STUK-A243 / APRIL 2010

A

Microwave Dosimetry in Biological Exposure Studies and in Practical Safety Evaluations

Tommi Toivonen

Säteilyturvakeskus
Strålsäkerhetscentralen
Radiation and Nuclear Safety Authority

STUK

STUK-A243 / APRIL 2010

Microwave Dosimetry in Biological Exposure Studies and in Practical Safety Evaluations

STUK – Radiation and Nuclear Safety Authority
Aalto University School of Science and Technology
Faculty of Electronics, Communications and Automation
Department of Radio Science and Engineering

DOCTORAL DISSERTATION
for the degree of Doctor of Science in Technology to be presented with due permission of the Faculty of Electronics, Communications and Automation for public examination and debate in Auditorium A202 (S4) at the Aalto University School of Science and Technology (Espoo, Finland) on the 7th of May 2010 at 12 noon.

STUK • **SÄTEILYTURVAKESKUS**
STRÅLSÄKERHETSCENTRALEN
RADIATION AND NUCLEAR SAFETY AUTHORITY

Osoite / Address • Laippatie 4 , 00880 Helsinki
Postiosoite / Postal address • PL / P.O. Box 14, FI-00881 Helsinki, FINLAND
Puh. / Tel. +358 9 759 881 • Fax +358 9 759 88 500 • www.stuk.fi

The conclusions in the STUK report series are those of the authors and do not necessarily represent the official position of STUK.

ISBN 978-952-478-522-8 (print)
ISBN 978-952-478-523-5 (pdf)
ISSN 0781-1705

Electronic version published:
http://www.stuk.fi and http://lib.tkk.fi/Diss/2010/isbn9789524785235

Edita Prima Oy, Helsinki 2010

Sold by:
STUK – Radiation and Nuclear Safety Authority
P.O.Box 14, FI-00881 Helsinki, Finland
Tel. +358 9 759 881
Fax +358 9 759 88500

Doctoral dissertation

Aalto University School of Science and Technology
Faculty of Electronics, Communications and Automation
Department of Radio Science and Engineering

Microwave Dosimetry in Biological Exposure Studies and in Practical Safety Evaluations

Author: Tommi Toivonen
STUK – Radiation and Nuclear Safety Authority
Non-ionizing Radiation Surveillance
(NIR-laboratory)
Helsinki, Finland

Supervising professor: Professor Pertti Vainikainen
Department of Radio Science and Engineering
Faculty of Electronics, Communications and Automation
Aalto University School of Science and Technology
Espoo, Finland

Pre-examiners: Professor Luc Martens
Department of Information Technology
Ghent University
Ghent, Belgium

Professor Andrew W Wood
Australian Centre for RF Bioeffects Research
Swinburne University of Technology
Hawthorn, Australia

Opponents: Research Professor Maila Hietanen
Finnish Institute of Occupational Health
New Technologies and Risks
Helsinki, Finland

Professor Yngve Hamnerius
Department of Signals and Systems
Chalmers University of Technology
Göteborg, Sweden

Preface

This work was carried out in the Non-ionizing Radiation Surveillance unit (NIR-laboratory) at STUK – Radiation and Nuclear Safety Authority during 2001–2009. The research work was financially supported by The Finnish Research Programme HERMO, Finnish Funding Agency for Technology and Innovation, Nokia Corporation, Fifth Framework Program of the European Union, Sonera, Elisa Corporation and Finnet Networks Ltd.

First of all, I am very thankful to Tim Toivo for his great work and friendship ever since I started at STUK. This work, as also many others, would not have been possible without him. I also wish to express my sincere gratitude to Research Professor Kari Jokela and Professor Pertti Vainikainen for their invaluable guidance. I am grateful to all colleagues in STUK and co-authors who made this work possible. Especially Lauri Puranen, Risto Pitkäaho and Sami Ilvonen made a great effort in the research included in this thesis. Furthermore, the great skills of Asko Turunen have been an inevitable prerequisite for all these studies. I would also like to express my sincere gratitude to Dr. Riikka Pastila, Hilkka Karvinen and Jaana Joenvuori for their guidance and help in reporting these studies and the pre-examiners, Professors Luc Martens and Andrew Wood for their invaluable comments.

My most special thanks belong to my family Leena, Peppi and Nuppu. Also my parents Anneli and Jorma as well as all other relatives are aknowledged for their invaluable support during this work and in general.

TOIVONEN Tommi. Microwave Dosimetry in Biological Exposure Studies and in Practical Safety Evaluations. STUK-A243. Helsinki 2010, 81 pp + Appendices 47 pp (only in print version).

Keywords: Microwave exposure, *SAR*, exposure limits, exposure assessment, mobile phone, base station

Abstract

This thesis considers the risk evaluation of microwaves from two important points of view. First, the methodology of the exposure studies elucidating the health effects of mobile phones is considered starting from the general aspects of designing setups and proceeding to the assessment of the exposure level (dosimetry) and practical execution of the experiments. Second, the exposure assessment in practical safety evaluations of fixed radio transmitters, such as mobile phone base stations, is studied.

The dosimetry and the exposure setup design are critical for the success of exposure studies since the biological results are worthless if the used exposure level is not known. Furthermore, the experiments with test animals or human volunteers are always very challenging in practice. This work aimed to design, implement and analyse setups for four separate biological experiments. The first experiment related to a novel study of the effects of mobile phone (*GSM*) radiation in human skin *in vivo*. In the second experiment the brain functions of domestic pigs exposed to high level *GSM* type radiation were studied. The third setup was used for long term exposure of over 200 unrestrained rats. The rat setup was further utilised in another experiment searching the effects of microwave radiation on central nervous system of juvenile rats.

The dosimetric analysis was performed by means of numerical simulations in all cases. The simulations were validated by measurements and the uncertainty of achieved results was analysed. The functionality of the setups was proven in practice; all experiments were successfully executed and the results of both methodological and biological studies were reported in peer reviewed journals.

The need for microwave safety evaluations has increased quickly during the last decade. The number of base station (*BS*) antennas has increased rapidly and they are often placed on roof tops etc. where various professionals have to work. Hence, efficient methods for assessing the compliance with exposure limits are needed.

The scope of the work, presented in this thesis, was to study the near field exposure caused by real commercial *BS* models. Experimental measurements

were utilised to achieve a set of specific absorption rate (*SAR*) and electric field data in the near field of six commonly used antenna models. Moreover, one of the antennas was studied in more detail by numerical simulations. The results were further analysed to compare the different methods for checking the compliance of an antenna installation with the exposure limits and to find out how significant the local exposure is as compared to the whole body average at different distances. These results provide useful information for the future revisions of the exposure limits and related measurement standards.

TOIVONEN Tommi. Mikroaaltodosimetria biologisissa altistuskokeissa ja käytännön turvallisuusarvioinneissa. STUK-A243. Helsinki 2010, 81 s. + liitteet 47 s. (vain sidotussa versiossa).

Avainsanat: Altistuminen mikroaalloille, *SAR*, altistumisrajat, altistumisen määritys, matkapuhelin, tukiasema

Tiivistelmä

Tässä työssä käsitellään mikroaaltoaltistukseen liittyvän riskin arviointia kahdesta näkökulmasta. Ensimmäisessä osassa tarkastellaan matkapuhelinten terveysvaikutuksia selvittävien biologisten altistuskokeiden teknistä suunnittelua ja toteutusta sekä altistumistason määritystä eli dosimetriaa. Työn toisessa osassa tarkastellaan kiinteiden lähettimien, kuten matkapuhelintukiasemien, aiheuttaman altistumisen määrittämistä käytännön turvallisuusarviointityössä.

Laadukas dosimetria ja koejärjestelyn suunnittelu ovat välttämättömiä altistuskokeiden onnistumiselle, koska saadut biologiset tulokset ovat hyödyttömiä ilman riittävää tietoa käytetystä altistustasosta. Lisäksi eläimillä ja vapaaehtoisilla koehenkilöillä tehtyihin tutkimuksiin liittyy lukuisia vaikeita käytännön ongelmia. Tämän työn ensimmäiseen osan tavoitteena oli suunnitella ja analysoida altistusjärjestely neljään biologiseen kokeeseen. Ensimmäisessä kokeessa selvitettiin *GSM*-puhelimen aiheuttaman säteilyn vaikutusta ihmisten ihon proteiineihin. Altistus oli ensimmäinen proteiinivaikutuksia selvittävä koe, jossa altistus toteutettiin *in vivo*. Toisessa biologisessa kokeessa tutkittiin korkeiden altistustasojen vaikutusta sikojen elektroenkefalogrammiin (*EEG*) *GSM*-signaalilla. Kolmannessa biologisessa kokeessa tutkittiin tunnetun karsinogeenin ja pitkäaikaisen *GSM*-altistuksen yhteisvaikutusta. Altistuskoe kesti kaksi vuotta ja altistettavia rottia oli yli kaksisataa. Neljäs biologinen koe tehtiin samalla rottien altistamiseen suunnitellulla laitteistolla. Siinä selvitettiin *GSM*-tyyppisen mikroaaltosäteilyn vaikutuksia nuorten rottien kehittyvään keskushermostoon.

Dosimetrinen analyysi perustui kaikissa neljässä kokeessa numeerisiin simulointeihin. Simulointitulokset validoitiin kokeellisilla mittauksilla ja tulosten epävarmuudet arvioitiin. Lisäksi kaikki laitteistot osoittautuivat käytännössä toimiviksi. Kokeet suoritettiin onnistuneesti ja sekä dosimetriset että biologiset tulokset raportoitiin vertaisarvioiduissa tieteellisissä julkaisuissa.

Kiinteiden radiolähettimien turvallisuusarviointien tarve on lisääntynyt merkittävästi viimeisten kymmenen vuoden kuluessa, etenkin

matkapuhelintukiasemien yleistymisen myötä. Tukiasemia asennetaan muun muassa katoille, joten monet ammattiryhmät joutuvat työskentelemään jatkuvasti niiden läheisyydessä. Tukiasemien suuren määrän vuoksi tarvitaan tehokkaita ja nopeita turvallisuusarviointimenetelmiä.

Tämän työn toisessa osassa tutkittiin kaupallisesti saatavilla olevien tukiasema-antennien aiheuttamaa altistumista lähikentässä. Kuuden antennimallin aiheuttamat häiriintymättömät lähikentät ja ominaisabsorptionopeudet (*SAR*) mitattiin laboratoriossa. Lisäksi yhdestä antennista tehtiin numeerinen malli altistuksen simuloimista varten. Kentänvoimakkuus- ja *SAR* tuloksia vertailtiin erilaisten turvallisuusarviointimenetelmien toimivuuden arvioimiseksi. Lisäksi tutkittiin koko kehon keskiarvona määritetyn ja paikallisen *SAR*-arvon suhdetta eri etäisyyksillä antennista. Tuloksia voidaan hyödyntää tulevaisuudessa mittausstandardien ja altistumisrajojen kehitystyössä.

Contents

List of publications

[P1] Toivonen T, Toivo T, Puranen L, Jokela K. 2008. Setup and Dosimetry for Exposure of Human Skin *In Vivo* to *RF-EMF* at 900 MHz. Bioelectromagnetics 29:207–212.

[P2] Toivonen T, Toivo T, Pitkäaho R, Puranen L, Silfverhuth M, Mennander A, Hannula M, Hyttinen J, Jokela K. 2008. Setup and Dosimetry for Exposing Anaesthetised Pigs *In Vivo* to 900 MHz *GSM* Mobile Phone Fields. Bioelectromagnetics 29:363–370.

[P3] Puranen L, Toivo T, Toivonen T, Pitkäaho R, Turunen A, Sihvonen A-P, Jokela K, Heikkinen P, Kumlin T, Juutilainen J. 2009. Space Efficient System for Whole-Body Exposure of Unrestrained Rats to 900 MHz Electromagnetic Fields. Bioelectromagnetics 30:120–128.

[P4] Toivonen T, Toivo T, Puranen L, Jokela K. 2009. Specific Absorption Rate and Electric Field Measurements in the Near Field of Six Mobile Phone Base Station Antennas. Bioelectromagnetics 30:307–312.

[P5] Ilvonen S, Toivonen T, Toivo T, Uusitupa T, Laakso I. 2008. Numerical Specific Absorption Rate Analysis and Measurement of a Small Indoor Base Station Antenna. Microwave and Optical Technology Letters 50:2516–2521.

Contributions of the author

[P1] This author had the main responsibility for the study, including designing the setup, executing the simulations, analysing the data and preparing the article. The validation measurements in the study, as well as the actual exposures, were designed and made in co-operation with Tim Toivo.

[P2] This author had the main responsibility for designing the setup and preparing the article. The numerical simulations were made by Risto Pitkäaho. The validation measurements were designed and made in co-operation with Tim Toivo.

[P3] Lauri Puranen had the main responsibility of this study. This author participated in designing and executing the measurements and assisted in preparing the article

[P4] This author had the main responsibility for preparing the article and assisted in the measurements. Tim Toivo had the main responsibility for the measurements. The data analysis was made in co-operation with Tim Toivo and Kari Jokela.

[P5] Sami Ilvonen had the main responsibility for this study. This author participated in designing the study and preparing the article. This author also designed and made the measurements in co-operation with Tim Toivo.

1 Introduction

1.1 Background

The health effects of microwave exposure have been investigated in thousands of studies. The early studies concerned often thermoregulation and acute thermal health effects, for example, hearing effects or cataract, caused by intense microwaves of radars [1]–[5], while present studies are often aimed to elucidate the risks related to mobile communications systems and other new emerging technologies. The knowledge on the acute effects exists and, based on this, the public authorities in most countries have established exposure limits to protect people [6]. However, studying biological basis of these limits is a very challenging and interdisciplinary task and, despite the large number of studies, the lack of conclusions on the existence of effects at lower exposure levels still remains.

The risk assessment is basically made by studies which can be roughly divided into groups of epidemiological studies and exposure studies. Furthermore, the exposure studies can be divided into experiments with human volunteers or animals *in vivo* and studies with isolated cell cultures or tissues *in vitro*. The epidemiological studies are searching adverse health effects, or lack of such, directly in human population and hence they are often considered the most suitable type of studies when assessing the safety in general [7]. However, the ability of the epidemiological studies to find weak effects (sensitivity) is depending on the ability to divide studied people into groups based on their exposure level. This is a major problem in mobile phone studies due to, for example, the adaptive power control of the phones. Other limitation is that the studies are concentrated on certain diseases, typically cancers, while the results give no information on other risks. For these reasons, the ability of epidemiological studies alone to assess the overall risk is limited, especially in cases when no statistically significant effects are found.

The exposure studies are made, with animals or human volunteers, in controlled conditions and hence many of the methodological problems can be overcome much easier than with epidemiological studies. One great limitation is that the link between laboratory results and real life is often difficult to establish. The biological effect *in vitro* is far from adverse health effects in humans, therefore positive findings do not necessarily mean lack of safety nor negative findings guarantee it. However, the exposure studies are a significant part of risk evaluation because with these studies very sensitive biological methods can be utilised to detect weak effects. Hence, the interaction mechanisms could be tested prior to epidemiological studies to generate sufficient hypotheses. The *in vitro* studies give the highest sensitivity but weakest connection to effects

in human population. Using animals causes some loss in sensitiveness yet the extrapolation is more reliable from another living mammal to humans than from a cell culture in a Petri dish. Finally, human volunteers could be used in exposure studies but the ethical reasons often limit the research methodologies significantly decreasing the sensitiveness of the study.

In practice, the overall risk assessment can only be done by pooling all available results of similar studies and connecting all study types. To make this process possible, it is crucial that all studies are published with sufficient information about the exposure conditions. Therefore the exposure assessment (dosimetry) is an inevitable part of this field of science.

The specific aim of the whole risk assessment process is to define the exposure levels that can be considered safe. The importance of dosimetry extends beyond this goal, since exposure limits would be worthless without the capability to assess the exposure level in practical conditions, such as working sites in the vicinity of radio transmitters.

1.2 Objectives of the work

The main scope of this work was to increase the knowledge on the methodologies supporting the microwave risk assessment, especially related to the use of mobile phones. This subject was studied starting from the point of view of experiments elucidating the health effects of mobile phones and proceeding to the practical safety evaluations of mobile phone base stations.

The first part of this work includes the methodological part of four biological exposure studies elucidating the health effects of mobile phones. The main objective of the work, presented in this thesis, was to design and implement setups and conduct reliable dosimetric analyses for these biological studies. Moreover, this work aimed to ensure the possibility of further utilisation of the achieved biological results in the future pooled analyses by extensive reporting of the used methods and the exposure conditions. The specific scope of this thesis is to study and summarise the lessons learned about the following research questions:

- What are the main factors in setup designs affecting the accuracy/ uncertainty of the dosimetric assessment?
- What are the main factors in setup design affecting the reliability of the dosimetric assessment?
- Which methods can be used for the validation of dosimetric simulations?
- What are the main technical and practical limitations to be taken into account in setup design?

The second part of this work presents a different, yet at least equally important view on the safety of mobile phone systems. The methods for the estimation of exposure in practical radiation safety assessments are studied in relation to the existing exposure safety standards. The means to analyse the exposure caused by mobile phone base stations are studied in two papers included in this thesis. The objective of these studies was to evaluate the applicability of numerical and experimental methods in practical dosimetric analyses. An important task was also to provide novel information on the near field exposure of widely used antenna types to be used for the standardisation purposes and in practical radiation protection.

1.3 Contents of the thesis

This thesis is divided into two parts. The first part consists of the exposure setup studies presented in the publications [P1]-[P3]. The scientific background of exposure setups, common to all three publications, is summarised and discussed in the first section based on the available literature and experiences achieved during this work. The formulation of the biological hypotheses and the resulting requirements are considered as well as the setup design and selection of exposure parameters. In the second section, the methods of numerical dosimetry are discussed. In the third section, the validation methods for dosimetric analyses are introduced. The specific results and solutions of the setup design, dosimetry and validation of the studies presented in [P1]-[P3] are summarised in the end of each section.

Publication [P1] introduces a setup for exposing the forearms of human volunteers to study microwave exposure -induced protein changes in humans *in vivo*. The study presented in [P2] resulted in a setup for delivering high microwave exposures to the brain of anaesthetised domestic pigs to find out whether the exposure causes changes in the electroencephalogram (*EEG*). The setup developed in the study presented in [P3] enabled the simultaneous exposure of over 200 rats while minimising the stress of the animals caused by the restraining and handling. The setup was first used in the study searching the combined effect of a known carcinogen and microwave exposure in rats. The same rat exposure setup was also used in a study looking for the effects of microwave exposure on the developing brains of juvenile rats. All three setups have proven their capability in practice; a pilot study of ten testees was made using the human exposure setup, 11 experiments were successfully executed with domestic pigs and two long term studies with rats were conducted [8]–[11].

The second part of this thesis includes two studies concerning dosimetry in practical safety evaluations in the close proximity of mobile phone base stations

(*BS*). These studies are presented in [P4] and [P5]. For the background, the relevant safety standards and exposure assessment procedures are introduced. Furthermore, the work made in these two studies is introduced and their results summarised. In [P4], a novel set of specific absorption rate (*SAR*) measurement results of six *BS* antennas is presented together with electric field values in free space at corresponding distances. One of the antennas is further studied by numerical simulations described in [P5]. The data is used to study the validity of the exposure assessment methods presented for example in [12]. Moreover, the results can be utilised for future revisions of exposure guidelines and related measurement standards.

