSM signal did not result in any effect in any age group.

In general, the studies in children provide no, but in a recent study limited indications of effects of exposure to radiofrequency electromagnetic fields on cognitive functions. In adults, effects were also found in some studies, but these are always minor and reversible, and the effects generally indicate improved performance.[61-72] Studies with larger groups of subjects generally show no effects.[59,73-83]

E.4 The blood-brain barrier

Animal studies

Kumlin *et al.* (2007)[46] exposed groups of 6 rats from the age of 24 days for 2 hours a day, 5 days a week for 5 weeks to a 900 MHz mobile telephone signal. There were two levels of exposure, resulting in a whole-body SAR of 0.3 or 3.0 W/kg. Neither of the SAR values resulted in effects on the blood-brain barrier.

Kuribayashi *et al.* (2005)[84] exposed 4 and 10-week old rats to a 1439 MHz radiofrequency field for 90 minutes per day for 1 or 2 weeks. The local SAR was 2 or 6 W/kg. Compared with sham exposure, there was no effect on the permeability of blood vessels in the brain or on expression of blood-brain barrier-related genes.

Finnie *et al.* (2006)[85] exposed mice immediately after birth to a 900 MHz mobile telephone signal for 7 days, 1 hour per day. The whole-body SAR was 4 W/kg. Control groups received sham exposure or no treatment, and there was a positive control. The latter showed an effect on albumin leakage in the brain, a sign of permeability of the blood-brain barrier, but this was not found after exposure to the GSM signal.

Despite the sometimes high SAR values, at which heating effects cannot be ruled out, no effects on the blood-brain barrier were found.

E.5 Physiology

Animal studies

The thyroid gland excretes the hormones thyroxin (T4) and triiodothyronine (T3), which play a key regulatory metabolic role. Thyroid function is regulated, among other things, by the hormone THS (thyroid stimulating hormone) which is made in the pituitary gland and is in turn regulated by TSH (thyrotropin stimulating hormone), made in the hypothalamus.

Saddiki-Traki (1986)[88] exposed rats to radar microwaves with a power density of 5 ± 2 mW/cm^2 (= 137 V/m) for the first 15 days after birth. The duration of exposure was not given, but was likely continuous. At an age of 75 days, TSH levels in the plasma had increased, but the TSH levels in the hypothalamus were unchanged. An increase in T4 plasma levels was also found. Histologic investigations of the thyroid gland showed a decrease in follicular diameter, as well as an increase in the height of follicular epithelium.

It is possible that these effects are due to a rise in body temperature. Based on research in three different types of rats, Lu *et al.* (1987) concluded that in adult animals, the limit value for thyroid gland stimulation at an environmental temperature of 24 °C was a minimum temperature rise of 0.24 °C, corresponding to an SAR of 2 W/kg.[168]

Studies in adult animals do not yield unequivocal results. Michaelson *et al.* (1967)[169] (cited in Michaelson, 1982[170]) exposed dogs to a pulsed 2880 MHz field at an SAR of 3.7-6.1 W/kg and observed thyroid gland stimulation.

Exposure of rats for 4 hours to a 1 mW/cm^2 (= 61 V/m) 2450 MHz field resulted in increased T4 serum concentrations (Lu *et al.,* 1977)[171], but not in an increase in TSH (Lu *et al.,* 1985).[172] TSH only decreased at exposures above 10 mW/cm^2, corresponding to an SAR of 2 W/kg.[172]

Parker (1973)[173] exposed rats to a 2450 MHz field at 15 mW/cm^2 (= 237 V/m) for 60 hours, and found a decrease in T4 serum concentration, indicating thyroid inhibition. Koyu *et al.* (2005)[174] exposed rats to a 900 MHz field (1 ± 0.4 mW/cm^2, SAR = 2 W/kg) for 30 min per day, 5 days per week for 4 weeks, and found decreased serum concentrations of TSH, T3 and T4.

Various biochemical parameters in the brains of 35 day-old rats were examined by Paulraj *et al.*[92-94] The animals were exposed for 35 days, 5 days per week, 2 hours per day. An electromagnetic field of 112 MHz, 16 Hz amplitude modulated, with a power density of 1 mW/cm^2 (= 61 V/m) resulted in an increase in the activity of the enzyme ornithine decarboxylase (ODC), a tumour marker, and in an increase in excretion of calcium from brain tissue, but these data were inconsistent.[92] A 2540 MHz field of 0.344 mW/cm^2 (= 36 V/m), resulting in a whole-body SAR of 0.11 W/kg, led to a drop in the activity of the enzyme protein kinase C (PKC) in the hippocampus. PKC plays a key role in various cellular functions and is assumed to be important in the development of cancer.[93,94]

Paulraj *et al.* (2006)[90] also studied DNA breaks after exposure to 2.54 GHz (SAR = 1,0 W/kg) or 16.5 GHz (SAR = 2.0 W/kg), again for 35 days, 5 days per week, 2 hours per day. An increase in the number of single-strand DNA breaks was found for both frequencies, respectively 70% (2.54 GHz) and 51% (16.5 GHz). In a follow-up experiment, the same treatment was given at an SAR of 0.11 W/kg.[91] Compared with sham exposed animals, there was an increase in double strand DNA breaks, and changes to various enzymes were measured that play a role in scavenging free radicals.

Research with children

Nam *et al.* (2006)[97] exposed 21 teens (15.9 ± 2.3 years) to a 824-848 MHz mobile telephone signal for 30 minutes. No effect was found on blood pressure and heart and respiratory rates. A decreased electrical resistance of the skin was measured, which the authors ascribed to an effect on the autonomic nervous system. The effect was only found in boys, not in girls or adults.

E.6 Pain

Animal studies

Takahashi *et al.* (2010)[55] exposed rats to a 2.14 GHz UMTS-like signal for 20 hours per day from 7 days after fertilisation until 21 days after birth. The whole-body SAR varied from 0.068-0.146 W/kg (high exposure level) or from 0.029-0.067 W/kg (low exposure level). During the post-natal exposure period, no abnormalities in pain perception were found for either exposure level compared with a control group.

