
A thesis submitted to attain the degree of DOCTOR OF SCIENCES of ETH ZURICH (Dr. sc. ETH Zurich)

presented by

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2016
The use of mobile phones has become very common in modern society. Over the last 15 years, the number of subscriptions worldwide has grown by almost a factor of 10. Even in developing countries, there are around 90 mobile phone subscriptions per 100 citizens. These devices are used not only by adult professionals, but also by other demographics: children, elderly people, low-income families, etc. Governmental and non-governmental organizations are asking for exposure information regarding mobile phone use and mobile networks, but also related to other wireless signals, like WiFi and DECT, which are gaining in popularity. Epidemiologic studies are investigating the hypothetical relationship between brain diseases and mobile phone use, but these studies require scientifically sound and robust exposure metrics, which are not yet easily accessible.

Further, this explosion of the number of mobile phone users is gradually leading to denser mobile networks from the various providers. Base station antennas on rooftop buildings have become a common component of urban sceneries, in particular in densely populated areas. Base station antenna installation and service personnel as well as other building maintenance employees can get very close to those antennas while performing their work. Although this type of exposure is not the focus of epidemiologic studies, it needs to be controlled such that it is compliant with the safety limits, without being overly conservative. Some studies have been performed to characterize the exposure of humans in the vicinity of base station antennas, but no general conclusions have been drawn and efficient ways to translate those results into practical recommendations are still missing.
The goal of this thesis was to develop tools and methods for a better, easier, and more comprehensive dosimetric evaluation of two typical scenarios: exposure to mobile phones operated at the head, typical for the general public, and whole-body and partial-body exposure from base station antennas, typical, e.g., for installation and service personnel.

As electromagnetic field (EMF) measurements in human bodies are invasive and thus not possible, and as laboratory measurements using homogeneous phantoms do not include the local effects of tissue layering for field propagation and absorption, sound dosimetric assessments in human bodies are performed numerically. Those require anatomical models of high resolution with a consistent tissue assignment and, usually, representing various age groups, sizes, genders, etc. Improvements of existing models have been requested, in particular to fulfill needs of the medical community to assess the safety and effectiveness of medical devices and applications. Chapter 2 presents the Virtual Population 3.0, a new generation of anatomically independent, accurate, and detailed models with smooth, yet feature-rich and topologically conforming surfaces. These models are suitable to a wider range of solvers and physics than the previously-developed Virtual Family. The improvements of the Virtual Population 3.0 include implementation of quality-control procedures, re-segmentation at higher resolution, more-consistent tissue assignments, enhanced surface processing, and numerous anatomical refinements. The impact of these improvements is shown in Chapter 2 for the magnetic resonance imaging (MRI) exposure of an adult woman with an orthopedic spinal implant. The models of the Virtual Population 3.0 are made available to the research community.

Various aspects of near-field dosimetric evaluations are investigated in Part III of this thesis. Although the maximum peak exposure of each commercial mobile phone is determined before market approval and publicly available, this information is not sufficient for epidemiologic studies aiming to correlate the use of mobile phones with specific cancers or to behavioral and cognitive alterations. To strengthen epidemiologic evaluations and improve information for the consumer, a methodology to determine tissue-specific exposure from measurements in homogeneous phantoms is introduced in Chapter 3. This extension of the post-processing algorithms to be applied to
surface- or volume-scan results of compliance measurements from specific absorption rate (SAR) scanners enables the reliable determination of the maximum and averaged exposure of specific tissues and functional brain regions without requiring additional measurement procedures or time. The outcome is a set of transformation factors derived to correlate the SAR induced in the specific anthropomorphic mannequin (SAM) head to the SAR in anatomical heads. Those transformation factors have been implemented in the commercial dosimetric measurement platform DASY 5, commonly used along with the SAM phantom for mobile phone compliance testing.

The exposure of children to mobile phones has been a concern for years and although numerical studies have validated the use of the SAM phantom — representative of a male head — no experimental evidence has ever been provided. Chapter 4 addresses issues related to the experimental assessment of children exposure to mobile phones. Using head phantoms of two children (3 and 8 years old), it establishes that the SAM phantom used in standardized compliance testing is also conservative for homogeneous child head models. On the other hand, the results demonstrate that the currently suggested numerical SAR averaging procedures may underestimate the actual peak spatial SAR and that the currently defined limits in terms of the average of a cubic mass are impractical for non-ambiguous evaluations.

While the exposure to radio-frequency (RF) fields from mobile phones has been comprehensively assessed in the past, the low-frequency (LF) fields have received much less attention. In Chapter 5 LF fields from mobile phones are assessed experimentally and numerically for the GSM and UMTS communication systems and the need for compliance testing including this frequency band is evaluated. It is shown that the B-field induced by currents in phones using the UMTS system is 2 orders of magnitude lower than that induced by GSM. Knowing that the RF exposure from UMTS is also 2 orders of magnitude lower than from GSM, it is now possible to state that there is an overall reduction of the exposure from this communication system.

The demonstration of compliance with guidelines for human exposure to base station antennas can be a time consuming process or often results in overly conservative estimates. The exposure of workers to base station antennas is addressed in Part IV of this thesis and aims
at alleviating the aforementioned burden and reducing the overestimation. In a first step, Chapter 6 assesses human exposure in the close vicinity of base station antennas using three human body models and various generic and commercial antenna types. The results demonstrate that the whole-body absorption generally determines the maximum permissible output power for collinear array antennas, whereas the local exposure depends on various body-resonance effects which vary strongly among individuals. Those two conclusions are exploited in Chapter 7, where estimation formulas for the exposure of humans to base station antennas are developed based on physical considerations and numerical results. The formulas, allowing to obtain the whole-body, 1g, and 10g SAR from readily available antenna parameters and the distance between the antenna and the body, are validated using numerical simulations of a comprehensive matrix of exposure configurations (all possible combinations of 12 antennas, 6 distances, 3 human bodies, and 2 sides of exposure). Ultimately, the estimation formulas can provide antenna manufacturers and access providers with an efficient way to calculate a safety radius around base station antennas solely from information provided on the datasheet and thus easily protect service and installation personnel in their vicinity. The formulas to estimate the exposure to base station antennas are included in the international standard IEC 62232.

In summary, the work performed in this thesis contributes to the improvement of dosimetric assessment of EMF exposure by providing more efficient methods to demonstrate compliance of various scenarios, without compromising safety, and by providing more comprehensive exposure evaluations to epidemiologists. All the results presented in this thesis have been published in peer-reviewed journals.
Résumé

L’utilisation de téléphones mobiles est très répandue au sein de notre société moderne. Au cours de 15 dernières années, le nombre d’abonnements à l’échelle mondiale a presque décuplé. Même dans les pays en voie de développement, il y a environ 90 abonnements par groupe de 100 habitants. Les dispositifs de téléphonie mobile ne sont pas seulement employés par des adultes travailleurs, mais leur utilisation s’étend à d’autres groupes démographiques : les enfants, les personnes âgées, les familles à faible revenu, etc. Plusieurs organisations gouvernementales et non-gouvernementales demandent plus d’information en lien avec l’exposition aux téléphones et réseaux mobiles, mais aussi reliée à d’autres signaux sans-fil, par exemple WiFi et DECT qui gagnent en popularité. Les études épidémiologiques examinant le lien hypothétiques entre différentes maladies cérébrales et l’utilisation de téléphones mobiles doivent être basées sur des indicateurs d’exposition sensés et fiables, généralement difficilement accessibles.

Cette explosion du nombre d’utilisateurs de téléphones mobiles mène graduellement à des réseaux de télécommunication de plus en plus denses. Les antennes de station de base sur les toits des bâtiments font maintenant partie intégrante du paysage urbain, en particulier en milieu densément peuplé. Le personnel d’installation et de service des antennes de station de base ainsi que d’autres employés de maintenance des bâtiments peuvent se trouver à proximité de ces antennes en effectuant leur travail. Bien que ce type d’exposition ne soit pas spécifiquement l’objet d’études épidémiologiques, il doit être contrôlé de sorte à ce qu’il soit conforme aux limites de sécurité en vigueur sans toutefois être trop restrictif. Des études ont été réalisées afin de caractériser l’exposition d’humains à proximité d’antennes de station
de base, sans toutefois être en mesure de tirer des conclusions générales. En outre, des moyens efficaces pour traduire ces résultats en recommandations pratiques sont toujours manquants.

L’objectif de cette thèse est de développer des outils et méthodes pour l’évaluation dosimétrique plus facile, plus complète et de plus grande qualité pour deux scénarios : l’exposition aux téléphones mobiles utilisés près de la tête, typique pour le grand public, et l’exposition à proximité d’antennes de station de base, typique, par exemple, pour le personnel d’installation et d’entretien.


Divers aspects en lien avec l’évaluation de la dosimétrie en champ proche sont étudiés dans la Partie III de cette thèse. Bien que le pic maximum d’exposition soit déterminé pour chaque dispositif de
éléctromagnétique avant leur approbation et mise en marché, l’informa-
tion mise à la disposition du public n’est pas suffisante pour être
utilisée dans les études épidémiologiques qui ont pour but d’établir une
corrélation entre l’utilisation de téléphones mobiles et certains can-
cers ou altérations cognitives et comportementales. Pour renforcer les
ev éuations épidémiologiques et fournir de l’information plus détaillée
aux consommateurs, une méthodologie ayant pour but de déterminer
l’exposition de tissus spécifiques à partir de mesures dans des fantômes
homogènes est introduite au Chapitre 3. Cette méthodologie peut être
implémentée dans le module de post-traitement d’appareils standards
de mesure de débit d’absorption spécifique (DAS) utilisés pour les
ev éuations de conformité de téléphones mobiles et ainsi procurer de
l’information sur l’exposition de tissus et régions fonctionnelles du
cerveau sans nécessiter de mesures ou temps additionnels. Le fruit de
cette étude est une collection de facteurs de transformation procura-
rant une corrélation entre le DAS induit dans le fantôme homogène
standard SAM et le DAS dans une tête anatomique. Ces facteurs de
transformation ont été implémentés dans la plateforme de mesure dosi-
métrique commerciale DASY 5 dont l’utilisation, en combinaison avec
le fantôme SAM, est très répandue pour les évaluations de conformité
des téléphones mobiles.

Depuis plusieurs années, l’exposition des enfants aux radiations
des téléphones mobiles est une préoccupation du public. Bien que
des études numériques aient validé l’usage du fantôme SAM — re-
présentatif d’une tête d’homme — aucune preuve expérimentale n’a
jamais été fournie. Le Chapitre 4 aborde des questions en lien avec
l’évaluation de l’exposition des enfants aux téléphones mobiles. En
utilisant des fantômes représentant la tête d’enfants de 3 et 8 ans,
il établit que le fantôme SAM utilisé pour les études de conformité
standardisées procure aussi une évaluation conservative de l’exposition
de modèles homogènes de têtes d’enfants. Par contre, les résultats dé-
montrent que les procédures couramment suggérées pour le calcul du
DAS moyen provenant de résultats numériques peuvent sous-estimer
la valeur réelle, et, par conséquent, que les limites actuellement définies
en terme de moyenne du DAS dans un volume cubique ne sont pas pra-
tiques et ne permettent pas une évaluation consistante non-ambiguë.
Alors que l’exposition aux champs radio-fréquence (RF) des téléphones mobiles a été étudiée de façon exhaustive dans le passé, beaucoup moins d’attention a été portée sur les champs à basse fréquence (LF). Dans le Chapitre 5, les champs LF de téléphones mobiles sont évalués expérimentalement et numériquement pour les systèmes de communication GSM et UMTS. Ces résultats permettent entre autres de déterminer la nécessité de l’ajout aux normes en vigueur d’études de conformité spécifiques à cette plage de fréquences. Il est démontré que le champ magnétique induit par les courants dans les téléphones utilisant le système UMTS sont 2 ordres de grandeur inférieurs aux champs induits en utilisant le système GSM. Sachant, d’autres études, que l’exposition aux champs RF des téléphones mobiles est aussi 2 ordres de grandeur inférieurs en UMTS qu’en GSM, il est maintenant possible d’affirmer que le système UMTS entraîne une réduction globale de l’exposition.

La démonstration de la conformité aux normes régissant l’exposition aux antennes de station de base peut prendre beaucoup de temps et aboutit souvent à des résultats trop prudents. L’exposition des travailleurs aux antennes de station de base est abordée dans le Partie IV de cette thèse, qui vise à alléger le fardeau susmentionné et de réduire la sur-estimation. Dans un premier temps, le Chapitre 6 évalue l’exposition d’humains à proximité d’antennes de station de base en utilisant trois modèles anatomiques ainsi que des modèles de différents types d’antennes génériques et commerciales. Les résultats démontrent que l’absorption moyenne dans tout le corps est normalement le facteur limitant la puissance maximale d’émission pour les antennes à réseaux colinéaires, tandis que l’exposition locale dépend principalement d’effets de résonance dans le corps, qui varient fortement selon les individus. Ces deux conclusions sont exploitées dans le Chapitre 7 où des équations estimant l’exposition des humains aux antennes de station de base sont développées en reposant sur des considérations physiques et des résultats numériques. Ces équations permettent la détermination du DAS moyen dans tout le corps ainsi que le pic dans 1 g et 10 g de tissus à partir de paramètres d’antennes facilement accessibles et de la distance entre le corps et l’antenne. Elles sont validées grâce à la simulation numérique d’une multitude de configurations : toutes les combinaisons possibles de 12 antennes, 6 distances, 3 corps humains et 2 côtés d’exposition. En définitive, ces
équations fournissent aux fabricants d’antennes et aux opérateurs de réseaux mobiles des moyens efficaces de calculer un rayon de sécurité autour des antennes uniquement basé sur des informations provenant de leur fiche technique et, par conséquent, de protéger facilement le personnel d’installation et d’entretien dans leurs environs. Les équations pour estimer l’exposition aux antennes de station de base ont été adoptées dans les recommandations internationales IEC 62232.

En résumé, le travail présenté dans cette thèse contribue à l’amélioration de l’évaluation dosimétrique de l’exposition aux champs électromagnétiques en fournissant des méthodes efficaces pour démontrer facilement la conformité de différents scénarios sans compromettre leur sécurité, et en procurant aux épidémiologistes des méthodes d’évaluation plus exhaustives. Tous les résultats introduits dans cette thèse ont été publiés dans des revues évaluées par des pairs.
Acknowledgments

This thesis would not have been possible without the support of Niels Kuster, whose standard for excellence pushed me to develop as a better scientist and thinker. Thanks Niels for having given me the opportunity to work with you on this thesis, of which I can be proud. Thanks to Prof. Dr. Qiuting Huang for allowing me to be part of the ETH Zurich. This great institution provided me with the academic structure to learn and develop as a scientist, as well as evolve as a person. Thanks to Prof. Dr. Juan Mosig for accepting to be part of my jury and for reading my thesis so quickly.

Over the years at IT’IS, I have had the chance to have the most wonderful ‘vis-à-vis’ officemates, many of which I could develop strong friendships with. Thanks to Clémentine Boutry for her never-dying optimism, Maria Christopoulou for her generosity and her friendship, Eugenia Cabot for her devotion, Earl Zastrow for her straightforwardness, Anastasija Ichsanow for her trust and being someone on whom I can always count, and Maria Cabanes for her refreshing attitude.

My time at IT’IS would not have been the same without Manuel Murbach, co-founder of IT’IS Fun, and Sven Kühn, whose door was always opened, for good news as well as bad news. You guys rock. Thanks to Eva Rojček-Jakubcaninova for sharing her positive outlook on life with her surroundings (and for her endless chocolate supply!). Thanks to Andreas Christ for introducing me to the field of bioelectromagnetics and for sharing so much of his knowledge with me. Thanks to Emilio Cherubini for his technical and personal support. Thanks to Pedro Crespo-Valero, the python master. Thanks to Erdem Ofli, Turkish style. Thanks to Mar Miñana for her rigour. Thanks to Yijian Gong and Aiping Yao for sharing the PhD experience with me.
Thanks to Jacqueline Pieper for her people skills. Thanks to Myles Capstick for his guidance. Thanks to Patricia Bound for her attention to details and her efficiency. Thanks to Jagadish Nadakuduti, Stefan Benkler, Adam Kyriakou, and Maximilian Fütterer for many fruitful collaborations. Thanks to Elliott Zastrow for his patience.

Thanks to the biologists that I have had the chance to work with during the development of the ViP models: Silvia Farcito, Livia Gerber, Heidi Moser, Eveline Huber, Maria Jedensjö, and Isabel Hilber. We have learned a lot from each other. Thanks to Davnah Payne for continuing this endeavor while I could not. Thanks to Bryn Lloyd and Esra Neufeld for supporting the team. Thanks to Prof. Klaas Prüssmann and Siemens Healthcare for their help in the imaging phase. And thanks to Theodoros Samaras, John Markakis, and the team of biologists at THESS for their high-quality contributions.

Thanks to all the funding sources that supported the work of this thesis: the Natural Sciences and Engineering Research Council of Canada (NSERC), the German Federal Office for Radiation Protection (BfS), the Netherlands Organization for Health Research and Development (ZonMw), the Research Foundation Mobile Communication (FSM), the Mobile Manufacturers Forum (MMF), the Groupe Speciale Mobile Association (GSMA), and the European Union’s Seventh Framework Programme (FP7/2007-2013).

Over the years, I have had the opportunity to work with collaborators from all over the world. Thanks in particular to the Belgium colleagues from iMinds for their support in various projects and their always very warm welcome: Günter Vermeeren, Luc Martens, Wout Joseph, Arno Thielens, and Sam Aerts. Thanks to Jurriaan Bakker and Gerard van Rhoon from Erasmus for their willingness to share knowledge. Thanks to Joe Wiart and Abdelhamid Hadjem from Orange for various collaborations. Thanks to Quirino Balzano for having shared his knowledge and his wisdom so eagerly over the years.

Unfortunate health issues have forced me to put this thesis on hold for a little while. Thanks to all those who have supported me during this period; your mental, professional, and financial support allowed me to focus, with success, on a proper recovery.

Thanks to my family and friends for believing in me and being their to support me in good times and bad times.
And of course, a thesis would not be a thesis without the mental pressure and the stress of the last few months... I want to thank my partner, Johann, for his support during this time, his patience, his encouragements, and his love. And for giving me the best gift that I could ever have wished for.
Contents

Summary v
Résumé ix
Acknowledgments xv

I Background and Motivation 1

1 Introduction 3
  1.1 Background and Motivation ................... 3
  1.2 Objectives .................................. 6
  1.3 Synopsis .................................... 6

II Methods 9

2 Development of a New Generation of High-Resolution Anatomical Models for Medical Device Evaluation: The Virtual Population 3.0 11
  2.1 Abstract .................................. 11
  2.2 Introduction ................................ 12
  2.3 Methods .................................... 15
    2.3.1 Tools for Model Generation ............... 15
    2.3.2 Tools for Model Processing ............... 19
  2.4 Results and Discussion ...................... 22
    2.4.1 Segmentation ............................ 22
CONTENTS

2.4.2 Model Generation ........................................... 23
2.4.3 Model Processing ........................................... 25
2.4.4 The Virtual Population ................................. 26
2.5 Case Study .................................................. 26
2.6 Conclusions .................................................. 31

III Near-Field Exposure ................................. 35

3 Estimation of Head-Tissue Specific Exposure from Mobile Phones, Based on Measurements in the Homogeneous SAM Head 37
3.1 Abstract .................................................. 37
3.2 Introduction .............................................. 38
3.3 Methods and Models ....................................... 40
  3.3.1 Anatomical Head Models ............................. 40
  3.3.2 SAM Phantom with Defined Brain Regions and Tissues ........................................... 40
  3.3.3 FDTD Simulations ..................................... 41
  3.3.4 Talairach Atlas ......................................... 43
  3.3.5 Generic Dipoles Exposure Matrix ..................... 43
3.4 Results ................................................... 47
  3.4.1 Determination of the Transformation Factors – Exposure to Generic Dipoles ..................... 48
  3.4.2 Validation of the Transformation Factors – Exposure to Realistic Mobile Phones .......... 56
3.5 Discussion and Conclusions ............................. 58

4 Experimental Evaluation of the SAR Induced in Head Phantoms of Three- and Eight-year-old Children 61
4.1 Abstract .................................................. 61
4.2 Introduction .............................................. 62
4.3 Methods ................................................... 63
  4.3.1 Phantoms ............................................... 63
  4.3.2 Transmitters and Position at the Heads ............... 64
  4.3.3 Experimental Evaluation ............................. 67
  4.3.4 Numerical Evaluation .................................. 68
  4.3.5 SAR Averaging ......................................... 70
**CONTENTS**

4.4 Results ........................................... 73
   4.4.1 Conservativeness of the SAM Head Phantom .... 73
   4.4.2 Validation of the Numerical Models ............. 74
   4.4.3 SAR Averaging Implementation .................. 76
4.5 Conclusions ........................................ 77

5 Experimental and Numerical Assessment of Low-Frequency Current Distributions from UMTS and GSM Mobile Phones 81
   5.1 Abstract ......................................... 81
   5.2 Introduction ..................................... 82
   5.3 Methods ......................................... 83
      5.3.1 Communication Systems ....................... 83
      5.3.2 Experimental Setup .......................... 84
      5.3.3 Numerical Assessment ....................... 90
      5.3.4 Compliance with Guidelines and Standards ... 92
   5.4 Validation of Experimental Setup .................. 96
   5.5 Experimental Assessment ........................ 96
      5.5.1 Frequency Content ........................... 96
      5.5.2 Spatial Distribution ......................... 96
      5.5.3 Decay with Separation from the DUT ........... 98
      5.5.4 Compliance with the ICNIRP Reference Levels ... 101
      5.5.5 Worst-Case Equivalent Sources ............... 101
   5.6 Development of Numerical Sources ................. 102
   5.7 Numerical Assessment ............................ 103
   5.8 Discussion and Conclusions ....................... 107

IV Workers’ Exposure 111

6 Dependence of the Occupational Exposure to Mobile Phone Base Stations on the Properties of the Antenna and the Human Body 113
   6.1 Abstract ......................................... 113
   6.2 Introduction ..................................... 114
   6.3 Objectives ....................................... 116
   6.4 Methods ......................................... 116
      6.4.1 Anatomical Body Models ....................... 116
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4.2 Antennas</td>
<td>118</td>
</tr>
<tr>
<td>6.4.3 FDTD Simulations</td>
<td>122</td>
</tr>
<tr>
<td>6.4.4 Measurements</td>
<td>124</td>
</tr>
<tr>
<td>6.5 Exposure Conditions</td>
<td>125</td>
</tr>
<tr>
<td>6.6 Experimental Evaluation</td>
<td>126</td>
</tr>
<tr>
<td>6.7 Results</td>
<td>127</td>
</tr>
<tr>
<td>6.7.1 Dependence on Frequency and Body Model</td>
<td>127</td>
</tr>
<tr>
<td>6.7.2 Dependence on Half-Power Beamwidth</td>
<td>130</td>
</tr>
<tr>
<td>6.7.3 Peak Spatial Average SAR</td>
<td>132</td>
</tr>
<tr>
<td>6.8 Discussion and Conclusions</td>
<td>132</td>
</tr>
<tr>
<td>7 Estimation Formulas for the Specific Absorption Rate in Humans Exposed to Base Station Antennas</td>
<td>135</td>
</tr>
<tr>
<td>7.1 Abstract</td>
<td>135</td>
</tr>
<tr>
<td>7.2 Introduction</td>
<td>136</td>
</tr>
<tr>
<td>7.3 Objectives</td>
<td>137</td>
</tr>
<tr>
<td>7.4 Methods</td>
<td>138</td>
</tr>
<tr>
<td>7.4.1 Anatomical Body Models</td>
<td>138</td>
</tr>
<tr>
<td>7.4.2 Antennas</td>
<td>140</td>
</tr>
<tr>
<td>7.4.3 Numerical Methods</td>
<td>140</td>
</tr>
<tr>
<td>7.5 Estimation Formulas</td>
<td>142</td>
</tr>
<tr>
<td>7.5.1 Generic Human Model</td>
<td>143</td>
</tr>
<tr>
<td>7.5.2 95th-Percentile Representative Phantom</td>
<td>143</td>
</tr>
<tr>
<td>7.5.3 Induced Power Density</td>
<td>144</td>
</tr>
<tr>
<td>7.5.4 Whole-body Average SAR</td>
<td>146</td>
</tr>
<tr>
<td>7.5.5 Tissue Layering</td>
<td>148</td>
</tr>
<tr>
<td>7.5.6 Whole-body Average SAR – Plane-Wave Exposure</td>
<td>149</td>
</tr>
<tr>
<td>7.5.7 Peak Spatial SAR</td>
<td>151</td>
</tr>
<tr>
<td>7.5.8 Cylindrical Propagation – Radiating Near Field</td>
<td>152</td>
</tr>
<tr>
<td>7.5.9 Whole-body Average SAR – Base-Station Antennas</td>
<td>154</td>
</tr>
<tr>
<td>7.5.10 Issues Relative to Short Antenna-Body Distances</td>
<td>156</td>
</tr>
<tr>
<td>7.5.11 Final Form of the Estimation Formulas</td>
<td>156</td>
</tr>
<tr>
<td>7.5.12 Compact Form of the 95th-Percentile Estimation Formulas</td>
<td>158</td>
</tr>
<tr>
<td>7.6 Numerical Validation</td>
<td>159</td>
</tr>
<tr>
<td>7.7 Discussion and Conclusions</td>
<td>163</td>
</tr>
</tbody>
</table>
## CONTENTS

V  Epilogue  

8  Conclusions & Outlook  
   8.1  Conclusions  
   8.2  Outlook  

VI  Appendix  

A  List of Acronyms  

B  List of Symbols  

C  List of Figures  

D  List of Tables  

E  List of Publications  
   E.1  Journal Publications Included in this Thesis  
   E.2  Other Journal Publications  
   E.3  Other Publications  

Bibliography
Part I

Background and Motivation
Chapter 1

Introduction

1.1 Background and Motivation

With almost as many mobile phones in use as the current world population, concerns about the exposure to the electromagnetic fields (EMFs) from such devices keep arising since the last few decades. Epidemiologic, experimental, and mechanistic studies have led the World Health Organization (WHO) in 2012 to classify EMF as possibly carcinogenic to humans [1], based on an increased risk for glioma, a malignant type of brain cancer, associated with wireless phone use. Prior to this classification, the exposure to radio-frequency (RF) fields has been limited by international guidelines and standards, in particular from the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [2,3] and the Institute of Electrical and Electronics Engineers (IEEE) [4,6]. The mechanisms of interactions of EMFs with the human body are frequency dependent, and those guidelines are designed to avoid adverse thermal effects (via the specific absorption rate, SAR, above 100 kHz; and via the power density, above 10 GHz) and effects on the nervous system (via the induced current density, up to 10 MHz). Those basic restrictions require knowledge about detailed field distributions and absorption in the complex human body; detailed assessment in realistic anatomies is only possible numerically.
Homogeneous measurement phantoms and tissue simulating media with standardized dimensions and dielectric properties are used as surrogates to anatomical models for compliance assessment. For mobile phone exposure, compliance to the guidelines must be assessed experimentally using the homogeneous standard anthropomorphic mannequin (SAM) or other phantoms, e.g., for body-worn devices, as described by the International Electrotechnical Commission (IEC) [7,8] and the IEEE [9]. Based on those standardized measurements, the maximum peak spatial SAR is reported for each device before market approval. This data is publicly available [10,11], providing worst-case exposure data to the customers and certifying the compliance of a particular device. However, it contains no information about the location of the maximum or the configuration in which it was found, making it of limited interest, e.g., for epidemiologic studies, which require sound dosimetric data. Methods have been developed in the past to assess the exposure by establishing clusters of mobile phone types leading to similar exposure or by performing additional measurements, but these are associated with large uncertainties or, when applied to the scale of epidemiologic studies, far too time demanding to be applicable.

As part of the research program NFP 57, the Swiss National Science Foundation (SNF) has been asking for improved, meaningful exposure metrics to support the dosimetric assessment needed for epidemiologic studies.

Other open issues with respect to mobile phone use are related to children exposure, some aspects of which were included in recent projects supported by the German Federal Office for Radiation Protection (BfS) and the Netherlands Organization for Health Research and Development (ZonMw). In particular, only numerical but no experimental evidence has ever been provided to validate the use of the SAM phantom, representative of an average male head. Also, a recommendation for the use of mobile phones in the GSM vs. UMTS networks has not been possible until now due to a lack of knowledge of the low-frequency fields induced by the use of the latter, an issue of interest for the Swiss Research Foundation Mobile Communication (FSM).

The exposure to mobile phones operated at the head is relatively well defined, i.e., the position of the device and tissue distribution of the human head in the vicinity of the radiator presents limited
variability, which renders the usage of the SAM phantom possible for compliance testing. Far-field exposure typically presents much more variations, in terms of possible field distributions, frequency of operation, position of the body in the field distribution, posture of the body itself, and tissue distribution, not to forget a much larger area of body to consider. The accurate evaluation of the SAR from far-field exposure is not always achievable in laboratory conditions due to the relatively large distances required between the radiator and the phantom. Besides, those whole-body measurements can be very time consuming. Therefore, the guidelines propose reference levels for the strength of the incident electromagnetic fields, which are derived from the basic restrictions. In the near field of radiating structures, e.g., close to base station antennas, the reference levels can be very conservative, i.e., the ratio between incident field values and SAR is much larger than that of reference levels and basic restrictions. Therefore, measurements of the fields around base station antennas lead to very conservative exposure estimates whereas measurements of SAR can be very time consuming and technically challenging. The Mobile Manufacturers Forum (MMF) and the German Research Association for Radio Applications (FGF) have been interested to thoroughly characterize the exposure to base station antennas to protect the workers in their vicinity. In particular, more information was required to support the elaboration of the new standard of the IEC about base station antenna exposure, seeking for more practical evaluation procedures.

Realistic dosimetric assessment requires numerical models based on a variety of anatomies. The Virtual Family [12] computational whole-body anatomical human models and its extension, the Virtual Population, were originally developed for near-field and far-field electromagnetic exposure evaluations. Although these models have proven to be invaluable for electromagnetic dosimetry, it became evident, in particular from discussions with the American Food and Drug Administration (FDA), that significantly enhanced models are needed for reliable effectiveness and safety evaluations of diagnostic and therapeutic applications, including medical implants safety, as also mentioned by the Medical Devices Research Forum (MDRF).
1.2 Objectives

The goal of this thesis is to research and develop tools and methods for a better, easier, and more comprehensive dosimetric evaluation of two typical scenarios: exposure to mobile phones operated at the head, typical for the general public, and whole-body and partial-body exposure from base station antennas, typical, e.g., for installation and service personnel. In particular, this includes to:

- present high-resolution anatomical models that overcome limitations of existing ones;
- establish a correlation between virtual regions of SAM and anatomical heads and provide transformation factors to be applied to compliance measurement post-processing;
- validate numerical and experimental SAR averaging schemes using head models of children;
- evaluate compliance of low-frequency exposure from mobile phones and assess the need for improved tools or compliance procedures for this frequency range;
- develop and validate estimation formulas for whole-body, 1 g, 10 g SAR in humans bodies exposed to base station antennas, based on physical considerations and numerical results.

1.3 Synopsis

This thesis is organized in three parts: Part II – Methods describes a new generation of anatomical models used for computational evaluations throughout this thesis; Parts III and IV present new tools, procedures, and estimation formulas relevant for the exposure assessment of common scenarios. These allow to, on the one hand, assess more easily the compliance of specific exposure configurations, and, on the other hand, extract more information from available data, e.g., datasheet of base stations, or mandatory compliance measurements, e.g., performed before market approval of mobile phones. Part III – Near-Field Exposure focusses on near-field exposure such as the RF
and low-frequency (LF) fields from mobile phones, whereas Part IV – Workers’ Exposure is related to exposure from base station antennas. The content is organized as follows:

**Part II – Methods**

**Chapter 2** Development of high-resolution anatomical models with more-consistent tissue assignment, enhanced surface processing, and numerous anatomical refinements. Those significantly improved models also provide extended population coverage and are suitable not only for electromagnetic dosimetric assessment, but also for reliable effectiveness and safety evaluations of diagnostic and therapeutic applications.


**Part III – Near-Field Exposure**

**Chapter 3** Estimation of head-tissue and brain-region specific exposure from mobile phones in human heads of adults and children based on measurements in the standard homogeneous SAM head. The implementation of the derived transformation factors and their uncertainties in an experimental dosimetric assessment system provides information about brain-region specific SAR from standard compliance measurements, information that can be used for future epidemiologic studies.


**Chapter 4** Experimental evaluation of the SAR induced in head phantoms of three- and eight-year-old children to evaluate the conservativeness of the SAM phantom. The use of those new experimental phantoms also raise issues about the numerical and experimental SAR averaging algorithms used worldwide for compliance assessment.


**Chapter 5** Compliance evaluation of low-frequency current distributions from UMTS and GSM mobile phones using
CHAPTER 1. INTRODUCTION

numerical and experimental techniques. In particular, assessment of the need for more comprehensive compliance testing including low-frequency fields.

Part IV – Workers’ Exposure

Chapter 6: Assessment of the dependence of the occupational exposure to mobile phone base stations on the properties of the antenna and the human body using a set of numerical simulations of generic and realistic antennas for frequencies between 450 and 2140 MHz.

Chapter 7: Development of estimation formulas for the SAR in humans in the close vicinity of base station antennas and validation based on an exhaustive set of exposure scenarios for frequencies between 300 MHz and 5 GHz.

Part V – Epilogue

Chapter 8: Conclusions and outlook on future related research topics.
Part II

Methods
Chapter 2

Development of a New Generation of High-Resolution Anatomical Models for Medical Device Evaluation: The Virtual Population 3.0

2.1 Abstract

The Virtual Family computational whole-body anatomical human models were originally developed for electromagnetic (EM) exposure evaluations, in particular to study how absorption of radiofrequency
radiation from external sources depends on anatomy. However, the models immediately garnered much broader interest and are now applied by over 300 research groups, many from medical applications research fields. In a first step, the Virtual Family was expanded to the Virtual Population to provide considerably broader population coverage with the inclusion of models of both sexes ranging in age from 5 to 84 years old. Although these models have proven to be invaluable for EM dosimetry, it became evident that significantly enhanced models are needed for reliable effectiveness and safety evaluations of diagnostic and therapeutic applications, including medical implants safety.

