# German Mobile Telecommunication Research Programme

**International Workshop on Final Results of Dosimetry Projects**
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**Federal Office for Radiation Protection (BfS)**
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**Rapporteur's Report**
**Simon Mann**

## Welcome and introduction

Dr Wolfgang Weiss, Head of Radiation Protection and Health at the Federal Office for Radiation Protection (BfS), welcomed the 41 attendees to the meeting and extended a special welcome to the present and previous chairs of ICNIRP. Apologies had been received from the WHO representative who was unable to attend. Dr Weiss explained that a Rapporteur, Dr Simon Mann of the UK's Health Protection Agency, had been appointed for the meeting and that his main objective would be to summarise outcomes from the projects and discussions. There were no objections to the meeting being audio taped in order to assist preparation of the report.

Dr Axel Böttger of the Ministry for the Environment, Nature Conservation and Nuclear Safety then summarised the history of the German Mobile Telecommunication Research Programme. He explained that Germany had had a commission, rather like the Stewart Group in the UK, which had evaluated the science and identified gaps in knowledge to be filled by further research. In December 2001 the cellular network operators had committed 8.5 million Euro to a research programme and Government had added a further 2.5 million Euro. BfS had formulated a programme on behalf of the Environment Department and around 50 projects had been supported.

Dr Weiss explained that BfS had a list of specific tasks that it wanted contractors to undertake, including microdosimetry, development of assessment methods involving measurement and modelling, and developing personal dosimeters and techniques for epidemiology. Multidisciplinary teams had been assembled in order to ensure collaboration between physicists and biologists. Dr Weiss put four questions to the attendees and said that he would like the workshop to consider them in its presentations, discussions and future reports.

- What has been achieved by the projects?
- What lessons have been learned?
- Where do we still have gaps in knowledge?
- Can minimum standards be defined for future work?

## Session 1
## Numerical Models and Computations

Blanka Pophof of BfS chaired this session during which there were three presentations followed by a panel discussion.

### *1.1) SAR distribution in human beings when using body-worn RF transmitters*
### *Andreas Christ, IT'IS Foundation*

The project carried out theoretical investigations relevant to the development of standards for SAR compliance testing of radio transmitters used near the body. It began by examining the interaction of plane waves with simple layered models of the body surface with various thicknesses of skin and fat above a muscle termination. The strongest coupling conditions at 900 MHz were with a skin layer of 2.6 mm and a fat layer of 24 mm and these gave an enhancement of over 3 dB in 1 g cubical volume averaged SAR with respect to a layer of muscle tissue alone. The enhancement was due to standing waves being formed in the skin/fat layers.

The analysis was then extended to include reactive fields and the near fields from dipole antennas in simple layered models. It was found that 1 g cubical averaged SARs could exceed those in a single layer of muscle by up to 5 dB. The enhanced coupling was again due to standing waves in the skin/fat layers but another enhancing effect was also found. High impedance fields, such as produced by short dipoles and by resonant dipoles at 450 MHz and below, were able to couple more strongly than plane waves into the low permittivity fat tissue.

Next, the enhanced coupling effects were investigated with models of generic radio transmitters designed to represent a walkie-talkie at 450 MHz, mobile phones at 900, 1800 and 1950 MHz, and a laptop computer with a WLAN card at 2450 MHz. The generic transmitters were coupled to the regions of male and female anatomically realistic whole-body models where the skin and fat thicknesses were most similar to the maximal coupling values deduced in the earlier investigations, as defined in the project specification. (The positions of the transmitters have been chosen according to the project specification.) The male model (the visible human) was developed from cryosection images (age 38, height 1.8 m, mass 90 kg, 112 tissues) and the female model was developed from MR images (age 22, height 1.6 m, mass 53 kg, 51 tissues, 2 $mm^3$ resolution). Homogeneous body-shaped phantoms were found to produce conservative assessments with respect to anatomically realistic phantoms in the near field for frequencies of 450 MHz and above. In the far field, standing wave effects occurred which were not reproduced by homogeneous phantoms.

The final stage of the project extended the calculations with simple layered structures and anatomically realistic body models to include thermal calculations with freely convecting and insulating boundary conditions. The output power of the generic transmitter placed near the body was adjusted to give a 10 g averaged SAR equal to the ICNIRP basic restriction of 2 W $kg^{-1}$. The greatest temperature rises were found near the surface of the body rather than in the internal organs and these were up to 0.23°C with free convection and 0.31°C without convection.

*Discussion*

A question was asked regarding the excitation of the dipole antennas and generic transmitters modelled. It was explained that the input power had been fixed, rather than current or radiated power.

The values of SAR quoted for the generic laptop were queried, as they seemed surprisingly high; up to 9.9 W $kg^{-1}$ averaged over 10 g with a laptop WLAN antenna above the thigh. Dr Christ said he would check the values against the written report. It was also asked whether the whole-body and laptop had been modelled, as it would have been difficult to achieve this while retaining sufficient resolution. Dr Christ said that he had cut off the head and other parts of the body with relatively low exposure in order to reduce the model to around 100 million computational cells, which would run in around 8 hours.

There was some discussion of the thermal model and whether vasculature had been included, since this, as well as diffusion and convection processes, would be expected to have an appreciable effect on local temperature. Dr Christ said the model did not include vasculature and had used the Pennes bioheat equation.

Dr Christ was asked to comment on the relative merits of specifying contiguous or cubical tissue regions for the averaging masses in standards, as this had been touched upon in the presentation. It was felt to be a complicated topic that could not be easily answered. He said the main issue arising from his research was the absence of a fat layer in homogeneous models, although he did not think there was a problem with the present mobile phone SAR testing standards.

### *1.2) SAR distribution in human beings exposed to RF radiation with regard to small structures and thermo-physiological parameters*
***Gernot Schmid, ARC Seibersdorf Research***

The project developed computational models of the inner ear, eye and pineal gland at 0.1 $mm^3$ resolution. It then implanted the models into a coarser resolution model of the complete head in order to evaluate the spatial distributions of SAR and temperature rise when a radio handset was held to the side of the head. Tissue dielectric and thermal parameters were measured, where they were not available in the literature, e.g. for the fluids in the inner ear. Generic handsets using a helical antenna at 400 MHz and monopole antennas at 900 and 1850 MHz were located in the "tilt" position.

SAR was found to vary at the anatomical resolution, and thus have steep spatial gradients, e.g. where there are alternating layers of bone and fluid in the helical structure of the cochlea. However, temperature rise did not reflect the gradients in SAR, and no “hot spots” were found at comparable resolutions because of efficient thermal diffusion within the tissues. Averaging over a 10 g mass was considered sufficient to protect against RF-induced temperature elevations in tissue.

The project considered a single high power pulse of 400 MHz RF exposure with durations from 10 to 180 seconds within a 6 minute period such that the time-averaged SAR was always 2 W $kg^{-1}$. Peak temperature rises were greater than with continuous exposure and increased with shortening pulse duration. With exposure to the side of the head, temperature rises of up to around 1°C could be produced in the pinna and other superficial tissues. The differences between pulsed and continuous exposures were more pronounced for the deeper tissues, although these were heated to a lesser extent than the surface tissues.

The heating effect of typical TDMA telecommunications signals would be indistinguishable from that of CW signals at the same average power level because the time constants of the signal envelope are much shorter than the thermal time constants associated with tissue. Maximum RF-induced temperature rises from GSM and UMTS terminals were expected to be around 0.1°C in the brain and up to around 0.5°C in superficial tissues (skin, fat, muscle). With a 1 W, 400 MHz handset held vertically in front of the eye and not tilted back at 45 degrees, as it would be a more normal usage position, maximum temperature rises in the eye can be approximately 0.5–1°C.

A simple computational model of the surface of the head had also been produced during the project involving planar layers of epidermis, dermis, subcutis, bone, CSF, grey matter and white matter with appropriate electrical and thermal properties. A generic handset model was placed in contact with the epidermis in order to examine the temperature distribution produced not only due to RF emissions from the handset but also due to thermal conduction from its internally heated body shell. The temperature in the model was determined at depths of 200 µm and 1 mm below the surface at various positions and the gradient between the two depths was determined, as this is understood to be the way the body senses temperature. The results were in line with experimental data from Straume *et al* 2005 and showed that perception of temperature rise when a phone is held to the head is due to conductive heat transfer and insulation of the head surface, rather than absorption of RF.

*Discussion*

Reference was made to a paper published by Hirata *et al* in Bioelectromagnetics in May 2006 and it was asked whether blood perfusion in the eye had been set too low in the models, leading to excessive temperature rises being predicted. Dr Schmid said that the models had allowed for perfusion in tissues other than the vitreous humour of the eye and the lens. Caution was urged in interpreting the results as the thermal models did not include blood vessels.

It was asked whether SAR was the right metric for these small tissues and whether temperature rise would be more appropriate. It was also queried how resolving smaller anatomical structures would help to identify consequences with an SAR exposure metric. The study was felt to have practical applications and Dr Schmid was asked to comment further on the use of microdosimetry to interpret biological results. He agreed that the topic could give valuable insights.

There was interest in the suggestion that temperature perception by the body is due to a perceived difference in temperature at two depths and Dr Schmid was asked to comment further on the importance of this gradient. He said that he was not a biologist but he understood thermoregulation is a response to temperature perception in the skin.