Mathur (2008)[95] exposed groups of 4 rats to a 16 Hz modulated 73.5 MHz field for 45 days, 2 hours per day from the 28th day after birth. The whole-body SAR was 0.4 W/kg. Exposure had a complex effect on pain sensation: the initial response to a pain stimulus was elevated, but later responses decreased.

E.7 Population studies

In a study among 1498 children aged 8-12 and 1524 children aged 13-17 years, Thomas *et al.* (2010)[10,98] determined 24-hour exposure to radiofrequency electromagnetic fields through individual measurements. Abnormalities in behaviour were determined using a questionnaire.[98] They found a small but significantly elevated percentage of behavioural problems in the highest exposure group for both age groups, but no relationship with emotional problems, hyperactivity or problems with relationships with peers. Additionally, in both groups, possession and use of a mobile phone was higher for lower socioeconomic status (SES).[10] In the youngest age group, possession and use of a DECT telephone was lower for lower SES, while there was no correlation in the highest age group. Heinrich *et al.* (2010)[99,175] reported on a number of additional aspects of this study. They found no relationship between measured exposure and the incidence of chronic complaints such as headache.[99] Associations were found between afternoon headaches and morning exposure, and between evening irritability and exposure in the afternoon among 13-17 year-olds, as well as between concentration problems and exposure in the afternoon among 8-12 year-olds.[175] As these findings are not consistent between groups, and many relationships were examined, the authors suggest they may be explained by chance. The study also showed that both groups tend to overestimate mobile telephone use, compared to what is realistic based on the exposure measurements.

Söderqvist *et al.* (2007)[11] looked at mobile telephone ownership and use in Sweden in a group of 1423 children aged 7-14 years. 57.7% of this group owns a mobile phone, and 79.1% uses it regularly. 26.7% make calls with their mobile telephone for more than 2 minutes a day. Among 7 year-olds, 7.3% owns their own mobile telephone, rising to 95% of 14 year-olds. For the group as a whole, 83.8% has a cordless telephone and 38.5% uses it for more than 5 minutes per day. Girls use a mobile or cordless telephone more often and for longer than boys.

Mezei *et al.* (2007)[12] looked at mobile telephone ownership and use among 1301 schoolchildren aged 9-12 years in three cities in Hungary. 76% of this group owns a mobile telephone; 24% uses one daily, and 33% does so several times per week. Ownership and use were more common among girls, children with no siblings, members of sports clubs and children who play computer games daily.

In a study in Melbourne among 317 schoolchildren aged 10-14 years, Inyang *et al.* (2010)[13] found that 77% owned a mobile telephone and 94% occasionally used a mobile telephone. Boys and children without siblings started using mobile telephones at a younger age than other groups. Regular use of a mobile telephone was associated to a minor degree with higher scores for psychotic character traits. Use of a mobile telephone was more common among children of parents with an average SES than among children of parents with a low or high SES. Parents who were worried about the potential effects of mobile telephones on health were more likely to have children with a mobile telephone.

A study among 800 teens aged 12-17 years in the United States showed that 75% owned a mobile telephone.[14] It is the most commonly used communication means in that age group, with text messaging being far more common than making calls. One in three teens sends more than 100 text messages per day. Worries about potential health effects of mobile telephone use by children were not examined in this study.

E.8 Dosimetry

Initially, dosimetry studies focused on the head, as this is the most important exposed body part when using a mobile telephone. Later, also due to increases in processing power, it became possible to perform calculations using models of the entire body. Initial studies used linearly scaled models of adults to represent children. This caused incorrect proportions in the child models. Later on, models were developed by shrinking adult models and transforming them based on data on growth of body parts. Also anatomically correct models have been developed, based on MRI scans of children.

Head

Gandhi *et al.* (1996)[176] found a higher peak SAR in children compared with adults. The models used for children were linearly scaled models of an adult.

Schönborn *et al.* (1998)[177] repeated this study with both anatomically correct and linearly transformed models, and found no differences between the peak SAR in children and adults.

Martínez-Búrdalo *et al.* (2004)[178] calculated the peak SAR_{1g} and SAR_{10g} in the brain. In the linearly scaled models used, the peak SARs for children were lower than in adults, but the percentage of emitted energy absorbed by the brain was greater. The authors suggest this indicates a higher whole-brain SAR in children.

Keshvari and Lang (2005)[179] performed SAR calculations using anatomically correct models of two adults and two children, aged 3 and 7 years. There were no consistent differences in the peak SAR between children and adults. They concluded that the differences between the four models were more significant than the differences between children and adults. What was clear was that inclusion or exclusion of the pinna in the models has a significant effect, as this leads to changes in the distance of the antenna to brain tissue.

Bit-Babik *et al.* (2005)[117] studied models of both linearly scaled and transformed heads of children aged 5 and 10 years. They found no differences with adults in terms of the peak SAR.

De Salles *et al.* (2006)[180] calculated that the SAR_{1g} in children is higher than in adults. In a model for a 10 year-old child, the SAR values were up to 60% higher than in adults, depending on the electromagnetic tissue parameters used.

In a review, Wiart *et al.* (2005)[120] indicated that the peak SAR in a linearly scaled model can be twice as high as in a transformed model. This may explain the conclusions from previous studies, in which peak SAR values were higher in children than in adults. In anatomically correct models, the differences between adults and children are comparable to the differences between various available models for adults. The authors also indicate that proper modelling of the pinna is important, in order to determine the correct distance from the antenna to the brain.

In an extensive study from 2008, Wiart *et al.*[103] compared 7 models of children and 6 of adults. The differences in the peak SAR_{10g} in the anatomically correct heads between children and adults were small compared with the variation between adults, a conclusion consistent with that of a previous review.[120] In the models of children aged 5-8 years, peak SAR_{1g} values were twice as high as in adults; the authors ascribe this to a thinner pinna, skull and skin.

