MMF-GSMA Dosimetry Program Phase 2: Scientific Basis for Base Station Exposure Compliance Standards

Project Work Package 5 "Plane-wave SAR evaluations"

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Final Report of Work Package 5

This research was conducted with funding from
the Mobile Manufacturers Forum and the GSM Association

Notification

Whilst the conducted research received funding from the MMF and GSMA, the views expressed by the authors may not be those of the MMF and GSMA or their member companies.

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Nomenclature

anterior exposure	Frontal exposure of a model, $\theta = 90°$ and $\phi = 180°$.
CSC	Finnish IT Center for Science (providing high-performance computing resources)
CPML	Convolutional Perfectly Matched Layer
FDTD	Finite-Difference Time-Domain method (see e.g. [1])
ICNIRP	International Commission on Non-Ionizing Radiation Protection. This report applies SAR limits (basic restrictions) and reference levels of ICNIRP.
IT'IS	Foundation for Research on Information Technologies in Society
max(10gSAR)	Maximum of 10g-averaged SAR, i.e., the peak 10g SAR [W/kg]
normalized max(10gSAR)	If this is >1, max(10gSAR) exceeds the SAR limit at reference level of exposure. Normalized max(10gSAR) is a unitless quantity. It is separately determined in the limbs and in the head/trunk.
normalized WBASAR	If this is >1, WBASAR exceeds the SAR limit at reference level of exposure. Normalized WBASAR is a unitless quantity. This report applies SAR limits and reference levels of ICNIRP.
posterior exposure	Back-side exposure of a model, $\theta = 90°$ and $\phi = 360°$.
SAR	Specific Absorption Rate [W/kg]
STD	Standard Deviation
TKK	Helsinki University of Technology
VFB	Virtual Family Boy
VFF	Virtual Family Female
VFM	Virtual Family Male
VHP	Visible Human Project
WBASAR	Whole-body-averaged SAR [W/kg]

Executive Summary

Objective: In January 2008 the dosimetry research group at Helsinki University of Technology started working for the WP5 of MMF-GSMA Dosimetry Program Phase 2. The objective was to obtain specific-absorption-rate (SAR) data via electromagnetic field simulations in order to establish uncertainty estimates and correction factors for SAR due to base station antenna exposure. The task was to perform free-space plane-wave simulations for vertical and horizontal polarization at 300, 450, 900, 2100, 3500 and 5000 MHz, with varying incoming angle and by applying a representative set of models and model postures. The primary results are whole-body-averaged SAR and peak 10g SAR in the head-and-trunk region and in the limbs.

Results: In-house parallel FDTD and SAR codes were run in an HP supercluster to perform the plane-wave SAR simulations. Before these bulk simulations, the modeling system was validated by the interlaboratory comparison. In this report, detailed results of SAR are plotted at 300, 450, 900, 2100, 3500 and 5000 MHz for vertical and horizontal polarization of the electric field. From these illustrations one can see the effect of the plane-wave incoming angle, the model phantom and the model posture on SAR. The results are shown in a normalized form which directly reveals whether or not a SAR value is properly below the ICNIRP SAR limit (basic restriction) at the reference level of exposure.

The limit of whole-body-averaged SAR is very clearly exceeded at the reference level of exposure with the Virtual Family (VF) Boy model. VF Female is close to the limit (but below) at 2100 MHz, which appears to be the frequency giving highest normalized SAR values. The peak 10g-SAR limits are not exceeded in any simulated case (720 cases), but with a homogeneous-male posture model the peak 10g-SAR in the head-and-trunk region was only 0.18 dB below the limit at 2100 MHz if the arms of the model were lifted up.

Relative SAR results in dB scale are presented. Importantly, these results show the variation/uncertainty of SAR due to specific variables in dB's, separately at each frequency and with vertical and horizontal polarization.

The incoming angle variation covered 11 angles, which are relevant in the sense of realistic exposure conditions, and 4 models VF Male and VF Boy (heterogeneous and homogeneous version for both). The extent of SAR variation depends essentially on the frequency and polarization. For the whole-body-averaged SAR this was typically a few decibels, around 0.6...3.5 dB, and for the peak 10g SAR around 1.7...7.5 dB.

The phantom variation covered 10 models (18 - 105 kg). The extent of SAR variation for the whole-body-averaged SAR was around 2.2...5.2 dB and for the peak 10g SAR around 1.6...6.5 dB. The extent of SAR variation depends on the polarization-frequency case and also on the incoming angle.

The posture variation covered 6 postures which seem to establish a representative set in terms of the whole-body-averaged SAR. The extent of SAR variation for the whole-body-averaged SAR was around 0.7...1.7 dB and for the peak 10g SAR around 0.6...6.1 dB. Again, the extent of SAR variation depends on the polarization-frequency case.

Finally, the actual SAR simulation results of 720 exposure cases were extended via certain approximations to cover 7920 exposure cases, and frequency distribution curves of SAR, comparable to probability distributions, were produced. From these curves one can see the number of occurrences of a SAR value being within a certain dB interval (for a specific population). 0 dB corresponds to the reference case of Virtual Family Male standing under frontal exposure. This approximate extended method is clearly more justified for the whole-body-averaged SAR than for the peak 10g SAR.

Main conclusions and recommendations:

- The whole-body-averaged SAR limits of ICNIRP may be clearly exceeded at the reference level of exposure, and there is even a possible risk of a peak 10g SAR exceeding in the head-and-trunk region with some male phantoms. The current reference levels of ICNIRP should be revised.
- The delivered SAR data in electronic format can be applied to produce or adjust SAR estimation formulas of base station antenna exposure.
- The presented SAR variation/uncertainty diagrams show the dependence of SAR on the incoming angle, model phantom and posture.
- The presented approximate frequency distributions, which were shown for a population consisting of 10x6x11 model-posture-angle combinations, give an idea about the probability of a SAR value being within a certain dB interval. However, these approximate distributions are clearly more justified and reliable for the whole-body-average SAR than for the peak 10g SAR.
- The results of this research are based on free-space simulations. Adding reflective surfaces near a body model may increase SAR values further.

1 Introduction

This document reports the results of MMF-GSMA Dosimetry Program Phase 2 / Work Package 5. The task was to perform plane-wave SAR simulations for vertical and horizontal polarization at 300, 450, 900, 2100, 3500 and 5000 MHz, with varying incoming angle and by applying a quite large set of human body models (see the Request for Proposal for the Phase II of the MMF/GSMA dosimetry program). In WP5, the plane-wave simulations were performed in free space, i.e., there were no reflective surfaces nearby the body models.

This final report will be accompanied with the files containing the obtained SAR data (such as the whole-body-averaged SAR, the peak 10g SAR in the head/trunk region and in the limbs, etc.). This SAR data has been broadly illustrated by curves and other diagrams in this report. Also some frequency distributions of SAR have been presented which are comparable to probability distributions, i.e., one can see how often a certain SAR value occurs with a certain population. These curves base on the performed FDTD-SAR simulations and some approximations. In general, there is quite a lot of computed SAR data which can be utilized in many ways.

2 Methods

2.1 Simulation codes

2.1.1 Parallel FDTD code EFSS

A parallel FDTD solver named as EFSS has been used in the field computation. EFSS has been optimized for very large problems (memory saving tricks are applied, parallel code), and it is using the CPML absorbing boundary condition which has proven to be effective. The solver has been implemented using Fortran and MPI (Message Passing Interface) libraries. The development has been done at the Helsinki University of Technology / Department of Radio Science and Engineering. CSC (Finnish IT Center for Science) has helped in the code optimization.

2.1.2 SAR computation

Together with the field solver there are SAR computation codes which utilize the field data and other necessary data to produce SAR distributions and the key figures such as the whole-body-averaged SAR (WBASAR) and the peak 10g-averaged SAR (max(10gSAR)). Above, "other necessary data" refers to e.g. body-parting data (needed to separate the head/trunk region and the limbs) and the sizes of the SAR averaging cubes around the voxels of a model.

SAR averaring is done as recommended in the IEEE Std C95.3-2002 (Annex E) [2] which classifies 3 different cell types. If a valid averaging cube can be grown on a cell, this cell is a "valid cell". If a valid averaging cube can not be grown on a cell (one face of the cube is completely in air region), the cell is marked as invalid. Most invalid cells belong to some valid averaging cube. If a cell does not belong to any valid averaging cube, it is marked as "unused cell", for which a special algorithm is applied in order to calculate an averaged SAR value. Fine tuning of averaging cubes is done as described in Caputa's paper [3]. I.e. an averaging cube consists of core of full voxels and an outermost layer of fractions of voxels.

2.1.3 User interface

The user interface of the FDTD-SAR codes is based on various Matlab functions and scripts which are applied in

- model correction and manipulation, and model preparation for the FDTD-SAR analysis
- simulation sweep generation: a set of input files are created for the FDTD solver and the job scripts for the CSC's supercomputer (sweep: e.g. certain incoming angles and frequencies)
- management of SAR data
- checking and plotting results

2.2 Simulation hardware

The parallel FDTD and SAR computations were run in CSC's HP supercluster "Murska" which has more than 2000 computation cores, see
`http://www.csc.fi/english/pages/murska_guide/hardware/overview/index_html`.

2.3 Validation of simulation codes and methods

The simulation codes and methods of TKK (Helsinki University of Technology) have been validated by an interlaboratory comparison which showed good agreement of the SAR results between different institutions (see the *Inter-Laboratory Comparison Report of work packages 5-7*). The validation simulations were done with heterogeneous and homogeneous Virtual Family Male (at 0.9 GHz) and heterogeneous and homogeneous Boy (at 0.9, 2.1, and 5 GHz).

2.4 Exposure setup

All the simulations were performed under plane-wave exposure in free space. Excitation signals were tapered sines at point frequencies. Figure 1 shows some essential symbols and definitions of plane-wave exposure.

2.5 Classification of body parts of the models

The limbs consist of arms and legs. The rest of the body is associated with the head/trunk region. Figure 2 shows the separation of arms and legs from the trunk as well as the head/trunk region which consists of genitals, trunk and head.

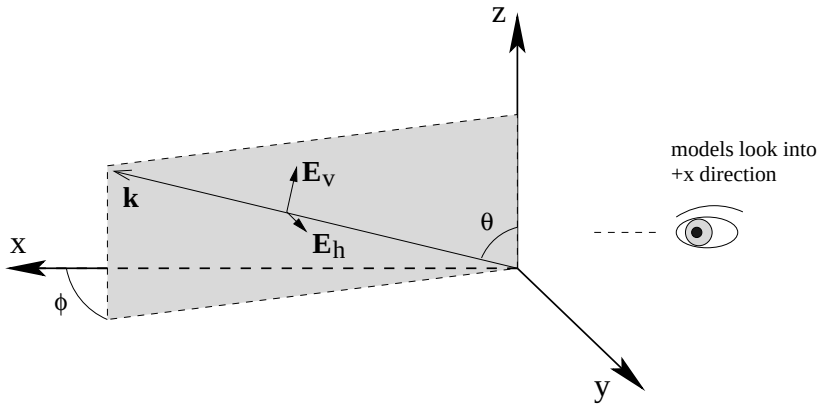

Figure 1: Necessary symbols and definitions of plane-wave exposure. In the simulations, propagation direction of an incoming plane wave ($\mathbf{k}$) is specified using the angles θ and ϕ. Vertical polarization means that the electric field vector ($\mathbf{E}_v$) lies in the shaded plane. Horizontal polarization means that the electric field vector ($\mathbf{E}_h$) is normal to this shaded plane. $\mathbf{E}_h$ does not have $\mathbf{u}_z$ component. $\mathbf{E}_v \perp \mathbf{E}_h$, $\mathbf{E}_v \perp \mathbf{k}$, and $\mathbf{E}_h \perp \mathbf{k}$. All the models, in every simulated case, are looking into +x direction. Thus, for example, the case where $\theta = 90°$ and $\phi = 180°$ corresponds to the anterior exposure case (frontal exposure).

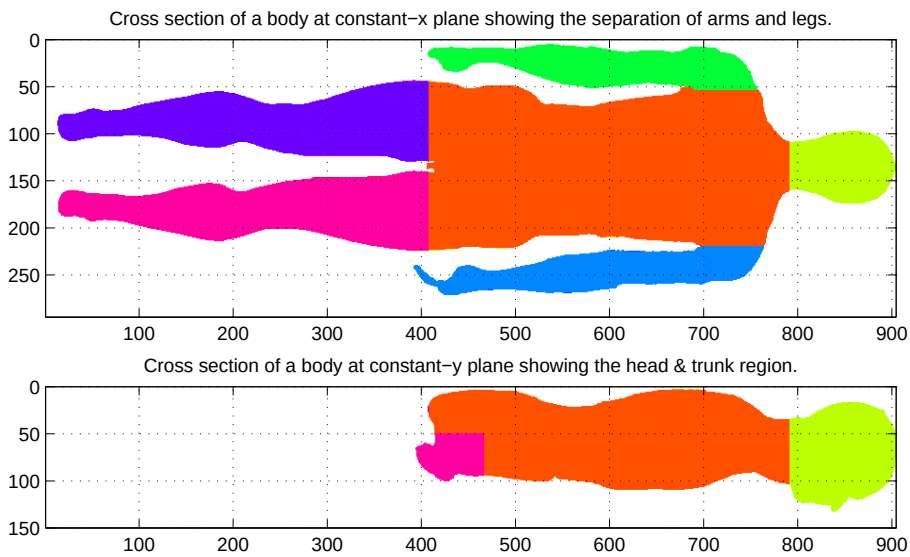

Figure 2: Classification of major body parts. Limbs consist of arms and legs whose separation from the trunk can be seen in the top figure. The rest of the body is associated with the head/trunk region (bottom figure).

Model name	mass (kg)	resolution (mm)	type (#tissue types)
Norman	72.98	2.022 / 1.011	heterogeneous (37)
Japan Male	68.95	2.000 / 1.000	heterogeneous (51)
Japan Female	53.44	2.000 / 1.000	heterogeneous (51)
VHP Male	105.38 / 105.29	3.000 / 1.000	heterogeneous (40)
Posture sit	65.38	2.000 / 1.000	homogeneous (1)
Posture examine	65.44	2.000 / 1.000	homogeneous (1)
Posture arms up	65.21	2.000 / 1.000	homogeneous (1)
Posture standing	65.05	2.000 / 1.000	homogeneous (1)
Posture sit on ground	65.66	2.500 / 1.250	homogeneous (1)
Posture arms out	65.52	2.500 / 1.250	homogeneous (1)
VF Male Homogeneous	68.54 / 68.55	2.000 / 1.000	homogeneous (1)
VF Male Heterog	72.24	2.000 / 1.000	heterogeneous (76)
VF Boy Homogeneous	18.28 / 18.27	2.000 / 1.000	homogeneous (1)
VF Boy Heterog	19.40 / 19.39	2.000 / 1.000	heterogeneous (76)
VF Female Heterog	58.15	2.000 / 1.000	heterogeneous (76)

Table 1: Applied models. Table shows model name, mass, resolutions (low / high) and type of each model. Low and high resolution model masses may slightly differ - if this happens still after rounding, both mass values are declared above (the first and second value correspond to low and high resolution models, respectively). Type of the model is homogeneous or heterogeneous and the number tells how many separate tissue types there are in the voxel data (external air is not counted). For heterogeneous VF models this number is 76, but note however that a set of tissue types may actually have same mapping, i.e., same ϵ, σ and ϱ values.

3 Applied body models in the SAR computations

3.1 Overview of the models

The FDTD-SAR computations were done by applying 15 different human body models which are listed in Table 1 with their masses and resolutions. Actually, there are two versions of each model: a low-resolution model is applied at 300, 450, 900 and 2100 MHz and a high-resolution model is applied at 3500 and 5000 MHz (an exception: high-resolution VHP Male is used also at 2100 MHz).

Figures 3 - 7 illustrate the body structure of the models. Figure 3 shows Norman, Figure 4 shows Japanese Male and Female, Figure 5 shows VHP Male, Figure 6 shows the posture models (male, originally from Poser software), and Figure 7 shows the applied Virtual Family models (Male, Female, Boy).

3.2 Model sources

The models have been obtained from various projects and institutions. The voxel data of Norman was obtained from Health Protection Agency/UK (Dimbylows work [4]). Japanese Male and Female were obtained from Biomedical EMC Group/NICT/Japan [5]. VHP Male is based on Visible Human Project data - 1-mm and 3-mm models have been obtained from Brooks Air Force Base /USA (website, few years ago). The posture models (homogeneous) were outputted from Poser software and eventually corrected and manipulated in Matlab

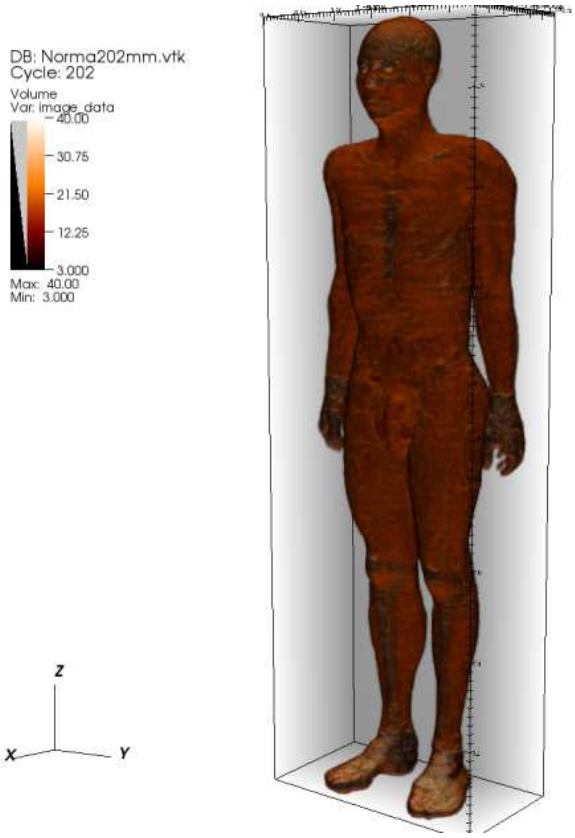

Figure 3: Norman.

(co-operation with STUK[1]). The voxel data of the original heterogeneous Virtual Family models were received from IT'IS Foundation/Switzerland (VF DVD v1.0) [6]. This project utilized VF Male ("Duke"), VF Boy ("Thelonious"), and VF Female ("Ella").

3.3 Tissue parameters of heterogeneous models

For the heterogeneous models the electrical properties of body tissues, conductivity and permittivity, were obtained from the data and models of Gabriel [7], [8], [9]. For most tissue types, the electrical properties can be also obtained from the web page `http://niremf.ifac.cnr.it/tissprop/`. For the tissue densities of Norman, VHP Male and the Japanese models, common values were used (Table 2). With the Japanese Male and Female, density and electrical parameters for some tissues were calculated by averaging certain tissue types. Especially, the skin was modelled as average of dry and wet skin (as was done by the model developers, too, Nagaoka et al. [5]). Note that the other heterogeneous models had "dry skin" whose conductivity and permittivity are a bit different from those of japanese models.

For the Virtual Family models, a tissue mapping table provided by IT'IS was applied ("Recommended Tissue Parameters for the Virtual Family"), although the mapping of some tissues was agreed separately before the interlaboratory comparison and the bulk simulations. Mapping was agreed such that all the needed electrical parameters could be found from the web page `http://niremf.ifac.cnr.it/tissprop/`. Essentially, the same

[1]STUK: Radiation and Nuclear Safety Authority (in Finland)

Tissue type	Density	Tissue type	Density
Aorta	1.04	Lymph	1.04
Bladder	1.03	Mucous Membrane	1.04
Blood	1.058	Muscle	1.0469
Blood vessel	1.04	Nail	1.03
Body fluid	1.01	Nerve	1.038
Bone (Cancellous)	1.92	Oseophagus	1.0425
Bone (Cortical)	1.99	Ovary	1.048
Bone Marrow (Not Infiltrated)	1.04	Pancreas	1.045
Brain (Grey Matter)	1.038	Prostate	1.05
Brain (White Matter)	1.038	Retina	1.026
Breast fat	0.916	Skin (Dry)	1.125
Cartilage	1.097	Skin (Wet)	1.125
Cerebellum	1.038	Small Intestine	1.0425
Cerebro Spinal Fluid	1.0072	Spinal Chord	1.038
Cervix	1.052	Spleen	1.0541
Colon	1.0425	Stomach	1.05
Cornea	1.076	Tendon	1.11
Duodenum	1.0425	Testis	1.044
Dura	1.097	Thymus	1.05
Eye Tissues (Sclera)	1.026	Thyroid	1.05
Fat (Not Infiltrated)	0.916	Tongue	1.0469
Gall Bladder	1.03	Tooth	2.16
Gall Bladder Bile	1.01	Trachea	1.097
Gland	1.05	Uterus	1.052
Heart	1.0298	Vitreous Humor	1.0089
Kidney	1.05	Bone Marrow (Infiltrated)	1.04
Lens Cortex	1.053	Fat (Average Infiltrated)	0.916
Liver	1.03	Lens Nucleus	1.053
Lung (Deflated)	1.05		
Lung (Inflated)	0.26		

Table 2: Tissue densities which were applied with Norman, VHP Male, Japanese Male and Japanese Female. Density is in kg/dm^3.

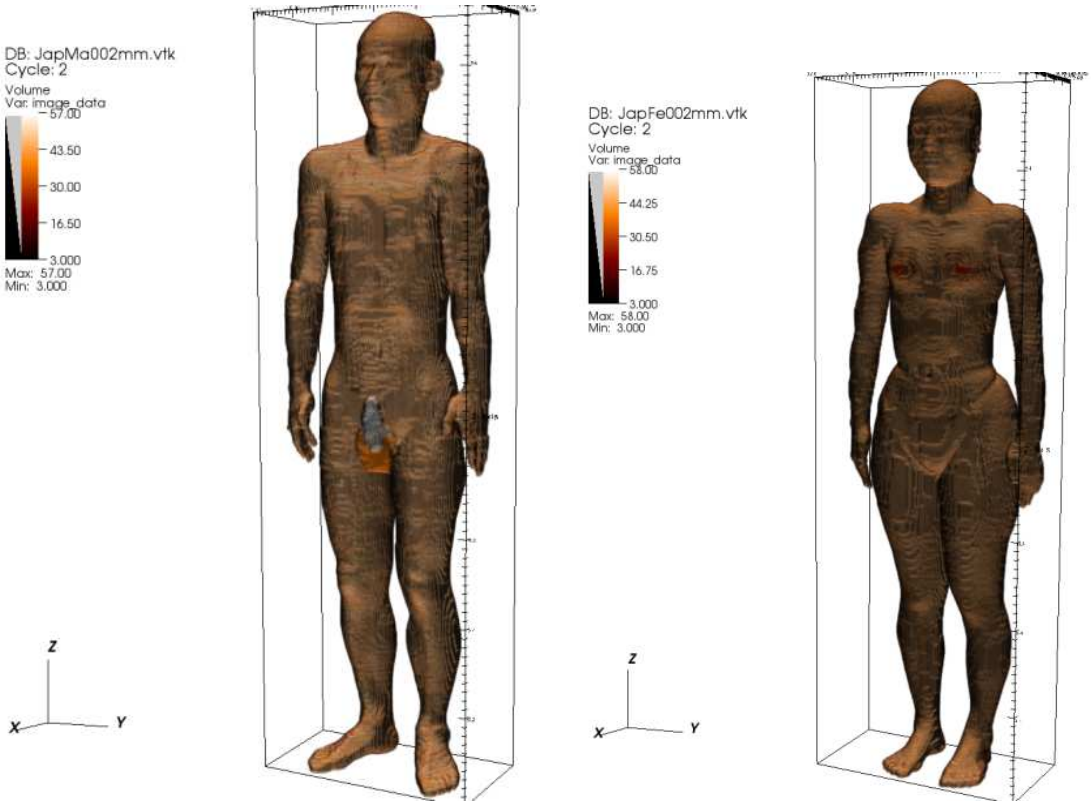

Figure 4: Japanese Male and Female.

parameter values were used in the interlaboratory comparison and in the bulk simulations.

3.4 Tissue parameters of homogeneous models

All the homogeneous models had tissue density 1 kg/dm^3. Relative permittivity and conductivity were chosen according to the Table 3. These same parameter values were also used in the validation simulations (interlaboratory comparison).

Frequency (MHz)	ϵ_r	σ (S/m)
300	45.3	0.87
450	43.5	0.87
900	41.5	0.97
2100	39.82	1.489
3500	38.25	2.95
5000	36.2	4.40

Table 3: Relative permittivity ϵ_r and conductivity σ applied with the homogeneous models. Parameter values correspond to tissue-equivalent liquid (e.g. standard IEC 62209-2.).

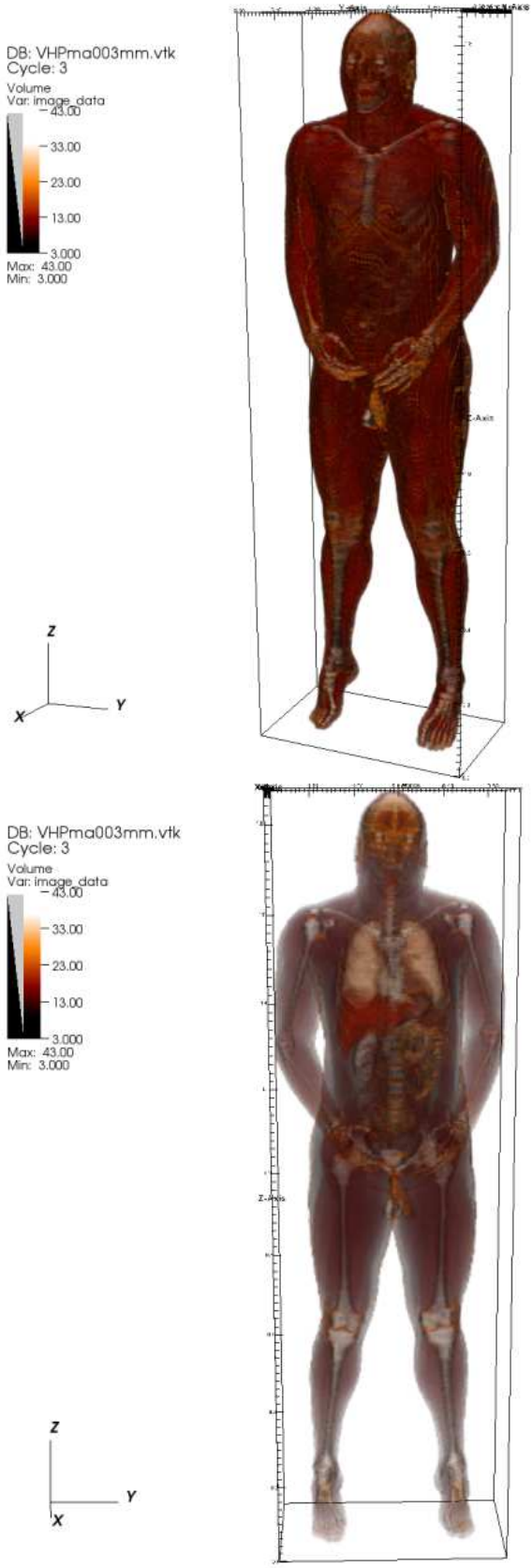

Figure 5: VHP Male. Top figure shows the body structure. Bottom figure shows also some inner organs. Note that VHP Male does not have its arms completely by the side of the body as the other standing-posture models have.

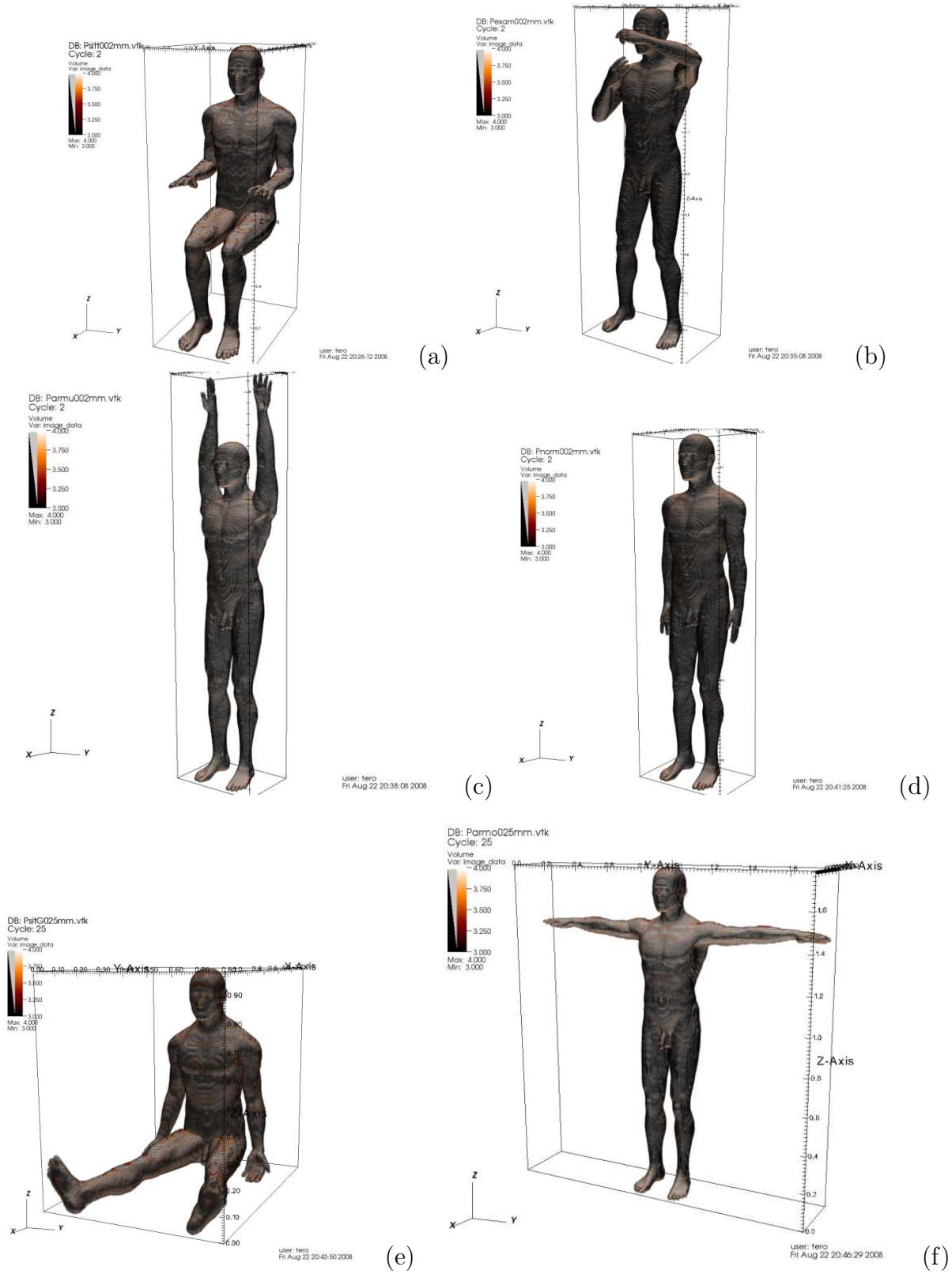

Figure 6: Posture models: (a) sit, (b) examine, (c) arms up, (d) standing, (e) sit on ground, (f) arms out. Note: "sit on ground" refers only to the posture of the model phantom. All simulations have been done in free space without any reflective surfaces.

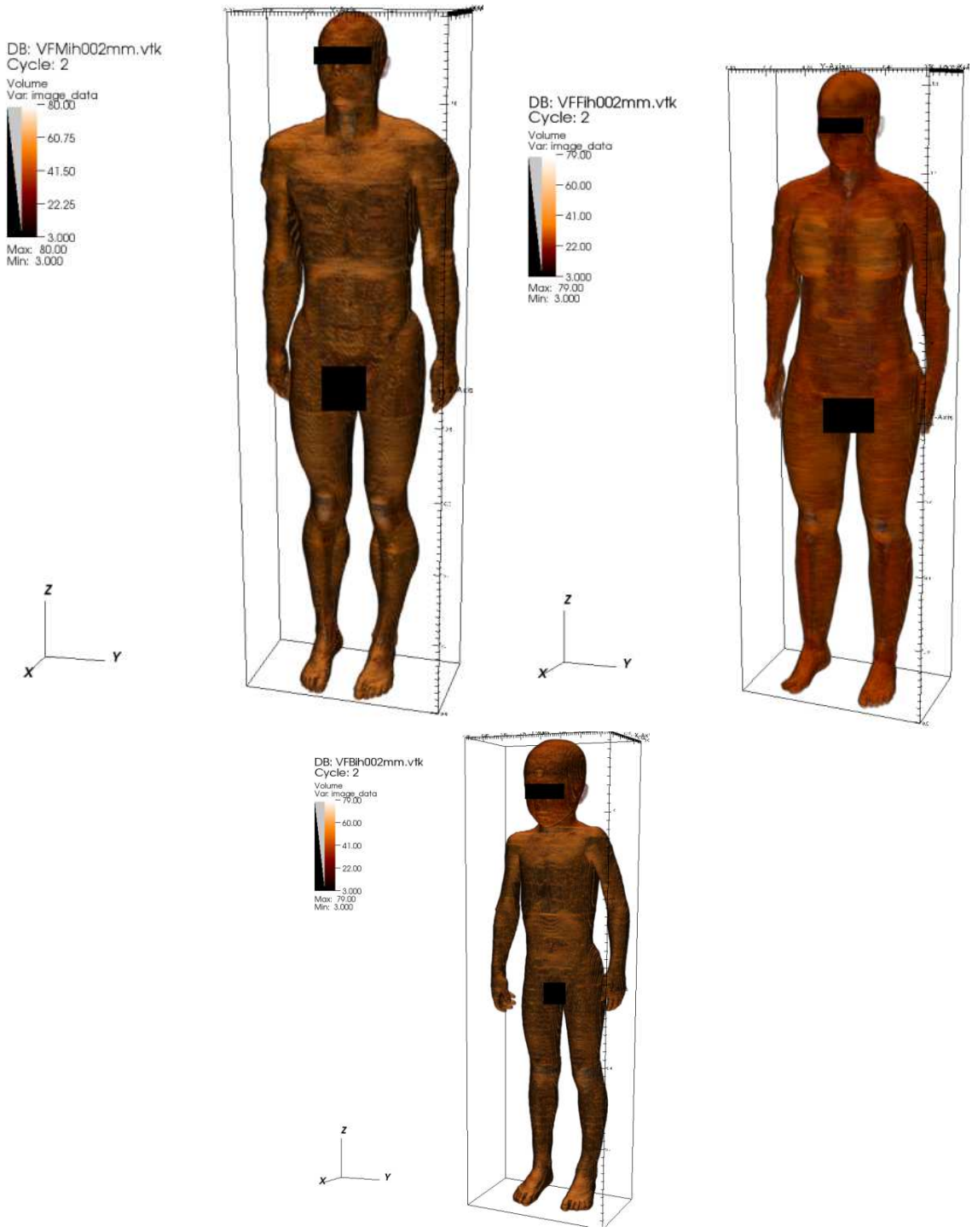

Figure 7: VF Male, VF Female and VF Boy.

4 SAR results

4.1 Overview of simulated cases

The FDTD-SAR simulations have been done

- with vertical and horizontal polarizations (Figure 1)
- using electric field amplitude $|\mathbf{E}_{\mathrm{rms}}| = 1$ V/m in every simulated case [2]
- at frequencies 300, 450, 900, 2100, 3500 and 5000 MHz
- by applying 15 different body models (Table 1)

The number of incoming angles depends on the model:

- VF Male (heterogeneous and homogeneous), VF Boy (heterogeneous and homogeneous): 11 angles (Figure 8)
- Norman, Japanese Male and Female, VHP Male, VF Female: 2 angles (anterior and posterior)
- Posture models: 1 angle (anterior)

The total number of simulated exposure cases is 720. In each case, the most important key figures are the whole-body-averaged SAR (WBASAR) and the peak 10-gram averaged SAR (i.e. max(10gSAR)) in the limbs and in the head/trunk region. Much other data has also been stored such as the peak 1-gram averaged SAR at higher frequencies, the peak SAR locations and SAR distributions.

4.2 Normalization of SAR results

Unless stated otherwise, the SAR results shown in this report have been normalized according to ICNIRP reference levels and SAR limits [10]. A normalized SAR value, $\mathrm{SAR_n}$, can be expressed as

$$\mathrm{SAR_n} = \mathrm{SAR}\ \frac{S_{\mathrm{eq}}}{(E_{\mathrm{rms}}^2/377\Omega)}\ \frac{1}{\mathrm{SAR_{limit}}} \tag{1}$$

where 'SAR' refers to the original SAR value[3] obtained with the electric field amplitude E_{rms}, S_{eq} is the plane-wave power density reference level and $\mathrm{SAR_{limit}}$ is the limit (basic restriction) of SAR. Essentially, if a normalized SAR value exceeds 1, this means that the SAR limit is exceeded even though exposure is at the reference level. This should not happen, but the latest research suggests that this can happen in some cases, i.e., the ICNIRP reference levels do not seem to be conservative. Note also that a normalized SAR has exactly same meaning for public and occupational exposure, because the occupational reference levels (S_{eq}) and SAR limits are *both* 5 times those of general public.

For example, at 2100 MHz, for occupational exposure, the reference level $S_{\mathrm{eq}} = 50$ W/m^2 and the $\mathrm{WBASAR_{limit}} = 0.4$ W/kg. Thus,

$$\mathrm{WBASAR_n} = \mathrm{WBASAR}\frac{50 \cdot 377}{0.4}\frac{1}{\mathrm{W/kg}}$$

where WBASAR has been obtained with $E_{\mathrm{rms}} = 1$ V/m in the FDTD simulation.