2 Biological exposure studies

2.1 Introduction

The scientific research related to human health is unavoidably an inter-disciplinary effort. The final aim of the research is to discover, explain, predict and manage the possible threats confro-nted by the human population in its living environment. The medical sciences are from the beginning tied with epidemiological, biological and engineering sciences in this task. The biological studies on the effects of microwaves are good examples of the importance of this co-operation.

Such a study is basically an experiment where a hypothesis of a certain biological effect is tested by irradiating humans or animals *in vivo* or cells *in vitro* by microwaves. The physical and biological methodologies for these experiments are various and there is no single correct solution for all purposes. The experimental planning of these studies can, however, be divided into the following important phases:

- Formulation of the hypothesis of a health effect
- Design and implementation of the exposure setup
- Dosimetry and its validation
- Execution of the irradiation, and
- Analysis of the biological results

The work made for this thesis concentrated on the setup design and dosimetric analysis for the *in vivo* studies. The formulation of biological hypotheses and the analysis of the results are out of the scope regarding this thesis. However, the studied biological effects as well as the biological research methods set the main requirements on the experimental planning. The evaluation of the suitable exposure parameters is the most challenging part of the setup design, not least because of the lack of well established direct (non-thermal) interaction mechanisms of the microwaves and biological processes. Therefore, the relation of biological hypotheses on one hand and exposure distribution, level and signal on the other hand are discussed in the beginning of this chapter based on the available literature. In this context, the solutions used in [P1]-[P3] are summarised.

The dosimetric analysis of a setup is basically the assessment of the exposure level as a function of microwave power fed to the system. The preferred exposure level, or levels, can be generated based on this information within the bounds of available power. The analysis is typically made by means of numerical simulations. Furthermore, it is crucial that the reliability of the achieved results is validated and the uncertainty of the assessment is estimated. These issues

are discussed in the latter sections of this chapter. Moreover, the results of the dosimetric analysis and validation presented in [P1]–[P3] are summarised.

2.2 Exposure setup design

This section summarises the basic requirements and challenges of designing an exposure setup. First the basic concepts of main exposure parameters are introduced and discussed whereas and the setups developed in the studies [P1]–[P3] are presented in this context at the end of this section.

2.2.1 The distribution of exposure

The spatial distribution of the exposure should be selected so that the biological hypothesis is tested effectively. In mobile phone studies the exposure distributions resembling a regular phone call are a typical choice, yet other exposure types, such as uniform whole body exposure, can be reasonable as well. The selection of exposure distribution is, however, very much limited by the exposed animal species.

The uniform whole body exposure is often used especially for small animals, such as rodents. Several implementations have been reported in the literature, such as [13]–[19]. The strength of an exposure distribution covering uniformly the whole body is that the origin of the studied biological effects can be anywhere in the body. The drawback is that the required setup is often very complicated. In the microwave frequencies the attenuation of incident wave in biological matter is fast which is why the uniform whole body exposure of larger animals or human volunteers is impossible.

Typical exposure distribution in mobile phone studies with human volunteers covers the area of the brain or parts of it. A setup delivering extended and smooth exposure distribution to the target hemisphere has been reported in [20]. Here, the exposure is imitating the combination of distributions of most phone models at the time. Moreover, many setups delivering a distribution of a single commercial model have been described, as for example in [20]–[22]. The benefit of using extended distribution is that the results represent a wider range of practical exposure scenarios. On the other hand, the extended spatial distribution is not a general solution for all cases. For example, in studies of effects based on changes in local metabolism [23], the non-exposed areas in the head are as significant as the exposed areas because of the heat transfer towards lower temperatures (i.e. lower exposure). Extended brain area distribution does not actually represent the exposure of any single phone model alone, and therefore other solutions, such as real commercial phones or simple dipoles can

be better. In case of animal exposures, the typical mobile-phone-use-distribution evidently does not exist which is the reason there is no clear justification of any specific distribution for the brain area. The irradiation could be therefore realised more freely according to the technical limitations of the study.

A few other types of exposure distributions have been reported. The reasons to expose other parts of the body than head vary from organ specific effects [2] to cosmetic reasons in human studies causing that punch biopsies cannot be harvested from visible areas [P1].

2.2.2 Exposure level

The microwave exposure level is generally defined as the amount of power absorption in tissues. The used measure is the specific absorption rate (*SAR*) which, in particular, describes the power absorption per unit mass (W/kg) and thus the thermal load targeted to the tissue. The definition of *SAR* is presented in Equation (1).

$$SAR = \frac{\sigma \cdot E^2}{\rho} = C\frac{\partial T}{\partial t} \quad , \tag{1}$$

where σ is the electrical conductivity (S/m) and ρ mass density (kg/m^3) of the tissue and E is the root-mean-square value of the electric field strength (V/m) in the tissue. C is the heat capacity of the tissue volume under consideration, T is the temperature and t time.

The exposure level and its effect on a biological study have to be considered carefully in experimental planning. A common approach is to select exposure levels that are present in typical living environment. This has been made in numerous reported mobile phone studies; the exposure level has been typically in the same order of magnitude than the exposure of real mobile phones, i.e. the *SAR* is somewhat below 2 W/kg [24]–[34]. In the head of a human this results in a temperature rise in the order of 0.1°C [35]. If an effect is found at this exposure level, it is an interesting and significant scientific discovery because here the effect cannot be explained by any known interaction mechanism. A well-established effect based on unknown interaction mechanism would make the present knowledge and the basis of current exposure limits questionable. The drawback of this approach is that in case no effect is found, the results reveal actually nothing new.

Another approach is to use as high exposure level as possible while, for example, metabolic cooling still prevents harmful heating. It is reasonable to assume that using a higher *SAR* level will increase the probability of finding the hypothesised effect [36], [37]. Therefore, this approach improves the value

of evidence in case no effect is found. In case an effect is found, the experiment can be repeated at lower *SAR* levels to find out if the effect is significant with respect to present exposure limits. However, if the temperature rise caused by the exposure is too high, the thermal interaction mechanisms can cause, for example, protein coagulation or other known adverse effects [6], [38], [39]. These effects can mask the possible effects of non-thermal origin, in which case the results provide no new information. It is therefore an important task in experimental design to estimate the temperature rise caused by the exposure.

Equation (1) can be applied to make an estimate on the temperature rise. Here, the cooling effect of blood circulation and heat conduction is not taken into account, and therefore the temperature is overestimated especially in case of long exposures. More accurate approximation formulas are useful, especially if the maximal *SAR* levels are preferred. The bio heat equation of Pennes, Equation (2), can be applied in case of local exposure and moderate temperature rise [40]. However, the availability of adequate data on metabolic cooling and tissue parameters for the exposed animal species and body part could be a problem.

$$\rho c \frac{\partial \boldsymbol{T}}{\partial \boldsymbol{t}} = \nabla \cdot \boldsymbol{k} \nabla \boldsymbol{T} - \boldsymbol{c}_b \boldsymbol{W}_b \left(\boldsymbol{T} - \boldsymbol{T}_{art} \right) + \rho \boldsymbol{SAR} \ , \tag{2}$$

where ρ is the density, c is the specific heat capacity and k thermal conductivity of the tissue. W_b is the perfusion of the blood flow, c_b specific heat capacity of blood and T_{art} the temperature of the incoming blood flow.

A temperature rise estimate can be made also by measurements during the exposure, since measurement equipment immune to intense microwaves are available [41]. However, the insertion of a probe directly to the studied area may damage the tissues and cause physiological changes. The temperature can be measured for example at the skin surface, ear canal, or under the skin [42], [P2]. The measured temperature change is, however, not the same deeper in the tissues. The fast attenuation of the incident wave and differences in absorption caused by variations of dielectric properties between different tissue layers (e.g. skin, fat, bone, muscle) limit the accuracy of this method significantly.

2.2.3 Exposure signal

The exposure studies are often conducted using a signal type characteristic to the studied technology, for example, a *GSM* or *UMTS* signal for mobile phone studies, as in [8]–[13]. Another possibility is to use a continuous wave (*CW*) signal, as in [43] and [44]. Selecting the technology-specific signal seems to be a straight-forward solution, yet it needs some considerations.

The strength of using the specific modulated signal, as compared to *CW* exposure, is that the experimental conditions are that way closer to the actual exposure conditions in everyday life. Hence, the results of a study have more credibility in the overall risk evaluation of certain technology, such as the *GSM*-type mobile phones. However, there are also many drawbacks in using specific signals. The most important disadvantage is that the use of dozens of different signal types and frequencies decreases the number of comparable studies significantly. New technologies are adopted all the time which makes the future pooled analyses problematic. Moreover, the use of a specific signal may increase the complexity and costs of an exposure setup. For example, a *GSM*-type pulsed signal requires approximately 8 times larger *RF* power amplifier than a *CW* signal for the same average power.

Because of the abovementioned drawbacks of using a specific signal, *CW* is preferred in general. Specific signal types should be used only if it is justified by the hypothesis of the study. In this respect, the study hypotheses of exposure studies can be divided into the following groups:

- No effect (null hypotheses)
- Effects based on thermal interaction mechanisms
- Effects that cannot be explained by any known interaction mechanism

Effects based on slow (e.g. in the order of minutes) thermal interaction, such as changes in body temperature or metabolism, can evidently be tested using *CW*. However, there are examples on suggested modulation-specific phenomena that are based on fast thermal interaction, such as microwave hearing, which should be studied using specific signal type [2], [6]. Also in case of a null-hypothesis or when the studied effect cannot be explained by any known interaction mechanism (such as in [10]), the studies clearly benefit from using a specific signal, because the possibility of modulation-specific interaction mechanisms cannot be neglected. In these cases, however, using both *CW* and a specific signal is a good choice, as has been done for example in [45]–[50]. This procedure generalises the results and makes the study comparable with other studies made with different signals.

2.2.4 Exposure setups

The system for realising the selected exposure distribution, level and signal contains typically at least a signal source, power amplifier, instrumentation for *RF* power measurement, suitable cables and controls and the actual exposure source, i.e. the device that delivers the *RF* power to the preferred part of the body. An example of such a setup is presented in Fig. 1. Besides the source,

the instrumentation can be realised using standard commercially available equipment. The need for accuracy and usability should, however, be considered in the design process to avoid loss of data or excessive costs.

The implementation of the actual exposure source depends strongly on the preferred spatial exposure distribution and the *SAR* level, which is why a large number of different implementations have been reported. The devices can be divided roughly in two categories, the antennas and the closed systems.

The antennas are especially suitable for exposing human volunteers or large test animals. Dipoles and monopoles are used in many studies, for example in [15], [45], [51], and [52]. Open ends of waveguides as well as horn antennas are used for example in [53], [54] and a parabolic reflector antenna in [55]. Also more specific antennas are designed for preferred exposure distribution, such as dipole array and patch antenna setups presented in [51]. The advantages of antenna type sources are the flexibility in setup design and often also the simplicity. On the other hand, the surroundings of the exposed area affect to the exposure and the *RF* power is not used efficiently if the source is not in the very close proximity of the exposed object. Moreover, the possibility of radio disturbances might cause limitations to the power levels and frequencies or require a shielded laboratory.

The closed systems consist of some type of an exposure chamber and a coupling element which feeds the microwave power via the coaxial cable to the chamber. Closed systems have been utilised especially for the whole body exposure of small animals and for *in vitro* studies. The exposure could be implemented with rectangular waveguides, as in [13], [56] and [57], *TEM* cells, as in [58], and other transmission lines and resonators, such as reverberation chamber [14], combined horn antenna and chamber [59], and modified coaxial line [60]. The advantage of the closed system is the efficiency, i.e. the ratio of *SAR* in the exposed animal and the output power of the *RF* amplifier. Also the boundary of the calculation volume in the dosimetric simulations is well defined. The drawback of the closed systems is often the strict space limits for the exposed animals. Most systems are also sensitive to the movements of the animal, which leads to difficult optimisation of the needed dosimetric accuracy and, for example, restraining stress of the animals.

2.2.5 Setups designed in this thesis

Setup for exposing human volunteers

The setup presented in [P1] relates to a novel biological study for researching the protein level effects of 900 MHz *GSM*-type microwave exposure. Protein

and other cell level effects of microwave exposure have been widely studied *in vitro*, for example in [47]–[50] and [61]. Yet, thus far our experiment was the first to study the protein effects with human volunteers exposed *in vivo*, thus such a setup has not been reported previously. The setup is illustrated in Fig. 1 and Fig. 2.

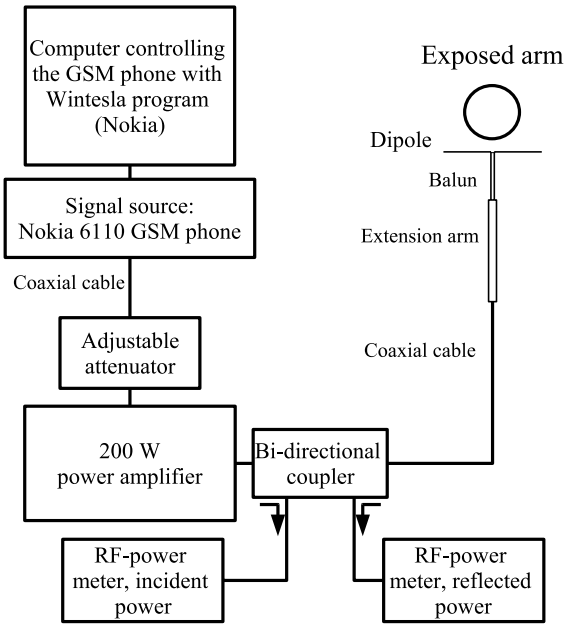

Fig. 1. A schematic diagram of the setup for exposing human skin *in vivo* to *GSM*-type *RF* fields at 900 MHz.

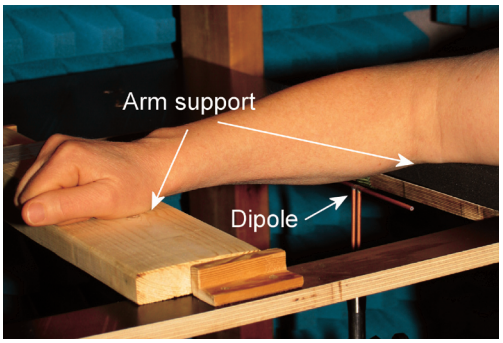

Fig. 2. Setup for exposing the skin of the forearms of human volunteers to 900 MHz microwaves.

The forearms of the volunteers were exposed to *SAR* of 1.3 W/kg for one hour, after which 5 mm skin biopsies were collected from the exposed region for protein analysis. Control skin samples were collected from the non-exposed forearm. An experiment with ten volunteers was successfully conducted. Indications on protein changes were found in the study. The complete results of the biological study are published in [8].

A half wave dipole, constructed for this purpose, was used as an exposure source. A maximally simple exposure source was used because the size of the studied skin sample was small and the exposure distribution outside the sample was not critical. The frequency tuning of the dipole was made mainly by adjusting the length of the balun and the dipole itself. The matching of 15 dB for the dipole in the exposure position (phantom) was achieved and the matching was better than 10 dB in a 100 MHz band. Moreover, the dipole was designed so that fine tuning was possible by adjusting the width of the gap between the dipole arms. The broadband input impedance measurements were made and the dipole was tuned mechanically to adjust the centre frequency accurately to the exposure frequency. Careful tuning of the dipole was important because the variations between the exposed individuals affected the centre frequency and matching. Here, the matching was better than 13 dB in all exposures.

The exposure level, 1.3 W/kg, was selected so that it is close to the exposure level of real mobile phones. Using significantly higher exposure levels would have posed a risk of masking effect caused by temperature increase in the studied tissue. The exposure was made with a *GSM* voice call signal. A *GSM* signal was selected because the experiment was a continuation in a series of *in vitro* experiments showing protein effects caused by *GSM*-type microwave exposure. This *in vivo* experiment was a pilot phase of a larger study. Further investigations with *CW* signal can be made later with the same setup in order to study whether the protein changes are only specific to the *GSM* signal.

Setup for exposing anaesthetised pigs

The setup designed in [P2] was used to study whether high level microwave exposure can cause changes in the *EEG* of domestic pigs. The effects of mobile phone exposure on the *EEG* of humans have been widely studied, for example in [29], [30] and [37]. However, such an experimental setup with pigs has not been previously reported. The setup is shown in Fig. 3.

The pigs were deeply anaesthetised to enable physiologically more stable experimental conditions and lower disturbances in the *EEG* pattern, compared with un-anaesthetised animals. The heads of the pigs were then exposed to *GSM*-type microwaves at 900 MHz. The *EEG* was monitored simultaneously with the exposure. The exposure procedure consisted of short (a few seconds)

bursts at two different *SAR* levels (31 W/kg and 7.3 W/kg). The changes in the *EEG* were monitored especially at the moments of switching the exposure on and off. After the short bursts, the pigs were exposed continuously for ten minutes at the *SAR* level of 31 W/kg. The experiment with eleven pigs was successfully conducted with the setup. The exposure seemed to cause no alterations in the *EEG*. The specific results are presented in [9].

The *EEG* is a measure of brain functions, and therefore the exposure was targeted in the head. The most challenging part in designing the setup was the overall complexity of the experiment, including the simultaneous recording of the *EEG*, the use of respirator, maintaining of the anaesthesia and several other tasks. These caused many additional elements to be taken into account in dosimetry. A simple dipole-type exposure source was therefore considered preferable.

The exposure source used also in [P1] was modified for this study. The dipole was located above the head in the middle of the brain where it produced a relatively uniform exposure distribution in the brain area. The distance of the source to the skin was increased to 20 mm because otherwise the ears of the pig would have touched the antenna. The decreased loading resulted in slightly narrower bandwidth. The matching was, however, better than 10 dB in an 80 MHz band. The fine tuning of the dipole was made in the beginning of the first exposure session by adjusting the gap between the dipole arms. The

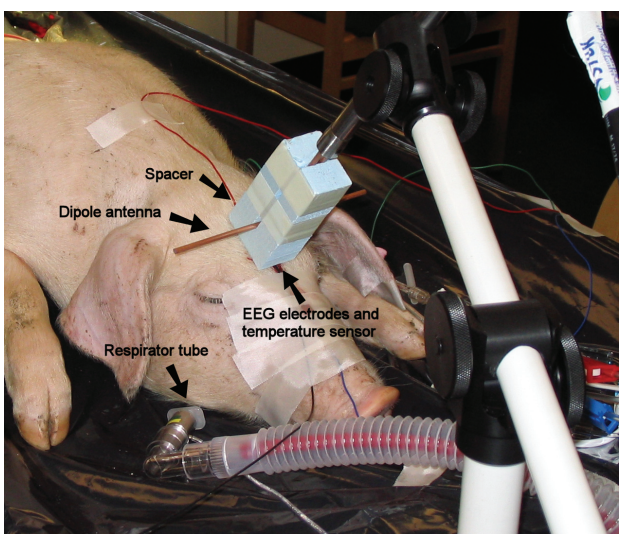

Fig. 3. Setup for exposing anaesthetised pigs to 900 MHz microwaves.

anatomical differences between the exposed animals affected the matching but because the centre frequency was accurately tuned, the matching remained above 15 dB in all exposures.