Christ *et al.* (2010)[121] studied the effect of compressing the pinna in various models of adults and children, as occurs when the telephone is held firmly against the ear. Most studies did not take this into account. In both adults and children, a realistically compressed pinna resulted in a ~50% increase in the SAR_{10g} if the maximum is located near the pinna.

In a second article, Christ *et al.* (2010)[118] indicate that the peak SAR_{10g} for children may be higher than for adults in certain parts of the brain. This is caused primarily by the smaller distance between telephone and brain tissue. No difference was found in the SAR averaged over the entire head, nor was there any effect of variations in electromagnetic properties of tissues. The conclusion was that on average, children's brains have greater exposure than those of adults. This is primarily due to differences in anatomic proportions. The authors also point out that exposure of the outer layers of the brain, the distributions of current density and the near field of the phone must be examined.

Joó *et al.* (2006)[123] performed calculations using linearly scaled child models (2-3 years and 9-10 years old) and mobile phone use. If a metal plate is present in the head, the peak SAR in children can be up to 100% higher than in adults. Exposure limits are sometimes exceeded under certain circumstances in both adults and children with implants; this applies to the SAR_{10g} (ICNIRP: 2 W/kg) as well as the SAR_{1g} ('old' IEEE limit: 1.6 W/kg).

Body

Dimbylow calculated the whole-body SAR for an adult male and linearly scaled models of children aged 10, 5 and 1 year. At frequencies above 0.8 GHz, exposure at ICNIRP reference levels leads to exposure that exceeds the basic restriction.[104] These findings were confirmed by a more extensive study (Dimbylow, 2002[115]). Comparable results were found at frequencies over 1.2 GHz in female models.[105] In more anatomically correct models, Dimbylow and Bolch (2007)[106] found that at frequencies higher than 1 GHz, exceeding ICNIRP basic restrictions at exposure to the reference level occurred in the smaller models of children aged 9 months and 4 years, but not in models of 8, 11 and 14 year-olds.

Nagaoka *et al.* (2008)[102] calculated the SAR in transformed and scaled models of a 3, 5 and 7 year-old and compared these findings with linearly scaled models. The whole-body SARs were not significantly different between both types of model, but local SARs were. Exposure to an electrical field at the ICNIRP reference level resulted at around 2 GHz in exceeding the ICNIRP basic restriction for all three ages.

In a follow-up study, Nagaoka *et al.* (2009)[181] looked at variation in the whole-body SAR in 30 children aged 3-4 years. They used homogenous models for this, as the differences between a heterogeneous (based on an MRI scan) and a homogenous model (based on a far simpler, more easily obtained surface scan) were found to be minimal: a maximum of 14% at resonant frequencies. The variation in the whole-body SAR in the group of 30 children was, on average, about 13%, but it was lower at the resonant frequency: about 6.5%.

In a scaled and transformed model of a 7 year-old child, Wang *et al.* (2006) found, at exposure to ICNIRP reference levels, that the basic restrictions were exceeded by about 30% for both the resonant frequency and around 2 GHz.[124]

Conil *et al.* (2008)[107] also found that basic restrictions were exceeded in children at a frequency of 2 GHz and at resonant frequency following exposure to ICNIRP reference levels. At 2 GHz, minor exceeding of the limits was also possible in adults. The authors considered 6 models of adults and scaled and transformed models of children aged 5, 8 and older than 12 years. A frequency-dependent variation in the whole-body SAR of up to about 30% was found in the adult models. In the models for children, the whole-body SAR was up to 48% higher than for adults.

Variation in the whole-body SAR and dependence on the polarisation of the electromagnetic field was studied by Kühn *et al.* (2009)[119] in anatomically correct models of two adults and children aged 6 and 11 years. The maximum SAR in the model of the smallest child (6 years old) was 2-3 times higher than in the largest adult. For the 6 year-old child model, the maximum whole-body SAR at 100 MHz and above 1450 MHz exceeded the ICNIRP limit. At frequencies above 450 MHz, a five-fold variation in the peak SAR for various exposure directions and polarisations, as well as a three-fold variation between various models was found.

In models of children aged 9 months to 7 years, Hirata *et al.* (2009)[182] found that the whole-body SAR is higher for horizontal polarisation of the electromagnetic field than for vertical polarisation for frequencies higher than 2 GHz. The models used were anatomically correct, with the exception of the model for 9 months old, which was scaled linearly based on a model of a 3-year old.

Bakker *et al.* (2010)[122] calculated the whole-body SAR and SAR_{10g} in six anatomically correct models of children aged 5-14 years. They found that ICNIRP basic restrictions were exceeded by up to 45% at frequencies around 2 GHz. An uncertainty analysis showed a large uncertainty of 53% for the whole-body SAR and 58% for the SAR_{10g}.

Findlay *et al.* (2009)[113] examined the influence of posture on the SAR in an anatomically correct and linearly scaled model. Both models were analysed in standing position with arms alongside the body ('standard posture'), standing with arms raised and extended upwards, and seated with arms bent, as if in an armchair. For the standing models, the maximum whole-body SAR was about 25% higher with arms raised. For seated posture, maximum whole-body SAR is about 40% lower. At the resonant frequencies of around 100 MHz and at frequencies above about 2 GHz, exposure to reference levels results in exceeding of the ICNIRP basic restrictions.

In a linearly scaled model of a 10 year-old child, Findlay and Dimbylow (2010) calculated the whole-body SAR for exposure to 2.4 and 5 GHz signals from a Wi-Fi access point. The maximum SAR was 19.1 µW/kg at a field strength of 1 V/m. According to the authors, under realistic circumstances, field strength at 1 m from a Wi-Fi access point is no more than 2 V/m, making the whole-body SAR significantly less than the ICNIRP SAR limit (0.08 W/kg) stipulated. The maximum local SAR for exposure by the laptop antenna is 5.7 mW/kg under the most unfavourable circumstances, again well below the SAR limit (2 W/kg) set by ICNIRP.