This paper describes the research and development performed to obtain anatomical models that meet the requirements necessary for medical implant safety assessment applications. These include implementation of quality control procedures, re-segmentation at higher resolution, more-consistent tissue assignments, enhanced surface processing, and numerous anatomical refinements. Several tools were developed to enhance the functionality of the models, including discretization tools, posing tools to expand the posture space covered, and multiple morphing tools, e.g., to develop pathological models or variations of existing ones. A comprehensive tissue properties database was compiled to complement the library of models. The results are a set of anatomically independent, accurate, and detailed models with smooth, yet feature-rich and topologically conforming surfaces. The models are therefore suited for the creation of unstructured meshes, and the possible applications of the models are extended to a wider range of solvers and physics. The impact of these improvements is shown for the MRI exposure of an adult woman with an orthopedic spinal implant. Future developments include the functionalization of the models for specific physical and physiological modeling tasks.

### 2.2 Introduction

Numerical simulations are increasingly used to investigate the impact of external stressors on the human body, thereby complementing experimental studies. In the long term, the significance of numerical
evaluations performed with computational human models can be expected to outweigh experimental studies. A simulation model must represent the interaction(s) under study by accurately adjusting the level of detail and relevant characteristics, which can range from the molecular or cellular level to tissue and whole-body anatomical representations. Historically, the latter are used routinely for dosimetric assessments of ionizing and non-ionizing radiation, but are also applied to other fields of research and applications, e.g., tissue mechanics, acoustics (in particular, ultrasound), crash and blast investigations, orthopedic implant development, and in the clothing industry. The complexity of the models has compounded significantly as a result of the increased availability and enhancement of computer resources over time. The 1950s saw the emergence of the first generation of models, namely generic or stylized models, consisting of geometrical shapes that only roughly represented the dimensions and outer shape of the body, and, depending on the application, of the organ(s) under investigation [14–17]. Voxel models based on data segmented from medical images were first developed in the 1980s [12,18–28] and are now commonly in use. Advanced models of the human body are currently represented by polygon meshes [12,29] or non-uniform rational B-spline (NURBS) surfaces [30–32].

The complexity of the coupling of electromagnetic (EM) near-field sources with the human anatomy resulted in the early utilization of computational anatomical head models in the context of safety guidelines for compliance testing. The growing public concern over EM exposure led to the development of the Virtual Family [12] by joint effort of the IT’IS Foundation and the United States Food and Drug Administration (FDA), funded by the Mobile Manufacturer Forum (Belgium), GSM Association (Switzerland), and SPEAG (Switzerland). It initially consisted of four anatomical models generated from the magnetic resonance (MR) images of healthy volunteers: average-sized male and female adults and two children (a 6-year-old boy and an 11-year-old girl). These models were made available to the scientific community in 2008. To further extend the population coverage, the MR images of additional child volunteers (5- and 8-year-old girls, and 8- and 14-year-old boys) were segmented to create the Virtual Classroom. Increased coverage of anatomical variability is provided with obese (37 years old, 1.82 m, 120 kg) and elderly (84 years old,
1.73 m, 65 kg) male models, an 8-week-old baby model, and three pregnant women models at gestational stages of 3, 7, and 9 months. Today, this widely used set of anatomical models is also known as the Virtual Population (ViP 1.0, Figure 2.1).

The ViP 1.0 has been applied in a large variety of exposure studies, such as to mobile phones, wireless devices, magnetic resonance imaging (MRI) scanners, home appliances, and safety and efficacy assessments of medical treatments, e.g., hyperthermia therapy or implant safety, product development and optimization, and basic research, e.g., mechanistic investigations. However, while they have been employed in selected cases to the assessment of medical devices and therapies, e.g., safety of implants during MRI scanning or focused ultrasound ablation, the first generation of the Virtual Population suffers from limitations related to limited local detail and accuracy, unsuitable tissue surface quality, missing fine structures and insufficient fine structure continuity, as well as inconsistent segmentation across the different models. Furthermore, current devices often combine complex interactions from multiple domains of physics and physiology, sometimes in a coupled manner, which require models adapted to different solvers, e.g., a finite-element method biomechanical solver. For example, the development and safety assessment of a cardiovascular implant requires modeling of computational fluid dynamics (CFD), electromagnetic (EM) compatibility (e.g., MR safety with regard to
heating, forces, and nerve stimulation), structural and tissue mechanics, treatment optimization, and short- as well as long-term tissue adaptation aspects. To be useful, anatomical models must therefore be adapted to the needs of different numerical methods and physics/physiology modes. The finite-element method for example typically requires high-quality unstructured meshes. The generation of these meshes is significantly simplified when the underlying models feature topologically compatible interfaces between tissues, i.e., neighboring tissues share identical surface triangles at their interfaces and avoid self-intersection.

A significant research and development effort was necessary to overcome these restrictions. The various steps for the generation and the processing of the segmented data leading to polygon meshes, the associated tissue properties database, and the tools developed to manipulate the meshes is presented and discussed herein. Finally, a case study is described in which the impact of the improvements of this new generation of models is shown in the context of exposure during a typical 1.5 T MRI scan of an adult woman with an orthopedic spinal implant.

2.3 Methods

2.3.1 Tools for Model Generation

The generation of each anatomical model includes the following steps (Figures 2.3 and 2.4):

1. recruitment and whole-body scanning of a volunteer,
2. pre-processing of the MRI data,
3. segmentation of the medical image data to generate a label-field,
4. processing of the label-field to remove artifacts,
5. extraction of the tissue surfaces, and
6. processing of the surfaces.

Imaging and Images Pre-Processing

The imaging of the volunteers was conducted in a 1.5 T whole-body scanner based on the MR protocol described in [12]. The resolution
Figure 2.2: Resampling of an MRI scan of the leg from $0.9 \times 0.9 \times 2.0 \text{ mm}^3$ (left) to $0.5 \times 0.5 \times 0.5 \text{ mm}^3$ (right) by means of the Lanczos interpolation method. Although no additional information has been used to generate the higher-resolution image, some structures appear more clearly.

of the resulting images was $0.5 \times 0.5 \times 1.0 \text{ mm}^3$ in the head and $0.9 \times 0.9 \times 2.0 \text{ mm}^3$ in the torso and the limbs. For the generation of the Virtual Population 3.0, the image data and label-fields generated for the first version of the models were up-sampled to $0.5 \times 0.5 \times 0.5 \text{ mm}^3$ by means of the Lanczos interpolation method \[33\] for the image data (Figure 2.2) and voxeling of the original surface model for the generation of the up-sampled label-field.

**Segmentation and Label-Field Processing**

The in-house software iSeg \[34\] (Zurich Med Tech AG, Switzerland) was used to identify the pixels belonging to different tissues (Figure 2.3). iSeg offers a large number of image processing algorithms, such as Live Wire \[35\], Level Sets \[36\], Region Growing \[37\], Fuzzy Connectedness \[38\], Interactive Watershed Transformation \[39\], etc. The segmentation tools range from highly interactive to fully automatic, and method-specific interaction paradigms are employed. iSeg also offers tools for topologically flexible interpolation that can be used to estimate tissue shapes between segmented layers to facilitate
2.3. METHODS

Figure 2.3: From left to right: raw MRI data, label-fields, surface model, and posed model (generated using the posing functionalities described herein).

the model creation process (based on [40] and [41]). Routines for hole, gap, and speckle removal, noise reduction, label-field smoothing (e.g., based on an implicit level-set approach), as well as adding skin layers are also available. All the functionalities of iSeg can be flexibly combined.

Surface Extraction and Processing

Subsequently, topologically conformal (i.e., neighboring solids share common surface triangles), non (self-)intersecting triangle surfaces are extracted and processed. Conformal surfaces offer the advantages of avoidance of gaps between solids, simplification of the creation of high-quality tetrahedral meshes (e.g., for FEM modeling), and the guarantee that structures do not overlap. Intersections and self-intersections of the surfaces can invalidate the models in the discretization (meshing) step. The created surfaces should be smooth
and the triangles not degenerated. The following steps are used in
the implemented approach (Figure 2.4): template-based tetrahedral
mesh extraction, surface extraction, feature- and volume-preserving
smoothing [42], and surface simplification. Self-intersections are
avoided during smoothing by constraining adjacent tetrahedra to be
positively oriented. Surface simplification avoids self-intersections by
testing each edge collapse. The Delauney edge flips [43] used to im-
prove the mesh quality also do not introduce self-intersections.

Quality Control

Despite our very accurate knowledge of the human body, the seg-
mentation of tissues and organs from MRI scans is subject to inter-
pretation. For example, the locations of the transitions between the
midbrain, pons, medulla oblongata, and spinal cord are not strictly
defined. Additionally, due to the resolution of the segmentation voxels
and the 2-pixel-minimum criteria necessary for good surface recon-
struction, structures thinner than 1mm, such as thin membranes or
blood vessels and nerves that are either of small diameter or too close
to the surface, are ignored.
However, studies of the variability between models that are exposed to given stimuli (e.g., (non)-ionizing radiation or acoustic exposure) require those models to be segmented in a uniform/consistent manner. The segmentation or re-segmentation of the Virtual Population 3.0 models is based on detailed internal guidelines as well as a system of quality control that ensures that the segmentation is consistent, both within a model and amongst models.

Those guidelines list the necessary structures that must be segmented and provide a description of how individual tissues are defined. For example, a list of mandatory arteries and veins, which must be segmented regardless of the quality of the images, is provided — in the worst case, the data needed to add these structures can be drawn from anatomical atlases. Arteries and veins that would add to the anatomical accuracy of the segmentation are also listed, with the requirement that each of them is continuous. Similar concerns are stated for each segmented tissue.

Human errors or discrepancies in the interpretation of the tissue list and/or of the MR images are reduced by a system of quality controls. Once a given stack of images has been segmented, the segmentation is assessed by a second team member for approval based on a checklist that includes all segmented tissues. After the stacks of images have been merged to generate a whole-body model, a similar quality control is also performed. Finally, a case-tracking system is used to gather comments from users, and those comments are then employed to remove errors and improve the models. The quality control procedure also includes the generation of a log file that describes the changes made in the newly released versions of each model.

### 2.3.2 Tools for Model Processing

**Discretization**

For numerical modeling, it is necessary to transform the models into discrete representations, i.e., voxels, tetrahedra, etc. Various discretization methods have been implemented in-house to create rectilinear (voxels, typically employed for finite-difference techniques) and tetrahedral (commonly employed in finite-element simulations) meshes from the anatomical models. The rectilinear, non-uniform
gridder developed uses ray-tracing and robust intersection testing to create voxel models. Conformal sub-cells can be generated \[44\] to reduce the impact of stair-casing. To create high quality, body-fitted, multidomain tetrahedron meshes, different meshing methods have been implemented: (i) Delauney refinement \[45\] followed by mesh optimization to remove slivers and improve mesh quality, and (ii) a cut-cell octree-based method \[46\] with a smoothing step.

Posing

Posing functionalities are available to parameterize the posture of the models. Two approaches have been developed: (i) a volume-preserving, skeleton- and influence-region-based approach that allows real-time posing and is based on methods from the field of computer graphics \[47\], and (ii) a physical-simulation-based approach, motivated by movement mechanics, that allows the user to prescribe the position of bones and performs a tissue mechanics simulation of the passive deformation of the soft tissues, resulting in more-realistic joint-region geometries. Approach (i) calculates deformation fields based on the influence regions and spherical blend skinning \[48\], which computes the interpolation of a set of transformations in the quaternion space. To ensure more-realistic deformation, the rigidity of the bone is considered and a simple spring correction is used on the non-rigid parts of the model. When approach (ii) is employed, the small strain, linear elastic approximation can be used for moderate posture changes. However, when strong warping is present, it is important to solve the full, non-linear problem. The simulations can be computationally very demanding, as they require on the order of 100,000,000 tetrahedral elements. Dedicated high-performance-computing-enabled solvers, based on the PETSc framework \[49\], have been developed for this purpose.

Morphing

To extend the population coverage, morphing functionality is provided that allows, e.g., the fat or muscle content to be increased or decreased to change the body-mass index (BMI) of the models while preserving realistic internal organ placement and tissue distributions. Two
2.3. METHODS

approaches are available: (i) a physical-simulation-based approach similar to that developed for model posing and (ii) an interactive deformation field-based warping approach. Approach (i) is motivated by physiological fidelity and uses tissue mechanics simulations where the bones are treated as rigid, the soft tissues deform passively, and selected fatty or muscle tissues are assigned growing or shrinking forces. Anisotropic forces can be used. In general, the small-strain, linear elastic approximation is valid, but the simulations are still computationally demanding. In approach (ii), a widget with a grid of control points that can be individually moved to define a deformation field that is then applied to the model is used. This approach has been used, e.g., to enlarge certain organs or to add breathing motion to the Virtual Population models. Multi-resolution rendering is used to provide real-time interactivity and visualization. It is also possible to precompute deformation fields for posing or morphing, e.g., with the physical-simulation-based approaches, and to interactively scale the displacement field to parameterize the degree of deformation.

Material Assignment

Depending on the physics to be applied in the simulation, parameters — electric and magnetic conductivity, permittivity, and permeability for EM simulations, or thermal conductivity, heat generation rate, heat transfer rate (perfusion), and heat capacity for thermal simulations — must be assigned to the tissues. Based on a comprehensive scientific literature review, a material parameter database [50] that aims to provide the modeling community with average and range-of-variation values of EM and thermal properties as well as density and perfusion of biological tissues was compiled (www.itis.ethz.ch/database). The Virtual Population 3.0 is fully compatible with this database of tissue parameters, thanks to the consistent tissue naming assured by the quality control procedure described in Section 2.3.1.
2.4 Results and Discussion

2.4.1 Segmentation

The list of tissues identified in Version 3.0 of the Virtual Population is more exhaustive than that of Version 1.0 (see Table 2.4.1), and most of the additional tissues have now been segmented as a result of the resampling described in Section 2.3.1, which provides more pixels within the structures. Limitations pointed out in the original Virtual Family publication [12] and issues reported by the scientific community are, for the most part, resolved in Version 3.0 of the models:

- No blood vessels smaller than 2 mm were segmented in Version 1.0; Version 3.0 includes blood vessels as small as 1 mm in diameter. All blood vessels are continuous.

- The spinal cord and optical nerve were segmented in Version 1.0; Version 3.0 also includes initial sections of the spinal nerves (ca. 2 cm) as well as the sciatic and tibial nerves.

- The pancreas was reconstructed only in the male adult in Version 1.0; it is now segmented in all models.

- The salivary glands are now segmented.

- The lumen of the small intestine is added using a wall thickness of 3.5 mm [51].

- The stomach and the gall bladder were hardly distinguishable from their lumens on the MRI scans; these are now segmented with fixed thicknesses of 6 mm [51] and 1.5 mm [52], respectively.

- Bone marrow (red) was segmented for the male models of the Virtual Family 1.0. In Version 3.0, three layers of bones are distinguished, cortical bone, cancellous bone, and bone marrow. The conversion of red marrow to yellow marrow in humans is age-dependent but differs from bone to bone. This age-dependent transformation is estimated by segmenting the marrow as red for models younger than 20 years of age and yellow for older models.
• The thymus is usually large at birth and increases in size with age until puberty. After puberty, the thymus degenerates and is transformed into fatty tissues. It is, thus, segmented only in children.

• In Version 1.0, the stacks of images were segmented independently, the surfaces were extracted for each stack separately, and those parts of the model were aligned and merged as a final step, which led to discontinuous tissues. In Version 3.0, the alignment and merging was performed with the label-fields, and the overlapping regions where the stacks of images are merged are corrected to obtain smooth transitions of the outside surface as well as the inner tissues prior to surface extraction.

The continuity and improved smoothness of the tissues and organs identified is a direct consequence of the higher resolution of the segmentation as well as the new algorithms used for the generation and processing of the surfaces. In addition to an extended list of well-defined segmented tissues, the strict internal quality control procedure developed and implemented by the segmentation group leads to very consistent segmentation, which will, in turn, lead to more-relevant variability studies.

2.4.2 Model Generation

While the image segmentation approach has remained largely unchanged from that used to generate the first Virtual Family models, the implicit label-field smoothing step is new and facilitates removal of unwanted features. Also, the surface extraction and processing have been updated: previously, the surface extraction, simplification, and smoothing routines from the Amira software \[53\] were used. However, while Amira can produce conformal interfaces, the surface processing results in self-intersecting surfaces and, occasionally, poor element quality. In addition, the processing is very time consuming and cannot cope with the whole-body high-resolution anatomical models. Therefore, the processing had to be performed piece-wise, and the resulting

\[1\] All bones are constituted of cortical bone, and some also include cancellous bone and/or bone marrow.
Table 2.1: Tissues segmented in the Virtual Population 3.0 models.

- **In all models:**
  - Adrenal gland
  - Air internal
  - Arteries
  - Bladder
  - Blood vessel
  - Bone
  - Brain (grey matter)
  - Brain (white matter)
  - Bronchi
  - Bronchi (lumen)
  - Cartilage
  - Cerebellum
  - Cerebrospinal fluid
  - Commissura anterior
  - Commissura posterior
  - Cornea
  - Corpus callosum
  - Diaphragm
  - Esophagus
  - Esophagus (lumen)
  - Eye (lens)
  - Eye (sclera)
  - Eye (vitreous humor)
  - Fat
  - Gallbladder
  - Gallbladder bile
  - Heart (lumen)
  - Heart (muscle)
  - Kidney (cortex)
  - Kidney (medulla)
  - Large intestine
  - Large intestine (lumen)
  - Liver
  - Lung
  - Meniscus
  - Midbrain
  - Mucosa
  - Muscle
  - Nerve
  - Pancreas
  - Pineal body
  - Pons
  - Salivary gland
  - SAT
  - Skin
  - Small intestine
  - Spinal cord
  - Spleen
  - Stomach
  - Stomach (lumen)
  - Teeth
  - Thyroid gland
  - Thalamus
  - Thymus
  - Ureter
  - Urethra
  - Urine

- **Bones:**
  - Calcaneus
  - Capitatum
  - Clavicle
  - Femur
  - Fibula
  - Foot
  - Hamatum
  - Humerus
  - Hyoid
  - Lunatum
  - Mandible
  - Metacarpus (I to V)
  - Os sacrum and coccyx
  - Patella
  - Pelvis
  - Phalanx distalis (I to V)
  - Phalanx media (II to V)
  - Phalanx proximalis (I to V)
  - Pisiforme
  - Radius
  - Rib
  - Scaphoideum
  - Scapula
  - Skull
  - Sternum
  - Talus
  - Tibia
  - Trapeziun
  - Trapezioideum
  - Ulna
  - Vertebra C1 to C7
  - Vertebra L1 to L5
  - Vertebra T1 to T12

- **In females only:**
  - Breast tissue
  - Ovary
  - Oviduct
  - Uterus
  - Vagina

- **In males only:**
  - Ductus deferens
  - Epididymis
  - Penis
  - Prostate
  - Seminal vesicle
  - Testes

- **In adults only:**
  - Yellow bone marrow

- **In children and adolescents only:**
  - Red bone marrow
  - Some bones are cartilage
  - Thymus
  - Two rows of teeth (milk & permanent)
solid sections had to be merged. The merging step introduces multiple problematic issues such as wrongly oriented triangles, gaps, or overlapping regions. The new surface extraction and processing routines avoid these problems and produce high-quality surfaces, possibly however, at the expense of limiting the degree of achievable simplification, which results in a larger number of triangles.

### 2.4.3 Model Processing

Discretization functionalities are required to make the models usable for numerical modeling. The specifications for models suitable for numerical methods requiring only rectilinear grids and voxels are relatively moderate, i.e., robust intersection detection must be possible, and there should be no inverted elements or other model aspects such as non-conformal surfaces that result in wrongly labeled voxels or holes. The requirements for unstructured mesh generation are far more demanding, including the need for good-quality triangle surfaces, i.e., non-degenerate triangles, smooth surface patches, and non-manifold edges, as well as closed, conforming surfaces without self-intersections, which obviate the need for complicated remeshing. Even when these requirements are mostly satisfied, meshing complex and often noisy anatomical models remains a challenging task. The Delaunay refinement meshing approach is quite sensitive to the quality of the extracted surfaces. In comparison, the cut-cell octree method is more tolerant: however, it re-generates the surfaces completely, which can sometimes remove desired features.

Having the capability to generate unstructured meshes as well as voxels allows the range of solvers that can be used and physical effects that can be simulated with the anatomical models to be considerably extended. In addition to the traditional applications in EM dosimetry, the Virtual Population 3.0 models and their predecessors have also been used for instance in biomechanical simulations, acoustic modeling, blood flow simulations [54–56].

The posing and morphing functionalities allow the population and situation coverage by the Virtual Population 3.0 to be extended. The simulation-based approaches, while being computationally very demanding and not interactive, produce more-realistic results, e.g., variation of BMI by up to 50% and more-realistic joint geometries.
The interactive warping has been used to change body and organ shapes, but also image-based information has been used to mimic a complete breathing cycle, including the rib movement, internal organ shifting, and lung volume changes (see Figure 2.5).

### 2.4.4 The Virtual Population

The four models of the Virtual Family (Duke, Ella, Billie, and Thelonious), the four models of the Virtual Classroom (Louis, Eartha, Dizzy, and Roberta), the obese male, Fats, and the elderly male, Glenn, were all generated from MRI scans of volunteers recruited by or for the IT’IS Foundation. Figure 2.6 illustrates how these models compare to statistical data of the German population [58]. Further models have been generated by morphing to extend the population coverage with a decreased effort compared to the segmentation of a whole body, which requires ca. one man-year, depending on the size of the model and the quality of the MRI data.

A three-year-old girl, Nina, was generated by morphing the 5-year-old Roberta with the field-based warping morphing tool described in Section 2.3.2. Scaling of the head was applied based on statistics from [59], followed by anisotropic morphing of the body based on data from [60] and [61]. Pregnant women models at three gestational stages presented in [62] are included in the Virtual Population. An 8-week-old baby girl, Charlie, is also included and has been adapted from the voxel baby developed by the Helmholtz Zentrum München (previously known as Gesellschaft für Strahlenforschung, or GSF) [22] to be consistent with the segmentation guidelines. Finally, a combination of the two morphing tools described above was used to generate 10 additional adult models of various BMIs based on Duke, Ella, and Fats.

### 2.5 Case Study

To see the impact of the differences between Versions 1.0 and 3.0 of the models, the finite-difference time-domain (FDTD) simulation platform SEMCAD X was used to run an application example. Figure 2.7 shows the simulation setup of cardiovascular MRI scans at
Figure 2.5: Triangular mesh of Duke’s ribcage, spinal column, and liver at a state of complete inhalation (red) and complete exhalation (gray). The deformation of the model was facilitated through 4D MRI data acquired during the respiratory cycle of a healthy volunteer \cite{57}. The image data were processed to extract the vectorial displacement fields and registered to a modified version of the original Duke 3.0 model, which was scaled to match the body type of the volunteer. The displacements were applied to that model with SEMCAD X at 14 stages throughout the breathing cycle.
### Table 2.2: Specifications of the Virtual Population models.

<table>
<thead>
<tr>
<th>Name</th>
<th>Gender</th>
<th>Age [year]</th>
<th>Height [m]</th>
<th>Weight [a] [kg]</th>
<th>BMI [kg/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glenn</td>
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<td>84</td>
<td>1.73</td>
<td>65.0</td>
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<tr>
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<td>1.82</td>
<td>120.0</td>
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<tr>
<td>Duke</td>
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<td>34</td>
<td>1.77</td>
<td>72.4</td>
<td>23.1</td>
</tr>
<tr>
<td>Ella</td>
<td>female</td>
<td>26</td>
<td>1.63</td>
<td>58.7</td>
<td>22.0</td>
</tr>
<tr>
<td>Louis</td>
<td>male</td>
<td>14</td>
<td>1.69</td>
<td>50.4</td>
<td>17.7</td>
</tr>
<tr>
<td>Billie</td>
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<td>1.47</td>
<td>35.4</td>
<td>16.5</td>
</tr>
<tr>
<td>Eartha</td>
<td>female</td>
<td>8</td>
<td>1.36</td>
<td>30.7</td>
<td>16.7</td>
</tr>
<tr>
<td>Dizzy</td>
<td>male</td>
<td>8</td>
<td>1.40</td>
<td>26.0</td>
<td>13.4</td>
</tr>
<tr>
<td>Thelonious</td>
<td>male</td>
<td>6</td>
<td>1.17</td>
<td>19.3</td>
<td>14.0</td>
</tr>
<tr>
<td>Roberta</td>
<td>female</td>
<td>5</td>
<td>1.09</td>
<td>17.8</td>
<td>14.9</td>
</tr>
<tr>
<td>Nina</td>
<td>female</td>
<td>3</td>
<td>0.92</td>
<td>13.9</td>
<td>16.4</td>
</tr>
</tbody>
</table>

*Pregnant Women (based on Ella; specifications refer to fetus)*

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>3rd month</td>
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<td>3 months</td>
<td>0.015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7th month</td>
<td>undefined</td>
<td>7 months</td>
<td>1.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9th month</td>
<td>female</td>
<td>9 months</td>
<td>2.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Charlie female 8 weeks 4.3

*aThe volume of given geometric structures is an information that is intrinsic to each individual model but the weight is calculated based on the density of each tissue as in the IT’IS parameter database [50].*
Figure 2.6: Comparison of height, weight, and BMI from the Virtual Population models with age-dependent statistical data of the German population [58].
1.5 T applied to the model of the adult woman Ella with a spinal implant. The simulation was run according to the specifications described in [63]. The 16-rung birdcage coil (length 750 mm, diameter 650 mm) is a numerical representation of the MITS1.5 (Medical Implant Test System, Zurich Med Tech, Switzerland). It was tuned with lumped elements placed at the end rings between the rungs to match previously performed measurements [63]. Due to the high resolution required by the implant and the large simulation domain required by the birdcage coil, the computation was performed in two steps: the fields in the birdcage coil were computed from the empty coil, and those fields were used to simulate the exposure in the body based on Huygens’ principle [64]. For the latter, the model was discretized with a resolution of 2 mm in the body and 0.5 mm in the implant, leading to 135 M cells in the computational domain. The assignment of the dielectric tissue properties at 64 MHz was done according to the material database (see Section 2.3.2), which includes work presented in [65], and all metallic parts of the coil and the implant were treated as perfect electrical conductors.

A generic thoracolumbar stabilization implant was modeled and placed realistically between the L2 and L4 vertebrae (Figure 2.8). Positioning of the implant was performed first in Version 3.0 of the model, then copied to Version 1.0, with slight adjustment to the positions of the screws, leading to very similar exposure configurations for both versions of the model. Positioning all the individual components of the implant, i.e. the 6 screws, 2 rods, and 4 parts of the bridge, in solely the Version 1.0 model would have been very inaccurate and would have led to an unrealistic, possibly unusable, setup. This accuracy of positioning will be even more critical for flexible cardiac or neural implants threaded through thin tissues or along a very specific path.

Figure 2.9 shows the local SAR distribution in the torso of Ella for both versions of the model. The more realistic shape of the lungs, liver, and kidneys can clearly be recognized from the SAR distribution of Version 3.0. The higher level of detail in the Version 3.0 model also leads to a better appreciation of the exposure in the vertebrae, where the layer of cortical/cancellous bones can clearly be distinguished; by comparison, Version 1.0 includes only one type of bone in the vertebrae, the cortical bone. The local distribution around one screw
2.6 Conclusions

The Virtual Population 3.0 (ViP 3.0) is a set of computational models of independent anatomies including both sexes, with ages spanning from fetus to 84 years old and adult BMIs ranging from 21.7 to 36.2. The models have been greatly enhanced and refined to make them suitable for medical applications involving a broad range of solvers and multi-physics couplings. In parallel, a database that provides access to various dielectric and thermal tissue parameters, as well as perfusion and density information from the literature has been created. The new generation of human models, ViP 3.0, includes re-segmentation at higher resolution, more-consistent tissue assignment,
Figure 2.8: Vertebrae, intervertebral discs, and spinal cord of Ella in Versions 1.0 and 3.0 (left). Generic thoracolumbar stabilization implant inserted in the L2, L3, and L4 vertebrae of Ella Versions 1.0 and 3.0 (right).
Figure 2.9: Comparison of the local SAR distribution in Ella Versions 1.0 (left) and 3.0 (right) from the exposure to a 1.5 T MRI birdcage coil. 0 dB corresponds to a local SAR of 1000 W/kg for operation at first level control mode, i.e. for a whole-body SAR of 4 W/kg.

several anatomical refinements, and offers the advantage to be based on truly independent anatomies. Functionalization of the models, e.g., by integration of inhomogeneous property maps or dynamic behavior (e.g., blood flow or neuron models), will be the next step.
Part III

Near-Field Exposure
Chapter 3

Estimation of Head-Tissue Specific Exposure from Mobile Phones, Based on Measurements in the Homogeneous SAM Head

3.1 Abstract

The maximum spatial peak exposure of each commercial mobile phone determined in compliance with the relevant safety and product standards is publicly available. However, this information is not sufficient
for epidemiologic studies aiming to correlate the use of mobile phones with specific cancers or to behavioral alterations, as the dominant location of the exposure may be anywhere in the head between the chin to above the ear, depending on the phone design. The objective of this study was to develop a methodology to determine tissue specific exposure by expanding the post-processing of the measured surface or volume scans using standardized compliance testing equipment, i.e., SAR scanners. The transformation matrix was developed using the results from generic dipoles to evaluate the relation between the SAR in many brain regions of the Virtual Family anatomical phantoms and in virtual brain regions mapped into the homogeneous SAM head. A set of transformation factors was derived to correlate the SAR induced in the SAM head to the SAR in the anatomical heads. The evaluation included the uncertainty associated with each factor, arising from the anatomical differences between the phantoms (typically less than 6 dB (4x)). The applicability of these factors was validated by performing simulations of four head models exposed to four realistic mobile phone models. The new methodology enables the reliable determination of the maximum and averaged exposure of specific tissues and functional brain regions to mobile phones when combined with mobile phone power control data, and therefore greatly strengthens epidemiologic evaluations and improves information for the consumer.

3.2 Introduction

With more than 4 billion mobile phone users worldwide, concerns about possible health effects of exposure to radio frequency (RF) electromagnetic fields remain high. Governmental and non-governmental organizations are asking for exposure information. Epidemiologic studies are investigating the hypothetical relationship between brain diseases and mobile phone use, e.g., [67] and [68]. These studies require scientifically sound and robust exposure metrics. Typical end-points of epidemiologic research in this field are toxicological, carcinogenic, and chronic effects in the tissues that are dominantly exposed [68]. The maximum local exposure, namely, the peak spatial specific absorption rate (SAR) that is determined to demonstrate compliance with the safety guidelines [2,6,69,70] is publicly available.
for each mobile phone, e.g., [10] and [11]. The location of the maximum exposure, however, is strongly dependent on the actual phone design [71–73] and can vary from the lower chin to above the ear of the user.

A method was developed by [74] to estimate the 3-D SAR distribution in a homogeneous human head from compliance testing data. The same group has applied this technique to map tumoral regions of the brain to the level of exposure [75]. However, this evaluated 3-D SAR distribution contains only region specific information and no organ specific information. In addition, it uses only a homogeneous head, thus neglecting the influence of the dielectric properties of the various tissues in the SAR distribution, which cannot be completely disregarded [76]. Variability assessment (or uncertainty) of the mapping was also omitted.

This study proposes a set of transformation factors and associated uncertainties to estimate the tissue specific SAR in an anatomical human head during mobile phone compliance measurements in the Specific Anthropomorphic Mannequin (SAM) head. Various head tissues as well as functional brain regions based on the Talairach atlas were investigated.

The aim of this study was to establish a correlation between the absorbed power in virtual regions of the homogeneous SAM head phantom and the absorption in anatomical human heads. In detail, this includes the development of a matrix of generic dipoles reproducing the exposure of typical mobile phones in the touch or tilt position. Using this matrix of dipoles, a statistical evaluation was performed to obtain a set of transformation factors correlating the exposure of virtual regions of the homogeneous SAM phantom with anatomical human heads. These transformation factors, based on generic sources, were validated by exposure to various realistic mobile phone models. To complete the study, the accompanied uncertainties and limitations were assessed.
3.3 Methods and Models

3.3.1 Anatomical Head Models

The heads of four anatomical human models from the Virtual Family (VF) were used: Duke, the virtual family male (VFM), Ella, the virtual family female (VFF), Billie, the 11-year-old virtual family girl (VFG), and Thelonious, the 6-year-old virtual family boy (VFB). These models are based on magnetic resonance images (MRI) of healthy volunteers. Their heads, represented in Figure 3.1, distinguish more than 50 tissue types with a resolution of $0.5 \times 0.5 \times 1.0 \text{mm}^3$. The dielectric parameters of the tissues were assigned according to the parametric model described in [65]. In addition, a high-resolution model of the middle and inner ear from [77] was added to the right and the left of every head model. Some properties of the various head models are listed in Table 3.1.

Figure 3.1: Four anatomical human models from the Virtual Family. From left to right: Duke, Ella, Billie, and Thelonious.

3.3.2 SAM Phantom with Defined Brain Regions and Tissues

The SAM head is made of a 2-mm thick shell (6 mm at the ear) filled with a homogeneous material of dielectric properties from [7]. This head model is completely generic and does not contain any information about inner anatomical details. In order to make possible the
Table 3.1: Characteristics of the VF human head models and the SAM phantom.