[2] In validation simulations, however, the *peak* amplitude was 1 V/m.

[3] Here, 'SAR' may refer to WBASAR or to peak 10g SAR in limbs or to peak 10g SAR in head/trunk.

4.3 Normalized WBASAR curves at each frequency for both polarizations

Figures 9 - 14 show normalized whole-body-averaged SAR at frequencies 300, 450, 900, 2100, 3500 and 5000 MHz, for vertical and horizontal polarization, for all the models. One can easily see the fluctuation of normalized WBASAR as the incoming angle is changing around the models which are all positioned in free space. Some observations on the results:

- Clearly, for VF Boy, the normalized WBASAR value exceeds 1 at 2100 and 3500 MHz. For homogeneous VF Boy, this happens also at 5000 MHz (horizontal polarization). Similar results have been obtained earlier by other researchers, i.e., a WBASAR value tends to exceed the SAR limit for child models at certain frequencies (e.g [11], [12], [13], [14]), even though exposure is at the reference level.

- Within the set of the simulated frequencies, 2100 MHz seems to give the highest normalized WBASAR values. The worst case is vertical 2100 MHz with VF Boy Heterogeneous (anterior) where the limit is exceeded by 54 %. Note that at 2100 MHz, also VF Female and Japanese Female are quite close to the limit (VF Female is 0.26 dB below the limit at H2100).

- Considering VF Male and VF Boy (heterogeneous and homogeneous): At frequencies 2100, 3500 and 5000 MHz, with both polarizations, a (local) minimum is observed in the normalized WBASAR curves when the wave comes from the (left) side, from beneath-front ($\theta = 30°, \phi = 180°$) or from the above-front ($\theta = 150°, \phi = 180°$). Actually, at these frequencies, the minimum-WBASAR angles would be $\theta = 0°$ (directly from beneath) and $\theta = 180°$ (directly from above), but these angles do not represent realistic exposure conditions. Anyway, with a good probability, the above "rule" holds for any common human body shape in regular standing posture (VF Female, Japanese models, Norman etc), because it holds for VF Male and VF Boy (heterogeneous and homogeneous). The rule is partly based on the angle-dependent absorption/capture area of the body.

4.4 Normalized max(10gSAR) curves at selected frequencies

Some normalized peak 10g SAR curves are shown in Figures 15 - 18 (to give some examples). Results are shown at 300 and 2100 MHz, for vertical and horizontal polarization, for all the models. (Number of shown figures was limited to limit the number of pages in this document.)

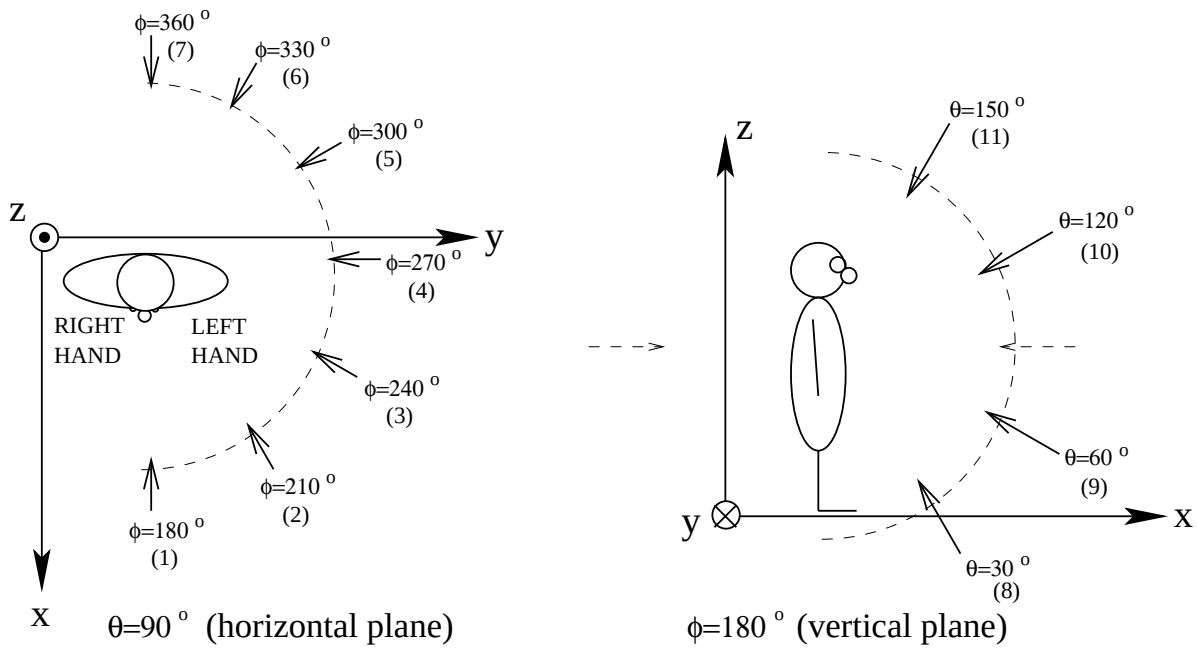

Figure 8: Incoming angles of the plane wave in the horizontal and vertical plane. Note that in the vertical plane (x-z plane) there are effectively 6 incoming angles. Angles have been given indices from 1 to 11.

4.5 Incoming angle variation results for Virtual Family Male and Boy

The exposed models are VF Male (heterogeneous and homogeneous) and VF Boy (heterogeneous and homogeneous). The results are shown for normalized WBASAR and for normalized max(10gSAR), separately in the limbs and in the head/trunk region. In the SAR Figures 19 - 24, each marker represents an incoming angle (11 angles total), and the polarization-frequency cases are indicated along the horizontal axis. For example, V2100 refers to vertical polarization at 2100 MHz.

In the Figures 19 - 24, one can see the SAR variation due to the incoming angle, in different polarization-frequency cases. Some observations on the normalized WBASAR (Figures 19 and 20):

- At 5000, 3500, 2100, 900 MHz:
  - With both polarizations, the WBASAR has its maximum when the wave comes directly from the front (anterior) or directly from the back (posterior). More often, the anterior exposure gives the maximum value.
  - With vertical polarization, WBASAR has its minimum when the wave comes from the (left) side. With horizontal polarization, minimum is obtained when the wave comes from the front and *above* ($\theta = 150°$,$\phi = 180°$).
- At 450 and 300 MHz:
  - There are no simple rules for the angles which maximize and minimize WBASAR.
  - The normalized WBASAR values are relatively low, i.e., they are far below 1.

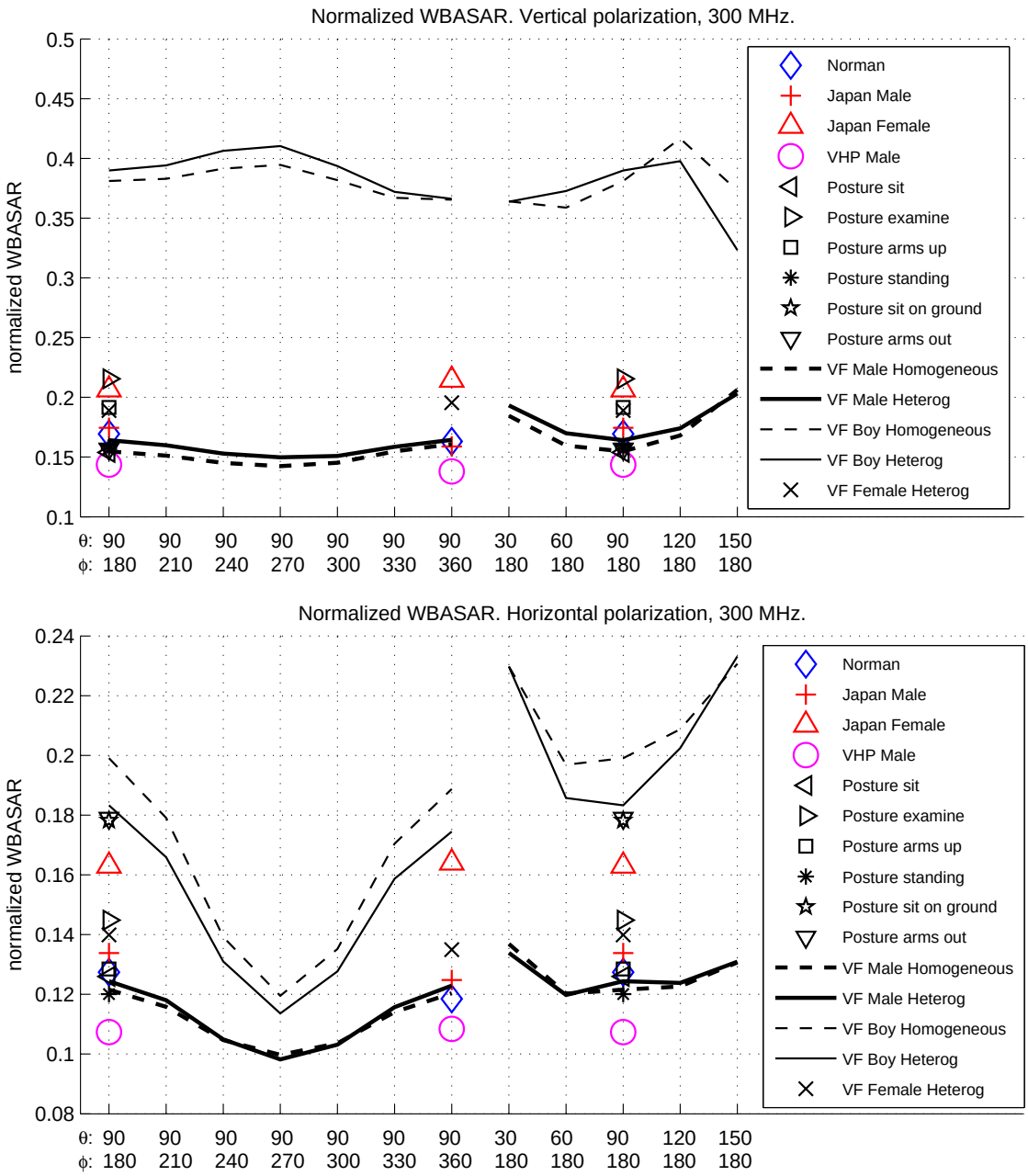

Figure 9: Normalized WBASAR at 300 MHz for vertical and horizontal polarization. Incoming angle of the plane wave, propagating in *free space*, is indicated by θ and ϕ.

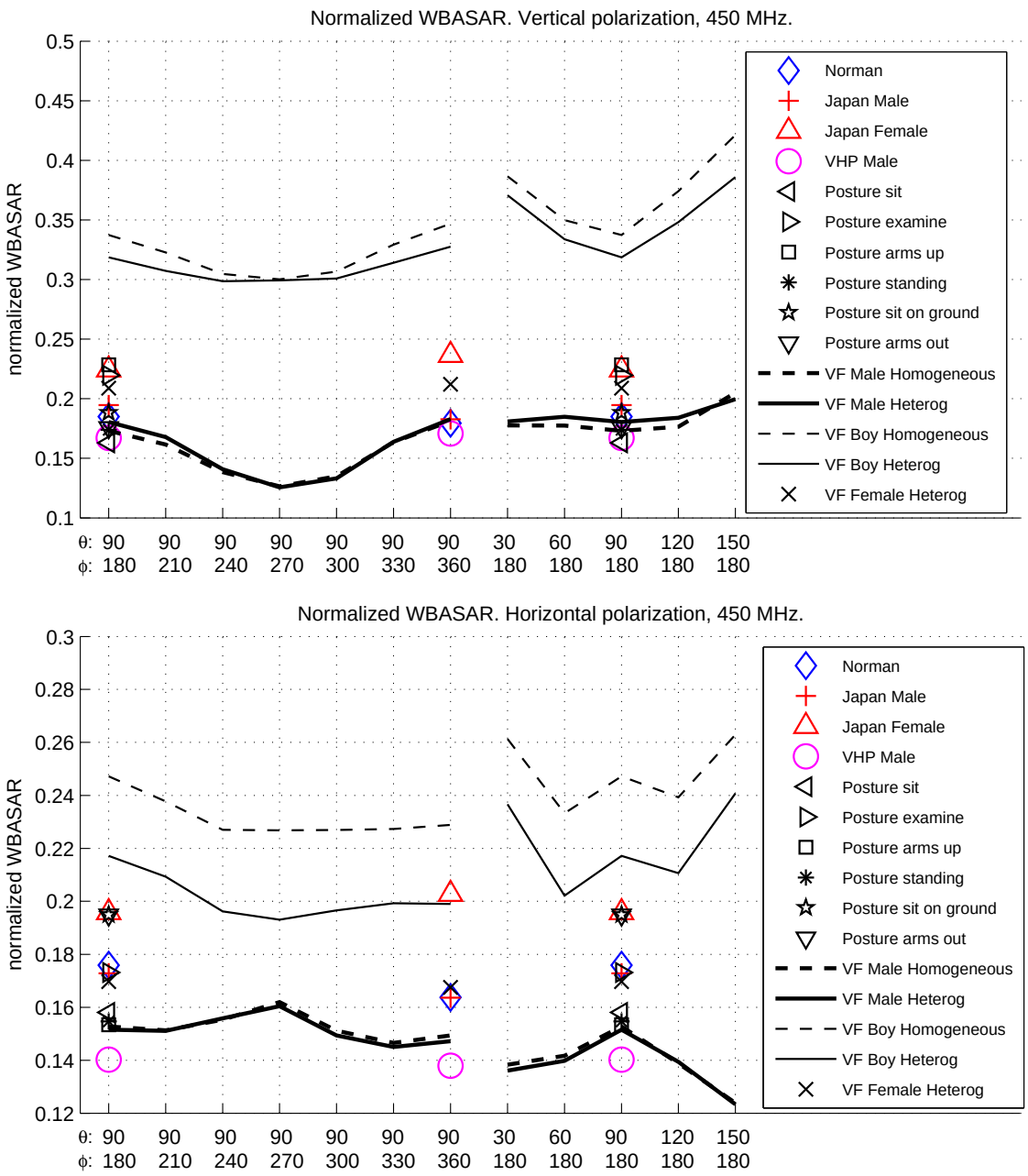

Figure 10: Normalized WBASAR at 450 MHz for vertical and horizontal polarization .

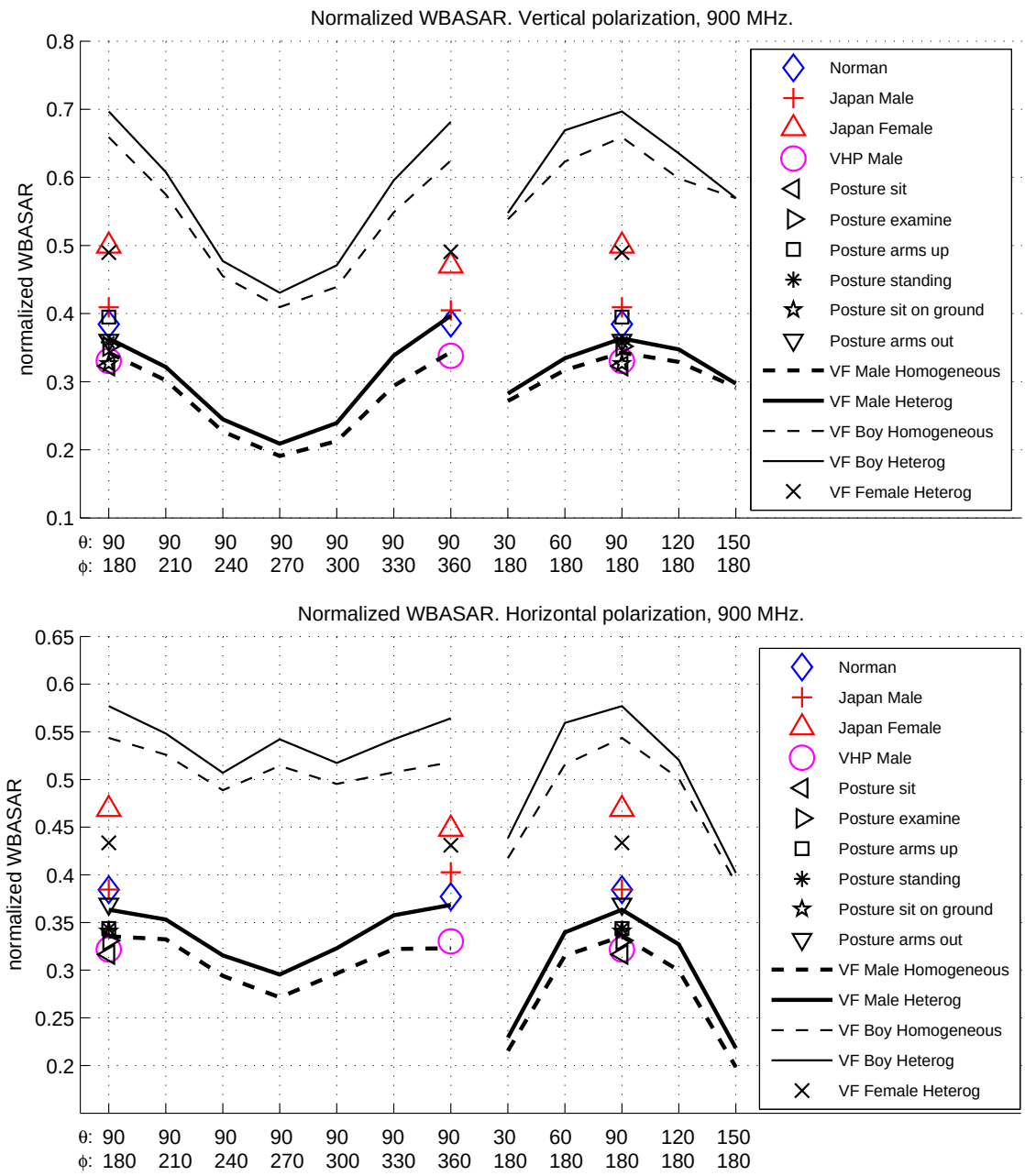

Figure 11: Normalized WBASAR at 900 MHz for vertical and horizontal polarization .

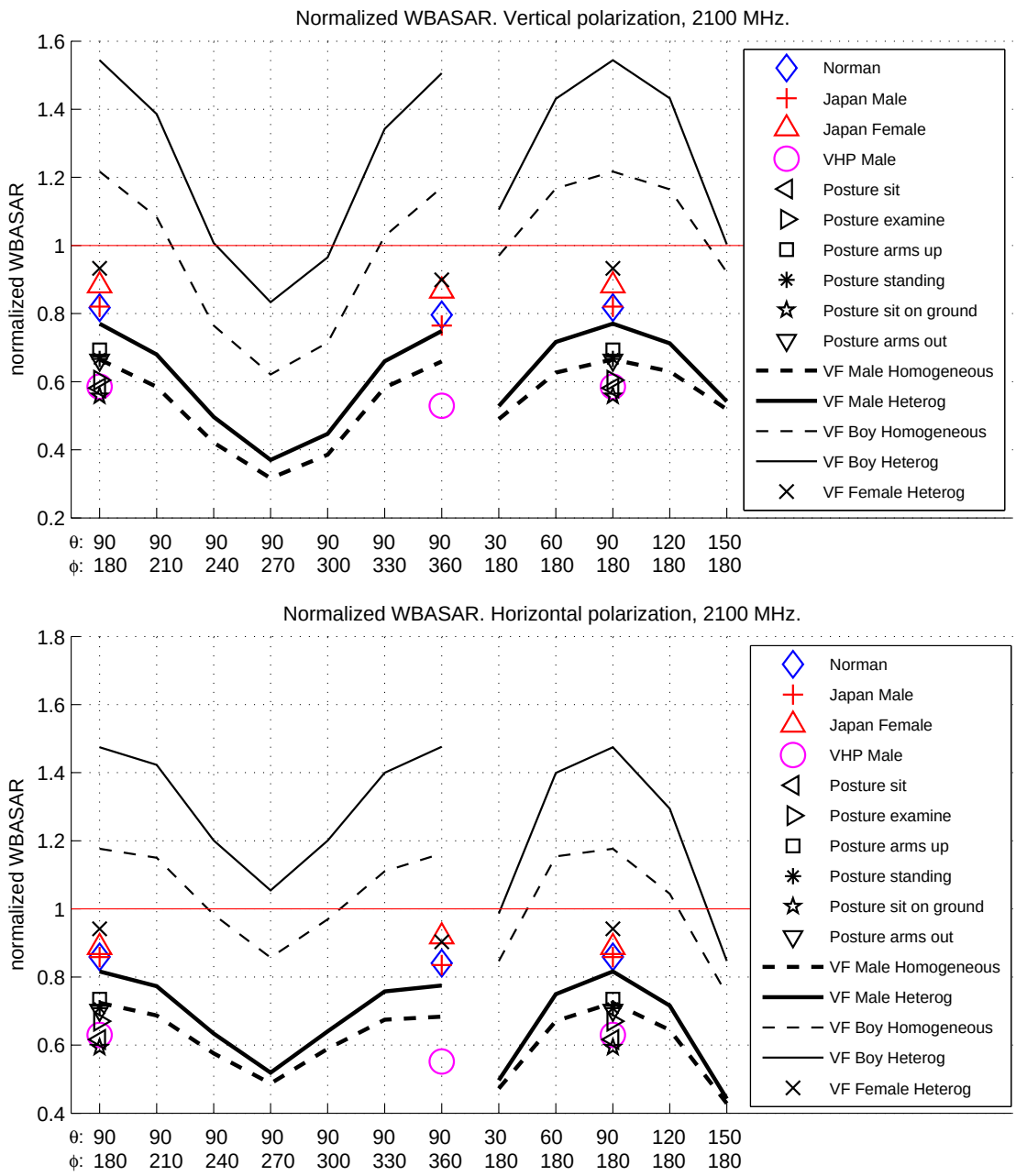

Figure 12: Normalized WBASAR at 2100 MHz for vertical and horizontal polarization .

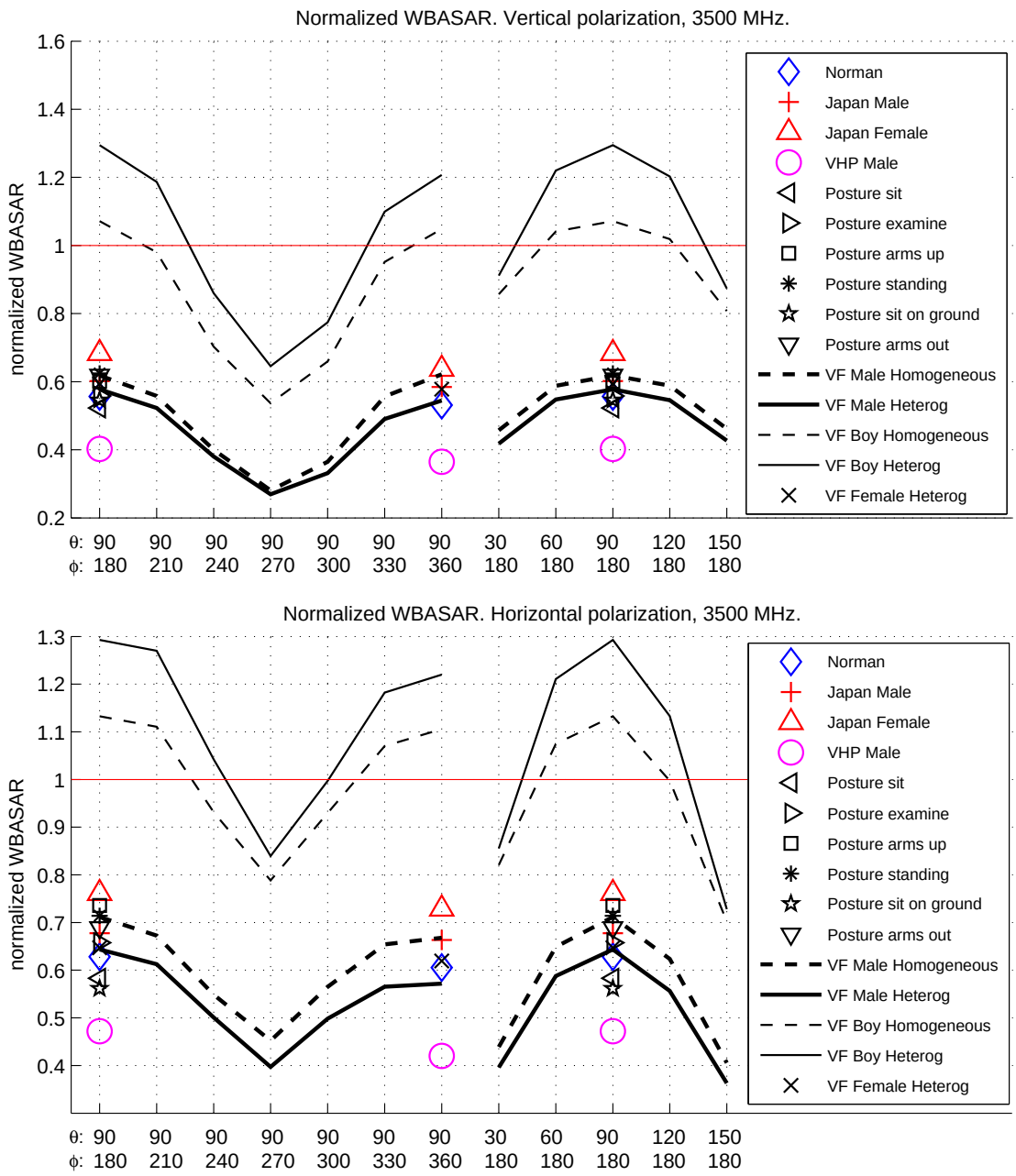

Figure 13: Normalized WBASAR at 3500 MHz for vertical and horizontal polarization .

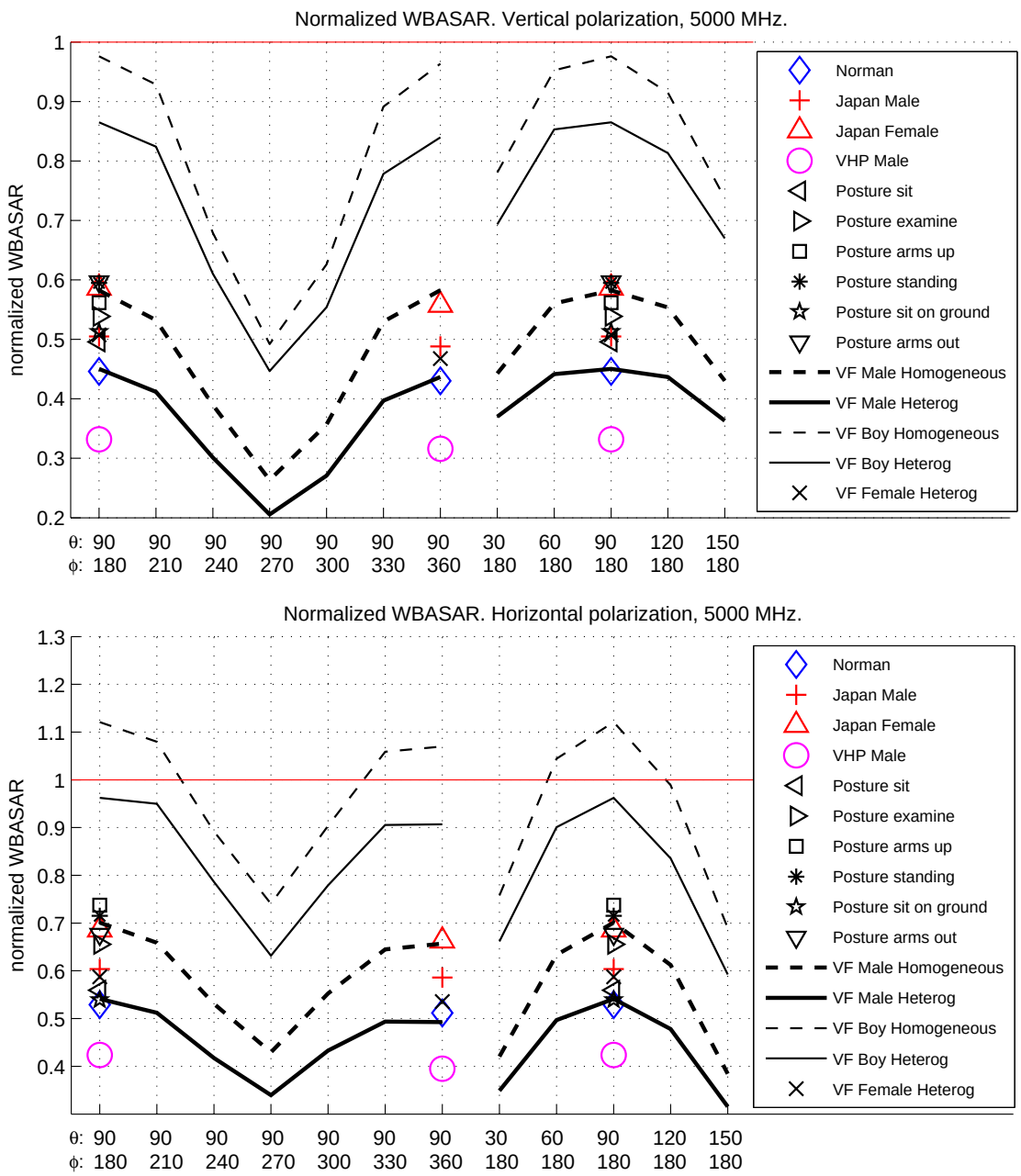

Figure 14: Normalized WBASAR at 5000 MHz for vertical and horizontal polarization .

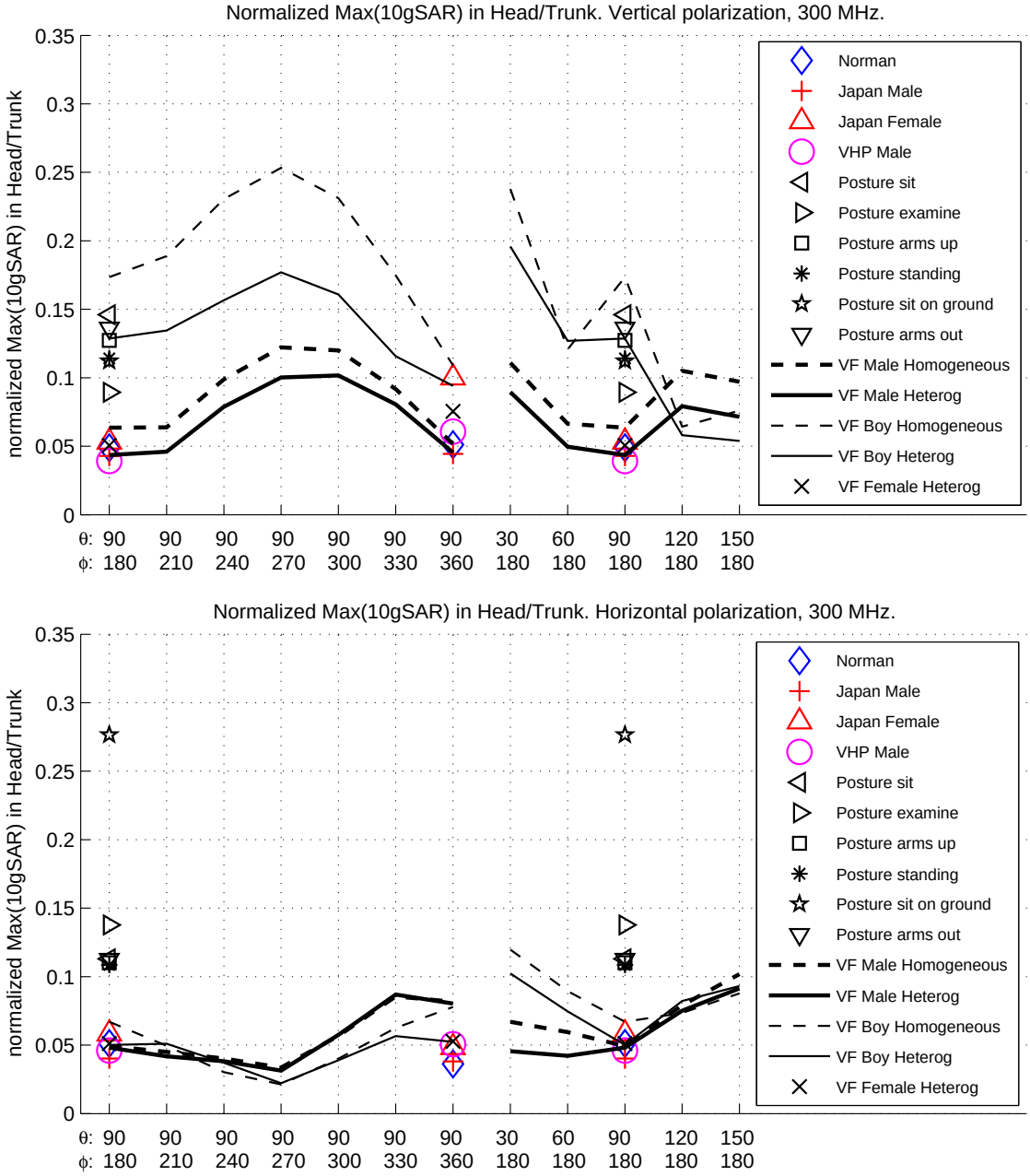

Figure 15: Normalized max(10gSAR) in the head/trunk at 300 MHz for vertical and horizontal polarization.

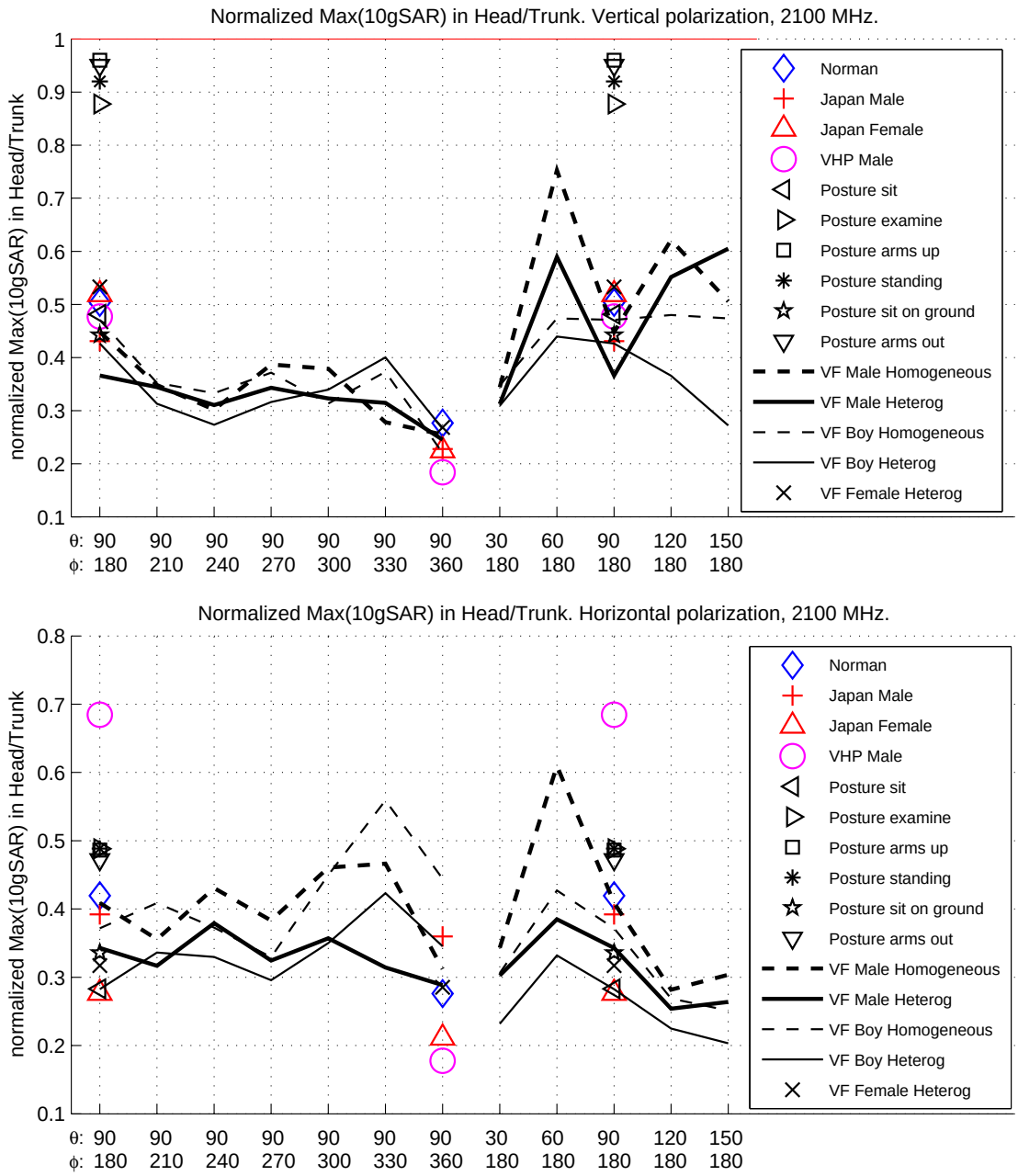

Figure 16: Normalized max(10gSAR) in the head/trunk at 2100 MHz for vertical and horizontal polarization.

