SAR Distribution in Human Beings when Using Body-Worn RF Transmitters

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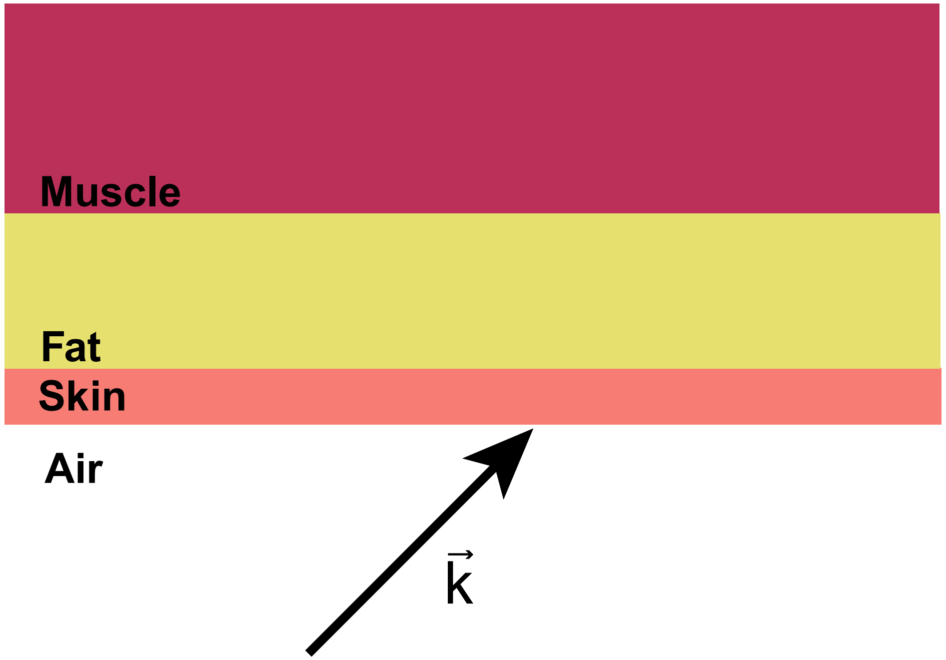
Motivation

- Standardized methods for the compliance testing with safety limits exist for wireless devices operated at the head of the user (IEEE 1528, IEC 62209 Pt. 1, CENELEC EN 50361).
- Standards for body-mounted and handheld devices considering a more general usage pattern (whole body tissue distribution, distances up to 200mm) and a frequency range from 30MHz to 6GHz are currently under development, such as IEC 62209 Pt. 2.