<table>
<thead>
<tr>
<th></th>
<th>Gender</th>
<th>Age</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thelonious</td>
<td>Male</td>
<td>6</td>
<td>3.25</td>
</tr>
<tr>
<td>Billie</td>
<td>Female</td>
<td>11</td>
<td>3.64</td>
</tr>
<tr>
<td>Ella</td>
<td>Female</td>
<td>26</td>
<td>4.53</td>
</tr>
<tr>
<td>Duke</td>
<td>Male</td>
<td>34</td>
<td>5.16</td>
</tr>
<tr>
<td>SAM</td>
<td>–</td>
<td>–</td>
<td>5.45</td>
</tr>
</tbody>
</table>

evaluation of the absorbed power in different regions of the head, an artificial anatomical tissue distribution was mapped into a CAD model of the SAM head (Figure 3.2). The dielectric parameters of all tissues remained equal to the standard head tissue simulating liquid (HSL). This procedure allows the absorbed power in the different regions of the head to be accessed during the post-processing of an electromagnetic simulation using the homogeneous SAM head.

The largest anatomical head model, Duke, was aligned and slightly scaled in various directions to fit the SAM shell as well as possible. The small amount of tissue emerging from the SAM shell was deleted and the new head was segmented. This way, different virtual tissues were made available in the SAM head, allowing the evaluation of tissue specific absorption as well as brain-region specific absorption via the Talairach atlas. The obtained tissue distribution is not meant to be representative of the average human head, but to be an approximation of the size and position of the different structures in a human head having the geometry of the SAM head.

3.3.3 FDTD Simulations

The numerical evaluations were performed using the finite-difference time-domain (FDTD) method implemented in SEMCAD X (SPEAG, Zurich, Switzerland). SEMCAD X combines a CAD environment, an
Figure 3.2: SAM model with virtual anatomical regions inside. From left to right: shell, tissues, and some structures of the brain.

FDTD solver [78] including hardware acceleration, and a postprocessor allowing the mapping of the Talairach atlas to the brain of the VF models as well as the enhanced SAM model, as described in [79]. All the software functions, from the modeling to the extraction of results, are interfaced in the Python [80] scripting language, allowing efficient handling of large simulation sets.

A resolution of maximum 2 mm was used in the head models, which is smaller than a tenth of wavelength in all tissues. In addition, a finer mesh of 1 mm was used in the various components of the middle and inner ear. The results of FDTD simulations involving realistic mobile phone models, however, are very sensitive to the mesh of the phone. In those cases, the grid was set such that the radiating properties of the phone model correspond to those of the specification sheet from the manufacturer, which in all cases required resolutions well below $\lambda/10$, the FDTD stability criterion.

For each simulation, the power budget was computed, i.e., the ratio of the absorbed power plus the power radiated on the boundaries of the computational domain to the input power. The simulation time and the quality of the absorbing boundary conditions were set such that the power budget was always better, i.e., higher, than 95%.
3.3.4 Talairach Atlas

A common resource for the identification of anatomical and functional regions of the brain is the stereotactic atlas developed by Talairach & Tournoux [81]. This atlas provides a description of the brain in different levels of abstraction, ranging from hemisphere to cell level, based on a set of landmarks defined in the brain.

A tool has been implemented in the simulation platform SEM-CAD X to make use of the possibilities offered by this atlas, based on [82]. The landmarks defined by the Talairach atlas are firstly identified in the heads of the VF models by locating nine markers in the brain CAD model. The reference system provided by these landmarks is used to scale and align the sample brain labeled according to the Talairach atlas with the CAD model. The brain regions of the VF heads can thus be analyzed using the segmentation provided by the Talairach atlas.

Mapping the Talairach atlas to the various regions of the anatomical heads is accurate for identifying functional regions in the brain [82]. Higher uncertainties may arise with mapping the regions to the quasi-anatomical head in SAM. These are, however, directly related to (and therefore compensated by) the transformation factors using the methodology presented in the paper.

3.3.5 Generic Dipoles Exposure Matrix

Depending on the mobile phone, the operating frequency, and the phone position, the maximum exposure at the head can be anywhere between the chin and above the ear, roughly within the dimensions of the phone. The near-field exposure from a mobile phone is approximated by a generic -dipole. Based on this, a matrix of -dipole antennas was designed to take into account the exposure of arbitrary mobile phones placed in either the tilt or touch position. As a first step, the matrix of dipoles was defined relative to the SAM head, which is the largest head. This fix matrix was then placed around the VF heads. The procedure is described in the following paragraphs.

Eighteen dipoles per frequency were excited, one at a time, at 900 MHz and 1800 MHz, leading to an exposure matrix of 36 configurations per head. The tip-to-tip length of the dipoles was set
to 333 mm and 167 mm for an exposure at 900 MHz and 1800 MHz, respectively. The dipoles, and later the realistic mobile phones, were placed on the left side of the heads. The conclusions could equally well be applied to an exposure on the right side of the head, as mentioned by [75].

**Definition of the Position – SAM Phantom**

Eighteen dipole positions were defined based on the geometry of the SAM head and the defined reference points: ear reference point (ERP) right, ERP left, and mouth (M). These points, forming the reference plane (RP), were used to place the dipoles around the head. The first 6 dipoles were confined in the RP. They were rotated by 15-degree steps in the RP, from -30 degrees to 30 degrees, and positioned such that the distance between the feeding point of the dipole and the SAM shell was 10 mm. The position called ‘0°’ was obtained by placing the dipole parallel to the tangent line, a line on the RP passing through the ERP and touching the SAM shell at one other point on the cheek, called the tangent point. Two dipoles were placed with this angle of rotation, one having its feeding point aligned with the ear (0°, ear) and the other one with the cheek (0°, cheek). Figure 3.3(a) shows the ear entrance canal (EEC) and, on its right, the tangent point.

The data used in [83] concerning the properties of the phones marketed in the US between 1999 and 2005 has been reprocessed in order to find out that their average width is 48 mm. The number of dipolar configurations was increased by copying the six dipoles in the RP twice: 24 mm below and above the RP (see Figure 3.4), the distance being measured perpendicular to the RP (noted RP ± 24 mm).

**Alignment – VF Heads**

In the anatomical heads, the RP and tangent plane (TP) were defined according to the procedure described in [84]. The intersection between the EEC line and the TP is called here the EEC point. The heads were positioned relative to the SAM head while the position of all the dipoles was fixed (see Figure 3.3(b) to Figure 3.3(e)). In a first step, the heads were placed such that the tangent line of the SAM and anatomical heads coincided and the EEC points were overlaid. As
Figure 3.3: Dipolar exposure – Alignment of the dipoles, viewed perpendicular to the RP (1800 MHz). For each head, the point close to the ear represents the position of the EEC and, on its right, the tangent point. (a) SAM; (b) Duke; (c) Ella; (d) Billie; (e) Thelonious.
Figure 3.4: Dipolar exposure – Matrix of eighteen dipoles placed around the SAM head, in the RP, RP + 24mm, and RP – 24mm (1800 MHz).
the SAM head is bigger than the anatomical heads, this positioning procedure caused the dipoles at the front of the head to be much closer to the cheek than the dipoles at the back are close to the skull. The anatomical heads were turned around the axis normal to the RP by an additional $10^\circ$. As a result, one can notice that the tangent line of the SAM head is horizontal (Figure 3.3(a)), while is it $10^\circ$ away from horizontal for the VF heads (Figure 3.3(b) to Figure 3.3(e)).

Mobile Phones

Four realistic phone models were placed in the touch position next to every head model: Motorola V180, Motorola T250, Motorola L7 (Motorola, Schaumburg, USA), and Nokia 8310 (Nokia, Espoo, Finland). The models of the T250 and L7 phones were validated in [85] and [86], respectively.

3.4 Results

The method proposed in this study aims at the estimation of the average SAR in brain regions and tissues of anatomical heads from the SAR in the homogeneous SAM head. The first step consists of simulating anatomical and SAM head models exposed to a number of generic dipoles and extracting the average SAR, i.e., the ratio of the total absorbed power to absorbing mass, in many brain regions and tissues. A statistical analysis of the correlation between the exposure in the anatomical heads and the exposure in virtual regions of the homogeneous SAM head leads to a set of transformation factors and uncertainties (variabilities), one for each region and frequency. The results are normalized to the head-average SAR in order to remove the dependency to the head-source distance. However, the head-average SAR of anatomical heads is not a quantity that is definable in the context of compliance testing. The dependency to the head-average SAR is thus replaced by a dependency to the total absorbed power, which can be obtained by extrapolation. The suggested method and the transformation factors (and associated uncertainties) derived from the generic sources are then validated by numerical simulations of the
same anatomical and homogeneous SAM heads exposed to realistic mobile phone models.

3.4.1 Determination of the Transformation Factors – Exposure to Generic Dipoles

An extensive list of tissues and brain regions was investigated in this project. The regions were based on either common anatomical properties (e.g., all parts of the eye, all parts of the inner ear, etc.) or on the Talairach atlas. This section focuses on nine regions of the brain to demonstrate the relevance of the developed estimation method. Focusing on these brain regions, the region specific absorption from the exposure to the 18 generic dipoles was evaluated in the SAM head as well as in the anatomical human heads. Transformation factors were determined to match the SAM head results with the results in the anatomical human heads for all the different configurations (anatomical heads and dipole positions) using a weighted least-squares fit of the type: \( Ax = b \), where \( x \) minimizes the sum of the squared errors between \( Ax \) and \( b \), while also considering associated weights \( w \). For each region, some dipoles lead to a much lower absorption than others, depending on the distance between the source and the region as well as on the anatomy of the head. The specific SAR in regions further away form the source of a dipole presents bigger inter-model variations due to the differences in the configuration of the absorbing layers between the source and the point of interest. These configurations also lead to a smaller SAR value and are therefore less relevant for epidemiologic studies. A smaller weight was thus associated to these configurations in the least-squares solution.

Following this procedure, a transformation factor corresponds to each studied brain region and frequency which can be applied to the SAR in the homogeneous SAM head in order to estimate the SAR in a typical anatomical head:

\[
\begin{bmatrix}
    SAR_{R}^{\text{VF}} \\
    SAR_{\text{head}}^{\text{VF}}
\end{bmatrix}_{\text{dB}} = \begin{bmatrix}
    SAR_{R}^{\text{SAM}} \\
    SAR_{\text{head}}^{\text{SAM}}
\end{bmatrix}_{\text{dB}} + [F_{R}(f)]_{\text{dB}}
\]

\[(3.1)\]

where \([F_{R}(f)]_{\text{dB}}\) is the frequency-dependent transformation factor for the region \( R \), \( SAR_{R}^{\text{SAM}} \) is the SAR in the region \( R \) in the SAM...
head, and $SAR_{head}^{SAM}$ and $SAR_{head}^{VF}$ are the total average SAR in the SAM and VF heads respectively, i.e., the total absorbed power, $P$, divided by the total mass, $m$. $SAR_{R}^{VF}$ is the approximation of the SAR in the region $R$ of an arbitrary heterogeneous anatomical head, i.e., the quantity of interest in epidemiologic studies.

In order to eliminate the dependency on the dipole-head distances, which might vary for the different dipoles placed around the anatomical heads, all results are normalized to the total average SAR in the individual heads, $SAR_{head}$. Figure 3.5 shows $SAR_{head}$ for all the different dipole configurations, head models, and frequencies. As expected, the dipoles placed around the SAM head in the RP lead to less variation of $SAR_{head}$ (variations of 0.017 W/kg and 0.016 W/kg at 900 MHz and 1800 MHz, respectively) than the dipoles in the other planes (for SAM, variations of 0.053 W/kg and 0.04 W/kg in RP–24 mm at 900 MHz and 1800 MHz) or the other heads (for Billie, variations of 0.08 W/kg in RP–24 mm at 900 and 1800 MHz) as their distance to the SAM head is set to a fixed value of 10 mm in the RP only.

![Figure 3.5: Dipolar exposure – Average SAR over the entire head, for the five head models, normalized to 1 W source radiated power. The dipoles are confined in three parallel planes: the reference plane (RP) and planes 24 mm above and below the RP (RP ± 24 mm). (right) 900 MHz; (left) 1800 MHz.](image-url)
CHAPTER 3. HEAD-TISSUE SPECIFIC EXPOSURE

The factors are a transformation taking into account anatomical geometries and heterogeneous tissue distributions. Table 3.2 shows the transformation factors to be added to the SAR in various brain regions of the homogeneous SAM head to estimate the SAR in the anatomical VF heads (dB and linear scales). The upper and lower boundaries of the uncertainty (variability) of the transformed values of SAR are also given. For each brain region and frequency, the uncertainty is calculated from the standard deviation \( (k = 2) \) over the ratio between the SAR in the VF heads and the transformed SAR in SAM for the various configurations, normalized to the corresponding total average SAR, in a dB scale. The upper and lower boundaries of the uncertainty were adjusted to take into consideration the fact that the average of the distribution was not always centered at 0 dB. As already mentioned, this paper focuses on the validation of the transformation factors for nine regions of the brain, namely, the whole brain, as well as the left part (i.e., the exposed half) of the gray matter, white matter, thalamus, and occipital, limbic, temporal, parietal, and frontal lobes. Tables 3.3 and 3.4 show the factors and associated uncertainties (variabilities) for an extensive list of tissues and brain regions, as could be used for epidemiologic studies when implemented, for example, in a SAR measurement system.

Good correlation between the SAR in the generic tissue regions of the SAM head and the SAR in the same regions of the anatomical heads of the VF was found for the generic dipole sources. Figures 3.6 and 3.7 show results of the exposure to generic dipole sources in the RP: comparison of the estimation of the SAR for various tissues in an anatomical head from the results in SAM, i.e., SAM results plus the transformation factors from Table 3.2 and associated uncertainty, to the simulation results of the region specific SAR in the VF heads. The points show the SAR values from the simulations using the anatomical heads from the Virtual Family. The results from the VF heads are within the uncertainty of the estimation for regions where the absorption is roughly more than \( \pm3 \) dB (2x), i.e., where the specific average SAR is higher than half the head-average SAR. Larger deviations occur for regions of lower absorption, which are less relevant for exposure assessment. These larger deviations are due to the fact that these regions are generally further away from the source and hence
Table 3.2: Transformation factors to the homogeneous SAM head ($F_R(f)$) and accompanied uncertainty on the final results ($\Delta_{\text{low}}$ and $\Delta_{\text{up}}$ the lower and upper boundaries of the uncertainty, respectively).

<table>
<thead>
<tr>
<th>Brain Region, $R$</th>
<th>900 MHz</th>
<th>1800 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_R(f)$</td>
<td>$\Delta_{\text{low}}$</td>
</tr>
<tr>
<td>Whole Brain</td>
<td>+0.1</td>
<td>−1.5</td>
</tr>
<tr>
<td>Gray Matter, left</td>
<td>+0.4</td>
<td>−1.5</td>
</tr>
<tr>
<td>White Matter, left</td>
<td>−0.7</td>
<td>−1.8</td>
</tr>
<tr>
<td>Thalamus, left</td>
<td>+2.7</td>
<td>−2.3</td>
</tr>
<tr>
<td>Occipital Lobe, left</td>
<td>+1.1</td>
<td>−1.9</td>
</tr>
<tr>
<td>Limbic Lobe, left</td>
<td>+1.6</td>
<td>−1.8</td>
</tr>
<tr>
<td>Temporal Lobe, left</td>
<td>−1.0</td>
<td>−1.7</td>
</tr>
<tr>
<td>Parietal Lobe, left</td>
<td>−2.2</td>
<td>−2.7</td>
</tr>
<tr>
<td>Frontal Lobe, left</td>
<td>+1.6</td>
<td>−2.7</td>
</tr>
</tbody>
</table>

The set of transformation factors presented here is meant to be used in the context of SAR compliance measurements. According to [7], each configuration measured in the compliance testing procedure is subjected to an area scan and at least one zoom scan. Whereas the area scan is a surface scan covering an area on the inside of the phantom head which is larger than the projection of the phone, the zoom scan is a small volume measurement performed at each maximum location of the area scan. An extrapolation technique using these two measurements was reported by [74], leading to correlation coefficients around 0.98 when compared to a volume scan of the whole phantom head. Implemented directly in the measurement software used for compliance testing, the application of the transformation factors presented here can provide the user with the SAR in a list of brain regions from an area and zoom scans, thus involving no additional measurements.
Table 3.3: Transformation factors to the homogeneous SAM head for every brain-region of the first two levels of the Talairach atlas and the uncertainty on the transformed SAR results ($\Delta_{\text{low}}$ and $\Delta_{\text{up}}$ the lower and upper boundaries of the uncertainty, respectively).

<table>
<thead>
<tr>
<th>Brain Region, $R$</th>
<th>$F_R(f)$</th>
<th>$\Delta_{\text{low}}$</th>
<th>$\Delta_{\text{up}}$</th>
<th>$F_R(f)$</th>
<th>$\Delta_{\text{low}}$</th>
<th>$\Delta_{\text{up}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Level 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter-Hemispheric</td>
<td>+2.3</td>
<td>−3.0</td>
<td>+4.9</td>
<td>+4.2</td>
<td>−2.5</td>
<td>+3.9</td>
</tr>
<tr>
<td>Left Brainstem</td>
<td>+1.8</td>
<td>−2.2</td>
<td>+4.5</td>
<td>+1.5</td>
<td>−4.0</td>
<td>+11.7</td>
</tr>
<tr>
<td>Left Cerebellum</td>
<td>+2.5</td>
<td>−2.3</td>
<td>+6.6</td>
<td>+0.2</td>
<td>−2.3</td>
<td>+5.7</td>
</tr>
<tr>
<td>Left Cerebrum</td>
<td>−0.6</td>
<td>−1.8</td>
<td>+2.2</td>
<td>−0.6</td>
<td>−2.8</td>
<td>+4.2</td>
</tr>
<tr>
<td>Right Brainstem</td>
<td>+2.2</td>
<td>−1.6</td>
<td>+3.3</td>
<td>+2.2</td>
<td>−3.1</td>
<td>+7.2</td>
</tr>
<tr>
<td>Right Cerebellum</td>
<td>+3.4</td>
<td>−2.2</td>
<td>+4.8</td>
<td>+5.7</td>
<td>−2.4</td>
<td>+3.5</td>
</tr>
<tr>
<td>Right Cerebrum</td>
<td>+4.0</td>
<td>−1.3</td>
<td>+1.4</td>
<td>+6.4</td>
<td>−2.8</td>
<td>+1.9</td>
</tr>
<tr>
<td><strong>Level 2, left</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior Lobe, left</td>
<td>+2.4</td>
<td>−2.1</td>
<td>+5.1</td>
<td>+0.2</td>
<td>−2.8</td>
<td>+7.0</td>
</tr>
<tr>
<td>Frontal Lobe, left</td>
<td>+1.6</td>
<td>−2.7</td>
<td>+6.6</td>
<td>+3.6</td>
<td>−2.9</td>
<td>+4.9</td>
</tr>
<tr>
<td>Frontal-Temporal Space, left</td>
<td>−2.4</td>
<td>−2.8</td>
<td>+6.4</td>
<td>−2.3</td>
<td>−2.8</td>
<td>+11.5</td>
</tr>
<tr>
<td>Limbic Lobe, left</td>
<td>+1.6</td>
<td>−1.8</td>
<td>+2.2</td>
<td>+2.1</td>
<td>−3.0</td>
<td>+5.0</td>
</tr>
<tr>
<td>Medulla, left</td>
<td>+1.8</td>
<td>−2.6</td>
<td>+5.4</td>
<td>+1.4</td>
<td>−4.5</td>
<td>+10.0</td>
</tr>
<tr>
<td>Midbrain, left</td>
<td>+2.2</td>
<td>−2.3</td>
<td>+4.3</td>
<td>+2.2</td>
<td>−3.9</td>
<td>+10.1</td>
</tr>
<tr>
<td>Occipital Lobe, left</td>
<td>+1.1</td>
<td>−1.9</td>
<td>+4.9</td>
<td>−0.2</td>
<td>−2.4</td>
<td>+8.2</td>
</tr>
<tr>
<td>Parietal Lobe, left</td>
<td>−2.2</td>
<td>−2.7</td>
<td>+9.2</td>
<td>+0.9</td>
<td>−2.1</td>
<td>+6.9</td>
</tr>
<tr>
<td>Pons, left</td>
<td>+1.8</td>
<td>−2.4</td>
<td>+5.1</td>
<td>−1.2</td>
<td>−4.4</td>
<td>+14.4</td>
</tr>
<tr>
<td>Posterior Lobe, left</td>
<td>+2.5</td>
<td>−2.3</td>
<td>+7.0</td>
<td>+0.3</td>
<td>−2.4</td>
<td>+6.0</td>
</tr>
<tr>
<td>Sub-lobar, left</td>
<td>+0.8</td>
<td>−1.7</td>
<td>+2.6</td>
<td>+0.3</td>
<td>−3.1</td>
<td>+6.5</td>
</tr>
<tr>
<td>Temporal Lobe, left</td>
<td>−1.0</td>
<td>−1.7</td>
<td>+2.7</td>
<td>−1.3</td>
<td>−2.4</td>
<td>+3.9</td>
</tr>
<tr>
<td><strong>Level 2, right</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior Lobe, right</td>
<td>+2.6</td>
<td>−2.1</td>
<td>+4.4</td>
<td>+3.0</td>
<td>−2.2</td>
<td>+5.0</td>
</tr>
<tr>
<td>Frontal Lobe, right</td>
<td>+4.1</td>
<td>−3.4</td>
<td>+2.0</td>
<td>+5.3</td>
<td>−2.2</td>
<td>+4.6</td>
</tr>
<tr>
<td>Frontal-Temporal Space, right</td>
<td>+1.6</td>
<td>−2.1</td>
<td>+3.4</td>
<td>+4.6</td>
<td>−2.4</td>
<td>+3.0</td>
</tr>
<tr>
<td>Limbic Lobe, right</td>
<td>+2.8</td>
<td>−1.5</td>
<td>+1.5</td>
<td>+4.7</td>
<td>−2.4</td>
<td>+1.9</td>
</tr>
<tr>
<td>Medulla, right</td>
<td>+1.7</td>
<td>−2.2</td>
<td>+4.4</td>
<td>+0.8</td>
<td>−4.6</td>
<td>+9.1</td>
</tr>
<tr>
<td>Midbrain, right</td>
<td>+3.1</td>
<td>−1.8</td>
<td>+3.2</td>
<td>+2.9</td>
<td>−3.3</td>
<td>+7.9</td>
</tr>
<tr>
<td>Occipital Lobe, right</td>
<td>+4.9</td>
<td>−0.9</td>
<td>+1.9</td>
<td>+7.5</td>
<td>−1.7</td>
<td>+2.9</td>
</tr>
<tr>
<td>Parietal Lobe, right</td>
<td>+4.8</td>
<td>−0.8</td>
<td>+1.5</td>
<td>+6.6</td>
<td>−1.9</td>
<td>+3.4</td>
</tr>
<tr>
<td>Pons, right</td>
<td>+1.2</td>
<td>−1.6</td>
<td>+3.2</td>
<td>−0.6</td>
<td>−3.6</td>
<td>+8.6</td>
</tr>
<tr>
<td>Posterior Lobe, right</td>
<td>+4.1</td>
<td>−2.2</td>
<td>+4.7</td>
<td>+7.9</td>
<td>−1.9</td>
<td>+2.5</td>
</tr>
<tr>
<td>Sub-lobar, right</td>
<td>+3.9</td>
<td>−1.9</td>
<td>+3.1</td>
<td>+4.7</td>
<td>−2.8</td>
<td>+4.7</td>
</tr>
<tr>
<td>Temporal Lobe, right</td>
<td>+3.6</td>
<td>−1.8</td>
<td>+1.3</td>
<td>+5.8</td>
<td>−3.5</td>
<td>+2.2</td>
</tr>
</tbody>
</table>
3.4. RESULTS

Table 3.4: Transformation factors to the homogeneous SAM head for every head tissue and the uncertainty on the transformed SAR results ($\Delta^{low}$ and $\Delta^{up}$ the lower and upper boundaries of the uncertainty, respectively).

<table>
<thead>
<tr>
<th>Brain Region, $R$</th>
<th>900 MHz</th>
<th></th>
<th></th>
<th>1800 MHz</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_R(f)$</td>
<td>$\Delta^{low}$</td>
<td>$\Delta^{up}$</td>
<td>$F_R(f)$</td>
<td>$\Delta^{low}$</td>
<td>$\Delta^{up}$</td>
</tr>
<tr>
<td>Bones</td>
<td>-8.2</td>
<td>-2.0</td>
<td>+3.4</td>
<td>-8.2</td>
<td>-2.9</td>
<td>+5.7</td>
</tr>
<tr>
<td>Brain</td>
<td>+0.3</td>
<td>-1.5</td>
<td>+1.9</td>
<td>+0.1</td>
<td>-2.3</td>
<td>+3.8</td>
</tr>
<tr>
<td>Brain, Grey matter</td>
<td>-0.3</td>
<td>-1.6</td>
<td>+1.9</td>
<td>-0.6</td>
<td>-2.6</td>
<td>+4.4</td>
</tr>
<tr>
<td>Brain, White matter</td>
<td>-0.2</td>
<td>-2.4</td>
<td>+4.0</td>
<td>+0.1</td>
<td>-3.8</td>
<td>+8.2</td>
</tr>
<tr>
<td>Cartilage</td>
<td>-3.7</td>
<td>-3.5</td>
<td>+10.6</td>
<td>-4.6</td>
<td>-4.2</td>
<td>+17.5</td>
</tr>
<tr>
<td>Cerebellum</td>
<td>+2.4</td>
<td>-2.8</td>
<td>+7.8</td>
<td>-0.2</td>
<td>-2.4</td>
<td>+7.6</td>
</tr>
<tr>
<td>Cerebrospinal fluid</td>
<td>+4.9</td>
<td>-1.7</td>
<td>+2.4</td>
<td>+3.8</td>
<td>-3.2</td>
<td>+6.5</td>
</tr>
<tr>
<td>Eyes, Sclera</td>
<td>+6.1</td>
<td>-2.6</td>
<td>+6.3</td>
<td>+9.0</td>
<td>-3.4</td>
<td>+5.4</td>
</tr>
<tr>
<td>Eyes, Lens</td>
<td>+6.9</td>
<td>-2.8</td>
<td>+4.9</td>
<td>+5.1</td>
<td>-3.5</td>
<td>+7.5</td>
</tr>
<tr>
<td>Eyes, Vitreous humor</td>
<td>+7.7</td>
<td>-2.8</td>
<td>+6.2</td>
<td>+11.5</td>
<td>-3.3</td>
<td>+5.0</td>
</tr>
<tr>
<td>Eyes</td>
<td>+7.2</td>
<td>-2.8</td>
<td>+6.3</td>
<td>+10.6</td>
<td>-3.3</td>
<td>+5.1</td>
</tr>
<tr>
<td>Fat</td>
<td>-3.4</td>
<td>-4.2</td>
<td>+4.6</td>
<td>-3.4</td>
<td>-5.5</td>
<td>+5.7</td>
</tr>
<tr>
<td>Head, no ears</td>
<td>0.0</td>
<td>-0.1</td>
<td>+0.1</td>
<td>0.0</td>
<td>-0.2</td>
<td>+0.2</td>
</tr>
<tr>
<td>Hippocampus</td>
<td>+2.9</td>
<td>-1.6</td>
<td>+2.5</td>
<td>+4.7</td>
<td>-2.9</td>
<td>+5.5</td>
</tr>
<tr>
<td>Hypophysis</td>
<td>-3.1</td>
<td>-1.8</td>
<td>+2.6</td>
<td>-5.5</td>
<td>-3.4</td>
<td>+3.6</td>
</tr>
<tr>
<td>Hypothalamus</td>
<td>+3.0</td>
<td>-1.6</td>
<td>+2.7</td>
<td>+4.0</td>
<td>-3.3</td>
<td>+6.9</td>
</tr>
<tr>
<td>Inner ear, left</td>
<td>-3.6</td>
<td>-1.9</td>
<td>+4.7</td>
<td>-5.0</td>
<td>-3.6</td>
<td>+12.1</td>
</tr>
<tr>
<td>Inner ear, right</td>
<td>-5.4</td>
<td>-3.0</td>
<td>+3.5</td>
<td>-5.8</td>
<td>-6.2</td>
<td>+7.8</td>
</tr>
<tr>
<td>Mandible</td>
<td>-6.3</td>
<td>-2.0</td>
<td>+4.6</td>
<td>-3.8</td>
<td>-2.3</td>
<td>+6.6</td>
</tr>
<tr>
<td>Medulla oblongata</td>
<td>+1.6</td>
<td>-3.3</td>
<td>+9.1</td>
<td>+7.4</td>
<td>-3.0</td>
<td>+7.0</td>
</tr>
<tr>
<td>Midbrain</td>
<td>+2.3</td>
<td>-2.1</td>
<td>+3.9</td>
<td>+1.9</td>
<td>-3.7</td>
<td>+10.6</td>
</tr>
<tr>
<td>Mucosa</td>
<td>+3.2</td>
<td>-1.6</td>
<td>+3.7</td>
<td>+5.7</td>
<td>-2.0</td>
<td>+4.8</td>
</tr>
<tr>
<td>Muscle</td>
<td>+2.3</td>
<td>-0.8</td>
<td>+1.0</td>
<td>+2.1</td>
<td>-1.3</td>
<td>+1.4</td>
</tr>
<tr>
<td>Nerve</td>
<td>+1.7</td>
<td>-2.3</td>
<td>+3.5</td>
<td>+3.7</td>
<td>-3.8</td>
<td>+6.8</td>
</tr>
<tr>
<td>Pineal body</td>
<td>+3.2</td>
<td>-3.1</td>
<td>+5.1</td>
<td>+3.4</td>
<td>-3.4</td>
<td>+7.5</td>
</tr>
<tr>
<td>Pons</td>
<td>0.0</td>
<td>-2.4</td>
<td>+5.9</td>
<td>-3.0</td>
<td>-4.5</td>
<td>+18.3</td>
</tr>
<tr>
<td>SAT</td>
<td>-8.7</td>
<td>-1.1</td>
<td>+1.5</td>
<td>-7.5</td>
<td>-1.3</td>
<td>+1.7</td>
</tr>
<tr>
<td>Skull</td>
<td>-9.0</td>
<td>-1.8</td>
<td>+2.5</td>
<td>-8.2</td>
<td>-2.8</td>
<td>+4.1</td>
</tr>
<tr>
<td>Teeth</td>
<td>-6.0</td>
<td>-2.7</td>
<td>+10.2</td>
<td>-2.8</td>
<td>-2.6</td>
<td>+9.5</td>
</tr>
<tr>
<td>Thalamus</td>
<td>+3.6</td>
<td>-2.9</td>
<td>+5.2</td>
<td>+5.1</td>
<td>-5.2</td>
<td>+10.7</td>
</tr>
<tr>
<td>Tongue</td>
<td>+6.4</td>
<td>-2.5</td>
<td>+6.7</td>
<td>+8.6</td>
<td>-2.2</td>
<td>+5.2</td>
</tr>
</tbody>
</table>
Figure 3.6: Dipolar exposure – Estimation of the average SAR in various regions of the anatomical heads from the results in the SAM head at 900 MHz, normalized to the average SAR in the whole head, for the six dipoles in the RP. The bars represent the estimation of the SAR from the results in SAM and its corresponding uncertainty. The points show the SAR in the regions of the four anatomical VF heads.

Figure 3.7: Dipolar exposure – Estimation of the average SAR in various regions of the anatomical heads from the results in the SAM head at 1800 MHz, normalized to the average SAR in the whole head, for the six dipoles in the RP. The bars represent the estimation of the SAR from the results in SAM and its corresponding uncertainty. The points show the SAR in the regions of the four anatomical VF heads.
In the case of compliance testing, although $SAR_{head}^{SAM}$ can be extrapolated from the measurements in the SAM head, $SAR_{head}^{VF}$ is not possible to compute. Consequently, the normalization used to apply the factors $F_R(f)$ to actual measurements has to be adapted differently. The total absorbed power in the anatomical heads, $P_{head}^{VF}$, is approximated by the total absorbed power in the SAM head, $P_{head}^{SAM}$, which introduced an error of less than 1.3 dB (30%) for the examined phones (Figure 3.8).

Knowing that the average SAR in the whole head is given by $SAR_{head} = P_{head}/m_{head}$ and assuming that $P_{head}^{VF} = P_{head}^{SAM}$, (3.1) becomes

$$[SAR_{R}^{VF}]_{dB\ W/kg} = \left( SAR_{R}^{SAM} \times \frac{m_{head}^{SAM}}{m_{head}^{VF}} \right)_{dB\ W/kg} + [F_R(f)]_{dB} \quad (3.2)$$

where $m_{head}^{VF}$ and $m_{head}^{SAM}$ represent the weight of the VF head and the SAM head, respectively. The weights of the anatomical heads studied in the paper are presented in Table 3.1. Depending on the purpose of a study, one could use (3.2) with, e.g., the mass of a specific head, or the average mass of an adult or a child head, to estimate the tissue and brain-region specific SAR.
3.4.2 Validation of the Transformation Factors – Exposure to Realistic Mobile Phones

The aim of this section is to show that the transformation factors and uncertainties derived above, using generic sources, can be used to predict the SAR in head tissues and brain regions of anatomical models when only the results in the SAM head are available. In this section, the transformation procedure and in particular the use of the generic dipole matrix are validated by assessing the exposure to four realistic mobile phones placed in the touch position on the left side of the four anatomical heads of theVF and the SAM head. The phones were operated at 900 and 1747 MHz with nominal source radiated powers of 250 and 125 mW, respectively. Figure 3.9 presents the deviation between the anatomical head results (dots), the original SAM results (crosses), and the SAM results transformed according to the transformation factors and uncertainties of Table 3.2 combined with (3.2) (circles). For each tissue and phone, the dB scale is set such that 0 dB corresponds to the transformed result from the SAM head.

In addition, Figure 3.10 shows the transformed SAM values for the various phones and brain regions. The names of the phones are not shown, due to non-disclosure agreements. The variation of the brain-region specific exposure from the various mobile phones is typically around 5 dB (3x), but can reach up to 18 dB (63x).

Although the VF heads present numerous anatomical differences, the variations in the absorption in the various heads are smaller than the variations between the brain regions. From Figure 3.9 one can see that at 900 MHz, the exposure in the adult and child heads are of the same level, but at 1747 MHz a slight increase can be noticed for the absorption in most regions of the child heads compared to adults. The smaller penetration depth at 1747 MHz leads to lower absorption in the deeper regions of the brain, thus to a less uniform exposure of the brain. As expected [87], the smaller sizes of the children’s brains as well as their thinner skulls bring the various subregions closer to the source, thus leading to higher absorption.