### *1.3) SAR distribution in test animals exposed to RF radiation*
### *Niels Kuster, IT’IS Foundation*

The project developed anatomically realistic numerical models of rats and mice at resolutions of 1.2 and 0.5 $mm^3$ respectively. Electromagnetic simulations had then been carried out at 450, 900, 1800 and 5000 MHz to determine the internal SAR distributions for exposures in E-, H- and k-polarisations with respect to the long axis of the animals. The rat was approximately resonant at 900 MHz and so had the greatest relative whole-body SAR at this frequency. Similarly, the (smaller) mouse had highest whole-body SAR at 1800 MHz, where it was approximately resonant. The tails of both animals were the highest SAR regions at 450 MHz. Variations in organ-averaged SARs (blood, brain, kidneys, liver) were examined in relation to the whole-body averaged SAR across the three polarisations. The variations were more pronounced at low frequencies and were greatest for the rat brain, with a range of 14 dB at 450 MHz reducing to 3 dB at 5000 MHz.

Next, a review was performed of six different broad categories of rodent exposure systems, with examples of each analysed in order to draw out their relative strengths and weaknesses. The categories were open-field systems with near- and far-field exposure from antennas, quasi-open waveguides with the animals inside, multimode and monomode resonant systems with animals arranged around an antenna, and statistical multimode resonant systems with animals inside. In general, resonant systems offer the greatest efficiency in terms of SAR produced per unit input power and monomode systems give better field uniformity than multimode systems. All exposure systems have to be validated against measurement and this can be done using water bottles filled with tissue-equivalent material to represent the animals.

In considering the minimal requirements for evaluation of exposure systems, the terms *dosimetry*, *uncertainty* and *variations* were used with respect to SAR. The *dosimetry* is evaluated for an "average" or standard situation in which parameters such as animal weight, size, position and posture are defined. *Uncertainty* is then defined with respect to changes in these parameters and is best evaluated through simulation. *Variations* are then evaluated on an *instant* or *lifetime* basis and include the influences of factors such as movement of the animals, changes in their weight, and interactions as the animals move close to their neighbours. Example results were shown drawn from the dosimetry in the EU FP5 project PERFORM A.

The project concluded that anatomical models with resolution <0.2 $mm^3$ are necessary, and that SAR distribution is strongly dependent on the animal, frequency and polarisation. Whole-body and organ-specific SARs are required for interpretation and comparison of studies, and these parameters, together with spatial peak SAR, should be reported. Only when investigating thermal effects was it felt that whole-body and localised SAR could be regarded as sufficient. A comprehensive uncertainty and variation analysis should also be done.

*Discussion*

One of the exposure systems reviewed was described as a statistical multimode resonance system and more information was requested about this, including the frequency range over which it operated. Dr Kuster explained that these were mode stirred chambers and added that the field variations due to the movement of the stirrer could be used to simulate power variations in mobile communications. Fixed rotation rates were envisaged of around a few seconds for CDMA systems and of around a minute for GSM systems.

A question was asked regarding the biological relevance of polarisation. Dr Kuster was of the opinion that polarisation-dependent effects can only be observed *in vitro*, because cell orientations can be fixed. Cells are arbitrarily oriented *in vivo*, so he didn't think effects would be detectable.

Whether such detailed information on the distribution of internal SAR would be necessary, or even useful, for all experiments was questioned and it was argued that SAR at organ level and for so many different conditions would only be necessary if an effect were found. Dr Kuster said the information would be necessary to interpret and compare different experiments. For example, if a study were to be published in the future reporting effects on the liver, already published studies reporting only values for whole-body SAR would not be useful to assist interpretation.

### ***1.4) Panel Discussion***

Blanka Pophof drew attention to the four previously presented over-arching questions and presented some more detailed questions, particularly with regard to dosimetric models. These were

- Are the models precise enough for SAR assessments, especially of sensitive organs, and do the models need improving, or are they too complicated so simpler ones can be used?
- What are the advantages and disadvantages of developing anatomical models, is there an optimal resolution and what is this?
- What is the optimal averaging volume and should cubic or contiguous averaging be used?
- What is the optimal period of time for temporal averaging?
- How hot and how small are any hot spots?
- Should SAR or thermal considerations determine limits?

There was a discussion on the relative merits of cubical and contiguous averaging volumes, and it was stated that any differences between results with the two shapes would be more marked for 10 g than for 1 g volumes. It was argued that the ICNIRP approach with a contiguous volume is advantageous because the cube is without physical or biological meaning and it was emphasised that contiguous tissue volumes are no more difficult to average over than cubic volumes within anatomical models. A counter-argument was that temperature rise within a thin contiguous region of elevated SAR would be less than that over a cube exposed at the same average SAR level, and hence, a cubical averaging region would be more conservative as a predictor of temperature rise. However, this counter-argument would not necessarily apply at higher frequencies where absorption becomes more superficial, as with WiFi operating above 5 GHz.

With regard to the complexity of the models, it was emphasised that increasing complexity results in increasing costs. However, it was felt better to commission good research that can be fully interpreted than research that may not be interpretable. The complexity requirements had to be defined with regard to the aims of individual projects and the required resolution would depend on the geometry of the item under investigation. Small structures have to be resolved in order to examine changes in them and a resolution of 0.5–1 $mm^3$ was felt to be sufficient for most human situations. For some situations, e.g. where small animals have thin skulls, even 0.5 $mm^3$ may not be sufficient. It was felt that compliance testing is designed to assess maximal exposures and so the models can be simplified, whereas biological experiments need exact values relevant to the tissues of interest and so cannot use very simple models.

An example was raised where considering organ-specific SAR had highlighted difficulties in assessing exposures that were not revealed through consideration of whole-body SAR. Two different rat models had been simulated, one from IT'IS Foundation and the other one from Brooks Air Force Base. For a near-field exposure situation, the whole-body SAR had been virtually the same in the two models, whereas the brain SAR had been rather different. It was suggested that the brain SAR depended strongly on slightly different distances between the antenna and the brain in the two models and it was asked what the situation would have been with the real rats.

Temperature rise was discussed as a possible quantity for restriction in future standards instead of SAR. It was argued that SAR is a theoretical number whereas temperature rise describes what is actually happening in the body and it was questioned whether evaluating SAR at fine resolutions gave useful information in terms of an effect on the body. Others felt that SAR should remain the restricted quantity because it was more readily measurable and uncertainties would be much greater with temperature. It was felt that a much better rationale than is available now would be required in order to change to temperature rise as a restricted quantity. In the case of biological experiments, it was considered helpful for interpretation if both SAR and temperature rise could be quoted.

It was noted that the literature on SAR in humans will soon encompass a virtual family with several models of adult males and females, and of children of various ages. However, no models of obese people, who form a large group of the population, are available and their absorption characteristics will be different to people with body mass indices in the normal range.

## Session 2
## Dosimetry in Biological Studies

Dirk Geschwentner of BfS chaired this session during which there were four presentations followed by a panel discussion.

### *2.1) Exposure setups for in vivo RF experiments using waveguides*
### *Tina Reinhardt, University of Wuppertal*

This project had designed and built exposure systems based on radial waveguides for mice at GSM and UMTS frequencies, which had already been used in published biological studies carried out by the University of Bremen. The systems were in the form of circular waveguides with absorbing material around the perimeter and a vertical central antenna designed to launch an outwardly propagating TEM mode. The rodents were in a ring of cages arranged in front of the absorbing material at a constant distance from the centre, so rotational symmetry was present. Computer modelling had been used to optimise the designs and to evaluate the SAR in animals inside the cages.

The waveguide height would ideally have been no more than half a wavelength in order to restrict propagation to the TEM mode, however this was not always possible due to animal welfare considerations. For example, a cage height of 16 cm was necessary for mice at 2 GHz, which is around a wavelength. In order to accommodate this, the waveguide was tapered from 6 cm height, i.e. less than half a wavelength, at the centre to 17 cm at the cages. Also, with multiple cages inside the radial waveguide, the scattered field from the animals in one cage could have had a significant influence on the exposure of animals in the adjacent cage. Hence, it was necessary to devise a technique to decouple adjacent sectors and to suppress higher order modes.

One method found useful for heights between $\lambda/2$ and $\lambda$ involved constructing metal bars attached to the upper and lower plates of the waveguide extending radially outwards between the cages. Another method, found useful even for heights greater than $\lambda$, was to construct metal walls between the cage sectors lined with dielectric-filled slots of appropriate depth to present an impedance at the surface of the corrugated walls that tended to infinity at the operating frequency. Both of these methods were designed and optimised using computer modelling.

Various scenarios of different animal locations and attitudes inside the cages were simulated using anatomically realistic numerical phantoms in order to predict SAR distributions and whole-body SAR. These scenarios involved various numbers of adult animals, scaled appropriately to represent animals of different ages, as present in the corresponding biological experiments. Considerable variations in SAR were found, and the results for the ranges of conditions were averaged in order to define mean and standard deviations of SAR. This allowed the input power to the waveguide to be predicted in order to attain a target mean SAR.

*Discussion*

An important topic during discussions was the question of how to define a sufficient number of fixed scenarios of animal locations and attitudes for simulation, and then how to weight the results of the scenarios in order to arrive at a statistical representation for the SAR of animals during an experiment. It was suggested that a statistical motion study of animals in cages would be useful in this context. Important factors might be how long the animals spend closely together in a group and how often an animal leaves such a group.