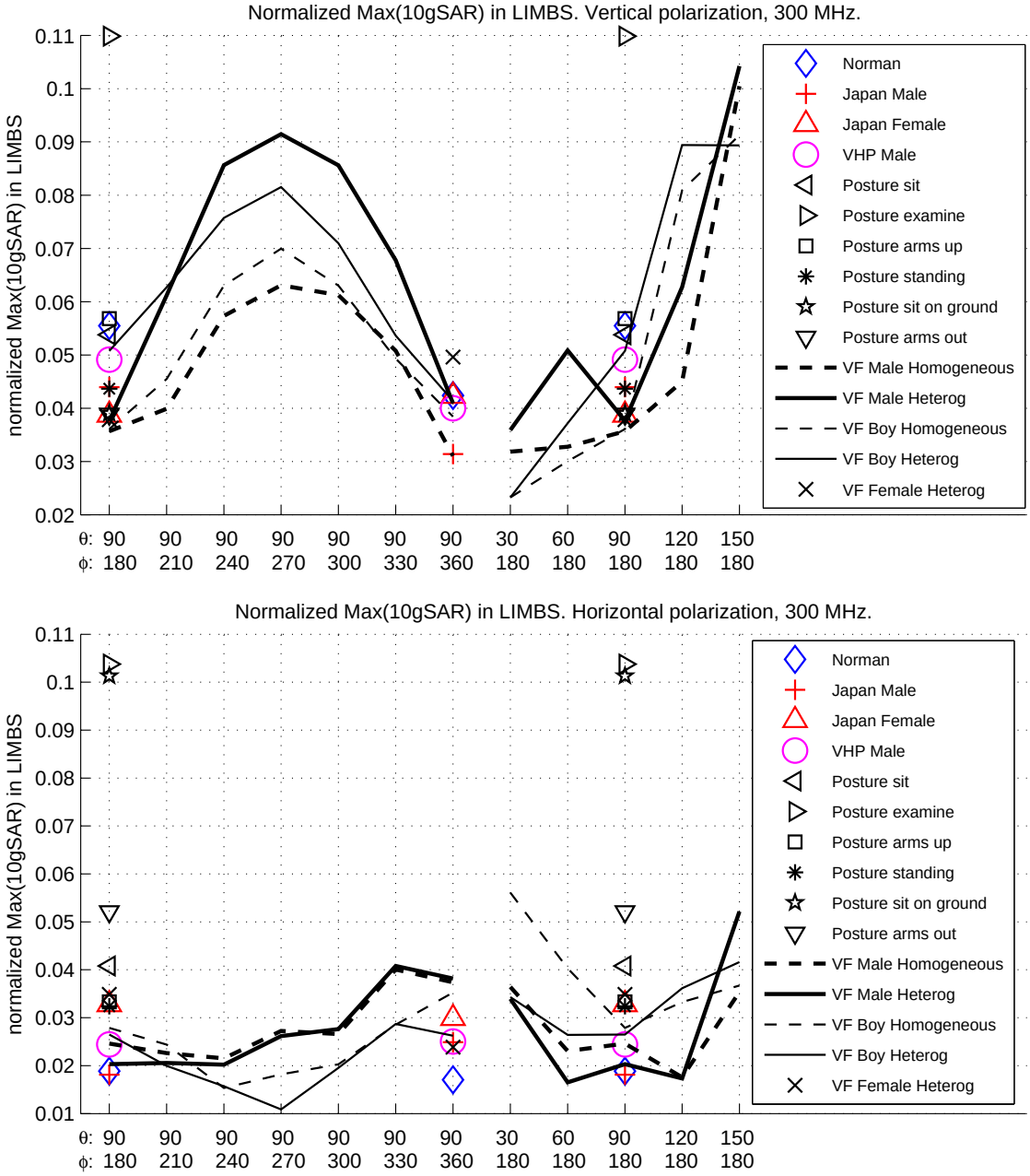

Figure 17: Normalized max(10gSAR) in the limbs at 300 MHz for vertical and horizontal polarization.

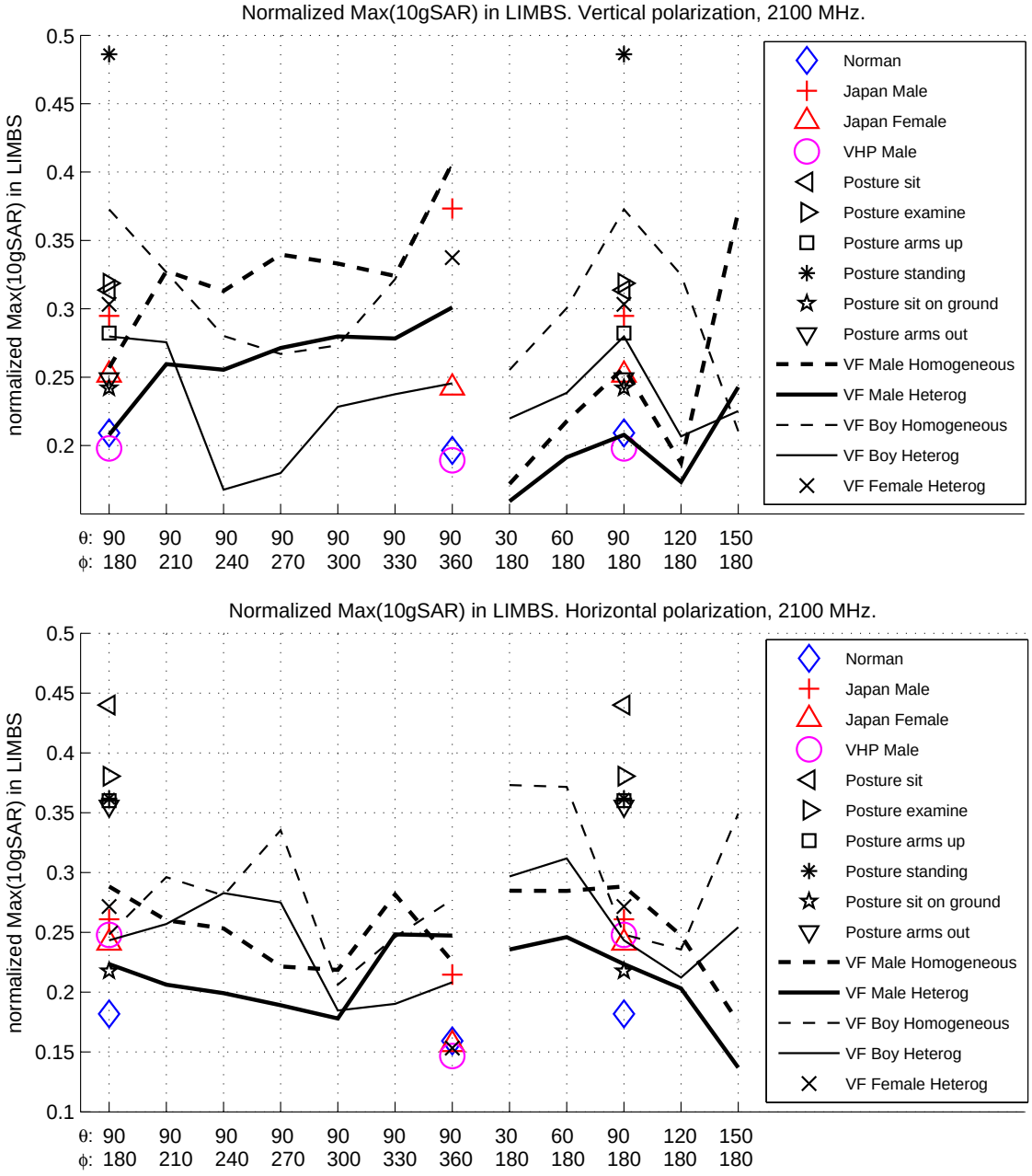

Figure 18: Normalized max(10gSAR) in the limbs at 2100 MHz for vertical and horizontal polarization.

Note that the above observations are based on 4 models and 11 incoming angles. Considering the presentability of this model set, at least the models are of very different size and both homogeneous and heterogeneous versions are included in the set. Also, the body shapes somewhat differ when comparing VF Boy and VF Male.

As a conclusion, based on Figures 19 and 20, at the frequencies 900, 2100, 3500 and 5000 MHz, with both polarizations, it is very probable that the WBASAR value of a random incoming angle is smaller than or comparable to max($\mathrm{WBASAR}_{\mathrm{anterior}}$, $\mathrm{WBASAR}_{\mathrm{posterior}}$) [4]. That is, if one simulated all the cases through again, but using a larger and denser set of incoming angles, one would not find remarkably higher WBASAR values. The conservativeness of this conclusion is increased, if it is applied above 900 MHz.

Above conclusion bases on 4 models and 11 incoming angles, but it can be expected to be valid for other models too, as long as they have a common body shape and size, and they are in regular standing posture [5]. Considering plane-wave WBASAR simulations of typical human bodies in standing posture, above conclusion or "rule" is beneficial: in order to get the maximum WBASAR value at a given (high enough) frequency and polarization, it suffices to simulate anterior and posterior cases only. It is unlikely that a random incoming angle could produce substantially higher WBASAR value than anterior or posterior exposure.

At lower frequencies 300 and 450 MHz, the situation is completely different. Close inspection of the Figures 19 and 20 reveals that the maximum value of WBASAR is *never* obtained in the case of anterior or posterior exposure - actually, maximum WBASAR at 300 and 450 MHz is often obtained with $\theta = 30°$ or $\theta = 150°$ (while $\phi = 180°$). However, the normalized WBASAR values are relatively small and clustered together. It is unlikely that a random incoming angle could deviate a normalized WBASAR value substantially away from this cluster. It is very unlikely that a WBASAR would rise close to the SAR limit at the reference level of exposure. (If it was necessary to find the maximum WBASAR and the corresponding incoming angle, at these low frequencies one could use low resolution in FDTD.)

Note that the incoming angle set in the simulations lacks the angles $\theta = 0°$ (wave from directly below) and $\theta = 180°$ (wave from directly above). If these angles were included, at frequencies 900, 2100, 3500 and 5000 MHz, the maximum WBASAR values would remain same as now, but the minimum WBASAR values could be somewhat smaller. This can be understood from Figures 11 - 14 and also via the angle-dependent absorption area of the body. However, at lower frequencies 300 and 450 MHz, the maximum WBASAR values could rise a bit if these directly-from-below/above angles were included in the simulations (see Figures 9 and 10). But essentially, based on the results in hand, it is *very unlikely* that a WBASAR value could exceed the SAR limit at the reference level of exposure at frequencies 300 and 450 MHz.

Figures 21 - 24 show the variation of normalised max(10gSAR) in the limbs and in the head/trunk. It is observed that the incoming angle maximizing the peak 10g-SAR value is quite random, which is not surprising. In the simulated cases, normalized max(10gSAR) never exceeds the limit 1. The normalized peak SAR values tend to be higher in the head/trunk region than in the limbs. The maximum value of normalized peak SAR in the head/trunk is 0.78 and this occurs with VF Boy Homogeneous in case H3500. In limbs the maximum is 0.48 and this occurs with VF Boy Heterogeneous in case V3500.

[4] I.e. taking the maximum from the already simulated results of $\mathrm{WBASAR}_{\mathrm{anterior}}$ and $\mathrm{WBASAR}_{\mathrm{posterior}}$.

[5] Mass about 20 - 100 kg, reasonable body mass index (BMI), standing arms by the side of the body.

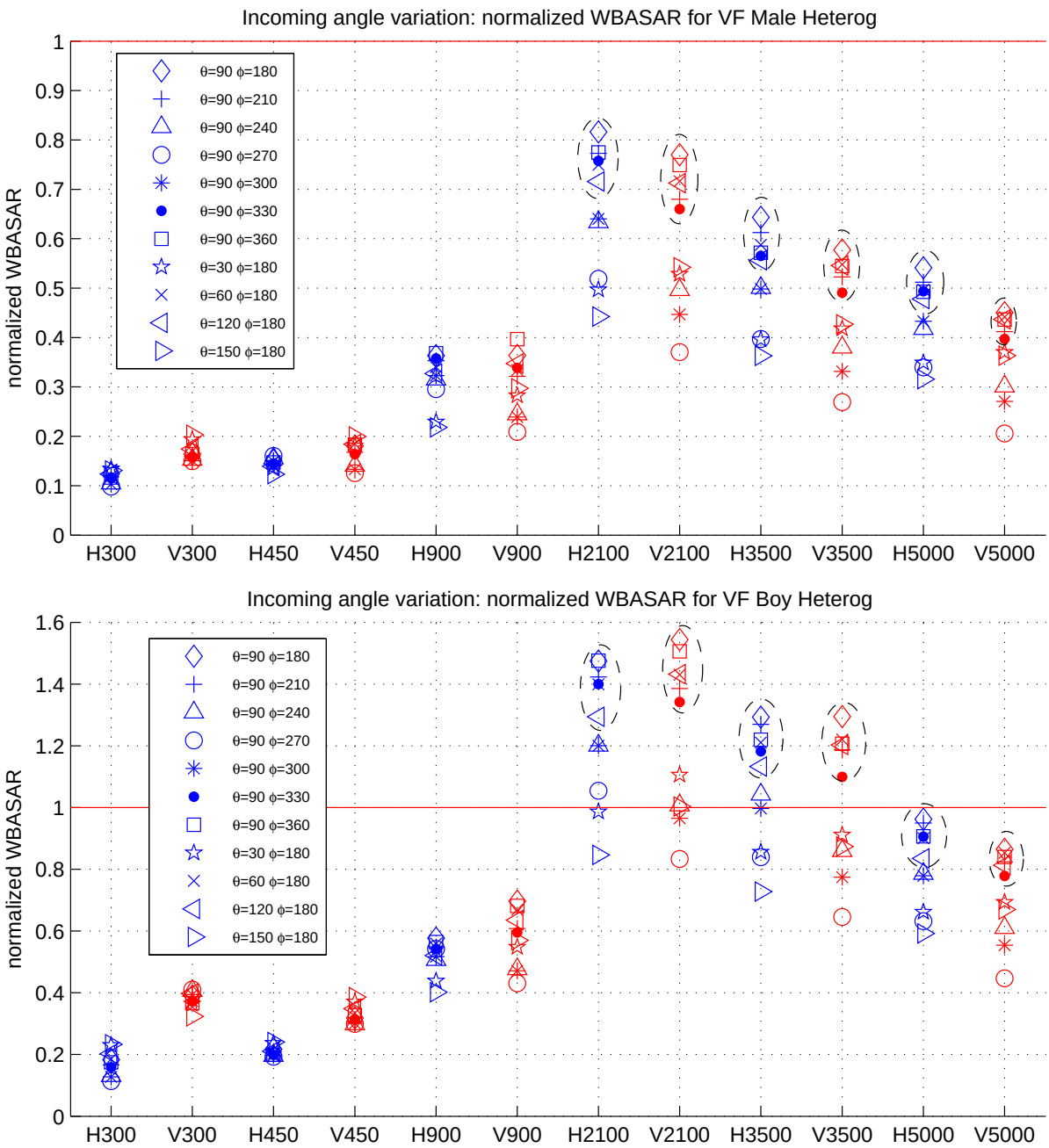

Figure 19: Incoming angle variation. Normalized WBASAR is shown for heterogeneous VF Male and Boy. At 2100, 3500 and 5000 MHz, a dashed-line ellipse is used to denote exposure cases of anterior, posterior, "almost anterior" and "almost posterior" - these correspond to 6 incoming angles $(\theta, \phi) = (90°, 180°)$, $(\theta, \phi) = (90°, 360°)$, $(\theta, \phi) = (120°, 180°)$, $(\theta, \phi) = (60°, 180°)$, $(\theta, \phi) = (90°, 210°)$, and $(\theta, \phi) = (90°, 330°)$. This kind of illustrative grouping of incoming angles is difficult or impossible at 300, 450 and 900 MHz, because at these lower frequencies the incoming-angle-WBASAR relation is quite random. Interestingly, for example, VF Boy Heterogeneous at V300 has its maximum WBASAR when the wave comes from the left-hand side of the model (see also Fig. 9). For comparison, at high frequencies, wave from the left typically minimizes (V-pol) or almost minimizes (H-pol) the WBASAR value.

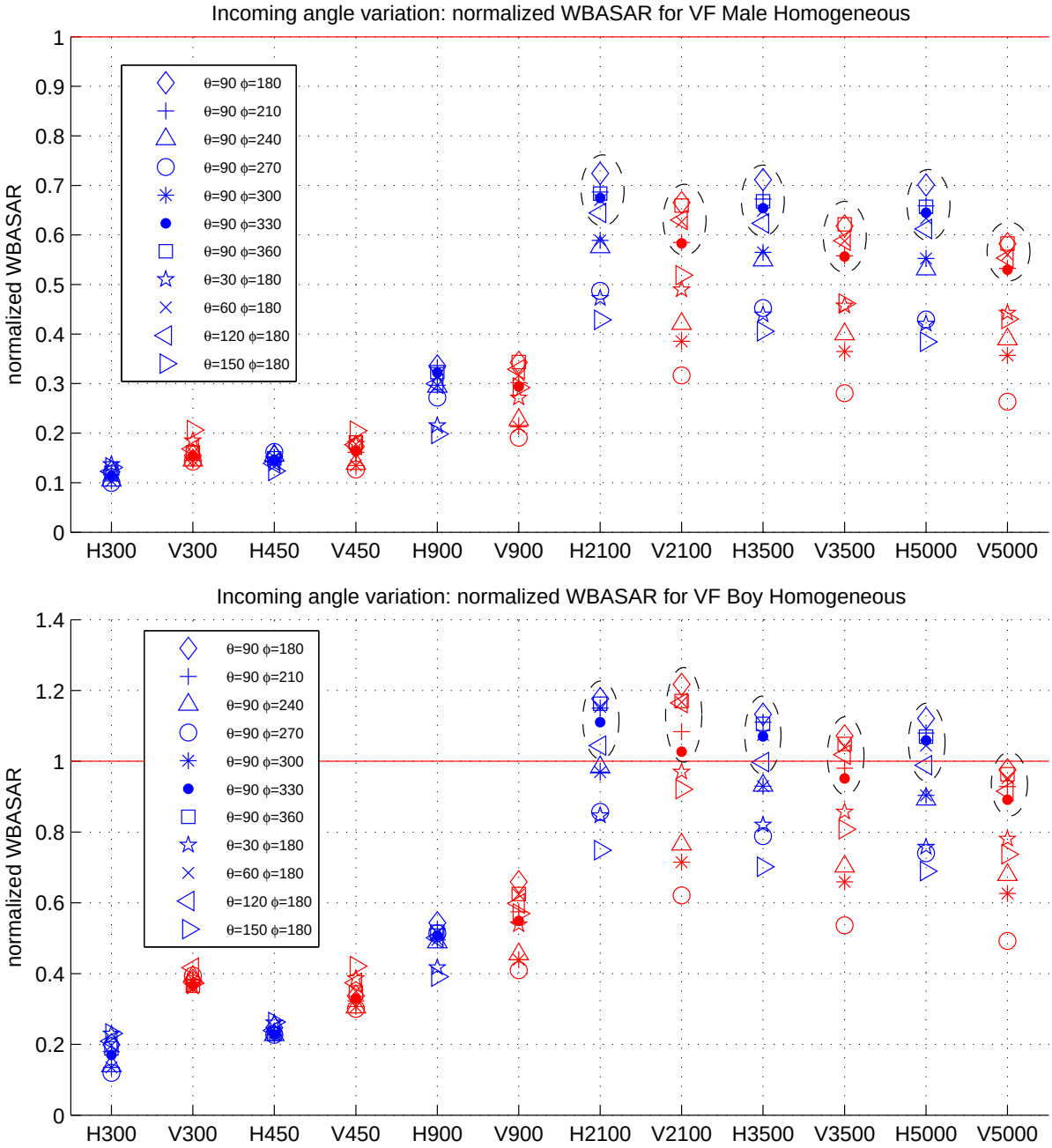

Figure 20: Incoming angle variation. Normalized WBASAR is shown for homogeneous VF Male and Boy. At 2100, 3500 and 5000 MHz a dashed-line ellipse is used to denote exposure cases of anterior, posterior, almost anterior and almost posterior. This kind of grouping of incoming angles is difficult or impossible at 300, 450 and 900 MHz.

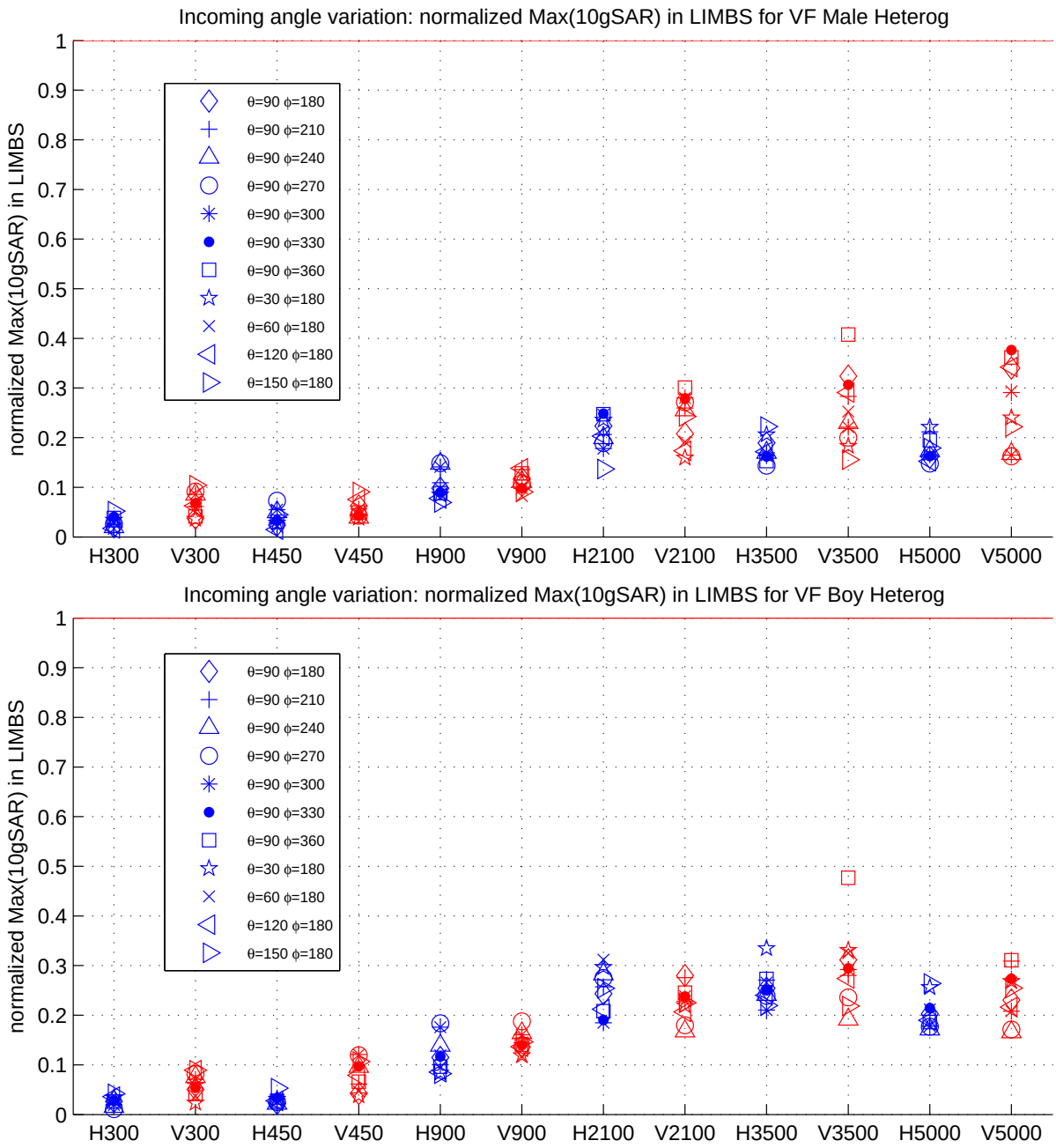

Figure 21: Incoming angle variation. Normalized max(10gSAR) in the limbs is shown for heterogeneous VF Male and Boy.

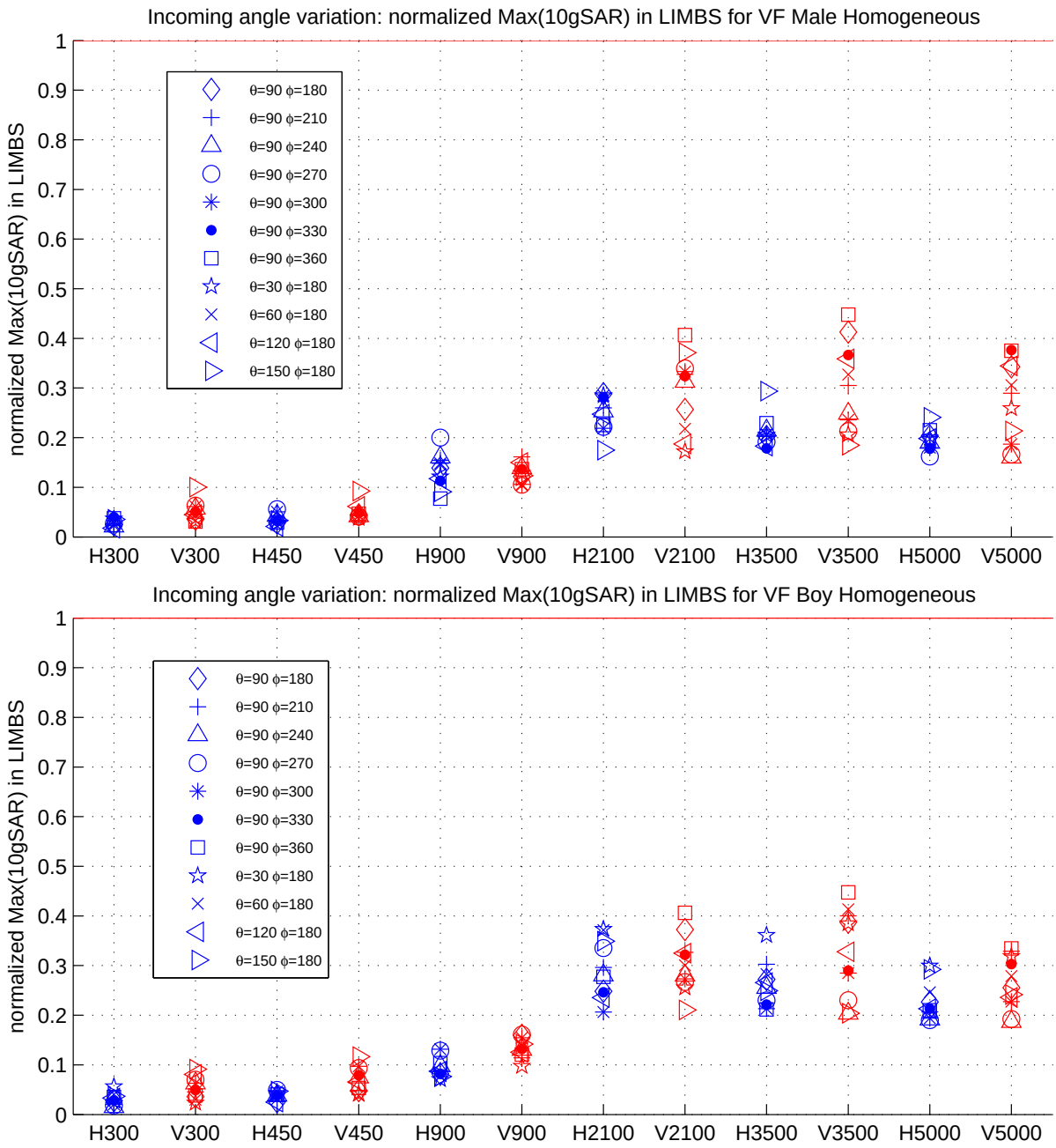

Figure 22: Incoming angle variation. Normalized max(10gSAR) in the limbs is shown for homogeneous VF Male and Boy.

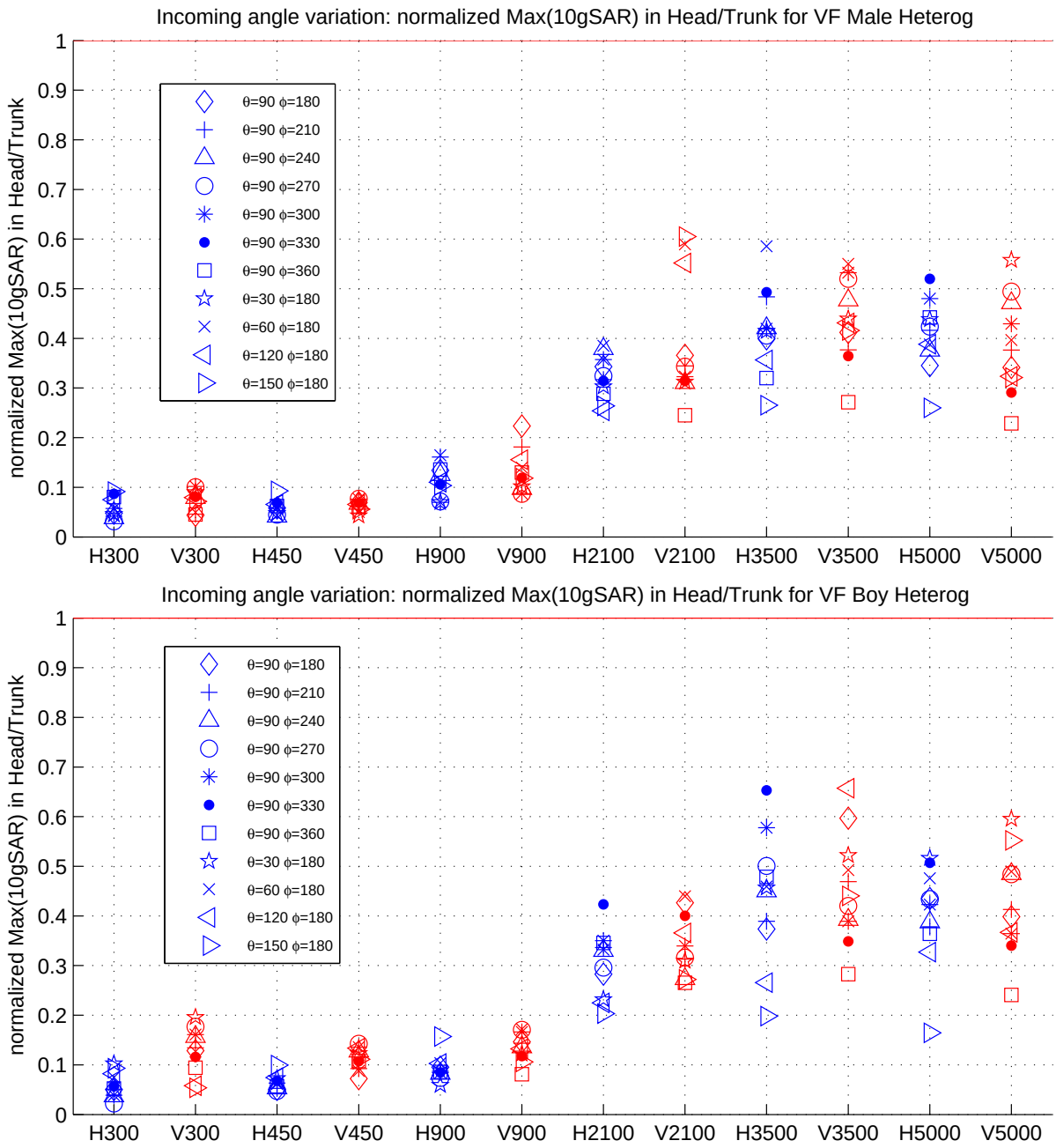

Figure 23: Incoming angle variation. Normalized max(10gSAR) in the head/trunk is shown for heterogeneous VF Male and Boy.

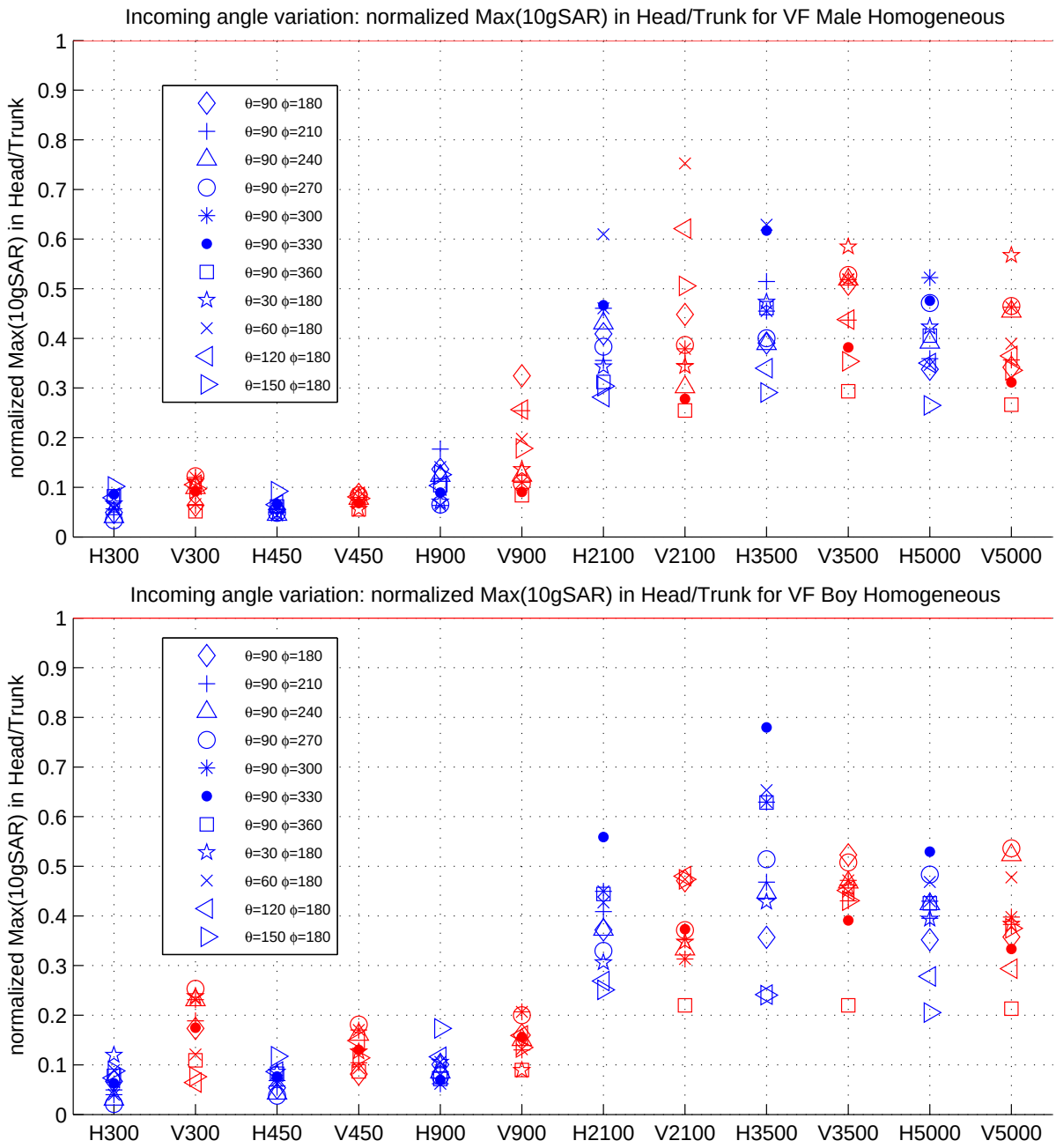

Figure 24: Incoming angle variation. Normalized max(10gSAR) in the head/trunk is shown for homogeneous VF Male and Boy.

4.6 Phantom variation results

The considered models are (see also Table 1)

- Norman (73.0 kg)
- Japan Male (69.0 kg)
- Japan Female (53.4 kg)
- VHP Male (105.4 kg)
- VF Male Homogeneous (68.5 kg)
- VF Male Heterogeneous (72.2 kg)
- VF Boy Homogeneous (18.3 kg)
- VF Boy Heterogeneous (19.4 kg)
- VF Female Heterogeneous (58.2 kg)
- Posture standing (homogeneous, 65.05 kg, anterior case only)

Special postures are excluded i.e. all the models are "standing normally". Results are shown for normalized WBASAR and for normalized max(10gSAR), separately in the limbs and in the head/trunk region. Both anterior and posterior cases are examined, except for the model "Posture standing".

Results are shown in the SAR Figures 25 - 27, where each marker now represents a certain model. In the figures one can see the variation of normalized SAR as well as whether the SAR limits are exceeded or not. Already earlier it was observed that, at the reference level of exposure, the WBASAR limit is exceeded with VF Boy (at several frequencies) and that the female models are quite close to the WBASAR limit at 2100 MHz. VHP Male (105.4 kg) has the lowest WBASAR in almost every case.

Figure 30 shows the ratio $\mathrm{SAR}_{\mathrm{anterior}}/\mathrm{SAR}_{\mathrm{posterior}}$ for WBASAR. At the higher frequencies this ratio is larger than 1 in most cases, i.e., typically frontal exposure gives somewhat higher WBASAR than posterior exposure (with a randomly chosen body model). This is probably so because the body surface is a bit more flat when seen from the back side (posterior), i.e. there is less absorption area compared to the front side. However, note that when $f \leq 900$ MHz, the above "rule" does not hold as well.

When examining the normalized max(10gSAR) results of Figures 26 and 27, it is observed that the limit is not exceeded by any model in any simulated case. In the case V2100, however, for "Posture standing" the normalized peak SAR value in the head/trunk is 0.92 (i.e. 0.36 dB below the limit, see Figure 27).