Table E2 Summary of studies with postnatal exposure.

Reference	Source	Exposure	Age at exposure	Endpoint	Number of subjects	Results
In vitro neurons						
Wang *et al.* (2004)[29]	900 MHz	2 h/d, 4-5 d 12 h SAR=3.2 W/kg	From newborn rat	Cytochrome oxidase activity	--	Both treatments: decrease cytochrome oxidase activity
Wang *et al.* (2005)[30]	900 MHz	2 h/d, 4 or 6 d SAR=1.1-3.2 W/kg 12 h SAR= 3.2 W/kg	From newborn rat	Activity receptor protein GluR2 and intracellular calcium	--	Both treatments: dose dependent decrease GluR2 and increase intracellular calcium
Wang *et al.* (2005)[134]	900 MHz	2 h/d, 6 d SAR=1.1-3.2 W/kg 12 h SAR= 1.1-3.2 W/kg	From newborn rat	GABA-receptor expression	--	Window effect

Xu *et al.* (2006)[28]	1800 MHz GSM	15 min/d, 8 d SAR=2.4 W/kg	From 1-d old rat	Synaptic activity	--	Decrease AMPA signals, non NMDA- receptors
Ning *et al.* (2007)[27]	1800 MHz GSM	15 min/d, 6 d SAR=0.8 or 2.4 W/kg	From newborn rat	Dendrite formation	--	No effect at SAR=0.8 W/kg
In vitro supporting cells						
Thorlin *et al.* (2006)[33]	900 MHz continuous or GSM-modulated	Cont: 24 h SAR=27 W/kg GSM: 4, 8, 24 h SAR=3 W/kg	From newborn rat	Gfap in astrocytes, ED1 in microglia; morphology, IL6, TNFα, protein in both	--	No effects
Höytö *et al.* (2007)[32]	872 MHz continuous or GSM-modulated	2, 8, 24 h SAR=1.5, 2.5, 6.0 W/kg	From 2-d old rat	Ornithine decarboxylase (ODC) activity in astrocytes	--	Decrease ODC when pooling exposure times, not when considered separately
Gene expression						
Zhao *et al.* (2006)[31]	1800 MHz GSM	24 h, 5 min on, 10 min off SAR=2 W/kg	From newborn rat	1200 genes in neurons	--	Effect in 34/1200 genes; increase Map2 expression
Histology animals						
Albert *et al.* (1981)[40]	2450 MHz	5 d, 7 h/d SAR=2 W/kg	6 d	Purkinje cells in cerebellum rat	3 rats 4-6 serial sections on 6-9 planes per animal	Significantly lower number Purkinje cells immediately after exposure; not present anymore at 40 d
Albert *et al.* (1981)[44]	2450 MHz	3 h/d SAR=3.4 W/kg	During pregnancy + 9,5 mo after birth	Purkinje cells in cerebellum Squirrel monkey	7 animals 7-8 sections per animal	No effect
Albert *et al.* (1988)[41]	2450 MHz	5 d, 7 h/d SAR=2 W/kg	1 or 6 d	Pyknotic cells in cerebellum rat	4 (1-d old); 8 (6-d old) 5 planes / hemisphere / animal; 3 section / plane	2x number pyknotic cells then in sham exposed
Inouye *et al.* (1983)[45]	2450 MHz	3 h/d SAR=1,16 > 0.79 W/kg	From 4th day of pregnancy to 40 d after birth	Various histological parameters rat	6 animals / group / assay time; 10 sections / animal	No effect
Cobb *et al.* (2000)[42]	Ultra wide band	Peak 55 kV/m, risetime 300 psec, puls width 1.8 nsec SAR=45 mW/kg	Before to 10 d after birth	Various histological parameters rat	6 animals / group; 6 regions / hippocampus	Increased ratio median -lateral length hippocampus
Hoffman *et al.* (2001)[43]	35.53 kHz, modulation 1, 8, 12, 29 or 50 Hz	Unknown	'young adult'	Cell proliferation in brain tissue gerbil	8-12 animals / group; 38 sections / animal	Decrease cell proliferation with 1, 20 or 50 Hz modulation, not with 8 and 12 Hz

Kumlin *et al.* (2007)[46]	900 MHz GSM signal	2 h/d, 5 d/wk, 5 wk SAR=0.3 or 3.0 W/kg	24 d	Morphology brain tissue rat	6 animals; 2 sections / animal	No degenerative changes or dying neurons
Ragbetli *et al.* (2009)[47]	GSM phone	12 h/d, 1 h 14 min stand-by, 15 min call	During pregnancy + 12 d	Pyramidal cells hippocampus mouse	5 animals / group; 15-20 section / animal	No effect
EEG animal						
Rosenstein (in McRee *et al.* 1979)[34]	425 or 2450 MHz	425 MHz: 200 V/m; 2450 MHz 100 V/m,	425 MHz: from d 12 after conception; 2450 MHz: from d 6 after conception both until 92 d after birth	spontaneous EEG and light stimulated potentials rat	Unknown number offspring of 6 (425 MHz) resp. 12 mothers (2450 MHz)	No effect at 140 d
EEG human						
Kramarenko & Tan (2003)[50]	900 MHz GSM phone	Unknown	12 yr	EEG spectrum	10	Induction slow EEG waves, more obvious then in adults
Krause *et al.* (2006)[49]	902 MHz GSM signal	60 min SAR_{1g}=1.4 W/kg	10-14 yr	EEG spectrum	15	EEG changes during cognitive processing
Croft *et al.* (2010)[52]	894.6 MHz GSM signal 1900 MHz W-CDMA signal	45 min peak SAR_{10g}=0.7 W/kg (GSM) and 1.7 W/kg (UMTS)	13-15 yr	Alpha waves non-sleep EEG	41	No effect of both types of signal
Leung *et al.* (2011)[51]	894.6 MHz GSM signal 1900 MHz W-CDMA signal	45 min peak SAR_{10g}=0.7 W/kg (GSM) and 1.7 W/kg (UMTS)	13-15 yr	EEG during cognitive task	41	Delayed response alpha-band with both GSM and UMTS
ERP human						
Kwon *et al.* (2009)[53]	902 MHz GSM signal	6 min SAR_{10g}=0.82 W/kg	11-12 yr	Auditory-induced potentials	17	No effect
Hearing animal						
Kizilay *et al.* (2003)[35]	Mobile phone	30 d, 1 h/d	30 d	Distortion product otoacoustic emission (DPOAE) rat	Adults: exposed: 7, sham: 7 Newborn: 4	No effect
Budak *et al.* (2009)[37]	1800 MHz GSM-like signal	7 d, 15 min/d	1 mo	DPOAE rabbit	9 / group	Increased DPOAE
Budak *et al.* (2009)[38]	1800 MHz GSM-like signal	14 d, 15 min/d ± between d 15 and 22 of pregnancy, 15 min/d	1 mo	DPOAE male rabbit	9 / group	Frequency and exposure dependent effect