Objectives

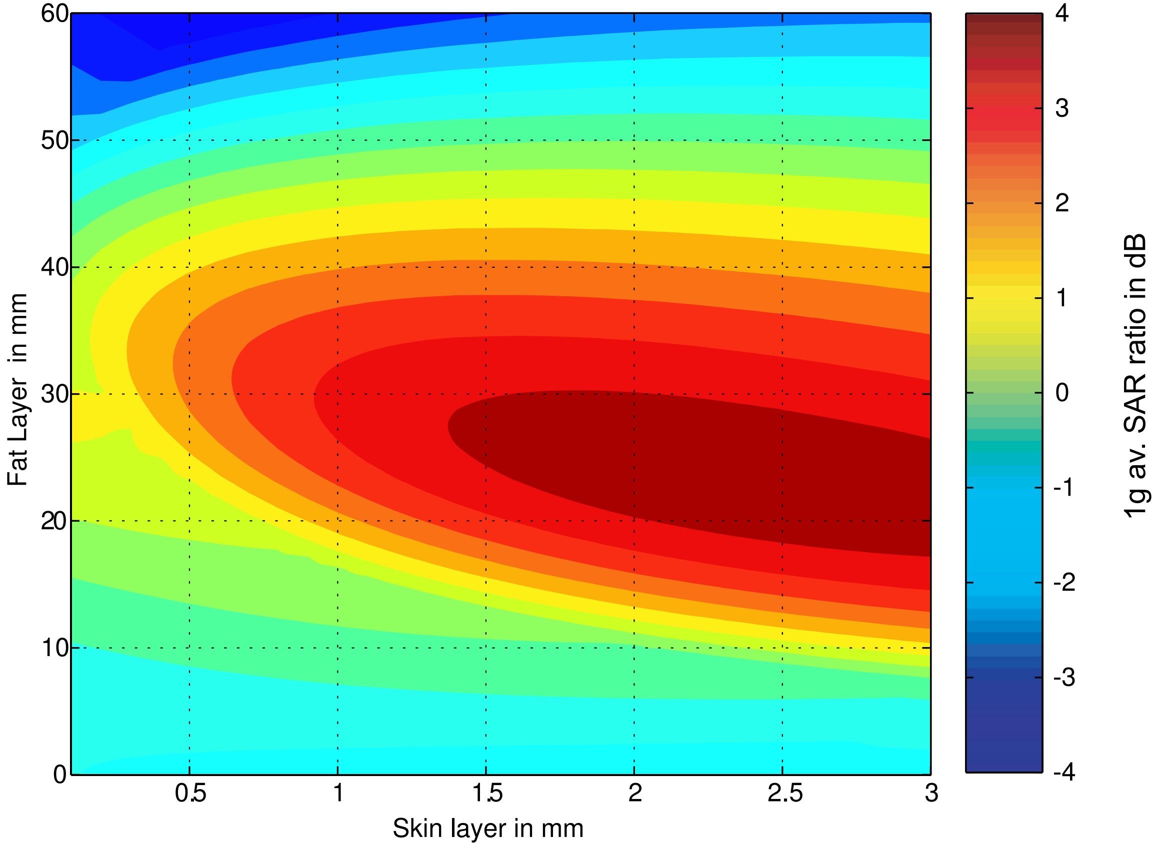
- theoretical analysis of near- and far-field coupling effects of electromagnetic fields into body tissue considering anatomically correct tissue distribution, distances from 5mm to 200mm and a frequency range up to 6GHz
- evaluation of worst-case tissue distribution considering the characteristics of the whole body
- analysis of the SAR distribution in anatomical models of the human body in order to validate worst-case coupling effects and to assess the exposure of inner organs
- analysis of the induced heating effects regarding worst-case situations and to the temperature of inner organs
- evaluation of the results with respect to existing standards for the compliance testing of wireless devices and their applicability for different organs

Generic Body Model



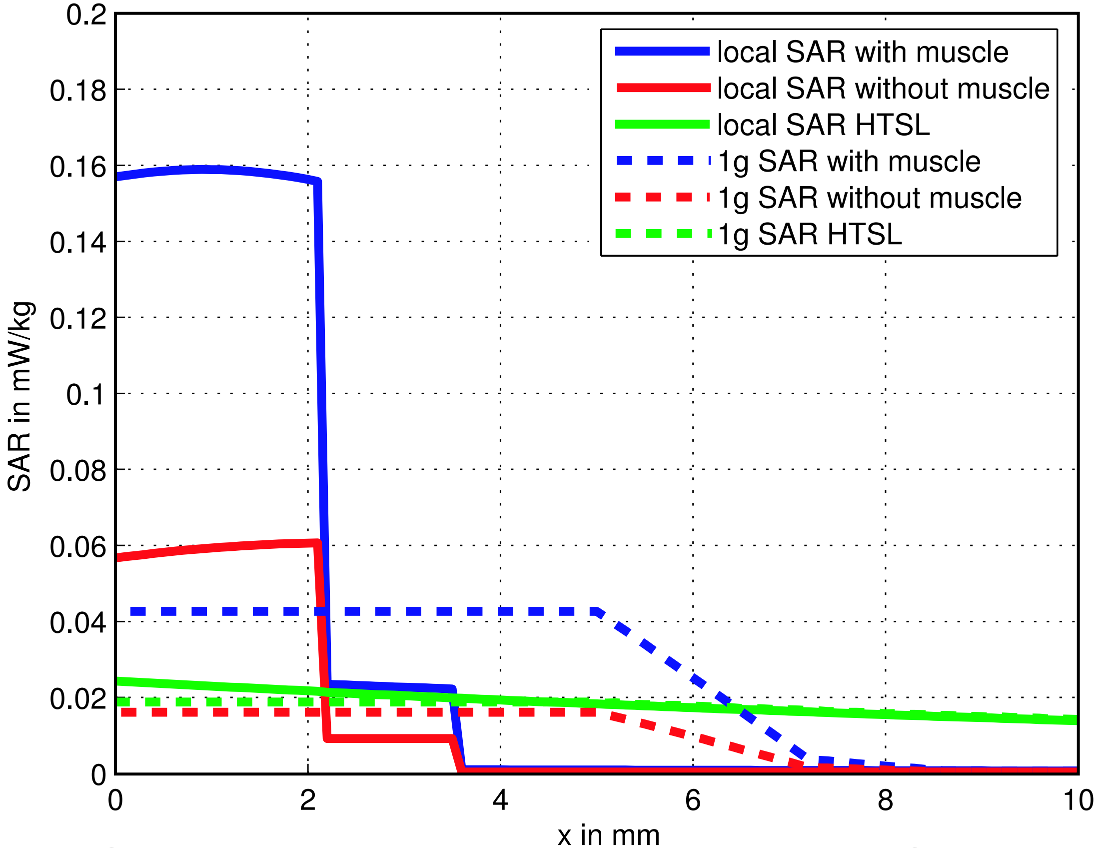
- high water content (up to 90%, skin, muscle, most inner organs)
- low water content (approx. 20%-30%, fat, breast tissue, bone, inflated lung)
- standing wave effects reported e. g. in Meier et al., 1997, Drossos et al., 2000
- three layer half space consisting of skin (0.4 - 2.6mm), fat (0 - approx. 100mm), muscle as termination

