Seminar

Physics and biology of mobile telephony

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Although safety guidelines—to which mobile telephones and their base-stations conform—do protect against excessive microwave heating, there is evidence that the low intensity, pulsed radiation currently used can exert subtle non-thermal influences. If these influences entail adverse health consequences, current guidelines would be inadequate. This review will focus on this possibility. The radiation used is indeed of very low intensity, but an oscillatory similitude between this pulsed microwave radiation and certain electrochemical activities of the living human being should prompt concern. However, being so inherently dependent on aliveness, non-thermal effects cannot be expected to be as robust as thermal ones, as is indeed found; nor can everyone be expected to be affected in the same way by exposure to the same radiation. Notwithstanding uncertainty about whether the non-thermal influences reported do adversely affect health, there are consistencies between some of these effects and the neurological problems reported by some mobile-telephone users and people exposed longterm to base-station radiation. These should be pointers for future research.

Public concern over possible adverse health impacts from exposure to the radiation used in GSM (Global System for Mobile communication) mobile telephony shows little sign of abating, despite assurances from the industry and official bodies such as the UK National Radiological Protection Board (NRPB) that all is well. In March, 1999, the UK Government set up the Independent Expert Group on Mobile Phones, under the chairmanship of Sir William Stewart. The Stewart Report,[1] published in May, 2000, makes some sensible recommendations, but unfortunately some of its greyer areas are now being exploited by the industry to obfuscate the issue. As yet unresolved is the question of adverse health impacts provoked by the contentious non-thermal effects of the low intensity, pulsed microwave radiation (MWR) used. For these effects are not taken into account in current safety guidelines,[2] which simply restrict the intensity of the radiation to prevent tissue heating in excess of what the body's thermoregulatory mechanism can cope with. Whilst these guidelines, which are the result of careful investigation over many years, are clearly necessary, the question remains as to whether they are comprehensive enough. For in the case of living systems (and only living ones) there are many reports over the past 30 years that MWR can exert non-thermal influences, at intensities well below those necessary to cause any detectable heating.[3]

The purpose of this review is to introduce clinicians to the physics of mobile telephony and to explain how low-intensity, pulsed microwaves can affect living organisms, both thermally and non-thermally; and then to identify some of the reported biological impacts of exposure to this radiation, particularly those provoked by the contentious non-thermal effects. It is thereby hoped to alert clinicians to the possibility that certain presenting symptoms might well be a consequence of non-thermal exposure to this kind of radiation. A companion *Lancet* review[4] covers the epidemiological evidence for effects of mobile telephony on human health.

Lancet 2000; **356:** 1833–36

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Physics of mobile telephony

Mobile (cellular) telephony is based on two-way radio communication between a portable handset and the nearest base-station. Every base-station serves a cell, varying from hundreds of metres in extent in densely populated areas to kilometres in rural areas, and is connected both to the conventional land-line telephone network and, by tightly focused line-of-sight microwave links, to neighbouring stations. As the user of a mobile phone moves from cell to cell, the call is transferred between base-stations without interruption.

The radio communication utilises microwaves at 900 or 1800 MHz to carry voice information via small modulations of the wave's frequency. A base-station antenna typically radiates 60 W and a handset between 1 and 2 W (peak). The antenna of a handset radiates equally in all directions but a base-station produces a beam that is much more directional. In addition, the stations have subsidiary beams called side-lobes, into which a small fraction of the emitted power is channelled. Unlike the mean beam, these side-lobes are localised in the immediate vicinity of the mast, and, despite their low power, the power density can be comparable with that of the main beam much further away from the mast. At 150–200 m, for example, the power density in the main beam near ground level is typically tenths of a μW/cm^2.

A handset that is in operation also has a low-frequency magnetic field associated, not with the emitted microwaves, but with surges of electric current from the battery that are necessary to implement "time division multiple access" (TDMA), the system currently used to increase the number of people who can simultaneously communicate with a base-station. Every communication channel has eight time slots (thus the average power of a handset is ⅛ of the peak values cited above—ie, is between 0·125 W and 0·25 W), which are transmitted as 576 μs bursts. Together, the eight slots define a frame, the repetition rate of which is 217 Hz. The frames transmitted by both handsets and base-stations are grouped into "multi-frames" of 25 by the absence of every 26th frame. This results in an additional low-frequency pulsing of the signal at 8·34 Hz, which, unlike that at 217 Hz, is unaffected by call density, and is thus a permanent feature of the emission. With handsets that have an energy-saving discontinuous transmission mode (DTX), there is an even lower frequency pulsing at 2 Hz, which occurs when the user is listening but not speaking.