The *EEG* leads in the vicinity of the source have been reported to receive unwanted interference from the *RF* field [62]. In our setup this was taken into account by locating the *EEG* leads, located closest to the antenna, perpendicular to the electric field. The interference level was tested by attaching the *EEG* leads to a phantom (no *EEG* signal) and irradiating it with significantly higher power level than in the actual exposures (200 W). No interference was observed.

The exposure levels were very high and therefore it was necessary to monitor the temperature rise of the tissues. The subcutaneous temperature rise below the antenna was measured with a small fluoroptic temperature probe which does not interfere with electromagnetic fields.

The exposure signal was a standard *GSM* voice call. Experiments with *CW* would have been interesting. Yet, this would have required sacrificing of additional animals, which was found unnecessary since any effects were not found.

Setup for exposing rats

The study presented in [P3] introduces a setup for whole body exposure of rats to *GSM*- type microwaves at 900 MHz. The requirements for the setup were very strict, including the exposure or sham exposure of 216 rats simultaneously while minimising the stress experienced by the animals (e.g. the floor area of 350 cm^2 in a cage required for each rat), and the limited available laboratory space for the whole setup. The chamber is illustrated in Fig. 4. Altogether, nine chambers were constructed. The setup has been successfully used in two studies. The first experiment was made for studying a combined effect of a known carcinogen and microwave exposure (cocarcinogenesis study). The exposures extended up to two years, after which the animals were sacrificed and the tumour incidences were observed by histopathological analysis. The second experiment was made to study effects of microwave exposure on central nervous system of developing juvenile rats (*CNS* study). The results of the cocarcinogenesis study showed no difference in tumour incidences between the exposed and non-exposed groups. In the CNS study, many biological indicators were studied. The only statistically significant difference was the improved learning and memory in one test (Morris water maze) in both exposed groups as compared to non-exposed group. The results of these studies are published in [10] and [11].

The setup was originally designed for the cocarcinogenesis study in 2000. By that time, there were several reports on setups for exposing rodents [19], [56] of which some setups of these were also capable to expose unrestrained animals

[63], [64]. However, none of the previous designs fulfilled the requirements of the laboratory space limitations, effective use of microwave power and frequency range of this study. The main shortcomings in previous designs for our purposes were that the animals were restrained and / or the use of laboratory space was not efficient. In this setup, the maximum number of test animals per square meter of laboratory was 24, whereas the best of the other implementations

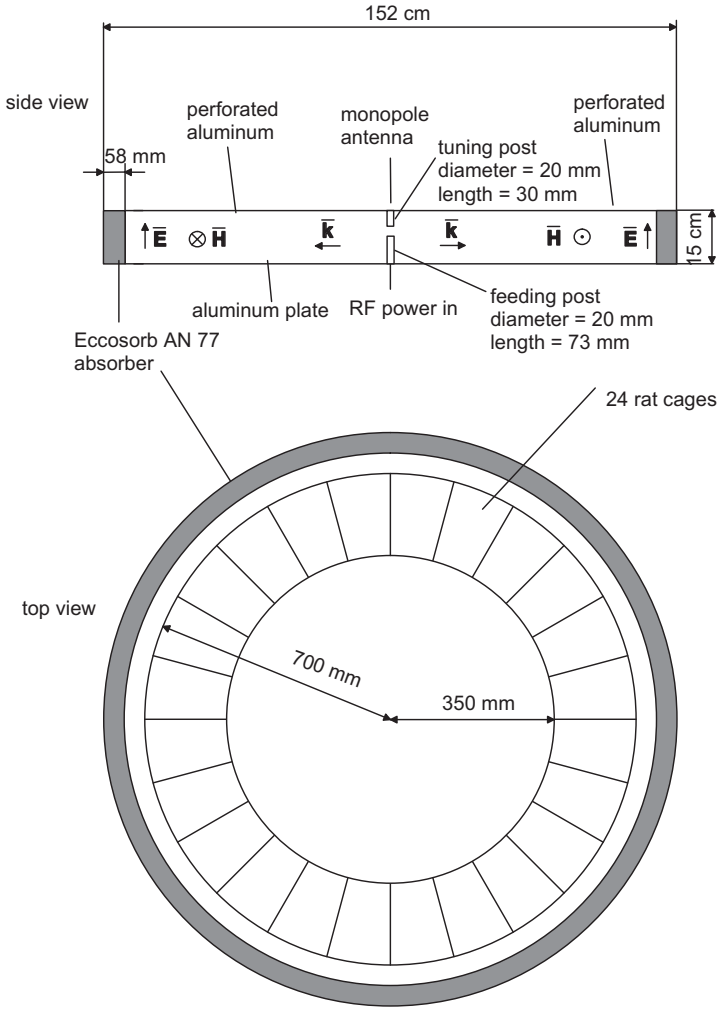

Fig. 4. A schematic diagram of the exposure chamber used in two long term exposure studies of rats. Nine identical chambers were constructed for simultaneous exposure of over 200 test animals.

allowed only 7 unrestrained animals (hamsters) [63]. The space efficiency of our setup has not been exceeded in any setups reported afterwards so far.

In this study the stress of the animals caused by the handling was minimised by designing the setup so that the rodents could stay in the exposure cages continuously. They were moved away from the exposure cages only for weekends to allow the cleaning and sterilising of the exposure chamber.

The mechanical construction of the chambers was very challenging. The optimisation between the tolerances, material thicknesses, weight, usability, rat gage size requirements and many other practical factors resulted that the mechanical tolerances were relatively large. The chambers differed from each other for example due to the mechanical distortion of the circular plates. Any effects caused by variations in individual exposures of rats due to these mechanical differences were precluded by changing the positions of each rat continuously during the exposures.

Because of the mechanical differences the chambers also had to be individually tuneable. This was implemented by using an adjustable (length) feeding probe to insert the *RF* power to the chamber. After the tuning input matching was better than 12 dB for all chambers loaded with medium sized phantoms. This was adequate to ensure that the changes in matching due to, for example, the growing or movements of the rats did not cause a significant error to the input power assessment.

In both the cocarcinogenesis and the *CNS* study, the exposed animals were divided into three groups. One group was not exposed (sham control). The second group was exposed to lower and the third to higher *SAR* levels. The *SAR* levels were 0.4 W/kg and 1.3 W/kg in the cocarcinogenesis study and 0.27 W/kg and 2.7 W/kg in the *CNS* study. Two different exposure levels were used to study the thresholds of any possible effect. If effects were found, it would have been an important addition to the results to see if the threshold of that particular effect was in between these two exposure levels. A *GSM*-type 900 MHz signal was used in both studies. The studies were very time-consuming and additional exposure routine for *CW* was therefore not possible due to the resource limitations.

2.3 Dosimetric analysis

The dosimetric analysis is essentially estimation of microwave power absorption in the exposed tissues in terms of microwave power fed to the setup. The absolute level of exposure can be adjusted by changing the input power. The exposures to all body parts and tissue types, relevant to the study hypotheses, have to be considered.

The methods of dosimetric assessment are basically *SAR* measurements, analytical solutions and numerical simulations. The *SAR* measurements are, in practice, possible only in homogeneous liquids and analytical solutions are limited to very simplified geometries. However, real biological materials contain geometrically complex boundaries and mixtures of solids and liquids. Hence, adequately detailed dosimetric information on the exposure setups can be achieved only by means of numerical simulations. The analytical solutions and experimental measurements can be used mainly in order to validate the reliability of simulations.

The simulation requires basically a numerical model including the source, the exposed object and the environment affecting the fields and a computing algorithm for solving the fields. A very widely used algorithm for dosimetric assessments is the finite difference time domain (*FDTD*) [65]. Well validated software packages and various numerical models have been made available during the last decade [66]–[70]. Therefore, the method was used in the studies included in this thesis, without going into more details of computing science. The numerical models and simulation procedures for dosimetric assessment are, however, case-specific. The system level procedures for conducting the simulations are discussed in this section as well as the available numerical models and model generation. In the end of this section, the specific results of dosimetric evaluations of [P1]–[P3] are summarised.

2.3.1 Simulation procedure

The conventional hardware-based limitation in simulations is the available computer memory. Moreover, a convenient simulation time is limited somewhere between few minutes or one day depending on the required amount of simulations. The voxel size should be less than one tenth of the wavelength in *FDTD*, i.e. 1–4 mm in the mobile phone bands in the tissue. The memory usage per one voxel is approximately 30 bytes, which is why the modelling of, for example, an adult human with uniform voxel grid takes up to 20 GB of memory. Moreover, the required amount of floating point operations is approximately $1000\times(\text{number of voxels})^{(4/3)}$ [71], resulting that the 20 GB grid takes more than two days with a 3 GHz computer.

These limitations lead to the fact that the dosimetric analysis in practice cannot be made by simulating accurately all objects inside a volume that encloses the source and the exposed parts. Furthermore, since the exposures are often made in the complex near field, the decision on which parts of the actual setup are modelled accurately and which parts can be simplified or left out cannot be

solved analytically. Therefore, the dosimetric analysis starts from an iterative process of generating the simulation model. Simplified models are first used to assess the significance and required accuracy of the different parts of the setup. In the final simulations all available memory and calculation capacity can be used to significant parts while unimportant parts can be left out.

Since the basic model with adequate details has been generated, the next step is to find out how well the model represents the actual setup. The exposed individuals, humans or animals, differ from each other anatomically. Moreover, the mechanical dimensions and electrical properties, used in the model, differ from the actual values due to the measurement uncertainty and movements of the exposed objects. The effects of these variations on the *SAR* are assessed by numerous additional simulations with a modified numerical model. The exposed object and the dimensions and parameters of the setup are varied in comparison with the basic model so that the studied cases cover the anatomical differences, possible postures, and uncertainties of other parameters present in the actual setup. The range of variations, assessed by these simulations, is the main contributor to the overall uncertainty of the dosimetry. These variations are considered in more detail in the following sections.

2.3.2 Numerical models

The numerical model for dosimetric assessment includes the source, the exposed object and the surroundings that influence the exposure. The accuracy and the spatial resolution of the dosimetry are conventionally limited by the quality of this model. The model is in practice an array of calculation cells, each cell describing the electrical properties of material located in a certain point in calculation space, and the electrical sources and termination of the calculation grid. The models can be made by the model generator included in the *FDTD* software packages or based on the available *CAD* (computer-aided design) or voxel data. These options are discussed in this section.

Source models

The source is a crucial part of the numerical model. The radiating structures include typically very small but important details which can increase the memory requirements significantly. Thus the possibilities for modelling are one of the major selection criteria for the exposure source and mechanically simple radiating structures are preferable.

The simplest antenna type sources can be modelled directly based on the physical dimensions of the structure. The dielectric properties of the antenna, however, have to be known. A good choice is to use materials especially intended

for radio frequency use supplied with reliable dielectric parameters. Otherwise the parameters should be measured, which is often difficult.

In closed exposure chambers (e.g. Fig. 4) the actual source is typically a simple coaxial-to-waveguide transition, such as a coupling probe or a loop. The chamber geometries can be designed so that the modelling is easy. Closed exposure systems are, however, typically sensitive to the dimensions of the chamber. Therefore, special attention has to be paid on the accuracy of the numerical model. The dielectric parameters of the materials, used in the chamber, have to be assessed carefully as well as the effects of critical production tolerances.

If parts of the actual source are not visible and the source cannot be disassembled, the model generation becomes very difficult. This is the typical case, for example, in studies using commercial mobile phones as sources. Numerical models have been generated, for example, based on X-ray images or production *CAD* models [20], [21], [72].

The microwave excitation in the model is typically simplified compared to the actual feeding. Actual sources are in practice fed with coaxial cables. The coaxial feeds can be, to some extent, modelled with present software packages, although this often makes the model significantly larger and more complex. Therefore, in practice the feeding has to be simplified in the numerical model. The typical way is to insert the excitation using a voltage gap between the points where the centre and outer conductors of the coaxial cable are attached or directly between the radiating element and the ground plane [20], [73]. This simplification is one of the main points emphasising the importance of adequate experimental validation of the numerical models. The effect of simplifications should be carefully studied by testing different feedings in the numerical model and ascertaining that the calculation results agree with the measurements with the actual source. This is discussed in more detail in Section 2.4. The possibility of making the simplified feeding in the numerical model is also an important selection criterion for the actual source.

The input matching of the numerical source should be similar to the actual source because the matching affects directly the radiated power. However, the return loss and centre frequency of any exposure source based on near field of an antenna or on a closed resonator is very sensitive to the positioning of the exposed body and the implementation of the feeding. Hence, the maximum return loss in the model and in the actual source will most likely differ from each other to some extent. The reflected power can be taken into account in the simulation results, yet in the actual exposures it is difficult because, for example, the matching is not necessarily constant during the experiment. Hence, the accuracy of the assessment of radiated power decreases if the reflections are high. The best situation is that the reflections are small enough to be neglected

in both numerical model and in the actual source. For example, input matching that is better than 10 dB is often achievable. This results approximately ±5 % additional uncertainty on the assessment of radiated power which is acceptable in most cases.

Models of biological bodies

Animals and humans are electrically and geometrically very complex even though the cell-level structures can be neglected in the microwave frequencies. The dielectric parameters of tissue types differ significantly from each other and the physical forms are diverse. Because of this, the accurate numerical modelling of these structures is challenging and important part of dosimetry and it can constitute a significant part of the work required for a dosimetric assessment project.

Simplified models of biological bodies are useful. For example, if the inner structures are not significant, homogeneous models can be used. These are relatively easy to generate based on any available imaging data. Other useful simplified geometries are co-centric spheres and cylinders or half planes, having outer parts that represent the skin and fat layer on top of muscle. These models are easy to generate and modify, and therefore they are especially useful for studying the effects of layer thicknesses and other anatomical differences between the exposed objects.

For detailed dosimetry, heterogeneous tissue models are needed. Accurate case specific numerical models can be generated from magnetic resonance imaging (*MRI*) or computer tomography data, as reported in [67]–[69] and [74]. Moreover, cryosection of deceased individuals have been utilised to achieve data for numerical models, as in [66]. Improvements in the accuracy and availability of especially *MRI* have increased the availability of numerical models in the past years. However, in order to generate a numerical model from imaging data, the tissue types have to be segmented, which means identifying the tissue types of different regions in the image. Moreover, the dielectric parameters of the tissue types have to be known. Altogether, this is a laborious process and therefore generating a model for a single irradiation study is seldom worth the effort. This is why the availability of suitable numerical models is an important factor in exposure setup design.

The tissue models of humans have been available for years and up to date a wide variety of body shapes, ages, races etc. have been published [67]–[70]. On the other hand, the modelled persons are just single individuals and the anatomy of the actual voluntary testees might differ significantly from these causing large uncertainties on *SAR* assessment. The variations can be compensated, to some extent, by scaling the available models. However, the accuracy of this approach is

limited due to the fact that the proportions of different tissue volumes and body parts vary, not only the overall size. For example, 30% differences (1 σ) in 10 g average *SAR* in brain caused by the anatomical differences between adults and children were reported in [75]. Moreover, it was shown in [76] that the maximum 10 g average *SAR* might vary ±20% even between different adult head models. For other human body parts, systematic data for *SAR* variations is not available, yet anthropomorphic data and variation ranges are widely reported in [77]. In animal experiments, the situation is slightly different. Numerical models of some of the most common test animal species are available, but different models or data about the age and other variations seldom. On the other hand, animals are in many cases same breed or even clones, hence the differences between individuals, other than age, are smaller than in case of human testees.

The dielectric parameters of the humans and also many animals are available in the literature [78]–[81]. These values are widely used and generally accepted. The estimated uncertainty of these values is ±5-10%, according to [80]. Higher uncertainties have been suggested for certain tissue types, such as 42% decrease for the parameters of bone due to aging of a rat in [82] and 15% decrease of conductivity of porcine brain tissue *post mortem* in [83]. In light of this, the uncertainty of dielectric parameters cannot be neglected. The effect of changes of dielectric properties on mass averaged *SAR* has been analysed for example in [84]. In that report, the water contents of tissues at different ages were analysed to estimate the changes of dielectric parameters. *SAR* values in the heads of child and adult models were calculated and it was shown that the typical change of dielectric properties does not have a major effect on 1 g or 10 g mass averaged *SAR* (<10% in all cases). This is because the increased absorption in children's tissues is partially cancelled by the decreased penetration of electric field to the inner parts of the averaging volume. Similar results, typical variations of ±5%, were achieved also in [85]. The effect of this uncertainty component on *SAR*, however, is important to assess. This can be done by running simulations with different parameters for the most critical parts of the model.

Models of surrounding objects

In the closed exposure systems the boundary of the calculation grid is typically the metal wall of the irradiation chamber. In the antenna-based setups this is not the case and the objects surrounding the source have to be modelled too. This should be noticed in setup design by avoiding any non-necessary metallic or lossy objects in the close proximity of the source.

The supporting structures and jigs can be made from styrofoam, plastics, wood or other low-loss materials that have only minor effect on the exposure. These can be therefore simplified or left out from the model. However, medical

devices and probes, often present in exposure experiments, contain metallic parts and wires which have to be included. These models can be drawn by the model generator. It is especially important to ensure that the attachment of metal wires is similar in the model and in the actual setup.

2.3.3 Uncertainty of dosimetry

Reliable uncertainty estimation is one of the most important parts of the dosimetry. *RF* measurements as well as dealing with animals or human volunteers contain often significant error sources. Thus, for further utilisation of the results of the biological study at least an estimation of the overall uncertainty should be included in the dosimetry report.

Another purpose of the uncertainty analysis is to assist concentrating the design effort of the setup to the most essential problems; the setup design is always an optimisation task balancing between accuracy, usability and costs. In this section the analysis of error sources and combined uncertainty is discussed. The assessment of uncertainty components related to the variations between the exposed individuals and differences between the numerical model and the experimental conditions are discussed above in Section 2.3.1.

Positioning accuracy

The main source of error in exposure setups is typically related to the locations of the source and exposed objects relative to each other. The error is caused by two types of variations occurring in the setups. The first error type is that the positioning in the numerical model and the actual irradiation setup differ from each other to some extent. This is caused by the variations between the anatomies of the irradiated individuals and the numerical model. The second one comes from the repeatability and stability of the positioning during the experiments.

As seen from the results presented, for example, in [P1], [P2] and [20], the accurate positioning of the antenna-type source is critical for the accuracy of dosimetry. Very small variations in the distance between the surface of the exposed object and the antenna change the *SAR* significantly, i.e. ±10–20%. A realistic repeatability of the distance varies from some tenths of a millimetre to a few millimetres.

The best distance accuracy is achieved by using a low loss (e.g. styrofoam) spacer between the antenna and the surface of the exposed object. In this case the accuracy is basically only limited by the accuracy of measuring the thickness of the spacer. This is typically in the order of ±0.1 mm, which is why the uncertainty is small. If using the spacer is not feasible, the distance error is significant due

to the movements of the irradiated body part and other practical limitations.

With closed irradiation setups, the source is basically fixed and therefore the uncertainty comes from the movements of the animals and differences in the animal individuals. This is discussed in more detail in Section 2.3.1.