Budak *et al.* (2009)[39]	1800 MHz GSM-like signal	14 d, 15 min/d ± between d 15 and 22 of pregnancy, 15 min/d	1 mo	DPOAE) rabbit	9 / group	Frequency and exposure dependent effect; different from male animals
Kayabasoglu *et al.* (2011)[36]	Mobile phone	30 d, 6 h/d	30 d	DPOAE rat	10 / group	No effect
Cognition / behaviour animal						
Takahashi *et al.* (2010)[55]	2.14 GHz UMTS	20 h/d SAR=29-67 or 68-146 mW/kg	Before up to 21 d after birth	Number of learning and behaviour tests	24 / group 3 exp.	No effect
Priakhin *et al.* (2007)[56]	925 MHz GSM	10 min/d, 12 d 1.2 mW/cm^2	2 and 3.5 mo	Learning and orientation rat	Unknown	No effect
Kumlin *et al.* (2007)[46]	900 MHz GSM signal	2 h/d, 5 d/wk, 5 wk SAR=0.3 or 3.0 W/kg	24 d	Open-field test, maze test, startle reaction test rat	18	Water maze test: improved learning and memory
Cobb *et al.* (2000)[42]	Ultra wide band	Peak 55 kV/m, risetime 300 psec, pulse width 1.8 nsec SAR=45 mW/kg	Before to 10 d after birth	Behaviour rat	6 / group	No effect
Galvin *et al.* (1986)[54]	2450 MHz	3 h/d 200 V/m	d 5-20 of pregnancy and d 2-20 after birth	Behaviour rat	11-18 / group	Lower swimming endurance on 30-36 d
Reiter (in McRee *et al.*,1979)[34]	425 or 2450 MHz	425 MHz: 200 V/m; 2450 MHz 100 V/m,	425 MHz: f rom d 12 after conception; 2450 MHz: from d 6 after conception both until 92 d after birth	Development reflexes in first 3 weeks of life, motion activity as adult	Unknown	No effects
Cognition human						
Haarala *et al.* (2005)[57]	902 MHz GSM signal	SAR=1 W/kg	10-14 yr	Cognition: reaction speed, accuracy	32	No effect
Preece *et al.* (2005)[58]	902 MHz GSM signal	Power=0.025 or 0.25 W maximum SAR=0.28 W/kg	10-12 yr	Cognition: reaction time	18	No effect
Riddervold *et al.* (2008)[59]	2140 MHz continuous, UMTS or UMTS base station signal	45 min 1 V/m	15-16 yr	Cognition	40	No effect

Abramson *et al.* (2009)[60]	Mobile phone	# calls / wk or # SMS / wk	Median 13 yr	Cognition memory, reaction time, accuracy, learning	317	More calls: faster and more accurate response with high-level cognitive tasks; same with more SMS
Leung *et al.* (2011)[51]	894.6 MHz GSM signal 1900 MHz UMTS signal	45 min peak SAR_{10g}=0.7 W/kg (GSM) and 1.7 W/kg (UMTS)	13-15 yr	Cognition: memory, reaction time, accuracy, learning	41	Visual memory test: decreased accuracy with UMTS; no other effects
Blood-brain barrier animals						
Finnie *et al.* (2006)[85]	900 MHz GSM signal	1 h/d, 7 d SAR=4 W/kg	0 d	Blood-brain barrier rat	10 animals / group	No effect on albumin permeability brain blood vessels
Kuribayashi *et al.* (2005)[84]	1439 MHz	90 min/d, 1 or 2 wk SAR=2 or 6 W/kg	4 or 10 wk	Blood-brain barrier rat	5 animals / group; 10 locations / animal	No effect on permeability brain blood vessels and expression of BHB-related genes
Kumlin *et al.* (2007)[46]	900 MHz GSM signal	2 h/d, 5 d/wk, 5 wk SAR=0.3 or 3.0 W/kg	24 d	Blood-brain barrier rat	6 animals / group; 2 sections / animal	No effect
Physiology animals						
Michaelson *et al.* (1967)[169] (in Michaelson, 1982[170])	2880 MHz pulsed	SAR=3.7-6.1 W/kg	Adult	Thyroid function dog	Unknown	Stimulation thyroid
Parker *et al.* (1973)[173]	2450 MHz	15 mW/cm²	Adult	Thyroid function	Unknown	Decrease serum T4
Lu *et al.* (1977)[171]	2450 MHz 120 Hz modulation	4 h 1 mW/cm²	Adult	Thyroid function rat	Unknown	Increase serum T4
Lu *et al.* (1985)[172]	2450 MHz 120 Hz modulation	4 h 1-40 mW/cm²	Adult	Thyroid function rat	4-8 / group	Decrease TSH > 10 mW/cm²
Guessab *et al.* (1983)[89]	Radar MW	15 d	0 d	Noradrenalin in hypothalamus adult animals	Unknown	Increase noradrenalin in hypothalamus
Saddiki-Traki *et al.* (1986)[88]	Radar MW	15 d 5 ± 2 mW/cm2	0 d	TSH + histology thyroid at 75 d	8-10 / group histology: 50 observations	Increase TSH in plasma, not in thyroid; increase plasma T4; decrease follicle diameter + increase height follicle epithelium
Paulraj *et al.* (1999)[92]	112 MHz, 16 Hz modulation	2 h/d, 5 d/wk, 35 d 1 mW/cm² (=60 V/m)	35 d	Calcium efflux and ornithine decarboxylase (ODC) in brain	4 / group	Increase ODC activity and calcium efflux (inconsistent Ca data)