Biological impacts: thermal

Heating of biological tissue is a consequence of microwave energy absorption by the tissue's water content. The amount of heating produced in a living organism depends primarily on the intensity (or power density) of the radiation once it has penetrated the system, on certain electrical properties of the biomatter, and on the efficiency of the body's thermoregulation mechanism. Above a certain intensity of the microwaves, temperature homoeostasis is not maintained, and effects on health ensue once the temperature rise exceeds about 1°C. Safety guidelines impose upper limits on the radiation intensity to ensure that this does not happen. Heating occurs whether the organism is alive or dead. The frequency of the radiation, as opposed to the intensity, is taken into account only in so far as it affects (via size resonance) the ability of the organism to absorb energy from the irradiating field.

Amongst the most thermally vulnerable areas of the body,[2] because of their low blood supply, are the eyes and the testes, and cataract formation and reduced sperm counts are well-documented acute exposure hazards. Animal studies indicate that a variety of behavioural and physiological disorders can be provoked by temperature rises below 1°C—ie, under much less acute exposure conditions.

There have been many investigations to estimate, using phantom heads,[5] the rate at which thermal energy is deposited in the head during use of a mobile phone—the so-called absorption rate. These studies indicate that, for most handsets, safety guidelines are not violated. In publicly accessible areas near a base-station, thermal influences of the emitted MWR can be totally discounted; the microwave intensity is far too low. Nevertheless, in both cases there are reports of adverse health effects of subthermal intensities, the possible origin of which will now be considered.

Biological effects: non-thermal

The possibility that the pulsed, low-intensity MWR currently used in GSM mobile telephony can exert subtle, non-thermal influences on a living organism arises because microwaves are waves; they have properties other than the intensity that is regulated by safety guidelines. This microwave radiation has certain well-defined frequencies, which facilitate its discernment by a living organism (despite its ultralow intensity), and via which the organism can, in turn, be affected. The human body is an electrochemical instrument of exquisite sensitivity whose orderly functioning and control are underpinned[6] by oscillatory electrical processes of various kinds, each characterised by a specific frequency, some of which happen to be close to those used in GSM. Thus some endogenous biological electrical activities can be interfered with via oscillatory aspects of the incoming radiation, in much the same way as can the reception on a radio.

The biological electrical activities that are vulnerable to interference from GSM radiation include highly organised electrical activities at a cellular level whose frequency happens to lie in the microwave region, and which are a consequence of metabolism.[7] Although not universally accepted, there is experimental evidence[7–9] consistent with these endogenous activities, in terms of which effects of ultralow-intensity microwave radiation of a specific frequency on processes as fundamental as cell division, for example, can be understood in a rather natural way.[10] Furthermore, the DTX pulse frequency at 2 Hz and the TDMA frequency of 8·34 Hz correspond to frequencies of electrical oscillations found in the human brain, specifically the delta and alpha brain-waves, respectively. It is thus quite possible that living organisms have a two-fold sensitivity to the pulsed GSM signal—ie, to both the microwave carrier and the lower frequency pulsings of the TDMA and DTX signals. To deny this possibility yet admit the importance of ensuring electromagnetic compatibility with electronic instruments by banning the use of mobile phones on aircraft[11] and hospitals (a prohibition driven by concerns about non-thermal interference) seems inconsistent.