It was asked whether all of the adult animals in a group were the same weight in the simulations. Ms Reinhardt explained that they were the same weight and thereby a good approximation to the experiment. Variable weights were considered as part of the uncertainty analysis for the experiments.

Another question was whether animals that were close to each other in the simulations were actually touching each other so they would be in direct contact. Ms Reinhardt said the animals were mostly separated from each other in the simulations. In some calculations however, the animals were touching each other. She accepted that the whole-body SAR would be slightly different with a merging contact, which could mean a deformation of the animal bodies, and felt that simulations of such scenarios could be done if suitable animal models could be provided.

### 2.2) *Exposure Setup for Animal Experiments using a Parabolic Reflector*
### *Simon Schelkshorn, University of Munich*

This project had developed exposure systems for rats using low cost 3.2 m parabolic reflectors fed by horn antennas in order to produce plane waves inside screened chambers. The plane wave area was large enough for seven rows of eight cages to be placed one above another in front of the antenna and thus over 100 animals could be exposed simultaneously. Three complete exposure systems were built in separate chambers: one for UMTS (1966 MHz), one for GSM (900 MHz) and one for sham exposure, so that experiments could be carried out simultaneously.

With the feed horn at the focal point 112 cm from the dish, problems were found with achieving a uniform illumination over the large area occupied by the cages and with radiation spillover past the dish edges introducing reflections and disturbing the homogeneity of the exposure. Simulations using the method of moments were carried out to optimise the feed antenna location to produce a uniform field at the cages and optimal placement distances of 59 cm for GSM and 56 cm for UMTS were found.

The power density at the cage positions was measured with an aperture antenna substituted for each cage in turn, both with animals in the cages surrounding the measurement position, in order to determine perturbations due to their movements, and without. With a feed power of 1 W, mean fields of 7.8 V $m^{-1}$ and 8.2 V $m^{-1}$, and standard deviations of 14% and 27%, were achieved for GSM and UMTS respectively over the best 40 cage locations.

Voxel models of scenarios involving male, female and baby rats exposed to plane waves from different directions were simulated using the Finite Integration Technique to determine the whole-body SAR. A statistical analysis of the whole-body SAR was then developed on the basis of six different multi-rat scenarios. To achieve a SAR of 0.4 W $kg^{-1}$, field strengths of 102 and 104 V $m^{-1}$ were required for 900 and 1966 MHz respectively. The SAR standard deviations achieved were 42% at 900 MHz and 45% at 1966 MHz. SAR variations were mainly due to changes in the size and attitude of the rats.

*Discussion*

During the discussion, it was stated that the system would be inherently less power-efficient than a waveguide based exposure system, and the claim of cost effectiveness was challenged. The system had needed 160 W amplifier power to achieve 0.4 W $kg^{-1}$ and it was argued that the cost of the amplifier would be the dominant cost of the system if SARs much above this figure were needed.

### 2.3) *Exposure Setups for Laboratory Animals and Volunteer Studies using Body-Mounted Antennas*
### *Andre Rennings, IMST GmbH*

The project developed and characterised two different exposure systems designed to produce localised exposures. The first was to simulate exposure from using GSM (900 MHz) and UMTS (1966 MHz) mobile phones, as well as sham exposure, in human volunteer studies examining sleep variables. The second was to provide a localised head and neck exposure, and sham exposure for rats in studies examining tinnitus. The GSM signal was a pulse modulated RF carrier with an on time of 553 μs and an off time of 4.062 ms, and the UMTS signal was QPSK modulated with power control characteristics taken from the literature (Mbonjo 2004). Both systems used a computer-controlled double-blind protocol.

The human exposure system was to produce an exposure for 8 hours during day and night and had to be comfortable to wear while sleeping. It was in the form of a 110 mm × 40 mm printed circuit board (PCB) with a dual band planar inverted F antenna fed *via* a cable. The PCB was covered by foam, then a washable cover, and taped over the volunteer's ear. Measured and predicted SAR distributions in a flat phantom showed good agreement and indicated the RF cable was not significantly affecting the exposure. FDTD simulations were carried out to predict the maximum 1 g and 10 g SARs from the exposure system inside the Visible Human's head, and also to examine the positioning dependency of these SAR values when the PCB was rotated by 15° parallel to the side of the head or moved away from the head by 2 mm. The maximum SAR variation was 28% and with 1 W antenna input power the 10 g SARs were around 6 W $kg^{-1}$ for GSM and around 12–13 W $kg^{-1}$ for UMTS, while the 1 g SARs were around 11–14 W $kg^{-1}$ for GSM and around 25–26 W $kg^{-1}$ for UMTS.

The animal exposure system involved a collar of metallised Kapton foil fixed around the rat's neck and fed *via* a cable entering through the top of the cage, with a rotary connector leaving the rat free to move about inside the cage. The antenna on the foil was in the form of a meandered line with its length optimised to give a good impedance match at 900 MHz when around the animal. For verification, the antenna was placed around a cylindrical phantom and SAR measurements along the cylinder axis were compared with predictions. Having obtained good agreement with the cylinder, SAR predictions were made for the experiment using a voxel model of a rat. With a time-averaged power of 1 W, the median SARs in the head area, ear area and whole-body were 16, 50 and 2.3 W $kg^{-1}$ respectively.

*Discussion*

Clarification was sought on the levels of SAR that had been used in the experiments on humans and rats. Dr Rennings explained that the SAR had been slightly lower than 2 W $kg^{-1}$ (10 g) for the human studies and up to 20 W $kg^{-1}$ (median in the ear area) for the animal studies.

It was remarked that the animal's head had been placed inside the loop for the investigations whereas the ear had not been inside a loop with the human head and it was asked whether this would have made a difference to the local SAR. It was accepted that this would have made a difference but considered that human volunteers would have been reluctant to wear a system enclosing the head.

Dr Rennings was asked what he meant by "localised exposure" with mobile phones and he explained that in his opinion a typical localised exposure for 800/900 MHz is one where the maximum SAR occurs near the centre of the body shell of a phone, and for higher frequencies it is one where the maximum SAR occurs near the antenna. It was then asked what sort of variation would exist in practice between phones and suggested that up to 20% of phones would produce a different distribution to that described. It was asked whether conclusions should be drawn to reassure the users of these phones on the basis of a negative result using this exposure system. Dr Rennings reiterated that the objective had been to produce a system emulating typical mobile phone exposures.

### *2.4) Exposure Setups for in vitro RF Experiments*
### *Niels Kuster, IT'IS Foundation*

The work was just beginning on this project and so the talk presented a general overview of the topic with examples drawn from *in vitro* systems that had been made by IT'IS for previous projects.

Prof Kuster explained that *in vitro* systems are generally easier to design than *in vivo* systems. The principal requirement is for exposed and sham exposed cell preparations to experience identical environmental conditions (temperature, light, airflow etc) in all respects except for the RF. Biological assays are standardised and cannot easily be changed so a different exposure system tends to be required for each assay.

The systems presented were in the form of sections of rectangular waveguides terminated in a short circuit at one end and fed at the other so standing waves were created. The short circuit plane could be removed in order to insert a dielectric holder containing the dishes with the cellular preparations and locating them at precise positions inside the waveguide. Dishes containing cell monolayer preparations are placed at the H-field maxima and dishes containing cell suspensions are placed at the E-field maxima. Since multiple field maxima are present inside the waveguides, the holders can be loaded with multiple dishes in line and stacked vertically, according to the waveguide size and operating frequency. Two separate guides are stacked one above another, one of which is the sham and the other of which is exposed, and the operator does not know which is which.

Computer simulation is used to predict the field and temperature distribution inside the cellular preparations while in the waveguide and it is important to account for the shape of the meniscus. Field and temperature measurements are performed for validation, with probes inserted through holes in the waveguide. The SAR distribution inside the cellular preparations is evaluated (the dosimetry), together with an uncertainty and variation analysis. The SAR is maximal at the centre of the dish, but reduces to zero at the edges due to the boundary conditions.

The project for DMF will have eight waveguides (four active and four sham) inside an incubator and all of the guides will be randomly assigned to one of four power levels. Commutators will be used to send individual GSM pulses from a single signal generator in slots 0, 2, 4 and 6 to different waveguides.

*Discussion*

It was asked whether the cells suspended in the liquid were accounted for in the modelling. Prof. Kuster explained that the liquid had been modelled as a bulk for the purposes of the assessments, however microdosimetry could be considered later on a quasistatic basis, if considered necessary.

As the monolayer and suspension cultures are exposed at different positions (E-max and H-max) to obtain the same SAR, it was remarked that the H-field inside the samples would be different. For experiments designed to look for non-thermal effects, this could be an important factor and might lead to different responses being observed with different cellular preparations, where the SAR was the same. Prof Kuster agreed that maybe there was too much emphasis placed on the E-field exposure.

A question was asked regarding the temperature rises in the cultures. Prof Kuster explained that a considerable air flow was established through the waveguide to make sure all of the samples were at the same temperature and cooled effectively. In the case of the monolayers, around 20 mK per W $kg^{-1}$ temperature rise resulted.

### *2.5) Panel Discussion on Session 2*

Mr Geschwentner reminded the participants of the four over-arching questions asked by Dr Weiss at the beginning of the workshop and asked some more specific questions in the context of this particular session.