SAR in the Generic Body Model



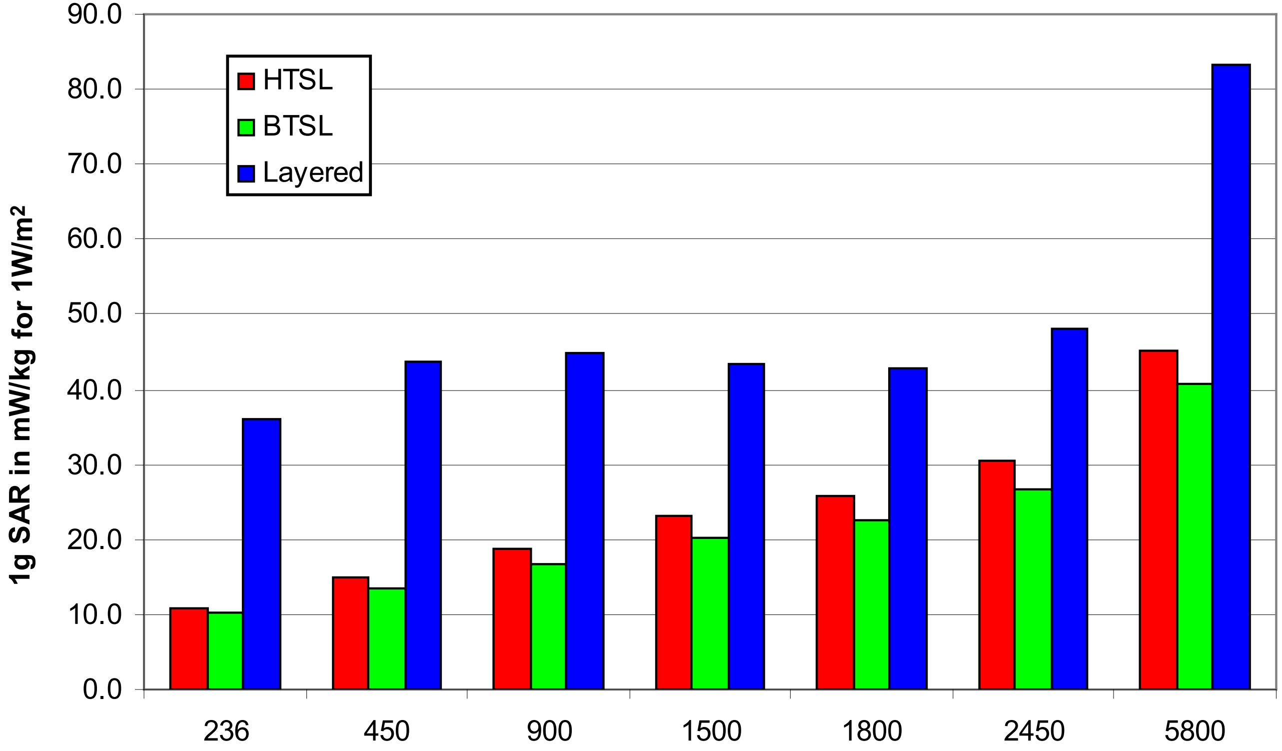
- 1g average SAR in the layered body model normalized to head tissue simulating liquid for plane wave conditions at 900MHz
- increase of more than 3dB due to standing wave effects for a skin layer thickness of 2.6mm and a fat layer thickness of 24mm