The normalized max(10gSAR) tends to be higher in the head/trunk region than in the limbs, especially in the case of anterior exposure. Figure 28 illustrates this by the ratio of normalized peak SAR in the head/trunk and normalized peak SAR in the limbs. Clearly, especially at frequencies $f \geq 2100$ MHz, the normalized peak SAR is higher in the head/trunk than in the limbs. In other words, the peak SAR values are closer to the SAR limit in the head/trunk than in the limbs [6]. Figure 29 shows the same ratio in the

[6] Of course, this is so quite easily because the peak 10g-SAR limit for the head/trunk (10 W/kg occupational) is only half of the limit applied in the limbs (20 W/kg).

posterior case. So obviously, this ratio depends on the incoming angle, polarization and the model, and is often also smaller than 1. But if one takes an average value of this ratio $SAR_{head/trunk}/SAR_{limbs}$ (averaging over anterior and posterior cases and over all the models except posture models), separately at each frequency and with each polarization, this mean ratio is always larger than 1: the mean varies between 1.05 (V3500) and 2.03 (H5000). If averaging over all simulated 11 angles and over the models VF Male (homogeneous,heterogeneous) and VF Boy (homogeneous,heterogeneous), the mean ratio is larger than 1, except at H900: mean ratio varies between 0.91 (H900) and 2.18 (H300).

Figures 31 and 32 show the ratio $SAR_{anterior}/SAR_{posterior}$ for the peak 10g SAR in the limbs and in the head/trunk, respectively. Considering Figure 32 at higher frequencies, with vertical polarization, it is seen that the peak 10g-SAR values in the head/trunk are higher when a model is exposed from the front side (anterior). This rule seems to work for a large variety of models in the gigahertz region.

By examining the peak 10g-SAR locations of the computed SAR data, one can find out that in the gigahertz region typical peak SAR locations in the limbs are fingers and toes, and in the head/trunk, nose, ear, chin, penis and testicles (because field can effectively enter inside these kind of body parts which have relatively small dimensions). But especially in the gigahertz region, the incident direction of the plane wave affects quite remarkably the peak SAR location, which may cause high values of $SAR_{anterior}/SAR_{posterior}$ for the peak 10g SAR in head/trunk. Here are a few examples related to Figure 32 in the gigahertz region:

- With VHP Male at horizontal 2100 MHz, $SAR_{anterior}/SAR_{posterior}$ is very high. In this case, the frontal-exposure peak SAR is in the testicles, but the posterior-exposure peak SAR is in the backside of the trunk (flat region of torso). At vertical 2100, 3500, 5000 MHz, $SAR_{anterior}/SAR_{posterior}$ is also quite high for VHP Male. Now, with frontal exposure the head/trunk peak-SAR value is in the penis or testicles, but with posterior exposure the head/trunk peak SAR is in the lower region of trunk (backside).

- With VFB Homogeneous, at vertical 3500 and 5000 MHz, frontal-exposure peak SAR is in the penis, but the posterior-exposure peak SAR is in the upper trunk or neck (flat body region), causing quite high $SAR_{anterior}/SAR_{posterior}$.

- Sometimes $SAR_{anterior}/SAR_{posterior} < 1$. For example, at horizontal 3500 and 5000 MHz with VFB Homogeneous and VFF, the frontal-exposure peak SAR is in the nose (VFF) or in the testicles/penis (VFB), but the posterior-exposure peak SAR is located in the ear.

When comparing the results of VF Male Homogeneous with Posture standing (homogeneous), it is observed that their WBASAR results are very similar. This is not a surprise because the models have roughly the same size and mass. However, because the models have some anatomical differences [7] their max(10gSAR) results differ. The model "Posture standing" tends to have higher peak 10g-SAR values, which is very clearly seen in the anterior-V2100 case, see max(10gSAR) in the head/trunk (Figure 27). This particular peak 10g-SAR value is located in the penis and it is quite close to the SAR limit at the reference level of exposure. Actually, it seems that the sum effect of the parameters

[7] Posture standing is very athletic in general - and the two models have also local anatomical differences e.g. in the penis.

such as orientation, shape and length of penis can be remarkable on the max(10gSAR) in the head/trunk region (several dB's). For example, in the case of Posture standing at 2100 MHz, the max(10gSAR) in the head/trunk is located in the penis with both polarizations, but the value is about 2.7 dB's higher with vertical polarization (which matches with the penis orientation).

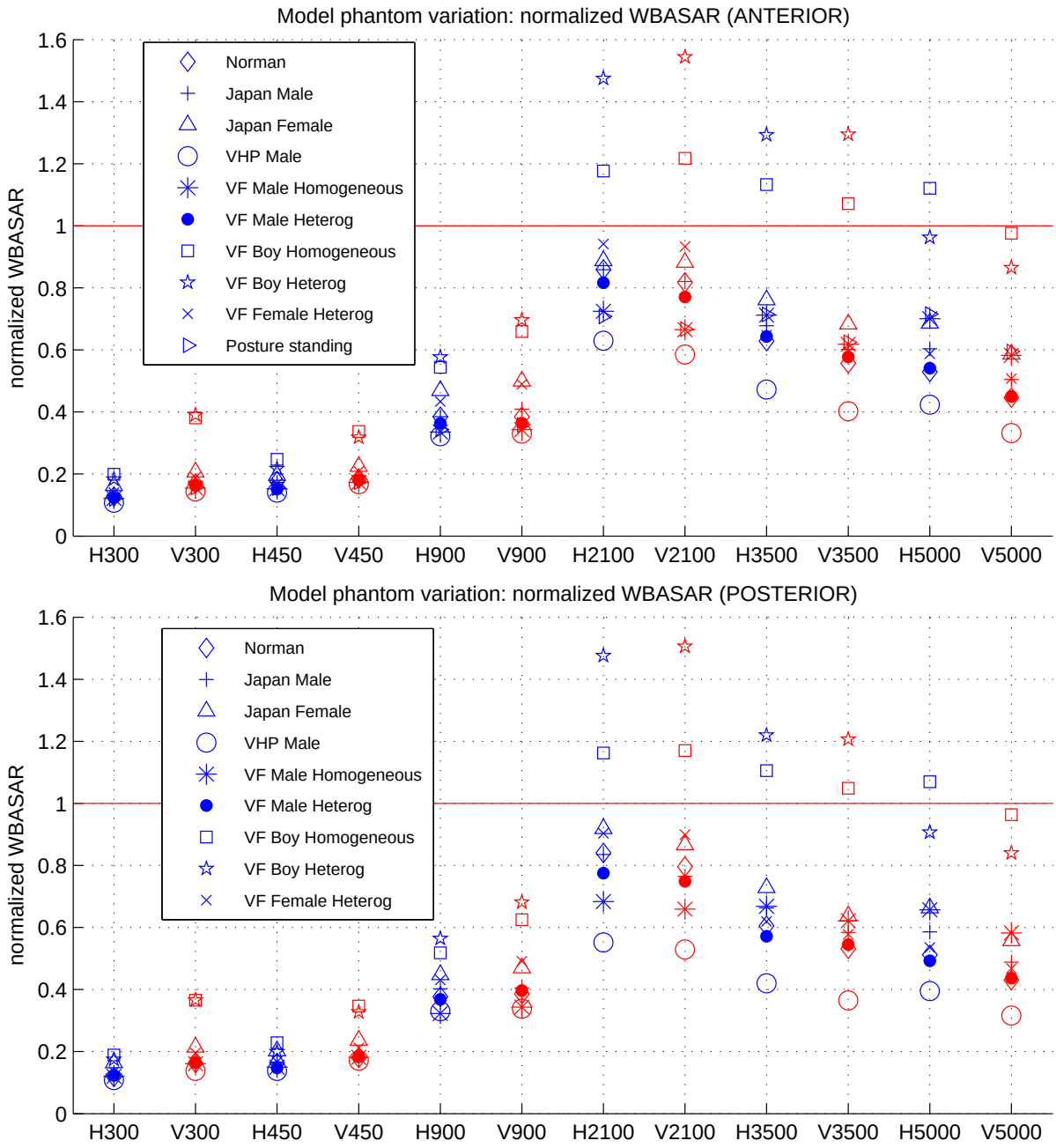

Figure 25: Model phantom variation (all the models are in the regular standing posture). Normalized WBASAR is shown for the anterior and posterior exposure cases.

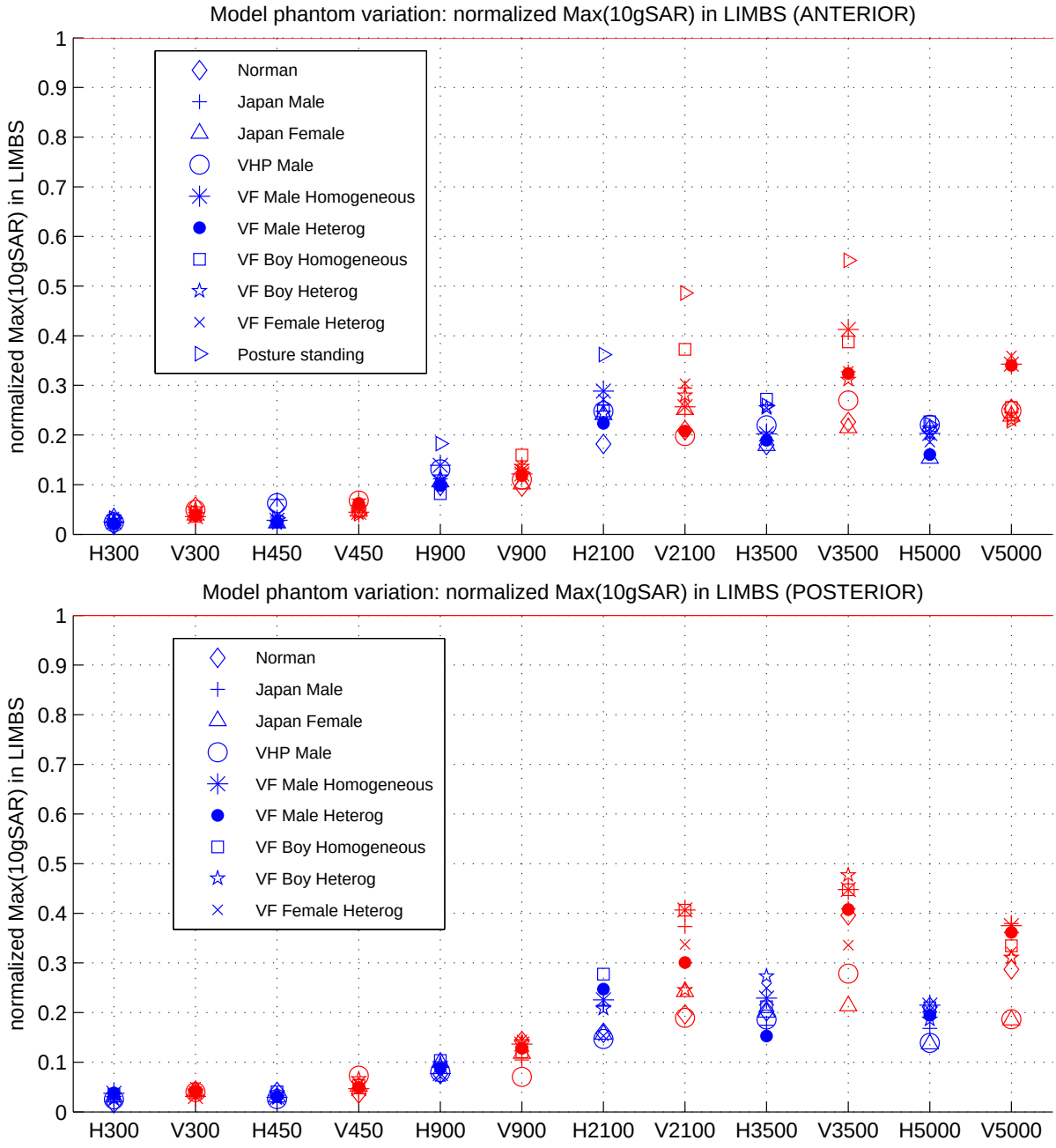

Figure 26: Model phantom variation (all the models are in the regular standing posture). Normalized max(10gSAR) in the limbs is shown for the anterior and posterior exposure cases.

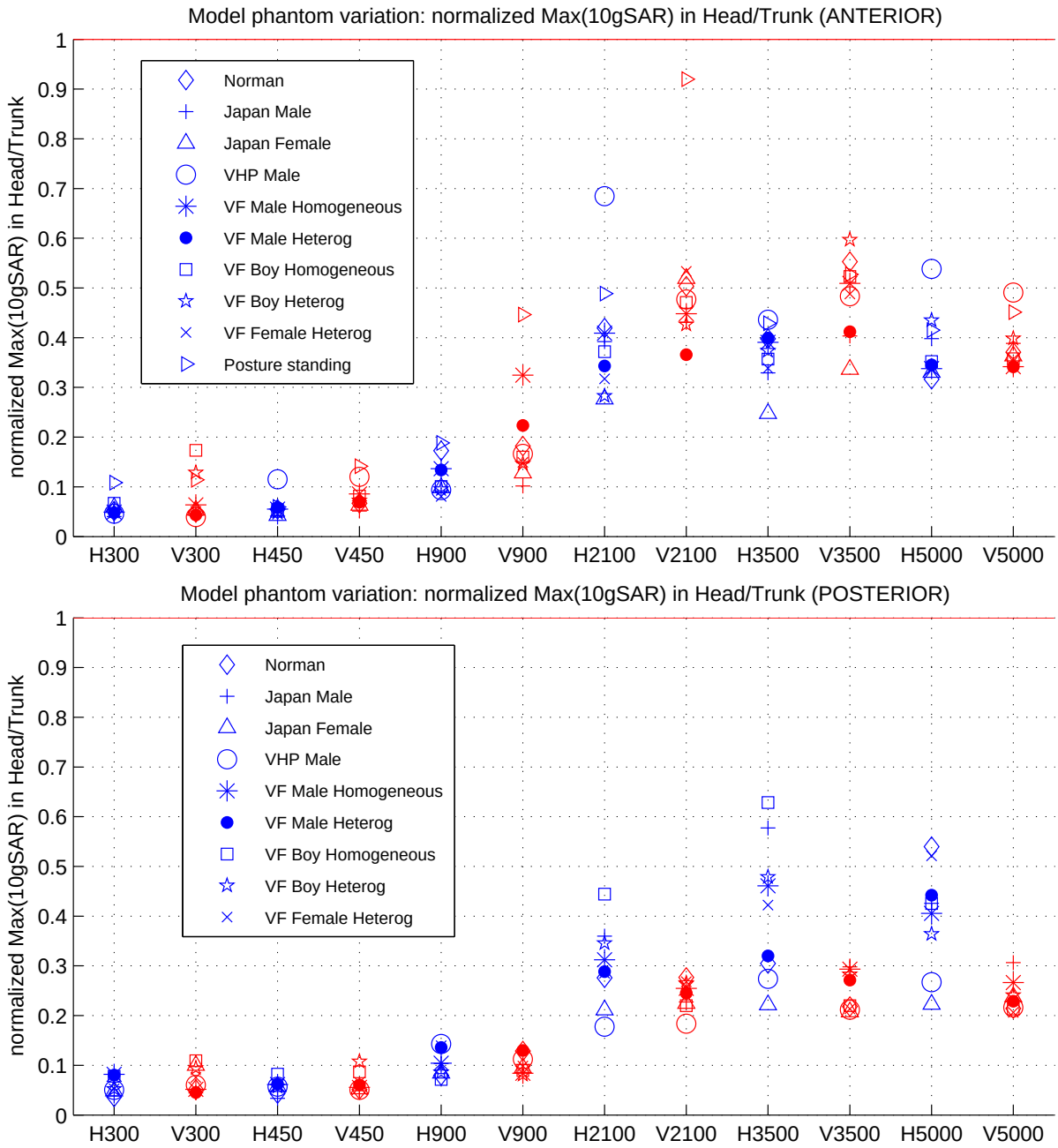

Figure 27: Model phantom variation (all the models are in the regular standing posture). Normalized max(10gSAR) in the head/trunk is shown for the anterior and posterior exposure cases. Note that for "Posture standing" the max(10gSAR) in the head/trunk is quite close to the limit at V2100 (the value is 0.92 i.e. 0.36 dB below the SAR limit).

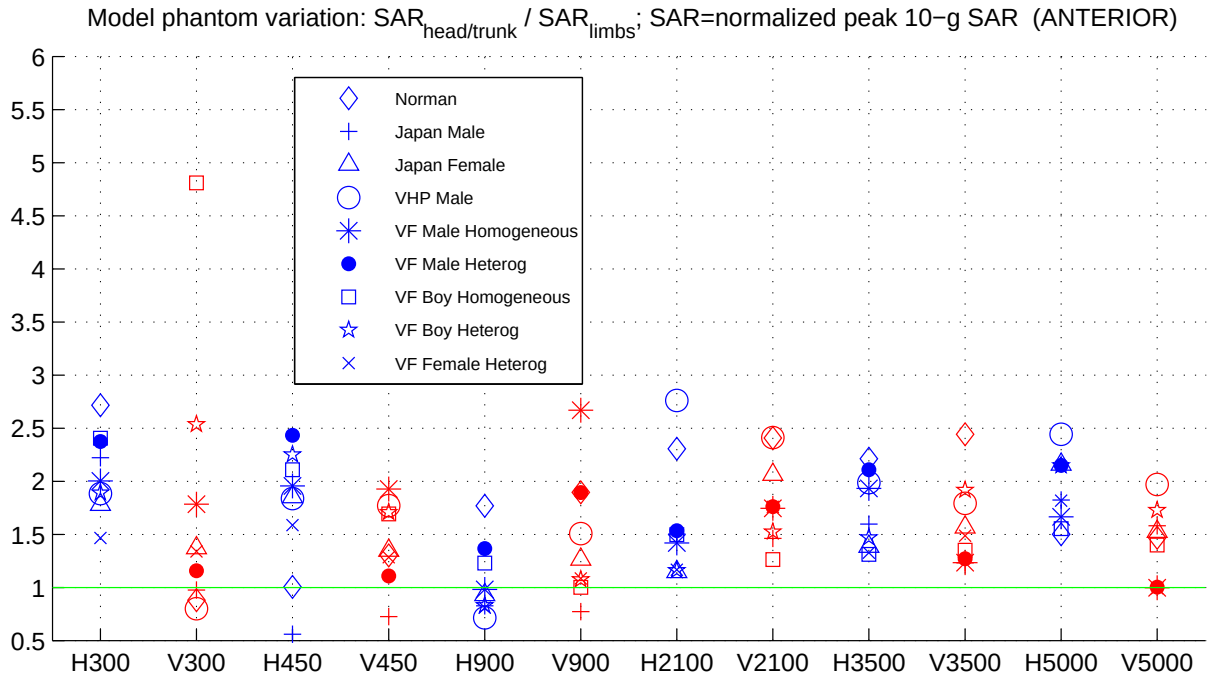

Figure 28: Model phantom variation (all the models are in the regular standing posture). The ratio of normalized peak SAR in the head/trunk and normalized peak SAR in the limbs is shown. Normalized peak SAR tends to be higher in the head/trunk than in the limbs.

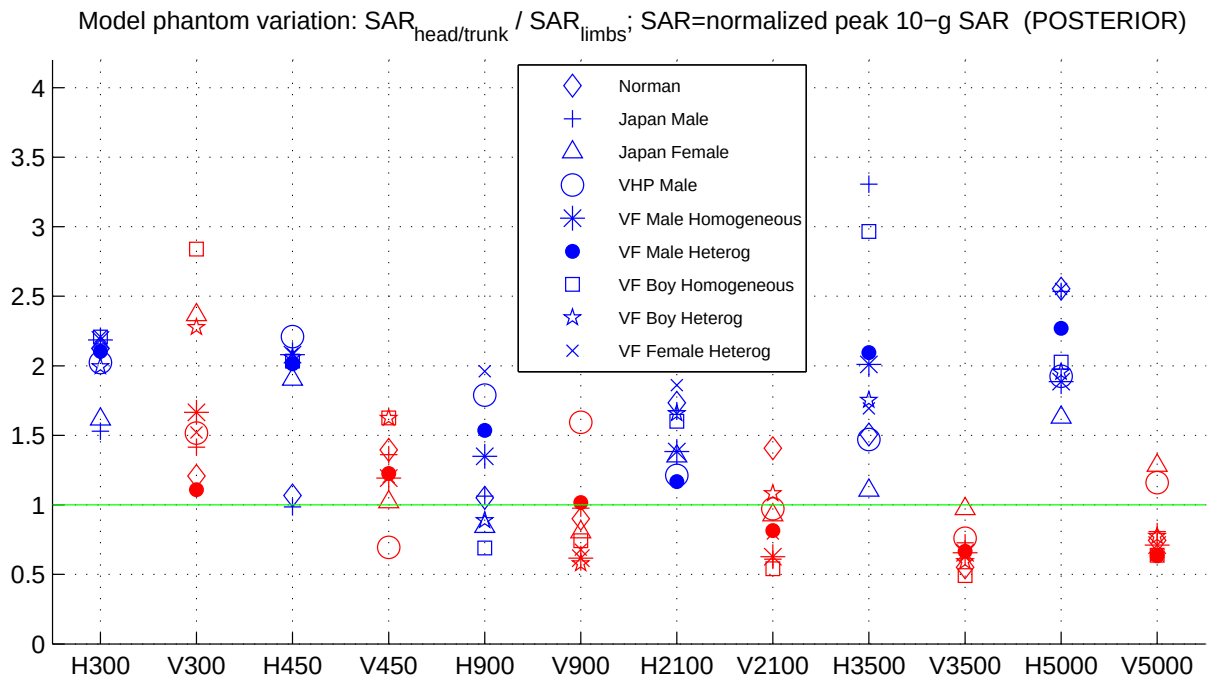

Figure 29: Model phantom variation (all the models are in the regular standing posture). The ratio of normalized peak SAR in the head/trunk and normalized peak SAR in the limbs is shown.

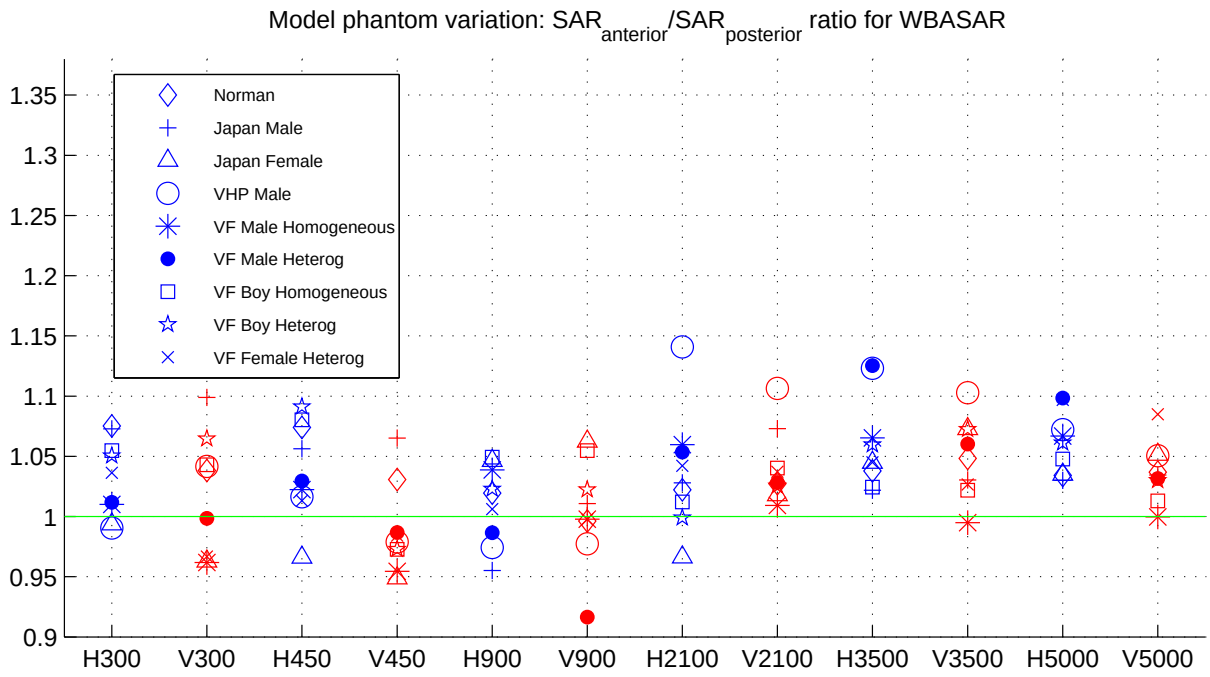

Figure 30: Model phantom variation (all the models are in the regular standing posture). $SAR_{anterior}/SAR_{posterior}$ ratio for WBASAR is shown for each model. Clearly, at higher frequencies this ratio is larger than 1 in most cases, i.e., typically frontal exposure gives somewhat higher WBASAR than posterior exposure.

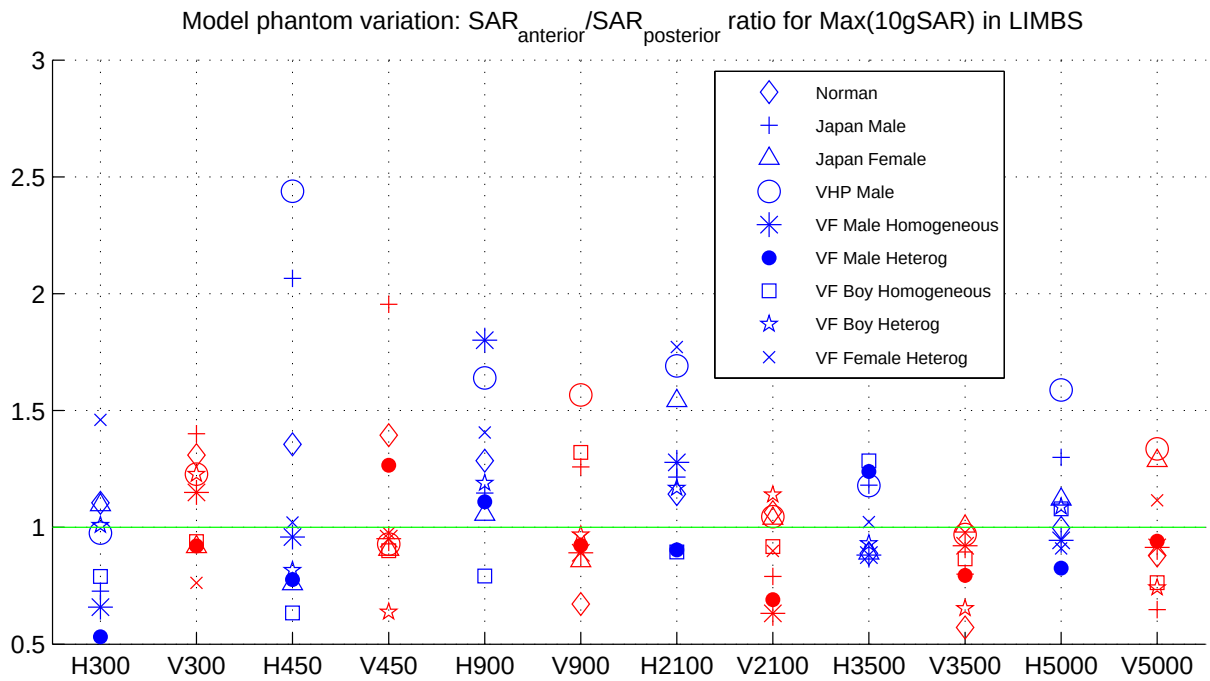

Figure 31: Model phantom variation (all the models are in the regular standing posture). $SAR_{anterior}/SAR_{posterior}$ ratio for max(10gSAR) in the limbs is shown for each model.

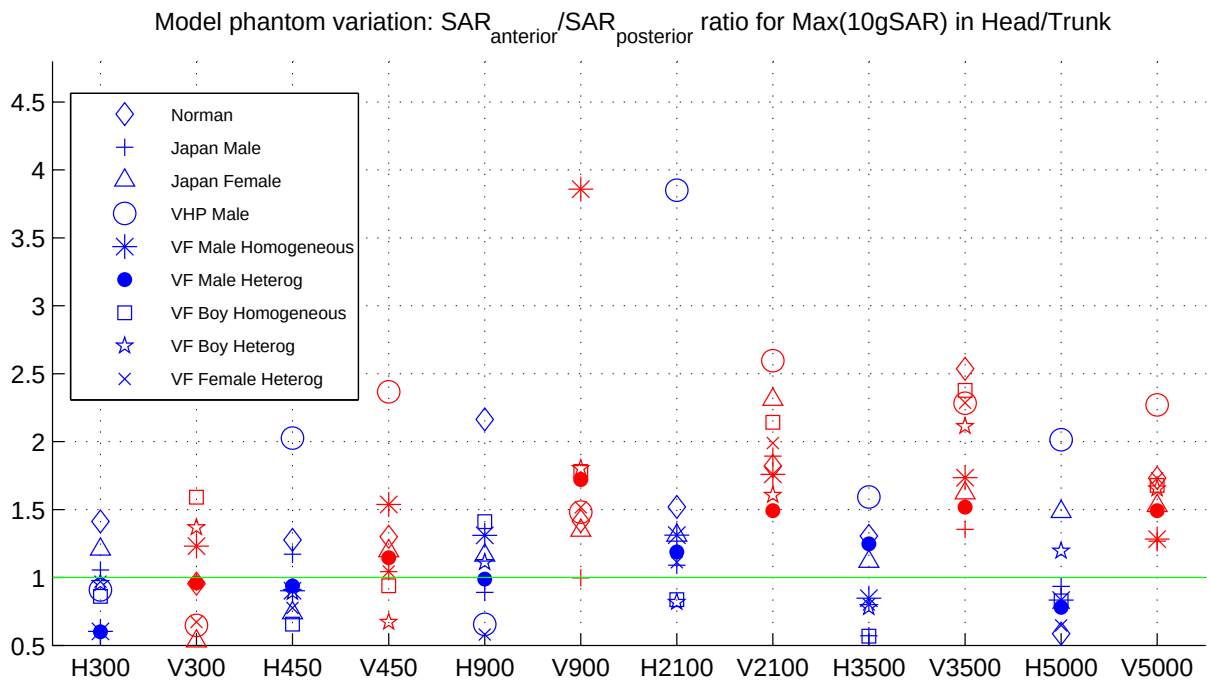

Figure 32: Model phantom variation (all the models are in the regular standing posture). $SAR_{anterior}/SAR_{posterior}$ ratio for max(10gSAR) in the head/trunk is shown for each model. It is seen that at higher frequencies, with vertical polarization, the peak 10g-SAR values are higher when a model is exposed from the front side (anterior).

4.7 Posture variation results

The effect of posture variation on SAR has been examined with 6 homogeneous male models which are listed in Table 1 and illustrated in Figure 6. Briefly, the models are:

- Posture sit (65.38 kg): kind of sitting on a chair, arms bent, "typing"
- Posture examine (65.44 kg): kind of examining or tuning an object in front of the eyes
- Posture arms up (65.21 kg)
- Posture standing (65.05 kg): the usual standing posture which is used as a reference posture
- Posture sit on ground (65.66 kg): a relaxed sitting posture. Note that "sit on ground" refers *only* to the posture of the model which is positioned in free space.
- Posture arms out (65.52 kg)

Results are shown for normalized WBASAR and for normalized max(10gSAR) in the limbs and in the head/trunk region. Only the case of anterior exposure is considered. In the SAR Figures 33 - 35, each marker now represents a certain posture.

Some observations on normalized WBASAR (Figure 33):

- At 5000, 3500, 2100 MHz, for both polarizations:

  - When the model is someway sitting, the WBASAR is minimized. As the model gets up to the examine posture (both arms still bent), the WBASAR increases more (horizontal polarization) or less (vertical polarization). Then if the model straightens its arms up or out, or takes the regular standing posture (arms down by the side of the body), the WBASAR increases further.
  - If the posture is transformed from the regular standing posture, the WBASAR does not seem to rise remarkably.

- 900, 450, 300 MHz:
  - With horizontal polarization, the arms-out posture tends to give relatively high WBASAR values. In the cases H300 and H450, the sitting-on-ground posture gives relatively high WBASAR, too.
  - Clearly, if posture is changed from the regular standing posture, the WBASAR can easily rise tens of percents. However, normalized WBASAR is relatively low at these frequencies.

Examination of the normalized max(10gSAR) values in Figures 34 and 35 reveals that these are, in general, higher in the head/trunk region than in the limbs. In some cases, the normalized peak SAR value in the head/trunk is very close to 1. One such a case is V2100 with the arms-up posture where the peak SAR value is only 0.18 dB below the limit. See also the 10g-SAR distributions in Figure 48 to better understand why this happens. In general, the 10g-SAR distributions of Figures 48 - 53 can be compared with the data in Figures 34 and 35.

Finally, the variation of max(10gSAR) is larger than variation of WBASAR [8].

4.7.1 Changing homogeneous model to a heterogeneous one - SAR increase?

One may ask what happens if the homogeneous posture model is replaced with a heterogeneous one. Because normalized SAR values are higher at $f \geq 2100$ MHz, these frequencies may be more relevant to consider than the lower frequencies. Close inspection of Figures 25 - 27 at frequencies $f \geq 2100$ MHz shows that quite often a homogeneous model gives higher SAR than a heterogeneous model, but this can not be guaranteed at all. That is, one can not say that a homogeneous model would give a conservative estimate of SAR [9]. For example, at 2100 MHz, $\mathrm{WBASAR_{het}} > \mathrm{WBASAR_{hom}}$ for VF Male and VF Boy, *even though* the model mass $\mathrm{m_{het}} > \mathrm{m_{hom}}$. Actually, for VF Male the maximum value of $\mathrm{WBASAR_{het}}/\mathrm{WBASAR_{hom}} \approx 1.18$, which occurs in the case V2100 (with $\theta = 90°$, $\phi = 240°$). For VF Boy the same ratio is 1.35, occurring also in the case V2100 (with $\theta = 90°$, $\phi = 300°$). This value corresponds to a WBASAR increase of 1.3 dB in a homogeneous-to-heterogeneous model change.

Also for the peak 10g SAR cases can be found where a heterogeneous-model SAR exceeds the homogeneous-model SAR. Here is some statistics for VF Boy covering both polarizations, 6 frequencies and 11 incoming angles (2x6x11=132 cases): The mean value of $\frac{\mathrm{max(10gSAR)_{het}}}{\mathrm{max(10gSAR)_{hom}}}$ in the head/trunk was 0.947, but in 42 cases of 132 this ratio was >1, and the maximum of this ratio was 1.552 (i.e. 1.9 dB; case V5000 with $\theta = 30°$, $\phi = 180°$,

[8] Also note that the variation of all SAR key figures is clearly larger than the mass variation of the posture models (< 1 %).

[9] Of course, this issue depends on how the electrical parameters are chosen. In this study the parameters were chosen as shown in Table 3.

peak SAR location: penis). The mean value of $\frac{\max(10\text{gSAR})_{\text{het}}}{\max(10\text{gSAR})_{\text{hom}}}$ in the limbs was 0.974, but in 54 cases of 132 the ratio was >1, and the maximum ratio was 1.548 (i.e. 1.9 dB; case H900 with $\theta = 60°$, $\phi = 180°$). For VF Male the same statistics is: The mean value of $\frac{\max(10\text{gSAR})_{\text{het}}}{\max(10\text{gSAR})_{\text{hom}}}$ in the head/trunk was 0.929, but in 42 cases of 132 this ratio was >1, and the maximum ratio was 1.544 (i.e. 1.9 dB; case V900 with $\theta = 90°$, $\phi = 360°$, peak SAR location: backside of trunk). The mean value of $\frac{\max(10\text{gSAR})_{\text{het}}}{\max(10\text{gSAR})_{\text{hom}}}$ in the limbs was 0.948, but in 39 cases of 132 this ratio was >1, and the maximum ratio was 1.552 (i.e. 1.9 dB; case V300 with $\theta = 60°$, $\phi = 180°$).

Thus, if a homogeneous posture model was replaced with a realistic heterogeneous one having exactly same anatomical (geometrical) features and body-part dimensions (penis, fingers, toes, etc.), the SAR values could increase with some polarization-frequency-angle combinations. Now it has been assumed that a homogeneous model applies the ϵ_r and σ values of tissue-equivalent liquid (Table 3) and that the corresponding heterogeneous model applies the electrical properties of tissues of Virtual Family. Based on the above statistics, an increase of 2 dB is very realistic for the peak 10g SAR. With worst-case tissue-layering analyses [15] even higher increase of peak 10g SAR may be obtained ($\approx$ 3 dB). So, with the anatomy (body shape) of the posture model, the peak 10g SAR in head/trunk might even exceed the SAR limit at the reference level of exposure if the homogeneous posture model was replaced with a realistic heterogeneous one.

4.7.2 Representativeness of the applied posture set

One may also ask how representative is the applied set of postures. Surely there are postures which give even smaller WBASAR values than sitting posture (maybe a very small WBASAR is obtained when taking a squatting posture, arms bent against the body). But it is more relevant to ask whether there are postures giving even larger SAR values than obtained in this study. Considering the WBASAR, Figure 33 suggests that it may be hard to find postures with clearly higher WBASAR, because the already applied models give rather clustered results [10]. For the max(10gSAR) the issue is more problematic, because small-scale posture and anatomy changes may have a large effect. Thus, in principle, there can be postures giving higher max(10gSAR) than obtained in the simulations of this study.

4.8 Results using 1-gram averaging cubes

At the higher frequencies 3500 and 5000 MHz, SAR results were also computed using 1-gram averaging cubes (for VHP male of 1-mm resolution also at 2100 MHz). This 1-g SAR data is maybe not as necessary data as the 10-g averaged SAR data and was not even required in the RFP[11]. Earlier IEEE standard C95.1-1999 also applied 1-g cubes, but the newer standard IEEE 95.1-2005 applies only 10-g cubes. Also ICNIRP recommends using 10-g averaging volumes. Currently, there are no SAR limits (ICNIRP, IEEE) related to 1-g averaging.