Koyu *et al.* (2005)[174]	900 MHz	30 min/d, 5 d/wk, 4 wk SAR = 2 W/kg	Adult	Thyroid function	10 / group	Decreased serum TSH, T3 and T4
Paulraj *et al.* (2006)[93,94]	2.54 GHz	2 h/d, 5 d/wk, 35 d 0.344 mW/cm^2 (=20 V/m) SAR=0.11 W/kg (random polarisation)	35 d	Protein kinase C (PKC) activity in brain	6 / group	PKC activity decreased in hippocampus
Paulraj *et al.* (2006)[90]	2.54 or 16.5 GHz	2 h/d, 5 d/wk, 35 d 2.54 GHz: 0.344 mW/cm^2 (=20 V/m) SAR=1,0 W/kg (E-polarisation) 16.5 GHz: 1,0 mW/cm^2 (=60 V/m) SAR=2.01 W/kg	35 d	DNA single strand breaks	6 / group, 100 cells / animal	Increased single strand breaks at both frequencies (resp.70% and 51%)
Kesari *et al.* (2010)[91]	2.54 GHz	2 h/d, 5 d/wk, 35 d 0.344 mW/cm^2 (=20 V/m) SAR=0.11 W/kg (random polarisation)	35 d	DNA double strand breaks in brain cells; activity of radical scavenger enzymes	6 / group, 40 cells / animal	Increase double strand breaks; change in several enzymes
Physiology human						
Nam *et al.* (2006)[97]	824-848 MHz CDMA mobile phone	30 min	15.9 ± 2.3	Blood pressure, heart rate, breathing frequency, skin conductivity	21	Decrease skin conductivity in men
Pain animal						
Takahashi *et al.* (2010)[55]	2.14 GHz UMTS	20 h/d SAR=29-67 or 68-146 mW/kg	Before to 21 d after birth	Pain perception	24 / group 3 exp.	No effect
Mathur (2008)[95]	73.5 MHz, 16 Hz modulation	2 h/d, 45 d SAR=0.4 W/kg	28 d	Reaction to pain stimuli	4 / group	Increase in initial reaction to pain stimulus, decrease in later reactions
Population studies						
Söderqvist *et al.* (2007)[11]	Mobile or wireless phone	Self reported possession and use	7-14 yr	Possession and use of phones in Sweden	1423	79.1% uses mobile phone, 26.7% calls > 2 min/d. 83.8% uses wireless phone; 38.5% calls > 5 min/d. Girls: higher use then boys.

Mezei *et al.* (2007)[12]	Mobile phone	Self reported possession and use	9-12 yr	Possession and use of phones in Hungary	1301	76% uses mobile phone; 24% uses daily; 33% multiple uses / wk
Thomas *et al.* (2010)[10]	Mobile / wireless phone	Measured 24 h RF exposure Self reported possession and use	8-12 yr 13-17 yr	RF exposure and social-economic status	8-12 yr: 1498 13-17 yr: 1524	No relation exposure / SES. In both groups possession and use of mobile phone higher with lower SES 8-12 yr: possession and use of DECT phone lower with lower SES; 13-17 yr: no difference
Thomas *et al.* (2010)[98]	Mobile / wireless phone	Measured 24 h RF exposure Self reported possession and use	8-12 yr 13-17 yr	Behaviour problems	8-12 yr: 1498 13-17 yr: 1524	Highest exposure: increase behavioural problems, no relation emotional problems, hyperactivity, problems in peer relations
Heinrich *et al.* (2010)[99]	Mobile / wireless phone	Measured 24 h RF exposure Self reported possession and use	8-12 yr 13-17 yr	Chronic symptoms	8-12 yr: 1498 13-17 yr: 1524	No relation with exposure
Heinrich *et al.* (2010)[175]	Mobile / wireless phone	Measured 24 h RF exposure Self reported possession and use	8-12 yr 13-17 yr	Acute symptoms	8-12 yr: 1498 13-17 yr: 1524	3/120 relations positive – chance?
Inyang *et al.* (2010)[13]	Mobile phone	Self reported	7-14 yr	Possession and use of phones in Australia	317	75% possesses mobile phone; texting more important than calls:1/3 sends >100 texts/d
Dosimetry head						
Gandhi *et al.* (1996)[176]	Monopole antenna 835, 1900 MHz	Emitted power 125, 600 mW	5, 10 yr, linear reduction	Peak-SAR_{1g}	--	Higher peak-SAR in children then adults, especially with 835 MHz
Schönborn *et al.* (1998)[177]	Dipole antenna 900, 1800 MHz	Antenna current 100 mA_{rms}	3, 7 yr anatomically correct, 3, 5, 7 yr linear scaled	Peak-SAR averaged over 1 or 10 cm^3	--	No difference SAR child / adult