SAR in Layered and Homogeneous Tissue



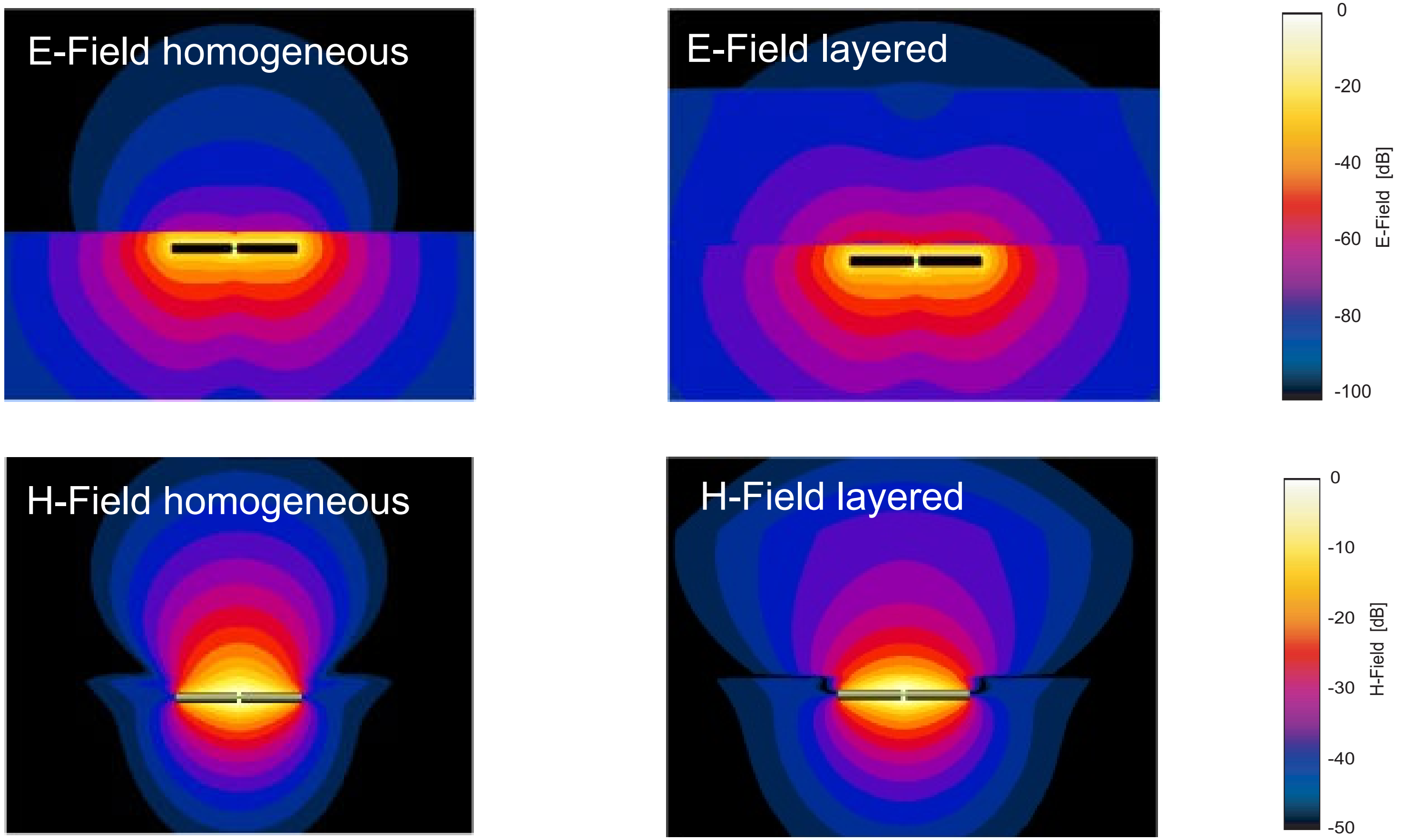
- local and 1g SAR in layered tissue and HTSL for $p_{inc} = 1W/m^2$
- 3dB increase of SAR average (layered vs. HTSL) in cubical volume
- averaging over contiguous tissue would correlate the local maxima and lead to a worst-case increase of more than 8dB