For most cases, all the values of SAR in the various head models are within the uncertainty of the estimation from the SAM head. It can also be noticed that the uncertainty is larger for the tissues of
Figure 3.9: Mobile phone exposure – Deviation of the SAR in the regions of the VF heads from the transformed results based on the SAM head. For each exposure configuration and region, 0 dB is equal to the transformed SAR in SAM. (top) 900 MHz; (bottom) 1747 MHz.
lower absorption. For example, at 1747 MHz, Figure 3.10 shows that the three brain regions with the lowest absorption are the thalamus, the occipital lobe, and the parietal lobe, and Figure 3.9 shows that these regions are associated with the largest uncertainty range. The same can be seen at 900 MHz with the occipital, parietal, and frontal lobes.

The correlation between the SAR in the VF heads and the SAR obtained from a transformation of the SAR in the SAM head is shown in Figure 3.11. The black signs represent the configurations (of phone, frequency, VF head, and tissue) for which the SAR in the VF head is not within the uncertainty of the transformed SAR in the SAM phantom. These represent 12% of the configurations studied here, indicating similar uncertainties for real phone exposures than predicted based on the dipole exposures.

### 3.5 Discussion and Conclusions

A novel technique has been developed to estimate the brain-region specific exposure based on data measured with SAR measurement
Figure 3.11: Mobile phone exposure – Correlation between the SAR in the nine studied brain regions of the VF and the transformed SAM in these regions, at 900 MHz (plus signs) and 1800 MHz (crosses). The black markers show occurrences for which the SAR in the VF head is not within the uncertainty of the transformed SAR from SAM.

systems that have been standardized for testing compliance of mobile phones with safety guidelines. A statistical approach was used to determine the tissue and brain-region specific transformation factors including the uncertainty of the transformation. These factors were validated numerically using realistic sources and found to give a good estimation of the SAR in anatomical heads. The uncertainties were estimated from lower than 2 dB (58%) to higher than 10 dB (900%) for the various tissues and frequencies. The transformation studied here can be straightforwardly implemented in the post-processor of any SAR scanner compliant with the current standards \([7,9]\). This was demonstrated by implementation in the commercial dosimetric scanner DASY 5 used for compliance testing \([88]\). As the brain exposure can differ considerably between devices of the same communication standard, both consumers and epidemiologists will benefit from the availability of such specific information that are a much better indicator of the users exposure, especially when combined with the average antenna input power as determined using over-the-air performance
data. Future work includes the validation of the phone models of the Motorola V180 and Nokia 8310 by comparison to measurements.
Chapter 4

Experimental Evaluation of the SAR Induced in Head Phantoms of Three- and Eight-year-old Children

4.1 Abstract

The exposure of children to mobile phones has been a concern for years, but so far the conclusions with respect to compliance with safety standards are based only on simulations. Regulators have requested that these conclusions be supported by experimental evidence. The objectives of this study are 1) to test if the hypothesis that the specific anthropomorphic mannequin (SAM) used in standardized compliance testing is also conservative for homogeneous child head models and 2) to validate the numerical prediction of the peak spatial SAR (psSAR) in child head phantoms. To achieve these objectives, head phantoms

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This Chapter was originally published in [89].
of 3- and 8-year-old children were developed and manufactured. The results confirm that SAM is also conservative for child head phan-
toms, and that the agreement between numerical and experimental values are within the combined uncertainty of 0.9 dB provided that
the actual peak spatial SAR (psSAR) is determined. The results also
demonstrate that the currently suggested numerical SAR averaging
procedures may underestimate the actual psSAR by more than 1.3 dB
and that the currently defined limits in terms of the average of a cubic
mass are impractical for non-ambiguous evaluations, i.e., for achieving
inter-laboratory repeatability.

4.2 Introduction

In the last two decades, scientists, engineers, and epidemiologists
have been investigating the potential health effects of the exposure
to mobile phones. A lot of the studies are triggered, in particular,
by growing concerns in society about the safety of children as mobile
phone use is becoming more and more common in youngsters. This
ongoing debate has led various groups to investigate the influence
of age-dependent parameters on the specific absorption rate (SAR).
Dosimetric analysis is frequently used to compare the exposure of the
studied configurations with the basic restrictions on the 1 g and/or
10 g peak spatial SAR (psSAR), as defined by the ICNIRP \[2\] and
the IEEE \[6,90\]. The specific anthropomorphic mannequin (SAM)
phantom has been adopted by \[7,9\] to easily assess the psSAR due
to the exposure to mobile telecommunication devices, and is interna-
tionally harmonized to demonstrate the compliance of every mobile
phone with the guidelines prior to market approval. Consequently,
the aim of most studies is to compare the psSAR in realistic human
heads with the value in SAM and ultimately demonstrate (or not)
compliance of specific configurations with the guidelines.

The impact of head size and tissue distribution on the SAR dis-
tribution has been thoroughly examined over the years. All reviews
of these studies conclude that the psSAR in SAM is a conservative
measure for the exposure in anatomical heads \[91,93\] and that varia-
tions between specific heads cannot be correlated with their age \[84\].
Although the average SAR in peripheral brain tissues can be higher
for young children [12, 94], the variations in the psSAR remain within the variability associated with anatomical adult heads. Other issues related to the thickness of the pinna and the age-dependency of the dielectric properties of tissues have been raised [84, 93, 94] and even studied [95, 96], but have only recently been addressed in a systematic manner in the context of mobile phone use [12, 97].

Several head models of children have been developed based on magnetic resonance imaging (MRI), allowing dosimetric assessment of a multitude of configurations. Furthermore, the psSAR values in SAM from numerical simulations and measurements have been reported for mobile phones of various shapes operating in diverse frequency bands. However, experimental validation of the findings related to child head models is not available. The aim of this study is to evaluate experimentally the psSAR induced in the heads of 3- and 8-year-old children by mobile handsets, to validate the numerical models of the respective children’s heads and exposure scenarios as well as the SAR averaging schemes used by the numerical and experimental platforms, and finally to compare the psSAR results with measurements in the standardized SAM head model to evaluate the conservativeness of the latter.

4.3 Methods

4.3.1 Phantoms

Similar to the procedure used with the SAM phantom to prove mobile phone compliance described in IEEE 1528-2003 [9] and IEC 62209-2005 [7], two child head shells were built and filled with the standardized tissue simulating liquid (TSL) to perform SAR assessments. The MRI-based models of a three-year old (INDY) [98] and an eight-year-old (ISABELLA) were used to develop a 3-D CAD representation of the two head phantom shells. The skin/shell was segmented to a thickness of 2mm, corresponding to the shell thickness of SAM. The skin was smoothed and the pinna was removed (see Figure 4.1). Spacers were placed at the ear during the measurements to ensure compatibility of the phantoms with the description of the SAM from IEEE 1528-2003 and IEC 62209-2005, specifying a shell thickness of
6 mm at the ear. The half heads were finally extruded to reach a total depth greater than 15 cm in order to minimize the impact of the reflections from the TSL boundary to air. The head phantoms were manufactured using a generative laser-sintering process. Pictures of the final phantoms are shown in Figs. 4.2 to 4.4. Figure 4.1 and Table 4.1 show the profiles and main dimensions of the two child phantoms and the SAM phantom.

4.3.2 Transmitters and Position at the Heads

The three heads (INDY, ISABELLA, and SAM) were exposed to two generic mobile phones with monopole antennas and external feeds, one working at 900 MHz and the other one at 1800 MHz [99] (Figure 4.5(a)). Additionally, the Motorola Timeport T250 phone (Motorola, Schaumburg, USA) represented on Figure 4.5(b) was used in the GSM900 and GSM1800 bands. The complex structure of this phone was modeled using metallic and dielectric parts. The validation of this particular numerical model is described in more details in [85] and the impedance of the source extracted here from a free-space

---

1 Depending on the nature of the elements, their conductivities have been set to values between 0.003 and 0.7 S/m and their relative permittivities between 2.5 and 4.5.
Table 4.1: Dimensions of the experimental head phantoms.

<table>
<thead>
<tr>
<th>Dimensions (mm)</th>
<th>INDY 3yo</th>
<th>ISABELLA 8yo</th>
<th>SAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: height of the head</td>
<td>198</td>
<td>198</td>
<td>246</td>
</tr>
<tr>
<td>2: stoma – vertex</td>
<td>161</td>
<td>156</td>
<td>210</td>
</tr>
<tr>
<td>3: eye – vertex</td>
<td>110</td>
<td>104</td>
<td>123</td>
</tr>
<tr>
<td>4: length of the head</td>
<td>193</td>
<td>179</td>
<td>213</td>
</tr>
</tbody>
</table>

Figure 4.2: Picture of the outside (left) and inside (right) of the physical phantom of INDY.

configuration (25 Ω−92 j Ω and 43 Ω+16 j Ω at GSM900 and GSM1800, respectively) compare well with the values reported in [85] for measurements and simulations.

The phones were positioned according to the procedure described in [84]. The psSAR from the mobile phones was experimentally and numerically assessed at the right hand side of the heads for the phones placed in the standard touch and tilt positions (IEEE 1528-2003,
CHAPTER 4. SAR IN CHILD HEAD PHANTOMS

Figure 4.3: Picture of the outside (left) and inside (right) of the physical phantom of ISABELLA.

Figure 4.4: Picture of the outside (left) and inside (right) of the physical phantom of SAM.
4.3. METHODS

(a) Generic Phone 1800MHz
(b) Motorola T250

Figure 4.5: Mobile phones used in this study: plastic shell from front (left), highlighted metallic structures from front (center), and highlighted metallic structures from side (right). The 900 MHz version of the generic phone is obtained by using at antenna twice as long.

IEC 62209-2005) as shown in Figure 4.6. The head phantoms were filled with the standard TSL compliant with IEC 62209-2005 (see Table 4.2).

4.3.3 Experimental Evaluation

The dosimetric measurements were performed using the DASY5 (SPEAG, Switzerland) dosimetric assessment system, which is the successor of the system described in [100]. The forward power of the generic phones was set to 0.25 W and the T250 was operated at the maximum power in each band, i.e. at PCL5 (peak power of 2 W) for GSM900 and at PCL0 (peak power of 1 W) for GSM1800.

The uncertainty associated with the experimental assessment of the psSAR was evaluated according to the procedure described in
Table 4.2: Dielectric properties of the tissue simulating liquid used for the numerical and experimental assessments (with uncertainty at $k = 1$).

<table>
<thead>
<tr>
<th>Frequency MHz</th>
<th>Simulations $\epsilon_r$</th>
<th>Simulations $\sigma$</th>
<th>Measurements $\epsilon_r$</th>
<th>Measurements $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic phones</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>900</td>
<td>41.5</td>
<td>0.97</td>
<td>40.2 ± 4.3 %</td>
<td>0.97 ± 4.3 %</td>
</tr>
<tr>
<td>1800</td>
<td>40.0</td>
<td>1.4</td>
<td>38.5 ± 4.3 %</td>
<td>1.33 ± 4.3 %</td>
</tr>
<tr>
<td>Motorola T250</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>902.4</td>
<td>41.5</td>
<td>0.97</td>
<td>40.2 ± 4.3 %</td>
<td>0.97 ± 4.3 %</td>
</tr>
<tr>
<td>1747.4</td>
<td>40.0</td>
<td>1.4</td>
<td>38.8 ± 4.3 %</td>
<td>1.33 ± 4.3 %</td>
</tr>
</tbody>
</table>

IEEE1528-2003 and IEC62209-2005, taking into account contributions from the measurement equipment, the mechanical constraints, the physical parameters, and the post-processing (see Table 4.3). The analysis led to an expanded standard uncertainty ($k = 2$) of 22.1% and 21.6% for the 1g and 10g psSAR, respectively.

### 4.3.4 Numerical Evaluation

For all simulations, the finite-difference time-domain (FDTD) solver of the in-house simulation platform SEMCAD X (jointly developed by the IT’IS Foundation and Schmid & Partner Engineering AG, Zürich and commercialized by the latter) was used. The code has been widely validated in the context of applications ranging from mobile communication devices \[101,102\] to medical resonance imaging \[103,104\].

The absorbing boundaries were set to 11 uniaxial perfectly matched layers. The computational domain was discretized with a resolution of 1 mm in the liquid, 0.5 mm or lower in the phone, 0.5 mm in the region of the liquid close to the phone, and a maximum of $\lambda/10$ in free-space. 25 periods were sufficient to reach steady state.
Table 4.3: Uncertainty contributions to the measurements performed with DASY5 according to IEEE 1528-2003 and IEC 62209-2005. Each source of uncertainty is evaluated independently using a normal (N) or rectangular (R) distribution. The uncertainty analysis is valid for frequencies between 300 MHz and 3 GHz.

<table>
<thead>
<tr>
<th>Error Description</th>
<th>SAR Unc. 1g, 10g</th>
<th>Prob. dist.</th>
<th>Div. 1g 10g</th>
<th>c_i 1g 10g</th>
<th>SAR Std. Unc. 1g 10g</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measurement Equipment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probe Calibration</td>
<td>±6.6%</td>
<td>N</td>
<td>1 1 1</td>
<td>±6.6%</td>
<td>±6.6%</td>
</tr>
<tr>
<td>Axial Isotropy</td>
<td>±4.7%</td>
<td>R</td>
<td>√3 1 1</td>
<td>±2.7%</td>
<td>±2.7%</td>
</tr>
<tr>
<td>Hemispherical Isotropy</td>
<td>±9.6%</td>
<td>R</td>
<td>√3 0 0</td>
<td>±0.0%</td>
<td>±0.0%</td>
</tr>
<tr>
<td>Boundary Effects</td>
<td>±1.0%</td>
<td>R</td>
<td>√3 1 1</td>
<td>±0.6%</td>
<td>±0.6%</td>
</tr>
<tr>
<td>Linearity</td>
<td>±4.7%</td>
<td>R</td>
<td>√3 1 1</td>
<td>±2.7%</td>
<td>±2.7%</td>
</tr>
<tr>
<td>System Detection Limits</td>
<td>±1.0%</td>
<td>R</td>
<td>√3 1 1</td>
<td>±0.6%</td>
<td>±0.6%</td>
</tr>
<tr>
<td>Readout Electronics</td>
<td>±0.3%</td>
<td>N</td>
<td>1 1 1</td>
<td>±0.3%</td>
<td>±0.3%</td>
</tr>
<tr>
<td>Response Time</td>
<td>±0.0%</td>
<td>R</td>
<td>√3 1 1</td>
<td>±0.0%</td>
<td>±0.0%</td>
</tr>
<tr>
<td>Integration Time</td>
<td>±0.0%</td>
<td>R</td>
<td>√3 1 1</td>
<td>±0.0%</td>
<td>±0.0%</td>
</tr>
<tr>
<td>RF Ambient Noise</td>
<td>±1.0%</td>
<td>R</td>
<td>√3 1 1</td>
<td>±0.6%</td>
<td>±0.6%</td>
</tr>
<tr>
<td>RF Ambient Reflections</td>
<td>±1.0%</td>
<td>R</td>
<td>√3 1 1</td>
<td>±0.6%</td>
<td>±0.6%</td>
</tr>
<tr>
<td>Probe Positioner</td>
<td>±0.8%</td>
<td>R</td>
<td>√3 1 1</td>
<td>±0.5%</td>
<td>±0.5%</td>
</tr>
<tr>
<td>Probe Positioning</td>
<td>±6.7%</td>
<td>R</td>
<td>√3 1 1</td>
<td>±3.9%</td>
<td>±3.9%</td>
</tr>
<tr>
<td>Max. SAR Eval.</td>
<td>±2.0%</td>
<td>R</td>
<td>√3 1 1</td>
<td>±1.2%</td>
<td>±1.2%</td>
</tr>
<tr>
<td><strong>Test Sample</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Device Positioning</td>
<td>±2.9%</td>
<td>N</td>
<td>1 1 1</td>
<td>±2.9%</td>
<td>±2.9%</td>
</tr>
<tr>
<td>Device Holder</td>
<td>±3.6%</td>
<td>N</td>
<td>1 1 1</td>
<td>±3.6%</td>
<td>±3.6%</td>
</tr>
<tr>
<td>Power Drift</td>
<td>±5.0%</td>
<td>R</td>
<td>√3 1 1</td>
<td>±2.9%</td>
<td>±2.9%</td>
</tr>
<tr>
<td><strong>Phantom and Setup</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phantom Uncertainty</td>
<td>±4.0%</td>
<td>R</td>
<td>√3 1 1</td>
<td>±2.3%</td>
<td>±2.3%</td>
</tr>
<tr>
<td>Liquid Conductivity (target)</td>
<td>±5.0%</td>
<td>R</td>
<td>√3 0.6 0.4</td>
<td>±1.8%</td>
<td>±1.2%</td>
</tr>
<tr>
<td>Liquid Conductivity (meas.)</td>
<td>±4.3%</td>
<td>R</td>
<td>√3 0.6 0.4</td>
<td>±1.6%</td>
<td>±1.1%</td>
</tr>
<tr>
<td>Liquid Permittivity (target)</td>
<td>±5.0%</td>
<td>R</td>
<td>√3 0.6 0.5</td>
<td>±1.7%</td>
<td>±1.4%</td>
</tr>
<tr>
<td>Liquid Permittivity (meas.)</td>
<td>±4.3%</td>
<td>R</td>
<td>√3 0.6 0.5</td>
<td>±1.5%</td>
<td>±1.2%</td>
</tr>
<tr>
<td><strong>Combined Standard Uncertainty</strong> (k = 1)</td>
<td>±11.0%</td>
<td>±10.8%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Expanded Standard Uncertainty</strong> (k = 2)</td>
<td>±22.1%</td>
<td>±21.6%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The uncertainty analysis was performed with the configuration of ISABELLA exposed to the generic phone at 1800 MHz. It included the effects of the absorbing boundary conditions (ABC) by extending the computational domain by 140 mm in each direction and the deviations from steady state by running the simulation 10 periods longer. The influence of these parameters on the 1 g and 10 g psSAR was negligible compared to the influence of the discretization. Using two additional discretizations (one twice as big, the other twice as low), the worst-case deviations of SAR were extracted and associated with a normal distribution. Table 4.4 shows that the expanded standard uncertainty of the numerical assessment of the 1 g and 10 g psSAR is 9.0 % and 5.5 %, respectively.

The normalization of the simulation results to the adequate power was obtained by controlling the reflected power at the source, similar to the procedure described in [85].

4.3.5 SAR Averaging

Localized exposure such as mobile phone exposure is typically limited by the psSAR averaged over a mass of 1 g or 10 g. For example, the
Figure 4.7: Picture of the measurement system DASY5 with the right-hand side of the SAM phantom exposed to a mobile phone in the tilt position.

Table 4.4: Uncertainty contributions to the numerical modeling due to the absorbing boundary conditions (ABC), deviations from steady state, and model discretization.

<table>
<thead>
<tr>
<th>Error Description</th>
<th>SAR Unc.</th>
<th>Prob. dist.</th>
<th>Div.</th>
<th>$c_i$</th>
<th>SAR Std. Unc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABC</td>
<td>±0.0%</td>
<td>±0.0%</td>
<td>R</td>
<td>$\sqrt{3}$</td>
<td>1</td>
</tr>
<tr>
<td>Deviation steady state</td>
<td>±0.0%</td>
<td>±0.0%</td>
<td>R</td>
<td>$\sqrt{3}$</td>
<td>1</td>
</tr>
<tr>
<td>Discretization</td>
<td>±4.5%</td>
<td>±2.8%</td>
<td>R</td>
<td>$\sqrt{3}$</td>
<td>1</td>
</tr>
<tr>
<td>Combined Standard Uncertainty $(k = 1)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>±4.5% ±2.7%</td>
</tr>
<tr>
<td><strong>Expanded Standard Uncertainty $(k = 2)$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>±9.0% ±5.5%</td>
</tr>
</tbody>
</table>
ICNIRP [2] defines a limit on the psSAR averaged over any 10 g of *contiguous* tissue. On the other hand, the IEEE (in ANSI C95.1-1999 [90] and IEEE C95.1-2005 [6]) defines the limit on the psSAR averaged over any *cube* of a 1 g and 10 g mass. The IEEE has also published a standard [105] (IEEE C95.3-2002) describing how to assess the cube average in an attempt to achieve reproducible results in the case of anatomical bodies. The cube, however, has severe shortcomings:

- it lacks any physical rational;
- the results depend on its orientation.

A sphere-like definition, for instance, would eliminate the above limitations.

The implementations in SEMCAD X and DASY5 are compliant with IEEE C95.3-2002 and IEEE 1528-2003, respectively. The latter has been defined such that it determines the most conservative cube with the z-axis normal to the surface of the phantom and the x-y-faces conforming to the surface of the phantom. This results in the actual psSAR for homogenous phantoms with locally smoothed surfaces.

Measurement and simulation results are usually only compared using the SAM phantom, as it is the only one available. But the curvature of this phantom at the location of the handset exposure is rather uniform and does not present abrupt changes. However, the main difference in the definitions from IEEE 1528-2003 and IEEE C95.3-2002 is their conformal or non-conformal nature. Eventual issues arising from this difference might not be obvious with the SAM phantom, but might take more importance when using another phantom. For the first time, this study brings a comparison of those widely used averaging definitions with other models than the SAM phantom.

The discrepancy between the two averaging procedures, and in particular the overestimation resulting from a cube whose orientation depends on the computation grid, is investigated here by applying the psSAR definition from IEEE 1528-2003 and IEEE C95.3-2002 to the same sets of simulation results (Section 4.4.3).
4.4 Results

4.4.1 Conservativeness of the SAM Head Phantom

Figures 4.8 and 4.9 show the measured 1g and 10g psSAR, respectively, for all the positions and head phantoms in the two frequency bands for the generic phones (a) and the Motorola T250 phone (b). The results obtained for homogeneous heads show that, for most cases, the worst-case of SAM for each phone is a conservative assessment of the 1g and 10g psSAR, e.g. 1800 MHz tilt for the generic phone in Figure 4.8(a) and 900 MHz touch for the T250 in Figs. 4.8(b) and 4.9(b). In Figure 4.9(a), the worst-case psSAR corresponds to the 1800 MHz tilt configuration, where the 10g in ISABELLA is about 1% higher than in SAM, a negligible variation compared to the expanded uncertainty of about 20%.

Table 4.1 shows that the dimensions of the two child phantoms are very similar, but Figures 4.8 and 4.9 show that the deviation between the psSAR from INDY and ISABELLA is significant. The psSAR value is rather influenced by the shape of the phantom than by its size.
Figure 4.9: Experimental 10 g psSAR from the exposure to the generic phones (top, operated at 0.25 W) and Motorola T250 (bottom, operated at the maximum power in each band). The error bars represent the expanded standard uncertainty (\(k=2\)) from the measurements.

### 4.4.2 Validation of the Numerical Models

Prior to comparing the implementation of the SAR averaging from DASY5 and SEMCAD X, the numerical models have to be validated with the experimental setup (using the same averaging technique in both cases). Figures 4.10 and 4.11 show the experimental and numerical 1g and 10g psSAR, respectively, for all the positions and head phantoms in the two frequency bands for the generic phones (a) and the Motorola T250 phone (b). For all cases, the reported psSAR is compliant to the definition from IEEE1528-2003, which can also be regarded as a cube with a minimum air content.

The deviation between the 1g and 10 g psSAR from the simulations and measurements of the homogeneous heads is at most 30%, but typically lower than 20%. The inter-head variability of the 1g and 10 g psSAR (averaged according to IEEE1528-2003) shown here is similar to that reported by [84] from simulations of 14 anatomical heads (averaged according to IEEE C95.3-2002), i.e. typically lower than 25%.

As an example of the absorption pattern in a homogeneous head, Figure 4.12 shows a slice of the numerical local SAR distribution in
Figure 4.10: Experimental and numerical $1g$ psSAR from the exposure to the generic phones (top, operated at 0.25 W) and Motorola T250 (bottom, operated at the maximum power in each band). The error bars represent the expanded standard uncertainty ($k=2$) from the numerical and experimental assessments.

Figure 4.11: Experimental and numerical $10g$ psSAR from the exposure to the generic phones (top, operated at 0.25 W) and Motorola T250 (bottom, operated at the maximum power in each band). The error bars represent the expanded standard uncertainty ($k=2$) from the numerical and experimental assessments.
Figure 4.12: Local SAR distribution in ISABELLA in the plane containing the mouth and ear canal points as well as the center of the phone. Exposure to the generic phone at 900 MHz (top) and 1800 MHz (bottom) in the touch position. 0 dB corresponds to 5 W/kg at 0.25 W.

ISABELLA exposed to the generic phone in the touch position at 900 MHz and 1800 MHz.

4.4.3 SAR Averaging Implementation

As described in Section 4.3.5, the requirements of the cube in the SAR averaging definition from IEEE1528-2003 and IEEE C95.3-2002 are divergent. The psSAR coming from those two implementations are compared here by investigating the following exposure scenarios: INDY with the generic phone at 900 MHz in touch and tilt positions (Figure 4.13). As already stated in Section 4.4.2, the implementation of IEEE1528-2003 applied to the experimental and numerical results...
(white and light-gray bars, respectively) is within the expanded standard uncertainty. However, the averaging implementation according to IEEE 1528-2003 and IEEE C95.3-2002 (light- and dark-gray bars, respectively) applied to the same numerical results can lead to a discrepancy of 1.6 dB and 1.3 dB for the 1 g and 10 g psSAR, respectively. As these figures are based on one particular case, it cannot be ruled out that larger deviations could occur for other configurations. As shown in Figure 4.14 for the touch position, the observed discrepancies are due to the larger air content and, incidentally, the greater cross-section of the cube used for the averaging based on IEEE C95.3-2002 (black vertices) compared to IEEE 1528-2003 (white vertices).

As FDTD simulations require a rectilinear discretization, the alignment of the grid is normally set according to the radiating structure, for example, the mobile phone antenna. Consequently, the orientation of the phantom is arbitrary, based on the positioning relative to the phone. An averaging technique which is dependent on the orientation of the phantom in the grid is bound to be unsuitable for achieving reproducible results. An implementation of the averaging based on a cubical volume should require, for each location, a rotation of the cube, searching for the maximum averaged SAR for the smallest amount of air in the cube. However, as the averaging in a cube is not based on any physical rational, a sphere-like definition that is intrinsically independent of its orientation could, for instance, be more suitable.

4.5 Conclusions

The aims of this study were to (1) examine the conservativeness of the SAM head used in mobile phone compliance testing with respect to homogeneous head models of 3- and 8-year-old children and (2) assess the influence of the variations in the averaging definitions from IEEE 1528-2003 and IEEE C95.3-2002 for the determination of the psSAR as implemented in experimental systems (such as DASY5) and numerical platforms (such as SEMCAD X).

Comparing the experimental results from the various exposure scenarios examined, the study has shown that although particular
Figure 4.13: Experimental and numerical 1 g and 10 g psSAR of INDY exposed to the generic phone at 900 MHz in the touch and tilt position. For the numerical results, the psSAR in an averaging cube aligned with the phantom’s surface IEEE 1528-2003 and aligned with the grid IEEE C95.3-2002 are shown. The error bars represent the expanded standard uncertainty ($k=2$) from the numerical and experimental assessments.

Figure 4.14: Cross-section of the INDY phantom exposed to the 900-MHz generic phone in the touch position. The vertices of the psSAR cubes from IEEE C95.3-2002 (black) are aligned with the axes of the phone, whereas the cubes from IEEE 1528-2003 (white) are positioned normal to the shell of the phantom.
configurations lead to a psSAR higher in the studied child head phantoms than in the SAM head, the latter is always conservative when the worst-case configuration of each phone is considered. The variability of the psSAR between the homogeneous head models has been found similar to that previously reported in the literature for simulations of the exposure of anatomical heads to mobile phones in the 900 and 1800 MHz bands.

Based on the numerical results, the comparison of an implementation where the cube is aligned parallel to the computational grid IEEE C95.3-2002 with an implementation where the cube is parallel to the phantom’s shell IEEE 1528-2003 showed that the discrepancy can be larger than 1.3 dB, but could reach higher values for other configurations. This clearly points out one of the shortcomings of the cube as an averaging volume dependent on the orientation of the phantom in the computational grid based on IEEE C95.3-2002, and demands a definition that yields reproducible results, for instance as an extension of the cubical definition where the cube can be rotated in space, searching for the highest average SAR with minimum air content. Alternatively, a volume definition that is orientation-independent and has more physical meaning could be used, e.g. a sphere.

Further work should focus on the elaboration of a new averaging definition that allows reproducible results, not only at the surface of the phantom but also when considering anatomical whole-body phantoms, at the fingers, joints, or locations including internal air.
Chapter 5

Experimental and Numerical Assessment of Low-Frequency Current Distributions from UMTS and GSM Mobile Phones

5.1 Abstract

The evaluation of the exposure from mobile communication devices requires consideration of electromagnetic fields (EMF) over a broad frequency range from DC to GHz. Mobile phones in operation have prominent spectral components in the low-frequency (LF) and radio-frequency (RF) ranges. While the exposure to RF fields from mobile phones has been comprehensively assessed in the past, the LF fields...
have received much less attention. In this study, LF fields from mobile phones are assessed experimentally and numerically for the GSM and UMTS communication systems and conclusions about the global (LF and RF) EMF exposure from both systems are drawn. From the measurements of the time-domain magnetic fields, it was found that the contribution from the audio signal at a normal speech level, i.e., $-16 \text{dBm}$, is the same order of magnitude as the fields induced by the current bursts generated from the implementation of the GSM communication system at maximum RF output level. The B-field induced by currents in phones using the UMTS system is two orders of magnitude lower than that induced by GSM. Knowing that the RF exposure from UMTS is also 2 orders of magnitude lower than from GSM, it is now possible to state that there is an overall reduction of the exposure from this communication system.

5.2 Introduction

Over the past two decades, numerous scientists have investigated the possible effects of electromagnetic fields (EMF) on humans. Studies have been conducted to identify potential biological effects due to exposure to weak EMF over a broad frequency range covering extremely low frequencies (ELF) to radio frequencies. Although there are various findings of biological effects reported in the low-frequency (LF) and radio-frequency (RF) ranges, a concrete mechanism has not yet been established. Thus, the effects from any particular frequency range cannot be disregarded when assessing the exposure to complex transmitters such as mobile phones, which generate fields in various frequency ranges (LF and RF).

Currently, mobile phones operated at the human head are considered the strongest source of human exposure to RF EMF, i.e., worst-case exposure can approach the established safety limits. Over the past decade, the majority of exposure assessment studies have focused on exposure to the strong RF EMF generated by phone antennas operating at frequencies between 400 MHz and 3 GHz. However, LF EMF, i.e., lower than 20 kHz, are also generated by other elements of the phone, e.g., by the supply currents or the audio speaker. There are
considerably fewer studies that address the characterization of exposure to these fields from mobile phones used in the normal operating mode, i.e., at the head.

While there are a very limited number of studies that have assessed LF exposure from mobile phones using Global System for Mobile Communications (GSM) experimentally \[107\]-\[110\] and numerically \[111\]-\[113\], there is no data at all in the literature on LF exposure from phones using the Universal Mobile Telecommunications System (UMTS) communication system. Despite this, UMTS technologies are becoming more and more common as GSM technology is slowly being phased out. Characterization of the RF output power of UMTS phones has shown that the average exposure to RF EMF of this communication is smaller than that of GSM by more than a factor of 100 \[114\]. Nevertheless, a recommendation for this technology cannot be made until evaluation of the LF exposure, which has the potential to be higher than that of GSM due to the higher current consumption of UMTS\(^1\) signal processors, has been completed.

The objective of this study is to close the gap in the knowledge of the LF exposure from mobile phones using GSM and UMTS networks. In detail, that includes:

- experimental assessment of the B-fields from mobile phones in GSM900, GSM1800, and UMTS1950 bands, and
- evaluation of the compliance with safety guidelines/standards based on induced fields and current density in anatomical heads.

5.3 Methods

5.3.1 Communication Systems

Communication channel separation in GSM \[115\] is implemented with time division multiple access (TDMA), which results in transmission bursts. Dominant supply currents are drawn in bursts with frequency components at 217 Hz (frame frequency) and 8.3 Hz (1/26 missing

\(^1\)Here, the term UMTS is be used to refer to UMTS frequency-division duplexing (UMTS-FDD), which is more frequently employed than UMTS time-division duplexing (UMTS-TDD), mainly used for data transfer.
frame). Wideband code division multiple access (W-CDMA) is used to separate the communication channels in UMTS. Since the transmission with the base station is quasi-continuous, the current from the battery is not drawn in bursts. Both communication systems might exhibit additional weak low-frequency spectral components due to power control contributions at $<2\,\text{Hz}$ for GSM as well as 750 Hz and 1500 Hz for UMTS.

### 5.3.2 Experimental Setup

**Equipment**

The measurements were performed with the dosimetric assessment system DASY 52 NEO (Schmid&Partners Engineering AG, SPEAG, Switzerland) (Table 5.1). The small probe size of this system allows measurements to be performed very close to the phones’ surfaces, which is not possible with the large probes used in previous studies. The Python interface implemented in the DASY 52 NEO software allowed flexible integration of the time-domain measurements into the software. The communication link from the phone was established and controlled with a radio communication tester (Rohde & Schwarz CMU200).

**Exposure Scenarios**

Table 5.2 shows the main characteristics of the 10 selected devices under test. The measurement planes were defined as parallel to the surface at a distance of 1 mm from the probe tip at the highest phone location, leading to a minimum distance of 4 mm between the sensor and the phone surface.

Area scans were performed with a resolution of $5 \times 7\,\text{mm}^2$ over the entire area of the phone. A higher-resolution scan ($3 \times 3\,\text{mm}^2$) was performed around the audio output with the audio signal turned on. The B-field decay from the phone surface was assessed by performing a 1D scan with a resolution of 1 mm perpendicular to the phone surface at one location on the front side of the phone. For all measurements, the microphone was turned off to prevent pick-up of sounds in the vicinity of the microphone.
Figure 5.1: Left: DASY52 NEO scanner with B-field probe. Right: LF B-field probe at a distance of 1 mm from the mobile phone surface (LG Optimum 3D P920).
Some measurements were performed using multiple RF power control levels (PCL) (see Table 5.3) to allow discrimination of the LF B-fields related to the communication system from other consumers. On the other hand, the influence of the power control in real networks and environments as well as the usage of discontinuous transmission (DTX) were not assessed in this study.