Martínez-Búrdalo *et al.* (2004)[178]	Dipole antenna 900, 1800 MHz	Emitted power 0.25 W (900 MHz), 0.125 W (1800 MHz)	2-3, 9-10 yr, linear reduction	Peak-SAR_{1g}, peak-SAR_{10g}	--	Peak-SARs in children lower than in adults, but suggestion higher total-brain SAR in children
Keshvari & Lang (2005)[179]	Dipole antenna 900, 1800, 2450 MHZ	Emitted power 1 W	3, 7 yr anatomically correct	Peak-SAR_{1g}, peak-SAR_{10g}	--	Inter-model differences more important than between children and adults; large influence pinna
Bit-Babik *et al.* (2005)[117]	Mobile phone 835, 900 MHz	Emitted power 250 mW	5, 10 yr, linear reduction, reduced & transformed	Peak-SAR_{1g}, peak-SAR_{10g}	--	No difference SAR child / adult
de Salles *et al.* (2006)[180]	Patch and monopole antenna 850, 1850 MHz	Emitted power 600 mW (850 MHz), 125 mW (1850 MHz)	10 yr	Peak-SAR_{1g}	--	SAR child up to 60% higher than in adult
Joó *et al.* (2006)[123]	Mobile phone 900, 1800, 2100 MHz	Emitted power 0.25 W (900 MHz), 0.125 W (1800, 2100 MHz)	2-3, 9-10 yr, linear reduction	Peak-SAR_{1g}, peak-SAR_{10g}	--	Presence metal implant: peak-SAR in child up to 100% higher than in adult; exposure limits may be exceeded
Wiart *et al.* (2008)[103]	Mobile phone, dipole antenna 900, 800 MHz	Normalised to peak-SAR_{10g}= 1 W/kg	5, 6, 8, 9, 12, 15 yr, anatomically correct	Peak-SAR_{1g}, peak-SAR_{10g}	--	5-8 jaar : peak-SAR_{1g} 2x that in adults
Christ *et al.* (2010)[121]	Mobile phones (2 types) 1800 MHz	Emitted power 1 W	6, 11 yr, anatomically correct	Peak-SAR_{10g}, effect pinna	--	~50% higher SAR_{10g} with compressed pinna
Christ *et al.* (2010)[118]	Mobile phones (3 types) 900, 1800 MHz	Normalised to peak-SAR_{10g} in SAM phantom	3, 6, 7, 11 yr, anatomically correct	Peak-SAR_{10g}	--	In some brain parts peak-SAR_{10g} in children higher than in adults; no difference total-brain SAR
Dosimetry body						
Dimbylow (1997)[104]	Plain wave, 10 MHz-1 GHz	1 V/m_{rms}	1, 5, 10 yr, linear transformation	Total-body SAR	--	Above 0.8 GHz exposure to ICNIRP reference level: exceeding basic restriction

Dimbylow (2002)[115]	Plain wave, 10 MHz-3 GHz	1 V/m_{rms}	1, 5, 10 yr, linear transformation	Total-body SAR	--	Above 0.8 GHz exposure to ICNIRP reference level: exceeding basic restriction
Wang *et al.* (2006)[124]	Plain wave, 30 MHz-3 GHz	ICNIRP reference level	7 yr, reduced, transformed	Total-body SAR	--	At resonance freq and around 2 GHz exposure to ICNIRP reference level: ~30% exceeding basic restriction
Dimbylow and Bolch (2007)[106]	Plain wave, 50 MHz-4 GHz	1 V/m_{rms}	9 mo, 4, 8, 9, 11 yr, anatomically correct	Total-body SAR	--	Above 1 GHz exposure to ICNIRP reference level: exceeding basic restriction in 9 mo, 4 yr models
Nagaoka *et al.* (2008)[102]	Plain wave, 30 MHz-3 GHz	Incident power 1 W/m^2	3, 5, 7 yr, reduced, transformed & linear scaling	Total-body SAR, peak-SAR	--	No difference total-body SAR, difference for peak-SAR. Around 2 GHz exposure to ICNIRP reference level: exceeding basic restriction
Conil *et al.* (2008)[107]	Plain wave, 20 MHz-2,4 GHz	Incident power 1 W/m^2	5, 6, 12 yr, scaled, transformed	Total-body SAR	--	Total-body SAR in children up to 48% higher than in adults; at resonance freq and around 2 GHz exposure to ICNIRP reference level exceeding basic restriction
Kühn *et al.* (2009)[119]	Plain wave, 50 MHz-2.45 GHz	ICNIRP reference level; 6 directions, 2 polarizations	6, 11 yr, anatomically correct	Total-body SAR, peak-SAR_{10g}	--	Max SAR 6 yr 2-3x higher than in largest adult. Max total-body SAR in 6 yr at 100 MHz and >1450 MHz higher than ICNIRP limit. Direction of exposure and polarizations: >450 MHz factor 5 variation in peak SAR + factor 3 variation between models

Findlay *et al.* (2009)[113]	Plain wave, 10 MHz – 3 GHz	1 V/m_{rms}	7 yr, linear scaling and anatomically correct	Total-body SAR; different postures	--	Standing: max Total-body SAR up to 25% higher with arms raised; sitting: up to 40% lower; exposure to ICNIRP reference levels: exceeding basic restrictions around 100 MHz and >2 GHz
Nagaoka *et al.* (2009)[181]	Plain wave, 30 – 300 MHz	Incident power 10 W/m^2	3-4 yr, anatomically correct, based on surface scan (homogeneous model)	Total-body SAR	--	SAR in homogeneous model at resonance freq ~14% higher than in heterogeneous model; variation in 30 homogeneous models at resonance freq lower (6,5%) than at other freqs (~13%)
Hirata *et al.* (2009)[182]	Plain wave, 1-6 GHz	Incident power 10 W/m^2	3, 5, 7 yr, anatomically correct; 9 mo linear scaling of 3-yr	Total-body SAR	--	>2 GHz total-body SAR higher with horizontal compared to vertical polarization
Bakker *et al.* (2010)[122]	Plain wave, 10 MHz – 5,6 GHz	ICNIRP reference levels	5, 6, 8, 11, 14 yr, anatomically correct	Total-body SAR, peak-SAR_{10g}	--	Around 2 GHz exposure to ICNIRP reference level up to 45% exceeding basic restriction
Findlay & Dimbylow (2010)[128]	Plain wave and antenna, 2,4 and 5 GHz (WiFi)	1 V/m	10 yr, linear scaling	Total-body SAR, peak-SAR_{10g}	--	In realistic conditions SAR far below ICNIRP limit