Worst Case SAR for Plane Wave Exposure



- enhancement between 2.0dB and 5.5dB due to standing wave effects which lead to high losses in the skin layer (3 layer model)
- SAR increase of the same order of magnitude for anatomical tissue layer distribution at various regions of the body

Coupling of Reactive Fields at Close Distances



- Electric fields can penetrate the low permittivity fat layer and lead to high absorption in the skin.
- The effect is dominant at frequencies below 450 MHz and for electrically small antennas

Plane Wave Spectral Component Representation

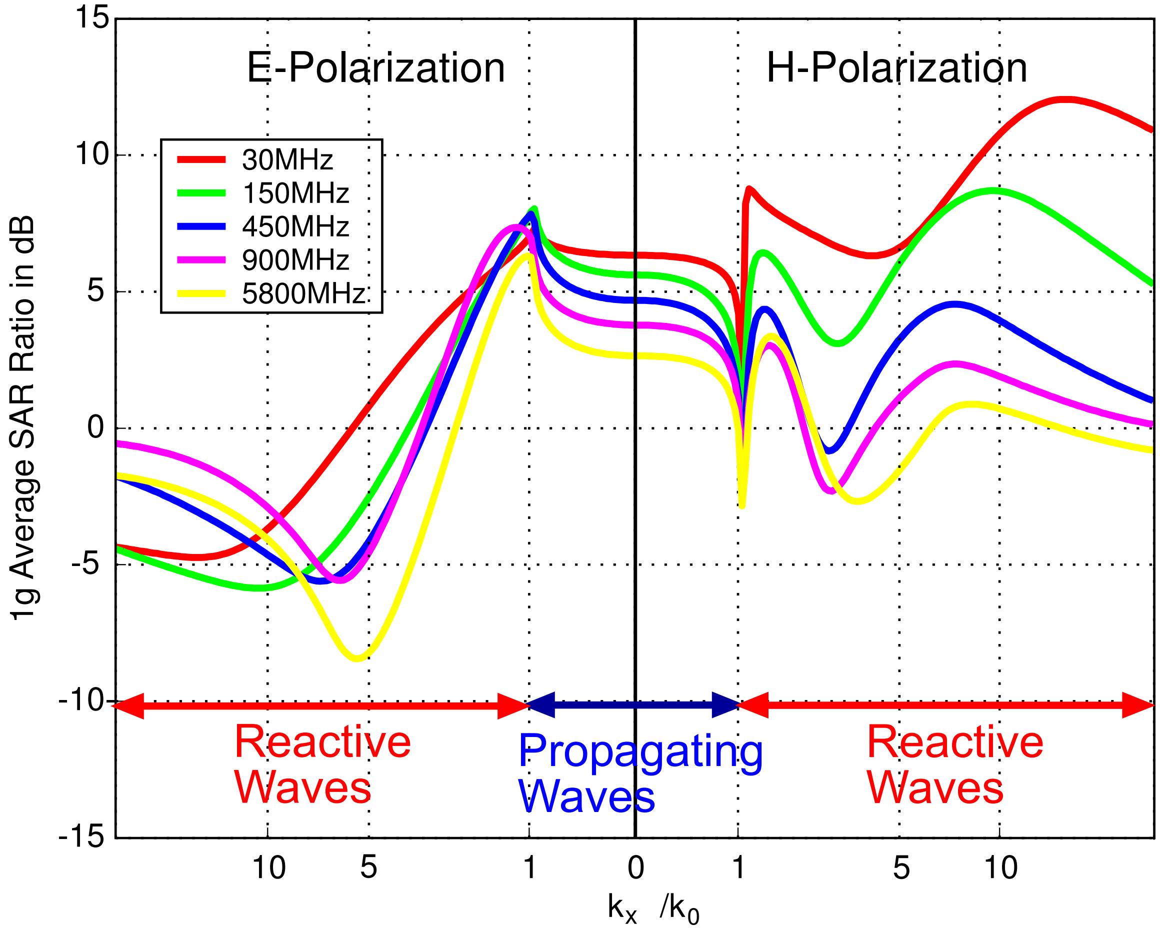
- All fields excited by an antenna can be expressed as superposition of radiating and reactive waves with E- and H-polarization. The absolute value of the wave vector **k** is the free space wave number k_0.
- The following cases can be distinguished:

  - $k_x/k_0 = 0$ is the plane wave case (perpendicular incidence).

  - $0 < | k_x/k_0 | < 1$ corresponds to the inclinated waves.

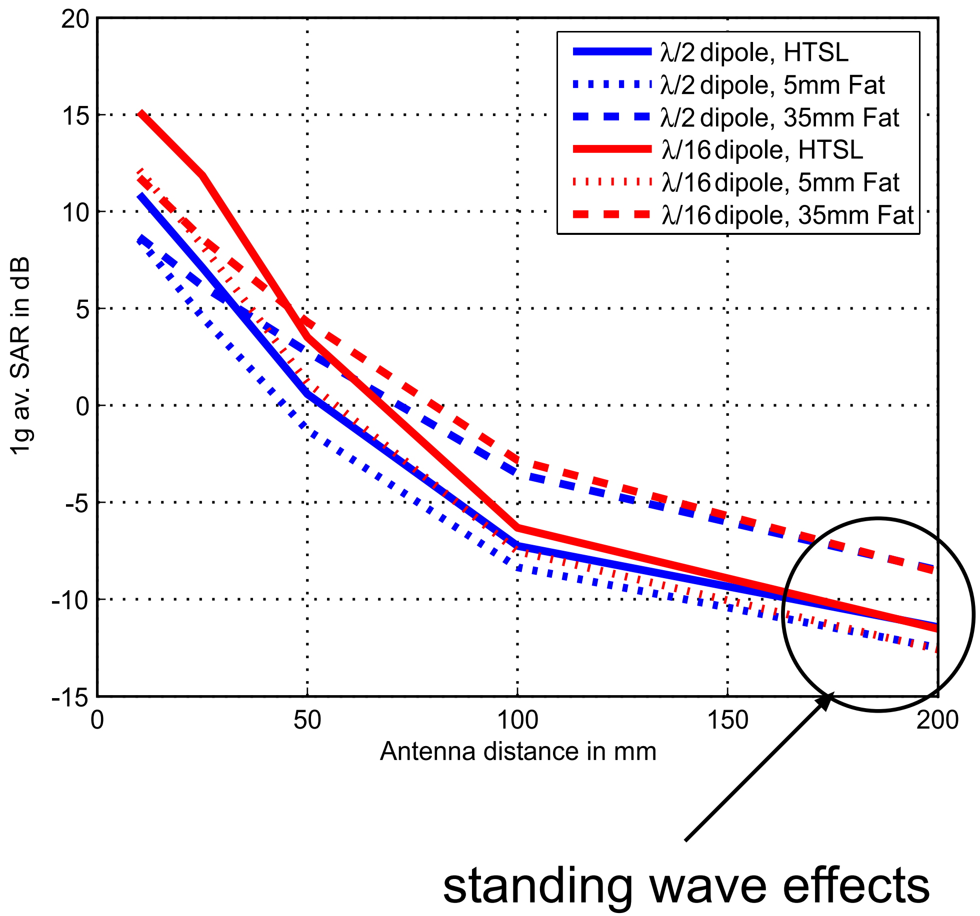
  - $k_x/k_0 > 1$ represents the reactive waves. k_z will be purely imaginary.
- Wave propagation in the tissue for each wave can be calculated using Snell's Law and transmission line relations. The SAR can then be calculated as a function of the incident wave.
- To rigorously calculate the spatial distribution for a real antenna, numerical tools must be applied.