For the above reasons, the 1-g SAR results are mostly skipped in this document, but the SAR data can be found in the delivered result tables. Due to smaller spatial averaging volume, the max(1gSAR) results are higher than the max(10gSAR) results. For example, at

[10] Worst case posture? If assuming an anatomically realistic heterogeneous model whose posture can be freely chosen, WBASAR might rise further if mouth was wide open (EM fields could enter inside and absorb also there) and the model was standing on tiptoes, arms and fingers widely open, etc.

[11] Request for Proposal for the Phase II of the MMF/GSMA dosimetry program.

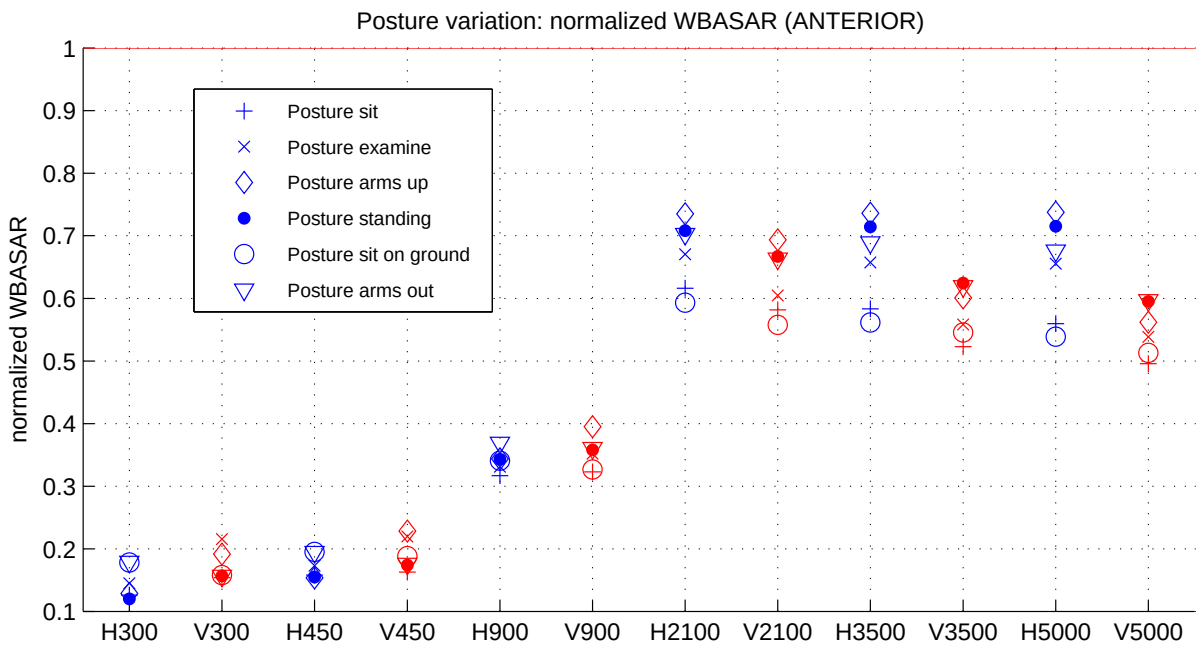

Figure 33: Posture variation. Normalized WBASAR is shown for the anterior exposure case.

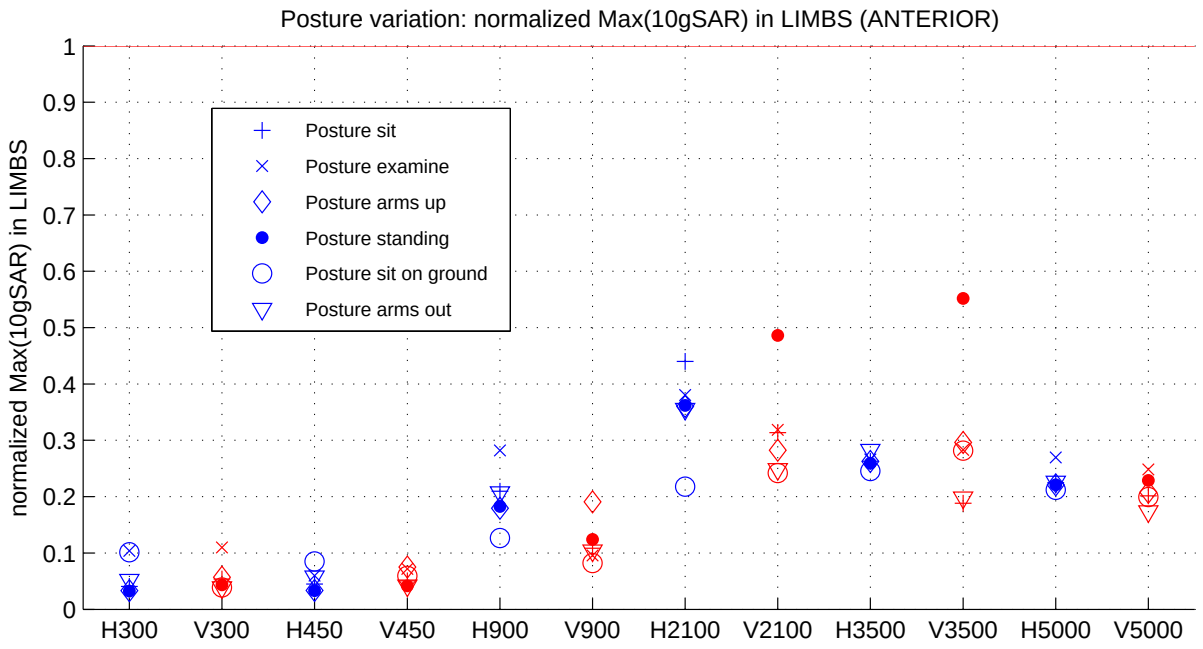

Figure 34: Posture variation. Normalized max(10gSAR) in the limbs is shown for the anterior exposure case.

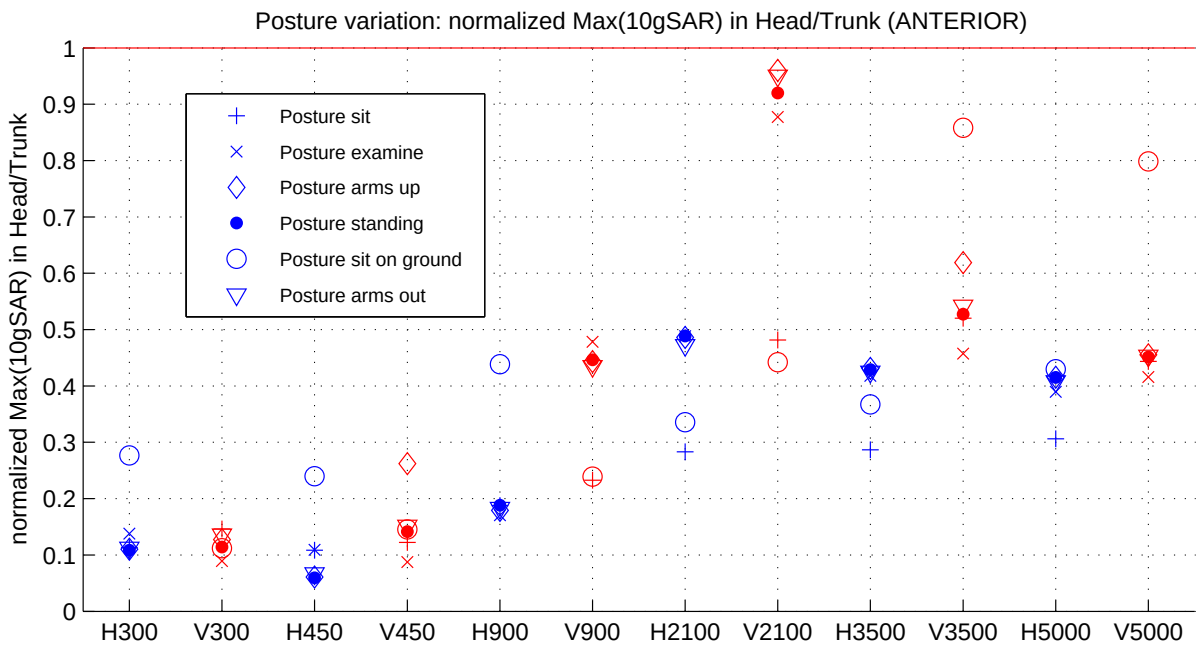

Figure 35: Posture variation. Normalized max(10gSAR) in the head/trunk is shown for the anterior exposure case.

3500 MHz, in the anterior case, the average value of the ratio max(1gSAR)/max(10gSAR) was 2.26, when the mean value was taken over all the models and both polarizations. At 5000 MHz, the same key figure was 2.62, i.e. somewhat higher. The increase of max(1gSAR)/max(10gSAR) ratio with frequency is expectable, because the ohmic losses concentrate more and more on the body surface as the frequency increases.

5 Results - SAR variation in dB scale

In this section the SAR variation results are shown in dB scale. The main point is to show how significantly the SAR values depend on the incoming angle, model phantom and posture, separately at each frequency and polarization. The bar diagrams in Figures 36 - 40 show the range of SAR variation due to a variable (e.g. incoming angle) around a reference case *in each fixed polarization-frequency case*. That is, each bar reaches from $10\log_{10}(\mathrm{SAR_{min}}/\mathrm{SAR_{ref}})$ to $10\log_{10}(\mathrm{SAR_{max}}/\mathrm{SAR_{ref}})$, where $\mathrm{SAR_{ref}}$ is a SAR reference value, and $\mathrm{SAR_{min}}$ and $\mathrm{SAR_{max}}$ are the minimum and maximum values of SAR (now "SAR" refers to any SAR key figure e.g. the WBASAR). In general, a relative value of SAR in dB's is

$$\mathrm{SAR_{dB}} = 10\log_{10}(\mathrm{SAR}/\mathrm{SAR_{ref}}) \tag{2}$$

Note that the values of $\mathrm{SAR_{min}}$, $\mathrm{SAR_{max}}$ and also $\mathrm{SAR_{ref}}$ are all dependent on the polarization-frequency case. See below for a concrete example.

5.1 SAR variation with the incoming angle

The set of incoming angles is shown in Figure 8. The effect of incoming angle variation on $10\log_{10}(\mathrm{SAR}/\mathrm{SAR_{ref}})$ is shown in Figures 36 - 37 for the heterogeneous and homogeneous models of VF Male and VF Boy. $\mathrm{SAR_{ref}}$ is different in each polarization-frequency case, but in each such a case it is the SAR value obtained under anterior exposure. For example, with VFM Heterogeneous,

$$\mathrm{SAR_{ref}} = \mathrm{SAR_{VFM\ Het,anterior}}(pol, f) \tag{3}$$

which is different for each polarization-frequency case [12]. Also

$$\mathrm{SAR_{min}} = \min_{\text{inc. angles}} \mathrm{SAR_{VFM\ Het}}(pol, f) \tag{4}$$

which is the minimum SAR for a polarization-frequency case, obtained with some incoming angle. Similarly,

$$\mathrm{SAR_{max}} = \max_{\text{inc. angles}} \mathrm{SAR_{VFM\ Het}}(pol, f) \tag{5}$$

which is the maximum SAR for a polarization-frequency case. For example, in the case vertical-2100 MHz, above values for the normalized WBASAR are (from Figure 19, top)

$$\begin{aligned} \mathrm{SAR_{ref}} &= 0.7703 \\ \mathrm{SAR_{min}} &= 0.3704 \\ \mathrm{SAR_{max}} &= 0.7703 \end{aligned}$$

Thus by using (2) in this particular case, the range of variation is -3.2 ...0 dB, or in other words, the minimum and maximum deviations are -3.2 and 0 dB, respectively (compare these numbers with the Figure 36 for VFM Heterogeneous at V2100). The *extent* of SAR variation is 3.2 dB in this case. Similarly as in the above example, the deviations are

[12] Polarization index *pol* has only two values which refer to vertical and horizontal polarization, frequency f is 300, 450, 900, 2100, 3500, or 5000 MHz.

obtained for the peak 10g SAR in the limbs and in the head/trunk, and this has been done for each model (VFM and VFB, heterogeneous and homogeneous), at each frequency and with both polarizations.

In sum, Figures 36 and 37 show that in each case with fixed frequency, polarization and model, the WBASAR deviation with the incoming angle is always between -3.5 . . . +1.3 dB. I.e. as the incoming angle is changed away from the anterior case $(\theta, \phi) = (90°, 180°)$, the maximum increase of WBASAR is about 1.3 dB (with VF Male Homogeneous, V300) and the maximum decrease of WBASAR is about 3.5 dB (with Male Homogeneous, V5000). At the lower frequencies, the sign of deviation clearly varies. But at the higher frequencies, the sign of deviation is usually minus, i.e., the reference (anterior exposure) tends to give the highest WBASAR.

Furthermore, Figures 36 and 37 show that in each case with fixed frequency, polarization and model, the deviation of max(10gSAR) in the limbs stays between -3.9. . .+4.8 dB. Similarly, the deviation of max(10gSAR) in the head/trunk is always between -5.9 . . .+3.7 dB.

The *extent* of WBASAR variation is typically a few dB's. Depending on the polarization-frequency case, it is around 0.6. . .3.5 dB (typically the larger values are obtained at the higher frequencies). For the max(10gSAR) in the limbs, the extent of SAR variation is around 1.7. . .6.9 dB, and for the head/trunk around 1.8. . .7.5 dB.

When comparing the results of VF Boy and VF Male, it is noted that the variation of WBASAR is usually somewhat larger for VF Male than for VF Boy, or the variations are about equal (these observations hold for both heterogenous and homogeneous models). Only exception to the above is the low-frequency case H300, where WBASAR variation of VF Boy is clearly stronger compared to VF Male.

Again, it is reminded that the incoming angle set did not include the angles $\theta = 0°$ and $\theta = 180°$ which correspond to directly-from-below and directly-from-above exposures, respectively. This was already discussed in p. 30. Briefly, if these angles were in the set, at 900, 2100, 3500 and 5000 MHz, the minimum WBASAR values could be somewhat smaller. In Figures 36 and 37 this would mean that the WBASAR bars would reach to a bit lower dB values (i.e. larger negative dB values). At 300 and 450 MHz, the maximum WBASAR values could rise a bit.

5.2 SAR variation with the model phantom

The applied model set consists of 9 (10 later) models which are Norman, Japanese Male and Female, VHP Male, VF Male (homogeneous and heterogeneous), VF Boy (homogeneous and heterogeneous) and VF Female. Note that "Posture standing" is at first excluded from this variation study (other posture models are completely excluded here, because posture variation is studied separately in section 5.3). The reference (0-dB level) corresponds to the model VF Male Heterogeneous (see below for a concrete example).

5.2.1 Anterior exposure (frontal)

The reference is now VFM Heterogeneous, anterior:

$$\mathrm{SAR}_{\mathrm{ref}} = \mathrm{SAR}_{\mathrm{VFM\ Het,anterior}}(pol, f) \tag{6}$$

which is different for each polarization-frequency case.

$$\mathrm{SAR}_{\mathrm{min}} = \min_{\mathrm{phantoms}} \mathrm{SAR}_{\mathrm{anterior}}(pol, f) \tag{7}$$

which is the minimum SAR for a polarization-frequency case, *obtained with some model phantom* in case of anterior exposure. Similarly,

$$\mathrm{SAR}_{\mathrm{max}} = \max_{\mathrm{phantoms}} \mathrm{SAR}_{\mathrm{anterior}}(pol, f) \tag{8}$$

which is the maximum SAR for a polarization-frequency case. For example, in the case vertical-2100 MHz, the above values for normalized WBASAR are (from Figure 25)

$$\begin{aligned} \mathrm{SAR}_{\mathrm{ref}} &= 0.7703 \quad \text{(VFM Heterogeneous)} \\ \mathrm{SAR}_{\mathrm{min}} &= 0.5854 \quad \text{(VHP Male 105 kg)} \\ \mathrm{SAR}_{\mathrm{max}} &= 1.544 \quad \text{(VFB Heterogeneous)} \end{aligned}$$

Thus by using (2) in this particular case of V2100, the range of variation is -1.2 ... 3 dB, or in other words, the minimum and maximum deviations are -1.2 and 3 dB, respectively (compare these numbers with the Figure 38 at V2100).

Figure 38 (top) shows that in each fixed polarization-frequency case, the WBASAR deviation due to a model change stays between -1.6 ... +3.8 dB, where -1.6 dB is caused by VHP Male and +3.8 dB is caused by VF Boy Heterogeneous. Similarly, the deviation of max(10gSAR) in the limbs is always between -1.8 ... +4.7 dB. Furthermore, the deviation of max(10gSAR) in the head/trunk is always between -3.4 ... +6 dB.

The *extent* of WBASAR variation, depending on the polarization-frequency case, is around 2.5...5.1 dB. For the max(10gSAR) in the limbs, the extent of SAR variation is around 1.7...4.9 dB, and for the head/trunk around 1.6...6.5 dB.

5.2.2 Posterior exposure (backside exposed)

Here, SAR variation with the model phantom is examined in the case of posterior exposure. Figure 38 (bottom) shows that in each fixed polarization-frequency case, the WBASAR deviation due to a model change stays between -1.7 ... +3.5 dB. Similarly, the deviation of max(10gSAR) in the limbs is always between -3.5 ... +2.5 dB. Furthermore, the deviation of max(10gSAR) in the head/trunk is always between -3.5 ... +3.8 dB.

The *extent* of WBASAR variation, depending on the polarization-frequency case, is around 2.2...5.2 dB. For the max(10gSAR) in the limbs, the extent of SAR variation is around 1.6...3.5 dB, and for the head/trunk around 1.6...4.5 dB.

5.2.3 Anterior exposure; including "Posture standing" in the model set

"Posture standing" was left out of the model set above so that it would be possible to compare two setups: 9 models/anterior and 9 models/posterior (Figure 38). The deviation results somewhat change if this model is included in the model set - one can compare Figure 38 (top figure) and Figure 39. For example, in the cases V450, V900 and V2100, the deviation of max(10gSAR) in the head/trunk is increased. However, the bars showing the WBASAR deviations remain unaffected by this model inclusion, because "Posture standing" is very similar to VF Male in terms of WBASAR.

So the extent of max(10gSAR) variation *is* changed due to this model inclusion *at certain frequencies*. However, the extent of WBASAR variation, depending on the polarization-frequency case, is still around 2.5...5.1 dB. Also, still, for the max(10gSAR) in the limbs, the extent of SAR variation is around 1.7...4.9 dB, and for the head/trunk 1.6...6.5 dB.

"Posture standing" is not a typical model of male, but not too unrealistic either. It is worthwhile to take its peak 10g-SAR results into account when assessing the effect of model variation, because its anatomy differs from the anatomy of VF Male Homogeneous.

5.3 SAR variation with the posture

The applied model set consists of different posture models (Figure 6). The reference (0-dB level) corresponds to the model "Posture standing". Only the case of anterior exposure is considered. So the reference is now

$$\mathrm{SAR}_{\mathrm{ref}} = \mathrm{SAR}_{\mathrm{Posture\ standing,anterior}}(pol, f) \tag{9}$$

which is different for each polarization-frequency case.

$$\mathrm{SAR}_{\mathrm{min}} = \min_{\mathrm{postures}} \mathrm{SAR}_{\mathrm{anterior}}(pol, f) \tag{10}$$

which is the minimum SAR for a polarization-frequency case, *obtained with some posture* under anterior exposure. Similarly,

$$\mathrm{SAR}_{\mathrm{max}} = \max_{\mathrm{postures}} \mathrm{SAR}_{\mathrm{anterior}}(pol, f) \tag{11}$$

which is the maximum SAR for a polarization-frequency case. For example, in the case vertical-2100 MHz, above values for normalized WBASAR are (from Figure 33)

$$\begin{aligned} \mathrm{SAR}_{\mathrm{ref}} &= 0.6669 \quad \text{(Posture standing)} \\ \mathrm{SAR}_{\mathrm{min}} &= 0.5576 \quad \text{(Posture sit on ground)} \\ \mathrm{SAR}_{\mathrm{max}} &= 0.6933 \quad \text{(Posture arms up)} \end{aligned}$$

Thus by using (2) in this particular case, the range of variation is -0.78 ... 0.17 dB, or in other words, minimum and maximum deviations of WBASAR are -0.78 and 0.17 dB, respectively (compare these numbers with Figure 40 at V2100).

Figure 40 shows the results. In each fixed polarization-frequency case, the WBASAR deviation due to a posture change stays between -1.2 ... +1.7 dB. Similarly, the deviation of max(10gSAR) in the limbs is always between -4.7 ... +5.1 dB. Furthermore, the deviation of max(10gSAR) in the head/trunk is always between -3.2 ... +6.1 dB.

The *extent* of WBASAR variation, depending on the polarization-frequency case, is around 0.7...1.7 dB, i.e., not very high in general. For the max(10gSAR) in the limbs, the extent of SAR variation is around 0.6...5.1 dB, and for the head/trunk around 1.5...6.1 dB.

5.4 Comparison of homogeneous "Posture standing" and VF Male Homogeneous

The SAR values of models Posture standing (65.05 kg) and VF Male Homogeneous (68.54 kg) are compared in Figure 41. It is seen that the WBASAR is almost same for them *at each frequency* and *with both polarizations*, i.e., in terms of WBASAR these models are very similar. However, due to the anatomical differences Posture standing has higher peak 10g-SAR values especially in the head/trunk region (this issue was discussed earlier in p.38).

6 SAR statistics

6.1 Approximate frequency distributions of SAR (primarily for WBASAR)

So-called frequency distributions of SAR which are comparable to probability distributions were produced by applying the simulation results with some approximations. From

these kind of illustrations one can see the number of occurrences of a SAR value being within a certain dB interval. Such distributions are shown for both polarizations at each frequency in Figures 42 - 47. It is important to be aware about what these curves mean and how these curves have been obtained. Below, VFM/VFB/VFF refer to Virtual Family Male/Boy/Female, respectively. The meaning of the SAR distribution curves is explained here:

- Firstly, the curves were primarily produced for whole-body-averaged SAR (WBASAR). This is emphasized by using a thick linewidth for WBASAR in Figures 42 - 47. Also the curves of max(10gSAR) are shown, but these should not be relied on too much because the approximations are clearly better justified for WBASAR.
- The curves illustrate how probable is a certain SAR value which is expressed in dB's. Actually, one can see how many occurrences there are within a certain dB interval. Importantly, these frequency distributions are based on a specific set of human models, postures and incoming angles (specified soon).
- **In each polarization-frequency case, the SAR level of 0 dB corresponds to the exposure setup where VFM Heterogeneous is standing normally under anterior exposure at ICNIRP reference level.**
- Of course, SAR values are perturbed away from the above-defined 0-dB level, when one replaces the model VFM Heterogeneous with another one, or perturbs the posture to something else than the regular standing posture, or changes the incoming angle.
- If any SAR value is closer than 5 dB to a SAR limit or the SAR limit is exceeded at the reference level of exposure, the corresponding limit line is shown with the SAR frequency distribution. In this case, one can see e.g. how close the reference is to the limit or how many cases exceed the limit.

Some statistical numbers of the distributions are shown in Tables 4, 5 and 6. The minimum value of SAR is obtained with some model-posture-angle combination. For a certain polarization-frequency case (pol, f) this is in dB's

$$\mathrm{SAR}_{\mathrm{Min}}(pol, f) = 10 \log_{10} \frac{\mathrm{SAR}_{\mathrm{min}}(pol, f)}{\mathrm{SAR}_{\mathrm{ref}}(pol, f)} \tag{12}$$

The maximum value of SAR in dB's is

$$\mathrm{SAR}_{\mathrm{Max}}(pol, f) = 10 \log_{10} \frac{\mathrm{SAR}_{\mathrm{max}}(pol, f)}{\mathrm{SAR}_{\mathrm{ref}}(pol, f)} \tag{13}$$

The ICNIRP SAR limit relative to the SAR of reference case, in dB's, is

$$\mathrm{SAR}_{\mathrm{LIMIT}}(pol, f) = 10 \log_{10} \frac{\mathrm{SAR}_{\mathrm{ICNIRP\ LIMIT}}}{\mathrm{SAR}_{\mathrm{ref}}(pol, f)} \tag{14}$$

where

$$\mathrm{SAR}_{\mathrm{ref}}(pol, f) = \mathrm{SAR}_{\mathrm{VFM\ Het,standing,anterior}}(pol, f) \tag{15}$$

is the SAR value at the reference level of exposure for VFM Heterogeneous standing normally under anterior exposure (i.e. this reference case depends on the polarization and

frequency). The dB numbers $\mathrm{SAR_{Max}} - \mathrm{SAR_{Min}}$ and STD (standard deviation) describe how much the SAR values are spread around the $\mathrm{SAR_{Mean}}$. If $\mathrm{SAR_{Max}}(pol, f) > \mathrm{SAR_{LIMIT}}(pol, f)$, there are cases exceeding the SAR limit at the reference level of exposure in polarization-frequency case (pol, f). The number of these cases is given by $N_{\text{over limit}}$ which naturally increases when $\mathrm{SAR_{Max}} - \mathrm{SAR_{LIMIT}}$ (dB) increases.

Here it is clarified how the distribution curves have been obtained (in a fixed polarization-frequency case). Because the actual simulation results are in a way extended via certain approximations, the idea below may be referred to as "extended approach":

- VFM Heterogeneous standing normally for anterior exposure is the reference case (SAR=0 dB). Anterior exposure corresponds to the incoming angle $(\theta, \phi) = (90°, 180°)$.
- The basic idea is to calculate the total SAR change (dSAR) relative to the reference case, in dB's, for all the combinations of model change, posture change and incoming angle change. Here is a simple example at vertical 2100 MHz: dSAR is calculated for the combination VHP Male - standing - $(90°, 270°)$, and dSAR refers to the WBASAR change now.
  - Changing the model from the reference (VFM Heterogeneous) to VHP Male gives $\mathrm{dSAR_m} = -1.19$ dB (from Figure 25, top: $10\log_{10}(0.585/0.77) = -1.19$).
  - Posture of VHP Male is kept "standing", thus $\mathrm{dSAR_p} = 0$ dB.
  - Changing the incoming angle from the reference $(\theta, \phi) = (90°, 180°)$ to $(90°, 270°)$ gives $\mathrm{dSAR_a} = -3.18$ dB (from Figure 19, top: $10\log_{10}(0.37/0.77) = -3.18$). That is, VHP Male utilizes the $\mathrm{dSAR_a}$ values of VFM Heterogeneous. (However, this is a simplified example in the sense that the actual $\mathrm{dSAR_a}$ also takes the ratio $\mathrm{SAR_{anterior}}/\mathrm{SAR_{posterior}}$ of the model into account while "copying" $\mathrm{dSAR_a}$ from VFM Heterogeneous).

  Thus, $\mathrm{dSAR}=\mathrm{dSAR_m} + \mathrm{dSAR_p} + \mathrm{dSAR_a}$ = -1.19 dB + 0 dB - 3.18 dB = -4.37 dB.
- **The default set of models contains 10 models**: Norman, Japan Male and Female, VHP Male, Posture standing, VFM Homogeneous, VFM Heterogeneous, VFB Homogeneous, VFB Heterogeneous and VFF Heterogeneous. This set corresponds to 10 different $\mathrm{dSAR_m}$ (dB) values where $\mathrm{dSAR_m}$ refers to a change in a SAR value (one of the $\mathrm{dSAR_m}$ values is 0 dB because the reference model is included in the set).
- **The set of postures has 6 postures** (including the reference "Posture standing"), see Fig. 6. Correspondingly, there are 6 $\mathrm{dSAR_p}$ values.
- **There are 11 incoming angles** and correspondingly 11 $\mathrm{dSAR_a}$ values ($\mathrm{dSAR_a}$ = 0 dB corresponds to the anterior case), see Fig. 8.
- Thus, **in this default set up, there are 10x6x11=660 combinations**, for which $\mathrm{dSAR}=\mathrm{dSAR_m} + \mathrm{dSAR_p} + \mathrm{dSAR_a}$ are calculated. These 660 results of dSAR are divided into bins having width e.g. 0.25 dB and a histogram/curve is plotted. One obtains a curve showing how many occurrences there are within a certain SAR range.
- Posture dependency of SAR has been obtained via simulations using the Posture models (homogeneous male). Now - an approximation has been made: all the 10 models have same posture dependency of SAR (same $\mathrm{dSAR_p}$ values). For WBASAR,

this approximation seems quite reasonable considering most of the models, for example, $\mathrm{WBASAR_{sit}}/\mathrm{WBASAR_{standing}}$ is probably roughly same for most of the models (assuming normal human anatomy/structure). Some proof for this is given below.

- Angle dependency of SAR: The models VFM (heterogeneous, homogeneous) and VFB (heterogeneous, homogeneous) have their angle dependency fully simulated with all the 11 angles, so no approximations are needed with these models. For the following models, the angle dependency $\mathrm{dSAR_a}$ was taken from VFM Heterogenous: Norman, Japan Male and Female, VHP Male, and VFF Heterogeneous. Also the available model-specific information on $\mathrm{SAR_{anterior}}/\mathrm{SAR_{posterior}}$ was utilized by weighting the angle dependency of VFM Heterogeneous properly [13]. For "Posture standing", angle dependency was taken from VFM Homogeneous, because these two models resemble each other in general and in terms of WBASAR.

- Above approximations of SAR cause error, of course, when considering a certain model in a particular posture, exposed from a certain direction. However, sometimes the error of dSAR is positive and sometimes negative. Importantly, when considering SAR frequency distributions, it is *not even necessary* to approximate the angle/posture dependency of SAR correctly for a model. It is sufficient that an approximated set of $\mathrm{dSAR_a}$ or $\mathrm{dSAR_p}$ values is representative (i.e. lowest and highest values of $\mathrm{dSAR_a}$ and $\mathrm{dSAR_p}$ are about correct as well as the distribution of the values). Thus, an approximated frequency distribution of WBASAR may actually be quite close to that what it would be if one truly simulated all the cases through (this would require 6x2x660=7920 simulations instead of 720 simulatinos actually performed - and a terribly lot of work to prepare different postures for all the models [14]). Finally, because the WBASAR is more predictable quantity than the max(10gSAR), the approximate frequency distributions are clearly better justified for WBASAR. Here are some comments on the max(10gSAR) distributions (a fixed polarization-frequency case is assumed):

  - A problem with the produced max(10gSAR) distributions is that there is quite high uncertainty with the $\mathrm{SAR_{Max}}$ and $\mathrm{SAR_{Mean}}$. This is substantially due to the values of $\mathrm{dSAR_{p,i}} = 10\log_{10}(\frac{\mathrm{SAR_{Posture\ i}}}{\mathrm{SAR_{Posture\ standing}}})$, $i = 1...6$. That is, the way how the $\mathrm{dSAR_p}$ (and thus dSAR) numbers are *biased*, depends on the value of $\mathrm{SAR_{Posture\ standing}}$ which is quite random for the max(10gSAR) (but not for the WBASAR).
  - The spread of SAR values, $\mathrm{SAR_{Max}} - \mathrm{SAR_{Min}}$, and the standard deviation STD are probably overestimated.
  - If in a polarization-frequency case $\mathrm{SAR_{Mean}}$ can be assumed about correct, then $\mathrm{SAR_{Max}}$ should be a quite conservative estimate in the sense that it has been obtained with a model-posture-angle combination which has simultaneously maximized $\mathrm{dSAR_m}$, $\mathrm{dSAR_p}$ and $\mathrm{dSAR_a}$

[13] I.e. the "copied" dB values of $\mathrm{dSAR_{a,VFM}}$ were properly adjusted in the angle range $(\theta, \phi) = (90°, 180°)$,...,$(90°, 360°)$ in the azimuth plane by an additional angle-dependent term which takes the model-specific $\mathrm{SAR_{anterior}}/\mathrm{SAR_{posterior}}$ into account.

[14] It is known that creating heterogeneous posture models of good quality is very difficult and time consuming.

Here is some reasoning/proof for the above approximation of the posture dependency of WBASAR. By examination of SAR data in papers [16], [17] and [18], and by comparing this data to the simulated results of Posture models of this work, one notes that roughly around 1 - 3 GHz, the ratio $\mathrm{WBASAR_{sit}}/\mathrm{WBASAR_{standing}}$ is about same when comparing

- a 10-y old boy and an adult male (Norman)
- Norman and Posture models

This ratio seems to somewhat match also when comparing the japanese models with Norman or Posture model. Surely there are differences, but it seems quite safe to say that the posture dependency of WBASAR may actually be similar for many different models around 1 - 3 GHz.

Above, also an approximation was made that the simulated angle dependency for VFM Heterogenous would be similar for Norman, Japan Male, Japan Female, VHP Male and VFF Heterogeneous. This approximation is supported by the following points:

- In Figure 36 one can compare the extreme values of WBASAR deviation of VF Male and VF Boy (heterogeneous). Even though these models are of very different size and shape, variation of incoming angle gives roughly same results for the extreme values of WBASAR deviation in the gigahertz range. (This is not the case at lower frequencies, but this does not matter considering the frequency distributions, because VF Boy does have its angle dependency fully simulated with 11 angles.)
- Figures 9 - 14 show WBASAR curves of angle dependency for VFB (heterogeneous, homogeneous) and VFM (heterogeneous,homogeneous). The shape of the curves is roughly similar for all these 4 models, when $f \geq 900$ MHz. (At lower frequencies, curve shapes are almost identical when comparing VFM Heterogeneous and VFM Homogeneous, even though these models are not identical in terms of EM fields.)
- In the gigahertz region the absorption/capture area of a body has a major role, i.e., the area "seen" by the plane wave incoming from certain direction is an important parameter. Thus, if a set of adult human models have roughly the same shape and posture, they are also likely to have similar angle dependency of WBASAR. (Note again that when considering the production of the frequency distributions of SAR and the approximation of the angle dependency for a model, it is not necessary to predict the curve dSAR(angle) correctly. It is sufficient that about the correct set of $\mathrm{dSAR_a}$ values are obtained, it does not matter in which order these $\mathrm{dSAR_a}$ values are obtained when changing the incoming angle.)

Also it is clear that, actually, the angle dependency of SAR is dependent on the posture (compare e.g. sit vs. standing). In order to take this into account accurately, it would be necessary to do many simulations with various postures with varying incoming angle (with both polarizations, at certain frequencies).

Considering the frequency distributions of WBASAR, it is likely that the applied set of angles is conservative in terms of mean WBASAR, i.e., if one used a full set of angles covering a spherical surface around the model, one would probably get a lower value for mean WBASAR (this may not hold as well at 300 and 450 MHz, but normalized SAR values are low there). Also, the applied angle set is representative when considering typical and realistic exposure scenarios near base-station antennas.

The above-described extended approach to produce frequency distributions of SAR[15] can generate somewhat higher SAR values than the actual simulations, because, for example, SAR_{Max} is obtained with a model-posture-angle combination which simultaneously maximizes $dSAR_m$, $dSAR_p$ and $dSAR_a$. Even though the 720 actual simulations did not directly produce any max(10gSAR) values exceeding SAR limits at the reference level, the extended approach covering 7920 exposure cases[16] does do that. These peak SAR exceedings take place only in the head/trunk at 2100, 3500 and 5000 MHz with vertical polarization, see Tables 5 and 6. In the cases V3500 and V5000, a major reason for the peak SAR exceedings is the "sitting on ground" posture (see also Fig. 35). In the case V2100, one gets a few exceedings even if excluding special postures, but keeping the model "Posture standing" in the model set. As other standing postures ("arms-up", "arms-out", "examine") are included in the population, the number of exceedings increase to 11 (see Table 5, vertical 2100 MHz). Briefly, these peak 10g-SAR values exceeding the SAR limit at the reference level are caused by the posture models (Fig.6).

Finally, as the actual simulations did, also the extended approach predicts that the whole-body-averaged SAR limit is exceeded at the reference level only by VF Boy, although VF Female is very close to the limit (only 0.11 dB below with the arms-up posture).

[15]It is reminded that the frequency distributions of max(10gSAR) should be taken as suggestive. The frequency distributions of WBASAR are more accurate, because for WBASAR one can quite fairly assume certain rules.

[16]12 polarization-frequency cases, 660 model-posture-angle combinations, 12x660=7920.

Freq MHz	Polarization	SAR_{Min}	SAR_{Max}	SAR_{LIMIT}	$SAR_{Max}-SAR_{Min}$	SAR_{Mean}	STD	$N_{over\ limit}$
300	Vertical	-1.143	5.429	7.850	6.572	1.251	1.604	0
300	Horizontal	-1.619	4.463	9.053	6.081	1.002	1.179	0
450	Vertical	-2.176	4.864	7.436	7.040	0.773	1.443	0
450	Horizontal	-1.266	3.398	8.196	4.664	0.873	0.915	0
900	Vertical	-3.403	3.253	4.394	6.656	-0.166	1.407	0
900	Horizontal	-3.091	2.329	4.396	5.420	-0.158	1.146	0
2100	Vertical	-5.305	3.189	1.134	8.494	-0.949	1.619	74
2100	Horizontal	-4.555	2.734	0.882	7.289	-0.803	1.413	81
3500	Vertical	-5.737	3.506	2.385	9.242	-0.801	1.753	43
3500	Horizontal	-4.877	3.160	1.915	8.037	-0.712	1.561	50
5000	Vertical	-5.565	3.372	3.464	8.937	-0.378	1.702	0
5000	Horizontal	-4.635	3.295	2.667	7.931	-0.493	1.531	16

Table 4: Statistics of WBASAR frequency distributions (Figures 42 - 47). The dB values of SAR_{Min}, SAR_{Max}, SAR_{LIMIT} and SAR_{Mean} are relative to the SAR of VF Male Heterogeneous frontally exposed (i.e. the reference exposure case is VFM Heterogeneous-standing-anterior, see (12) - (15)). $N_{over\ limit}$ is the number of model-posture-angle cases where the SAR limit is exceeded at the reference level of exposure. Population includes 10x6x11=660 model-posture-angle combinations in each polarization-frequency case. $N_{over\ limit}$ is quite large especially at 2100 MHz. All the limit exceedings are due to VF Boy (heterogeneous and/or homogeneous).