The following configurations were measured for each DUT in the GSM900, GSM1800, and UMTS bands:

- at highest PCL, i.e., 0 dB, with audio on: area scans (front, back, speaker);

- at PCL = –6 dB with audio off: area scan (front)

---

2 for devices of power class 3

3 Although the specifications of the Motorola V1050 phone include UMTS, the connection in this band was very unstable and did not allow complete measurement; similar behavior was observed for GSM900 and GSM1800 at lower PCLs.

4 For the slide and flip phones, only the surface of the phone on which the highest fields were measured, i.e., the bottom part close to the battery, was monitored at the lower power level.
### Table 5.2: Main characteristics of the DUTs.

<table>
<thead>
<tr>
<th>ID</th>
<th>Phone Model</th>
<th>Type</th>
<th>OS</th>
<th>Release Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nokia6120</td>
<td>Nokia 6120</td>
<td>bar</td>
<td></td>
<td>April 2007</td>
</tr>
<tr>
<td>SonyEricssonW910</td>
<td>Sony Ericsson W910i</td>
<td>slide</td>
<td></td>
<td>Oct 2007</td>
</tr>
<tr>
<td>SonyEricssonW760i</td>
<td>Sony Ericsson W760i</td>
<td>slide</td>
<td></td>
<td>May 2008</td>
</tr>
<tr>
<td>MotorolaV1050</td>
<td>Motorola V1050</td>
<td>flip</td>
<td></td>
<td>January 2005</td>
</tr>
<tr>
<td>HTCdiam100</td>
<td>HTC Diam100 Touch Diamond</td>
<td>smart</td>
<td>Windows Phone</td>
<td>May 2008</td>
</tr>
<tr>
<td>HTCtopa100</td>
<td>HTC Topa100 Touch Diamond2</td>
<td>smart</td>
<td>Windows Phone</td>
<td>April 2009</td>
</tr>
<tr>
<td>iPhone3g</td>
<td>Apple iPhone 3g</td>
<td>smart</td>
<td>iOS</td>
<td>July 2008</td>
</tr>
<tr>
<td>iPhone4</td>
<td>Apple iPhone 4</td>
<td>smart</td>
<td>iOS</td>
<td>June 2010</td>
</tr>
<tr>
<td>SamsungGT-I9001</td>
<td>Samsung Galaxy GT-I9001</td>
<td>smart</td>
<td>Android</td>
<td>June 2010</td>
</tr>
<tr>
<td>LG</td>
<td>LG P920 Optimus 3D</td>
<td>smart</td>
<td>Android</td>
<td>July 2011</td>
</tr>
</tbody>
</table>
Table 5.3: Power Control Levels (PCL) and corresponding typical average RF power for each communication system.

<table>
<thead>
<tr>
<th>Communication system</th>
<th>0 dB</th>
<th>-6 dB</th>
<th>-12 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PCL</td>
<td>mW</td>
<td>PCL</td>
</tr>
<tr>
<td>GSM900</td>
<td>PCL5</td>
<td>250</td>
<td>PCL8</td>
</tr>
<tr>
<td>GSM1800</td>
<td>PCL0</td>
<td>125</td>
<td>PCL3</td>
</tr>
<tr>
<td>UMTS</td>
<td></td>
<td>~250</td>
<td></td>
</tr>
</tbody>
</table>

- at PCLs = 0, −6, −12 dB:
  - audio off: z-scan, e.g., perpendicular to the phone surface (front, one location);
  - audio on: area scan (speaker), limited to 4 DUT;
  - audio on: z-scan (speaker, one location), limited to 4 DUT.

For audio on measurement configurations, a 1 kHz audio signal was transmitted from the AMMI to the CMU200 and then to the phone speaker via the radio interface. The audio signal was set at a normal speech level for GSM and UMTS, i.e., −16 dBm [120].

**Uncertainty Budget**

The uncertainty budget of the measurement system was determined according to [120] (see Table 5.4). The calibration of the probe was performed using a Helmholtz coil (AMCC, SPEAG, Switzerland).

**Frequency Range**

The measurement setup characterization has shown that currents are induced in the coil sensor by vibrations when placed next to a permanent magnet, resulting in parasitic spectral components in the range 20 Hz – 60 Hz with levels up to 1 µT, the same order of magnitude as the fields measured close to the phones’ surfaces. As several permanent magnets can be found in mobile phones, e.g., at the speaker, to hold a pen, in the sliding mechanism, etc., the spectra were filtered to cut off frequencies below 60 Hz.
Table 5.4: Uncertainty budget of the magnetic field measurements.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Probe Sensitivity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference Voltage at AMMI Output</td>
<td>±3.0%</td>
<td>N</td>
<td>1</td>
<td>±3.0%</td>
</tr>
<tr>
<td>AMCC Geometry</td>
<td>±0.4%</td>
<td>R</td>
<td>√3</td>
<td>±0.2%</td>
</tr>
<tr>
<td>AMCC Current</td>
<td>±1.0%</td>
<td>R</td>
<td>√3</td>
<td>±0.6%</td>
</tr>
<tr>
<td>Probe Positioning during Calibration</td>
<td>±0.07%</td>
<td>R</td>
<td>√3</td>
<td>±0.04%</td>
</tr>
<tr>
<td>Noise Contribution</td>
<td>±0.7%</td>
<td>R</td>
<td>√3</td>
<td>±0.4%</td>
</tr>
<tr>
<td><strong>Probe System</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repeatability / Drift</td>
<td>±1.0%</td>
<td>R</td>
<td>√3</td>
<td>±0.6%</td>
</tr>
<tr>
<td>Linearity / Dynamic Range</td>
<td>±0.6%</td>
<td>R</td>
<td>√3</td>
<td>±0.3%</td>
</tr>
<tr>
<td>Probe Angle</td>
<td>±2.3%</td>
<td>R</td>
<td>√3</td>
<td>±1.3%</td>
</tr>
<tr>
<td>Field Disturbance</td>
<td>±0.2%</td>
<td>R</td>
<td>√3</td>
<td>±0.1%</td>
</tr>
<tr>
<td><strong>Positioning</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probe Positioning</td>
<td>±1.9%</td>
<td>R</td>
<td>√3</td>
<td>±1.1%</td>
</tr>
<tr>
<td>DUT Positioning</td>
<td>±8.3%</td>
<td>R</td>
<td>√3</td>
<td>±4.8%</td>
</tr>
<tr>
<td><strong>Combined Uncertainty</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined Std. Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td>±6.0%</td>
</tr>
<tr>
<td>Expanded Std. Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td>±12.0%</td>
</tr>
</tbody>
</table>
CHAPTER 5. LOW-FREQUENCY EXPOSURE

Detection Limit

The response of the probe leads to a frequency-dependent detection limit. The sensitivity was assessed in the actual setup as well as with a mu-metal shielding (see Figure 5.2). The detection limit was approximated by two linear functions (lower and higher than 80 Hz); any measurement data lower than this limit was considered as noise and was filtered out.

![Detection limit](image)

Figure 5.2: Detection limit of the measurement system with and without shielding from the ambient fields, mu-metal and free-space measurements, respectively.

5.3.3 Numerical Assessment

LF Numerical Solver

The LF currents induced in the human body by magnetic fields were analyzed with the Biot-Savart solver and the finite-element method implemented in SEMCAD X 14.8 [21]. Unlike typical finite-element methods, this implementation operates on rectilinear meshes, like the finite-difference time-domain (FDTD) method, allowing complex anatomical models to be easily rendered at various geometrical resolutions.
It is important to note that, when using the Biot-Savart quasi-static approximation, only the conductivity of the tissues needs to be specified. The E-field distribution of a simulation at a specific frequency $f_0$ can be scaled to another frequency ($f/f_0$), assuming that the conductivity contrasts between the tissues at $f$ and $f_0$ are similar.

**Anatomical Heads**

The numerical evaluations were conducted on the four anatomical heads from the Virtual Family [12] (Figure 5.3) developed and distributed by IT’IS (www.itis.ethz.ch/vip): Duke (34-year-old male), Ella (26-year-old female), Billie (11-year-old girl), and Thelonious (6-year-old boy).

![Figure 5.3: Anatomical head models from the Virtual Family: Duke, Ella, Billie, and Thelonious.](image)

For exposure to RF EMF, the dielectric properties of the tissues are typically assigned based on the 4-terms cole-cole fit of broadband measurement data presented by Gabriel et al. [65,122]. However, for frequencies lower than 1 MHz, these values are associated with a large uncertainty.

The tissue properties used in this project are taken from the compilation available online at www.itis.ethz.ch/database [123] and based on conductivity values from the literature review of [124] for frequencies up to 120 Hz (for more details, consult the documentation available online). For tissues for which no LF measurement was available, values from the 4-terms cole-cole fit were used.
The conductivity of skin at low frequency is problematic. For segmented models, in particular those of the Virtual Population, a homogeneous skin with a thickness of 2 mm – 4 mm is modeled. Reported LF conductivities of the skin often take only the outermost layer into consideration, the *stratum corneum*, which is ca. 0.1 mm thick and mainly made of dead cells ($1 \times 10^{-4}$ S/m). The uncertainty on this value is very high, particularly because it is highly dependent on the degree of moisture; reported values for wet skin in the LF range reach $2 \times 10^{-3}$ S/m. These very low values of conductivity result in high and very localized induced fields, the volume of which is overestimated due to the homogeneous skin layer of the anatomical models. Additionally, the nerve endings do not reach the *stratum corneum* and the ICNIRP limits at low frequencies are based on nerve stimulation. Thus, a value of skin conductivity based on a weighted average of its deeper layers (mainly muscles, fat, and blood), i.e., $1 \times 10^{-1}$ S/m, as suggested by [24], is more realistic and was used in this study.

**Exposure Scenarios**

The numerical sources were placed on the left side of the heads according to the procedure described in [84]. For the loop source that is used to model the fields from the communication system and the audio speaker, the uncertainty regarding the location of the maxima on the phone was taken into account by translating the sources by ±10 mm in the plane of the phone, leading to a $3 \times 3$ exposure matrix.

**5.3.4 Compliance with Guidelines and Standards**

The exposure to non-ionizing radiation is regulated in most countries by guidelines developed either by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) or the Institute of Electrical and Electronics Engineers (IEEE). The ICNIRP 1998 guidelines (ICNIRP-1998) cover frequencies from DC up to 300 GHz, whereas the 2010 guidelines (ICNIRP-2010) are specific for low frequency EMF (1 Hz to 100 kHz). As both guidelines are presently in force,

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5 The symmetry of the head and the exposure source allows us to assume similar results for exposure on the right side, as was already confirmed by [66,75].
5.3. METHODS

research groups interested in LF exposure usually compare compliance to both, as we also do here. The IEEE has published a safety standard for exposure to EMF at frequencies up to 3 kHz \(^5\) (IEEE C95.6-2002).

**Basic Restrictions**

In ICNIRP-1998, EMF up to 10 MHz are limited by the maximum current density in the head and trunk (see Table 5.5) to prevent effects on the nervous system, e.g., peripheral nerve stimulation and induction of phosphenes in the retina. The current density should be averaged over a cross-section of \(1 \text{ cm}^2\), \(\langle \mathbf{J} \rangle_{1 \text{ cm}^2}\). In the low-frequency guidelines ICNIRP-2010, the internal electric field averaged over a small contiguous tissue volume of \(2 \times 2 \times 2 \text{ mm}^3\), \(\langle \mathbf{E} \rangle_{8 \text{ mm}^3}\), is used as the basic restriction (Table 5.5). For each specific tissue, the guidelines specify that the 99th percentile value should be reported, an approach which has been criticized by several groups \(^{121, 126-128}\). The influence of the definition of each tissue on the 99th percentile value is particularly relevant for localized exposure such as here. Finally, IEEE C95.6-2002 defines basic restrictions in terms of the electric field averaged over a straight line segment of 5 mm length, \(\langle \mathbf{E} \rangle_{5 \text{ mm}}\). The implementation of these averaging schemes in SEMCAD X is described in \(^{121}\).

**Table 5.5:** ICNIRP 1998 and ICNIRP 2010 basic restrictions for general public exposure.

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>ICNIRP 1998</th>
<th>ICNIRP 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current density</td>
<td>Internal electric field</td>
</tr>
<tr>
<td></td>
<td>mA m(^{-2}) (rms)</td>
<td>V m(^{-1}) (rms)</td>
</tr>
<tr>
<td>head and trunk</td>
<td>CNS head</td>
<td>head and body</td>
</tr>
<tr>
<td>up to 1 Hz</td>
<td>8</td>
<td>–</td>
</tr>
<tr>
<td>1 Hz to 4 Hz</td>
<td>(8/f)</td>
<td>0.1/(f)</td>
</tr>
<tr>
<td>4 Hz to 10 Hz</td>
<td>2</td>
<td>0.1/(f)</td>
</tr>
<tr>
<td>10 Hz to 25 Hz</td>
<td>2</td>
<td>0.01</td>
</tr>
<tr>
<td>25 Hz to 1 kHz</td>
<td>2</td>
<td>(4 \times 10^{-4} f)</td>
</tr>
<tr>
<td>1 kHz to 3 kHz</td>
<td>(f/500)</td>
<td>0.4</td>
</tr>
<tr>
<td>3 kHz to 100 kHz</td>
<td>(f/500)</td>
<td>1.35 (\times 10^{-4} f)</td>
</tr>
<tr>
<td>100 kHz to 10 MHz</td>
<td>–</td>
<td>1.35 (\times 10^{-4} f)</td>
</tr>
</tbody>
</table>
CHAPTER 5. LOW-FREQUENCY EXPOSURE

Table 5.6: IEEE C95.6-2002 basic restrictions on the induced E-field, $E_i$, for general public exposure. $E_i = E_0$ for $f \leq f_e$; $E_i = E_0(f/f_e)$ for $f \geq f_e$.

<table>
<thead>
<tr>
<th>Exposed Tissue</th>
<th>$f_e$</th>
<th>$E_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>20</td>
<td>$5.89 \times 10^{-3}$</td>
</tr>
<tr>
<td>Heart</td>
<td>167</td>
<td>0.943</td>
</tr>
<tr>
<td>Hands, wrists, feet, and ankles</td>
<td>3350</td>
<td>2.10</td>
</tr>
<tr>
<td>Other tissue</td>
<td>3350</td>
<td>0.701</td>
</tr>
</tbody>
</table>

Complex Waveforms

The peak value of a time-domain signal cannot be directly compared to the safety limits, which are frequency dependent. A frequency-weighting technique for how to treat signals with frequency contents lower than 100 kHz has been published by the ICNIRP in 2003 [129] and allows assessment independent of signal characteristics. This approach has been applied in various contexts, either including a frequency-dependent phase shift [108,130], omitting it [131], or comparing both [132]. We do not consider this phase shift here, as the rationale for doing so is unconvincing.

The ICNIRP-2003 guidance suggests to use the basic restrictions to assess the conservativeness of the exposure, which is expressed in the original statement [2] in terms of current density. The time derivative of the magnetic flux density, $dB/dt$, can be derived from the current density $dB/dt = J/K_B$, where $K_B = 0.064 \text{ A m}^{-2} \text{s T}^{-1}$. At each measurement point, the time-domain signal is first transformed to the frequency domain, where the normalized weighting function derived from the ICNIRP guidelines, based on $B$ or $dB/dt$, is applied. The inverse Fourier transform (IFT) is then applied, and the weighted time-domain signal can be analyzed in terms of $B$ or $dB/dt$ and compared to the limits used for the normalization of the weighting function. This treatment ensures that when there is constructive addition of the spectral components, it is taken into account in the compliance
5.3. METHODS

analysis. Thus, the ratio to the considered limit, or compliance factor, $CF$, can be expressed as

$$CF_{\text{max}} = \max \left( \sum_{i=x,y,z} \left( \frac{d}{dt} \text{IFT} \left( \frac{B_{i}^{\text{meas}}(f)}{J_{\text{lim}}(f)} K_B \right) \right)^2, (5.1)$$

for consideration of the basic restrictions, i.e., the limit in terms of $J$ (or $dB/dt$).

The corner frequency used in the 2003 guidance (820 Hz) is based on the limit on occupational exposure. Here, we have chosen an approach consistent with the 1998 guidelines for general public exposure, using the current density values up to 100 kHz (see Table 5.5).

**Evaluation of Numerical Results**

Simulations were performed at the frequency $f_0 = 217$ Hz for the communication system and 1 kHz for the audio signal — and the quantity of interest, $Q^{\text{sim}}(f_0)$ — which can be $\langle J \rangle_{1 \text{cm}^2}$ (ICNIRP-1998), $\langle E \rangle_{8 \text{mm}^3}$ (ICNIRP-2010), or $\langle E \rangle_{5 \text{mm}}$ (IEEE C95.6-2002) — is extracted. To assess the exposure from the measured signals with a complex waveform, frequency scaling is applied. The results are normalized to the appropriate current by comparing the B-field from the measurement ($B_{z}^{\text{meas}}(f_0)|_{z=z_0}$) and the simulation ($B_{z}^{\text{sim}}(f_0)|_{z=z_0}$) in the plane $z = z_0$, and multiplied by the normalized spectral content ($B_{z}^{\text{meas}}(f_0)/B_{z}^{\text{meas}}(f_0)$):

$$Q^{\text{sim}}(f) = Q^{\text{sim}}(f_0) \times \frac{f}{f_0} \times \frac{\max \left( B_{z}^{\text{meas}}(f_0)|_{z=z_0} \right)}{\max \left( B_{z}^{\text{sim}}(f_0)|_{z=z_0} \right)} \times \frac{B_{z}^{\text{meas}}(f)}{B_{z}^{\text{meas}}(f_0)}. (5.2)$$

Additional scaling to the conductivity should be performed for the current density, but since here the low-frequency dielectric properties are used for most tissues (Section 5.3.3), this is not necessary. The frequency-domain signal is weighted with the frequency-dependent limits, $\text{Lim}(f)$, and transformed back to the time domain, where the maximum is extracted. The compliance factor is, thus, given by

$$CF_{\text{max}}^{\text{sim}} = \max \left( \text{IFT} \left( \frac{Q^{\text{sim}}(f)}{\text{Lim}(f)} \right) \right). (5.3)$$
5.4 Validation of Experimental Setup

The experimental setup was validated by measuring the magnetic fields of a calibrated Telephone Magnetic Field Simulator (TMFS, SPEAG, Switzerland) and a thin wire fed by a sinusoidal source. The peak magnetic field reading 10 mm above the TMFS deviated < 3% from the target value. The maximum value of magnetic field measured with a resolution of 0.7 mm in a plane 1 mm above the thin wire was $3.45 \mu T$, deviating < 3% from the analytically determined target value of $3.42 \mu T$. Both deviations are well within the total expanded measurement uncertainty of the system of 7.3% (Table 5.4) when the uncertainty due to the phone positioning is disregarded.

5.5 Experimental Assessment

5.5.1 Frequency Content

Figure 5.4 shows the frequency content for all phones at frequencies up to 500 Hz. As expected for the GSM communication system, fields at 217 Hz and harmonics are measured with all phones at 900 and 1800 MHz. Although the experimental setup did not allow measurements lower than 60 Hz, the 8.3 Hz component of the GSM communication system is seen by the presence of its harmonics in Figures 5.4(a) and 5.4(b).

For UMTS, the fields are in general much smaller than for GSM — note that the B-field axis in Figure 5.4(c) is a factor of 100 smaller than for 5.4(a) and 5.4(b). Further, no frequency component is systematically much larger than the others, e.g., the power control performed at a frequency of 1500 Hz does not draw current bursts from the battery. A more detailed analysis showed that, for all phones, a 100 Hz component can be detected, most probably due to the time frame of 10 ms used in UMTS.

5.5.2 Spatial Distribution

The spatial distribution of the fields — 217 Hz for GSM and 100 Hz for UMTS — was extracted for all phones, and the maximum was
5.5. EXPERIMENTAL ASSESSMENT

Figure 5.4: Superposition of the frequency spectra from all phones up to 500 Hz. The maximum value of the B-field axis is $15 \, \mu \text{T}$ for GSM and $0.15 \, \mu \text{T}$ for UMTS.
always found near the feedpoint of the battery: e.g., Figure 5.5 shows the B-field spatial distribution of the SamsungGT-I9001 phone. At each measurement point, the field at the target frequency is extracted from the frequency-domain signal by integrating the B-field over a 3 dB bandwidth. Equivalent high-resolution scanning was performed around the speaker area with the 1 kHz signal, shown in Figure 5.6. The speaker pattern is consistent with a current loop and is independent of the communication system.

Figure 5.5: B-field spatial distribution on the front of the SamsungGT-I9001 phone at maximum PCL for (a) GSM900 (217 Hz), (b) GSM1800 (217 Hz), and (c) UMTS (100 Hz); the outline of the phone and the battery are shown; the B-field scale for GSM is up to 6 µT and for UMTS up to 0.4 µT.

5.5.3 Decay with Separation from the DUT

The decay with the separation from the surface of each DUT, investigated by performing a scan along a 3-cm line perpendicular to the DUT surface at the location of the maximum, was performed at three PCLs. Figure 5.7 shows the decay of the B-field close to the battery.
5.5. EXPERIMENTAL ASSESSMENT

Figure 5.6: B-field spatial distribution at 1kHz around the speaker of the SamsungGT-I9001 phone with audio ON for (a) GSM900, (b) GSM1800, and (c) UMTS.

feedpoint (217Hz for GSM⁶) and Figure 5.8 shows the decay near the speaker (1kHz). The results confirm that the 217Hz component in GSM mode is directly related to the current drawn from battery as a consequence of the radio communication, yet the 1kHz signal at the speaker is directly related to the audio signal.

Figure 5.7: B-field along a line perpendicular to the surface of the SamsungGT-I9001 phone at 217Hz for (a) GSM900 and (b) GSM1800.

⁶The decay in UMTS is not shown, as the level is very low and mainly consists of noise.
Figure 5.8: B-field along a line perpendicular to the surface of the SamsungGT-I9001 phone at 1kHz close to the speaker with audio ON for (a) GSM900, (b) GSM1800, and (c) UMTS.
5.5. EXPERIMENTAL ASSESSMENT

5.5.4 Compliance with the ICNIRP Reference Levels

The compliance of complex waveforms with the ICNIRP reference levels is assessed as described in Section 5.3.4, and the compliance factor (in terms of $dB/dt$) is calculated according to (5.1). Table 5.7 reports the maximum extracted ratio for each phone and communication system. The maximum ratios of measured waveform to the ICNIRP limits for GSM900 are higher than for GSM1800, which is consistent with the higher output power used. For all phones, the exposure in UMTS is lower than in GSM by at least 25%, and up to a factor of 19 when compared to GSM900.

Table 5.7: Compliance factor in terms of the ICNIRP limit on $dB/dt$ with all frequencies from the communication systems under consideration.

<table>
<thead>
<tr>
<th>Phone</th>
<th>GSM900</th>
<th>GSM1800</th>
<th>UMTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTCdiam100</td>
<td>4.33</td>
<td>2.95</td>
<td>0.23</td>
</tr>
<tr>
<td>HTCtopa100</td>
<td>4.32</td>
<td>1.99</td>
<td>0.23</td>
</tr>
<tr>
<td>LG</td>
<td>2.39</td>
<td>1.58</td>
<td>0.24</td>
</tr>
<tr>
<td>MotorolaV1050</td>
<td>1.20</td>
<td>1.17</td>
<td></td>
</tr>
<tr>
<td>Nokia6120</td>
<td>2.75</td>
<td>2.10</td>
<td>0.37</td>
</tr>
<tr>
<td>SamsungGT-I9001</td>
<td>2.24</td>
<td>1.65</td>
<td>0.15</td>
</tr>
<tr>
<td>SonyEricssonW760i</td>
<td>1.15</td>
<td>1.01</td>
<td>0.52</td>
</tr>
<tr>
<td>SonyEricssonW910</td>
<td>5.63</td>
<td>3.81</td>
<td>0.27</td>
</tr>
<tr>
<td>iPhone3g</td>
<td>1.25</td>
<td>1.06</td>
<td>0.73</td>
</tr>
<tr>
<td>iPhone4</td>
<td>1.44</td>
<td>1.51</td>
<td>0.59</td>
</tr>
</tbody>
</table>

5.5.5 Worst-Case Equivalent Sources

To derive the envelope of the exposure (for GSM900, GSM1800, and UMTS), the compliance factor in terms of $dB/dt$ was extracted (5.1) from the spatial distributions on the front side of every phone. The
speaker point of each phone was superposed, and, for each location, the maximum value from all phones is reported.

Figure 5.9 shows the envelope of the exposure from GSM900, GSM1800, and UMTS from all phones at the maximum PCL. These results are used for the development of the numerical source (Section 5.6).

Figure 5.9: Envelopes of the point-wise maximum ratio of exposure to the ICNIRP 1998 limits from all phones at the maximum PCL, excluding the contribution from the audio signal, for (a) GSM900, (b) GSM1800, and (c) UMTS.

5.6 Development of Numerical Sources

As reported in Section 5.5.2, the maximum LF fields are typically located close to the feedpoint of the phone battery, thus distributions are strongly phone-design dependent. The worst-case equivalent source should not be representative of any single phone, but rather a conservative estimate for all phones. We have, thus, designed a numerical source from an array of loops that produces a rather uniform B-field enveloping the measured distributions. The loops are fed with ideal current sources. The distance of this array from the head has been set such that the decay of the fields corresponds to the measurements.
performed in GSM mode, since measurements made in UMTS mode are too close to the detection limit. The loops’ currents have been set such that the maximum B-field at 4mm distance matches the maximum measured field in this plane for the individual phones.

In the LF range, the induced current density is the quantity that limits the exposure, and maximum coupling is obtained with the B-field perpendicular to the surface of the body. Thus, the numerical source has been developed with the focus mainly on the fields perpendicular to the phone’s surface, i.e., along the z-axis.

Figure 5.10 shows the $B_z$-field from the numerical source. The effective distance of the loops was found to be 11 mm.

![Figure 5.10: $B_z$ generated by the array of rectangular loops (left) and superposed on the loops in white (right); the same plotting area is used as in Figure 5.9](image)

The same procedure was applied to the 1kHz fields from the speaker, where the loop radius was set to 4mm; from the comparison to the measurements, a distance of 3mm was found for the location below the phone surface.

## 5.7 Numerical Assessment

The compliance factor calculated from (5.3) with respect to the corresponding limit from ICNIRP or IEEE was evaluated for all averaging
schemes, phones, communication systems, and anatomical heads. Figure 5.11(a) shows that the ratio of the surface-averaged current density does not exceed 40% of the ICNIRP limit for GSM900. The spread of the values for the various positions of the numerical source is larger than the difference between adults and children. However, the spread of the compliance factors for any particular phone for the children is larger than for the adults, which is expected, since a translation of 10 mm is larger in proportion to the head size.

At GSM1800 (Figure 5.11(b)), the distribution is similar although all the values are slightly smaller than for GSM900. For UMTS (Figure 5.11(c)) the maximum value is lower than for GSM by about two orders of magnitude. Only the results of GSM900 are used to compare the remaining parameters of the analysis.

Figure 5.12 shows that the application of the current density limits from the ICNIRP 1998 guidelines to all tissues (Figure 5.12(a)) or to the central nervous system (CNS) tissues only (Figure 5.12(b)) does not lead to significant differences for the type of exposure presented here. The spread of the line-averaged E-field values (IEEE, Figure 5.13) from various positions is larger for CNS tissues than for all tissues. Indeed, the structure of the tissues around the cheek area, where the exposure is maximum, is rather smooth, such that small translations of the loop array do not lead to very different exposure patterns; the structures of the CNS, however, are more complex, and relatively small translations can lead to significantly different exposures. Also, as the CNS tissues do not include peripheral tissues, smaller E-field-to-limit ratios are found. Similar results were obtained for the volume-averaged induced E-field (ICNIRP-2010, Figure 5.14).

Among the three quantities and averaging schemes used for compliance assessment, the current density from the ICNIRP 1998 guidelines is the most restrictive, by roughly one order of magnitude.

Finally, the exposure was assessed for an audio signal at 1 kHz. Figure 5.15 shows the induced current density (ICNIRP 1998), and Figure 5.16 shows the induced fields averaged along a line according to the IEEE standard. The ear is a more complex structure than the cheek and is located very close to the loop, such that small translations can lead to large differences in the peak exposure: a larger variation with the position of the loop is observed with this more localized
5.7. NUMERICAL ASSESSMENT

Figure 5.11: Ratio of the surface-averaged current density to the ICNIRP 1998 limits for all tissues, in (a) GSM900, (b) GSM1800, and (c) UMTS.
Figure 5.12: Ratio of the surface-averaged current density to the ICNIRP 1998 limits in GSM900 for (a) all tissues and (b) CNS tissues.

Figure 5.13: Ratio of the line-averaged induced electric field to the IEEE limits in GSM900 for (a) all tissues and (b) CNS tissues.
5.8 Discussion and Conclusions

From the assessment of compliance with the ICNIRP guidelines for the complex waveforms generated, we have found that the reference levels were exceeded by up to a factor of 5.6 in the measurement plane, i.e., 4mm from the phone surface. Considering the measured decay along the axis perpendicular to the phone surface, we found that the compliance factor reduces to a factor of 3 at the distance of the gray matter from the phone surface (12.6mm for Billie). For the worst-case phone, compliance with the reference levels would be achieved only at a distance of 18mm. The LF fields generated by mobile phone battery currents are, thus, not compliant with the ICNIRP reference levels for normal use, i.e., at the head. However, the assessment in terms of basic restrictions related to the induced fields or currents has shown that the exposure reaches at most 40% of the limits for ICNIRP 1998, but one order of magnitude lower for ICNIRP 2010 and IEEE C95.6-2002. In addition, it is interesting to note that the contribution from the audio signal at a normal speech level, i.e., $-16 \text{ dBm}$,
Figure 5.15: Ratio of the surface-averaged current density to the ICNIRP 1998 limits for the audio signal at 1 kHz for (a) all tissues and (b) CNS tissues.

Figure 5.16: Ratio of the line-averaged induced electric field to the IEEE limits for the audio signal at 1 kHz for (a) all tissues and (b) CNS tissues.
is the same order of magnitude as the fields induced by the current bursts generated from the implementation of the GSM communication system.

The current-induced B-field generated from the communication system via UMTS are two orders of magnitude lower than via GSM, which disproves the hypothesis that higher LF fields are generated with UMTS due to the high current consumption of the complex processing circuitry. This finding provides useful information regarding LF fields generated during UMTS use, and, together with the knowledge that RF exposure from UMTS is two orders of magnitude lower than from GSM, we may now state that there is an overall reduction in the average exposure when this communication system is used.

Open questions remain, e.g., related to the use of UMTS time-domain duplexing (UMTS-TDD), which could lead to different results. We did not consider UMTS-TDD in this project, as the devices used do not support this technology. In addition, TDD is intended mainly for data transfer, where the exposure at the head is not a main concern other than for voice over internet protocols (VoIP). Further studies should include UMTS-TDD in the context of VoIP as well as very recent communications technologies such as TD-SCDMA, LTE for VoIP, and EV-DO (an extension of CDMA2000) for VoIP.

Finally, the power control scheme in GSM based on hard handovers could lead to additional LF components in the spectrum, but these would be dependent on the network and the movements of the user holding the mobile device. These components are expected to carry much less energy than those related to the time-frame structure of the communication system.
Part IV

Workers’ Exposure
Chapter 6

Dependence of the Occupational Exposure to Mobile Phone Base Stations on the Properties of the Antenna and the Human Body

6.1 Abstract

This study assesses human exposure in the close vicinity of mobile phone base station antennas by finite-difference time-domain simulations. The peak spatial average specific absorption rate (SAR) and the whole-body average SAR are analyzed in three different anatomical models (55 kg – 101 kg) with respect to the basic restrictions for...
occupational exposure. The models are at distances between 0.5 m and 4 m from various antenna types operating at frequencies ranging from 450 MHz to 2140 MHz. The validity of the simulations is confirmed by an analysis of the impact of the mesh resolution on local and whole-body average SAR and by experimental validation of the numerical models. The results demonstrate that the whole-body absorption generally determines the maximum permissible antenna output power for collinear array antennas. Local exposure depends on various body-resonance effects which vary strongly among individuals. In particular for short antennas, the peak spatial average SAR can be more restrictive than the whole-body absorption because they may only expose a fraction of the body. Therefore, compliance must be demonstrated for both quantities.

6.2 Introduction

In the year 2004, the European Union issued a directive \cite{134} which regulates the exposure of workers to electromagnetic fields according to the guidelines on the safety of human exposure issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) \cite{2}. The German employers’ liability insurance association and the regulations for the prevention of accidents \cite{135,136} require compliance with basic restrictions according to \cite{2}. The field strengths in the close vicinity of base station antennas may exceed the reference levels. In such cases, safety guidelines recommend particular measures to demonstrate whether the basic restriction for the exposure of workers are met.

The safety guidelines for the exposure of humans to electromagnetic fields \cite{2} define basic restrictions for the power absorbed in the entire body and in spatially confined regions of a total tissue mass of 10 g. Since the accurate evaluation of these quantities generally requires laboratory conditions with well characterized body phantoms, the guidelines propose reference levels for the strength of the incident electromagnetic fields. These reference levels can easily be evaluated in practical situations. The correlation of the reference levels with the basic restrictions, however, is based on simplified models for whole-body average specific absorption rate (SAR) calculation or for
plane-wave exposure \cite{20,137,138}, which renders the assessment of the local SAR difficult. The present measurement standard for the exposure evaluation in the environment of base station antennas \cite{139} defines a cross section or volume over which the electric or magnetic field be averaged for comparison with the reference levels. A new internationally harmonized standard for fixed transmitters in service is currently under development \cite{140}. It will define methods for the evaluation of the exposure in the entire source environment plane.