- Are the exposure systems that have been presented reliable and simple enough to be used by researchers from other disciplines, or is the assistance of engineers still required during biological studies?
- In terms of minimum standards, how homogeneous must be the fields produced by exposure systems?
- Can the systems shown be accepted as validated standards now, or is one concept more suitable than another?
- Has cooperation between engineers and biologists been improved by the projects?

On the first question, it was commented that, even with the best exposure system possible, people will make mistakes and misinterpret instructions. Hence, there will always be a need for some level of technical help. A sensible precaution, where an exposure system is installed in the laboratory of a biological partner, would be that there should be no facility for any settings to be changed that are not required to be changed as part of the experimental protocol.

It was felt important to distinguish between field homogeneity in an exposure system and exposure homogeneity in cells or animals within the system. The minimum required level of field homogeneity would depend on the experimental objectives and the considerations would be different for *in vitro* systems, with fixed exposure positions, and for *in vivo* experiments, where animals are moving around. Exposure of animals changes by large amounts as they move about their cages and it was felt not to make sense to strive for field homogeneity better than the variations that are present in the experiment itself. The important parameter to evaluate accurately would be the mean exposure over time.

With *in vitro* systems, any field non-uniformity in the exposed cultures would be reflected in the response of the cells and so it was felt that a minimum homogeneity requirement should be defined. If this was not attainable, the researcher planning an experiment should have to find arguments why it is sufficient to carry out the experiment with the poorer uniformity. Sometimes biological requirements limit the homogeneity that can be achieved by an exposure system, for example, if a particular container, which is not ideal from an electromagnetic perspective, has to be used for a cellular preparation. It was suggested that *in vitro* experiments having variations as large as 300–400% would definitely not be acceptable.

There was a discussion on the choice of appropriate SAR levels for experiments and it was remarked that the SAR levels being used in the DMF programme for long term exposure of animals are lower than in some other national programmes. Also, the quasi-open systems using parabolic reflectors were felt to be inherently less efficient than radial waveguides and to "burn" much of their output power in absorbers. The SAR level being used in DMF is 0.4 W $kg^{-1}$, whereas the levels used in PERFORM A had been 4 W $kg^{-1}$ and the American programme was reported to be planning to use 6 W $kg^{-1}$.

The reply was that whenever animals or humans are used, one is limited in terms of the numbers that can be exposed practically. A range of SAR levels up to 10 W $kg^{-1}$ was being used for *in vitro* experiments, but a single SAR level of 0.4 W $kg^{-1}$ was being used for long term studies on mice and rats. This long-term SAR level was chosen because DMF was not interested in thermal responses. Another aim was to be sure that present whole-body exposure limits are not too high. The costs would have been much greater to examine for effects at several W $kg^{-1}$, and such a level would be well above present exposure limits.

Limits defined for human exposure were not necessarily felt to be a good basis for defining exposure levels in experiments on animals or cells. Previous experiments had progressively increased the SAR in animals while measuring their temperatures in order to define a threshold above which a thermal reaction occurred. This method had been used in PERFORM A and no thermal effects had been observed up to 4 W $kg^{-1}$.

It was asked whether the experiment examining long terms effects spanning three generations should be done at a higher SAR level than 0.4 W $kg^{-1}$, given that only one level is being used, however no level was proposed.

The meaning of the terms *thermal* and *non-thermal* effects was discussed and the point was made that non thermal effects might not only occur at low exposure levels in the absence of temperature rises, but that they might also occur at high exposure levels in the simultaneous presence of thermal effects. More generally, a thermal effect is generally taken as an effect that occurs where there is an overt rise in temperature. However, at this stage, the body's own compensation mechanisms have been overcome and there could have been many other (possibly adverse) effects occurring during that compensatory process. It was also unclear whether the concept of whole-body SAR was relevant for non-thermal effects and it was stated that brain SARs in the long term mouse study would be well below 0.4 W $kg^{-1}$ and so below the range of localised SARs produced by mobile phones in humans.

## Session 3
## Exposure of the General Public

Roger Matthes of BfS chaired this session during which there were six presentations followed by a panel discussion.

### *3.1) Determination of individual exposures from base stations*
### *H-Peter Neitzke, ECOLOG-Institute*

The presentation described exposure assessment work carried out in support of a cross-sectional epidemiological study to test the hypothesis that the electromagnetic fields from mobile phone base stations cause medical disorders for people living in the vicinity of the antennas and that there are some people especially sensitive to these fields. Also, it is hypothesised that people are especially sensitive during night-time and so there is a particular interest in bedroom exposures. The effects being studied are short term in nature, e.g. headaches, and so there is no need to consider historical exposures.

The epidemiological study involves 30,000 participants randomly selected from the German population and so it is not practical to make measurements in all of their homes. The aim of the exposure assessment project was to develop a model for predicting the mean exposure inside a particular room within a residence, and measurements were made inside 1100 rooms and at 120 outdoor locations to test and optimise this model. Power density spectra were gathered over the following frequency bands: broadcast radio and television, GSM and UMTS downlinks, GSM uplinks and DECT. Base stations contributed less that 10% of the total power density in 21% of the rooms and dominated by producing greater than 90% of the power density in 24% of the rooms. The total power density from base stations was below 10 μW $m^{-2}$ in 63% of the rooms and above 100 μW $m^{-2}$ in 9% of the rooms. At distances beyond 500 m, the contribution from a given base station was negligible.

Power densities were greatest inside rooms with windows facing towards base stations, and strong attenuation was caused by vegetation and walls in the line of sight path from the room to the base station. Although power density generally reduced with distance, the measurements at any given distance were spread over four decades, meaning that distance was only a very poor indicator of exposure.

The calculation approach involved using typical base station emission data for the nature of the urban environment where the flat was located, e.g. the EIRP was taken as 165 W, and then using simple inverse-square law propagation models with multiplication by a succession of transmission coefficients to account for obstacles such as walls. The correlation coefficient between the measured and calculated power densities was acceptable to good at 0.64 (0.48–0.86) and a Bland Altman Plot did not show any systematic error. Kappa testing also indicated acceptable to good agreement with k = 0.52 (0.41–0.68). Sensitivity was low to high at 0.56 (0.43–0.76) and specificity was high at 0.93 (0.89–0.97). Overall, the model showed good agreement in low density areas with houses up to three floors and acceptable agreement for low-density areas with houses more than three floors, high density areas with courtyards and/or small greens, and closed high density areas.

Based on example assumptions that, of the 30,000 participants in the study, 2000 were exposed cases, 1000 were non exposed cases, 13,500 were exposed controls and 13,500 were non-exposed controls, it was possible to calculate that misclassification would cause a correct risk of 2.0 (CI: 1.9-2.2) to be observed as 1.5(CI:1.2-1.7).

*Discussion*

It was asked how FM signals would be treated in the epidemiological study since, in a similar study, it had been found that they often give the highest power densities, particularly indoors, because they are attenuated less by walls. It was also pointed out that FM signals couple more effectively into the body than base station signals and so give a greater SAR for a given power density. The epidemiological study has no information on distance from FM transmitters and it was accepted that this is a weakness and would result in some misclassification of RF exposures. However, epidemiologists argue that this is not a problem because exposures to FM signals and base station signals are uncorrelated and any effect should average out in the results.

Personal use of mobile phones would contribute to exposure in the epidemiological study and it was asked how this would be considered. This was a topic for the epidemiologists to consider; however, it was understood that the questionnaire gathers some information on use of mobile and DECT phones.

It was asked whether the correlation between the measurements and the model had been tested on a logarithmic scale. It had been tested on both linear and logarithmic scales, however the epidemiologists were more familiar with the log scale. It was then asked to within how many decades the correlation coefficient of 0.64 actually implied agreement. Given the logarithmic scale, it implied that the predictions were accurate to within ±1 decade.

Next, there was a question about where a cut-off for high exposure level could be drawn based on the data. This was really a decision for the epidemiologists, but various values had been considered. A figure of 100 μW $m^{-2}$ had been suggested and would include around the top 10% of base station exposures.

In describing the statistical tests it had been mentioned that there were particular exposure situations where calculations had the poorest correlation with measurements and it was asked for more information on the nature of these situations. The most critical values had been those associated with the base station technical data, which had been derived purely as typical values derived from a large number of sites in a given type of area. Angle of the measurement site with respect to main beam was a critical parameter and absence of information about downtilt for the particular site caused loss of accuracy for short distances.

### *3.2) Exposure of general public due to GSM and UMTS base stations*
### *Christian Bornkessel, IMST GmbH*

The project first carried out measurements and simulations in order to characterise the exposure environment around GSM and UMTS base stations. It then developed optimal techniques for making measurements in the context of the German Exposure ordinance (26. BImSchV). Factors affecting exposure, such as distance and antenna pattern, were then examined through measurement. Finally the performance of several commercially available field strength prediction programs was evaluated and their results were compared with measurements for different base station scenarios.

In typical exposure environments such as indoor rooms, multipath propagation conditions are present leading to variations in field strength over space and time. Measurements made with 2 cm steps along a line across a room were shown and these illustrated spatial variations of around 10 dB. Short-term variations in RMS power over time occurred due to varying traffic load and power control. There was also a longer term cyclical trend over 24 hours with an evening peak and a minimum in the small hours of the morning.