RF measurements

The *SAR* is directly proportional to the *RF* power fed to the system, and therefore the power measurement is an essential part of the uncertainty. The uncertainty of *RF* power measurement is due to the accuracy of the actual *RF* power meters and the assessment of the losses in the signal pathway between the point of power measurement and the radiating element. Moreover, the stability of the signal generator and amplifier contribute to the uncertainty.

The uncertainties related to the *RF* power meters and the stability of the signal sources are relatively straightforward to assess if calibrated devices are used and the instruments are well warmed up and stabilised before the exposures. The order of magnitude of these errors varies from a few percent up to ±10%, depending on the used equipment.

The assessment of the losses between the point of *RF* power measurement and the radiating element can be somewhat complex. In practice, the propagating power cannot be measured on the signal path any further than at the input connector of the radiating element. The numerical model, fed by a lossless voltage gap in the radiating element, does not take into account the attenuation of the signal after the input connector. Hence, the internal losses of the exposure source cause error to *SAR* directly. For an example, a 30-cm coaxial line between the radiating element of the antenna and the input connector attenuates the signal typically by 1–10% at 1 GHz. If this attenuation is not taken into account, i.e. simulated ratio of *SAR* and radiated power is used directly to set the input power, the *SAR* in the actual experiment will be 1–10% below the target value. If the exposure source consists of other lossy circuit elements (e.g. tuning circuitry) or longer cables this error can be easily several decibels. It is therefore reasonable to design the feeding networks of exposure sources such that the internal losses after the connector are low or can be estimated reliably.

For antenna-type sources the losses can be estimated by the means of a free space measurement. The total radiated power is integrated from the directional pattern and compared to the measured input power. The reliability of such a measurement can, however, be poor for omnidirectional antennas.

Discretisation

The numeric models represent a continuous structure in discrete form. The medical imaging methods are typically modelling biological bodies in slices

which are, furthermore, modelled by adjacent rectangular voxels (staircase) in the *FDTD* model. This causes unavoidably an error to the calculated *SAR*. The order of magnitude of staircase error is strongly dependent on the accuracy of the original model and the calculation grid density used.

The general rule of thumb for *FDTD* simulations is that the maximum calculation cell size should be smaller than one tenth of a wavelength. The results presented, for example, in [86] suggest that such grid density leads to computational accuracy better than ±10 %. However, the required grid density depends on many things, such as the size and shape of the target organs and preferred *SAR* averaging volumes, and therefore it is good practice to test the adequacy of the used grid size. If, for example, results with 1-mm grid size do not differ significantly from the results achieved with 1.5-mm and 2-mm grid, it can be concluded that the staircase error does not contribute to the overall uncertainty significantly if a grid density better than 1 mm is used.

In case the maximum available accuracy of the model or computing resources limits the grid density so that the above mentioned quality checking still shows some difference the accurate estimation of this uncertainty component is difficult. One solution is to run simulations with slightly different grid densities (close to the maximum density) and angular positions of the model compared to the calculation grid. The discretisation uncertainty is at least in the order of magnitude of these variations. For example, in [87], a discretisation uncertainty of ±14% for a local *SAR* was reported in a study with rat models.

Overall uncertainty

The overall uncertainty of the dosimetry is a combination of all error sources; the quality of the numerical model and how well it represents the actual setup, uncertainty related on the instrumentation, source positioning and other error sources related to the practical execution of the experiment. The acceptable overall uncertainty should be evaluated based on the needs of the biological study. The minimisation of uncertainty below the biological variabilities may be waste of resources.

The overall uncertainty is calculated by taking a root sum square (*RSS*, square root of the sum of the squares) of all significant uncertainty components, providing that the components are independent from each other. Furthermore, the achieved *RSS* value is multiplied by the coverage factor *K*. The combined uncertainty of several components can be assumed as normally distributed, even though single components are not [88]. Therefore, for example, for a 95% confidence level, the value K=2 can be used.

2.3.4 Dosimetric analyses in the studies included in this thesis

Setup for exposing human volunteers

The source used in [P1] was a half wave dipole with balun matching (Fig. 2 and Fig. 5) attached 10 mm from the surface of the skin. The mechanical structure of the antenna was simple and therefore easy to model accurately. The gap between the dipole arms provided a good symmetrical place for the voltage source in the numerical model. The voltage source was possible to place accurately at the same point where the feeding coaxial line ends. Here, the frequency response of the numerical model showed a good agreement with the measurements and further tuning of the model was found unnecessary. The matching was better than 13 dB in all exposures, hence the reflections had only minor contribution on the uncertainty of dosimetric analysis. The only potential discrepancy between feedings of the model and the actual antenna was the plastic insulator between the dipole arms. Several values for the dielectric parameters for bakelite were found from the literature. Moreover, measuring the value accurately with an open end coaxial probe was found difficult because the differences in the

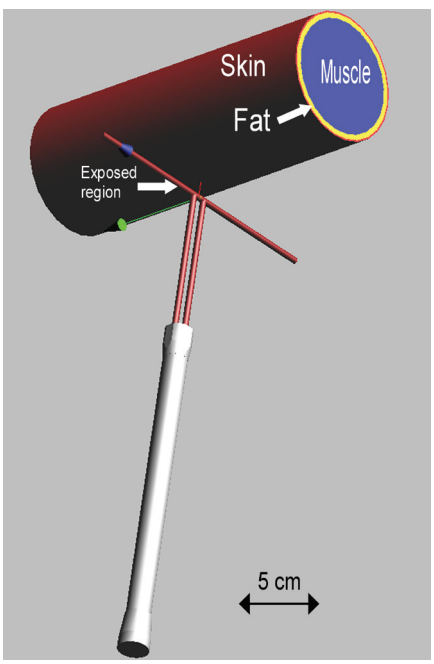

Fig. 5. Simplified numerical model for simulating *SAR* in the skin of a human forearm.

finishing of the measured surface seemed to alter the results to some extent. The effect of the dielectric parameters of the insulator was therefore studied by running simulations varying the parameter from the lowest to the highest value achieved from the literature or measurements. The effect of the parameter on the operation of the numerical model was found to be only minor.

The input connector was attached before the balun, which is why the cable losses between the connector and the voltage gap had to be estimated. The feeding network was a straight section of semi-rigid coaxial cable (RG 402), for which the transmission loss was available. Attenuation of 0.1 dB was estimated from the length of the cable.

The dosimetric analysis in [P1] was concentrated on a small sample of skin in the human forearm. The thickness of the skin varied from 0.5 mm to 2 mm between the exposed volunteers. In the preliminary simulations this variation was found to have a significant effect on *SAR*. Other significant parameters were the thickness of the fat layer and the diameter of forearm. Therefore, the required resolution of the tissue model was very high and the model had to be modified in many ways to cover the anatomies of the exposed volunteers. Such modifications in realistic tissue models are very difficult. The larger structures, such as bones in the forearm, were found to have only minor effect on *SAR*. Hence, the only reasonable solution was to use a simplified geometry instead of a realistic tissue model. The final model (Fig. 5) consisted of three co-centric cylinders representing the skin, fat and muscle. The model was easy to modify and made the analysis of different layer thicknesses and uncertainty possible.

Besides the anatomical differences between the exposed individuals, the accuracy of the distance between the skin and the source was found to be an important parameter. The positioning accuracy in the setup was limited to ±1 mm because of the muscle movements and deformation of the skin. The use of a spacer was not feasible because the chemical or mechanical stress in the exposed skin, or even the possibility of them, would have decreased the value of the biological results.

The *SAR* used in the experiment was 1.3 W/kg in the skin biopsy. The estimated overall uncertainty was ±20% (K=2). This was caused mainly by the positioning (±12%), variations of the anatomy between the exposed individuals (±11%) and the stability of the signal (±7%).

Setup for exposing anaesthetised pigs

In [P2] the exposure source (Fig. 3) was the same half wave dipole used in [P1], yet it was mechanically tuned and the distance to the skin surface was larger (20 mm). It was found in the preliminary simulations that the centre frequency of the numerical model was slightly lower than the centre frequency

measured with a vector network analyser. Therefore, the numerical model was tuned by shortening the dipole arms for 1.5 mm each. After the modification, the simulation and measurement results were in good agreement.

The exposure was focused to the head area of young domestic pigs. The *SAR* distribution especially in the brain was essential and therefore, a detailed realistic numerical model was needed. A head area model of a pig was available for the study [74]. Other parts of the pig, however, such as the ears, affected the exposure source. This problem was solved by means of using a hybrid model of simplified and realistic parts. The realistic head area model was completed by manually drawn simplified additions whose inner parts were homogeneous and they were covered with skin layer. This solution saved a lot of work, compared to generating a complete tissue model, yet provided all the needed accuracy and realism in the simulations. In addition to the biological model, the medical devices, such as the *EEG* electrodes, had to be included in the model because metallic objects located in the vicinity of the source might alter the *SAR* distribution. The final model and the detailed tissue model are presented in Fig. 6.

The exposed pigs were young and differed in size. The size of the simulation model was scaled directly with the ratio of weights of the 11 animals used in the experiments in comparison with the weight of the modelled pig. The size of

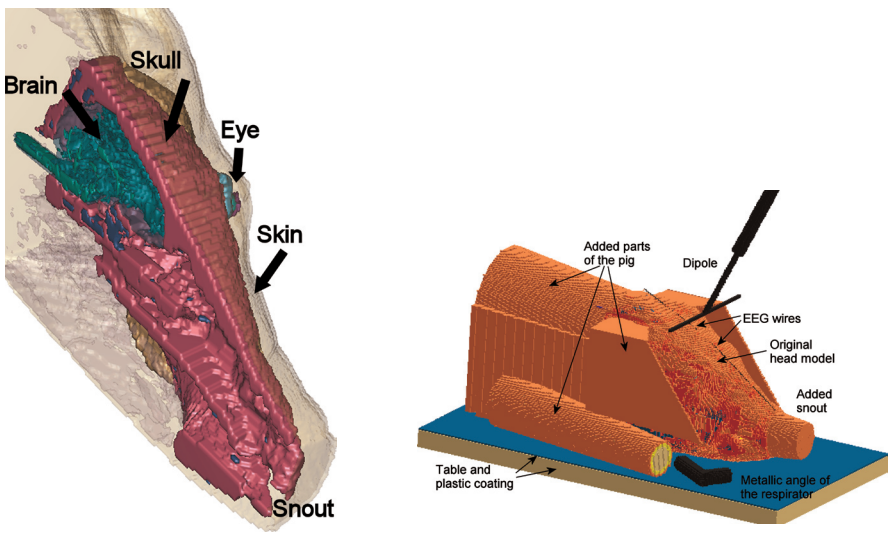

Fig. 6. Tissue model (halved) of a pig head and a complete numerical model for dosimetric analysis of the exposure setup.

Table 1. The *SAR* in the exposures of domestic pigs [P2]. The radiated power of 2.90 W was used in the first set of short (1–3 s.) bursts. The radiated power of 12.4 W was used in the second set of short bursts and in the 10-minute continuous exposure. The powers are temporal averages over the sequence of the *GSM* pulse. The temporal peak values of *SAR* are eight times higher.

Averaging volume	*SAR* at 2.9 W of radiated power [W/kg]	*SAR* at 12.4 W of radiated power [W/kg]
Whole brain	3.8	16
Maximum value in brain (one voxel, 4 mg)	11	48
Maximum value in skin (one voxel, 4 mg)	38	160
Maximum 1 g in brain	8.4	36
Maximum 10 g in brain	6.4	27
Maximum 1 g	12	50
Maximum 10 g	7.3	31

the brain increases less than the size of the whole animal during maturing, but this conservative estimation method was used to cover also the variations of the shape of the heads between the individuals. The distance between the antenna and skin was, in this setup, very accurate due to the spacer used between the antenna and the exposed animal. However, the accuracy of the transversal positioning of the antenna was in practice limited to approximately ±10 mm, which is why several possible antenna positions were studied.

The *SAR* values, used in the study, were 7.3 W/kg and 31 W/kg as an average of 10 g cubical tissue mass. All calculated tissue volumes are presented in Table 1. An overall uncertainty of ±25% (K=2) for *SAR* in brain was estimated. This was mainly due to the head size variations (±15%), other anatomical variations (±15%) and the source positioning accuracy (±10%). The measured temperature rise during 10 minutes continuous exposure at 31 W/kg was 3 K.

Setup for exposing unrestrained rats

The exposure chamber used in [P3] was a circular *TEM* waveguide (Fig. 4). The coaxial-to-waveguide transition was made by a probe extending the centre conductor. The probe was attached vertically at the centre of the chamber and the outer conductor of the coaxial feed in contact with the ground plate of the chamber. The voltage gap in the numerical model was therefore possible to place between the probe and the ground plate at exactly the same point where the actual coaxial feeding ends.

The shape of the chamber was simple symmetrical cylinder, and therefore easy to model. However, the edges of the chamber were covered with absorbing material to suppress the standing wave in the chamber. The modelling of the

absorber was the most challenging part because the dielectric parameters of the material were difficult to establish. The manufacturer did not give any data and literature values were unavailable. The parameters were measured with a commercial open end coaxial probe, yet repetitions showed that the measurement uncertainty was high. The absorber model was therefore made by iteration. Simulations were made with several sets of dielectric parameters which were based on measured values and their estimated measurement uncertainty. Then, the electric field distribution inside the chamber was measured and the dielectric parameters providing the best agreement with the measurements were selected.

A complete tissue model of a rat was made available for the study by Brooks Air Force Base (San Antonio, TX, USA). Different postures and rat sizes were analysed by scaling and modifying the model. The number of variables affecting the dosimetry of rats was very large. The rats were growing significantly during the studies, they could freely change location and posture in their gages, and moreover, adjacent rats in the chamber affected each others' exposure. The main task was to limit the assessment to the most essential factors. The short term variations of *SAR* were assessed by observing the behaviour of the rats and conducting simulations with most typical rat locations and posture combinations. Furthermore, since the rats were growing during the study, the average *SAR* in typical postures was assessed in terms of rat weight. In order to decrease the overall uncertainty of the dosimetry, the effect of the growing was compensated in the experimental routines; the input power of the chambers was adjusted during the experiment to keep the *SAR* constant.

The challenge in [P3] was the optimisation between the restraining stress, complexity and accuracy. The achieved uncertainty was 3 dB (+100%, -50%). This uncertainty seems large, but on the other hand, the setup provided an adequate space for keeping rats in the setup continuously (requirements by Council of Europe). Moreover, this uncertainty covered the whole lifetime variation (1.2–1.3 dB) as well as instantaneous variations (2.2–2.3 dB) and uncertainty related on the dosimetric methodologies and instrumentation (3 dB).

2.4 Validation of dosimetry

A major problem of numerical simulations is that the method is sensitive to many parameters. Flaws in the numerical model may be hard to recognise based on the simulation results only. Hence, the simulations should always be validated by another independent method, such as an experimental measurement setup, analytical solution in a simplified case or at least simulation with a different numerical model and an algorithm.

2.4.1 Validation method

A widely used validation procedure for *in vivo* exposure studies described in [87] is based on an experimental measurement simulating the actual exposure conditions. The reliable measurement of *SAR*, however, is very difficult in a complex biological structure consisting of heterogeneous tissue. Thus, the main challenge of the validation setup design is to create conditions where the electrical loading of the exposure source is similar than in the actual experimental setup and the *SAR* measurements are possible. This can be done by first constructing the exposure source and its numerical model. Second, a homogeneous phantom and its numerical model are made. The shape of the phantom should correspond approximately to the numerical heterogeneous model. The inner parts of the phantom are filled with homogeneous matter (phantom liquid) whose dielectric parameters are equal to the average parameters of the heterogeneous model. Third, *SAR* measurements as well as numerical simulations are conducted with the source and the phantom positioned in a similar way as in the actual experiment. Finally, the results of the *SAR* measurements and the simulations are compared. If the results are close to each other, the simulation model of the source is satisfactory. This method is applicable for both open and closed exposure setups.

The antenna feeding in the numerical model is often simplified as compared to the actual antenna. Moreover, the tuning circuitry or any frequency-selective structures of the source are difficult to model accurately. It is therefore important for reliable validation to study the input impedance of the numerical model and the actual antenna in addition to the *SAR* measurements. Moreover, these measurements can easily be made in broader band and hence they can reveal shortcomings in the model that are difficult to recognise from single frequency results.

For antenna-type exposure sources, more extensive validation procedures can be followed. For example, comparison of the measured and simulated free space field patterns of the exposure source can give additional information on the quality of the numerical model.

2.4.2 Measurement setups

The validation measurements are made using the same instrumentation as in the actual irradiation. Thus, only the phantoms and the method for the *SAR* measurement are additionally needed. The *SAR* measurement procedures and instrumentation for e.g. mobile phone exposure assessments are well established and standardised [89]–[91]. These *SAR* scanner-based methods can be utilised for validation setups as well. The limitation is that the *SAR* scanner

measurements require an open top phantom and they are basically usable only for measurements of local exposure. This limits the use of *SAR* scanner-based methods to the validation measurements of antenna-type open sources. The standard phantoms exist only for human head and trunk. A flat phantom [12] could be used as an approximation but for more realistic loading conditions it is necessary to construct a specific phantom representing the exposed body part.

Open top phantoms and *SAR* scanners are not feasible for the validation in case of closed exposure systems. One possibility in these cases is to use a thermally isolated phantom and very high microwave power to produce a measurable temperature rise, as done in [92] and [P3]. The whole body average *SAR* can be calculated from Equation (1).

2.4.3 Comparison of the simulated and measured values

The simulated and measured values can be compared to each other in many ways. The peak *SAR* and other local *SAR* values are very sensitive to positioning accuracies and hence, if in good agreement, they give the best validation. However, the errors of local peak values can be high both in measurements and simulations. Moreover, the measurement of a detailed *SAR* distribution is not often possible. In these cases only spatially averaged *SAR* values have to be used for comparison.

The good agreement of validation measurements and simulations means a situation where the measured and simulated values are within the estimated uncertainties of both evaluation methods, or in other words, E_n, as in Equation (3), is less than one [87].

$$E_n = \sqrt{\frac{(v_{sim} - v_{meas})^2}{(v_{sim}u_{sim})^2 + (v_{meas}u_{meas})^2}}, \tag{3}$$

where v_{sim} and v_{meas} are the simulated and measured values and u_{sim} and u_{meas} the estimated uncertainties (K=2), correspondingly.

2.4.4 Validation setups developed in this thesis

In [P1] and [P2], the same dipole antenna was used as with the exposure source. The simulation models, however, were different, which is why the validations were made for both models separately. In [P1] the simulation model was cylindrical and the exposure was very local thus constructing an open top liquid filled phantom was fairly easy. The phantom is shown in Fig. 7. The advantage of this setup was the symmetric structure, which makes very accurate positioning

of the source possible. Moreover, modelling the phantom was possible only using the model generator of the software package.

The situation was somewhat more complex in [P2]. A realistic pig head phantom was needed but the construction of such turned out to be very complicated. The solution was to make a *CAD* model using the same *MRI* data as for the actual numerical model. The *CAD* data was utilised to construct the phantom out of solid polyethen (*PE*) block using a *CNC* (computerised numeric control) milling machine. The validation setup is shown in Fig. 8. The numerical model of the phantom was then made also using the *CAD* data.