The evaluation of the basic restrictions, i.e., of the local and the whole-body average SAR, requires the knowledge of the field distribution and absorption in the human body considering realistic worst-case exposure situations and individual anatomical features for a wide range of the population. Whereas several theoretical studies develop convenient means to derive compliance distances for the reference levels based on free-space measurements or simple geometrical characteristics of the antenna \cite{141,143}, the assessment of the actual absorption is only feasible using numerical simulations. These simulations should include a set of anatomical high resolution models which is representative for the broad range of the population. Because of the large domain which should encompass both the antenna and the human body, these simulations pose high demands on computational resources. In the past, several research groups simulated whole-body average and local SAR of anatomical body models using the finite-difference time-domain (FDTD) method \cite{144-148} or hybrid techniques, which yield a certain reduction of the associated computational costs \cite{149,150}. Most of these studies are based on one or very few antenna models, and all but two use the Visible Human model \cite{151,152} to quantify the exposure of the body. Studies with a larger set of human models were carried out for plane-wave exposure only \cite{153,155}. The mesh resolutions used in most of these studies range from 3 mm to 5 mm. According to, e.g., \cite{59,156}, the thickness of the epidermis and the dermis layers of the skin of adults does not exceed 2.6 mm. Using mesh steps in the order of magnitude of 5 mm to render the skin layer in the computational domain may lead to, e.g., gaps in the skin because of spatial undersampling, or to a spurious

\footnote{The main objective of Chapter 7 is to support the development of this standard.}
increase of the skin thickness and therefore of the losses in the skin layer.

6.3 Objectives

This study aims at the quantification of the absorption in the human body exposed to base station antennas, considering various anatomical characteristics of the exposed subject and typical parameters of base station antennas. In detail, this includes:

- assessment of worst-case configurations with respect to tissue distribution, body mass, and height using various anatomical models of the human body,
- evaluation of the absorption for typical base station antenna designs with various frequencies, beamwidths, and distances between the body and the antenna, and
- comparison of the local exposure (peak spatial average SAR) against the whole-body absorption with respect to the reference levels and the radiated antenna power for various antenna configurations.

6.4 Methods

6.4.1 Anatomical Body Models

Three different anatomical body models of strongly different body heights and sizes were used (Figure 6.1):

- The Visible Human (VH) model is based on cryosection images of a 38-year-old male of 1.80 m height and 101 kg body weight. The model distinguishes more than 100 different tissues and organs. It is discretized in the SEMCAD-Compound

\(^{2}\)The body weight of the anatomical models varies with the content of their body lumina, such as the stomach and the intestines. Here, the lumina were filled with a substitute material with the density and the dielectric properties of the surrounding tissue.
Figure 6.1: Anatomical body models: Visible Human (left), Japanese Male (center), Japanese Female (right).

format. This format retains the outlines of the tissue interfaces of the original image slices in a 2.5-dimensional structure at the resolution of the original images. Like this, the model can be placed into the computational grid independently of the mesh and be discretized at arbitrarily fine resolutions. Details on this data format can be found in [157].

- The Japanese Male (JM) model is based on magnetic resonance images (MRI) of a 22-year-old volunteer of 1.73 m height and 71 kg mass. It is available as voxel data in a resolution of 2 mm × 2 mm × 2 mm and distinguishes more than 50 different tissue types [158]. The model has been converted into a particular data format for use with SEMCAD X which allows to adapt the resolution of the computational grid to the numerical demands of the simulation.
• The Japanese Female (JF) model has been developed from MRI data of a 22-year-old volunteer of 1.60 m height and 55 kg mass. Technically, it corresponds to the JM model described above.

The dielectric parameters of the tissues were assigned according to the parametric model described in [65]. Additionally, the ratios of the cross sections of the models to their masses (CM ratios) and the body-mass-index (BMI) are given for frontal projection of their body profiles. Here the cross section is defined as the projected surface of the body onto a plane perpendicular to the direction of the main beam of the antenna. In contrary to the BMI, the CM ratio takes into account the surface area exposed to the incident field and therefore the orientation of the body with respect to the antenna, i.e., the CM ratio changes when the body rotates about its vertical axis. A good correlation between the whole-body average SAR and the CM ratio has already been observed in [159]. Table 6.1 summarizes the properties of the body models.

<table>
<thead>
<tr>
<th>Human model</th>
<th>Mass (kg)</th>
<th>CM ratio (m²/kg)</th>
<th>Height (m)</th>
<th>BMI (kg/m²)</th>
<th>Age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible Human</td>
<td>101</td>
<td>6.0×10⁻³</td>
<td>1.80</td>
<td>31.2</td>
<td>38</td>
</tr>
<tr>
<td>Japanese Male</td>
<td>71</td>
<td>7.7×10⁻³</td>
<td>1.73</td>
<td>23.7</td>
<td>22</td>
</tr>
<tr>
<td>Japanese Female</td>
<td>55</td>
<td>8.8×10⁻³</td>
<td>1.60</td>
<td>21.5</td>
<td>22</td>
</tr>
</tbody>
</table>

6.4.2 Antennas

Numerical Antenna Models

A set of generic base station antennas with differing characteristics has been modeled following typical designs for 450 MHz and 900 MHz. They consist of collinear arrays of dipole elements or stacked patch antennas uniformly fed. In order to reduce the horizontal beamwidth, two parallel panels of the antennas are used; D2-900 and P2-900 are made of two side-by-side panels of D-900 and P-900, respectively. All the generic antenna models use vertical polarization and lossless
dielectric materials. The 900-MHz antennas are covered by a radome with a relative permittivity of 3.0.

Additionally, a numerical model of the commercial base station antenna Kathrein 742 215 [160] has been developed which operates in the GSM1800 and UMTS bands at ±45° polarization. The relative permittivity and the conductivity of its radome are set to 4.3 and 0.001 S/m, respectively. Figure 6.2 shows the generic and Kathrein 742 215 antenna models. Table 6.2 shows their mechanical and electrical characteristics. The Kathrein 742 215 antenna is modeled as single-fed antenna elements without modeling the feeding network.

Figure 6.2: Base station antenna models.
## Table 6.2: Mechanical dimensions and simulated electrical characteristics of the base station antenna models. $r_0$ is given in 6.2.

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>Freq (MHz)</th>
<th>Elements</th>
<th>Height (mm)</th>
<th>Width (mm)</th>
<th>Dir. Hor. (deg)</th>
<th>Dir. Vert. (deg)</th>
<th>Pol. radome</th>
<th>Vert. Elem.</th>
<th>Height (mm)</th>
<th>Width (mm)</th>
<th>DBi</th>
<th>HPBW</th>
<th>HPBW</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-450</td>
<td>450</td>
<td>4</td>
<td>1776</td>
<td>400</td>
<td>12.1</td>
<td>114</td>
<td>vert.</td>
<td>4.6</td>
<td>4.6</td>
<td>742</td>
<td>215</td>
<td>8.3</td>
<td>4.3</td>
</tr>
<tr>
<td>D-900D</td>
<td>900</td>
<td>8</td>
<td>1936</td>
<td>88</td>
<td>15.8</td>
<td>98</td>
<td>vert.</td>
<td>3.0</td>
<td>9.0</td>
<td>742</td>
<td>215</td>
<td>6.0</td>
<td>3.0</td>
</tr>
<tr>
<td>D2-900</td>
<td>900</td>
<td>2×8</td>
<td>1936</td>
<td>316</td>
<td>18.5</td>
<td>54</td>
<td>vert.</td>
<td>6.8±45°</td>
<td>10.3</td>
<td>742</td>
<td>215</td>
<td>8.3</td>
<td>4.3</td>
</tr>
<tr>
<td>P-900Stacked Patch</td>
<td>900</td>
<td>8</td>
<td>1936</td>
<td>60</td>
<td>17.2</td>
<td>72</td>
<td>vert.</td>
<td>3.0</td>
<td>10.2</td>
<td>742</td>
<td>215</td>
<td>8.3</td>
<td>4.3</td>
</tr>
<tr>
<td>D2-900</td>
<td>900</td>
<td>8</td>
<td>1936</td>
<td>60</td>
<td>17.2</td>
<td>72</td>
<td>vert.</td>
<td>3.0</td>
<td>10.2</td>
<td>742</td>
<td>215</td>
<td>8.3</td>
<td>4.3</td>
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<tr>
<td>D-450</td>
<td>450</td>
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<td>8.3</td>
<td>4.3</td>
</tr>
</tbody>
</table>
Comparison to a Theoretical Antenna Model

The generic antenna models are compared to the cylindrical model derived in [143]. In the near field of a collinear radiator, cylindrical wave propagation can be assumed, and most of the power flux is confined within the azimuthal angle, i.e., its horizontal half-power beamwidth (HPBW) $\Phi_{3dB}$, and within the overall height of the antenna $L$. For observation points outside the reactive near field of the individual radiating elements, the power density $P_D$ along the antenna axis at a distance $r$ can be given as

$$P_D(r, \Phi_{3dB}) = \frac{P_{rad}}{\Phi_{3dB} r L \sqrt{1 + \left(\frac{r}{r_0}\right)^2}}, \quad (6.1)$$

where $P_{rad}$ is the power radiated from the antenna and $\varphi$ the azimuthal angle, and for azimuthal angles within the horizontal HPBW. For an antenna directivity $G_A$, the distance $r_0$ is defined as

$$r_0 = \frac{\Phi_{3dB}}{4\pi} G_A L. \quad (6.2)$$

For validation purposes, the power density $P_{D_{sim}}$ of the generic antenna models is simulated in free space and averaged along a vertical line of a length of $L$ in the direction of the main beam of the antenna at different distances $r$. $P_{D_{sim}}$ is then compared to the power density calculated using (6.1) and the properties of the antennas given in Table 6.2.

As shown in Figure 6.3, the deviation is about 1 dB in most cases. Larger deviations ($< 1.5$ dB) are only observed for the antenna D-450 at short distances. This is due to the smaller energy confinement of the D-450 in its close near-field. Equation (6.1) assumes that the power radiated from the antenna is entirely confined in its horizontal HPBW and, given a distance $r$, distributed uniformly over the horizontal aperture. The uncertainty of this assumption is higher in the near-field of low directivity antennas such as the D-450. On the other hand it confirms that (6.1) always yields a conservative approximation of the power density $P_D$. The results of the near-field measurements and SAR evaluation in an elliptical phantom in front of the Kathrein 742215 antenna are shown in Section 6.6.
CHAPTER 6. BASE STATION EXPOSURE

6.4.3 FDTD Simulations

For all numerical evaluations, the simulation platform SEMCAD X (SPEAG, Switzerland) was used. SEMCAD X integrates a CAD environment for the modeling and positioning of antennas and body models, an FDTD solver [78] and a postprocessor for evaluation of the peak spatial average SAR according to [105].

The simulation of phased array base station antennas can require about 100 periods of simulation time to reach steady state in a large computational space. Steady state was evaluated by calculating the power budget of the simulation, i.e., the ratio of the antenna input power to the sum of the losses in the anatomical model and the power radiated into the absorbing boundary conditions of the computational domain. For all simulations, the error of the power budget was less than 3%.

Prior to the numerical evaluations, the impact of the mesh resolution on the local SAR distribution and whole-body average SAR was evaluated considering the following points:

- Standing wave effects at the body surface occur if the layer of fat or subcutaneous adipose tissue between the skin and the inner organs or muscle tissue has a thickness of approximately $\lambda/4$. 

Figure 6.3: Comparison of the average power density computed from (6.1) with the one obtained from free-space simulations.
These standing waves can lead to an increase of the local SAR in the skin layer of more than 5 dB \cite{161,162}. For the assessment of the necessary grid resolution, a prolate spheroid consisting of a skin and fat layer around a muscle core was simulated in front of a base station antenna at 450 MHz. The layer thicknesses were chosen according to the worst-case distribution given in \cite{162}, and the grid resolution was gradually reduced to 1 mm in the propagation direction. Converging results for the local SAR were obtained at a mesh resolution of $2 \times 2 \times 2$ mm.

- For many cases, local SAR maxima were observed in concave regions or protruding parts of the body, such as the root of the nose, the frontal region of the neck under the chin, the wrists and the calves (Section 6.7.3). The head of the JF model was simulated in front of the three top elements of the antenna P-900 using mesh resolutions ranging from $2 \times 2 \times 2$ mm down to $0.6 \times 0.6 \times 0.6$ mm. Both the 10g peak spatial average SAR and the SAR averaged over the entire head showed deviations of less than 0.35 dB within the evaluated range.

- Whole-body average SAR and 10g SAR were calculated for the JM phantom under plane wave exposure for frequencies from 450 MHz to 2140 MHz. The values of whole-body SAR and 10g SAR converge for resolutions lower than 2 mm for every frequency (Figure 6.4). Coarser resolutions tend to underestimate the whole-body average SAR, which is consistent with the findings of \cite{153}.

In consequence, a minimum step size of 2 mm was used for the resolution of the anatomical models for frequencies up to 900 MHz. For the simulations in front of the Kathrein 742215 antenna, the human model was meshed with a maximum step of 1 mm in the first half of the trunk\footnote{The representation of the geometrical details of the Kathrein 742215 antenna required a further reduction of the minimum mesh step to 0.5 mm. Because of the computer resources required for the higher resolution, the maximum distance between antenna and exposed body has been limited to 2 m for simulations using the Kathrein 742215 antenna at 1840 MHz and 2140 MHz.}. In free space, the maximum grid step was always limited to $\lambda/10$ or smaller. Mesh sizes of up to 200 million cells were
CHAPTER 6. BASE STATION EXPOSURE

(a) 10g SAR
(b) Whole-body SAR

Figure 6.4: Deviation of the whole-body average SAR and 10g SAR values from the results obtained with a mesh step of 0.75mm (900 MHz – 2140 MHz) and 1.0 mm (450 MHz). Meshes using a grid step of 2mm to 5mm are uniform, whereas finer resolution is only applied to the regions of high local absorption.

required for a domain which encompassed both the antenna and the anatomical body model at distances of up to 4m. The simulations were performed on a ClusterInABox 1500 with 4 parallel graphics processing units and 32 GB of memory, manufactured by Acceleware, Canada. The execution time for the computationally most demanding configurations was approximately 30 hours.

6.4.4 Measurements

The validation measurements (Section 6.6) are carried out using the near-field scanner DASY5 NEO, SPEAG, Switzerland, which is the successor of the system described in [100]. Electric and magnetic fields of the Kathrein 742215 antenna are measured in free space, and the SAR is evaluated in the elliptical body phantom (length of the axes 600 mm and 400 mm, flat bottom, 2 mm shell thickness, \( \varepsilon_r = 3.7 \)) specified in [8] for compliance testing of body-worn wireless devices. The setup including the scanner and the phantom is shown on Figure 6.5. The dosimetric properties of the phantom are characterized in [163]. The frequency range of the Kathrein 742215 antenna,
the free-space E- and H-field amplitudes as well as the SAR induced in the body phantom are within the specification of the free-space and dosimetric probe used. During all measurements, the feeding power has been monitored using two power meters connected to a directional coupler. The uncertainty for these measurements is better than $\pm 1.3\, \text{dB} \,(k = 2)$ for the free-space E- and H-fields and better than $\pm 1.0\, \text{dB} \,(k = 2)$ for the SAR assessment.

### 6.5 Exposure Conditions

For the assessment of the exposure, the human models were placed into the main beam of the antennas with their body axis parallel to the antenna and, in case of the generic antennas, parallel to the incident E-field vector. Several previous studies have shown that the

![Measurement setup for the SAR evaluation of the Kathrein 742215 antenna using DASY5 NEO and the elliptical phantom specified in [8](#).

Figure 6.5: Measurement setup for the SAR evaluation of the Kathrein 742215 antenna using DASY5 NEO and the elliptical phantom specified in [8](#).
highest exposure can be expected for vertical polarization. The models were placed at distances of 0.5 m, 1.0 m, 2.0 m, and 4.0 m from the generic antennas, and 0.5 m, 1.0 m, and 2.0 m from the Kathrein 742 215 antenna. Simulating three orientations of the JM model (450 MHz), exposure from the front, from the back, and from the side, showed that frontal exposure yields the highest whole-body absorption, which corresponds to the findings of.

Thus, for all subsequent simulations, the body models are placed facing the antenna, with the center of their body axis aligned to the antenna center. Reflections from walls in the direction of the main beam were not considered in the simulations because their contribution to the whole-body absorption can be regarded as irrelevant for practical mounting positions of base station antennas.

6.6 Experimental Evaluation

The numerical model of the Kathrein 742 215 antenna is validated by near-field measurements (free space) and SAR measurements using the near-field scanner DASY5 NEO (Section 6.4.4) at 1840 MHz. The whole-body average SAR and the 10 g peak spatial average SAR were assessed in the elliptical flat phantom which was placed concentrically at a distance of 0.5 m above the antenna with its major axis parallel to the axis of the antenna (Figure 6.5).

E- and H-fields in free space are evaluated in the plane spanned by the antenna axis and the axis of the main beam in the center of the antenna. For the assessment of the absorption, the SAR was measured in 5 planes parallel to the phantom bottom at distances from 10 mm to 50 mm. An exponentially decaying function was fit in perpendicular direction to the measurement planes. The loss coefficient was determined for every measured point using a least square fit. The SAR in the entire phantom was calculated by extrapolating the measurements from the bottom to the liquid surface. The 10 g peak spatial SAR was assessed according to.

Figure 6.6 shows measurement and simulation results for an antenna input power of 33 dBm. Whereas the simulated far-field pattern is in good agreement with the specifications, the differences in the close near-field are obvious and are due to simplifications in modeling.
the antenna structure concerning feed point and losses. Nevertheless, the integrated values such as the measured whole-body average SAR and peak spatial average SAR in the phantom correspond well to the numerical results. For an antenna forward power of 36 dBm, a whole-body average SAR of 15 mW/kg has been determined. The deviation from the simulated value of 17 mW/kg is 0.5 dB. Figure 6.6 shows that the free-space field distribution is very inhomogeneous at the distance of the phantom (0.5 m). This leads to differences in the field distribution in the liquid above the phantom surface. Yet the power density is mainly directed normal to the antenna, and the ratio of the electric on magnetic fields is close to $377 \Omega$, as expected in the far field. The qualitative comparison of the SAR distribution shows satisfactory agreement. Although the absolute maximum 10 g peak spatial SAR is not located in the same position of the phantom in the measurement and in the simulation, the measured maximum 10 g peak spatial SAR of 0.13 W/kg is in good agreement with the simulation result of 0.14 W/kg. This confirms that integrated values, i.e., far field values or values at larger distances, are not sufficient to validate and predict the absorptions in the close near field [71].

6.7 Results

6.7.1 Dependence on Frequency and Body Model

The antenna output power at which the basic restrictions for occupational exposure (Table 6.3) are reached has been calculated for all three body models and four frequencies. Figure 6.7 shows the maximum permissible power for the JM, the JF, and the VH, standing at distances of 0.5 m, 1 m, 2 m and 4 m from the D-450 and P-900 generic antennas, and 0.5 m, 1 m, and 2 m from the Kathrein 742 215 antenna. When comparing the power levels in Figure 6.7 it should be noted that the horizontal and vertical beamwidths of the P-900 and the Kathrein 742 215 are in the same order of magnitude, whereas they are almost twice as high for the D-450 (Table 6.2).

In most cases, the maximum power is limited by the whole-body average SAR. Several exceptions occur for the VH which will be discussed in detail in Section 6.7.3. In general, the maximum permissible
Table 6.3: Basic restrictions for occupational exposure at frequencies between 10 MHz and 10 GHz according to [2].

<table>
<thead>
<tr>
<th>Exposure limit</th>
<th>W/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole-body average SAR</td>
<td>0.4</td>
</tr>
<tr>
<td>Localized SAR (head and trunk) in a 10g volume</td>
<td>10</td>
</tr>
<tr>
<td>Localized SAR (limbs) in a 10g volume</td>
<td>20</td>
</tr>
</tbody>
</table>

power with respect to the whole-body average SAR increases monotonically with distance, weight of the model, and wavelength. Plotting the maximum permissible power as a function of the CM ratio shows a simple linear correlation (Figure 6.8). For further validation, the width and the depth of the JM model have been scaled by ±10% and ±20% while keeping its height constant (Table 6.4). Its minimum and maximum body weights and CM ratios correspond approximately to

Figure 6.6: Simulated and measured E- and H-fields in the center plane of the Kathrein 742215 antenna operating at a frequency of 1840 MHz normalized for an antenna input power of 33 dBm. 0 dB correspond to 150 V/m and 0.5 A/m for the E-field and H-field plots, respectively. The dimensions of the plotted area are 0.5 m by 1.4 m.
Figure 6.7: Maximum permissible antenna output power at which the basic restrictions for occupational exposure are not exceeded. The white circles indicate that the 10 g SAR maximum in the head or trunk is more restrictive than the 10 g SAR maximum in the limbs. The opposite is marked by black squares.
those of the VH and the JF models. Additional simulations have been performed using the scaled JM models 0.5 m away from the antenna P-900. As shown in Figure 6.8(a), the results confirm the previously observed trend that the maximum permissible power with respect to the whole-body average SAR is inversely proportional to the CM ratio of the body. The remaining small deviations from the linear behavior can be attributed to different anatomical details of the models.

The shortest and most lightweight body model (JF) therefore poses the highest restrictions for the antenna output power. At 0.5 m distance, the maximum permissible power for the exposure of this model ranges from 180 W at 450 MHz to 74 W at 2140 MHz for the power beamwidths given in Table 6.2.

Table 6.4: Characteristics of the scaled JM model.

<table>
<thead>
<tr>
<th>Resizing</th>
<th>Mass (kg)</th>
<th>CM ratio (m$^2$/kg)</th>
<th>BMI (kg/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20%</td>
<td>45</td>
<td>9.6×10$^{-3}$</td>
<td>15.0</td>
</tr>
<tr>
<td>-10%</td>
<td>57</td>
<td>8.5×10$^{-3}$</td>
<td>19.0</td>
</tr>
<tr>
<td>0%</td>
<td>71</td>
<td>7.7×10$^{-3}$</td>
<td>23.7</td>
</tr>
<tr>
<td>+10%</td>
<td>86</td>
<td>7.0×10$^{-3}$</td>
<td>28.7</td>
</tr>
<tr>
<td>+20%</td>
<td>102</td>
<td>6.4×10$^{-3}$</td>
<td>34.1</td>
</tr>
</tbody>
</table>

6.7.2 Dependence on Half-Power Beamwidth

The correlation of the horizontal HPBW and the maximum permissible antenna power has been evaluated for the JM phantom at 900 MHz for antennas with horizontal beamwidths between 38° and 98°. Figure 6.9 shows the maximum permissible power (whole-body average SAR, occupational exposure) for the JM at 900 MHz. The results show that the whole-body absorption decreases linearly with the horizontal HPBW. This conclusion can be assumed to hold good for distances $r$ within which the cylindrical model (6.1) is valid.
6.7. RESULTS

131

(a) 0.5m

(b) 1m

Figure 6.8: Maximum permissible power in the antenna in order not to exceed whole-body average SAR basic restrictions for occupational exposure, as a function of the cross section on mass ratio of the human model, for four different frequencies: 450 MHz (D-450), 900 MHz (P-900), 1800 MHz (Kathrein 742 215) and 2140 MHz (Kathrein 742 215).

Figure 6.9: Maximum permissible power in the antenna, 900 MHz, in order not to exceed the basic restrictions on whole-body average SAR for occupational exposure for different horizontal HPBW for the Japanese male placed at four different positions.
6.7.3 Peak Spatial Average SAR

Figure 6.7 also shows the maximum permissible output power levels required to reach the basic restrictions for the local SAR maximum averaged over a cubical tissue mass of 10 g \cite{105}. Since the 10 g SAR limit for the head and trunk is different from the one for the limbs, only the more restrictive cases are shown on the charts. The bars are marked with white circles for a restriction by the head or trunk value and with black squares for a restriction by the limbs value. Figure 6.10 shows typical locations where the spatial average SAR maxima can be observed. These include extremities like fingers, the penis, wrists, and calves, or the root of the nose, and the neck. The reasons for these local enhancements can be attributed to various effects, such as partial body resonances, standing waves in layered tissues \cite{161,162} or focusing in concave regions.

Additional local maxima occur in the hands and the abdomen of the VH model. These are due to the particular position of its arms and hands which form a loop with a small gap in front of the abdomen. Furthermore, the size of this gap and the value of the local maximum in this area are strongly dependent on the grid resolution. A difference of 0.8 dB has been observed at 900 MHz for local mesh resolutions between $1 \text{ mm} \times 1 \text{ mm} \times 1 \text{ mm}$ and $2 \text{ mm} \times 2 \text{ mm} \times 2 \text{ mm}$. This local maximum has therefore not been considered in Figure 6.7.

In most of the cases shown in Figure 6.7 the 10 g peak spatial average SAR in the VH which restricts the antenna power occurs in the penis. Changing the length of the penis of the model leads to resonance effects which cause variations of the 10 g peak spatial average SAR of approximately 3 dB.

6.8 Discussion and Conclusions

The whole-body absorption and the 10 g peak spatial average SAR have been calculated for three adults (55 kg – 101 kg) exposed to typical collinear base station antennas (450 MHz – 2140 MHz) at distances from 0.5 m to 4 m. The results could be validated by assessing the impact of the grid resolution and by experimental methods.
For long antenna arrays exposing the human body rather homogeneously over a large portion of its length, the maximum whole-body average SAR is mainly a function of the antenna input power and horizontal HPBW, the distance, and the CM ratio. The maximum 10 g peak spatial SAR depends on various body-resonance effects which vary strongly among individuals.

Short antenna arrays at short distances from the exposed person may only expose a fraction of the body. Since peak spatial average SAR depends on the local incident field, the probability that the local SAR poses the limit on the permissible power increases.

In other words, compliance can not be conclusively demonstrated by one individual model or a family of models. Nevertheless, this study revealed that worst-case whole-body average SAR can be determined by applying a worst-case CM ratio. Compliance with peak spatial SAR limits is ensured by determining the peak local E- and H-field at the closest body distance. An extension of this study covering a larger range of antennas, a broader frequency range and additional anatomical body models \[12\] follows in Chapter \[7\]. This study will allow a more detailed analysis of the uncertainty and variability of the exposure to base station antennas and will give more comprehensive guidelines for the assessment of the whole-body exposure to base station antennas.
Figure 6.10: Typical locations of local SAR maxima (900 MHz).
Chapter 7

Estimation Formulas for the Specific Absorption Rate in Humans Exposed to Base Station Antennas

7.1 Abstract

The demonstration of compliance with guidelines for human exposure to base station antennas can be a time consuming process or often results in overly conservative estimates. To alleviate this burden and reduce the overestimation, approximation formulas for the whole-body average specific absorption rate (SAR) and the peak spatial SAR of human bodies using readily available basic antenna parameters have
been developed and validated in this study. The formulas can be used for adults standing in the radiating near field of base station antennas operating between 300 MHz and 5 GHz, at distances larger than 200 mm. It is shown that the 95th-percentile absorption for the human population can be well approximated by the absorption mechanism and statistical data of weight, height, and body-mass index (BMI) of the human population. The validation was performed numerically using three anatomical human models (Duke, Ella, and Thelonious) exposed to twelve generic base station antennas in the frequency range 300 MHz to 5 GHz at six distances between 10 mm and 3 m. From the 432 evaluated configurations, the estimation formulas for adult models are proven to be conservative in predicting the SAR exposure values of the two adults, but as expected not of the child.

7.2 Introduction

In most countries, exposure to RF fields from base station antennas is regulated by the guidelines published by the ICNIRP [2] or by the rules from the IEEE [4].

In [2], two different types of limits are defined: the basic restrictions, limiting the SAR and the current density inside the body, and the reference levels, limiting the incident electric and magnetic fields. The latter are secondary and derived from the basic restriction limits. In the near field of radiating structures, e.g., close to base station antennas, the reference levels can be very conservative, i.e., the ratio between incident field values and SAR is much larger than that of reference levels and basic restrictions. Therefore, measurements of the fields around base station antennas lead to very conservative exposure estimates. On the other hand, on-site SAR measurements are technically challenging and laboratory measurements at large distances from RF sources are not always possible.

In the vicinity of base station antennas, where the highest RF fields are present, the exposure scenarios are, however, relatively well defined. The data-sheet of the antenna typically contains information about its dimensions and radiating properties. Thus, the development of a SAR estimation for humans standing in the radiative near field or far field of base station antennas is desirable.
Exposure of anatomical human bodies to base station antennas has already been studied in the past [133,152], but the exposure matrices used were not extensive. Moreover, most studies involving simulation of detailed heterogeneous human models in front of base station antennas have used the Visible Human model [144,165]. This model has been found to be neither representative of the average human nor leading to worst-case absorption. Plane-wave exposure of various human models show that a compliant SAR for the Visible Human does not necessarily lead to a compliant exposure of a smaller model [155] and that the guidelines are not always conservative for the exposure of children [155,166].

Some work has been done in [167] to extract formulas to estimate the SAR due to exposure to base station antennas. This estimation is based on a fit of a large set of SAR data extracted from the literature. However, it only includes a few adult models and the statistical evaluation is biased by the use of the Visible Human model. Moreover, the frequency range is limited to 800 MHz to 2200 MHz.

A more general approach to this problem consists of applying physical considerations to develop estimation formulas and comparing the results from the obtained formulas with the SAR values from an extensive exposure matrix of humans in front of base station antennas.

### 7.3 Objectives

The main objective of this study is to support the development of the IEC standard PT62232. In detail, this includes the following:

1. development of estimation formulas for the whole-body, 1 g, and 10 g SAR based on physical considerations as well as numerical results;

2. validation of the formulas by numerical evaluation of the wbSAR and psSAR of high resolution anatomical models exposed to several base station antennas at various distances and sides of exposure.
### Table 7.1: Characteristics of the human models.

<table>
<thead>
<tr>
<th></th>
<th>VFM</th>
<th>VFF</th>
<th>VFB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>34</td>
<td>26</td>
<td>6</td>
</tr>
<tr>
<td>Weight</td>
<td>kg</td>
<td>72.2</td>
<td>58.1</td>
</tr>
<tr>
<td>Height</td>
<td>m</td>
<td>1.80</td>
<td>1.63</td>
</tr>
<tr>
<td>$S_{cs}$</td>
<td>m$^2$</td>
<td>0.560</td>
<td>0.484</td>
</tr>
<tr>
<td>$S_{DuBois}$</td>
<td>m$^2$</td>
<td>1.91</td>
<td>1.62</td>
</tr>
</tbody>
</table>

The cross-section, defined as the area of the projection of the body in a plane perpendicular to the direction of propagation of a plane wave, is given for exposure from the front or the back of the models.

### 7.4 Methods

#### 7.4.1 Anatomical Body Models

As shown in Figure 7.1, three members of the Virtual Family were used: Duke, the VFM, Ella, the VFF, and Thelonious, the 6-year-old VFB. These models, distinguishing about 80 tissue types, are based on magnetic resonance images (MRI) of healthy volunteers. The dielectric parameters of the tissues were assigned according to the parametric model described in and to the equivalence table provided with the VF models. Table 7.1 presents the age, weight, height, cross-section surface, $S_{cs}$, and skin surface, $S_{DuBois}$, given by (7.1) of Section 7.5.1 of the three models.

The human models developed for the Virtual Family are representative of average humans in the population (based on statistical data from ). As the estimation formulas are developed based on the premise of being conservative for 95% of the adult population, it is not expected that the simulation results from the Virtual Family models exceed the exposure predicted by the estimation formulas.
Figure 7.1: Three anatomical human models from the Virtual Family. From left to right: VFM, VFF, and VFB.
7.4.2 Antennas

Twelve generic base station antenna models were developed based on realistic antennas, 2 for each of 6 frequencies within the range 300 MHz to 5 GHz. The antennas were selected to represent typical wireless base station antennas. Table 7.2 summarizes their specifications, including $N$, the number of elements, $D$, the largest dimension of the antenna, $\Phi_{3dB}$, the horizontal HPBW, and $\Theta_{3dB}$, the vertical HPBW. The antenna models were validated by comparing their far-field characteristics, as well as the electric and magnetic fields in 4 planes at various distances in front of the antennas, from FDTD method and MoM simulations to the values from the data-sheet of the manufacturer.

7.4.3 Numerical Methods

All the numerical evaluations of the exposure of a human body in front of a base station antenna were performed using the in-house simulation platform SEMCAD X (SPEAG, Switzerland), which includes a postprocessor for evaluation of the psSAR according to [105] for any user-specified averaging mass.

Placement of the models at great distances in terms of wavelength causes the computational problem to become very large when using the traditional FDTD method. A new method, called the GHB method [64], has been developed and implemented in SEMCAD X. In this method, the incident fields from the antenna are computed in free-space using either FDTD, MoM, an analytical method, or some other method, and recorded on the surface of the GHB surrounding the human model. For the exposure evaluation, which requires a locally very fine grid resolution, the previously recorded fields are interpolated and enforced on the FDTD grid at the surface of the GHB [64] while the model is inside. The SAR computation is then performed as when using the traditional FDTD method. The GHB method was only used for configurations where the coupling between the human model and the antenna could be neglected.
Table 7.2: Specifications of the generic base station antennas.