The Ordinance requires that a measurement is made at the spatial maximum field strength inside a room and this dictates that some form of spatial scanning of the measurement antenna is required, rather than a fixed antenna on a tripod. The Ordinance also requires a measurement to be made with the base station emitting its maximum possible power, or a measurement at a lower power level to be made and corrected to represent that power. Frequency selective (spectrum analyser) techniques were used to measure the power of the BCCH carrier from GSM base stations and then the reading was multiplied by the number of installed transmitters. Extrapolation of frequency selective measurements to a maximum for UMTS is not very accurate and code selective methods are preferred. With code selective methods, the power of the P-CPICH can be measured, multiplied by the ratio of the maximum channel power to the P-CPICH power (P-CPICH is normally set to 10% of the maximum channel power) and then multiplied by the maximum number of channels.

Three measurement instruments with code-selective facilities were evaluated, the Rohde and Schwarz TSMU, the Narda SRM3000 portable probe with spectrum analyser, and a Rohde and Schwarz FSP/ESPI spectrum analyser with a code-selective option. All were found to be satisfactory, although the SRM3000 was slower to decode than the other instruments, meaning that spatial sweeping of the measurement antenna had to be done more slowly.

Tests were done in an anechoic chamber to examine the influence of personnel on a measurement antenna. With a transmitting antenna at one end of the chamber and a receiving antenna at the other, it was found that the response of biconical antennas was much more affected by a person moving behind them than was the response of log-periodic antennas, which have no back-lobe. Hence log-periodic antennas are preferred for spatial sweeping.

Eleven base stations serving different types of coverage area were visited and electric field strength measurements were made at several different locations at each. Where GSM and UMTS base stations were at the same site, the highest exposures were measured due to the GSM component. This was because the higher frequency resulted in a narrower beam from the antenna with the UMTS signal, which did not intersect the ground until a greater distance, and because the exposure limit (reference level) is less restrictive at the higher frequency. Higher exposures were measured with the lower height antennas, even where they were low power sites for indoor coverage, again because their beam could be encountered at lesser distances. The highest electric field strengths measured represented 12.8% and 8.4% of the reference level for GSM and UMTS respectively. The medians were 0.72% for UMTS and 1.75% for GSM.

The influence of various parameters on exposure was examined graphically. Distance from outdoor antennas was not a predictor of outdoor exposure for distances up to 200 m, where the exposure locations would have been in the sidelobe pattern beneath the main beam. However, there was some suggestion of an underlying trend for exposure reduction with increasing distance at greater distances, but with considerable variations at any given distance. Indoor exposures from indoor antennas seemed to generally reduce with increasing distance up to 50 m, probably due to the more isotropic pattern of typical indoor antennas. Vertical angle subtended to the main lobe from the antenna showed a strong influence on exposure, as consistently greater exposures were measured at distances in the 111–704 m range with elevation angles to the antenna of –5° to +10° than at distances in the 49–136 m range where the angles were in the range 10° to >30°. Greater exposures were also measured at locations with a clear line of sight path to the antenna than at those without, although strong reflections could alter the situation and had to be taken into account.

The final part of the project evaluated the capabilities and suitability for public exposure prediction of eight different commercially available computer programs. The ray-optical packages (EFC-400, EMF-Visual, Quickplan, Winprop and Wireless Insite) were most suited to the task, although they differed in the way buildings and terrain could be input and in the way they were treated electromagnetically, leading to differing predictions for the same situations. The programs generally over-predicted field strength by several orders of magnitude at locations beneath the antenna, but were otherwise generally within ±5 dB for both line of sight and non-line of sight situations.

*Discussion*

Clarification was requested regarding the small and large scale variations in base station signal strength over time in two graphs shown during the presentation. The first graph showed variations over 24 hours with a range from around 1.8 to 3.5 V $m^{-1}$, while the second appeared to show the same data over a week, but the range was now from 1.35 to 1.8 V $m^{-1}$. Dr Bornkessel explained that the data were from different base stations and it was probable that the first graph was for a much larger base station with more available channels.

Surprise was expressed that the range of base station power variations over time was only around 2 dB and it was asked whether this was typical. Dr Bornkessel said it depended on the base station. A smaller base station in a rural area would have less power variations, however the base station shown with the larger variations had been specially selected as one with a high capacity. Measurements with UMTS base stations had shown much smaller variations.

The results from the testing of the relative performance of biconical and log-periodic antennas inside an anechoic chamber were accepted, however it was questioned whether the log-periodic antenna would perform so well with practical measurements, as it would be difficult to sweep over all the possible angles of incidence, as would be necessary given its relatively narrow beam, and so the maximum could be missed. Dr Bornkessel said this was a debate that had been ongoing in the measurement community for several years. He felt it was important to think about the different sources of uncertainty and include them into the overall uncertainty budget. The project team's opinion was that log-periodic antennas are more suited to the task because the argument over non-captured angles of incidence with directional antennas is only theoretical and has not been tested in practice.

Also concerning the tests of antenna performance in the anechoic chamber, it was queried whether the influence of the person on the measurement with a log-periodic antenna would be greater in a real situation due to the presence of multipath and greater interaction of the person with the measured field. Calculations had been done, which showed a person inside the room changed the field distribution, but the spatial maximum value stayed the same.

A question was asked regarding the reproducibility of the sweeping measurements and it was stated that this had been around 1.5–1.8 dB.

Further explanation of the phrase "a slow sweeping rate", as had been stated is required for UMTS, was requested and a demonstration with hand movements was provided. The need for slow sweeping was because of the slow decoding rate of the measurement instruments. The Narda SRM 3000 has a decoding rate of around one sample per second, whereas other systems, such as those used from Rohde and Schwarz, are able to decode ten or more samples per second. These rates are for an isotropic probe with three sensors, however use of a directional single axis antennas allows a decoding rate three times faster.

### 3.3) Exposure of the General Public due to Wireless LAN Applications in Urban Environments Gernot Schmid, ARC Seibersdorf Research

The project was carried out because of public concern about an increasing number of access points (APs) in public areas and a scarcity of measured exposure data in the literature. Where data were available, they had been obtained with a variety of different measurement techniques, meaning they were not comparable. The aspects of the WLAN signals relevant to exposure assessment were reviewed in order to develop optimal measurement techniques. Then measurements were made in six real scenarios and compared with computational predictions for the same situations. The scenarios were in the vicinity of two indoor, two outdoor city centre, and two outdoor residential APs.

Wireless LAN systems operate in accordance with the IEEE 802.11x family of standards and the standards allow for operation in one frequency band close to 2.4 GHz (2.4–2.4835 GHz) and several frequency bands in the range 5–6 GHz. However, the higher frequency bands are hardly used in Europe and so this project made measurements only in the 2.4 GHz band.

Direct sequence spread spectrum modulation can be used in the 2.4 GHz band and this results in a signal bandwidth of around 22 MHz. Orthogonal frequency division multiplexing can be used in any of the bands and this results in a signal bandwidth of around 17 MHz.

The signal is in the form of data packets of variable length, according to the nature of the data being transferred. When no data are being transferred there are 2.5 ms bursts emitted every 100 ms as a beacon signal. In the 2.4 GHz band, the peak EIRP is limited to 100 mW, whereas systems operating the 5-6 GHz bands can use up to 200 mW if they have adaptive power control, but otherwise are limited to 30 mW. The maximum duty factor at full load is around 80% so the maximum time-averaged EIRP for 2.4 GHz will be no more than 80 mW at full capacity and no more than 2.5 mW when idle.

The measurement system used the probe from the Narda SRM3000 mounted on a tripod and connected to an Agilent spectrum analyser. In addition to the RF cable connected to the probe, a second cable was used to connect to a control box with a switch enabling selection of the measurement axis for the SRM probe. The signal bandwidth was wider than the maximum bandwidth of the spectrum analyser and so a correction factor was derived and applied to the measured power. It was chosen to use the analyser in max-hold mode in order to record the power during packet transmission, and an RMS detector was used because of the stochastic nature of the signal.

The indoor measurement scenarios were inside a coffee shop with the AP located under the serving counter so people were able to stand immediately in front of it, and inside an airport terminal building with APs mounted on the ceiling in the vicinity of two separate gate departure areas. The outdoor city centre scenarios involved an AP mounted on the corner of a university library building several metres above ground level and a retail park with the AP located above a shop front at a height of around 2 m. The outdoor residential scenarios involved one area with an AP located on a building to provide internet connectivity for surrounding flats and another area with two APs mounted on buildings for the same purpose.

The measurement protocol was designed to yield a spatially averaged power density over the volume occupied by the body. Hence, spot measurements were made over a horizontal area of 50 cm by 50 cm at five heights spread from 50 to 175 cm above floor level and averaged. Computer modelling was also carried out for each scenario using the ray tracing software Wireless insite 2.0.5. This software considers transmissions, reflections and diffractions, and accounts for the amplitude and phase of rays.

In indoor scenarios, where the distance to the antennas is usually small, spatial and temporal peak exposures can be up to around 100–200 mW $m^{-2}$, while spatially averaging over the body dimensions and a 6-minute time period yields values 1–2 orders of magnitude lower, i.e. less than 0.1% of the reference level. The distance to the AP antennas is generally larger outdoors so exposures are lower. Peak exposures were up to 1 mW $m^{-2}$ and averaged values were again 1-2 orders of magnitude lower, i.e. less than 0.001% of the reference level. It was concluded that, in comparison with other RF sources, such as radio and TV broadcast, GSM, UMTS and DECT, public exposure from WLAN applications seems to be small.