In both studies the local peaks as well as mass averaged *SAR* values were compared. In addition, the simulated and measured free space directional patterns of the source were compared in [P2]. The differences of the simulated and measured values are presented in Table 2. Taking into account the measurement uncertainty present in the *SAR* and free space measurements, the agreement of the values was very good in both studies.

In [P3] the exposure source was closed and the exposure targeted to the whole body. A validation setup based on the *SAR* scanner was therefore impossible. Instead, regular plastic bottles filled with muscle simulating phantom liquid were used as phantoms. Four different bottle sizes (56, 110, 280, and 550 ml), whose dimensions were similar to rats of different ages, were used. Phantoms were placed in all 24 rat cages for the measurements. One of the bottles was made to a calorimeter by insulating it with a styrofoam box. Two hundred watts of microwave power was fed to the chamber for up to three hundred seconds. The temperature of the insulated phantom was measured before and after the irradiation with a sensitive thermistor probe. *SAR* in the phantom depended on the phantom position but, for example, at the *SAR* level of 5.3 W/kg the resulting temperature rise was 1.1 mK/s or 340 mK in 300 seconds for 110-ml phantom. The differential sensitivity of the temperature probes was approximately 10 mK, hence the temperature rise was well in the measurable range. The average *SAR* was then calculated from Equation (1). The specific heat capacity of the liquid was measured with a calorimeter and the heat capacity of the phantom bottle was calculated from the values available in the literature and using the mass of the bottle. The temperature difference between the phantom and the environment was minor and significant errors due to heat conduction were not observed. This was studied by comparing the results achieved with several different *SAR* levels and heating times. The differences between the measured and simulated values were less than 20%. Thus, the agreement was good taking into account the complexity of the system and the measurement uncertainty of *SAR* (±20%).

Fig. 7. Phantom setup for validating simulated values of *SAR* in the skin of human.

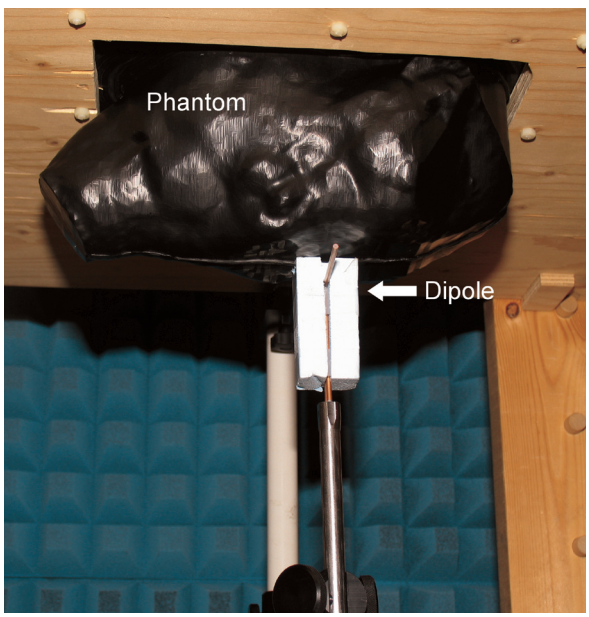

Fig. 8. Phantom setup for validating dosimetric simulations with head of a pig. The phantom was constructed with a *CNC* milling machine and a *CAD* model based on the *MRI* data.

Table 2. The results of the validation of the numerical models in [P1] and [P2].

Compared quantity	Difference of the simulated and measured value [%]
Human volunteer study [P1]	
Local peak *SAR*	2
10 g averaged SAR	8
Study with anaesthetised pigs [P2]	
Local peak *SAR*	-1
10 g averaged *SAR*	2
Free space gain	3
Free space directional pattern (10 dB beam)	8

3 Dosimetry in practical safety evaluations

3.1 Introduction

The highest microwave exposures to the general public are, in practice, caused by the transmitters that are in contact with the human body while used such as mobile phones. The exposure caused by the fixed antennas, such as mobile phone base stations, to the general public is typically significantly lower because the antennas are generally either transmitting low power or situated remotely from places of public access [93]–[95]. The situation is somewhat different concerning occupational exposure. Many professionals, such as firemen, janitors and construction workers, have to work e.g. on roof tops in the proximity of mobile phone base station antennas and other radio transmitters.

The exposure caused by the highest power transmitter antennas, placed on the roofs, can exceed the *SAR* limits significantly within several meters, while most of the base stations cause only minor limitations on working in the close proximity [93], [96]. This sets high demands on the exposure assessment. The safety distances have to be adequate to protect the worker. On the other hand, too conservative estimates impede the work and excessive dosimetric evaluations cause unnecessary costs. Therefore, simple methods for realistic exposure evaluation are crucial.

The main purpose of this part of the study was to examine the feasibility of methods used for practical radiation safety evaluations of mobile phone base stations. The practical safety evaluations can be based on technical specifications of the transmitter, *in situ* measurements or calculations of unperturbed fields, *SAR* measurements or numerical simulations. These methods are introduced and discussed in this chapter together with relevant *RF* safety standards and regulations. This information is the inevitable background for the studies in [P4] and [P5] included in this thesis. The results of the studies are summarised in the end of this chapter.

3.2 *SAR* limits and reference levels

The guidelines for limiting the exposure to microwaves have been published, for example, by the International Commission on Non-Ionising Radiation Protection (ICNIRP) [6] and the Institute of Electrical and Electronics Engineers (IEEE) [97]. The European Union (EU) has adopted the ICNIRP guidelines directly [88] and the IEEE guidelines are followed, among others, in the United States and Canada. The guidelines are derived by assessing an exposure level at which the first well established adverse health effects will occur. The uncertainties related

to this assessment are then analysed and, based on this, exposure levels given below which any known adverse health effects will not occur. The limits are therefore based solely on the presently known well-established health effects of microwaves. These effects are all caused by excessive temperature rise in the tissues caused by the absorption of microwave power.

The ICNIRP guidelines include basic restrictions for *SAR* as an average over the whole body ($SAR_{br,wb}$) and for an average over 10 g contiguous tissue mass ($SAR_{br,10g}$). Moreover, limit values are given separately for the general public and for occupational exposure. The limits for the general public are set five times stricter based on the fact that workers are generally all healthy adults while general public also includes more sensitive groups, such as children and elderly persons. The basic restrictions are presented in Table 3. The ICNIRP and IEEE limits are relatively similar to each other. Different exposure limits are issued, for example, in Russia and some countries in the Eastern Europe. In this thesis, only the methods followed by ICNIRP and EU are considered.

Table 3. The ICNIRP basic restrictions for limiting the microwave exposure (ICNIRP 1998).

Exposure type	Occupational exposure *SAR* [W/kg]	General public exposure *SAR* [W/kg]
Whole body	0.4	0.08
Local (10 g average) head and torso	10	2
Local (10 g average) limbs	20	4

Direct measurement of *SAR* is virtually impossible *in vivo* and measurements with a phantom simulating the exposed human are practical only in laboratory conditions. The safety evaluations are done typically in difficult outdoor and occupational conditions which is why more practical measures of exposure are needed. For that purpose, reference levels are given in the ICNIRP guidelines for unperturbed electric (E) and magnetic (H) fields and plane wave equivalent power density (S). The reference levels are defined to ensure that a human entering such free space field strength will not be exposed to *SAR* values exceeding the basic restrictions. The reference levels are presented in Table 4 and the definition of plane wave equivalent power density in Equation (4).

$$S = \frac{E^2}{\eta_0} = H^2 \eta_0 \ , \tag{4}$$

where η_0 is the wave impedance of free space (377 Ω), and E and H are root-mean-square values of electric and magnetic field strengths.

Table 4. The ICNIRP reference levels for limiting the microwave exposure (ICNIRP 1998). Values are given as occupational / general public exposure. *f* is the frequency in MHz.

Frequency range	Electric field [V/m]	Magnetic field [A/m]	Equivalent plane wave power density [W/m^2]
10 MHz–400 MHz	61 / 28	0.16 / 0.073	0.2 / 0.092
400 MHz–2000 MHz	$3\sqrt{f}$ / $1.375\sqrt{f}$	$0.008\sqrt{f}$ / $0.0037\sqrt{f}$	*f*/40 / *f*/200
2 GHz–300 GHz	137 / 61	0.36 / 0.16	50 / 10

The reference levels are defined based on the worst exposure scenario of all possible body orientations, postures, and sizes and also on all field distributions and polarisations. Because of this definition, the unperturbed field measurements result in conservative estimates of the exposure in all other exposure scenarios. On the other hand, the estimation of the worst case is limited by the dosimetric accuracy available at the time the limits were published. Current ICNIRP reference levels were established in 1998, when for example the considerations on dosimetry in heterogeneous tissue structures were very limited. This is a problem especially in very inhomogeneous near field of antennas where the local exposure could reach the basic restrictions before the whole body average. For these reasons, the studies on the relation of unperturbed field strengths and the actual exposure are crucial to ascertain the validity of the reference levels or to further improve them in the future.

3.3 Standards

The *SAR* and field strength measurements as well as dosimetric simulations are complicated and the uncertainties are high. An inevitable requirement for the enactment of safety limits is, however, that there are comparable and reproducible methods to assess the exposure. Therefore, detailed standards for the safety evaluations are crucial. Widely used standards are published by the International Electrotechnical Commission (IEC), European Committee for Electrotechnical Standardization (CENELEC) and the IEEE. The CENELEC

and IEC standards are referred directly for example in the EU directives [98] on how the compliance with the ICNIRP guidelines should be demonstrated. Moreover, the standards specify important details that are not included or have been left unclear in the exposure guidelines.

The base station exposure is one of the most common exposure scenarios present in everyday life and in certain occupations. The European standards EN 50383 and EN 50400 together with related product standards EN 50384, EN 50385 and EN 50401 define the methodology for the compliance assessment of radio base stations of wireless telecommunication systems [12], [99]–[102]. An international standard on the topic is to be published in the near future by the IEC. Moreover, several other related standards are published [103]–[107].

3.4 Procedure for practical safety evaluation

The safety evaluation is basically an assessment of one of the following parameters or their combination:

- The worst case exposure with the actual antenna input power and with the position of the person that leads to highest exposure. The position here is typically the closest distance limited by the physical obstacles around the antenna.
- The maximum allowed antenna input power for which the exposure limits are not exceeded in any possible position of the person.
- A region around the antenna outside which the exposure limits are not exceeded with the actual antenna input power.

The assessment of these parameters can be made by means of analytical considerations, calculations or *in situ* measurement of the unperturbed fields, dosimetric laboratory measurements or numerical simulations. It is reasonable to do the safety evaluation with a minimum effort required to ascertain that the basic restrictions for neither local nor whole body exposure are exceeded in any case. A schematic illustration of the procedure presented in EN 50383 is shown in Fig. 9. The main idea is that simplified compliance checks should always overestimate the exposure compared to more realistic exposure assessment methods. Then, if the safety at a certain location can be demonstrated, for example, by means of electric field measurements the laborious *SAR* measurements or numerical simulations are not required for showing the compliance. It is therefore crucial that the used simplified methods actually do overestimate the exposure.

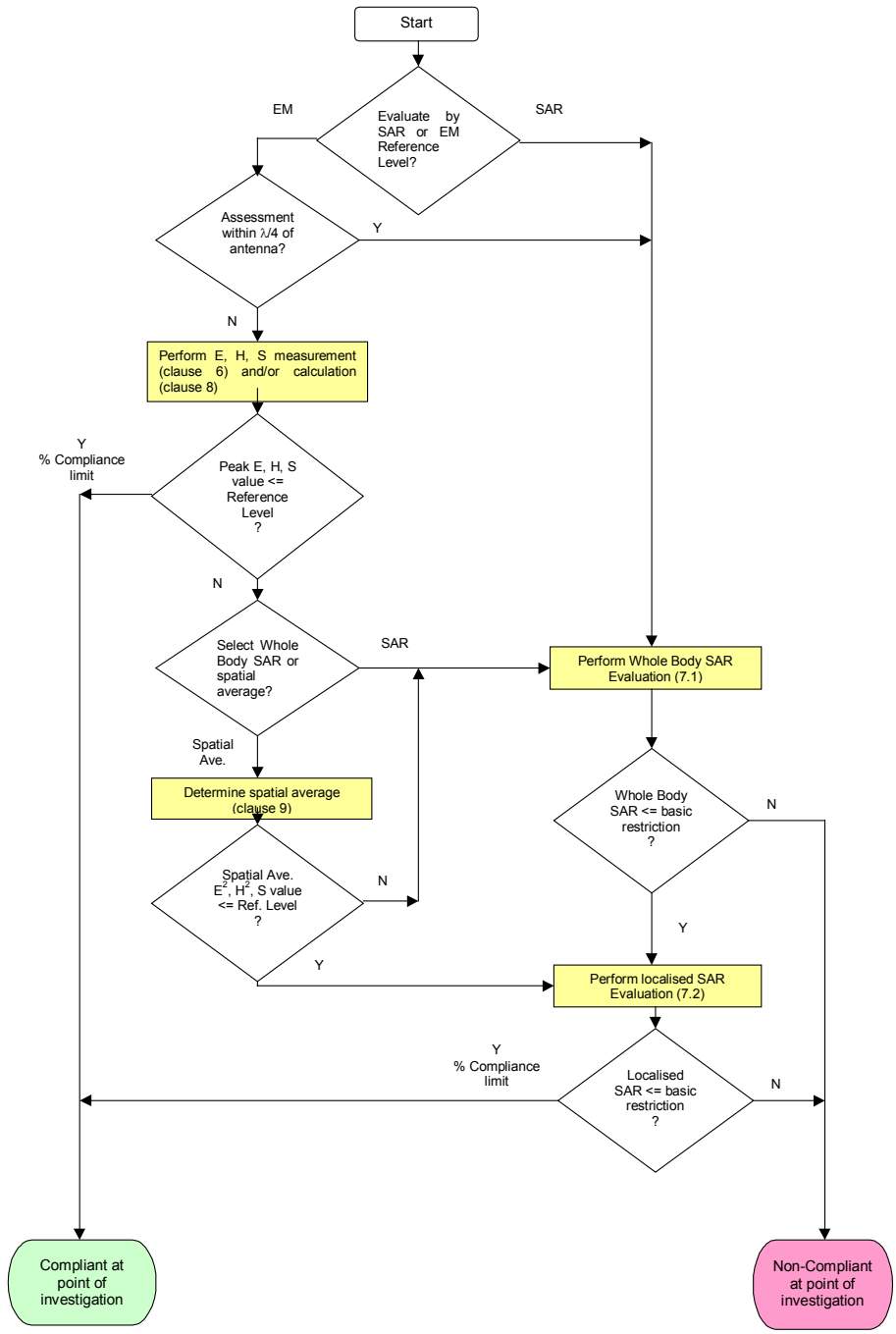

Fig. 9. A schematic illustration of the safety evaluation procedure given in CENELEC EN 50383:2002 (© CENELEC)

3.5 The exclusion criteria and field calculations

The first step of safety evaluation is to consider if the compliance of whole body average *SAR* (SAR_{wb}) or 10 g average *SAR* (SAR_{10g}) can be demonstrated without any measurements. For SAR_{wb}, the theoretical maximum is the radiated power of the antenna divided by the body weight of the exposed person. This relation is used to define an exclusion level for whole body *SAR* assessment; according to EN 50383 the minimum body weight is 42 kg for a worker and 12.5 kg for general public. The radiated powers below 17 W cannot cause the exceeding of $SAR_{br,wb}$ for occupational exposure for a person weighting at least 42 kg (17 W/42 kg = 0.4 W/kg) and radiated powers below 1 W cannot cause the exceeding of $SAR_{br,wb}$ for general public for a person weighting at least 12.5 kg (1 W/12.5 kg = 0.08 W/kg). Therefore, 17 W and 1 W of radiated power can be used as an exclusion level for occupational and general public whole body exposure, respectively. This is the case in many mobile phone base stations.

Present standard EN 50383 does not contain an exclusion criterion for SAR_{10g} assessment. However, if the field distribution varies relatively smoothly over the cross-section of the exposed person, it may be assumed that $SAR_{br,10g}$ will not be exceeded if the SAR_{wb} is well below the limit for whole body exposure. This assumption is based on data presented in [108] and [109]. In these studies, different exposure scenarios were analysed with four heterogeneous numerical human models and up to three simultaneously incident plane waves. In mobile phone bands, the ratio of SAR_{10g} and $SAR_{br,10g}$ was less than ratio of SAR_{wb} and $SAR_{br,wb}$ in all worst case exposure conditions and in nearly all other cases. A peak-to-average ratio of 6 dB for the incident field in the area of the exposed person is suggested in [110] for the exclusion of SAR_{10g} assessment above 600 MHz. This is, however, based on a very simplified quasi-optic analysis.

The calculation procedures for unperturbed fields, presented in [12], are very helpful in the far field region. The calculation of the maximum field strength is simple based on antenna gain and input power. These parameters are often available for base stations. However, the far field method overestimates the exposure significantly in the near field. Calculation methods providing more accuracy in the near field, such as the 'Synthetic method' in [12] require detailed information about the internal structures and feeding circuitry of the antenna, and hence they are an applicable tool mainly for antenna manufacturers. This thesis considers the practical safety evaluations, mainly in the near field of base station antennas, and therefore these calculation methods are not discussed in detail here.

3.6 Measurements of the unperturbed fields *in situ*

If the exclusion criteria, described in the previous section, do not apply, the safety evaluation has to be made based on measurements or simulations. It is reasonable to start the evaluation from the easiest method. The effort required for the assessment depends on the case, but the simplest method is often the measurements of unperturbed free space field strengths in the areas where exposed persons can go. Equipment for these measurements is presently commercially available in adequate quality. These are therefore not considered in more detail in this work.

In practice only E measurement is possible *in situ* in microwave frequencies. The reliability of the measurement depends strongly on the distance between the studied location and the antenna. In the far field of the antenna, the wave impedance is known, and hence the energy of the wave can be calculated reliably from E. In the reactive near field, the wave impedance depends on the type of the source, and hence the measurement of the E gives only a rough estimate on the energy.

In the far field of the antenna, fairly reliable estimation of SAR_{wb} can be made based on the measured maximum value of E (E_{max}) [110]. This is due to the fact that at microwave frequencies the power absorption in the exposed human is superficial and significant resonances do not occur. Moreover, the field distribution is typically smooth in the far field of *BS* antennas due to the relatively wide beams used in them. Therefore the local exposure does not differ from the whole body average significantly and separate assessment of SAR_{10g} is not necessary. These claims are supported by the results presented in [108] and [109] where the SAR_{wb} and SAR_{10g} were analysed with numerical simulation models of humans exposed to plane waves equal to the ICNIRP reference level. In [108], the worst case SAR_{wb} was 47% of the $SAR_{br,wb}$ and worst case SAR_{10g} was 31% of $SAR_{br,10g}$. The analysis was based on one heterogeneous numerical human model (male). In [109] similar analysis was made with four numerical human models including two models based on children, one based on an adult female and one based on an adult male. The highest corresponding ratios were 143% for whole body and 44% for local exposure, correspondingly. In light of this, the measurement of E leads to fairly realistic estimate of both SAR_{wb} and SAR_{10g}. The slight exceeding of the basic restrictions observed in [109], however, suggests that the reference levels need to be revised in some frequency bands. Yet, the exceeding is small compared to the safety margins of the basic restrictions and the uncertainties related to in situ measurements.