7 Conclusion and Discussion

Specific-absorption-rate (SAR) data of 720 plane-wave exposure cases has been computed. Simulations have been done in free space. Parallel FDTD method has been used in the field computation. Body type and posture of the models, excitation frequency, field polarization and incoming angle of the plane wave have been varied. The SAR results base on models whose mass varies between 18 - 105 kg. The assessed models are: Norman, Japanese Male, Japanese Female, VHP Male, 6 homogeneous male posture models, VF Male (heterogeneous and homogeneous), VF Boy (heterogeneous and homogeneous), and VF Female (15 models total). The simulated frequencies are 300, 450, 900, 2100, 3500 and 5000 MHz which have been assessed for vertical and horizontal polarization. The number of incoming angles depends on the model. For VF Male and VF Boy (heterogeneous and homogeneous), the incoming angle set consisted of the following 11 angles (θ, ϕ): $(90°, 180°)$, $(90°, 210°)$, $(90°, 240°)$, $(90°, 270°)$, $(90°, 300°)$, $(90°, 330°)$, $(90°, 360°)$, $(30°, 180°)$, $(60°, 180°)$, $(120°, 180°)$, and $(150°, 180°)$. That is, the angle varies in the elevation and azimuth plane. The angles $\theta = 0°$ (wave directly from below) and $\theta = 180°$ (wave directly from above) are not in the set. For the other models, there were 2 (anterior and posterior) or 1 (anterior) incoming angles.

Firstly, detailed normalized SAR results were presented and discussed. Normalization was done according to the reference levels and SAR limits of ICNIRP (if a normalized SAR value exceeds 1, the SAR limit is exceeded at the reference level of exposure). Normalized whole-body-averaged SAR (WBASAR) curves were shown to illustrate the effect of the incoming angle on SAR. Detailed normalized-SAR results of the incoming angle variation were shown for VF Male and VF Boy. Normalized WBASAR and peak 10g-

Freq MHz	Polarization	SAR_{Min}	SAR_{Max}	SAR_{LIMIT}	$SAR_{Max}-SAR_{Min}$	SAR_{Mean}	STD	$N_{over\ limit}$
300	Vertical	-1.512	8.721	13.610	10.233	3.551	2.141	0
300	Horizontal	-3.705	10.739	13.171	14.444	1.577	2.566	0
450	Vertical	-5.465	6.866	11.602	12.331	0.468	2.165	0
450	Horizontal	-3.481	11.057	12.349	14.538	1.737	2.606	0
900	Vertical	-9.681	3.308	6.509	12.989	-3.809	2.354	0
900	Horizontal	-5.460	6.285	8.730	11.746	-1.006	2.157	0
2100	Vertical	-6.170	6.440	4.367	12.610	-0.146	2.280	11
2100	Horizontal	-5.225	3.505	4.648	8.730	-0.578	1.554	0
3500	Vertical	-3.598	4.650	3.852	8.248	0.629	1.405	4
3500	Horizontal	-5.596	3.088	3.988	8.684	-0.339	1.498	0
5000	Vertical	-2.542	6.183	4.667	8.724	1.157	1.533	16
5000	Horizontal	-4.540	3.117	4.618	7.657	0.466	1.185	0

Table 5: Statistics of frequency distributions of max(10gSAR) in the head/trunk (Figures 42 - 47). The dB values of SAR_{Min}, SAR_{Max}, SAR_{LIMIT} and SAR_{Mean} are relative to the SAR of VF Male Heterogeneous frontally exposed. $N_{over\ limit}$ is the number of model-posture-angle cases where the SAR limit is exceeded at the reference level of exposure. Population includes 10x6x11=660 model-posture-angle combinations in each polarization-frequency case. $N_{over\ limit} > 0$ in some polarization-frequency cases. The limit exceedings are due to posture models (Fig. 6).

Freq MHz	Polarization	SAR_{Min}	SAR_{Max}	SAR_{LIMIT}	$SAR_{Max}-SAR_{Min}$	SAR_{Mean}	STD	$N_{over\ limit}$
300	Vertical	-2.595	10.118	14.244	12.713	2.974	2.339	0
300	Horizontal	-2.712	11.505	16.925	14.216	3.543	2.683	0
450	Vertical	-3.408	5.422	12.049	8.830	0.458	1.801	0
450	Horizontal	-2.302	11.981	16.210	14.283	4.155	2.625	0
900	Vertical	-4.705	3.881	9.281	8.586	-0.516	1.518	0
900	Horizontal	-3.118	6.172	10.086	9.290	0.829	1.669	0
2100	Vertical	-4.400	5.685	6.822	10.085	-0.795	1.765	0
2100	Horizontal	-5.225	3.077	6.509	8.303	-0.229	1.509	0
3500	Vertical	-9.640	2.668	4.895	12.307	-4.096	2.212	0
3500	Horizontal	-1.439	3.367	7.229	4.806	0.594	0.872	0
5000	Vertical	-6.735	0.830	4.684	7.565	-2.387	1.599	0
5000	Horizontal	-1.409	3.631	7.940	5.040	1.024	0.903	0

Table 6: Statistics of frequency distributions of max(10gSAR) in the limbs (Figures 42 - 47). The dB values of SAR_{Min}, SAR_{Max}, SAR_{LIMIT} and SAR_{Mean} are relative to the SAR of VF Male Heterogeneous frontally exposed. $N_{over\ limit}$ is the number of model-posture-angle cases where the SAR limit is exceeded at the reference level of exposure. Population includes 10x6x11=660 model-posture-angle combinations in each polarization-frequency case. Clearly, for max(10gSAR) in the limbs, $N_{over\ limit} = 0$ always. A comparison of the numbers SAR_{Max} and SAR_{LIMIT} suggests that maybe the highest risk of SAR-limit exceeding is at 2100 MHz with vertical polarization (see text which discusses the high uncertainty of max(10gSAR) frequency distributions, e.g. p. 55).

SAR (max(10gSAR)) were covered, and the max(10gSAR) results were separately shown for the limbs and for the head/trunk region. Similarly, detailed phantom-variation and posture-variation results were presented.

The results of this research suggest that ICNIRP SAR limits may be exceeded at the reference level of exposure. The whole-body-averaged SAR limit was exceeded by VF Boy (heterogeneous and homogeneous model) at 2100 and 3500 MHz with both polarizations, and by VF Boy Homogeneous also at 5000 MHz with horizontal polarization. Within the set of the simulated frequencies, 2100 MHz gave the highest normalized whole-body-averaged SAR values. The worst case was vertical 2100 MHz with VF Boy Heterogeneous under frontal exposure where the normalized WBASAR was 1.54 (the limit was exceeded by 54 % i.e. by 1.9 dB). At 2100 MHz, also VF Female and Japanese Female were quite close to the limit (VF Female was 0.26 dB below the limit at horizontal 2100 MHz). At lower frequencies 300 and 450 MHz, for both polarizations and for all incoming angles, the normalized WBASAR values were low for all the applied models.

The peak 10g-SAR limits were not exceeded in any simulated case at the reference level of exposure. However, peak 10g SAR in the head/trunk was close to the limit with a homogeneous model "Posture standing" at vertical 2100 MHz (0.36 dB below the limit, and only 0.18 dB below if the arms were up). In general, the normalized peak 10g SAR tends to be higher in the head/trunk than in the limbs, especially in the gigahertz range under frontal exposure (a major reason for this is that the peak-SAR limit for the head/trunk is half of the limit applied in the limbs). Thus, the peak 10g SAR exceeds the limit more probably in the head/trunk than in the limbs.

At 2100, 3500 and 5000 MHz, frontal exposure gives usually somewhat higher WBASAR than posterior exposure, which can be explained by smaller effective absorption area in the backside (posterior). Furthermore, it seems that with both polarizations in the gigahertz region, a WBASAR value for a random incoming angle is smaller than or comparable to $\max(\mathrm{WBASAR}_{\mathrm{anterior}}, \mathrm{WBASAR}_{\mathrm{posterior}})$, where max(...) stands for taking the maximum value of the arguments. Considering plane-wave WBASAR simulations of typical human bodies in standing posture in the gigahertz region, above rule is beneficial: in order to get the maximum WBASAR value, it suffices to simulate anterior and posterior cases only. It is unlikely that a random incoming angle could produce substantially higher WBASAR value than anterior or posterior exposure. At lower frequencies 300 and 450 MHz, the situation is completely different: anterior or posterior exposure will *not* give the maximum WBASAR.

A set of 6 different postures was assessed by using homogeneous male phantoms under frontal exposure. The postures were: "sit", "examine", "arms up", "standing", "sit on ground" and "arms out", where "sit on ground" only refers to the posture of the model phantom (all the simulations have been performed in free space). In terms of whole-body-averaged SAR (WBASAR), this set seems to be representative, i.e., it may be difficult to find a posture giving significantly higher WBASAR values. At 2100, 3500 and 5000 MHz, a sitting posture ("sit" or "sit on ground") minimizes WBASAR. If the posture is transformed to something else from the regular standing posture (arms by the side of the body), the WBASAR does not seem to rise remarkably, even though typically, lifting the arms up increases WBASAR a bit. At 300 and 450 MHz, a posture change from the regular standing posture can increase WBASAR some tens of percents (about 1 - 2 dB). Finally, in general, the peak 10g-SAR values were more sensitive to the posture than the WBASAR values. Also, there were some quite high normalized peak 10g-SAR values in the head/trunk at 2100, 3500 and 5000 MHz with vertical polarization: this happened at 2100 MHz with several standing

postures, and at 3500 and 5000 MHz with the "sit on ground" posture.

It was also studied how the SAR values could increase if a homogeneous model was replaced with a realistic heterogeneous one having exactly same anatomical features and body-part dimensions. This study was done with VF Male and VF Boy models, for all angles, frequencies and polarizations. The homogeneous models were composed of tissue-equivalent liquid and the corresponding heterogeneous models applied the electrical properties of tissues of Virtual Family. At the lower frequencies 300 and 450 MHz, the WBASAR was about same for the homogeneous and heterogeneous models. However, at 2100 MHz, a WBASAR increase of 1.3 dB was obtained in the worst case. An increase of about 2 dB was obtained for the peak 10g SAR. Thus, it seems that with the body shape of the posture models, the peak 10g SAR in head/trunk might even exceed the SAR limit at the reference level of exposure, if a homogeneous posture model was replaced with a heterogeneous one.

After the detailed normalized SAR results, relative SAR results in dB scale were presented. Importantly, these results show the range of SAR variation in dB's separately at each frequency and for vertical and horizontal polarization (Figures 36 - 40). Furthermore, Table 7 shows the SAR variation (sensitivity) data in a compressed form.

Four models, VF Male and VF Boy (heterogeneous and homogeneous version) were applied when studying the incoming angle dependency of SAR. The incoming angle set consisted of 11 angles. In each case with fixed frequency, polarization and model, the WBASAR deviation with the incoming angle stayed always between -3.5 ... +1.3 dB (0 dB corresponds to the frontal exposure in each case). For max(10gSAR) in the limbs, the deviation stayed between -3.9...+4.8 dB, and for max(10gSAR) in the head/trunk, the deviation stayed between -5.9 ...+3.7 dB. See Figures 36 and 37 to see how the min/max deviations due to the incoming angle variation depend on the polarization, frequency and the model. The *extent* of WBASAR variation was typically a few dB's. Depending on the polarization-frequency case, it was around 0.6...3.5 dB. For the max(10gSAR) in the limbs, the extent of SAR variation was around 1.7...6.9 dB, and for the head/trunk around 1.8...7.5 dB. It is reminded that the incoming angle set did not include the angles $\theta = 0°$ and $\theta = 180°$ which represent quite unrealistic exposure conditions. If these angles were in the set, at 900, 2100, 3500 and 5000 MHz, the maximum WBASAR values, caused by anterior or posterior exposure, would remain same as now. The minimum WBASAR values could be somewhat smaller. At 300 and 450 MHz, the maximum WBASAR values could possibly rise a bit, but the values would still lie well below the WBASAR limit.

The effect of model phantom variation on SAR was studied relative to VF Male and by keeping all the models in regular standing posture. At first, 9 models were taken into account in this study. In the case of frontal exposure, in each fixed polarization-frequency case, WBASAR deviation due to a model change stayed between -1.6 dB (VHP 105 kg) and +3.8 dB (VF Boy 18 kg), where 0 dB corresponds to the heterogeneous VF Male. For max(10gSAR) in the limbs, the deviation stayed between -1.8 ... 4.7 dB, and for max(10gSAR) in the head/trunk, the deviation stayed between -3.4 ... 6 dB. The *extent* of WBASAR variation, depending on the polarization-frequency case, was around 2.5...5.1 dB. For the max(10gSAR) in the limbs, the extent of SAR variation was around 1.7...4.9 dB, and for the head/trunk around 1.6...6.5 dB. In the case of posterior exposure, the min/max deviations due to model variation were somewhat different: the deviation of WBASAR stayed between -1.7 ... +3.5 dB, the deviation of max(10gSAR) in the limbs stayed between -3.5 ... +2.5 dB, and the deviation of max(10gSAR) in the head/trunk stayed between -3.5 ... +3.8 dB. The *extent* of WBASAR variation, depending on the polarization-frequency case, was around 2.2...5.2 dB. For the max(10gSAR) in the limbs,

	Extent of WBASAR variation (dB)	Extent of max(10gSAR)$_{\text{LIMBS}}$ variation (dB)	Extent of max(10gSAR)$_{\text{HEAD/TRUNK}}$ variation (dB)
angle variation (covers 4 models, 11 angles)	0.6 ... 3.5	1.7 ... 6.9	1.8 ... 7.5
model variation, frontal	2.5 ... 5.1	1.7 ... 4.9	1.6 ... 6.5
model variation, posterior	2.2 ... 5.2	1.6 ... 3.5	1.6 ... 4.5
posture variation	0.7 ... 1.7	0.6 ... 5.1	1.5 ... 6.1

Table 7: Sensitivity of SAR to varied parameters. The extent of SAR variation is around the shown values. Essentially, the extent of SAR variation depends on the polarization-frequency case.

the extent of SAR variation was around 1.6...3.5 dB, and for the head/trunk around 1.6...4.5 dB. See Figure 38 to see how the min/max deviations depend on the polarization and the frequency.

The phantom variation results somewhat change if a 10th model "Posture standing" is included in the model set (Figure 39). Importantly, the extent of max(10gSAR) variation in the head/trunk is increased at some frequencies and thus, this model should be taken into account when assessing the effect of model variation. The WBASAR deviations remain unaffected by this model inclusion, because "Posture standing" is very similar to VF Male in terms of WBASAR.

The effect of posture variation on SAR was studied with 6 homogeneous male posture phantoms, the model "Posture standing" as a reference. In each fixed polarization-frequency case, the WBASAR deviation due to a posture change stayed between -1.2 ... +1.7 dB, where 0 dB corresponds to the normal standing posture. The deviation of max(10gSAR) in the limbs stayed between -4.7 ... +5.1 dB, and the deviation of max(10gSAR) in the head/trunk stayed between -3.2 ... +6.1 dB. The *extent* of WBASAR variation, depending on the polarization-frequency case, was around 0.7...1.7 dB. For the max(10gSAR) in the limbs, the extent of SAR variation was around 0.6...5.1 dB, and for the head/trunk around 1.5...6.1 dB. See Figure 40 to see how the min/max deviations depend on the polarization and frequency.

Finally, based on the simulated SAR data and certain approximations, frequency distribution curves of SAR (comparable to probability distributions) were generated at 300, 450, 900, 2100, 3500, and 5000 MHz, for both polarizations. Because the actual simulation results were in a way extended via the approximations, the method may be referred to as "extended approach". From these distribution curves one can see the number of occurrences of a SAR value being within a certain dB interval (0 dB corresponds to the reference case of Virtual Family Male (heterogeneous) in standing posture, exposed from the front side of the model). Of course, importantly, these curves depend on the utilized population. The default population included 10 models (18 - 105 kg) in standing posture, 6 postures and 11 incoming angles. I.e., there were 10x6x11=660 model-posture-angle combinations. These were applied at 6 frequencies for both polarizations, which means that 6x2x660=7920 exposure cases were assessed using this approximate extended approach.

The approximations which were used to produce SAR frequency distributions are clearly

more justified for WBASAR than for max(10gSAR), because for the WBASAR one can quite fairly assume certain "rules". For example, the angle dependency of WBASAR is similar for many models which resemble each other, or the posture dependency of WBASAR is quite similar. Those kind of rules are hard to establish for max(10gSAR), because this key figure is more unpredictable than WBASAR. This is due to the fact that small anatomical differences between the models have a notable effect on max(10gSAR) and its location. So, because the WBASAR is more predictable quantity than the max(10gSAR), the approximate frequency distributions are better justified for WBASAR. The frequency distributions of max(10gSAR) can be taken as suggestive, but they should not be relied on too much.

Note that the potential SAR increase due to the replacement of a homogeneous posture model with a heterogeneous one was not taken into account in the frequency distributions or in the corresponding tables of SAR statistics. To recap, a WBASAR increase of 1.3 dB was obtained in the worst case when comparing SAR of homogeneous and heterogeneous VF Male/VF Boy. An increase of about 2 dB was obtained for the peak 10g SAR.

Next, the occurred and potential SAR-limit exceedings at the reference level of exposure are discussed briefly. In the actual simulations and also with the extended approach, the whole-body-averaged SAR limit was exceeded by VF Boy only (heterogeneous and homogeneous). The actual simulations did not directly produce any peak 10g-SAR values exceeding the SAR limits, but the extended approach did do that in the head/trunk region (see p. 57). The peak 10g-SAR values in the limbs never exceeded the corresponding SAR limit (neither in actual simulations, nor in the extended approach). Considering an adult female whose mass is around 50 - 60 kg (or less), it is realistic to assume that the WBASAR limit could be exceeded around 2 GHz: via actual simulations, VF Female was only 0.26 dB below the limit at 2100 MHz, and only 0.11 dB below the limit after applying the extended approach (the small 0.15-dB increase of WBASAR is due to a posture change, i.e., the original simulated result is for the normal standing posture but the extended approach covers also the arms-up posture). Considering male phantoms, it is realistic to assume that the peak 10g-SAR limit of head/trunk could be exceeded in penis. A simulation of the homogeneous model "Posture standing" at vertical 2100 MHz resulted to a value in penis only 0.36 dB below the limit. With the arms-up posture, this peak 10g SAR was only 0.18 dB below the limit. If changing the homogeneous model to a heterogeneous one having same body shape and body-part dimensions, a peak 10g-SAR value might even rise over the SAR limit. In general, with male phantoms exposed from the front side, the peak 10g SAR in the head/trunk may be quite sensitive to parameters such as orientation, shape and length of penis. Finally, the simulations in this work package were done with plane waves in free space, i.e., the above predictions about potential SAR-limit exceedings did not even take reflections or field non-uniformities into account which may increase the SAR values further.

SAR data tables in electronic format are delivered together with this final report. The data can be inspected and applied in many ways, for example, to produce or adjust SAR estimation formulas. In this report, the data was plotted, analyzed and applied to produce SAR variation/uncertainty diagrams and SAR frequency distributions with the approximate extended approach.

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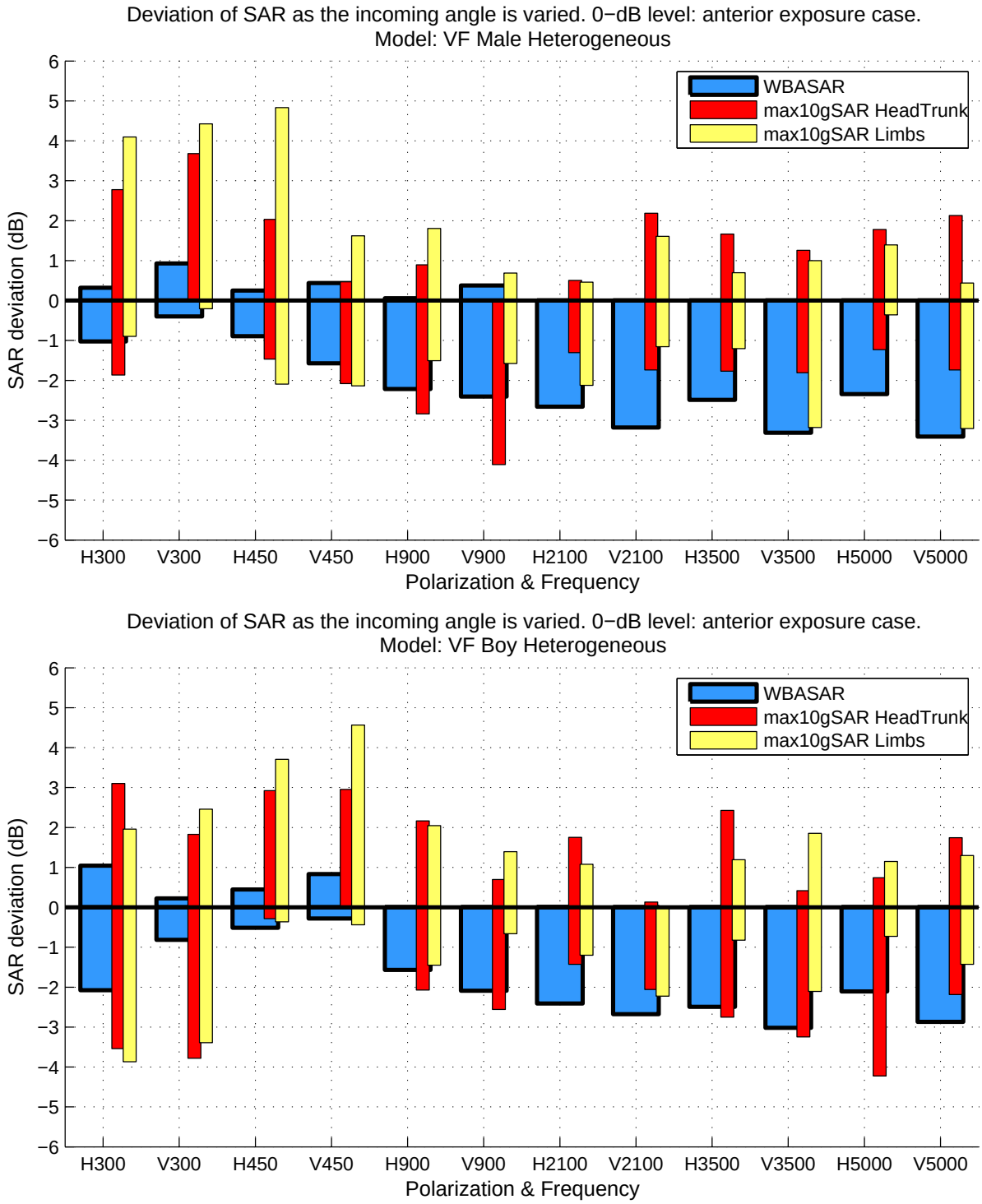


Figure 36: Maximum and minimum deviation of SAR in dB scale, due to incoming angle variation, is shown for heterogeneous VF Male (top) and heterogeneous VF Boy (bottom). The main point is to show how sensitive the SAR values are to the incoming angle. The **0-dB level corresponds to the anterior exposure** in each polarization-frequency case. Clearly, changing the incoming angle away from the anterior case (frontal exposure) tends to decrease WBASAR, especially when $f \geq 900$ MHz. This incoming angle variation covers 11 angles which were shown in Figure 8.

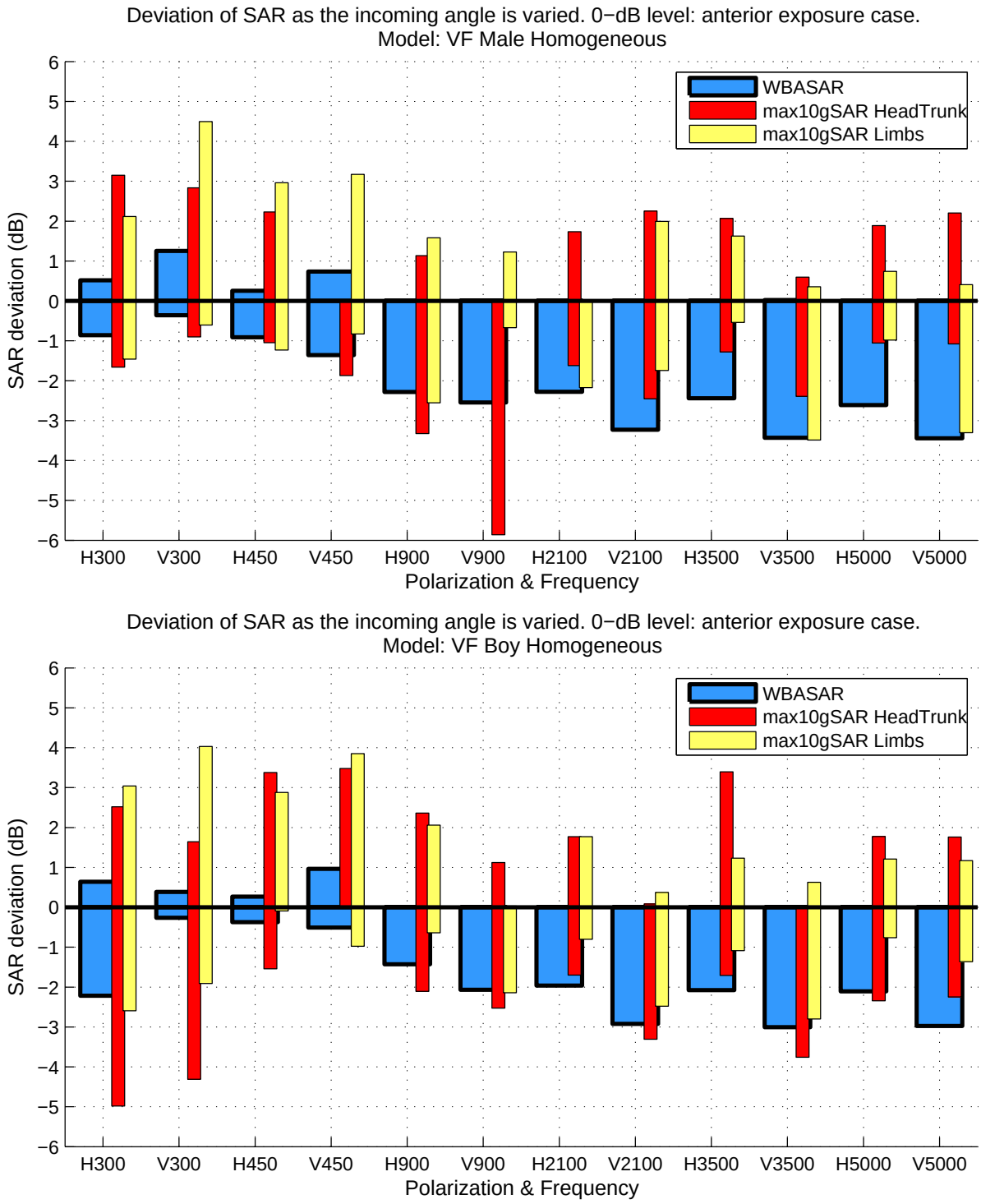
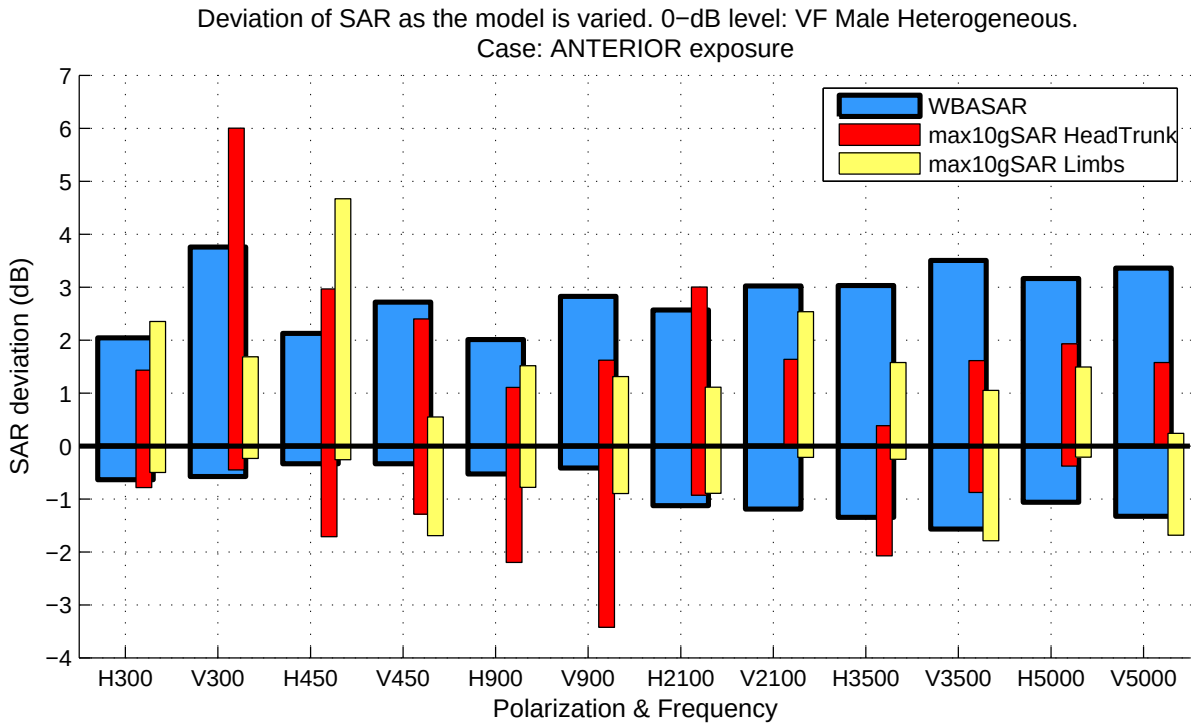


Figure 37: Maximum and minimum deviation of SAR in dB scale, due to incoming angle variation, is shown for homogeneous VF Male (top) and homogeneous VF Boy (bottom). The main point is to show how sensitive the SAR values are to the incoming angle. The **0-dB level corresponds to the anterior exposure** in each polarization-frequency case. This incoming angle variation covers 11 angles which were shown in Figure 8.



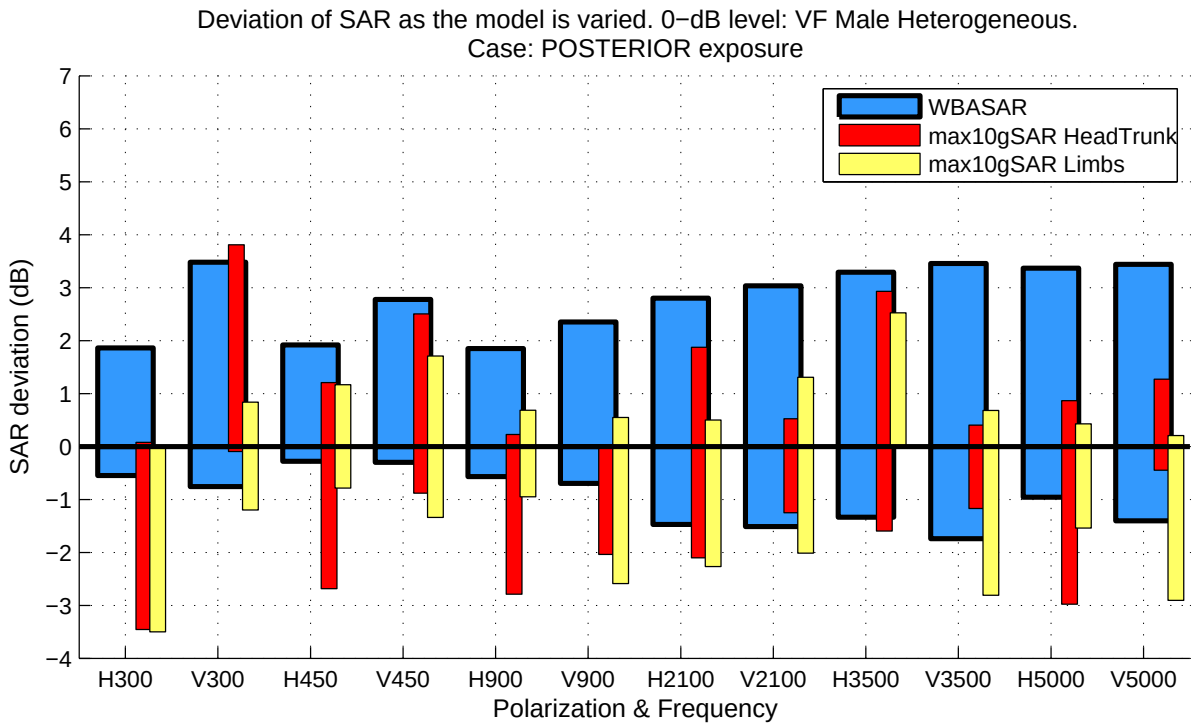


Figure 38: Maximum and minimum deviation of SAR in dB scale, due to model phantom variation. The model set consists of 9 models: Norman, Japanese Male and Female, VHP Male, VF Male (homogeneous and heterogeneous), VF Boy (homogeneous and heterogeneous) and VF Female. All these models are in the regular standing posture. Note that "Posture standing" is excluded from this comparison as well as other posture models. The **0-dB level corresponds to VF Male Heterogeneous** (72 kg). For example, maximum deviation of WBASAR is given by VF Boy heterogeneous or homogeneous (mass roughly 20 kg). Minimum WBASAR is usually given by VHP Male (105 kg).

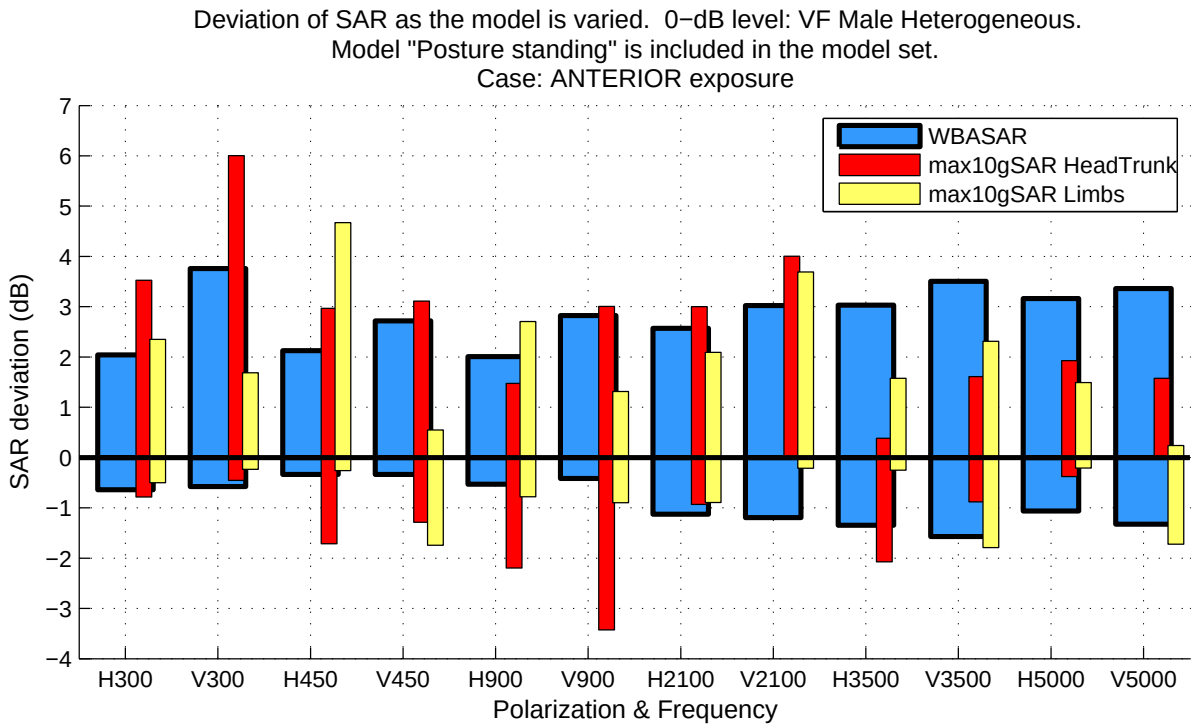


Figure 39: Maximum and minimum deviation of SAR in dB scale, due to model phantom variation, but now also including the model "Posture standing". By comparing this with Figure 38 (anterior) it is noted that including "Posture standing" in the set increases the deviation of max(10gSAR) values in some polarization-frequency cases (e.g. V2100).