Absorption of Inclinated and Reactive Waves



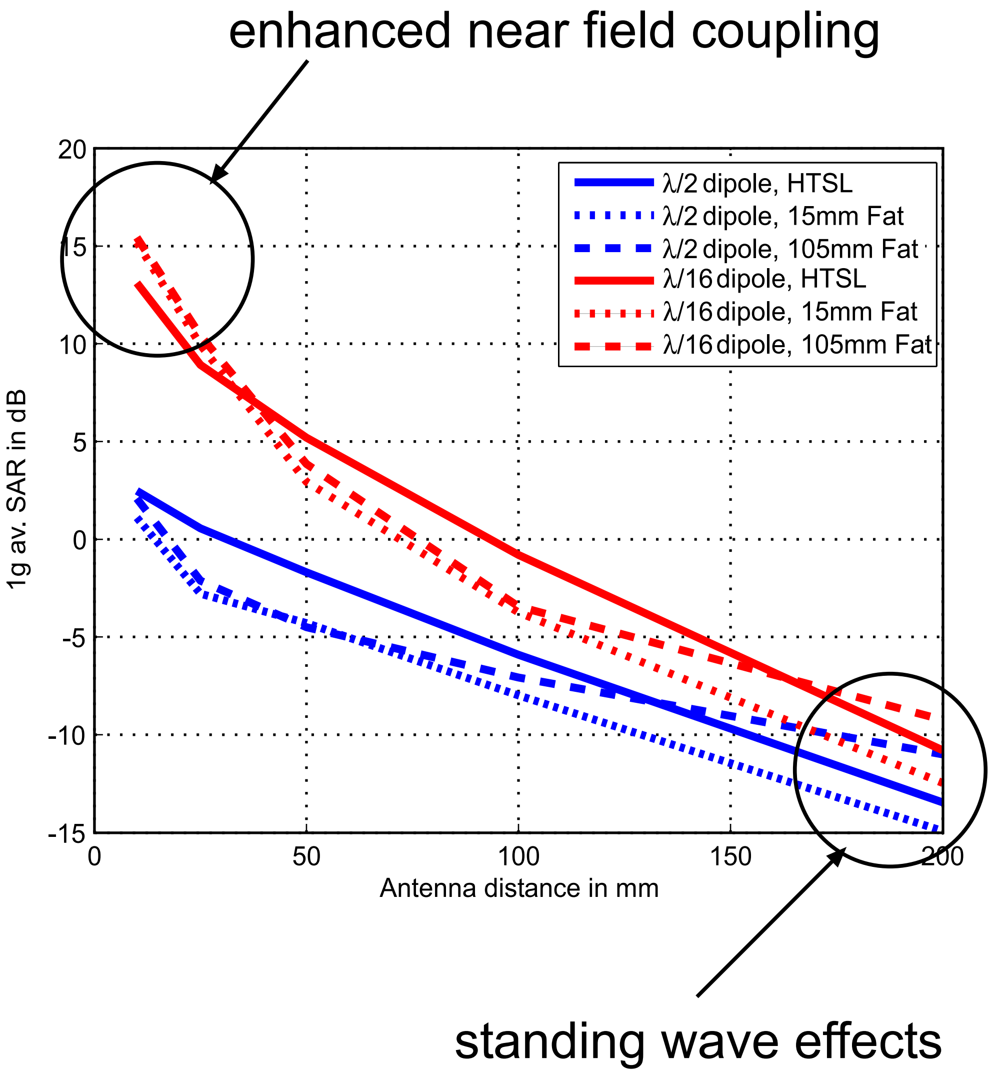
- 1g average SAR ratio for worst case tissue composition as function of the incident spectral wave component normalized to head tissue simulating liquid (HTSL)