In the radiating near field of an antenna the field distribution is highly non-uniform and hence the SAR_{wb} and SAR_{10g} are, to some extent, independent

on each other and the situation is much more complex. The assessment of SAR_{wb} could, however, be made reliably by E measurements; the wave impedance is fairly close to the free space conditions, and therefore the energy of the wave can be estimated from E. By means of spatial averaging of the field a relatively realistic estimate of the whole body exposure can be achieved. The local exposure, however, can be significant in this region. The direct comparison of E_{max} to reference level (E_{ref}) is very practicable way to check the compliance, yet the reliability of this method needs to be further studied [P4], [P5].

In the reactive near field of an antenna the wave impedance is not known which is why the compliance check by means of E measurement alone is questionable. For example, due to the results presented in [111], the H field strength, rather than E, defines the SAR value in objects close to the dipoles. The coupling of RF power to biological tissues in the reactive near field has been further studied for example in [112] and [113] showing that neither H nor E field alone defines the SAR value but the local composition of the tissues affects significantly. However, at microwave frequencies the E measurements are the only available method to estimate the exposure in the field conditions.

3.7 Dosimetric laboratory measurements

If the compliance of an antenna installation at a certain location cannot be shown by means of exclusion criteria or *in situ* E measurements, the options are either to decrease the radiated power or to define a larger safety region around the antenna. Moreover, the compliance can still be possibly demonstrated by less conservative methods, i.e. SAR measurements in a laboratory or by numerical simulations.

The instrumentation and procedures for SAR measurements are standardised for mobile phones and other small antennas radiating in the close proximity of the body [12], [90], [91]. Moreover, SAR measurements provide a good option for validating dosimetric simulations, as discussed later in this chapter.

According to the standard EN 50383, the safety evaluation made with SAR measurements is limited to local exposure [12]. Therefore, the whole body exposure should be assessed otherwise, for example, by means of measurements of unperturbed E.

3.7.1 Measurement methods

The SAR measurement setups specified in standards EN 50383 and IEC62209-1 and -2 are based on a SAR scanner [12], [90], [91]. In the measurements, the

body of the exposed person is replaced with a box phantom whose cross section is 800 mm x 500 mm and liquid height up to 200 mm. The dimensions correspond approximately to the outer dimensions of a trunk of an average adult. An example of such a setup is shown in Fig. 10 [P4].

For the measurements, the antenna is positioned below the phantom so that the main lobe points up. The requirement for the antenna, given in the measurement standard, is that the cross section of the antenna is smaller than 600 mm x 300 mm, i.e. smaller than the cross section of the phantom. However, this requirement can be relaxed for the measurement of SAR_{10g} in some cases. The base station antennas are typically long but narrow linear arrays of radiating elements. The exposure maximum values in the close proximity of such an antenna are caused by single radiating elements rather than the combined field. Furthermore, the highest powers are typically fed to the elements at the centre. This is why locating the centre of the antenna below the centre point of the phantom gives reliable results on the SAR_{10g} maximum.

The measurement of SAR_{wb} is not included in the EN 50383 but, however, suggestive data on the whole body absorption can be achieved by measuring the total absorbed power in the phantom with the *SAR* scanner. If the antenna under test is smaller than the phantom, or trunk, the situation between the measurement and the actual exposure scenario does not differ significantly. On the other hand, if the antenna is significantly larger than the phantom, the total absorption in humans is most likely higher than in the phantom; the limbs and head absorb power in addition to the trunk and therefore, box phantom measurement underestimates the exposure.

3.7.2 Limitations and strengths

The main advantage in using dosimetric measurements for safety evaluation is the insensitiveness against coarse errors. The actual antenna is used in the measurements, thus knowledge on the inner structures of the antenna is not necessary. Moreover, *SAR* measurement methods are well established and reliable calibrations are available, too. Furthermore, the *SAR* measurement setup can be checked, for example, by means of standard source measurement (dipole) prior to the actual measurements to see that the results are reasonable. Therefore, the risk of major flaws in the assessment is low. Moreover, the assessments using a box phantom are very reproducible and commensurable, which is an inevitable requirement for any compliance testing. The reliability and reproducibility of the *SAR* measurements especially supports the use of these measurements as a validation method for numerical simulations.

The use of the box phantom poses the main limitation of this assessment

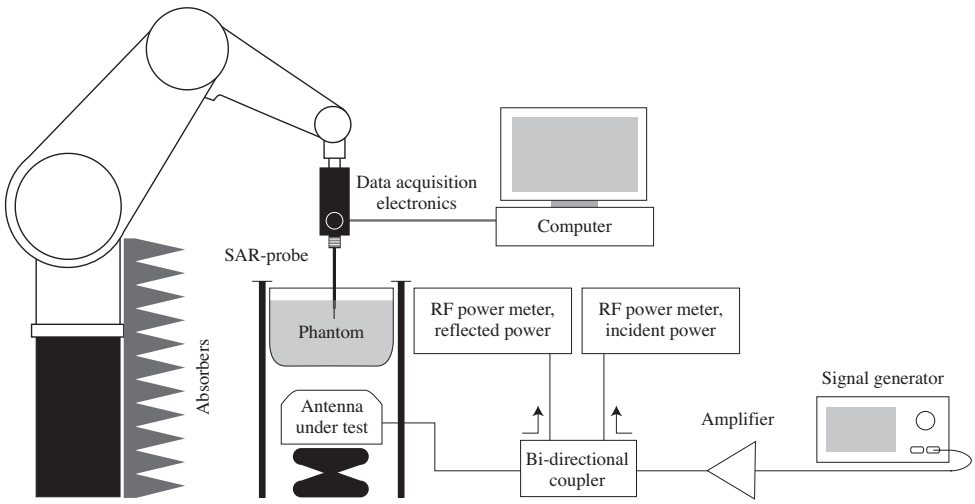

Fig. 10. A setup for measuring local *SAR* in the near field of base station antennas.

method; it does not take into account the tissue layers and curvatures of the body surface. Hence, the measurement result cannot be considered as the worst case exposure directly, but correction factors as high as 2-3 have been suggested [12], [114]. The other significant limitation is that the whole body exposure cannot be assessed reliably by box phantom measurements. In case of general public exposure this is a significant limitation, since the SAR_{wb} assessment has to be made for all antennas whose radiated powers are above 1 W. In case of occupational exposure, however, the whole body exposure assessment has to be made only for antennas whose radiated powers are above 17 W and in practice large fraction of mobile phone base stations fall below this exclusion level.

3.7.3 Uncertainty

The expanded uncertainty of ±30% or better is required for the dosimetric measurements in EN 50383. In practice, better uncertainties down to ±20% could be reasonably achieved [115], [116]. These values, however, include only the error sources related to the measurement setup which are the measurement uncertainty of the *SAR* scanner, positioning uncertainty of the antenna under test, and uncertainties related to the measurement of the input power and perturbation of the environment of the antenna. Additional errors, with relation to the actual scenario, are mainly related to the difference of *SAR* in the homogeneous box phantom and a human. This error can be up to 300% in the worst case, as shown, for example, in [114].

3.8 Numerical simulations

The most realistic, thus least conservative, safety assessment can be achieved by the numerical simulations, as shown in [117] and [118], for example. The recent developments in numerical human models and also in affordable computing power have made the simulations a very reasonable option for dosimetric assessment. Yet, the modelling of large structures and modelling the source still pose many challenges to overcome.

The numerical methods and basic procedure of conducting dosimetric assessment, discussed in Section 2.3.1, are used in practical safety evaluations as well. In this section, the challenges specific to the simulations in practical scenarios are discussed as well as the necessary validation procedures of these simulations.

3.8.1 Simulation methods

In practical safety evaluations the sources are commercial antennas, whose radiating structures are inside radomes and are often difficult to model without opening the antenna. Moreover, mobile phone base stations are typically array antennas, consisting of several dipole-type elements, where the field pattern is formed by the amplitude and phase distribution between the elements. The relative amplitudes and phases are important to determine, which can be difficult if they are not given by the manufacturer. Also, the internal losses of the antenna, caused by for example the feeding network, should be assessed for accurate dosimetry. Therefore, the main challenge in practice is the modelling of the source.

Many reports concerning studies of simplified base station antennas have been published [96], [119]–[124]. The models are consisting of dipole or patch-type elements and ground planes. The realistic amplitude and phase distributions of the generic models can be selected based on antenna array theories knowing the typical gains, side lobe levels and other parameters of the base station antennas. These studies provide important qualitative knowledge on the base station exposure, especially for the far field of the antennas. In the close proximity of the antenna, however, the gains and other far field parameters are less significant and the exposure is depending rather on the structure of single radiating elements. The structures are varying between the different antenna models, and therefore actual antenna models are worth studying as well.

Studies of commercial antenna models have been reported for example in [117], [121], [96], and [125]. In these studies the antennas are typically deconstructed for the modelling of the mechanical structure of the radiating

elements. Another possible option would be, for example, using X-ray or other imaging methods for the modelling of the antenna.

The phase distribution of the array antennas is not significant for the exposure in the close proximity because the local exposure maximums are caused by single elements. Hence, the modelling can be simplified by using constant phase. Amplitude distribution, however, is important. Only the total power, fed to the antenna, is known in practice. Therefore the power fed to single elements relative to the total power need to be known. In many cases the distributions of amplitudes can be estimated from the deconstructed antenna. A typical implementation for the feeding circuitry is a network of power dividers. In this case, the number of dividers in the signal path before each radiating element can be seen and the relative amplitudes of the elements can be calculated. Otherwise, near field measurements of E can be utilised to estimate the amplitude distribution of the elements.

Since the source model is generated, the safety evaluation proceeds to find the worst case exposure scenario. The exposure is mainly depending on the position of the exposed person relative to the antenna. The worst case is therefore searched by running several simulations with different postures and locations. Moreover, the effect of any possible obstacles in the close proximity of the antenna should be studied.

The shortest possible distance between the body and the antenna is obviously the worst case but also the direction and position of the antenna has a significant effect. The SAR_{10g} depends strongly on the tissue types and the shape of the surface at the maximum field, while SAR_{wb} depends on the fraction of the radiated power absorbed in the person. Therefore, the antenna direction and position should be searched independently for largest SAR_{wb} and SAR_{10g}. Moreover, important additional information is the distance dependency of the exposure. This can be assessed by running simulations with different distances.

3.8.2 Limitations and strengths

The main advantage in using simulations for dosimetry is that they enable achieving very detailed information on exposure. Moreover, since the source model is generated, different human models, postures and distances can be analysed with relatively small effort.

On the other hand, the generation of the source model is difficult. Moreover, especially in case of large antennas and whole body models, the calculation grid becomes very large for even relatively small distances. Furthermore, even if

there are several numerical models of humans, these are the only single cases. For the assessment of whole body exposure, the difference between the body size of the exposed human and the numerical model causes error to dosimetry directly. This is due to the fact that SAR_{wb} is inversely proportional to body weight. For the assessment of local exposure, the differences of the model and the exposed person, for example, in skin and fat layer thicknesses, muscle sizes and shapes of the bodies, can cause significant errors to SAR_{10g}.

3.8.3 Validation methods

The validation procedure for dosimetric simulations in practical exposure scenarios is essentially the same as in the exposure setups discussed in Section 2.4; a simplified scenario is measured and simulated and the results compared. If the results are in a good agreement, the numerical source model is valid.

For the measurements, the setup based on a *SAR* scanner and a box phantom, described in Section 3.7, is a convenient choice since the setup is widely used and validated and the modelling of such a simplified phantom is easy. For further validation, data measured or given by the manufacturer on the far field parameters of the directional pattern of the antenna can be compared to simulated values.

3.9 Contributions of this thesis

The safety evaluation process, described above in Sections 3.4–3.8, is based on standards. The main purpose of these standards is to provide systematic methodology for manufacturers and users of base station antennas to show the compliance of an installation with applicable regulations. For this purpose, it is useful that the simple and low cost methodologies are available. On the other hand, from the point of view of public authorities and practical safety evaluations, it is crucial that these simplified methods are reliable. The reason to execute the studies [P4] and [P5], included in this thesis, was to increase the knowledge on the reliability of safety evaluations based on free space measurements of unperturbed fields.

In [P4], six common commercially available mobile phone base station antenna types were studied with *SAR* and *E* measurements. The smallest antenna was 231 mm and the largest 1916 mm long and the gains varied from 7 to 18 dBi. The *SAR* measurements were conducted for the antennas according to the measurement procedure described above in Section 3.7.1. The setup is shown in Fig. 10. Measurements were made at four different distances between

the antenna and the phantom. The distances were 10 mm, 100 mm, 300 mm and 600 mm. The *SAR* in the whole phantom at each distance was scanned in order to find the maximum local *SAR*. Moreover, the total power absorbed in the phantom was assessed from the results. The measurements of unperturbed *E* were made in the main lobe of the antenna at the same distances than the *SAR* measurements. The same setup was used for the measurements phantom removed.

Standard safety evaluation procedure (Fig. 9) allows bypassing the exposure assessment for both local and whole body exposure, if local peak value of *E* is below the reference levels. This method is the easiest and hence it should be the most conservative compliance check. The validity of this approach was evaluated based on the measurement data achieved in [P4]. It was shown that the measurement of local peak value of *E* was sufficient measure for the antenna types included in the study. The results showed, however, that the safety margin was surprisingly small in some cases. The smallest ratio of the exposure estimate based on E_{max} and SAR_{10g} in the box phantom was 3.1 ($SAR_{10g}/SAR_{br,10g}$:$E_{max}^{\ 2}/E_{ref}^{\ 2}$, factor *LEEF* as in [P4]). Remembering that correction factors up to 3 have been suggested to achieve SAR_{10g} in human from the SAR_{10g} in box phantom, the ratio becomes as small as 1.1, hence the conservativeness of the exposure estimation based on *E* cannot be guaranteed in all cases.

An interesting topic in the *BS* safety evaluations is the overall need of the local exposure assessment. The spatial field distribution of any antenna gets smoother when the distance to the antenna increases. Therefore, compared to whole body exposure, the local exposure is evidently more significant in the close proximity of an antenna than in the far field. Therefore, in [P4] distance ranges were established inside which the $SAR_{br,10g}$ exceeds before the $SAR_{br,wb}$. The distances were estimated for a 42-kg person. The results are shown in Table 5. The longest distance was 240 mm.

In [P5], one of the *BS* antennas considered in [P4] was studied in more detail by numerical simulations. The studied antenna was a small indoor antenna typically used in picocells. The antenna was deconstructed for the modelling. The antenna consisted of two radiating elements and a frequency selective circuitry. The circuitry guided RF frequencies in the 900 MHz band to the other radiating element and the frequencies between the 1.7 GHz and 2.5 GHz to the other. The elements were close to each other, because they had to be included in the model, yet only the upper frequency bands were studied here. The *RF* field in the model was fed to the upper band element directly, which is why the feeding circuitry was not modelled.

The generated antenna model was validated by measurements. The *SAR* and *E* distribution data at different distances, achieved in [P4], was compared to corresponding simulation results with a flat box phantom. The median of the pointwise difference of measured and calculated *SAR* and *E* was 3.4–11% and -1.3–13%, correspondingly, depending on the distance. Hence, the model was relatively accurate.

The numerical model of the antenna was utilised by calculating *SAR* in a head of heterogeneous numerical model of a human (NORMAN, [68]) placed at different distances from the antenna. Moreover, the fields radiated by the antenna in free space were simulated. The *SAR* values in the head of NORMAN were compared to unperturbed *E*, *H* and *S* with different averaging schemes in order to find out how conservative different compliance check methods are in this case.

According to the results presented in [P5], the most reasonable and always conservative compliance check was achieved by comparing *S* to the corresponding ICNIRP reference level. The use of spatial averaging over the standardised 400 mm x 700 mm plane leads to underestimation of the compliance distance in the close proximity of the antenna, since the averaging scheme is aimed to be used only in cases where the $SAR_{br,wb}$ is more limiting than the SAR_{br10g}. The use of local peak value of *E* or *H* leads to very conservative compliance distances in many cases, yet they do not underestimate the exposure in any case.

Table 5. The distance below which the local *SAR* limits the occupational exposure for a person weighing 42 kg. The distance (*D1*) is calculated assuming that all power fed to the antenna is absorbed to the exposed person. The distance (*D2*) is calculated by assuming that the absorption in the exposed human corresponds to absorption measured in box phantom.

Antenna	***GSM* 900, 947.5 MHz**		***GSM* 1800, 1842.5 MHz**		***UMTS*, 2140 MHz**	
	D1 [mm]	*D2* [mm]	*D1* [mm]	*D2* [mm]	*D1* [mm]	*D2* [mm]
a	54	100	91	240	120	200
b	25	100	-	-	-	-
c	0	60	0	78	0	240
d	-	-	116	160	114	190
e	-	-	58	160	83	160
f	-	-	13	90	49	213

4 Summary of publications

4.1 Setup and Dosimetry for Exposure of Human Skin *In Vivo* to *RF-EMF* at 900 MHz

The aim of this study was a dosimetric analysis of an experimental setup used in the exposure of 10 female volunteers to *GSM* 900 radiation. The exposure was carried out by irradiating a small region of the right forearm of the volunteers for 1 h, after which biopsies were taken from the exposed skin for protein analysis. The source of irradiation was a half-wave dipole fed with a computer-controlled *GSM* phone. The specific absorption rate (*SAR*) induced in the skin biopsy was assessed by computer simulations. The numerical model of the arm consisted of a muscle tissue simulating cylinder covered with thin skin (1 mm) and fat (3 mm) layers. The simulation models were validated by measurements with a homogeneous cylindrical liquid phantom. The average *SAR* value in the biopsy was 1.3 W/kg and the estimated uncertainty ±20% (K=2). The main source of error was found to be variations in the distance of the forearm from the dipole (10±1 mm). Other significant sources of uncertainty are individual variations of the fat layer and arm thicknesses, and the uncertainty of radio frequency (*RF*) power measurement.

4.2 Setup and Dosimetry for Exposing Anaesthetised Pigs *In Vivo* to 900 MHz *GSM* Mobile Phone Fields

The aim of this study was a dosimetric analysis of the setup used in the exposure of the heads of domestic pigs to *GSM*-modulated radio frequency electromagnetic fields (*RF-EMF*) at 900 MHz. The heads of pigs were irradiated with a half wave dipole using three different exposure routines; short bursts of 1–3 s at two different exposure levels and a continuous 10-min exposure. The electroencephalogram (*EEG*) was registered continuously during the exposures to search for *RF-EMF* originated changes. The dosimetry was based on simulations with the anatomical heterogeneous numerical model of the pig head. The simulation results were validated by experimental measurements with the exposure dipole and a homogeneous liquid phantom resembling the pig head. The specific absorption rate (*SAR*), defined as a maximum average over 10 g tissue mass (SAR_{10g}), was 7.3 W/kg for the first set of short bursts and 31 W/kg for the second set of short bursts. The SAR_{10g} in the continuous 10-min exposure was 31 W/kg. The estimated uncertainty for the dosimetry was ±25% (K=2).