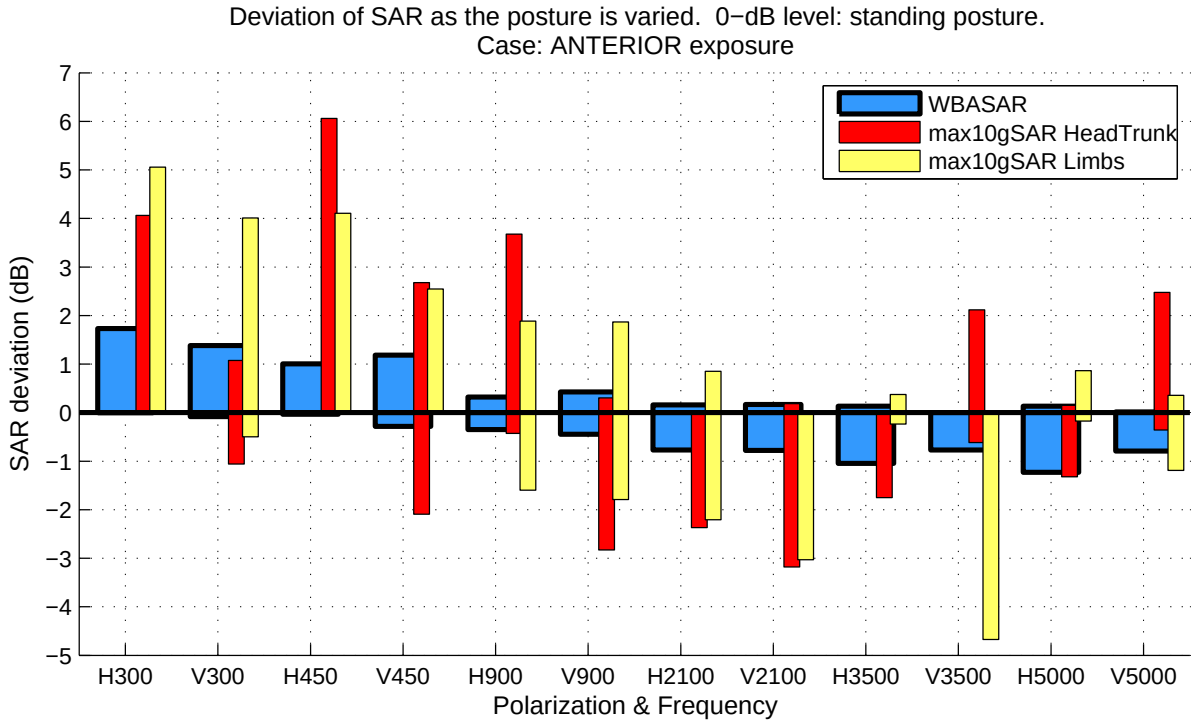


Figure 40: Maximum and minimum deviation of SAR in dB scale due to posture variation of a homogeneous male phantom (the applied set of 6 postures is shown in Figure 6). The **0-dB level corresponds to "Posture standing"** which is a regular standing posture, arms by the side of the body (=reference posture). Note that at the higher frequencies, $f \geq 2100$ MHz, the reference posture gives WBASAR which is actually quite close to the maximum WBASAR. However, at the lower frequencies 300 and 450 MHz, the reference posture tends to give relatively *low* WBASAR values, which means that changing a posture from standing to sitting can increase WBASAR about 2 dB (300 MHz) or 1 dB (450 MHz). One should also see Figures 33 - 35 for detailed results.

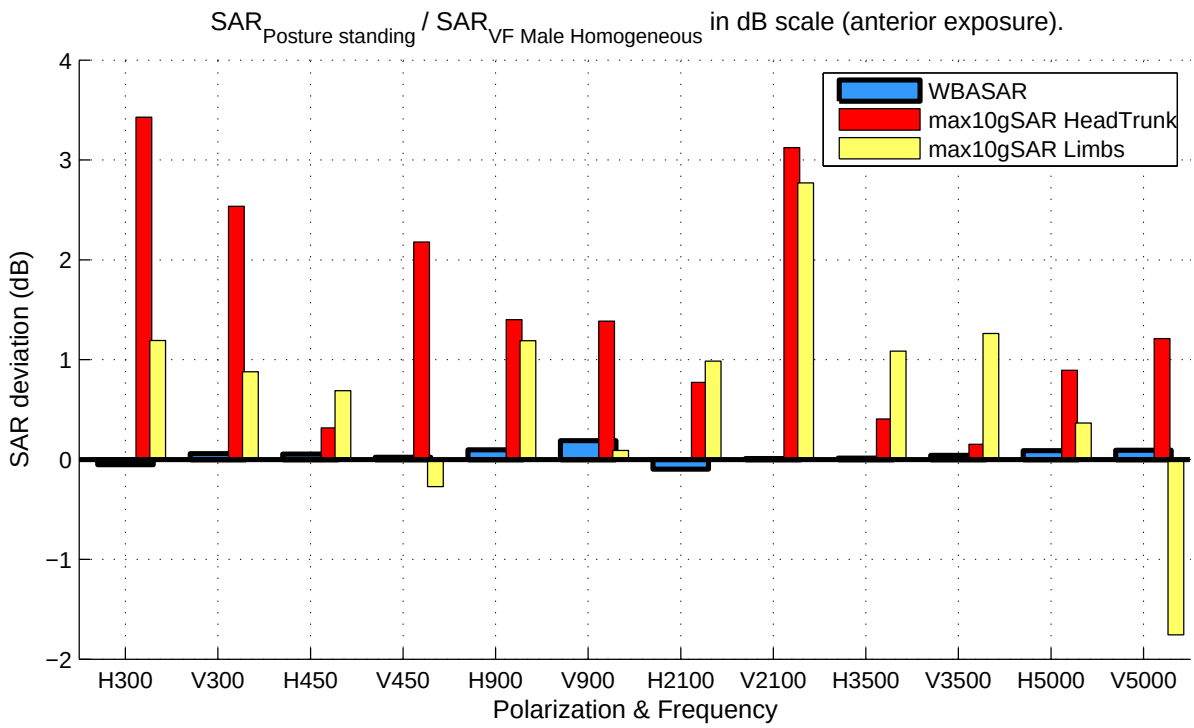


Figure 41: Comparison of models Posture standing (65.05 kg) and VF Male Homogeneous (68.54 kg). Both models are homogeneous, but their masses differ 3.5 kg and they have some anatomical differences. It is seen that the WBASAR is almost same for them, but due to the anatomical differences Posture standing has higher peak 10g-SAR values especially in the head/trunk region.

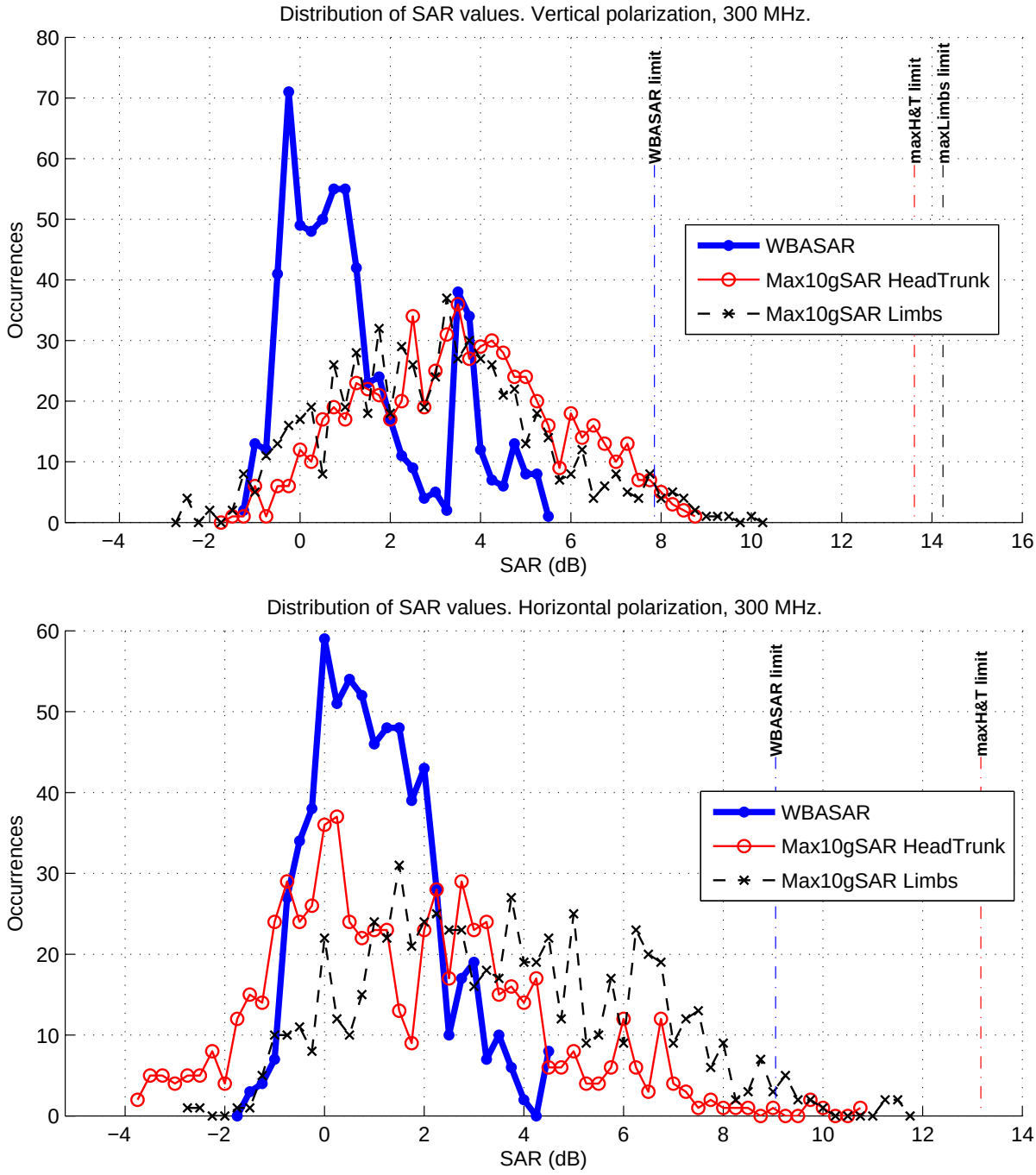


Figure 42: Frequency distributions of SAR at 300 MHz for vertical (top) and horizontal (bottom) polarization. Population includes 10x6x11=660 model-posture-angle combinations (see p. 54). 0 dB corresponds to the model-posture-angle combination of VFM Heterogeneous - standing - ($\theta = 90°, \phi = 180°$), exposed at the ICNIRP reference level. $\theta = 90°, \phi = 180°$ corresponds to the anterior (frontal) exposure. The applied bin width along the SAR axis is 0.25 dB. At 300 MHz, there are no model-posture-angle cases exceeding any SAR limits.

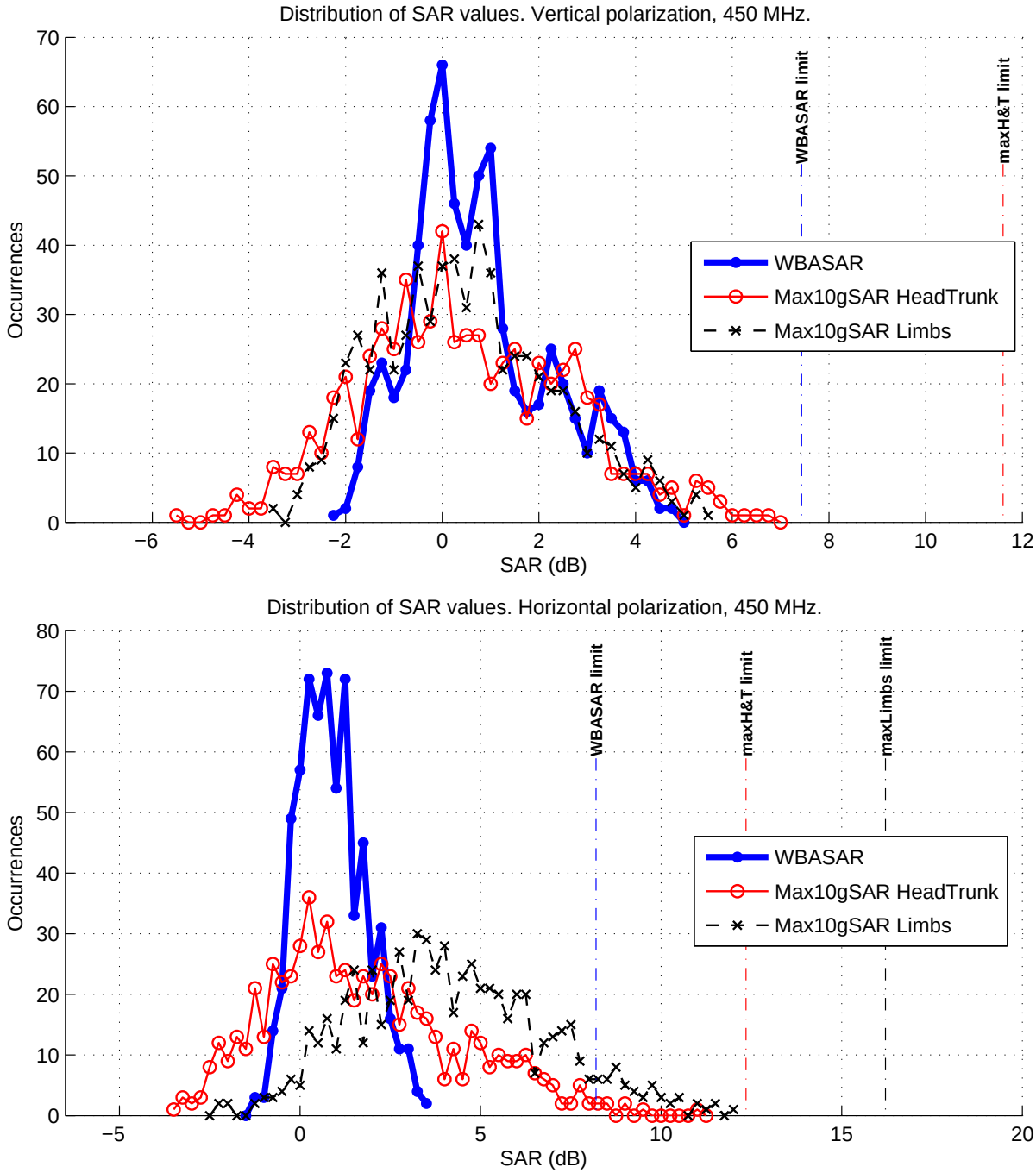


Figure 43: Frequency distributions of SAR at 450 MHz for vertical (top) and horizontal (bottom) polarization. Population includes 10x6x11=660 model-posture-angle combinations (see p. 54). 0 dB corresponds to the model-posture-angle combination of VFM Heterogeneous - standing - ($\theta = 90°, \phi = 180°$), exposed at the ICNIRP reference level. $\theta = 90°, \phi = 180°$ corresponds to the anterior (frontal) exposure. The applied bin width along the SAR axis is 0.25 dB. At 450 MHz, there are no model-posture-angle cases exceeding any SAR limits.

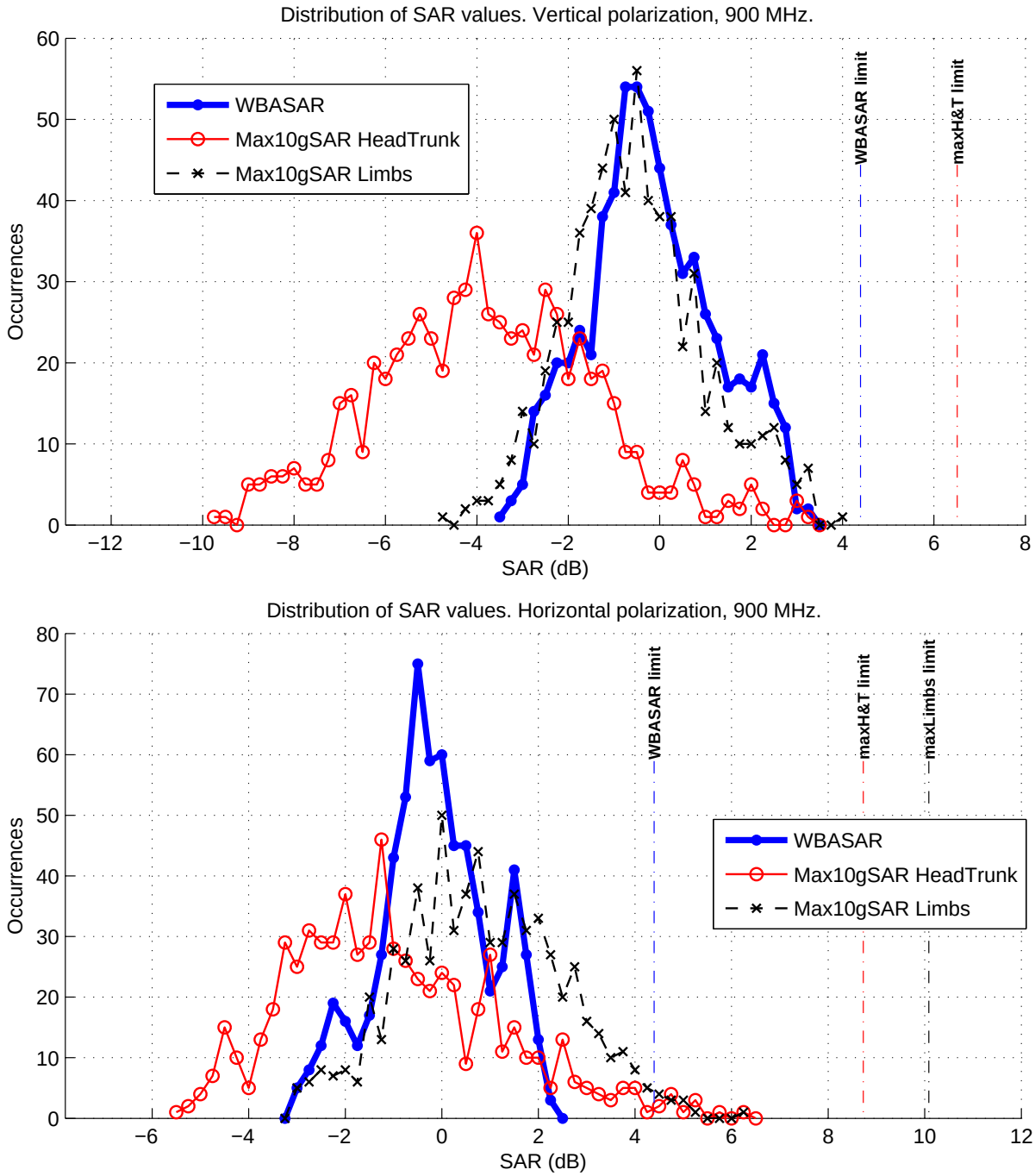


Figure 44: Frequency distributions of SAR at 900 MHz for vertical (top) and horizontal (bottom) polarization. Population includes 10x6x11=660 model-posture-angle combinations (see p. 54). 0 dB corresponds to the model-posture-angle combination of VFM Heterogeneous - standing - ($\theta = 90°, \phi = 180°$), exposed at the ICNIRP reference level. $\theta = 90°, \phi = 180°$ corresponds to the anterior (frontal) exposure. The applied bin width along the SAR axis is 0.25 dB. At 900 MHz, there are no model-posture-angle cases exceeding any SAR limits.

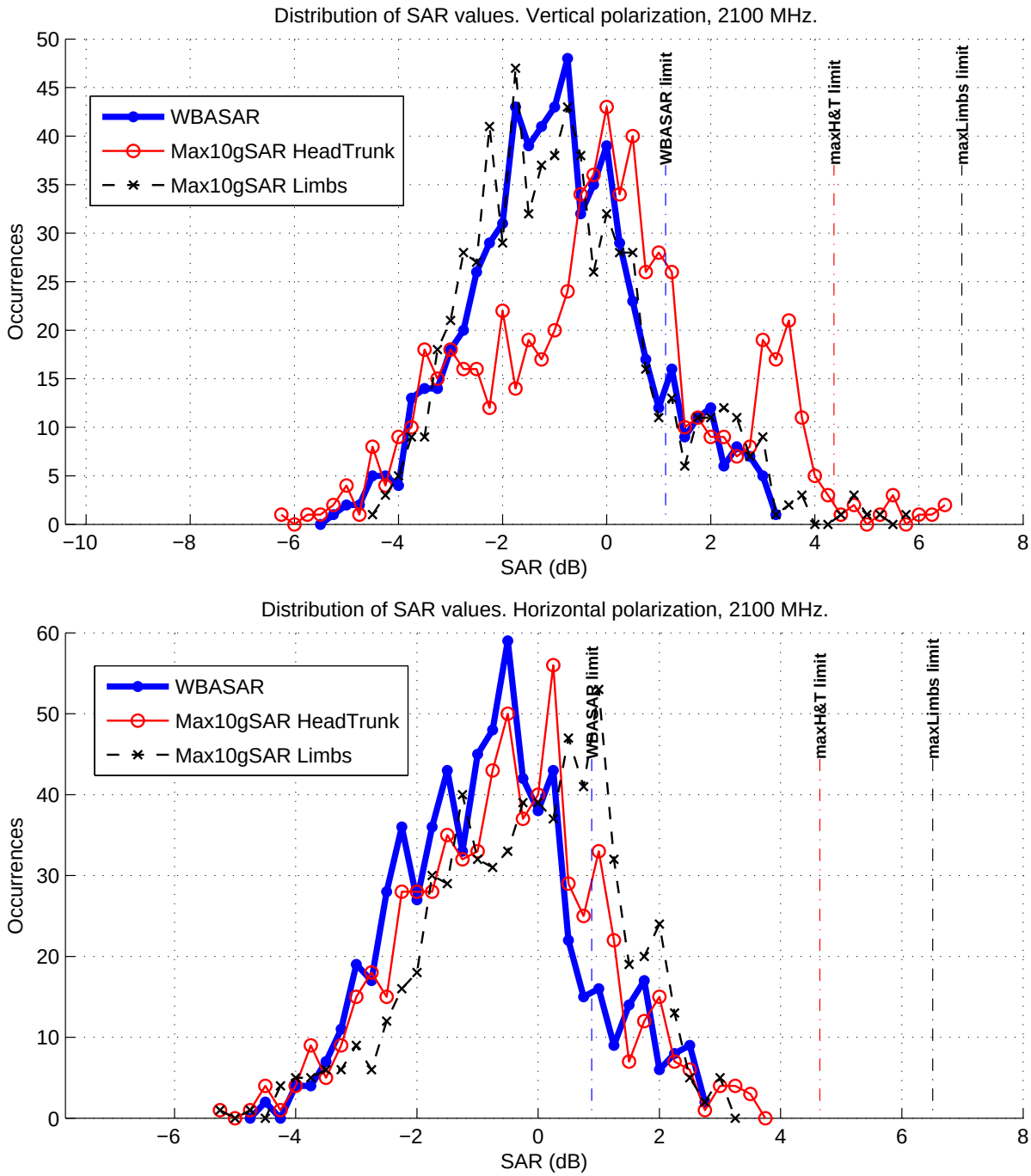


Figure 45: Frequency distributions of SAR at 2100 MHz for vertical (top) and horizontal (bottom) polarization. Population includes 10x6x11=660 model-posture-angle combinations (see p. 54). 0 dB corresponds to the model-posture-angle combination of VFM Heterogeneous - standing - ($\theta = 90°, \phi = 180°$), exposed at the ICNIRP reference level. $\theta = 90°, \phi = 180°$ corresponds to the anterior (frontal) exposure. The applied bin width along the SAR axis is 0.25 dB. At 2100 MHz, there are model-posture-angle cases exceeding SAR limits at the reference level of exposure: the WBASAR-limit exceedings are due to VF Boy (heterogeneous and homogeneous) and the max(10gSAR) limit exceedings in the head/trunk are due to the posture models.

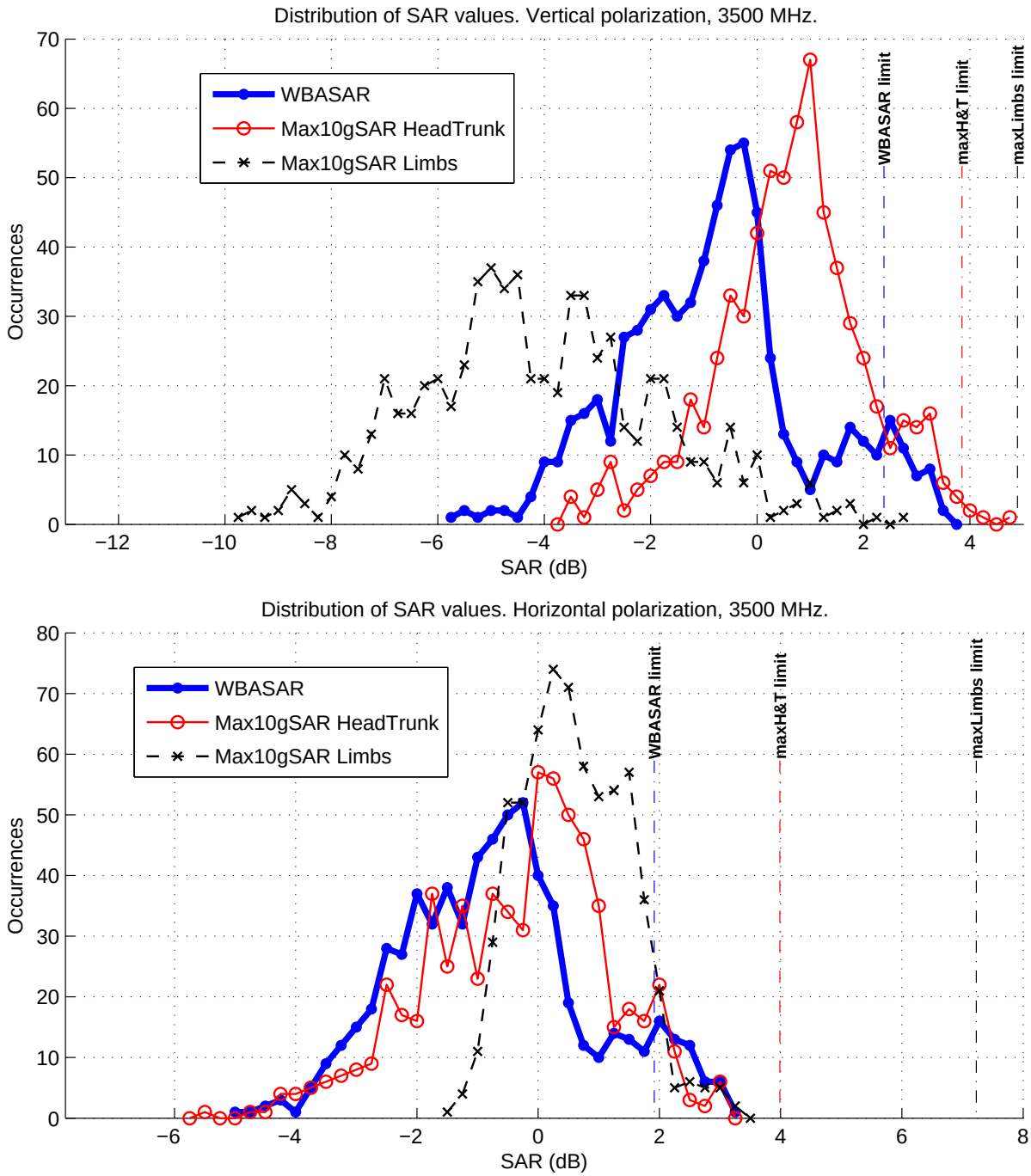


Figure 46: Frequency distributions of SAR at 3500 MHz for vertical (top) and horizontal (bottom) polarization. Population includes 10x6x11=660 model-posture-angle combinations (see p. 54). 0 dB corresponds to the model-posture-angle combination of VFM Heterogeneous - standing - ($\theta = 90°, \phi = 180°$), exposed at the ICNIRP reference level. $\theta = 90°, \phi = 180°$ corresponds to the anterior (frontal) exposure. The applied bin width along the SAR axis is 0.25 dB. At 3500 MHz, there are model-posture-angle cases exceeding SAR limits at the reference level of exposure: the WBASAR-limit exceedings are due to VF Boy (heterogeneous and homogeneous) and the max(10gSAR) limit exceedings in the head/trunk are due to the posture models.

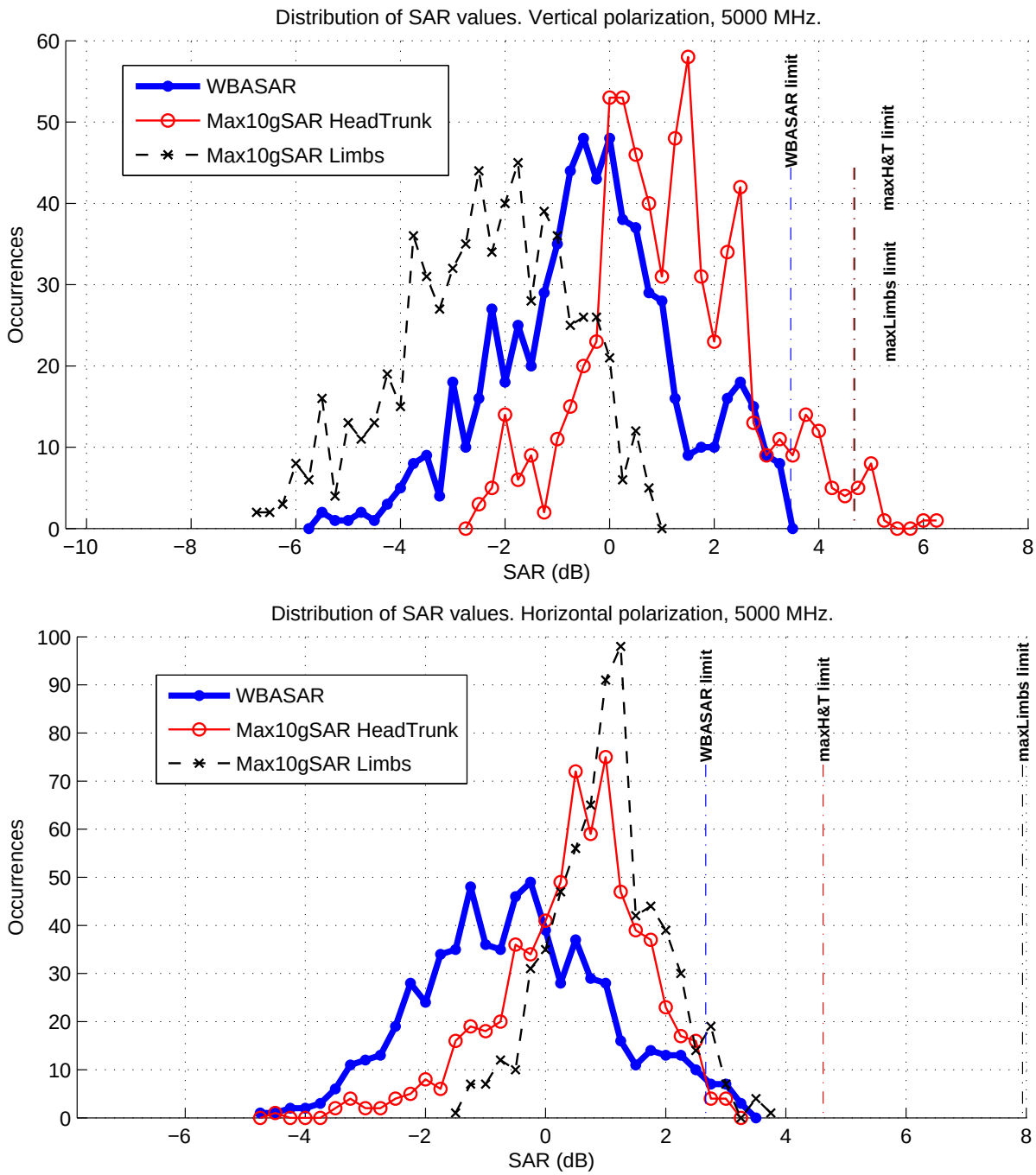


Figure 47: Frequency distributions of SAR at 5000 MHz for vertical (top) and horizontal (bottom) polarization. Population includes 10x6x11=660 model-posture-angle combinations (see p. 54). 0 dB corresponds to the model-posture-angle combination of VFM Heterogeneous - standing - ($\theta = 90°, \phi = 180°$), exposed at the ICNIRP reference level. $\theta = 90°, \phi = 180°$ corresponds to the anterior (frontal) exposure. The applied bin width along the SAR axis is 0.25 dB. At 5000 MHz, there are model-posture-angle cases exceeding SAR limits at the reference level of exposure: the WBASAR-limit exceedings are due to VF Boy Homogeneous and the max(10gSAR) limit exceedings in the head/trunk are due to the posture models.

Appendix: Illustrations of 10g SAR on models

Figures 48 - 59 show distributions of 10g-SAR on models in selected exposure cases. Note that, unless stated otherwise, in these illustrations the SAR distributions have not been normalized, i.e., the 10g-SAR values correspond to electric field amplitude $|\mathbf{E}_{\mathrm{rms}}| = 1$ V/m. Most importantly, the figures aim to illustrate how polarization, frequency and the anatomy affect the 10g-SAR distribution. It is a good idea to compare these samples of distributions with the previous figures which showed normalized peak 10g-SAR values. The Figures 48 - 59 should be seen in color and using a computer so that one is able to zoom in.

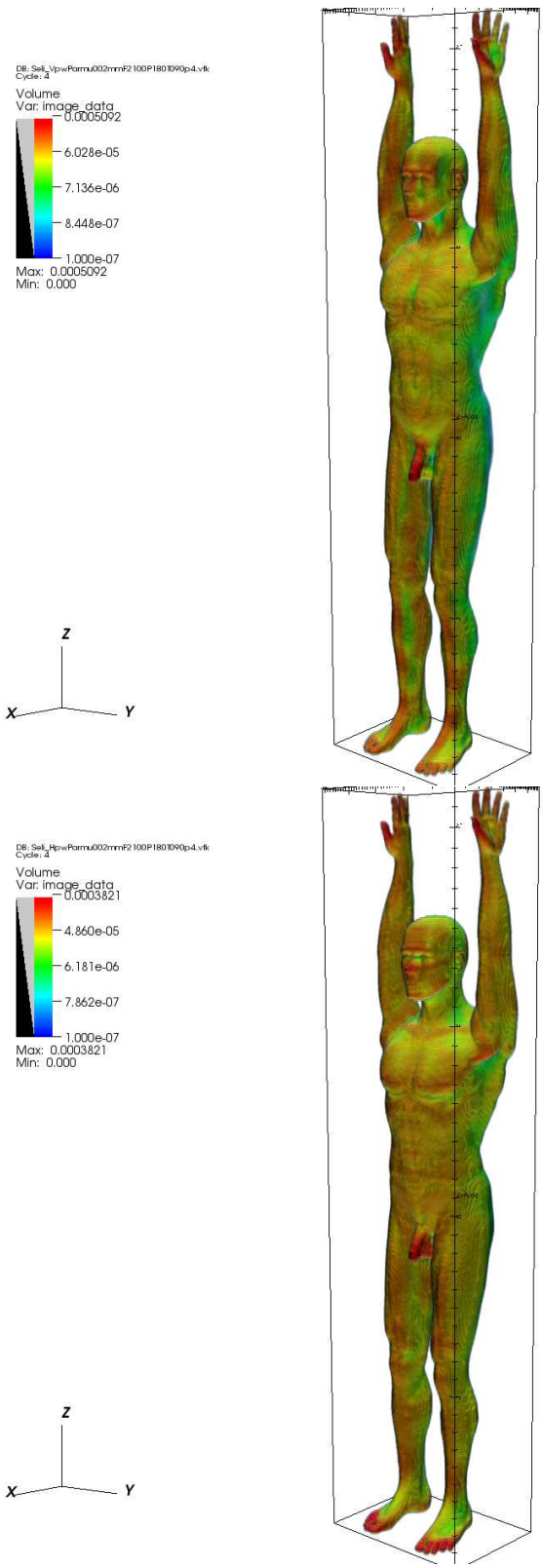


Figure 48: 10g-SAR distribution on the model "Posture arms up" at 2100 MHz (anterior). Top figure: vertical polarization with max(10gSAR)=5.092e-4 W/kg (in penis). Bottom figure: horizontal polarization with max(10gSAR)= 3.821e-4 W/kg (in little toe of left foot). These SAR values correspond to incoming field amplitude $E_{\mathrm{rms}} = 1$ V/m, i.e., these are *not* normalized SAR values. Note the logarithmic scale in the SAR-color mapping.