Thus, in contrast to heating, which relies on an organism's ability to absorb energy from the irradiating field, the possibility of non-thermal effects arises from an "oscillatory similitude" between the radiation and the living organism, which makes it possible for the living organism to respond to low-intensity, pulsed MWR via its ability to recognise certain frequency characteristics of that radiation. The intensity of radiation needed for this recognition is many orders of magnitude below even that currently associated with non-thermal effects. This influence is possible only when the organism is alive, with excited endogenous frequencies; the dead have flat electroencephalograms. Non-thermal effects thus depend on the state of the person when exposed to the radiation—ie, non-thermal effects are non-linear. A low-intensity field can entail a seemingly disproportionately large response (or none at all), and vice versa, quite unlike the predictable thermal responses. Thus not everyone can be expected to be affected in the same way by identical exposure to the same radiation.

A good example of human vulnerability to a non-thermal, electromagnetic influence is the ability of a light flashing at about 15 Hz to induce seizures in people with photosensitive epilepsy.[12] It is not so much the amount of energy absorbed from the light that provokes the seizure, but rather the information transmitted to the brain by the (coherent) regularity of its flashing, at a frequency that the brain "recognises" because it matches or is close to a frequency utilised by the brain itself.

Panel 1: **Selected in vitro studies of non-thermal effects of microwave radiation of various frequencies and intensities**

Effect	Ref
Epileptic activity in rat brain slices in conjunction with certain drugs	13
Resonant effects on cell division of *Saccharomyces cerevisiae,* and on the genome conformation of *Escherichia coli*	9, 14
Synchronisation of cell division in *S carlsbergenis*	15
"Switch-on" of epigenetic processes, such as λ-phage and colicin synthesis	16, 17
Altered ornithine decarboxylase activity	18
Reduced lymphocyte cytotoxicity	19
Increased permeability of erythrocyte membrane	20
Effects on brain electrochemistry (calcium efflux)	21
Increase in chromosome aberrations and micronuclei in human blood lymphocytes	22
Synergism with cancer-promoting drugs such as phorbol ester	23

Panel 2: Selected in vivo studies of non-thermal microwave exposure, including GSM radiation

Effect	Ref
Epileptiform activity in rats, in conjunction with certain drugs	24
Depression of chicken immune systems (melatonin, corticosterone and IgG levels)	25
Increase in chick embryo mortality	25
Increased permeability of blood-brain barrier in rats	26
Effects on brain electrochemistry (dopamine, opiates)	27
Increases in DNA single and double strand breaks in rat brain	28
Promotion of lymphomas in transgenic mice	29
Synergistic effects with certain psychoactive drugs	30

What do we know experimentally about non-thermal biological influences of MWR (both pulsed and continuous) of an intensity close to that near a mobile phone handset, but often at higher microwave carrier frequencies? A selection of in vitro studies is given in panel 1.

In vivo evidence of non-thermal influences, including exposure to actual GSM radiation, comes predominantly from animal studies (panel 2). Finally, human in vivo studies, under GSM or similar conditions, include effects on the EEG and on blood pressure. A delayed increase in spectral power density (particularly in the alpha band) has been corroborated[31] in the "awake" EEG of adults exposed to GSM radiation. Influences on the "alseep" EEG include a shortening of rapid-eye-movement (REM) sleep during which the power density in the alpha band increases,[32] and effects on non-REM sleep.[33] Exposure to mobile phone radiation also decreases the preparatory slow potentials in certain regions of the brain[34] and affects memory tasks.[35] In 1998, Braune et al[36] recorded increases in resting blood pressure during exposure to radiofrequencies.

Although the power density of the radiation used in these experiments is typical of that found at the head when a mobile handset is used, and thus much higher than that close to a base-station, the information content of the radiation emitted by base-stations is the same. Accordingly—apart from near/far field differences (ie, localised exposure to the near field during handset use and whole body exposure to the far field from a base-station)—these results are not irrelevant to any consideration of potential adverse health effects associated with chronic exposure to base-station radiation.

Non-thermal effects have proved controversial, and independent attempts to replicate them have not always been successful. Such difficulties are not unexpected, however, because these effects depend on the state of the organism when it is exposed, particularly in vivo. In in vitro studies, discrepant findings can sometimes be traced to differences in the conditions or design of the experiment. Examples of this are the unsuccessful attempts to replicate an earlier yeast-growth experiment,[37,9] and the reported increased incidence of DNA strand breaks.[38,28] The highly non-linear nature of living systems makes them hypersensitive (via deterministic chaos,[39] as exemplified by the so-called "butterfly effect", for example) to the prevailing conditions, and thus militates against the realisation of the identical conditions necessary for exact replication.