4.3 Space Efficient System for Whole-Body Exposure of Unrestrained Rats to 900 MHz Electromagnetic Fields

The aim of this study was to design, implement and analyse a space-efficient setup for the whole-body exposure of unrestrained Wistar rats to radiofrequency (*RF*) electromagnetic fields at 900 MHz. The setup was used for 2 years in a cocarcinogenesis study and a part of it in a central nervous system (*CNS*) study for 5 weeks. Up to 216 rats could be placed in separate cages in nine different exposure chambers on three racks requiring only 9 m^2 of floor area (24 rats per m^2). Chambers were radial transmission lines (*RTL*), where the rats could freely move in their cages and food and drinking water was provided ad libitum except during the *RF* exposure periods. Dosimetric analysis was based on *FDTD* computations with heterogeneous rat models and was validated with calorimetrical measurements carried out with homogeneous phantoms. The estimated whole-body average specific absorption rates (*SAR*) of rats were 0 (sham), 0.4, and 1.3 W/kg in the cocarcinogenesis study and 0 (sham), 0.27, and 2.7 W/kg in the *CNS* study with an estimated uncertainty of 3 dB (K=2). The instantaneous and lifetime variations of whole-body average *SAR* due to the movement of rats were estimated to be 2.3 and 1.3 dB (K=1), respectively.

4.4 Specific Absorption Rate and Electric Field Measurements in the Near Field of Six Mobile Phone Base Station Antennas

In this article, the exposure to radio frequency electromagnetic fields was studied in close proximity (distances of 10, 100, 300, and 600 mm) to six base station antennas. The specific absorption rate (*SAR*) in 800mm×500mm×200mm box phantom and the unperturbed electric field (E) in air was measured. The results were used to determine whether the measurement of a local maximum of unperturbed electric field can be used as a compliance check for local exposure. Also, the conservativeness of this assessment method compared to the ICNIRP basic restriction was studied. Moreover, the assessment of the whole-body exposure was discussed and the distance ranges presented in which the ICNIRP limit for local exposure could be exceeded before the limit for the whole-body *SAR*. The results show that the electric field measurement alone can be used for an easy compliance check for the local exposure at all distances and for all antenna types studied. However, in some cases where the local peak value of E was compared directly to the ICNIRP reference level for unperturbed E, the exposure was overestimated only very slightly (by factor 1.1) compared to the basic restriction for localised *SAR* in a human, and hence these results cannot be generalised to all antenna types. Moreover, it was shown that the limit for the

localised exposure could be exceeded before the limit for the whole-body average *SAR*, if the distance to the antenna was less than 240 mm.

4.5 Numerical Specific Absorption Rate Analysis and Measurement of a Small Indoor Base Station Antenna

A comparison of different compliance rules for a small indoor base station antenna is presented at frequencies 1800, 2140, and 2450 MHz using a computational model. The numerical model of the antenna is validated using measurements of free space electric field values in close proximity of the antenna and specific absorption rate in a flat liquid phantom. Losses of the antenna are approximated using the measured radiation efficiency as a scaling factor between the input and output power of the antenna. The compliance distances are then computed using the reference levels for field values and equivalent power density. Obtained values are compared to the basic restriction limit in the upper torso of an anatomically realistic numerical model of a human body. The results show that in this case the reference level of the maximum value of equivalent power density gives conservative compliance distances.

5 Conclusions

The ability to assess the exposure in practical scenarios is a prerequisite for setting the exposure limits, and on the other hand, the dosimetry is also an inevitable part of the research that forms the basis of these limits. The recent development in simulation methods has exploded the possibilities for detailed dosimetry with realistic human models and detailed sources. However, it should be remembered that the reliability, in particular, is important in safety assessment and therefore the experimental measurement methods remain significant as a validation method.

In this thesis, the measurement methods were studied especially from the point of view of validation of numerical simulations. Although good agreement between the numerical simulations and measurements was achieved in all cases, it was also recognised that this seldom succeeded without any further corrections. The numerical models as well as the setups are very complicated and some parameters are almost always defective at first. Most of the flaws are trivial, e.g. forgotten cable attenuation in *RF* power scaling, which can be corrected once recognised. However, without cross validation, many of these flaws could remain in the final results. Therefore, the numerical simulations alone are not a sufficient method for dosimetric problems but always require experimental support.

The dosimetric analysis process in safety evaluation of the microwave exposure was studied from two points of view in this thesis. The studies presented in [P1]–[P3] introduced three setups for studying the health effects of the exposure while studies presented in [P4] and [P5] concentrated on the exposure assessment in practical safety evaluations.

The main objectives of the studies presented in [P1]–[P3] were to provide a practical setup, a reliably defined exposure level and well reported methodology for studying different types of biological hypotheses. These objectives were successfully met. Ten volunteered humans were exposed with the setup presented in [P1], 11 domestic pigs were studied with the setup presented in [P2] and two long term exposure studies were executed with the setup presented in [P3]. To ensure adequate reliability, validation phantom setups were designed for all studies. *SAR*-scanner based validation measurements utilising case-specific open top phantoms were used for human and pig exposures. In the rat exposure study, the validation measurements were made with calorimetric approach. The accuracy of these measurements was found adequate for validation and good agreement with the simulation results was achieved.

The separate publishing of methodology was found to be a good practice. It enables detailed descriptions of the setups and dosimetry to be reported and the

peer review is made by the dosimetry experts. Later on, the biological results can be introduced and discussed with no need to question the exposure methodology. The ideal case is, if possible, that the methodological report is published before the actual exposures are started, only this way the full advantage on the scientific evaluation process is achieved and unnecessary loss of research work due to flaws in the dosimetry is avoided.

The instant variations of the exposure seem to be caused mainly by the positioning of the source relative to the exposed person / animal. On the other hand, the trade off for good positioning accuracy is often for example the usability of the setup (e.g. laborious adjustment) or ergonomics and convenience (e.g. restraining, spacer touching the skin). For this reason the main task in the setup design is the assessment of the required accuracy of the dosimetry. The use of complex setup for just improving the accuracy is seldom justified. At this point of knowledge, the studies are made to find out is there an effect at all rather than trying to establish clear thresholds. In this light, the uncertainties of some tens of percents do not seem important. In fact, more important for the future use of the results is the reliable estimation of the uncertainty. Therefore, it is good to keep the setups as simple as possible. This is also supported by the challenges that are present in the practical execution of these studies.

The adequate accuracy is the key issue in practical safety evaluations as well. The aim of the safety evaluations is to check the compliance with the exposure limits rather than the accurate estimation on the exposure. Therefore, many methods are used to simplify the assessment. The most important simplification in the safety evaluations is the use of unperturbed E as a measure of exposure.

In the far field conditions, the relation of whole body SAR and unperturbed E is somewhat straightforward in the microwave frequencies. On the other hand, for local SAR or near field conditions, the safety evaluation based on E is questionable. However, in practice the measurement of unperturbed E is the only feasible method for the safety evaluations of fixed antennas *in situ*. Therefore, the relation of unperturbed fields and SAR was studied in [P4] and [P5]. The studies concentrated on the exposure in the inhomogeneous near fields of mobile phone base station antennas.

In [P4] it was shown that the E, compared directly to the ICNIRP reference level, can be used as an easy compliance check for local exposure. The spatial averaging routines, however, should not be applied in the near field, but the local peak value should be used [P5]. This compliance check was valid for the studied six commercial antenna models even at 10 mm distance from the antenna. However, the safety evaluation based on the maximum value of E was not conservative in some cases compared to basic restriction for SAR_{10g}. The studied

antennas represented several of the most commonly used base station antenna types, although not all, and therefore more research is needed to generalise these results to all antennas. Especially study of antennas with significantly different types of radiating elements would be an interesting addition.

References

[1] Frey, A. M. 1961. Auditory system response to radiofrequency energy. Aerospace Medicine 32:1140–1142.

[2] Guy A W, Lin J C, Kramar P O, Emery A. 1975. Effect of 2450-MHz radiation on the rabbit eye. IEEE Transactions on Microwave Theory and Techniques 23:492– 498.

[3] Cook H F. 1952. A physical investigation of heat production in human tissues when exposed to microwaves. British Journal of Applied Physics 3:1–6.

[4] Barron C I, Baraff A A. 1958. Medical considerations of exposure to microwaves (radar). Journal of American Medical Association 168:1194 –1199.

[5] Michaelson SM. 1972. Cutaneous perception of microwaves. Journal of Microwave Power 7:67–73.

[6] International Commission on Non-Ionizing Radiation Protection (ICNIRP). 1998. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300GHz). Health Physics 74:494–522.

[7] International Commission on Non-Ionizing Radiation Protection (ICNIRP). 2002. General Approach to Protection against Non-Ionizing Radiation. Health Physics 82: 540-548.

[8] Karinen A, Heinävaara S, Nylund R, Leszczynski D. 2008. Mobile phone radiation might alter protein expression in human skin. BMC Genomics 9:77.

[9] Lipping T, Rorarius M, Jäntti V, Annala K, Mennander A, Ferenets R, Toivonen T, Toivo T, Värri A, Korpinen L. 2009. Using the nonlinear control of anesthesia-induced hypersensitivity of EEG at burst suppression level to test the effects of radiofrequency radiation on brain function. Nonlinear Biomedical Physics 3:5.

[10] Heikkinen P, Ernst H, Huuskonen H, Komulainen H, Kumlin T, Mäki-Paakkanen J, Puranen L, Juutilainen J. 2006. No effects of radiofrequency radiation on 3-chloro-4-(dicholoromethyl)-5-hydroxy-2(5H)-furanone-induced tumorigenesis in female Wistar rats. Radiation Research 166:397–408.

[11] Kumlin T, Iivonen H, Miettinen P, Juvonen A, van Groen T, Puranen L,

Pitkäaho R, Juutilainen J, Tanila H. 2007. Mobile phone radiation and the developing brain: Behavioral and morphological effects in juvenile rats. Radiation Research 168:471–479.

[12] European Committee for Electrotechnical Standardization (CENELEC). 2002. Basic standard for the calculation and measurement of electromagnetic field strength and SAR related to human exposure from radio base stations and fixed terminal stations for wireless telecommunication systems (110 MHz–40 GHz). European standard EN 50383. August 2002. Brussels, Belgium.

[13] Heikkinen P, Kosma V-M, Hongisto T, Huuskonen H, Hyysalo P, Komulainen H, Kumlin T, Lahtinen T, Lang S, Puranen L, Juutilainen J. 2001. Effects of mobile phone radiation on X-ray-induced tumorigenesis in mice. Radiation Research 156:775–785.

[14] Jung K B, Kim T H, Kim J L, Doh H J, Chung Y C, Choi J H, Pack J K. 2008. Development and Validation of Reverberation-Chamber Type Whole-Body Exposure System for Mobile-Phone Frequency. Electromagnetic Biology and Medicine 27:73–82.

[15] Wang J, Fujiwara O, Kawai H, Wake K, Watanabe S. 2008. Development and Dosimetry Analysis of a 2-GHz Whole-Body Exposure Setup for Unrestrained Pregnant and Newborn Rats. IEEE Transactions on Microwave Theory and Techniques 56: 2008–2013.

[16] Wake K, Mukoyama A, Watanabe S, Yamanaka Y, Uno T, Taki M. 2007. An Exposure System for Long-Term and Large-Scale Animal Bioassay of 1.5-GHz Digital Cellular Phones. IEEE Transactions on Microwave Theory and Techniques 55:343–350.

[17] Kainz W, Nikoloski N, Oesch W, Berdinas-Torres V, Frohlich J, Neubauer G, Kuster N. 2006. Development of novel whole-body exposure setups for rats providing high efficiency, National Toxicology Program (NTP) compatibility and well-characterized exposure. Physics in Medicine and Biology 51:5211–5229.

[18] Ardoino L, LoprestoV, Mancini S, Marino C, Pinto R, Lovisolo GA. 2005. A radio-frequency system for in vivo pilot experiments aimed at the studies on biological effects of electromagnetic fields. Physics in Medicine and Biology 50:3643–3654.

[19] Balzano Q, Chou C-K, Cicchetti R, Faraone A, Tay RY-S. 2000. An efficient RF exposure system with precise whole-body average SAR determination for in vivo animal studies. IEEE Transactions on Microwave Theory and Techniques 48:2040–2049.

[20] Boutry CM, Kuehn S, Achermann P, Romann A, Keshvari J, Kuster N. 2008. Dosimetric evaluation and comparison of different RF exposure apparatuses used in human volunteer studies. Bioelectromagnetics 29:11–19.

[21] Kwon M-S, Jääskeläinen S, Toivo T, Hämäläinen H. 2009. No Effects of Mobile Phone Electromagnetic Field on Auditory Brainstem Response. Bioelectromagnetics (in press) DOI 10.1002/bem.20526.

[22] Hillert L, Akerstedt T, Lowden A, Wiholm C, Kuster N, Ebert S, Boutry C, Moffat SD, Berg M, Arnetz BB. 2008. The effects of 884 MHz GSM wireless communication signals on headache and other symptoms: an experimental provocation study. Bioelectromagnetics 29:185–196.

[23] Haarala C, Aalto S, Hautzel H, Julkunen L, Rinne J O, Laine M, Krause B, Hämäläinen H. 2003. Effects of a 902 MHz mobile phone on cerebral blood flow in humans: a PET study. Neuroreport 14:2019–2023.

[24] Kwon M S, Kujala T, Huotilainen M, Shestakova A, NäätänenR, Hämäläinen H. 2009. Preattentive Auditory Information Processing Under Exposure to the 902 MHz GSM Mobile Phone Electromagnetic Field: AMismatch Negativity (MMN) Study. Bioelectromagnetics 30:241–248.

[25] Mizuno Y, Moriguchi Y, Hikage T, Terao Y, Ohnishi T, Nojima T, Ugawa Y. 2009. Effects of W-CDMA 1950 MHz EMF emitted by mobile phones on regional cerebral blood flow in humans. Bioelectromagnetics (in press)

[26] Stefanics G, Thuroczy G, Kellenyi L, Hernadi I. 2008. Effects of twenty-minute 3G mobile phone irradiation on event related potential components and early gamma synchronization in auditory oddball paradigm. Neuroscience 157:453–462.

[27] Kleinlogel H, Dierks T, Koenig T, Lehmann H, Minder A, Berz R. 2008. Effects of weak mobile phone - electromagnetic fields (GSM, UMTS) on event related potentials and cognitive functions. Bioelectromagnetics 29:488–497.

[28] Kleinlogel H, Dierks T, Koenig T, Lehmann H, Minder A, Berz R. 2008. Effects of Weak Mobile Phone Electromagnetic Fields (GSM, UMTS) on Well-Being and Resting EEG. Bioelectromagnetics 29:479–487.

[29] Croft RJ, Hamblin DL, Spong J, Wood AW, McKenzie RJ, Stough C. 2008. The effect of mobile phone electromagnetic fields on the alpha rhythm of human electroencephalogram. Bioelectromagnetics 29:1–10.

[30] Arnetz BB, Akerstedt T, Hillert L, Lowden A, Kuster N, Wiholm C. 2007. The Effects of 884 MHz GSM Wireless Communication Signals on Self-reported Symptom and Sleep (EEG) - An Experimental Provocation Study. PIERS Online 3:1148–1150.

[31] Kwon MS, Koivisto M, Laine M, Hämäläinen H. 2008. Perception of the electromagnetic field emitted by a mobile phone. Bioelectromagnetics 29:154–159.

[32] Fritzer G, Göder R, Friege L, Wachter J, Hansen V, Hinze-Selch D, Aldenhoff J B. 2007. Effects of short- and long-term pulsed radiofrequency electromagnetic fields on night sleep and cognitive functions in healthy subjects. Bioelectromagnetics 28:316–325.

[33] Koivisto M, Haarala C, Krause CM, Revonsuo A, Laine M, Hamalainen H. 2001. GSM phone signal does not produce subjective symptoms. Bioelectromagnetics 22:212–215.

[34] Wagner P, Röschke J, Mann K, Hiller W, Frank C. 1998. Human sleep under the influence of pulsed radiofrequency electromagnetic fields: a polysomnographic study using standardized conditions. Bioelectromagnetics 19:199–202.

[35] Van Leeuwen G, Lagendijk J, Van Leersum B, Zwamborn A, Hornsleth S, Kotte A. 1999. Calculation of change in brain temperatures due to exposure to a mobile phone. Physics in Medicine and Biology 44:2367–2379.

[36] Kuster N, Schuderer J, Christ A, Futter P, Ebert S. 2004. Guidance for exposure design of human studies addressing health risk evaluations of mobile phones. Bioelectromagnetics 25:524–529.

[37] Regel S J, Tinguely G, Schuderer J, Adam M, Kuster N, Landolt H P, Achermann P. 2007. Pulsed radio-frequency electromagnetic fields: dose-

dependent effects on sleep, the sleep EEG and cognitive performance. Journal of Sleep Research 16:253–258.

[38] Adair E R, Black D R. 2003. Thermoregulatory Responses to RF Energy Absorption. Bioelectromagnetics Supplement 6:S17–S38.

[39] Adair E R. 2008. Reminiscences of a Journeyman Scientist: Studies of Thermoregulation in Non-Human Primates and Humans. Bioelectromagnetics 29:586–597.

[40] Pennes H. 1948. Analysis of Tissue and Arterial Blood Temperatures in Resting Human Forearm. Journal of Applied Physiology 1:93–122.

[41] Walters T, Ryan K, Belcher J, Doyle J, Tehrany M, Mason P. 1998. Regional brain heating during microwave exposure (2.06 GHz), warm-water immersion, environmental heating and exercise. Bioelectromagnetics 19:341–353.

[42] Tahvanainen K, Nino J, Halonen P, Kuusela T, Alanko T, Laitinen T, Länsimies E, Hietanen M, Lindholm H. 2007. Effects of cellular phone use on ear canal temperature measured by NTC thermistors. Clinical Physiology and Functional Imaging: 27:162–172

[43] Mazor R, Korenstein-Ilan A, Barbul A, Eshet Y, Shahadi A, Jerby E, Korenstein R. 2008. Increased levels of numerical chromosome aberrations after in vitro exposure of human peripheral blood lymphocytes to radiofrequency electromagnetic fields for 72 hours. Radiation Research 169:28–37.

[44] Joubert V, Bourthoumieu S, Leveque P, Yardin C. 2008. Apoptosis is Induced by Radiofrequency Fields through the Caspase-Independent Mitochondrial Pathway in Cortical Neurons. Radiation Research 169:38–45.

[45] Perentos N, Croft RJ, McKenzie RJ, Cvetkovic D, Cosic I. 2007. Comparison of the effects of continuous and pulsed mobile phone like RF exposure on the human EEG. Australasian Physical and Engineering Sciences in Medicine 30:274–280.

[46] Riddervold IS, Pedersen GF, Andersen NT, Pedersen AD, Andersen JB, Zachariae R, Molhave L, Sigsgaard T, Kjaergaard SK. 2008. Cognitive function and symptoms in adults and adolescents in relation to rf radiation from UMTS base stations. Bioelectromagnetics 29:257–267.