*Discussion*

The interpretation of exposures for the coffee shop scenario was queried, as the shop assistant or a customer being served could stand immediately next to the AP antenna for several minutes. It was accepted that localised SAR data would be a more appropriate measure of exposure in such situations. Dr Schmid agreed that it was important to carry out SAR compliance testing for products based on localised exposure.

### *3.4) Exposure of the General Public due to Digital Broadcast Transmitters Compared to Analogue ones*
***Markus Schubert, IMST GmbH***

The project ran from October 2004 to March 2006 during which digital video broadcasting systems for television (DVB-T) were installed in regions in the North of Bavaria around Nuremburg and in the South of Bavaria around Munich. The project aimed to address the question of whether exposures were increased or decreased by the transfer to digital TV broadcasting systems. The project also examined the relative exposures from FM and DAB systems, which are broadcast simultaneously. First, a survey was carried out to characterise the technical aspects of FM, DAB, analogue TV and DVB-T systems, and transmitter spatial density and established calculation methods for signal strength were examined.

Next, methods for exposure estimation were developed based on measurement and calculation. Finally, an extensive series of measurements was performed and comparisons were made with calculations.

DVB-T has three levels of coverage defined based on the local signal strength produced by its transmitters, and the level of coverage achieved in a given area broadly depends on the distance from the broadcast antenna and the intervening terrain. The *portable indoor* region is where there is adequate signal strength for use of receivers with low gain antennas indoors, the *portable outdoor* region is where there is adequate signal strength for the use of receivers with low gain antennas outdoors, and the *fixed antenna* region is where there is coverage for receivers with fixed directive antennas, such as yagis. Analogue transmission systems did not aim to provide indoor coverage, which would be expected to require higher environmental signal strengths, however digital systems have coding gain, hence it was unclear whether exposures would be higher or lower with digital systems.

For the comparison, 200 statistically distributed points were selected in the coverage areas of the Nuremburg transmitter and the Munich transmitter, with the density of points proportional to the population density. Additionally, measurements were made near both transmitters along a line and to evaluate height dependence, meaning that over 300 measurement points were examined in total. Measurements were made for “before” and “after” situations at each point.

Measurements were made with a Narda SRM3000 probe. For both analogue TV and FM radio systems, the spectrum analyser was used with a peak detector, and the bandwidth was set to 200 kHz for FM and 1 MHz for analogue TV. With these settings, the measured TV signal power was determined by the peak synch pulse, and the average signal power would have been obtained by applying a 2.3 dB reduction factor in the worst case (black screen), but was actually obtained by applying a 4 dB reduction factor to account for more typical picture conditions. An RMS detector was used with digital TV and DAB signals in order to avoid significant overestimation. Sweep times of at least 100–200 ms were used, again in order to avoid overestimations. The bandwidth had to be large enough to include the signal energy, which spanned 7.6 MHz in the UHF band and 6.6 MHz in the VHF band for DVB-T, and 1.5 MHz for DAB. Hence, correction factors are necessary with spectrum analysers not capable to measuring over such large bandwidths.

The data gathered over the 200 measurement points were spread over a 50 dB range, from less than 0.1 μW $m^{-2}$ to a few mW $m^{-2}$, with the maximum measured exposure being 0.3% of the power density reference level. Mean exposures were dominated by a small number of high measured values and so median exposure was a more representative statistic. TV exposure was increased by 6.8 dB at Nuremburg following the introduction of digital TV, mainly because the transmitter had been moved from a hill to the South of the city to the city centre. At Munich, exposure had been increased by 6.5 dB and this appeared to be due to an increase in the ERP of the transmitter. At both sites, the increase was mainly in the portable indoor region and no significant change in exposure was found in the other regions. DAB signals were on average 11.3 dB lower in strength than those of FM radio and so their addition had not significantly altered the exposure situation.

A field prediction tool based on the propagation curves in ITU-R P.1546 was developed. This was a fairly simple model with very few input parameters, such as height of the antenna, ERP in kW and horizontal plane antenna pattern. The model was optimised with respect to 1135 measured values first in order to minimise the mean prediction deviation, in which case 9 dB was achieved, and then in order to achieve a high percentage of points with an overestimation, in which case 100% overestimation was achieved, but with a high mean deviation of 30 dB.

Measurements of FM radio and DVB-T signal strengths were made along a line from a transmitter at Dillberg to another at Nuremburg in order to test the model with the two different optimisations. The limitations of the model in not accounting for the changes in terrain elevation were apparent, as the measured FM signal strength increased with increasing terrain height in a way that was not accounted for by the model. This effect was not so pronounced with the DVB-T signals.

*Discussion*

More explanation was requested on how the model optimisations had been carried out. Mr Schubert explained that, of the four configurations in the model (dense urban area, urban area, suburban area and open land area), the points in the dense urban area had been used to derive a mean deviation. Then a new factor was added to each calculated point and it was examined whether the mean deviation decreased. This was done for all configurations and yielded a lot of additional factors and they resulted in mean deviations for all configurations.

### 3.5) *Exposure from using Mobile Phones in Typical Day-to-day Situations and in Partly Shielded Rooms.* *Reinhard Georg, Telekom-Consult & Gernot Schmid, ARC Seibersdorf Research*

Dr Georg explained that the talk would describe two projects on exposure from mobile phones. The first, covering typical exposure in day-to-day situations, was already completed and the second, covering use of mobile phones in partially shielded rooms, was ongoing.

Comparison of recent data for the handover rates of mobile phones with data published six years ago (Wiart et al) suggests the rate when travelling has increased. This would be expected because the spatial density of base stations has increased in order to serve an increased number of users. As the power of mobile phones can be returned to the maximum level following a handover, frequent handovers could be expected to raise the time-averaged output power of phones.

The first project had examined the output power levels from mobile phones over time in various normal use situations, and paid particular attention to handovers and the subsequent behaviour of the output power as the power management recommenced. Various car journeys had been made while a phone was used, including cross-country, highway, and city routes. Typically, there was a handover every 1 to 1.5 minutes

Measurements were made while walking around a technical exhibition, where many technology applications were in use and there was a high density of mobile phone users. Different network operators were found to manage handovers in different ways. With one operator, calls were initiated in the 900 MHz band and then immediately handed over to the 1800 MHz band. With another, handovers in the 900 MHz band were found to set the mobile power to the 0.5 W level, rather than the 2 W maximum power level. Another operator used one-shot power control where the power jumped from 1 W to 1 mW in a single step.

The mobile transmission power was examined when stationary in a room so there were no handovers. A Maschek ESM120 SAR meter (a lossy spherical structure containing field sensors) was used with a mobile phone fixed to it while the SAR value was measured. A difference in phone output power was found when different people used the phone in the same room. The same test was carried out in rooms with different signal strengths from the base stations, but the differences between the output powers for different people remained. Another situation, where a person was stationary for half an hour while making a phone call (so there were no handovers) showed variable power throughout, with the power sometimes reaching the band maximum of 1 W.

UMTS was examined next, and handovers and power control are different with UMTS to those with GSM. In general, very low output powers were found with UMTS. Data transfers were set up and other traffic situations were examined. Typical output powers were from ten to a few hundred microwatts and smaller than those with GSM by a factor of around a thousand. Sometimes counter-intuitive results were found, for example, when using a bluetooth adaptor near the Maschek SAR meter, higher SARs were found from the adaptor than from the UMTS phone to which it was attached.

The second project involved gathering SAR levels using the Maschek SAR meter in various situations, such as outside and inside an elevator, inside/outside a bus, inside/outside a plane, and inside/outside a train. A series of videos were shown illustrating these measurements being performed and showing the technical data in real-time. These data were for comparison with computer modelling results.

Dr Schmid presented progress on the modelling aspects of the second project, which was to consider SAR levels in partially shielded rooms such as an elevator, bus, train or plane. The work was just starting and so only a few preliminary results for an elevator were shown. The situation considered involved four whole-body phantoms being stood within the elevator while either one or four of them had a mobile phone used against their head. With one phone in the elevator, the maximum 10 g SAR was 2.03 W $kg^{-1}$ and this was raised to 2.09 W $kg^{-1}$ with four phones in the elevator. FDTD was able to model small computational domains such as cars and elevators. The challenge for the project was how to model large scenarios such as buses and trains and various techniques exploiting symmetry were being considered.

*Discussion*

A question was asked regarding the level of use of the UMTS networks during the measurements and it was queried whether differences between measured powers with different users and situations could have been due to differences in traffic at different times of day. Levels of UMTS traffic were unknown during the measurements, although measurements had been made at a stand in the technical exhibition where UMTS was being presented, and it was expected that traffic levels would have been high. With GSM, traffic levels would not have affected the output power measurement from the phone because it remained connected to the same base station and this was all that mattered.

A short summary and conclusion for each of the two projects was requested. Dr Georg said the conclusion of Project 1 was that the quoted SAR value was never reached for the phones tested and the conclusion of Project 2 was that there were no measurable resonant fields present inside vehicles. It was questioned whether the study design could have detected that the compliance testing SAR value was exceeded, hence the summary of Project 1 was regarded as unsurprising.