<table>
<thead>
<tr>
<th>Freq. MHz</th>
<th>Antenna</th>
<th>Pol.</th>
<th>$N$</th>
<th>Height mm</th>
<th>Width mm</th>
<th>$D$ mm</th>
<th>Dir. dBi</th>
<th>$\Phi_{3\text{dB}}$ degrees</th>
<th>$\Theta_{3\text{dB}}$ degrees</th>
<th>Example of commercial model</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>300MHz H66V60</td>
<td>vertical</td>
<td>2</td>
<td>750</td>
<td>1000</td>
<td>1250</td>
<td>9</td>
<td>66</td>
<td>60</td>
<td>K 52 30 57</td>
</tr>
<tr>
<td>300</td>
<td>300MHz H116V32</td>
<td>vertical</td>
<td>2</td>
<td>1530</td>
<td>420</td>
<td>1587</td>
<td>9</td>
<td>116</td>
<td>32</td>
<td>K 73 95 04</td>
</tr>
<tr>
<td>450</td>
<td>450MHz H118V35</td>
<td>vertical</td>
<td>2</td>
<td>1020</td>
<td>280</td>
<td>1058</td>
<td>9.3</td>
<td>118</td>
<td>35</td>
<td>K 739504</td>
</tr>
<tr>
<td>450</td>
<td>450MHz H188V19</td>
<td>vertical</td>
<td>4</td>
<td>1960</td>
<td>140</td>
<td>1965</td>
<td>10</td>
<td>188</td>
<td>19</td>
<td>DAPA 1280</td>
</tr>
<tr>
<td>900</td>
<td>900MHz H65V7</td>
<td>vertical</td>
<td>8</td>
<td>2562</td>
<td>302</td>
<td>2580</td>
<td>18.5</td>
<td>65</td>
<td>7</td>
<td>K 739 624</td>
</tr>
<tr>
<td>900</td>
<td>900MHz H90V9</td>
<td>vertical</td>
<td>6</td>
<td>1922</td>
<td>242</td>
<td>1937</td>
<td>15.9</td>
<td>90</td>
<td>9</td>
<td>K 736 863</td>
</tr>
<tr>
<td>2100</td>
<td>2100MHz H66V7</td>
<td>vertical</td>
<td>45°</td>
<td>1302</td>
<td>132</td>
<td>1309</td>
<td>19.25</td>
<td>66</td>
<td>7</td>
<td>K 742 212</td>
</tr>
<tr>
<td>2100</td>
<td>2100MHz H90V81</td>
<td>vertical</td>
<td>10</td>
<td>204</td>
<td>164</td>
<td>262</td>
<td>8.1</td>
<td>90</td>
<td>81</td>
<td>K 742 149</td>
</tr>
<tr>
<td>3500</td>
<td>3500MHz H20V19</td>
<td>vertical</td>
<td>4×4</td>
<td>245</td>
<td>245</td>
<td>346</td>
<td>20</td>
<td>20</td>
<td>19</td>
<td>Alvarion</td>
</tr>
<tr>
<td>3500</td>
<td>3500MHz H65V9</td>
<td>vertical</td>
<td>12</td>
<td>482</td>
<td>62</td>
<td>486</td>
<td>17.3</td>
<td>65</td>
<td>9</td>
<td>Alvarion</td>
</tr>
<tr>
<td>5000</td>
<td>5000MHz H66V35</td>
<td>vertical</td>
<td>4</td>
<td>81</td>
<td>41</td>
<td>91</td>
<td>11.8</td>
<td>66</td>
<td>35</td>
<td>Huber &amp; Suhner</td>
</tr>
<tr>
<td>5000</td>
<td>5000MHz H360V8</td>
<td>vertical</td>
<td>6</td>
<td>330</td>
<td>0.5</td>
<td>330</td>
<td>10.5</td>
<td>360</td>
<td>8</td>
<td>SMCANT-00M10</td>
</tr>
</tbody>
</table>
7.5 Estimation Formulas

The following section describes the steps in the elaboration of the estimation formulas of the wbSAR and psSAR for exposure from base station antennas. A diagram of these steps is presented in Figure 7.2. First, the exposed human body is represented by a cuboid, as already proposed in [169,170], but never before used with the aim of developing any kind of analytical estimation. An analysis of the population statistical distribution of weight, height, and BMI allows to derive the dimensions of a human body leading to a conservative exposure for 95% of the population. A simple expression of the wbSAR is found and validated for plane-wave exposure, including enhancement due to tissue layers. An analysis of plane-wave results is then performed to derive worst-case ratios of wbSAR on psSAR.

The expression of the average power density along a vertical line in the boresight direction of the antenna is taken from [143]. Knowing that exposure from a base station antenna is not uniform over the entire cross-section of the body, an effective radiated surface of the exposed cuboid is defined. Thereafter, the formulas of the wbSAR and psSAR are determined, depending on readily available antenna parameters, the radiated power, the antenna-cuboid distance, and the dimensions of the 95th-percentile human.

![Diagram](image.png)

Figure 7.2: Diagram representing the steps in elaborating the SAR estimation formulas.
7.5.1 Generic Human Model

As a first step, the human phantom is approximated by a cuboid with the same height, weight, and skin surface as the human it represents. The cuboid is homogeneous with a density $\rho = 1000 \text{ kg/m}^3$. The skin surface of a human, $S$, can for example be approximated from its weight, $m$, and its height, $H$, by DuBois and DuBois \[171\]:

$$S_{DuBois} \left[ \text{cm}^2 \right] = 71.84 \left( m \left[ \text{kg} \right] \right)^{0.425} \left( H \left[ \text{cm} \right] \right)^{0.725}. \quad (7.1)$$

The total surface of the cuboid is calculated using (7.1) and its volume is found from its weight and density. The surface area and the volume, $V$, can also be expressed as a function of the dimensions of the cuboid: its height, $H$, width, $W$, and depth, $D$. The latter two are found by solving this system of equations of $S$ and $V$. The largest of the two obtained dimensions is associated with the width and the smallest with the depth, which maximizes the cross-section for frontal exposure and leads to a unique cuboid for each considered body. The dielectric properties of the homogeneous cuboid are set according to \[8\].

7.5.2 95th-Percentile Representative Phantom

Instead of generating the cuboid from the dimensions of a specific human body, a more general approach of the estimation formulas consists of using the dimensions of a realistic human body that would lead to a worst-case exposure covering 95% of the adult human population. The highest wbSAR is reached for a maximum ratio of $\frac{S_{cs}}{m}$ \[133,155\]. For a uniform exposure over the entire cross-section of the cuboid, the wbSAR, $SAR_{wb}$, can be estimated by

$$SAR_{wb} = \frac{S_{cs}}{m} P_{D,t}, \quad (7.2)$$

where $P_{D,t}$ is the power density transmitted into the solid and $S_{cs} = W \cdot H$ is taken as the frontal surface of the cuboid, as it has been shown that frontal exposure leads to the highest wbSAR when exposed either to plane waves \[155,172\] or to base station antennas \[133,144\].

Reference \[168\] provides anthropometric data (mean and standard deviation of weight, height, and BMI) for several groups of adults.
from the US, Europe, and Asia. Assuming that these data are repre-
sentative of the global population, 95% of the population have their
weight, height, and BMI included in the range ‘mean ± 2 × standard
deviation’. Figure 7.3 shows the cross-section to mass ratio of cuboids
based on weights, heights, and BMI within the range containing
95% of the population. The highest cross-section to mass ratio of
12.0 \cdot 10^{-3} \text{m}^2/\text{kg}, indicated by a circle on Figure 7.3, is obtained for
the lightest human and a maximum height which is limited by the
minimum BMI.

Under base-station antenna exposure, however, the entire body is
typically not uniformly exposed; the power density is higher around
the vertical center of the antenna. In this case, a shorter and wider
human body would absorb more radiation. The shortest and lightest
human, shown by a square on Figure 7.3, leads to a cross-section on
mass ratio of 11.2 \cdot 10^{-3} \text{m}^2/\text{kg}. In the case of exposure to base-station
antennas, this is more likely to lead to the highest wbSAR, thus these
dimensions were chosen to represent the 95th-percentile human (see
Table 7.3). For a typical base station exposure, i.e. stronger in the
center, the estimation will be conservative for 95% of the adults in
the population. If, however, the base station antenna is such that the
exposure is uniform over the entire height of the model, we expect this
cuboid to lead to a conservative estimation of the exposure for 90%
of the adults: the chosen value of cross-section on mass ratio (square
marker) is 94% of the maximum value (circle marker), itself leading
to a 95% estimation.

### 7.5.3 Induced Power Density

The SAR is defined as a function of the electric field in a solid, $E_{rms,t}$,

$$\text{SAR} = \frac{\sigma |E_{rms,t}|^2}{\rho},$$

where $\sigma$ and $\rho$ are the conductivity and density of the material, respectively. On the other hand, one can use the properties of a base station
antenna to compute the power density averaged along a vertical line
having the same height as the antenna (see Section 7.5.9). In the
next paragraphs, the relationship between the transmitted electric
Table 7.3: Dimensions of the cuboid representing the 95th-percentile human body.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>kg</td>
<td>46.7</td>
</tr>
<tr>
<td>Height</td>
<td>m</td>
<td>1.54</td>
</tr>
<tr>
<td>Width</td>
<td>m</td>
<td>0.339</td>
</tr>
<tr>
<td>Depth</td>
<td>m</td>
<td>0.089</td>
</tr>
<tr>
<td>$S_{cs}$</td>
<td>m$^2$</td>
<td>0.522</td>
</tr>
<tr>
<td>$S_{DuBois}$</td>
<td>m$^2$</td>
<td>1.40</td>
</tr>
</tbody>
</table>

Figure 7.3: Cross-section to mass ratio of the associated cuboid as a function of the weight and height of the human body. Only the points for which the weight, the height, and the BMI are within the range ‘mean $\pm 2 \times$ standard deviation’ are displayed, i.e. $46.7 \text{ kg} < m < 98.2 \text{ kg}$, $1.55 \text{ m} < H < 1.82 \text{ m}$, $16.9 \text{ kg/m}^2 < \text{BMI} < 34.1 \text{ kg/m}^2$. 
field and the incident power density will be developed and used to express the SAR as a function of a quantity related to base station antenna exposure: the incoming power density, $P_{D,i}$.

The power density of an electromagnetic wave, $P_D$, is defined from its electric and magnetic fields, $E$ and $H$ respectively:

$$\vec{P}_D = \Re \{ \vec{E}_{rms} \times \vec{H}^*_{rms} \}. \quad (7.4)$$

Assuming plane-wave propagation, the electric and magnetic fields are orthogonal and the impedance of the wave is defined as $Z = E/H = \sqrt{\mu/\epsilon}$, where $\mu$ is the complex permeability and $\epsilon$, the complex permittivity.

For a plane wave coming from free space at normal incidence to a non-magnetic medium of relative complex permittivity $\epsilon_r$, the transmitted electric field, $E_t$, is related to the incident electric field, $E_i$, via the transmission coefficient, $t = \frac{2}{1+\sqrt{\epsilon_r}}$. Using these definitions, the transmitted power density, $P_{D,t}$, can be expressed as

$$P_{D,t} = Z_i |t|^2 \Re \left\{ \frac{1}{Z^*_t} \right\} P_{D,i}, \quad (7.5)$$

where $Z_i$ and $Z_t$ are the impedance in the incidence and transmission media, respectively. And the transmitted electric field can be written as

$$|E_{rms,t}|^2 = Z_i |t|^2 P_{D,i}. \quad (7.6)$$

Using the SAR definition from (7.3), one can find the SAR at $x = 0$ inside a medium, $SAR(0)$, using (7.6), if the incident face of the medium is perpendicular to the direction of propagation of the incident wave:

$$SAR(0) = \frac{\sigma}{\rho} Z_i |t|^2 P_{D,i}(0). \quad (7.7)$$

### 7.5.4 Whole-body Average SAR

This section presents a general expression for the wbSAR, based on the same type of development as used in [173] for the 10 g psSAR, i.e., from an approximation based on the SAR at the surface of the model.
The average wbSAR, $SAR_{wb}$, is defined as the ratio of the total absorbed power to the total absorbing mass. In the case of a homogeneous solid, the average over the total volume, $V_{tot}$, can be written as a function of the position-dependant local SAR, $SAR(x, y, z)$:

$$SAR_{wb} = \frac{1}{V_{tot}} \iiint_{vol} SAR(x, y, z) dx dy dz.$$ (7.8)

This expression is valid for a homogeneous solid of arbitrary shape, but the integral becomes much simpler to evaluate in the case of a cuboid. The edge effects and the reflections from the back of the cuboid are neglected, i.e., the cuboid is treated as a portion of half-space. For a wave propagating in the $x$-direction, we assume that the SAR in the $yz$-plane is uniform over the ‘exposed region’, $R_{yz}$, and zero outside. The SAR decays exponentially along $x$ from the surface of the medium to its depth, $x_d$, so (7.8) becomes

$$SAR_{wb} = \frac{1}{V_{tot}} \iiint_{vol} SAR(x) dx dy dz$$ (7.9)

$$= \frac{1}{V_{tot}} \int_{R_{yz}} dy dz \int_{0}^{x_d} SAR(0) e^{-\frac{2x}{\delta}} dx$$ (7.10)

where $\delta$ is the penetration depth. Worst case will be reached for a thick model that will absorb all the power ($x_d \gg \delta$):

$$SAR_{wb} = \frac{1}{V_{tot}} \frac{\delta}{2} SAR(0) \int_{R_{yz}} dy dz.$$ (7.11)

For plane waves, the penetration depth is expressed as a function of the angular frequency, $\omega$, the real part of the relative permittivity, $\epsilon_r$, and the conductivity, $\sigma$, \[9\]:

$$\delta = \frac{1}{\omega} \left[ \left( \frac{\mu_0 \epsilon_r \epsilon_0}{2} \right) \left( \sqrt{1 + \left( \frac{\sigma}{\omega \epsilon_r \epsilon_0} \right)^2} - 1 \right) \right]^{-1/2}. \quad (7.12)$$

\[1\]For exposure from base station antennas, the evaluation of the power density from the properties of the antenna is averaged over the height of the antenna.
Figure 7.4: CDF of the enhancement of the absorbed power in a layered volume compared to a homogeneous volume [8] exposed to plane waves.

7.5.5 Tissue Layering

The enhancement of the SAR due to a layered structure compared to a homogeneous one has been shown exhaustively in the past [162, 174, 175]. In particular, the authors of [161] used far-field like exposure, a simplified one-dimensional model of tissue-layer compositions, and a set of all the possible layer compositions at any location at the surface of any human body in the population. They have shown that the effect on the 10 g psSAR could be up to 3 dB.

Using the same set of layer compositions, computation model, and exposure, we have assessed the enhancement on the absorbed power integrated along the depth of the body, assuming that no reflections are coming from the back surface of the structure. We exposed the half-spaces layers of tissues to incident plane waves at seven different frequencies between 30 MHz and 5.8 GHz. The absorbed power in these structures was compared to the absorbed power in the homogeneous body with dielectric properties set according to [8].
7.5. ESTIMATION FORMULAS

Figure 7.4 shows the CDF of the enhancement of the total absorbed power in the different configurations of layers compared to a homogeneous solid. The configurations of layers causing the worst-case enhancement (3 dB) are not found in every human body. Considering a realistic scenario where these configurations are present, it would be unreasonable to assume that they cover the entire cross-section. So even if these configurations are present, the increase of the whole-body SAR would be lower than 3 dB. Furthermore, most of the configurations leading to enhancements higher than 2.5 dB include a thick layer of fat, which is inconsistent with the cuboid chosen in Section 7.5.2 representing a thin human body. To avoid this overestimation, a more reasonable enhancement factor of 2.5 dB was chosen. The wbSAR including the layer enhancement factor will be a factor \(10^{2.5/10}\) higher than the wbSAR of a homogeneous volume. This value is validated using plane-wave simulations in Section 7.5.6.

7.5.6 Whole-body Average SAR – Plane-Wave Exposure

For a cuboid exposed to uniform plane waves, the exposed region \(R_{yz}\) is simply the area of the surface of incidence, \(S_{cs}\), and (7.11) becomes

\[
\text{SAR}_{wb} = \frac{1}{V_{tot}} \frac{\delta}{2} W_{body} H_{body} \text{SAR}(0) \quad (7.13)
\]

\[
= \frac{\delta}{2D_{body}} \text{SAR}(0), \quad (7.14)
\]

where \(D_{body}, W_{body},\) and \(H_{body}\) are the depth, width, and height of the cuboid, respectively.

To validate the cuboid approach and the layer enhancement factor of 2.5 dB, simulation results of plane waves were compared to the estimation of the wbSAR from (7.14) and (7.7). Figure 7.5 shows the results from plane-wave exposure (worst-case of polarization and exposure side) of the VFB from [155] and [172] between 300 MHz and 5 GHz. The results are expressed as the percentage of the wbSAR basic restriction reached for a plane-wave exposure at the reference level (according to ICNIRP, see Tables 7.4 and 7.5). Additional simulations were performed using a homogeneous cuboid based on the
Table 7.4: ICNIRP-1998 \cite{2} (10 kHz to 10 GHz) and IEEE C95.1-1991 \cite{4} (300 kHz to 100 GHz) basic restrictions for occupational exposure.

<table>
<thead>
<tr>
<th>Source</th>
<th>SAR W/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole-body average</td>
<td>ICNIRP/IEEE 0.4</td>
</tr>
<tr>
<td>10 g in head and trunk</td>
<td>ICNIRP 10</td>
</tr>
<tr>
<td>10 g in limbs</td>
<td>ICNIRP 20</td>
</tr>
<tr>
<td>1 g in body(^a)</td>
<td>IEEE 8</td>
</tr>
</tbody>
</table>

height and weight of the VFB (cuboid: 19.4 kg, 0.065 m × 0.253 m × 1.176 m) frontally exposed to vertically polarized plane waves. The dielectric properties were set according to \cite{8}, which are based on a 95% requirement for near-field exposure. The compensation factors introduced in \cite{8} were not taken into account, since the enhancement due to tissue layering was considered separately here.

Figure 7.5 shows that the simulation of the cuboid (gray markers) as well as the estimation of the wbSAR based on its dimensions (gray line) are much lower than the wbSAR of the VFB (black markers) over the entire frequency range. The estimation based only on homogeneous considerations (gray line) is close to the simulation results of wbSAR of the homogeneous cuboid. On the other hand, the estimation including the layering enhancement of 2.5 dB (black line) is at the same level as the results of the VFB.

For frequencies higher than 2 GHz, the dielectric properties from \cite{8} lead to more conservative results from the cuboid simulations, as well as from the approximation including the layering enhancement. We can conclude that (7.14) and (7.7) combined with a layering enhancement factor of 2.5 dB are a good approximation for frequencies between 300 MHz and 2000 MHz, and more conservative than the plane-wave simulation results for higher frequencies.
Table 7.5: ICNIRP reference levels for occupational exposure.

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>Plane-wave power density ( W/m^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-400 MHz</td>
<td>10</td>
</tr>
<tr>
<td>400-2000 MHz</td>
<td>( f/40 )</td>
</tr>
<tr>
<td>2-300 GHz</td>
<td>50</td>
</tr>
</tbody>
</table>

7.5.7 Peak Spatial SAR

The psSAR is highly dependent on the anatomical properties and posture of the phantom [172]. The position of the potential local enhancement parts of the body, typically the wrists, ankles, nose, or groin, relative to the local field maxima also has a direct influence on the psSAR value. Thus, the psSAR for a specific configuration of antenna and phantom is hard to evaluate without a simulation. However, the ratio between the wbSAR and the psSAR determined from plane-wave simulations allows a rough but simple worst-case estimation. Figure 7.6 uses plane-wave exposure data of standing models from [155] and [172] to show \( R_{wb}/R_{1g,10g} \), the ratio between the wbSAR (to its ICNIRP basic restriction: \( R_{wb} = SAR_{wb}/SAR_{limit}^{wb} \)) and the psSAR (to its ICNIRP basic restriction: \( R_{10g} = SAR_{10g}/SAR_{limit}^{10g} \) or \( R_{1g} = SAR_{1g}/SAR_{limit}^{1g} \)).

A ratio depending on the frequency range is used to estimate the psSAR from the estimation of the wbSAR:

\[
R_{wb/1g} = \begin{cases} 
0.6 & \text{if } 300 \text{ MHz} \leq f \leq 2.5 \text{ GHz} \\
0.3 & \text{if } 2.5 \text{ GHz} < f \leq 5 \text{ GHz}
\end{cases} \tag{7.15}
\]

\[
R_{wb/10g} = \begin{cases} 
1.5 & \text{if } 300 \text{ MHz} \leq f \leq 2.5 \text{ GHz} \\
1 & \text{if } 2.5 \text{ GHz} < f \leq 5 \text{ GHz}
\end{cases} \tag{7.16}
\]

This frequency dependent ratio is based on plane-wave exposure of standing models. Since it does not consider the eventual local enhancements due to the radiation pattern of the antenna or the
posture of the model, it should at least be conservative enough to include all the results of plane-wave exposure presented here. Other postures might cause substantially higher psSAR, as shown in [172].

The expression of the psSAR (\(SAR_{1g}\) or \(SAR_{10g}\)) based on these ratios and on (7.14) for wbSAR is:

\[
\frac{SAR_{1g,10g}}{SAR_{1g,10g}^{\text{limit}}} = \frac{1}{R_{wb/1g,10g}} \frac{SAR_{wb}}{SAR_{wb}^{\text{limit}}},
\]

\[
SAR_{1g,10g} = \frac{1}{2R_{wb/1g,10g}} \frac{SAR_{1g,10g}^{\text{limit}}}{SAR_{wb}^{\text{limit}}} \frac{\delta}{D_{\text{body}}} SAR(0).
\]

7.5.8 Cylindrical Propagation – Radiating Near Field

It was shown in [143] that cylindrical propagation could be assumed in the radiating near field of a collinear array antenna. The power flux is then confined within the horizontal HPBW, \(\Phi_{3\text{dB}}\), and the overall height of the antenna, \(L\). The average power density, \(\overline{P_D}\), along a
vertical line of length $L$, at a distance $r$ from the center of phase of the antenna in the boresight direction is given by

$$
\overline{P_D}(r, \Phi_{3dB}) = \frac{P_{rad}}{\Phi_{3dB} r L \sqrt{1 + \left(\frac{r}{r_0}\right)^2}},
$$

where $P_{rad}$ is the power radiated from the antenna and $G_A$ its directivity.

Equation (7.19) and the physical characteristics of the antennas were used to compute the average power density along a vertical line parallel to the axis of the 12 antennas described in Section 7.4.2. Figure 7.7 compares the results of (7.19) with the computation of the average power density from free-space simulations.

Equation (7.19) should be used with caution at small distances from very large antennas (where $D/2 > 200$ mm, such as the 300-, 450-, and 900-MHz antennas on Figure 7.7) as well as with antennas for which the width is comparable to the height (such as the 300MHz H66V60 and the 3500MHz H20V19) since (7.19) is based on
the hypothesis that the antenna has a slender shape. However, for the twelve antennas used in this paper and for distances larger than 500 mm, the equation either underestimates the simulation results by no more than to 0.4 dB or overestimates them, leading to a more conservative SAR estimation, by at most 0.8 dB. Figure 7.7 shows that (7.19) is also a good approximation in the far field of the antennas.

![Figure 7.7: Comparison of average power density from simulations and calculated from (7.19). For each antenna, the $D/2$ limit is shown by a point on the curve.](image)

7.5.9 Whole-body Average SAR – Base-Station Antennas

In (7.11), the exposed region, $R_{yz}$, depends strongly on the human model in front of the antenna and the characteristics of the antenna itself. Once again, a simple case is to approximate the human body by a cuboid of depth $D_{body}$, width $W_{body}$, and height $H_{body}$. However, the entire height or width of its cross-section might not be homogeneously exposed by the wave coming from the antenna. The exposed portion
7.5. ESTIMATION FORMULAS

of its width and height are named $W_{eff}$ and $H_{eff}$, respectively. In this case, (7.11) for the wbSAR can be written as

$$SAR_{wb} = \frac{1}{V_{tot}} \frac{\delta}{2} W_{eff} H_{eff} SAR(0)$$

$$= \frac{1}{2} \frac{\delta}{D_{body}} \frac{W_{eff}}{W_{body}} \frac{H_{eff}}{H_{body}} SAR(0).$$

We consider that the model is exposed over its entire width ($W_{eff} = W_{body}$), which is a worst-case assumption. However, we assume that the exposed portion of its height varies with the distance between the body and the antenna, the height of the phantom, and the beam spread, $H_{beam}$, calculated from the far-field characteristics of the antenna (vertical HPBW, $\Theta_{3dB}$):

$$H_{beam} = 2d \tan(\Theta_{3dB}/2),$$

where $d$ is the distance between the outer most point of the antenna and a box bounding the human model. The expression of $H_{eff}$ chosen is shown in (7.23) and represented in Figure 7.8:

$$H_{eff} = \begin{cases} 
H_{body} & \text{if } H_{body} \leq L \\
L & \text{if } H_{beam} < L, H_{body} \\
H_{beam} & \text{if } L \leq H_{beam} < H_{body} \\
H_{body} & \text{if } H_{body} \leq H_{beam}
\end{cases}.$$ (7.23)

If the phantom is shorter than the antenna, $H_{eff}$ is equal to $H_{body}$, regardless of the antenna-body distance. Otherwise, if the phantom is taller than the antenna and the beam spread (Figure 7.8 position p1), $H_{eff}$ is equal to the height of the antenna. If the beam spread is bigger than the antenna height, but still shorter than the phantom (Figure 7.8 position p2), the height of the beam spread is taken for $H_{eff}$. And if the phantom is shorter than the beam spread, the entire height of the body is exposed (Figure 7.8 position p3), so $H_{eff}$ is equal to $H_{body}$. Vertically and horizontally, the center of the human body is considered to be aligned with the center of the antenna, which maximizes the exposed height and width (trunk), thus leading to worst-case exposure.
Figure 7.8: Schematic side view of the exposed vertical length as defined in (7.23), at various distances from the antenna, depending on its vertical opening angle. The red lines indicate the upper and lower boundaries of $H_{eff}$.

7.5.10 Issues Relative to Short Antenna-Body Distances

For short antenna-human body distances, the complex shape of the human body leads to a high uncertainty of the distance. Moreover, the assumptions made in the last paragraphs are no longer valid very close to the antenna ($d < \lambda/2\pi$). The field is complex and no general equation can easily be assumed or derived. The energy reflected by the human can possibly be very strong, changing the impedance of the sources and thus the radiating properties of the antenna [161]. References [69] and [8] suggest measurements for distances up to 200 mm from the antenna. We also propose that dosimetric measurements be made closer than 200 mm to ensure compliance with the guidelines.

7.5.11 Final Form of the Estimation Formulas

This section presents the final version of the estimation formulas in their general form, with $r \approx d$. The frequency range has been

$^2$The distance $r$ used in (7.19) is measured from the center of phase of the antenna, which corresponds to the surface of the back reflector when there is one.
7.5. ESTIMATION FORMULAS

restricted to the range within which we could validate the formulas with the simulation results (Section 7.6), i.e. 300 MHz to 5 GHz. The equations do not include possible effects produced by the presence of reflective walls or ground plane as studied in [176].

\[
SAR_{wb} = \frac{10^{0.25}}{2} \frac{\delta}{D_{body}} \frac{W_{eff}}{W_{body}} \frac{H_{eff}}{H_{body}} SAR(0), \quad (7.24)
\]

\[
SAR_{1g,10g} = \frac{10^{0.25}}{2R_{wb/1g,10g}} \frac{SAR_{limit}^{1g,10g}}{SAR_{limit}^{wb}} \frac{\delta}{D_{body}} SAR(0), \quad (7.25)
\]

with

\[
SAR(0) = \frac{\sigma Z_i |t|^2 P_{rad}}{\rho \Phi_{3dB} L d} \left[ 1 + \left( \frac{4\pi d}{\Phi_{3dB} G_A L} \right)^2 \right]^{-1/2}, \quad (7.26)
\]

\[
R_{wb/1g} = \begin{cases} 
0.6 & \text{if } 300 \text{ MHz} \leq f \leq 2.5 \text{ GHz} \\
0.3 & \text{if } 2.5 \text{ GHz} < f \leq 5 \text{ GHz} 
\end{cases}, \quad (7.27)
\]

\[
R_{wb/10g} = \begin{cases} 
1.5 & \text{if } 300 \text{ MHz} \leq f \leq 2.5 \text{ GHz} \\
1 & \text{if } 2.5 \text{ GHz} < f \leq 5 \text{ GHz} 
\end{cases}, \quad (7.28)
\]

\[
H_{eff} = \begin{cases} 
H_{body} & \text{if } H_{body} \leq L \\
L & \text{if } H_{beam} < L, H_{body} \\
H_{beam} & \text{if } L \leq H_{beam} < H_{body} \\
H_{body} & \text{if } H_{body} \leq H_{beam}
\end{cases}, \quad (7.29)
\]

\[
H_{beam} = 2d \tan(\Theta_{3dB}/2), \quad (7.30)
\]

On the other hand, \(d\) is defined as the distance between the outer most point of the antenna and a box enclosing the body. Taking \(r \approx d\) leads to an underestimation of \(r\), so a higher power density, thus a higher SAR estimation. Antenna users can only measure the distance from the radom of a given antenna, so that the approximation \(r \approx d\) is both more representative of practical measurements and more conservative.
\[ W_{eff} = W_{\text{body}}, \quad (7.31) \]

\[ t = \frac{2}{1 + \sqrt{\varepsilon_r}}, \quad (7.32) \]

\[ \delta = \frac{1}{\omega} \left[ \left( \frac{\mu_0 \varepsilon_r \varepsilon_0}{2} \right) \left( \sqrt{1 + \left( \frac{\sigma}{\omega \varepsilon_r \varepsilon_0} \right)^2} - 1 \right) \right]^{-1/2}. \quad (7.33) \]

### 7.5.12 Compact Form of the 95th-Percentile Estimation Formulas

The estimation formulas are written here in a more compact form based on the premise of covering 95% of the adult human population. To simplify the expression of the estimation formulas, the parameters that present only a frequency dependency have been gathered into a separate parameter \( C(f) \):

\[ SAR_{wb} = C(f) \frac{H_{\text{eff}}}{0.089 \text{ m} \cdot 1.54 \text{ m}} \frac{P_{\text{rad}}}{\Phi_{3\text{dB}} L d} \left[ 1 + \left( \frac{4 \pi d}{\Phi_{3\text{dB}} G_A L} \right)^2 \right]^{-1/2}, \quad (7.34) \]

\[ SAR_{1g,10g} = 25 \cdot SAR_{wb} \frac{1.54 \text{ m}}{H_{\text{eff}}} \frac{1}{R_{wb/1g,10g}}, \quad (7.35) \]

\[ H_{\text{eff}} = \begin{cases} 1.54 \text{ m} & \text{if } 1.54 \text{ m} \leq L \\ L & \text{if } H_{\text{beam}} < L, 1.54 \text{ m} \\ H_{\text{beam}} & \text{if } L \leq H_{\text{beam}} < 1.54 \text{ m} \\ 1.54 \text{ m} & \text{if } 1.54 \text{ m} \leq H_{\text{beam}} \end{cases}, \quad (7.36) \]

\[ H_{\text{beam}} = 2d \tan(\Theta_{3\text{dB}}/2), \quad (7.37) \]

\[ R_{wb/1g} = \begin{cases} 0.6 & \text{if } 300 \text{ MHz} \leq f \leq 2.5 \text{ GHz} \\ 0.3 & \text{if } 2.5 \text{ GHz} < f \leq 5 \text{ GHz} \end{cases}, \quad (7.38) \]
\[ R_{wb/10g} = \begin{cases} 1.5 & \text{if } 300 \text{ MHz} \leq f \leq 2.5 \text{ GHz} \\ 1 & \text{if } 2.5 \text{ GHz} < f \leq 5 \text{ GHz} \end{cases}, \quad (7.39) \]

\[ C(f) = \frac{10^{0.25}}{2} \delta(f) |t(f)|^2 \frac{\sigma(f)}{\rho} \sqrt{\frac{\mu_0}{\epsilon_0}}. \quad (7.40) \]

Table 7.6: Piecewise linear approximation of \( C(f) \)

<table>
<thead>
<tr>
<th>( f ) MHz</th>
<th>( C(f) ) ( 10^{-4} \text{ m}^3/\text{kg} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>6.3</td>
</tr>
<tr>
<td>900 - 5000</td>
<td>8.1</td>
</tr>
</tbody>
</table>

The coefficient \( C(f) \) is frequency dependent. It can be evaluated using the values of conductivity and permittivity from [8]. Table 7.6 shows the approximation of \( C(f) \). The deviation in \( C(f) \) is less than 5%, which will lead to an error lower than 5% in the SAR.

7.6 Numerical Validation

The SAR in heterogeneous structures such as a human body is impossible to measure, even with state-of-the-art systems. The results of wbSAR and psSAR from the approximation formulas were thus validated by comparison to numerical results from the commercial FDTD simulation platform SEMCAD X using an extensive list of configurations of humans in front of base station antennas. To further verify the simulation results, a few specific configurations were run independently by various groups using other simulation tools, such as the commercial platforms FEKO (EMSS, South Africa) and XFtdt (Remcom, USA), as well as the in-house codes from Hokkaido University, France Telecom Research & Development, and Aalto University.

\(^3\)The approximation of \( C(f) \) results in a deviation of less than 5%. For frequencies between 300 MHz and 900 MHz, a linear interpolation should be used.
The extensive exposure matrix consists of all the possible combinations of the following specifications:

- 12 antennas (6 frequencies: 300, 450, 900, 2100, 3500, and 5000 MHz);
- 6 distances: 10, 50, 300, 500, 1000, and 3000 mm;
- 3 human models: VFM, VFF, and VFB;
- 2 exposure sides: front and back.

Only exposure from the front and the back of the model were simulated as it has already been shown to lead to the worst-case wb-SAR [133, 144, 155, 172]. The human models and the antennas are aligned center-to-center both horizontally and vertically.

The comparison between the wbSAR and psSAR from the estimation formulas and from the simulations is presented in Figure 7.9 for the antenna 900MHzH65V7. The results are displayed as a ratio to the SAR limit (Table 7.4), normalized such that the average power density 200 mm from the antenna computed with (7.19) is equal to the ICNIRP power density limit. For this antenna, this corresponds to a radiated power of 13.1 W. The curve of the ratio of the power density calculated from the antenna properties (7.19) to the ICNIRP power density limit is also shown.

It can be observed in Figure 7.9 that the estimation formulas are conservative for the adult models at distances further than 200 mm, but not always for the VFB when considering the wbSAR. This is also the case for the eleven other antennas. At low frequencies, the ICNIRP power density limit is more conservative than the estimation formulas of the wbSAR and the psSAR (as can be seen on Figure 7.9). For higher frequencies (not shown here), the ICNIRP power density limit is more conservative than the wbSAR estimation formula in almost every case and the 10 g psSAR estimation formula is only about 1 dB more conservative than the ICNIRP power density limit. However, the estimation of the 1 g psSAR is about 5 dB more conservative than the ICNIRP power density limit.