Possible associated adverse health reactions

It is important to stress that the existence even of established non-thermal effects does not make adverse health consequences inevitable. Nonetheless GSM radiation does seem to affect non-thermally a variety of brain functions (including the neuroendocrine system), and health problems reported anecdotally do tend to be neurological, although formal confirmation of such reports, based on epidemiological studies, is still lacking. For example, reports of headache are consistent with the effect of the radiation on the dopamine-opiate system of the brain[27] and the permeability of the blood-brain barrier,[26] both of which have been connected to headache.[40,41] Reports of sleep disruption are consistent with effects of the radiation on melatonin levels[25] and on rapid-eye-movement sleep.[32] Furthermore, since there is no reason to suppose that the seizure-inducing ability[12] of a flashing visible light does not extend to microwave radiation (which can access the brain through the skull) flashing at a similarly low frequency, together with the fact that exposure to pulsed MWR can induce epileptic activity in rats,[24] reports of epileptic activity in some children exposed to base-station radiation are perhaps not surprising. I have heard of one child whose seizures diminish when, unbeknown to her or her family, the mast is not functioning (or when she is away), only to increase again when the base-station is working again or when she returns home.

Finally, the significant increase (by a factor of between 2 and 3) in the incidence of neuroepithelial tumours (the laterality of which correlates with cell-phone use) found in a nationwide US study[42] is consistent not only with the genotoxicity of GSM radiation, as indicated by increased DNA strand breaks[28] and formation of chromosome aberrations and micronuclei but also with its promotional effect on tumour development.[43] However, as Rothman's accompanying review shows,[4] the overall epidemiological evidence for an association with cell-phone use is rather weak. Nevertheless, it cannot be denied that non-thermal effects of the MWR used in mobile telephony do have the potential to induce adverse health reactions of the kind reported, and this possibility should not be ignored even if only a small minority of people are at risk. Whether a person is affected or not could depend, for example, on the level of stress before exposure; if it is high enough, the additional contribution from MWR exposure might be sufficient to trigger an abnormality that would otherwise have remained latent. It is often argued that anecdotal reports of health problems should be dismissed. However, given the paucity of systematic epidemiological studies of this new technology, such reports are an indispensable source of information, a point acknowledged in the 1999 report of the UK parliamentary committee.[44]

Preadolescent children can be expected to be more vulnerable to any adverse health effects than adults because absorption of GSM microwaves is greatest[5] in an object about the size of a child's head, because of the "head resonance" effect and the greater ease with which the radiation can penetrate the thinner skull of an infant[1]. Also the multiframe repetition frequency of 8·34 Hz and the 2 Hz pulsing in the DTX mode of cellphones lie in the range of the alpha and delta brain-waves, respectively. In a child, alpha waves do not replace delta waves as a stable activity until the age of about 12 years. Furthermore, the immune system, whose efficacy is degraded[19,25] by this kind of radiation, is less robust in children. This makes them less able to cope with any adverse health effect that might be provoked by chronic exposure, not only to the pulsed microwave radiation but also to the the more penetrating low-frequency magnetic fields associated with the current surges from the handset battery which can reach 40 μT (peak) near the back of the case.[45] Indications of the biological noxiousness of these magnetic fields (in animals) can be found in ref 25.

In the context of base-station radiation, reports relating to animals are of particular value since it cannot here be claimed that the effects are psychosomatic. Of particular interest is a publication on cattle,[43] recording severely reduced milk yields, emaciation, spontaneous abortions, and stillbirths. When cattle are removed to pastures well away from the mast, their condition improves, but it deteriorates once they are brought back. The adverse effects appeared only after GSM microwave antennae were installed on a tower formerly used to transmit only non-pulsed television and radio signals.

Finally, in support of the reality of an adverse health impact of non-thermal influences of the kind of radiation used today in mobile telephony, we should recall that during the "cold war" the Soviet irradiation of western embassies with microwave radiation (of an intensity intermediate between that in the vicinity of a handset and a base-station), done with the express intention of inducing adverse health effects, was quite successful.[47]

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