Staying in the same position had been assumed to mean that a phone remained connected to the same base station. However, Dr Georg was informed that measurements made in several countries had found a high rate of congestion handovers taking place with stationary users of mobile phones. It was felt that the results of the project may not be generalisable to other situations or to other points in time. Dr Georg agreed with this and added that base stations from different manufacturers also cause phones to behave differently.

How could the specific measurements made in this project be generalised to produce useful statistical information was asked. Dr Georg explained that the aim of the UMTS part of the project was not to produce such statistical information, but more to give a feeling for how the systems work. The scientific usefulness of the project was questioned, however Dr Georg felt that the project was of value because it was the first project to look at mobile performance in so much detail.

It was noted from the pictures shown that a lot of cables had been introduced to the cavities where measurements were made and it was argued that cables introduced to cavities effectively open the cavities so the internal fields are different and they no longer resonate so strongly. Dr Georg said the cables had ferrite beads on them and did not accept that they would have changed the nature of the resonances inside the cavity.

### 3.6) Exposure Caused by Wireless Technologies used for Short Range Indoor Communications in Homes and Offices
### Gernot Schmid, ARC Seibersdorf

The project began with a survey of typical short range wireless devices used in homes and offices, and their technical parameters, in order to identify those devices likely to be most relevant in terms of exposures created. Measurement methods were then developed for each category of device and samples of the devices were assessed in laboratory and practical installations in order to determine SAR levels in close proximity to the transmitters and electric field strengths at various distances. Finally, computer models were developed of the devices used in realistic scenarios in order to estimate worst case exposures.

Measurements were made where IEEE 802.11a/g WLAN systems were installed at a nurse support point in a hospital and in an office. Both scenarios were also simulated using Wireless Insite. An RMS detector was used with the spectrum analyser in max-hold mode and a correction factor was applied to account for insufficient measurement bandwidth. Power density values spatially averaged over the body height were measured in the range 0.14–0.29 mW $m^{-2}$. The computer modelling predictions were around 7 dB higher, possibly because the real devices had less than the 100 mW radiated power used for the simulations. Localised SAR measurements were made for a client device in the form of a PCMCIA card inserted into a laptop computer first laid parallel to a flat phantom and then tilted to bring its tip into contact with the phantom. For these two situations, the 10 g SAR levels were 0.034 and 0.052 W $kg^{-1}$ respectively. In comparison, Kühn et al 2005 reported measurements on some WLAN devices and found maximum 10 g SAR levels of 0.81 W $kg^{-1}$.

Adaptive Dynamic Frequency Control (ADFC), i.e. the capacity of handsets and base stations to change their frequency channel during calls, is the main difficulty in developing a suitable measurement method for DECT. Hence, it was decided to use a channel power measurement over the entire allocated frequency band. First, measurements were made in a professional DECT installation with over 250 mobile stations and spatially (over the body height) and temporally averaged power densities were in the range 0.007–0.03 W $m^{-2}$. Measurements were also made of electric field strengths at 1 m and 3 m from four different home cordless phones inside an anechoic chamber. These found RMS fields up to 3.6 V $m^{-1}$ at 1 m distance and 1.5 V $m^{-1}$ at 3 m distance.

Bluetooth allows for three power classes of device: 1, 2.5 and 100 mW, and power control is mandatory for the 100 mW systems. SARs inside a flat phantom were measured with a 100 mW Belkin Bluetooth Stick and values of 0.087 and 0.024 W $kg^{-1}$ were measured with the stick in two different orientations. Other authors have investigated other devices and reported higher values, e.g. Kühn et al measured up to 0.47 W $kg^{-1}$ in 2005.

Baby monitors (or babyphones) can use several bands, and one device was tested operating at each of the following frequencies: 40.68, 446, 864.7 and 2450 MHz. Generally, the powers were around 10 mW, except for the 446 MHz device, which had 500 mW power. E-fields at distances of 1 m and 3 m were up to 0.045 and 0.014 V $m^{-1}$ respectively, other than for the 500 mW device, for which they were 1.1 and 0.41 V $m^{-1}$ respectively. SAR levels from the 500 mW device placed next to a flat phantom in two different orientations were 0.133 and 0.074 W $kg^{-1}$.

Other devices tested were two wireless stereo headphones operating at 864 MHz, a wireless webcam and a wireless video transmission system each operating at 2.45 GHz, and three remote control units for toys operating at 27 MHz. The webcam and both headphone transmitters produced E-fields up to 0.35 V $m^{-1}$ at 1 m distance and up to 0.11 V $m^{-1}$ at 3 m distance, consistent with radiated powers up to 10 mW. The wireless video transmission system produced E-fields up to1.66 V $m^{-1}$ at 1 m, indicating a radiated power nearer 100 mW. Remote controls for toys produced fields up to 4.5, 0.5 and 0.15 V $m^{-1}$ at distances of 20 cm, 1 m and 3 m respectively, also consistent with radiated powers of up to 10 mW.

A generic office model was developed to represent a room in a typical call-centre in which there were three workstations, each with a DECT phone and a WLAN client. There were two WLAN access points and 1 DECT base station on the ceiling. Over the three workstations, spatially and temporally averaged exposures were calculated between 0.018 to 0.061% of the reference level. A generic home model was also developed consisting of two adjoining rooms with an open door between them. One room was a child's bedroom containing a baby monitor and the other room was a study with a large desk on which were a DECT base station and phone, a computer (WLAN client), and a wireless webcam and headphone transmitter. The baby monitor gave the largest exposure contribution at the desk and at the child's bed. Exposures at the desk and bed were 0.06% and 0.27% of the reference level with a 20 mW baby monitor, however they were raised to 0.38% and 5.86% with a 500 mW monitor. Without a baby monitor, exposures were 0.017% and 0.012%.

The project concluded that typical exposures in the far-field of DECT, WLAN and Bluetooth devices can be expected to be below 0.1% of the reference level. Near-field exposure situations in the close vicinity of WLAN and Class 1 (100 mW) Bluetooth devices can in some cases produce SARs of the order of the basic restrictions, although under more normal conditions, exposures would be 1-2 orders of magnitude lower. At distances of 1 m and 3 m, E-fields from baby monitors, DECT devices, wireless headphone transmitters, webcams and wireless video transmission systems were well below the reference levels. At distances very close to the transmitters higher field strengths can occur and SAR measurements were recommended for such situations.

*Discussion*

The E-field exposure data had been presented as spatial peak and average values over the body dimensions and the body-averaged values had been compared with the reference level. It was asked why this approach had been taken and Dr Schmid replied that this was because the ICNIRP guidelines state that the reference levels should be understood to be averaged over the body dimensions. Dr Schmid was pressed as to whether he felt this approach made sense and he accepted that it would not be appropriate in some cases, such as where exposure occurred close to the source. He said he had presented spatial peak and body averaged values to give a better feeling for the nature of the exposure

It was remarked that the exposure data shown for generic home and office scenarios showed similar or even higher values than living close to mobile phone base stations. Dr Schmid said it would depend on the distance from the base station, but it could easily be the case that exposure to wireless devices in the home and office would exceed that from mobile phone base stations.

### *3.7) Panel Discussion on Session 3*

Mr Matthes presented the four general questions presented for the earlier discussions and opened the discussion with the specific question ***does dosimetry allow studies around base stations***? He said that whether they should be done would be a topic for a future workshop on epidemiology.

Scepticism was expressed as to the possibility of producing reasonable classifications within the range of base station exposures. Given the results presented by Dr Neitzke that only 9% of bedroom exposures were above 100 µW $m^{-2}$, it was argued that a 0.1 second phone call would give the same brain exposure as 8 hours in bed at 100 µW $m^{-2}$, assuming a cumulative exposure model. Since exposures have such a large dynamic range, it was felt to be very difficult to find a good argument to do studies at such low levels. Moreover, standing in a coffee shop at a counter with an access point beneath for maybe only one second could give a higher exposure than being in the bed for 8 hours.

From a biological perspective, it was argued that there is some evidence from studies that effects might happen, even at these low levels. It was felt that to dismiss the possibility of future epidemiological studies on the basis of a dosimetric comparison with mobile phones may not be appropriate because the exposure characteristics are so different. Base station exposures correspond to many hours of more or less continuous exposure and this was felt to be a situation about which there is no evidence.

Dosimetry had been improved and information had been gained on the huge extent of the variations in exposure from one place to another, which complicate epidemiological studies. The answer to whether dosimetry allowed studies to take place depended on the type of studies being contemplated. In the case of short-term studies, e.g. sleep-related studies, it was argued that these would be better done under controlled laboratory conditions. However, for longer-term studies, it was felt that it made sense to ask the question whether there should be epidemiological studies. A particular criticism of the study in which Dr Neitzke is involved would be that night-time exposure is very low compared to that at other times of day, e.g. exposure is two times higher at 6 pm. It was asked whether the study would have assessed the right exposure if it was the exposure at another time of day that caused sleep disturbances.

For long-term outcomes from high exposures, it was felt most appropriate to examine effects such as cancer in relation to mobile phone use. For long-term outcomes from low exposures, it was felt a historical study of exposures had to be carried out over the period before the advent of mobile phones when there were just radio and television transmitters. In such a study, it was felt the sources could be well defined and exposures could be modelled rather well.