Annex **F**

ICNIRP and IEEE limits for the general population

F.1 Basic restrictions 100 kHz – 300 GHz

Table F1

Frequency band	ICNIRP					IEEE				
	Average whole-body SAR (W/kg)	Local SAR (head and torso) (W/kg)	Local SAR (limbs) (W/kg)	Power density, S (W/m^2)	Averaging time (min)	Average whole-body SAR (W/kg)	Local SAR (W/kg)	Local SAR (limbs and pinna) (W/kg)	Power density, S (W/m^2)	Averaging time (min)
100 kHz-10 GHz	0.08	2	4			0.08	2	4		
10-30 GHz				10	68/f$^{1.05}$				10	150/f
30-100 GHz				10	68/f$^{1.05}$				10	25,24/ f$^{0.476}$
100-300 GHz				10	68/f$^{1.05}$				(90×f-7000)/200	5048/ [(9×f-700)× f$^{0.476}$]
	ICNIRP: - SAR averaged over 6 min - local SAR averaged over 10 g of contiguous tissue - S averaged over 20 cm^2 - f as indicated in the column Frequency band					IEEE: - SAR averaged over 6 min - local SAR averaged over 10 g of tissue in the form of a cube - limbs are arms from the elbow and legs from the knee - f as indicated in the column Frequency band				

F.2 Reference levels for electrical field and power density

Table F2

Frequency band	ICNIRP			IEEE		
	Electrical field strength, E (V/m)	Equivalent power density, S_{eq} (W/m^2)	Averaging time (min)	Electrical field strength, E (V/m)	Power density, S (W/m^2)	Averaging time (min)
0.1-1 MHz	87		6	614	$1000/f^2$	6
1-1.34 MHz	$87/f^{0.5}$		6	614	$1000/f^2$	6
1.34-3 MHz	$87/f^{0.5}$		6	823.8/f	$1800/f^2$	$f^2/0.3$
3-10 MHz	$87/f^{0.5}$		6	823.8/f	$1800/f^2$	30
10-30 MHz	28	2	6	823.8/f	$1800/f^2$	30
30-100 MHz	28	2	6	27.5	$2/f^{3.336}$	30
100-400 MHz	28	2	6	27.5	2	30
400-2000 MHz	$1.375\times f^{0.5}$	f/200	6		f/200	30
2-5 GHz	61	10	6		10	30
5-10 GHz	61	10	6		10	150/f
10-30 GHz	61	10	$68/f^{1.05}$		10	150/f
30-100 GHz	61	10	$68/f^{1.05}$		10	$25,24/ f^{0.476}$
100-300 GHz	61	10	$68/f^{1.05}$		(90×f-7000)/200	$5048/ [(9\times f-700)\times f^{0.476}]$
	- f as indicated in the column Frequency band - Averaging time for E^2					

F.3 Proposed changes to electrical field reference levels

As the reference levels as provided by ICNIRP[17] and the Health Council[130] for the frequency band around 2 GHz correspond to values higher than the basic restrictions for smaller individuals, the reference levels must be adjusted downwards. The proposal is for the values indicated in Table F3 to be used for frequencies from 400 MHz. These values lie below the calculated values for smaller individuals (see Figure F1).

Table F3 Reference levels for electrical field strength: values proposed by the Health Council in 1997 and new proposals.

Frequency	Health Council 1997[129]	Health Council New
10 – 400 MHz	28	28
400 MHz – 2 GHz	$53\times f^{0.72}$ (f in GHz)	28
2-4 GHz	87	28
4-10 GHz	87	$10.53\times f^{0.705}$ (f in GHz)
10-20 GHz	$78\times f^{0.16}$ (f in GHz)	$10.53\times f^{0.705}$ (f in GHz)
20-300 GHz	$78\times f^{0.16}$ (f in GHz)	$35.85\times f^{0.296}$ (f in GHz)

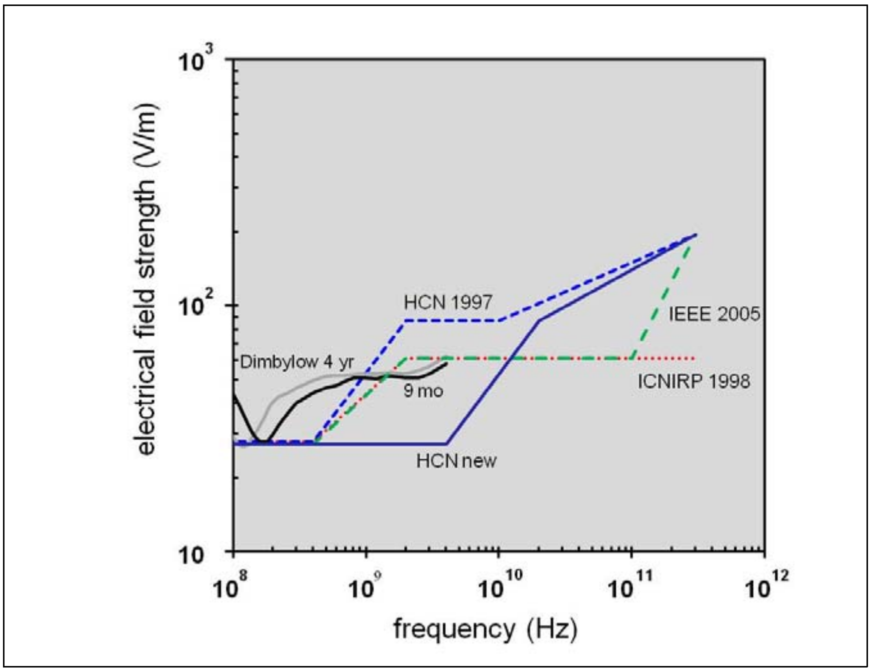

Figure F1 Exposure limits proposed by the Health Council[130], ICNIRP[17] and IEEE[18], and calculations by Dimbylow of electrical field strength for exposure of children to the maximum SAR of 0.08 W/kg.[106]