[47] Dawe AS, Nylund R, Leszczynski D, Kuster N, Reader T, De Pomerai DI. 2008. Continuous wave and simulated GSM exposure at 1.8 W/kg and 1.8 GHz do not induce hsp16-1 heat-shock gene expression in Caenorhabditis elegans. Bioelectromagnetics 29:92–99.

[48] Höytö A, Sokura M, Juutilainen J, Naarala J. 2008. Radiofrequency radiation does not significantly affect ornithine decarboxylase activity, proliferation, or caspase-3 activity of fibroblasts in different physiological conditions. International Journal of Radiation Biology 84:727–733.

[49] Franzellitti S, Valbonesi P, Contin A, Biondi C, Fabbri E. 2008. HSP70 expression in human trophoblast cells exposed to different 1.8 Ghz mobile phone signals. Radiation Research 170:488–497.

[50] Luukkonen J, Hakulinen P, Mäki-Paakkanen J, Juutilainen J, Naarala J. 2009. Enhancement of chemically induced reactive oxygen species production and DNA damage in human SH-SY5Y neuroblastoma cells by 872 MHz radiofrequency radiation. Mutation Research 662:54–58.

[51] Huber R, Schuderer J, Graf T, Jütz K, Borbély AA, Kuster N, Achermann P. 2003. Radio frequency electromagnetic field exposure in humans: Estimation of SAR distribution in the brain, effects on sleep and heart rate. Bioelectromagnetics 24:262–276.

[52] Wang J, Fujita M, Fujiwara O, Wake K, Watanabe S. 2006. Uncertainty evaluation of an in vivo near-field exposure setup for testing biological effects of cellular phones. IEEE Transactions on Electromagnetic Compatibility 48:545–551.

[53] Wake K, Hongo H, Watanabe S, Masao T, Kamimura Y, Yamanaka Y, Uno T, Kojima M, Hata I, Sasaki K. 2007. Development of a 2.45-GHz Local Exposure System for In Vivo Study on Ocular Effects. IEEE Transactions on Microwave Theory Techniques 55:588–596.

[54] Furubayashi T, Ushiyama A, Terao Y, Mizuno Y, Shirasawa K, Pongpaibool P, Simba AY, Wake K, Nishikawa M, Miyawaki K, Yasuda A, Uchiyama M, Yamashita HK, Masuda H, Hirota S, Takahashi M, Okano T, Inomata-Terada S, Sokejima S, Maruyama E, Watanabe S, Taki M, Ohkubo C, Ugawa Y. 2009. Effects of short-term W-CDMA mobile phone base station exposure on women with or without mobile phone related symptoms. Bioelectromagnetics 30:100–113.

[55] Schelkshorn S, Tejero S, Detlefsen J. 2007. Exposure setup for animal experiments using a parabolic reflector. Radiation Protection Dosimetry 124:27–30.

[56] Guy AW, Wallace J, McDougall JA. 1979. Circularly polarized 2450-MHz waveguide system for chronic exposure of small animals to microwaves. Radio Science 14 (6S):63–74.

[57] Höytö A, Sihvonen AP, Alhonen L, Juutilainen J, Naarala J. 2006. Modest increase in temperature affects ODC activity in L929 cells: Low-level radiofrequency radiation does not. Radiation and Environmental Biophysics 45:231–235.

[58] Dawe AS, Smith B, Thomas DW, Greedy S, Vasic N, Gregory A, Loader B, de Pomerai DI. 2006. A small temperature rise may contribute towards the apparent induction by microwaves of heat-shock gene expression in the nematode Caenorhabditis Elegans. Bioelectromagnetics 27:88–97.

[59] Wilson BW, Faraone A, Sheen D, Swicord M, Park W, Morrissey J, Creim J, Anderson LE. 2002. Space efficient system for small animal, whole body microwave exposure at 1.6 GHz. Bioelectromagnetics 23:127–131.

[60] Cranfield CG, Wood AW, Anderson V, Menezes KG. 2001. Effects of mobile phone type signals on calcium levels within human leukaemic T-cells (Jurkat cells). International Journal of Radiation Biology 77:1207–1217.

[61] Nylund R, Leszczynski D. 2006. Mobile phone radiation causes changes in gene and protein expression in human endothelial cell lines and the response seems to be genome- and proteome-dependent. Proteomics 6:4769–4780.

[62] Schmid G, Cecil S, Goger C, Trimmel M, Kuster N, Molla-Djafari H. 2007. New head exposure system for use in human provocation studies with EEG recording during GSM900- and UMTS-like exposure. Bioelectromagnetics 28:636–647.

[63] Hansen V, Bitz A, Streckert J. 1999. RF Exposure of Biological Systems in Radial Waveguides. IEEE Transactions on Electromagnetic Compatibility 41:487–493.

[64] Repacholi M, Basten A, Gebski V, Noonan D, Finnie J, Harris A. 1997.

Lymphomas in Eμ-*Pim1* Transgenic mice exposed to pulsed 900 MHz electromagnetic fields. Radiation Research 147:631–640.

[65] Yee K. 1966. Numerical Solution of Initial Boundary Value Problems Involving Maxwell's Equations in Isotropic Media. IEEE Transactions on Antennas and Propagation 14:302–307.

[66] Ackerman M J. 1998. The Visible Human Project. Proceedings of the IEEE 86:504–11.

[67] Nagaoka T, Watanabe S, Sakurai K, Kunieda E, Watanabe S, Taki M, Yamanaka Y. 2003. Development of realistic high-resolution whole-body voxel models of Japanese adult males and females of average height and weight, and application of models to radio-frequency electromagnetic-field dosimetry. Physics in Medicine and Biology 49:1–15.

[68] Dimbylow PJ. 1997. FDTD calculations of the whole-body averaged SAR in an anatomically realistic voxel model of the human body from 1 MHz to 1 GHz. Physics in Medicine and Biology 42:479–490.

[69] Dimbylow P J 2005 Development of the female voxel phantom, NAOMI and its application to calculations of induced current densities and electric fields from applied low frequency magnetic and electric fields. Physics in Medicine and Biology 50:1047–1070.

[70] Kühn S, Jennings W, Christ A, Kuster N. 2009. Assessment of induced radio-frequency electromagnetic fields in various anatomical human body models. Physics in Medicine and Biology 54:875–890.

[71] Kunz SK, Luebbers RJ. 1993. The finite difference time domain method for electromagnetics. Boca Raton, FL, USA: CRC Press.

[72] Pisa S, Cavagnaro M, Lopresto V, Piuzzi E, Lovisolo GA, Bernardi P. 2005. A procedure to develop realistic numerical models of cellular phones for an accurate evaluation of SAR distribution in the human head. IEEE Transactions on Microwave Theory and Techniques 53:1256–1265.

[73] Chavannes N, Tay R, Nikoloski N, Kuster N. 2003. Suitability of FDTD based TCAD tools for RF design of mobile phones. IEEE Antennas and Propagation Magazine 45:52–66.

[74] Hannula M, Arola T, Hyttinen J, Kauppinen P, Silfverhuth M, Jäntti V, Malmivuo J. 2005. Segmentation of the pig head. 3rd European Medical & Biological Engineering Conference, EMBEC'05. IFMBE Proceedings. Prague, Czech Republic, 20–25.11.2005, vol. 11(1), on CD, paper ID 2145.

[75] Wiart J, Hadjem A, Wong MF, Bloch I. 2008. Analysis of RF exposure in the head tissues of children and adults. Physics in Medicine and Biology 53:3681–3695.

[76] Kainz W, Christ A, Kellom T, Seidman S, Nikoloski N, Beard B, Kuster N. 2005. Dosimetric comparison of the specific anthropomorphic mannequin (SAM) to 14 anatomical head models using a novel definition for the mobile phone positioning. Physics in Medicine and Biology 50:3423–3445.

[77] ICRP. 1974. Report of the Task Group on Reference Man. International Commission on Radiological Protection, publication No. 23.

[78] Gabriel C. 1996. Compilation of the dielectric properties of body tissues at microwave frequencies. Brooks Air Force Technical Report AL/OE-TR-1996-0037. Brooks Air Force Base, Texas.

[79] Gabriel C, Gabriel S, Corthout E. 1996. The dielectric properties of biological tissues: I. Literature survey. Physics in Medicine and Biology 41:2231–2249.

[80] Gabriel C, Gabriel S, Corthout E. 1996. The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz. Physics in Medicine and Biology 41:2251–2269.

[81] Gabriel C, Gabriel S, Corthout E. 1996. The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues. Physics in Medicine and Biology 41:2271–2293.

[82] Peyman A, Rezazadeh AA, Gabriel C. 2001. Changes in the dielectric properties of rat tissue as a function of age at microwave frequencies. Physics in Medicine and Biology 46:1617–1629.

[83] Schmid G, Neubauer G, Illievich UM, Alesch F. 2003. Dielectric properties of porcine brain tissue in the transition from life to death at frequencies from 800 to 1900 MHz. Bioelectromagnetics 24:413–422.

[84] Wang J, Fujiwara O, Watanabe S. 2006. Approximation of Aging Effect on Dielectric Tissue Properties for SAR Assessment of Mobile Telephones. IEEE Transactions on Electromagnetic Compatibility 48:408–413.

[85] Keshvari J, Keshvari R, Lang S. 2006. The effect of increase in dielectric values on specific absorption rate (SAR) in eye and head tissues following 900, 1800 and 2450 MHz radio frequency (RF) exposure. Physics in Medicine and Biology 51:1463–1477.

[86] Laakso I. 2009. Assessment of the computational uncertainty of temperature rise and SAR in the eyes and brain under far-field exposure from 1 to 10 GHz. Physics in Medicine and Biology 54:3393–3404.

[87] Kuster N, Berdiñas Torres V, Nikoloski N, Frauscher M, Kainz W. 2006. Methodology of detailed dosimetry and treatment of uncertainty and variations for in vivo studies. Bioelectromagnetics 27:378–391.

[88] BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML. 1995. Guide to the expression of uncertainty in measurement 1st edition (Geneva: ISO), ISBN 92-67-10188-9.

[89] Schmid T, Egger O, Kuster N. 1996. Automated E-field scanning system for dosimetric assessments. IEEE Transactions on Microwave Theory and Techniques 44:105–113.

[90] International Electrotechnical Commission (IEC). 2005. Human exposure to radio frequency fields from handheld and body-mounted wireless communication devices—Human models, instrumentation and procedures—Part 1: Procedure to determine the specific absorption rate (SAR) for hand-held devices used in close proximity to the ear (frequency range of 300 MHz to 3 GHz). International standard 62209-1. Geneva, Switzerland.

[91] International Electrotechnical Commission (IEC). 2007. Human exposure to radio frequency fields from Handheld and Body-Mounted wireless communication devices—Human Models, Instrumentation and Procedures–Part 2: Procedure to determine the Specific Absorption Rate (SAR) in the head and body for 30 MHz to 6 GHz Handheld and Body-Mounted devices used in close proximity to the Body. International standard 62209-2. Geneva, Switzerland.

[92] Olsen G, Griner TA. 1993. Specific absorption rate and radiofrequency current-to-ground in human models exposed to near-field irradiation. Health

Physics 64:633–637.

[93] Cooper T G, Mann S M, Khalid M, Blackwell R P. 2006. Public exposure to radio waves near GSM microcell and picocell base stations. Journal of Radiological Protection 26:199–211.

[94] Bornkessel C, Schubert M, Wuschek M, Schmidt P. 2007. Determination of the General Public Exposure Around GSM and UMTS Base Stations. Radiation Protection Dosimetry 124:40–47.

[95] Frei P, Mohler E, Neubauer G, Theis G, Bürgi A, Fröhlich J, Braun-Fahrländer C, Bolte J, Egger M, Röösli M. 2009. Temporal and spatial variability of personal exposure to radio frequency electromagnetic fields. Environmental Research (in press)

[96] Thors B, Strydom M L, Hansson B, Meyer F J C, Kärkkäinen K, Zollman P, Ilvonen S, Törnevik C. 2008. On the Estimation of SAR and Compliance Distance Related to RF Exposure From Mobile Communication Base Station Antennas. IEEE Transactions on Electromagnetic Compatibility 50:837–848.

[97] The Institute of Electrical and Electronics Engineers (IEEE). 2006. IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz, IEEE Std C95.1 - 2005. New York, USA.

[98] European Council. 1999. Council recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz). Official Journal of the European Communities L 199:59–70.

[99] European Committee for Electrotechnical Standardization (CENELEC). 2002. Product standard to demonstrate the compliance of radio base stations and fixed terminal stations for wireless telecommunication systems with the basic restrictions or the reference levels related to human exposure to radio frequency electromagnetic fields (110 MHz - 40 GHz) – Occupational. European standard EN 50384. August 2002. Brussels, Belgium.

[100] European Committee for Electrotechnical Standardization (CENELEC). 2002. Product standard to demonstrate the compliance of radio base stations and fixed terminal stations for wireless telecommunication systems with the basic restrictions or the reference levels related to human exposure to radio frequency

electromagnetic fields (110 MHz - 40 GHz) – General public. European standard EN 50385. August 2002. Brussels, Belgium.

[101] European Committee for Electrotechnical Standardization (CENELEC). 2006. Basic standard to demonstrate the compliance of fixed equipment for radio transmission (110 MHz - 40 GHz) intended for use in wireless telecommunication networks with the basic restrictions or the reference levels related to general public exposure to radio frequency electromagnetic fields, when put into service. European standard EN 50400. June 2006. Brussels, Belgium.

[102] European Committee for Electrotechnical Standardization (CENELEC). 2006. Product standard to demonstrate the compliance of fixed equipment for radio transmission (110 MHz - 40 GHz) intended for use in wireless telecommunication networks with the basic restrictions or the reference levels related to general public exposure to radio frequency electromagnetic fields, when put into service. European standard EN 50401. June 2006. Brussels, Belgium.

[103] European Committee for Electrotechnical Standardization (CENELEC). 2004. Generic standard to demonstrate the compliance of electronic and electrical apparatus with the basic restrictions related to human exposure to electromagnetic fields (0 Hz - 300 GHz). European standard EN 50392. January 2004. Brussels, Belgium.

[104] European Committee for Electrotechnical Standardization (CENELEC). 2008. Basic standard on measurement and calculation procedures for human exposure to electric, magnetic and electromagnetic fields (0 Hz - 300 GHz). European standard EN 50413. December 2008. Brussels, Belgium.

[105] European Committee for Electrotechnical Standardization (CENELEC). 2006. Basic standard for the evaluation of human exposure to electromagnetic fields from a stand alone broadcast transmitter (30 MHz - 40 GHz) European standard EN 50420. June 2006. Brussels, Belgium.

[106] European Committee for Electrotechnical Standardization (CENELEC). 2006. Product standard to demonstrate the compliance of stand alone broadcast transmitters with the reference levels or the basic restrictions related to public human exposure to radio frequency electromagnetic fields (30 MHz - 40 GHz). European standard EN 50421. June 2006. Brussels, Belgium.

[107] European Committee for Electrotechnical Standardization (CENELEC).

2008. Determination of workers' exposure to electromagnetic fields and assessment of risk at a broadcast site. European standard EN 50496. November 2008. Brussels, Belgium.

[108] Neubauer G, Preiner P, Cecil S, Mitrevski N, Gonter J, Garn H. 2009. The relation between the specific absorption rate and electromagnetic field intensity for heterogeneous exposure conditions at mobile communications frequencies. Bioelectromagnetics 30:651–662.

[109] Kühn S, Jennings W, Christ A, Kuster N. 2009. Assessment of induced radio-frequency electromagnetic fields in various anatomical human body models. Physics in Medicine and Biology 54:875–890.

[110] Jokela K. 2007. Assessment of complex EMF exposure situations including inhomogeneous field distribution. Health Physics 92:531–540.

[111] Kuster N, Balzano Q. 1992. Energy absorption mechanism by biological bodies in the near field of dipole antennas above 300 MHz. IEEE Transactions on Vehicular Technology 41:17–23.

[112] Kivekäs O, Lehtiniemi T, Vainikainen P. 2004. On the General Energy Absorption Mechanism in the Human Tissue. Microwave and Optical Technology Letters 43:195–201.

[113] Christ A, Samaras T, Klingenböck A, Kuster N. 2006. Characterization of the electromagnetic near-field absorption in layered biological tissue in the frequency range from 30 MHz to 6000 MHz. Physics in Medicine and Biology 51:4951–4965.

[114] Joseph W, Vermeeren G, Martens L. 2007. Correction factor to be applied to the SAR in phantom models for occupational electromagnetic exposure. Microwave and Optical Technology Letters 49:652–655.

[115] SPEAG. 2004. Dasy4 system handbook. Switzerland: Schmid and Partner Engineering AG.

[116] Davis C C, Balzano Q. 2009. The International Intercomparison of SAR Measurements on Cellular Telephones. IEEE Transactions on Electromagnetic Compatibility (in press, DOI 10.1109/TEMC.2008.2010328).

[117] Joseph W, Martens L. 2005. Comparison of safety distances based on the electromagnetic field and based on the SAR for occupational exposure of a 900-MHz base station antenna. IEEE Transactions on Electromagnetic Compatibility 47:977–985.

[118] Cooper J, Marx B, Buhl J, Hombach V. 2002. Determination of safety distance limits for a human near a cellular base station antenna, adopting the IEEE standard or ICNIRP guidelines. Bioelectromagnetics 23:429–443.

[119] vanWyk M, Bingle M, Meyer F. 2005. Antenna Modeling Considerations for Accurate SARCalculations in Human Phantoms in Close Proximity to GSM Cellular Base Station Antennas. Bioelectromagnetics 26:502–509.

[120] Thors B, Hansson B, Törnevik C. 2009. The generation of simple compliance boundaries for mobile communication base station antennas using formulae for SAR estimation. Physics in Medicine and Biology 54:4243–4256

[121] Gosselin M-C, Christ A, Kühn S, Kuster N. 2009. Dependence of the Occupational Exposure to Mobile Phone Base Stations on the Properties of the Antenna and the Human Body. IEEE Transactions on Electromagnetic Compatibility 51:227–235.

[122] Abd-Alhameed RA, Excell PS, Mangoud MA. 2005. Computation of specific absorption rate in the human body due to base-station antennas using a hybrid formulation. IEEE Transactions on Electromagnetic Compatibility 47:374–381.

[123] Cicchetti R, Faraone A. 2004. Estimation of the peak power density in the vicinity of cellular and radio base station antennas. IEEE Transactions on Electromagnetic Compatibility 46:275–290.

[124] Altman Z, Begasse B, Dale C, Karwowski A, Wiart J, Wong MF. 2002. Efficient models for base station antennas for human exposure assessment. IEEE Transactions on Electromagnetic Compatibility 44:588–592.

[125] Catarinucci L, Palazzar P, Tarricone L. 2003. Human exposure to the near field of radiobase antennas - a full-wave solution using parallel FDTD. IEEE Transactions on Microwave Theory and Techniques 51:935–940.

A

STUK
Laippatie 4, 00880 Helsinki
Puh. (09) 759 881, fax (09) 759 88 500
www.stuk.fi

ISBN 978-952-478-523-5
ISSN 0781-1705
Edita Prima Oy, Helsinki 2010