The results from Figure 7.9 as well as the ones obtained for the eleven other antennas, are statistically analyzed to allow general observations and conclusions to be derived. Figure 7.10 presents the deviation between the estimation formulas and the simulation results (>200 mm) for all the human models, sides of exposure, and antennas, where values lower than 0 dB represent configurations for
Figure 7.9: Comparison of the simulation results of wbSAR and psSAR with the estimation formulas developed in Section 7.5 and the ratio of (7.19) to the ICNIRP power density limit, for the antenna 900MHz H65V7. The SAR is expressed as a ratio to the ICNIRP basic restrictions for a radiated power of 13.1 W.

which the formulas give a conservative estimation of the SAR. These histograms show that the estimation formulas for the wbSAR are more conservative than the results of the bulk simulations using the adult models, VFM and VFF, for all the simulation configurations (for distances higher than 200 mm). However, the estimation formulas for the wbSAR do not constitute a conservative approximation of the absorption in the VFB as only adults are taken into account in the statistical analysis leading to the 95th-percentile human. For the 1 g
and 10 g psSAR, governed by the shape of the body rather than that of its cross-section, the results of the VFB are distributed similarly to the results from the adult models, and the estimation formulas are conservative for all the models and configurations.

Figure 7.10: Histograms of the deviation between the bulk simulation results of the three models (> 200 mm) and the estimation formulas based on the 95th-percentile human body cuboid (simulation/estimation).
7.7 Discussion and Conclusions

The developed estimation formulas are based on the identified absorption mechanisms derived from physical considerations combined with plane-wave simulations of anatomical human bodies. They estimate the 95th-percentile whole-body and peak spatial SAR values of adults (i.e., maintenance personnel) in the vicinity of base station antennas. The estimation formulas were validated with extensive simulations.

The validation by numerical means also demonstrates that the approximation is not always conservative for children. However, the available data do not allow determination of the uncertainty of the approximation with respect to the 95th-percentile exposure due to missing worst-case anatomical/generic models. Nevertheless, confidence is high due to the step-by-step approximation with uncertainty analysis. The comparison with the simulated configurations provides no indication of a strong overestimation or underestimation of the 95th-percentile exposure. However, the estimation formulas only consider standing models, whereas a different posture could increase the psSAR.

In the reactive near-field region, estimation formulas as well as full-wave simulations have been found to be problematic in estimating human exposure due to the strong dependence of the localized absorption on the human anatomy. Furthermore, the effects of reflections of the human body on the antenna impedance, the feeding network in particular and possibly the power amplifier, are not predictable with state-of-the-art simulation tools without detailed knowledge of the antenna feed system and its RF power source. Thus, at close antenna-body distances of less than 200 mm, SAR measurements are strongly recommended for demonstrating compliance. The selection of the most appropriate phantom needs to be investigated in future work.
Part V

Epilogue
Chapter 8
Conclusions & Outlook

8.1 Conclusions

Numerous dosimetric assessment tools and improved procedures for the exposure to radio-frequency (RF) electromagnetic fields (EMF) were developed, evaluated, and validated within the framework of this thesis. The methods and results presented here allow for better, easier, and more comprehensive dosimetric evaluations, thus improving safety assessment and allowing complex epidemiologic studies to be based on more detailed exposure data. Two very common scenarios were considered, addressing the typical exposure to two groups of people: near-field exposure from mobile phones, relevant for the general population, and near-field and far-field exposure from base station antennas, relevant for, e.g., rooftop personnel.

Anatomical models are a cornerstone of realistic dosimetric assessment. The limitations of existing models prevent their application to emerging research fields, e.g., medical implant safety assessment or new therapies efficacy evaluation. Development was performed to obtain anatomical models that meet the new necessary requirements. These include implementation of quality control procedures, re-segmentation at higher resolution, more-consistent tissue assignments, enhanced surface processing, and numerous anatomical refinements. A comprehensive tissue properties database was compiled to
complement the library of models. The results are a set of anatomically independent, accurate, and detailed models, the Virtual Population 3.0, with smooth, yet feature-rich and topologically conforming surfaces suitable to a wide range of solvers and physics. The anatomical models and the database of material properties described herein are available to the research community.

To strengthen epidemiologic evaluations and improve information for the consumer as well as health and radiation safety agencies, a methodology was developed to determine tissue-specific exposure by expanding the post-processing of the measured surface or volume scans using standardized compliance testing equipment, i.e., specific absorption rate (SAR) scanners. This enables the reliable determination of the maximum and averaged exposure of specific tissues and functional brain regions to mobile phones when combined with mobile phone power control data, results that can ultimately be used to formulate a recommendation for exposure reduction.

The exposure of children to mobile phones has been a concern for years and although numerical studies have validated the use of the specific anthropomorphic mannequin (SAM) phantom — developed from measurements of male heads — no experimental evidence has ever been provided. Issues related to the exposure of children were also addressed by comparing the maximum exposure in the SAM head to the exposure in homogeneous child head models. Although it was found that SAM is a conservative assessment in the studied cases, the results also demonstrate that the currently suggested numerical SAR averaging procedures may underestimate the actual peak spatial SAR and that the currently defined limits in terms of the average of a cubic mass are impractical for non-ambiguous evaluations, i.e., for achieving inter-laboratory repeatability. It points to a need to update the current numerical standards for mass-averaged SAR evaluation.

Next, the gap of knowledge concerning the exposure to the low-frequency (LF) fields from mobile phones was addressed. Numerical and experimental assessment has shown that the B-field induced by currents in phones using the UMTS system is 2 orders of magnitude lower than that induced by GSM. Knowing that the RF exposure from UMTS is also 2 orders of magnitude lower than from GSM, it is now possible to state that there is an overall reduction of the exposure from this communication system. The general public as well as health
and radiation safety agencies can now benefit from a recommendation for the use UMTS systems over GSM formulated based on these new results.

Finally, the demonstration of compliance with guidelines for human exposure to base station antennas can be a time consuming process or often results in overly conservative estimates. To alleviate this burden and reduce the overestimation, approximation formulas for the whole-body average SAR and the peak spatial SAR of human bodies using readily available basic antenna parameters have been developed and validated. The formulas can be used for adults standing in the radiating near field of base station antennas operating between 300 MHz and 5 GHz, at distances larger than 200 mm. Those estimation formulas were included in IEC 62232 [140], an international standard about human exposure describing methods for the determination of the fields in the vicinity of base station antennas. Besides providing a method to easily and quickly assess the safety of workers, the results presented here allow antenna manufacturers to perform safety evaluations as part of the development process, and eventually reach better time to market.

In summary, the work performed in this thesis has contributed to the improvement of dosimetric assessment of EMF exposure by providing more efficient methods to demonstrate compliance, without compromising safety, and by providing more comprehensive exposure evaluations to epidemiologists. All the results presented in this thesis have been published in peer-reviewed journals and discussed in several international conferences, hence ensuring large-scale dissemination.

8.2 Outlook

The research performed in this thesis has revealed a major issue in numerical SAR averaging procedures implemented in the most common electromagnetic simulation softwares used for dosimetric assessment and applied daily by researchers and engineers. This demands the elaboration of a new averaging definition that allows reproducible results, not only at the surface of the phantom and independent on the computational grid/phantom orientation, but also when considering
anatomical whole-body phantoms, at the fingers, joints, or locations including internal air.

With all the improvements of the Virtual Population, those anatomical models are now suitable for simulations using various physics and fulfills compelling needs of the medical community, seeking for means to assess the safety of medical implants and the efficacy of new therapies. The consistent tissue assignments, higher-resolution segmentation, and anatomical refinements of the new generation of models now opens the door to their functionalization, e.g., by integration of inhomogeneous property maps or dynamic behavior (e.g., blood flow or neuron models). Also, the application of the models to new physics and computational methods will certainly lead to additional demands, and further improvements, specific processing, or features will be needed to even better fulfill those requirements.

The estimation formulas for the exposure to base station antennas can be used to assess the safety of workers standing in the vicinity of the antennas. The effect of a reflective environment as well as various relevant body postures have already been investigated in the framework of the same research project [172,176]. However, the radiation from the antenna cables was not included in this study and neither was the exposure behind the antenna, which might be overestimated by the estimation formulas. In addition, as microcells leading to uncontrolled exposure are becoming more common, the electromagnetic fields in such rooms and environments should be further investigated to protect not only workers but also the general public.

The estimation factors derived to estimate the SAR in anatomical brain regions from measurements in the homogeneous SAM phantom can be applied to head exposure, but mobile phones are nowadays used not only at the head; corresponding estimation factors and uncertainties could be derived for the exposure of various body regions following a similar procedure. The study should also be extended to higher frequencies relevant for more recent technologies such as LTE for VoIP and WiFi. Those new technologies should also be considered in terms of the LF magnetic field they induce in order to provide a sound recommendation for their usage.
Part VI

Appendix
## Appendix A

### List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABC</td>
<td>Absorbing Boundary Conditions</td>
</tr>
<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
</tr>
<tr>
<td>BfS</td>
<td>Bundesamt für Strahlenschutz (German Federal Office for Radiation Protection)</td>
</tr>
<tr>
<td>BMI</td>
<td>Body Mass Index</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CM</td>
<td>Cross-Section to Mass</td>
</tr>
<tr>
<td>CNS</td>
<td>Central Nervous System</td>
</tr>
<tr>
<td>CSF</td>
<td>Cerebrospinal Fluid</td>
</tr>
<tr>
<td>DASY</td>
<td>Dosimetric Assessment System</td>
</tr>
<tr>
<td>DUT</td>
<td>Device Under Test</td>
</tr>
<tr>
<td>ECC</td>
<td>Electronic Communications Committee</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>EMF</td>
<td>Electromagnetic Field</td>
</tr>
<tr>
<td>ETHZ</td>
<td>Eidgenössische Technische Hochschule Zürich</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communication Commission</td>
</tr>
<tr>
<td>FDA</td>
<td>Food and Drug Administration</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplexing</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>FDTD</td>
<td>Finite-Difference Time-Domain</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transformation</td>
</tr>
<tr>
<td>FGF</td>
<td>Forschungsgemeinschaft Funk (Research Association for Radio Applications)</td>
</tr>
<tr>
<td>FSM</td>
<td>Research Foundation Mobile Communication</td>
</tr>
<tr>
<td>GHB</td>
<td>Generalized Huygens Box</td>
</tr>
<tr>
<td>GSF</td>
<td>Gesellschaft für Strahlenforschung</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communications</td>
</tr>
<tr>
<td>HSL</td>
<td>Head Tissue Simulating Liquid</td>
</tr>
<tr>
<td>ICNIRP</td>
<td>International Commission on Non-Ionizing Radiation Protection</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IT’IS</td>
<td>IT’IS Foundation for Information Technologies in Society</td>
</tr>
<tr>
<td>JF</td>
<td>Japanese Female</td>
</tr>
<tr>
<td>JM</td>
<td>Japanese Male</td>
</tr>
<tr>
<td>LF</td>
<td>Low Frequency</td>
</tr>
<tr>
<td>MDRF</td>
<td>Medical Devices Research Forum</td>
</tr>
<tr>
<td>MMF</td>
<td>Mobile Manufacturers Forum</td>
</tr>
<tr>
<td>MoM</td>
<td>Method of Moments</td>
</tr>
<tr>
<td>MR</td>
<td>Magnetic Resonance</td>
</tr>
<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>NSERC</td>
<td>Natural Sciences and Engineering Research Council of Canada</td>
</tr>
<tr>
<td>NURBS</td>
<td>Non-Uniform Rational B-Spline</td>
</tr>
<tr>
<td>PCL</td>
<td>Power Control Level</td>
</tr>
<tr>
<td>psSAR</td>
<td>Peak Spatial SAR</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>SAM</td>
<td>Specific Anthropomorphic Mannequin</td>
</tr>
<tr>
<td>SAR</td>
<td>Specific Absorption Rate</td>
</tr>
<tr>
<td>SAT</td>
<td>Subcutaneous Adipose Tissue</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>SEMCAD</td>
<td>Simulation Platform for Electromagnetic Compatibility Antenna Design and Dosimetry</td>
</tr>
<tr>
<td>SNF</td>
<td>Swiss National Science Foundation</td>
</tr>
<tr>
<td>SPEAG</td>
<td>Schmid &amp; Partner Engineering AG</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplexing</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TSL</td>
<td>Tissue Simulating Liquid</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
</tr>
<tr>
<td>VF</td>
<td>Virtual Family</td>
</tr>
<tr>
<td>VFB</td>
<td>Virtual Family Boy (Thelonious)</td>
</tr>
<tr>
<td>VFG</td>
<td>Virtual Family Girl (Billie)</td>
</tr>
<tr>
<td>VFF</td>
<td>Virtual Family Female (Ella)</td>
</tr>
<tr>
<td>VFM</td>
<td>Virtual Family Male (Duke)</td>
</tr>
<tr>
<td>VH</td>
<td>Visible Human</td>
</tr>
<tr>
<td>ViP</td>
<td>Virtual Population</td>
</tr>
<tr>
<td>W-CDMA</td>
<td>Wideband Code Division Multiple Access</td>
</tr>
<tr>
<td>wbSAR</td>
<td>Whole-Body Average SAR</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organization</td>
</tr>
<tr>
<td>ZonMw</td>
<td>Netherlands Organization for Health Research and Development</td>
</tr>
<tr>
<td>ZMT</td>
<td>Zurich MedTech</td>
</tr>
</tbody>
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## Appendix B

### List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{rms}}$</td>
<td>electric field (root mean square)</td>
<td>V/m</td>
</tr>
<tr>
<td>$H_{\text{rms}}$</td>
<td>magnetic field (root mean square)</td>
<td>A/m</td>
</tr>
<tr>
<td>$P_D$</td>
<td>power density</td>
<td>W/m²</td>
</tr>
<tr>
<td>$f$</td>
<td>frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$\omega$</td>
<td>angular frequency</td>
<td>rad</td>
</tr>
<tr>
<td>$\delta$</td>
<td>penetration depth</td>
<td>m</td>
</tr>
<tr>
<td>$Z$</td>
<td>wave impedance</td>
<td>Ω</td>
</tr>
<tr>
<td>$\hat{\varepsilon}$</td>
<td>complex permittivity, $\hat{\varepsilon} = \varepsilon_0 \cdot \hat{\varepsilon}_r$</td>
<td>F/m</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>permittivity of free space, $\varepsilon_0 = 8.854 \times 10^{-12}$</td>
<td>F/m</td>
</tr>
<tr>
<td>$\hat{\varepsilon}_r$</td>
<td>complex relative permittivity, $\hat{\varepsilon}_r = \varepsilon_r + j\varepsilon''_r$</td>
<td></td>
</tr>
<tr>
<td>$\hat{\mu}$</td>
<td>magnetic permeability, $\mu = \mu_0 \cdot \mu_r$</td>
<td>H/m</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>permeability of free space, $\mu_0 = 4\pi \times 10^{-7}$</td>
<td>H/m</td>
</tr>
<tr>
<td>$\hat{\mu}_r$</td>
<td>relative magnetic permeability, $\hat{\mu}_r = \mu_r + j\mu''_r$</td>
<td></td>
</tr>
<tr>
<td>$D$</td>
<td>largest dimension of the antenna</td>
<td>m</td>
</tr>
<tr>
<td>$L$</td>
<td>overall height of the antenna</td>
<td>m</td>
</tr>
<tr>
<td>$G_A$</td>
<td>directivity of the antenna</td>
<td>dBi</td>
</tr>
<tr>
<td>$\Theta_{3\text{dB}}$</td>
<td>vertical HPBW</td>
<td>degrees</td>
</tr>
<tr>
<td>$\Phi_{3\text{dB}}$</td>
<td>horizontal HPBW</td>
<td>degrees</td>
</tr>
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</table>
APPENDIX B. LIST OF SYMBOLS

- $r$: distance from the center of phase of the antenna (m)
- $H$: height of the irradiated body (m)
- $V$: volume of the irradiated body ($m^3$)
- $m$: mass of the irradiated body (g)
- $\rho$: mass density ($kg/m^3$)
- $S_{cs}$: surface of the cross-section of a body, i.e. projected surface in a plane perpendicular to the irradiation ($m^2$)
- $S_{DuBois}$: skin surface estimation ($m^2$)
- $SAR_{1g,10g}$: peak SAR spatially averaged over 1 g or 10 g ($W/kg$)
- $SAR_{wb}$: whole-body average SAR ($W/kg$)
- $SAR_{\text{limit}}$: limit on the SAR ($W/kg$)
- $R_{1g,10g}$: ratio of the 1 g or 10 g psSAR to its respective ICNIRP limit, i.e. $SAR_{1g,10g}/SAR_{\text{limit}}^{1g,10g}$
- $R_{wb}$: ratio of the wbSAR to its ICNIRP limit, i.e. $SAR_{wb}/SAR_{\text{limit}}^{wb}$
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>The complete Virtual Population representing humans (males and females) of different age groups and body shapes.</td>
<td>14</td>
</tr>
<tr>
<td>2.2</td>
<td>Resampling of an MRI scan of the leg from $0.9 \times 0.9 \times 2.0 \text{mm}^3$ to $0.5 \times 0.5 \times 0.5 \text{mm}^3$ by means of the Lanczos interpolation method.</td>
<td>16</td>
</tr>
<tr>
<td>2.3</td>
<td>Raw MRI data, label-fields, surface model, and posed model.</td>
<td>17</td>
</tr>
<tr>
<td>2.4</td>
<td>Surface extraction and processing: results from surface extraction, feature- and volume-preserving smoothing, and surface simplification.</td>
<td>18</td>
</tr>
<tr>
<td>2.5</td>
<td>Triangular mesh of Duke’s ribcage, spinal column, and liver at a state of complete inhalation and complete exhalation.</td>
<td>27</td>
</tr>
<tr>
<td>2.6</td>
<td>Comparison of height, weight, and BMI from the Virtual Population models with age-dependent statistical data of the German population.</td>
<td>29</td>
</tr>
<tr>
<td>2.7</td>
<td>Ella Version 3.0 in cardiovascular imaging position in the birdcage coil MITS1.5.</td>
<td>31</td>
</tr>
</tbody>
</table>
### APPENDIX C. LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>Vertebrae, intervertebral discs, and spinal cord of Ella in Versions 1.0 and 3.0. Generic thoracolumbar stabilization implant inserted in the L2, L3, and L4 vertebrae of Ella Versions 1.0 and 3.0.</td>
<td>32</td>
</tr>
<tr>
<td>2.9</td>
<td>Comparison of the local SAR distribution in Ella Versions 1.0 and 3.0 from the exposure to a 1.5 T MRI birdcage coil.</td>
<td>33</td>
</tr>
<tr>
<td>3.1</td>
<td>Four anatomical human models from the Virtual Family: Duke, Ella, Billie, and Thelonious.</td>
<td>40</td>
</tr>
<tr>
<td>3.2</td>
<td>SAM model with virtual anatomical regions inside: shell, tissues, and some structures of the brain.</td>
<td>42</td>
</tr>
<tr>
<td>3.3</td>
<td>Dipolar exposure – Alignment of the dipoles, viewed perpendicular to the RP.</td>
<td>45</td>
</tr>
<tr>
<td>3.4</td>
<td>Dipolar exposure – Matrix of eighteen dipoles placed around the SAM head, in the RP, RP + 24 mm, and RP – 24 mm.</td>
<td>46</td>
</tr>
<tr>
<td>3.5</td>
<td>Dipolar exposure – Average SAR over the entire head, for the five head models, normalized to 1 W source radiated power.</td>
<td>49</td>
</tr>
<tr>
<td>3.6</td>
<td>Dipolar exposure – Estimation of the average SAR in various regions of the anatomical heads from the results in the SAM head at 900 MHz, normalized to the average SAR in the whole head, for the six dipoles in the RP.</td>
<td>54</td>
</tr>
<tr>
<td>3.7</td>
<td>Dipolar exposure – Estimation of the average SAR in various regions of the anatomical heads from the results in the SAM head at 1800 MHz, normalized to the average SAR in the whole head, for the six dipoles in the RP.</td>
<td>54</td>
</tr>
<tr>
<td>3.8</td>
<td>Mobile phone exposure – Total absorbed power in the heads from the exposure to four realistic mobile phone models operating at 900 MHz and 1747 MHz.</td>
<td>55</td>
</tr>
<tr>
<td>3.9</td>
<td>Mobile phone exposure – Deviation of the SAR in the regions of the VF heads from the transformed results based on the SAM head.</td>
<td>57</td>
</tr>
<tr>
<td>3.10</td>
<td>Mobile phone exposure – Comparison of the relative exposure from the different phones operating at 900 MHz and 1747 MHz.</td>
<td>58</td>
</tr>
</tbody>
</table>
3.11 Mobile phone exposure – Correlation between the SAR in the nine studied brain regions of the VF and the transformed SAM in these regions, at 900 MHz and 1800 MHz.

4.1 Definition of the dimensions of the head phantoms as measured on the 3-year-old INDY, 8-year-old ISABELLA, and SAM phantoms.

4.2 Picture of the outside and inside of the physical phantom of INDY.

4.3 Picture of the outside and inside of the physical phantom of ISABELLA.

4.4 Picture of the outside and inside of the physical phantom of SAM.

4.5 Mobile phones used in this study.

4.6 Picture of ISABELLA exposed to the generic phone at 1800 MHz in the touch position and at 900 MHz in the tilt position.

4.7 Picture of the measurement system DASY5 with the right-hand side of the SAM phantom exposed to a mobile phone in the tilt position.

4.8 Experimental 1g psSAR from the exposure to the generic phones and Motorola T250.

4.9 Experimental 10g psSAR from the exposure to the generic phones and Motorola T250.

4.10 Experimental and numerical 1g psSAR from the exposure to the generic phones and Motorola T250.

4.11 Experimental and numerical 10g psSAR from the exposure to the generic phones and Motorola T250.

4.12 Local SAR distribution in ISABELLA in the plane containing the mouth and ear canal points as well as the center of the phone.

4.13 Experimental and numerical 1g and 10g psSAR of INDY exposed to the generic phone at 900 MHz in the touch and tilt position. For the numerical results, the psSAR in an averaging cube aligned with the phantom’s surface and aligned with the grid are shown.
APPENDIX C. LIST OF FIGURES

4.14 Cross-section of the INDY phantom exposed to the 900-MHz generic phone in the touch position showing the vertices of the psSAR cubes from IEEE C95.3-2002 (aligned with the axes of the phone) and IEEE 1528-2003 (positioned normal to the shell of the phantom). 78

5.1 DASY52 NEO scanner with B-field probe and LF B-field probe at a distance of 1 mm from the mobile phone surface. 85

5.2 Detection limit of the measurement system with and without shielding from the ambient fields. 90

5.3 Anatomical head models from the Virtual Family: Duke, Ella, Billie, and Thelonious. 91

5.4 Superposition of the frequency spectra from all phones up to 500 Hz. 97

5.5 B-field spatial distribution on the front of the phone SamsungGT-I9001 at maximum PCL for GSM900 (217 Hz), GSM1800 (217 Hz), and UMTS (100 Hz). 98

5.6 B-field spatial distribution at 1 kHz around the speaker of the phone SamsungGT-I9001 with audio ON for GSM900, GSM1800, and UMTS. 99

5.7 B-field along a line perpendicular to the surface of the phone SamsungGT-I9001 at 217 Hz for GSM900 and GSM1800. 99

5.8 B-field along a line perpendicular to the surface of the phone SamsungGT-I9001 at 1 kHz close to the speaker with audio ON for GSM900, GSM1800, and UMTS. 100

5.9 Envelopes of the point-wise maximum ratio of exposure to the ICNIRP 1998 limits from all phones at the maximum PCL, excluding the contribution from the audio signal, for GSM900, GSM1800, and UMTS. 102

5.10 $B_2^{rms}$ generated by the array of rectangular loops. 103

5.11 Ratio of the surface-averaged current density to the ICNIRP 1998 limits for all tissues in GSM900, GSM1800, and UMTS. 105

5.12 Ratio of the surface-averaged current density to the ICNIRP 1998 limits in GSM900. 106
<table>
<thead>
<tr>
<th>Page</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>106</td>
<td>Ratio of the line-averaged induced electric field to the IEEE limits in GSM900.</td>
</tr>
<tr>
<td>107</td>
<td>Ratio of the volume-averaged induced electric field to the ICNIRP 2010 limits in GSM900.</td>
</tr>
<tr>
<td>108</td>
<td>Ratio of the surface-averaged current density to the ICNIRP 1998 limits for the audio signal at 1kHz.</td>
</tr>
<tr>
<td>108</td>
<td>Ratio of the line-averaged induced electric field to the IEEE limits for the audio signal at 1kHz.</td>
</tr>
<tr>
<td>117</td>
<td>Anatomical body models: Visible Human, Japanese Male, Japanese Female.</td>
</tr>
<tr>
<td>119</td>
<td>Base station antenna models.</td>
</tr>
<tr>
<td>122</td>
<td>Comparison of the average power density computed from (6.1) with the one obtained from free-space simulations.</td>
</tr>
<tr>
<td>124</td>
<td>Deviation of the whole-body average SAR and 10g SAR values from the results obtained with a mesh step of 0.75 mm (900 MHz – 2140 MHz) and 1.0 mm (450 MHz).</td>
</tr>
<tr>
<td>125</td>
<td>Measurement setup for the SAR evaluation of the Kathrein 742215 antenna using DASY5 NEO and the elliptical phantom.</td>
</tr>
<tr>
<td>128</td>
<td>Simulated and measured E- and H-fields in the center plane of the Kathrein 742215 antenna operating at a frequency of 1840 MHz normalized for an antenna input power of 33 dBm.</td>
</tr>
<tr>
<td>129</td>
<td>Maximum permissible antenna output power at which the basic restrictions for occupational exposure are not exceeded.</td>
</tr>
<tr>
<td>131</td>
<td>Maximum permissible power in the antenna in order not to exceed whole-body average SAR basic restrictions for occupational exposure, as a function of the cross section on mass ratio of the human model, for four different frequencies.</td>
</tr>
</tbody>
</table>
APPENDIX C. LIST OF FIGURES

6.9 Maximum permissible power in the antenna, 900 MHz, in order not to exceed the basic restrictions on whole-body average SAR for occupational exposure for different horizontal HPBW for the Japanese male placed at four different positions. .......................... 131

6.10 Typical locations of local SAR maxima (900 MHz). 134

7.1 Three anatomical human models from the Virtual Family: VFM, VFF, and VFB. .......................... 139

7.2 Diagram representing the steps in elaborating the SAR estimation formulas. .......................... 142

7.3 Cross-section to mass ratio of the associated cuboid as a function of the weight and height of the human body. 145

7.4 CDF of the enhancement of the absorbed power in a layered volume compared to a homogeneous volume exposed to plane waves. .......................... 148

7.5 Comparison between wbSAR of the heterogeneous VFB from plane-wave exposure and the cuboid approximation, for a power density exposure at ICNIRP level. 152

7.6 Ratio of the wbSAR to the psSAR for standing models under plane-wave exposure. .......................... 153

7.7 Comparison of average power density from simulations and calculated from (7.19). .......................... 154

7.8 Schematic side view of the exposed vertical length as defined in (7.23), at various distances from the antenna, depending on its vertical opening angle. .......................... 156

7.9 Comparison of the simulation results of wbSAR and psSAR with the estimation formulas developed in Section 7.5 and the ratio of (7.19) to the ICNIRP power density limit, for the antenna 900 MHz H65 V7. 161

7.10 Histograms of the deviation between the bulk simulation results of the three models (> 200 mm) and the estimation formulas based on the 95th-percentile human body cuboid. 162
Appendix D

List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Tissues segmented in the Virtual Population 3.0 models</td>
<td>24</td>
</tr>
<tr>
<td>2.2</td>
<td>Specifications of the Virtual Population models</td>
<td>28</td>
</tr>
<tr>
<td>3.1</td>
<td>Characteristics of the VF human head models and the SAM phantom</td>
<td>41</td>
</tr>
<tr>
<td>3.2</td>
<td>Transformation factors to the homogeneous SAM head and accompanied uncertainty on the final results</td>
<td>51</td>
</tr>
<tr>
<td>3.3</td>
<td>Transformation factors to the homogeneous SAM head for every brain-region of the first two levels of the Talairach atlas and the uncertainty on the transformed SAR results</td>
<td>52</td>
</tr>
<tr>
<td>3.4</td>
<td>Transformation factors to the homogeneous SAM head for every head tissue and the uncertainty on the transformed SAR results</td>
<td>53</td>
</tr>
<tr>
<td>4.1</td>
<td>Dimensions of the experimental head phantoms</td>
<td>65</td>
</tr>
<tr>
<td>4.2</td>
<td>Dielectric properties of the tissue simulating liquid used for the numerical and experimental assessments</td>
<td>68</td>
</tr>
<tr>
<td>4.3</td>
<td>Uncertainty contributions to the measurements performed with DASY5 according to IEEE 1528-2003 and IEC 62209-2005</td>
<td>69</td>
</tr>
</tbody>
</table>
**APPENDIX D. LIST OF TABLES**

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4</td>
<td>Uncertainty contributions to the numerical modeling due to the absorbing boundary conditions (ABC), deviations from steady state, and model discretization.</td>
<td>71</td>
</tr>
<tr>
<td>5.1</td>
<td>Measurement equipment specifications.</td>
<td>86</td>
</tr>
<tr>
<td>5.2</td>
<td>Main characteristics of the DUTs.</td>
<td>87</td>
</tr>
<tr>
<td>5.3</td>
<td>PCLs and corresponding typical average RF power for each communication system.</td>
<td>88</td>
</tr>
<tr>
<td>5.4</td>
<td>Uncertainty budget of the magnetic field measurements.</td>
<td>89</td>
</tr>
<tr>
<td>5.5</td>
<td>ICNIRP 1998 and ICNIRP 2010 basic restrictions for general public exposure.</td>
<td>93</td>
</tr>
<tr>
<td>5.6</td>
<td>IEEE C95.6-2002 basic restrictions on the induced E-field for general public exposure.</td>
<td>94</td>
</tr>
<tr>
<td>5.7</td>
<td>Compliance factor in terms of the ICNIRP limit on dB/dt with all frequencies from the communication systems under consideration.</td>
<td>101</td>
</tr>
<tr>
<td>6.1</td>
<td>Characteristics of the human body models.</td>
<td>118</td>
</tr>
<tr>
<td>6.2</td>
<td>Mechanical dimensions and simulated electrical characteristics of the base station antenna models.</td>
<td>120</td>
</tr>
<tr>
<td>6.3</td>
<td>Basic restrictions for occupational exposure at frequencies between 10 MHz and 10 GHz according to [2].</td>
<td>128</td>
</tr>
<tr>
<td>6.4</td>
<td>Characteristics of the scaled JM model.</td>
<td>130</td>
</tr>
<tr>
<td>7.1</td>
<td>Characteristics of the human models.</td>
<td>138</td>
</tr>
<tr>
<td>7.2</td>
<td>Specifications of the generic base station antennas.</td>
<td>141</td>
</tr>
<tr>
<td>7.3</td>
<td>Dimensions of the cuboid representing the 95th-percentile human body.</td>
<td>145</td>
</tr>
<tr>
<td>7.4</td>
<td>ICNIRP (10 kHz to 10 GHz) and IEEE (300 kHz to 100 GHz) basic restrictions for occupational exposure.</td>
<td>150</td>
</tr>
<tr>
<td>7.5</td>
<td>ICNIRP reference levels for occupational exposure.</td>
<td>151</td>
</tr>
<tr>
<td>7.6</td>
<td>Piecewise linear approximation of $C(f)$.</td>
<td>159</td>
</tr>
</tbody>
</table>
Appendix E

List of Publications

E.1 Journal Publications Included in this Thesis

Within the framework of this thesis, the following peer-reviewed scientific journal publications have been written by the author.


(3) Marie-Christine Gosselin, Sven Kühn, Andreas Christ, Marcel Zefferer, Emilio Cherubini, Jurriaan F. Bakker, Gerard C. van Rhoon, and Niels Kuster. Experimental evaluation of the SAR induced in head phantoms of three- and eight-year-old children.

187
APPENDIX E. LIST OF PUBLICATIONS


E.2 Other Journal Publications

In addition, the author has co-authored the following peer-reviewed journal publications.


E.3. OTHER PUBLICATIONS


E.3 Other Publications

The author has presented or co-authored various other publications.

(1) Myles Capstick, Marie-Christine Gosselin, Esra Neufeld, and Niels Kuster. Novel applicator for local RF hyperthermia treatment using improved excitation control. In *Proceedings of the*
31st URSI General Assembly and Scientific Symposium, Beijing, China, August 2014.


(6) Ilaria Liorni, Marta Parazzini, Serena Fiocchi, Valerio De Santis, Mark Douglas, Marie-Christine Gosselin, Niels Kuster, and Paolo Ravazzani. Exposure of woman models at different stages of pregnancy to uniform magnetic fields at 50 Hz. In Proceedings of the Joint Meeting of the Bioelectromagnetics Society (BEMS) and the European BioElectromagnetics Association (EBEA), Thessaloniki, Greece, June 2013.
(7) Ilaria Liorni, Marta Parazzini, Serena Fiocchi, Valerio De Santis, Mark Douglas, Marie-Christine Gosselin, Niels Kuster, and Paolo Ravazzani. Exposure of high resolution fetuses in advanced pregnant woman models at different stages of pregnancy to uniform magnetic fields at the frequency of 50 Hz. In *Proceeding of the 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC 2013)*, Osaka, Japan, July 2013.


(12) Marie-Christine Gosselin, Sven Kuehn, and Niels Kuster. ELF exposure from GSM and UMTS mobile phones. In *Proceedings of the 34th Annual Conference of Bioelectromagnetics Society (34BEMS)*, Brisbane, Australia, June 2012.


(18) Marie-Christine Gosselin, Esra Neufeld, Manuel Murbach, Andreas Christ, Eugenia Cabot, and Niels Kuster. Analysis of the SAR enhancement from a multitransmit coil. In *Proceedings*
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of the 10th International Conference of the European Bioelectromagnetics Association (EBEA 2011), Rome, Italy, February 2011.


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