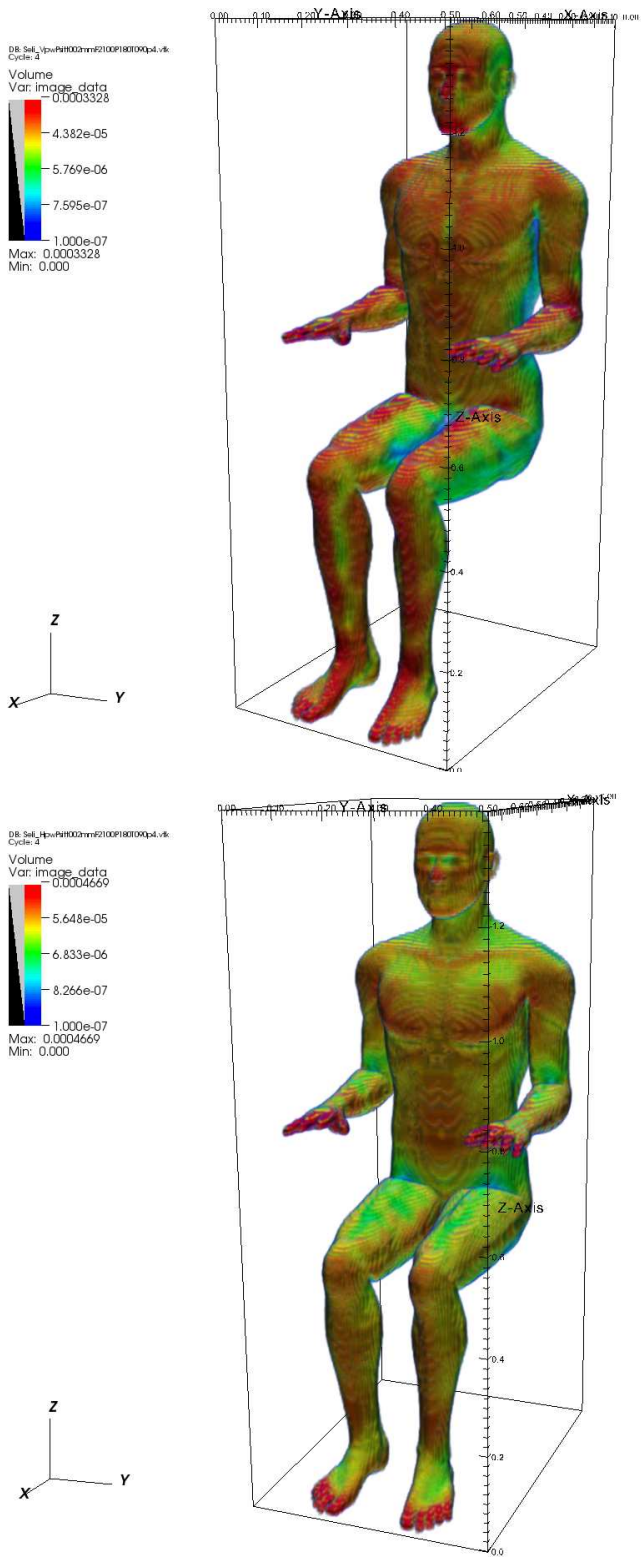
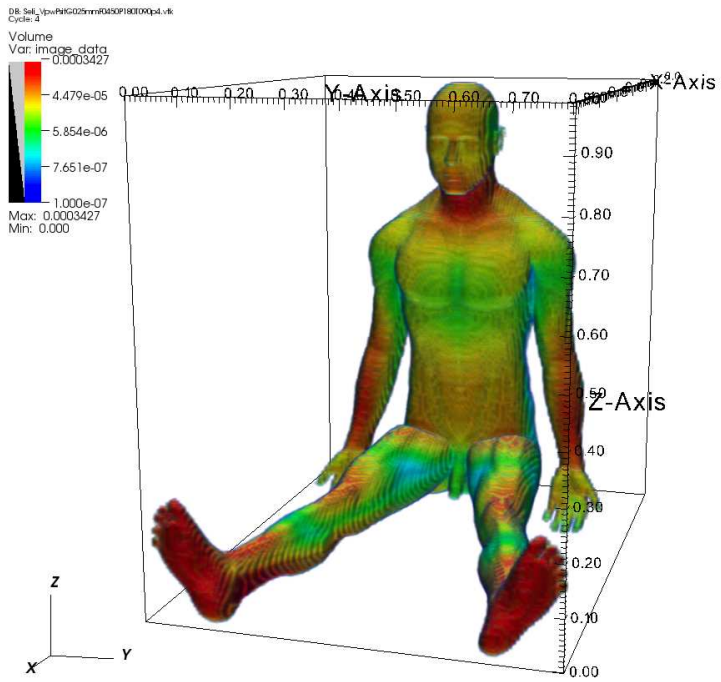


Figure 49: 10g-SAR distribution on the model "Posture sit" at 2100 MHz (anterior). Top figure: vertical polarization with max(10gSAR)= 3.328e-4 W/kg (in a finger of left hand). Bottom figure: horizontal polarization with max(10gSAR)=4.669e-4 W/kg (in a finger of right hand). These SAR values correspond to incoming field amplitude $E_{\mathrm{rms}} = 1$ V/m. Note the hot spots especially in the fingers and toes with horizontal polarization (see also Fig. 34 which shows that actually this posture gives the highest normalized peak 10g SAR in the limbs in the case H2100).



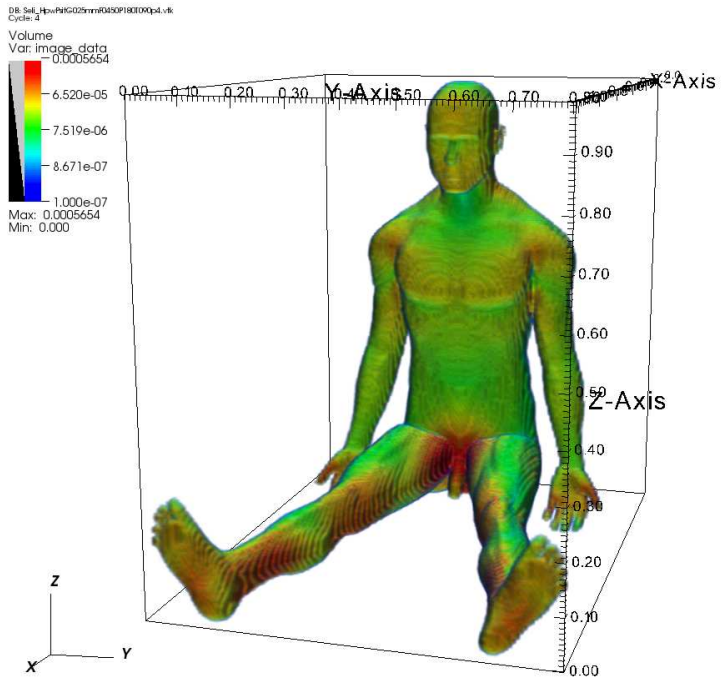


Figure 50: 10g-SAR distribution on the model "Posture sit on ground" at 450 MHz (anterior; also this model is in free space, the label "sit on ground" refers only to the posture). Top figure: vertical polarization with max(10gSAR)=3.427e-4 W/kg (in head/neck region). Bottom figure: horizontal polarization with max(10gSAR)=5.654e-4 W/kg (in genital region). These SAR values correspond to incoming field amplitude $E_{\mathrm{rms}} = 1$ V/m. See also Fig. 35 which shows that actually this posture gives the highest normalized peak 10g SAR in the head/trunk in the cases H300, H450 and H900.

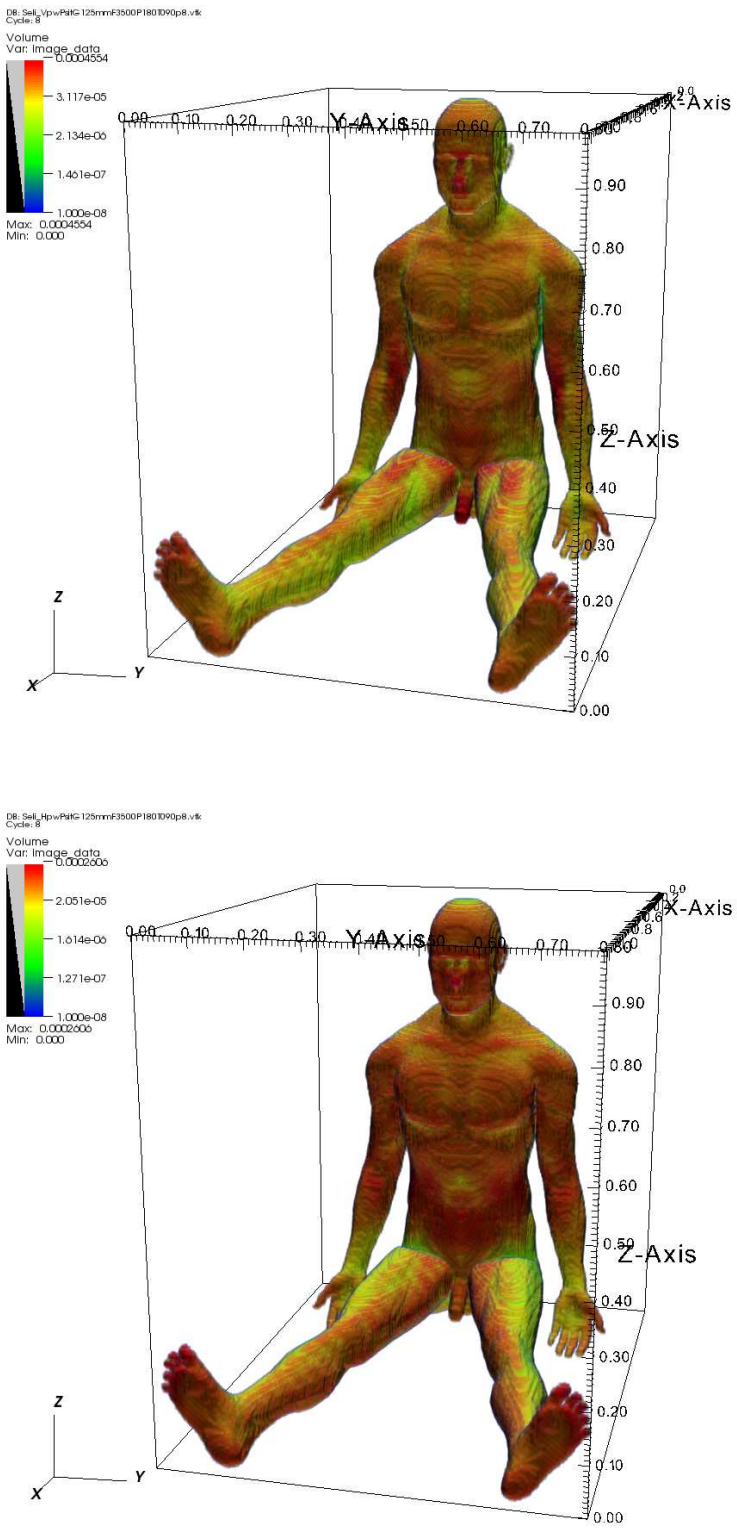


Figure 51: 10g-SAR distribution on the model "Posture sit on ground" at 3500 MHz (anterior). Top figure: vertical polarization with max(10gSAR)=4.554e-4 W/kg (in penis). Bottom figure: horizontal polarization with max(10gSAR)=2.606e-4 W/kg (in index toe of left foot). These SAR values correspond to incoming field amplitude $E_{\mathrm{rms}} = 1$ V/m. See also Fig. 35 which shows that actually this posture gives the highest normalized peak 10g SAR in the head/trunk in the cases V3500 and V5000.

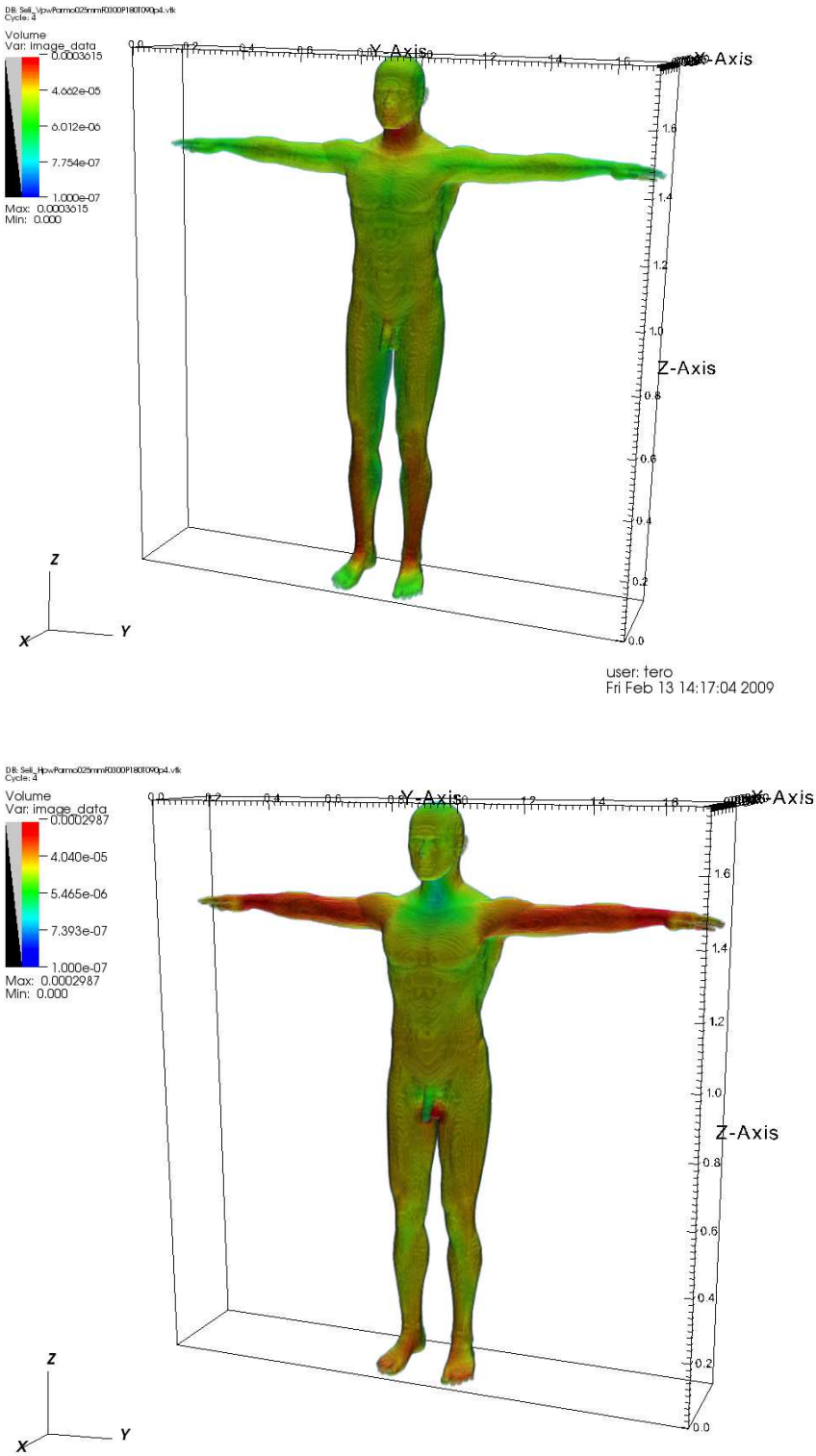


Figure 52: 10g-SAR distribution on the model "Posture arms out" at 300 MHz (anterior). Top figure: vertical polarization with max(10gSAR)=3.615e-4 W/kg (in head/neck region). Bottom figure: horizontal polarization with max(10gSAR)=2.987e-4 W/kg (in genital region), in limbs max(10gSAR)=2.764e-4 W/kg (in wrist of right arm). These SAR values correspond to incoming field amplitude $E_{\mathrm{rms}} = 1$ V/m.

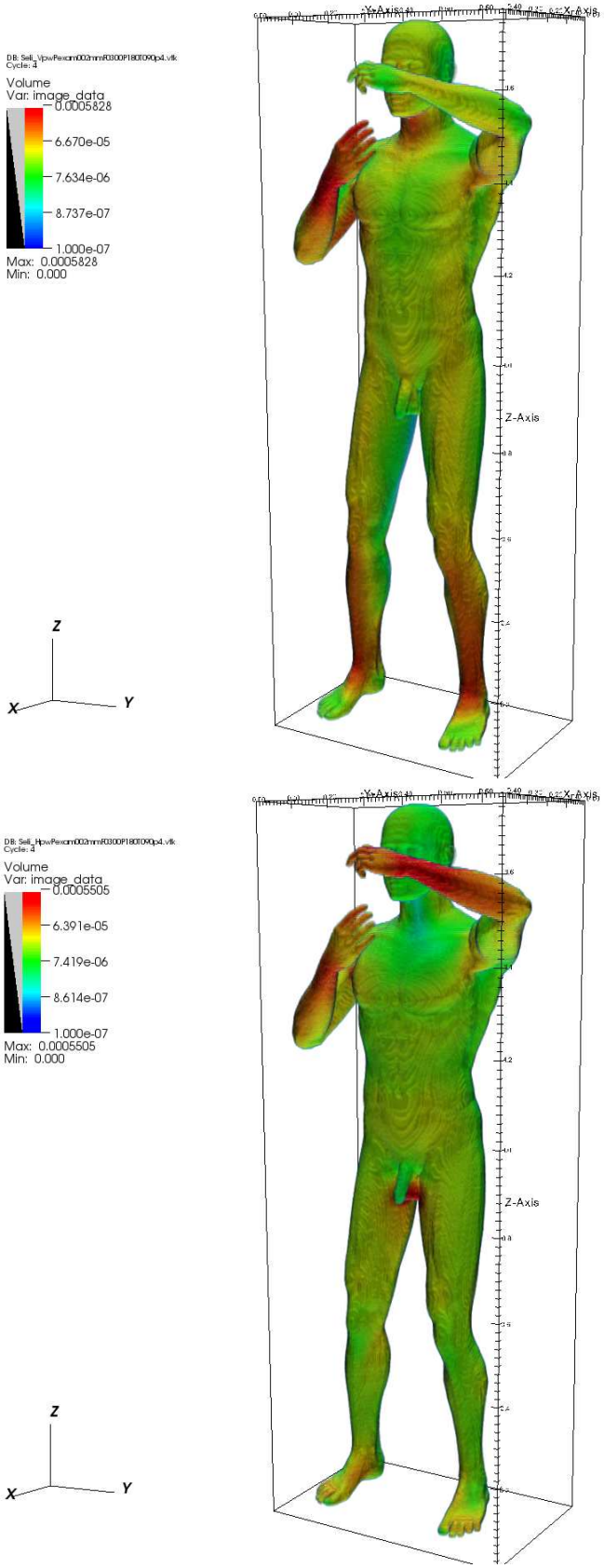


Figure 53: 10g-SAR distribution on the model "Posture examine" at 300 MHz (anterior). Top figure: vertical polarization with max(10gSAR)= 5.828e-4 W/kg (in right arm/wrist). Bottom figure: horizontal polarization with max(10gSAR)= 5.505e-4 W/kg (in left arm/wrist). These SAR values correspond to incoming field amplitude $E_{\mathrm{rms}} = 1$ V/m.

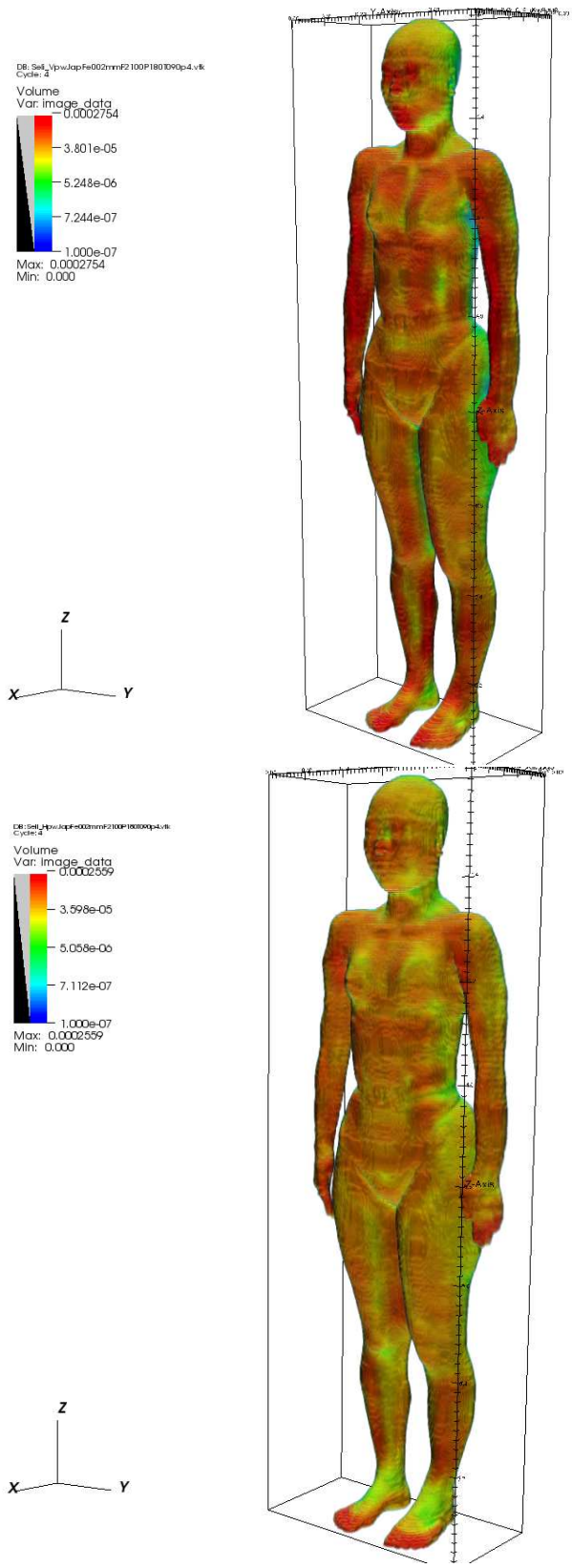


Figure 54: 10g-SAR distribution on the Japan Female model at 2100 MHz (anterior). Top figure: vertical polarization with max(10gSAR)=2.754e-4 W/kg (in head/chin), in limbs max(10gSAR)=2.670e-04 (in right middle arm). Bottom figure: horizontal polarization with max(10gSAR)=2.559e-4 W/kg (in a toe of right foot). These SAR values correspond to incoming field amplitude $E_{\mathrm{rms}} = 1$ V/m.

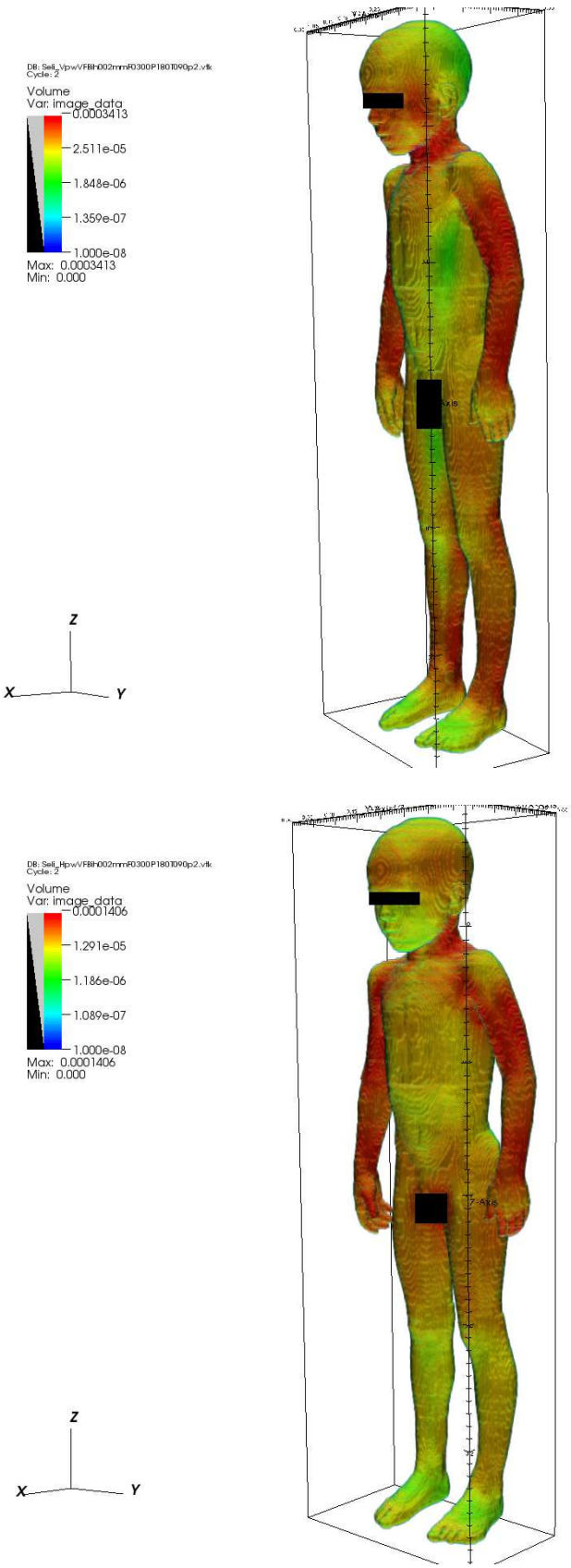


Figure 55: 10g-SAR distribution on VF Boy Heterogeneous at 300 MHz (anterior). Top figure: vertical polarization with max(10gSAR)= 3.413e-4 W/kg (in head/neck region). Bottom figure: horizontal polarization with max(10gSAR)= 1.406e-4 W/kg (in right upper arm). These SAR values correspond to incoming field amplitude $E_{\mathrm{rms}} = 1$ V/m.

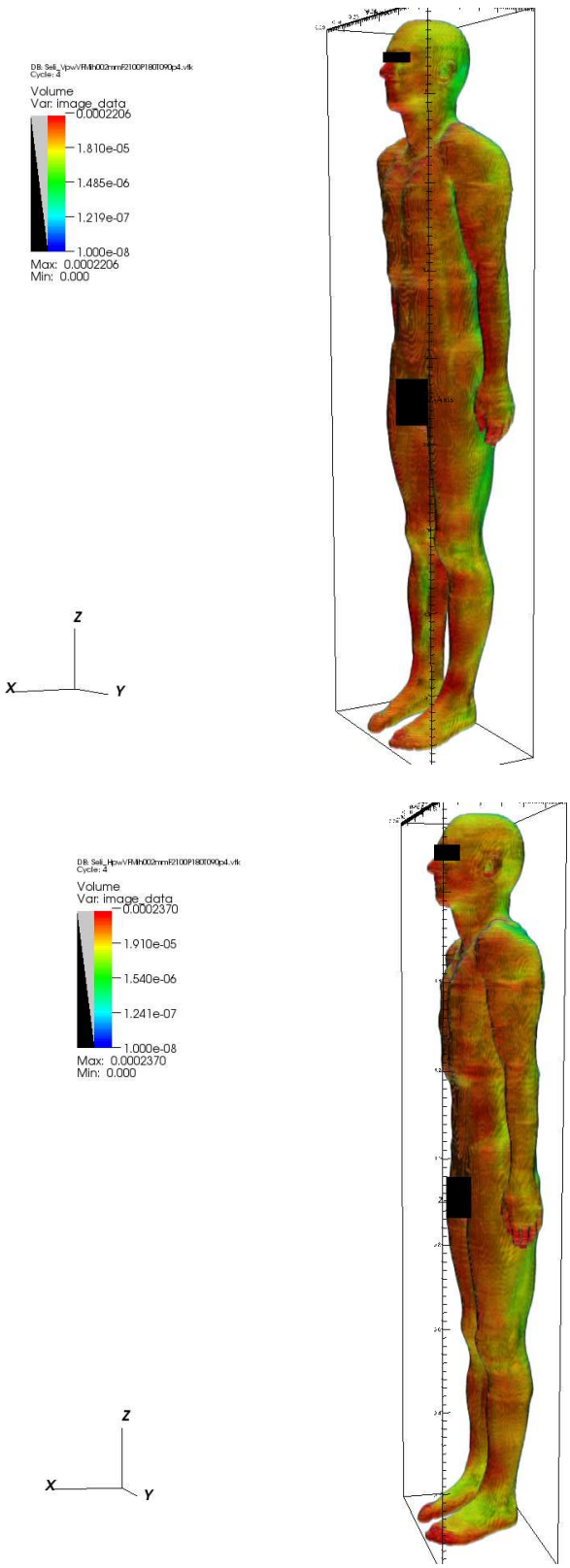


Figure 56: 10g-SAR distribution on VF Male Heterogeneous at 2100 MHz (anterior). Top figure: vertical polarization with max(10gSAR)=2.206e-4 W/kg (in right leg, ankle), in head/trunk max(10gSAR)=1.941e-4 W/kg (in head, nose). Bottom figure: horizontal polarization with max(10gSAR)=2.370e-4 W/kg (in left hand, finger), in head/trunk max(10gSAR)=1.819e-4 W/kg (in penis). These SAR values correspond to incoming field amplitude $E_{\mathrm{rms}} = 1$ V/m.

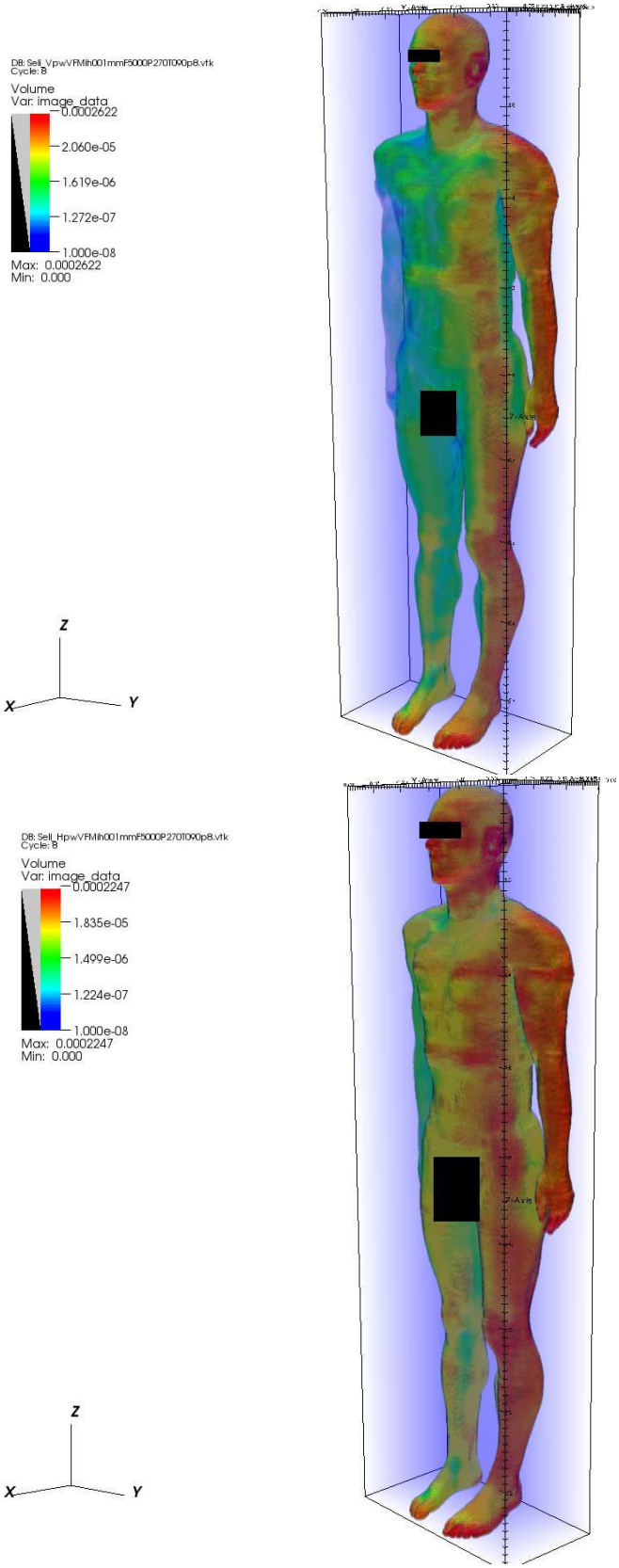


Figure 57: 10g-SAR distribution on VF Male Heterogeneous at 5000 MHz (left side exposure). Top figure: vertical polarization with max(10gSAR)= 2.622e-4 W/kg (in head, left ear). Bottom figure: horizontal polarization with max(10gSAR)= 2.247e-4 W/kg (in head, left ear). These SAR values correspond to incoming field amplitude $E_{\mathrm{rms}} = 1$ V/m.

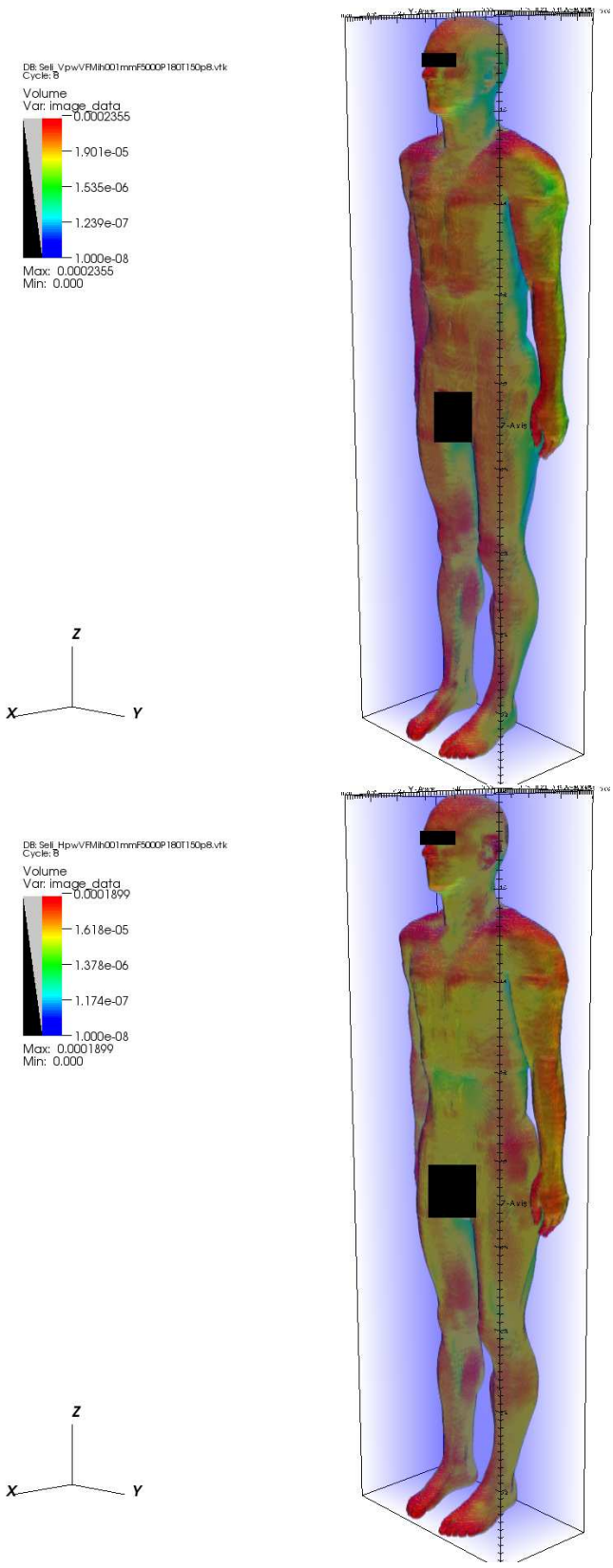


Figure 58: 10g-SAR distribution on VF Male Heterogeneous at 5000 MHz (above-front exposure i.e. $\theta = 150°$ and $\phi = 180°$). Top figure: vertical polarization with max(10gSAR)= 2.355e-4 W/kg (in left arm, wrist). Bottom figure: horizontal polarization with max(10gSAR)= 1.900e-4 W/kg (in left foot, toe). These SAR values correspond to incoming field amplitude $E_{\mathrm{rms}} = 1$ V/m.

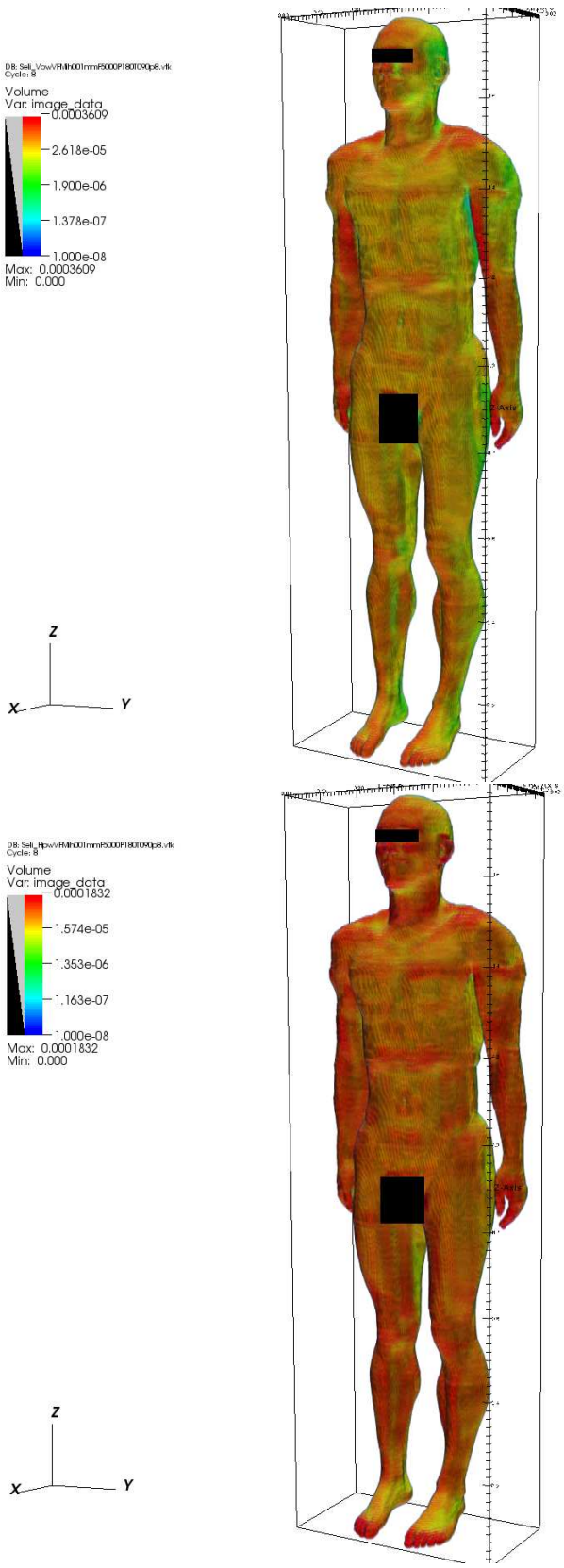


Figure 59: 10g-SAR distribution on VF Male Heterogeneous at 5000 MHz (anterior). Top figure: vertical polarization with max(10gSAR)= 3.609e-4 W/kg (in left hand, thumb). Bottom figure: horizontal polarization with max(10gSAR)=1.832e-4 W/kg (in penis), in limbs max(10gSAR)=1.705e-4 W/kg (left foot toe). These SAR values correspond to incoming field amplitude $E_{\mathrm{rms}} = 1$ V/m.