The view was expressed that, in general terms, there is now enough knowledge about exposure from base stations and that there is no need for further measurement campaigns on the topic. Another important issue was the level of dosimetric sophistication that was needed for a given purpose. For epidemiology, given all its problems, it would seem that dosimetry to within an order of magnitude might be sufficient, and this seems now to be possible. For compliance assessments, where exposure is small fractions of the limit, it makes no sense to strive for the 3 or 4 significant figures of accuracy presented in this session's talks. There was interest and surprise that distance from a base station is not so relevant in determining exposures and this was felt to be an important message. The conclusion that we have sufficient knowledge about exposures from base stations was felt to contrast with the situation for biological studies, where any improvement in sophistication would be welcome.

It was felt important to separate the questions of whether base station measurements were required for scientific purposes from whether they were required for risk communication. People tend to trust readings they can see on a measurement instrument, but they are less trusting of calculations, and so there would continue to be a need for reassurance measurements. Having information on exposures with sources combined in practical situations was also felt to be useful for risk communication purposes, as was having exposure data for individual new technology devices. Another outcome from the projects was considered to be improved measurement techniques and standardisation, and this would help communication because exposure data would be more comparable in future.

There was a discussion as to the implications for mobile phone epidemiology arising as a consequence of the great differences in SAR levels during handovers from those at other times. It was asked whether these differences would average out between different people as they used their phones in different places over time. It was accepted that the handover dominates exposure, so spatial peak SAR should be a good measure of exposure for phones used in different scenarios. However, the situation will change dramatically with UMTS, which gives much lower exposures. It was commented that the period before GSM use fades out could be the last opportunity to do a high exposure RF epidemiology study with large numbers of people.

Mr Matthes asked ***whether enough is now known about complex scenarios and should more scenarios in daily life be investigated?***

It was argued that, since the exposure fall-off with distance from devices is dramatic, exposure in practical situations is dominated by the closest device. Thus, as each device has its own separate compliance criteria, a problem only arises if two devices are very close to each other so they can deposit energy into the same localised tissue region. Mr Matthes asked whether there would be a problem in situations where one device takes up a large proportion of the limit, e.g. 90%, and then a smaller exposure contribution from a second device causes total exposure above the limit. It was still felt that both devices would have to be very close together for this situation to arise, which would be unlikely to occur in practice.

The issue of multiple devices contributing significantly to exposure is of particular interest to regulatory authorities because current product standards allow single devices to expose people up to 100% of the limit. One regulator had been arguing against this approach for several years and requiring producers to specify the maximum percentage of the limit that a device is capable of producing. However, from the presentations, it seemed that the limit would not be exceeded irrespective of how many devices are used, and it was unclear whether there was any point in testing devices. Another issue was whether a precautionary view should be taken in respect of the development of baby monitors, given the exposure levels reported and the development of higher-powered ones.

It was argued that the UMTS exposures shown had been for a network that is not heavily used and it was asked whether SAR levels will increase again as the number of users increases and as people start downloading large files while carrying the devices on their bodies. Another situation worth considering is that where a 3G phone and GSM phone are located together on the body, perhaps in the same pocket.

The topic of occupational exposures was raised as there are many technologies using high power sources in workplaces using the ISM bands. The situations are complex and the people exposed are not only those using the sources, but also other people in the vicinity. Given the forthcoming Directive on occupational EMF exposures, this is an important issue to address for radiation protection bodies and ministries. There had been important messages in the workshop pertaining to the use of telecommunications devices in occupational scenarios, but it was also important to look at other sources.

There were still felt to be gaps in knowledge where sources are used close to the body, since the number of scenarios considered in the workshop had been not more than five. Another area was that of exposure near to large high-powered transmitter masts, as used for broadcast radio and television.

In drawing the discussion to a close, Mr Matthes asked whether there had been any omissions from the programme and ***whether there were any pressing gaps for future research in this area that had not already been mentioned***.

It was remarked that the exposure results in the workshop had been for specific places, however it would be interesting to gain information about the exposure of people as they move around and over time. As personal dosimeters are now available, it will be interesting to see the results that are obtained.

Gaps were also identified in the range of phantoms available. Much work had been done using the visible human, but there was a need for work to be done with small children, babies and fetuses.

Returning to the biological topics of the earlier sessions, it was felt there was a need for a better understanding of the relationship between temperature rise and SAR in the context of biological effects. In particular, there was a need to look at the time taken to reach a steady temperature state for a given SAR level. In relation to *in vitro* modelling, it was felt important to consider exposures with cells in the dish.

## Final Discussion
## Exposure of the General Public

Dr Weiss thanked all of the participants for their contributions. He said that it had been an interesting workshop with much new information presented and he had learned a lot. He was glad to hear that some of the areas seemed to be well covered since this is a positive message to take back to those funding the programme. He referred again to the four over-arching questions and noted that the answers had been different for the different sessions in the workshop. However, before he returned to the topic of the answers to the questions he asked if any of the attendees would like to raise any issues that had not yet been discussed.

Hands free devices are often recommended to reduce exposure, however data had been presented in the workshop showing that, if a Bluetooth headset is used with UMTS phones, exposure is actually higher. In the light of this and more generally, there were felt to be gaps in knowledge about exposure with wired and hands free devices for mobile phones. Moreover, it was noted that present UMTS phones, although they give very low exposure, have a GSM phone within and the user does not know which mode is being used at a given time.

Very little is known about the correlation between the spatial distribution of incident field over the body and SAR, both in terms of spatial peak and whole-body average. The ICNIRP guidelines allow for spatial averaging with whole-body SAR, however it was felt that this did not make sense for frequencies above the body resonance. It was asked whether ICNIRP was willing to address this question. Dr Vecchia replied that he agreed in principle with the objection and that a better justification for averaging with whole-body and localised exposures is needed. ICNIRP was in the process of revising its guidelines, but ICNIRP could not fill the gaps in evidence. INCIRP provides guidelines based on the best science available, but it could not invent a solution. Dr Weiss felt ICNIRP could give guidance as to which direction for others to go in so they would not head off in different directions. He felt it would be best for ICNIRP to lead the process in a certain direction and then approach scientists in order to gain feedback and solve the practical details.

In terms of gaps for further research, more and more applications need more and more bandwidth and so higher frequencies are being used. Transmissions may be short and of limited power, but this is a new exposure situation. For example, the use of WiMax in the home and workplace has not yet been covered.

On the topic of model complexity, it was noted that the reference levels, which ICNIRP produced in the past, are based on very simple models such as prolate spheroids. The models have been generally supported by more recent data based on numerical calculations with anatomically realistic models, but around a gigahertz there are new data suggesting they are not so conservative, for example with infants whose resonance tends towards that frequency.

It was reiterated that very little is known about occupational exposure and this was felt to be an area that has been strongly neglected. There are occupational exposure situations where fields are close to or even exceed the reference levels, and so it is necessary to use more complex models in assessments to allow the processes to continue. Example processes where complex models are needed are using RF heater sealers or induction heaters, and carrying out live-line working. These assessments require articulated models that can easily be bent into different working positions while preserving the integrity of the internal anatomy. It was felt that such work should continue across the whole spectrum and not just those parts used for telecommunications.

In presenting proposals for future research, it was recommended that gaps in the evidence should not be over-emphasised and that the considerable amounts of data that are available should be stressed. It was felt useful to be able to say that certain gaps had been filled by the programme; however, it was regarded to be the nature of research that there will always be gaps.

In terms of what had been achieved by the projects, it was stated that what has to be done in order to calculate or measure SAR in tissue or in models is now known, even with microdosimetric models. There was a discussion on the use of SAR as an exposure quantity for microdosimetric investigations and it was argued that this was confusing and might lead people to think the SAR value should be compared with the exposure limit. It was suggested that it might be better if such work were to use another basic quantity, such as electric field, rather than SAR to avoid this confusion.

It was felt that further progress could be made in temperature calculations and that there was scope to improve thermal models by including better representations of vascularisation, metabolism and other physiological processes. Changing from SAR to temperature rise as a limit quantity was felt to make no sense at the moment, although it was accepted that it might make sense in the future. A biological perspective was offered in that temperature is a very complex quantity in living animals and even in cells. Physical changes happen in the internal structures of cells when they get heated and so it becomes quite complicated to gain an understanding of temperature. Also, when high SARs are applied to humans, a lot of sweating occurs before there is a rise in core temperature, and the whole metabolism has changed before this point is reached.

The final comment was a question: is more dosimetric knowledge needed to learn more as an academic exercise, or is it required to support some specific public health outcome? There were many possible answers to this question. For example, animal experiments are done to get the best exposure assessments, assessments are done near base stations for risk communication and, they are also done to seek compliance with standards. The question thus became, where are the gaps in the knowledge for those specific tasks and is more dosimetry needed to fill them?

## Summing up

Dr Weiss explained that the four main questions which had been presented were those that he will be asked at the end of the programme and he wanted to gain as much input as possible to formulate the answers to them. He explained that the way forward would be from the session chairs and the rapporteur, together with him, to draft answers to the questions and send them to all those in attendance for comment. Comments should consider such issues as whether anything has been missed out, misinterpreted, or overemphasised. The feedback received will then be discussed and used to revise the answers and then the document will be sent to the attendees again as the final outcome. The rapporteur will take the answers to the questions forward to the final workshop, where they will be presented alongside reports from the other four workshops. Dr Weiss thanked everyone for their attendance and said that he looked forward to getting as much feedback as possible.

Simon Mann
20 November 2006