SAR in Layered Tissue at 900MHz



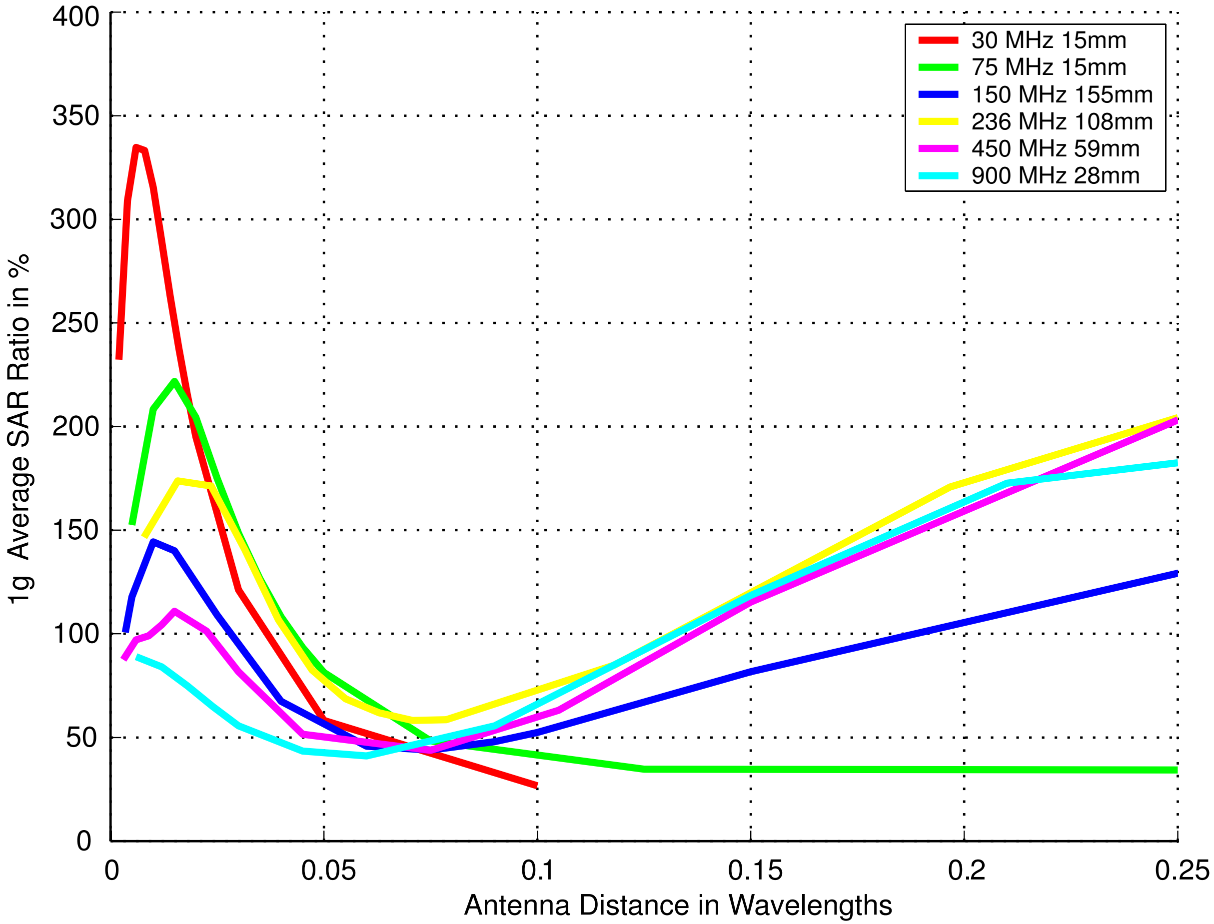
- 1g average SAR in layered and homogeneous tissue structures for a λ/2 and a λ/16 dipole antenna at 900MHz
- normalization to 1W radiated power (0dB = 1W/kg)
- higher SAR in head tissue simulating liquid (HTSL) at close distances
- SAR increase due to standing wave effects at an antenna distance of approximately λ/3

SAR in Layered Tissue at 236MHz



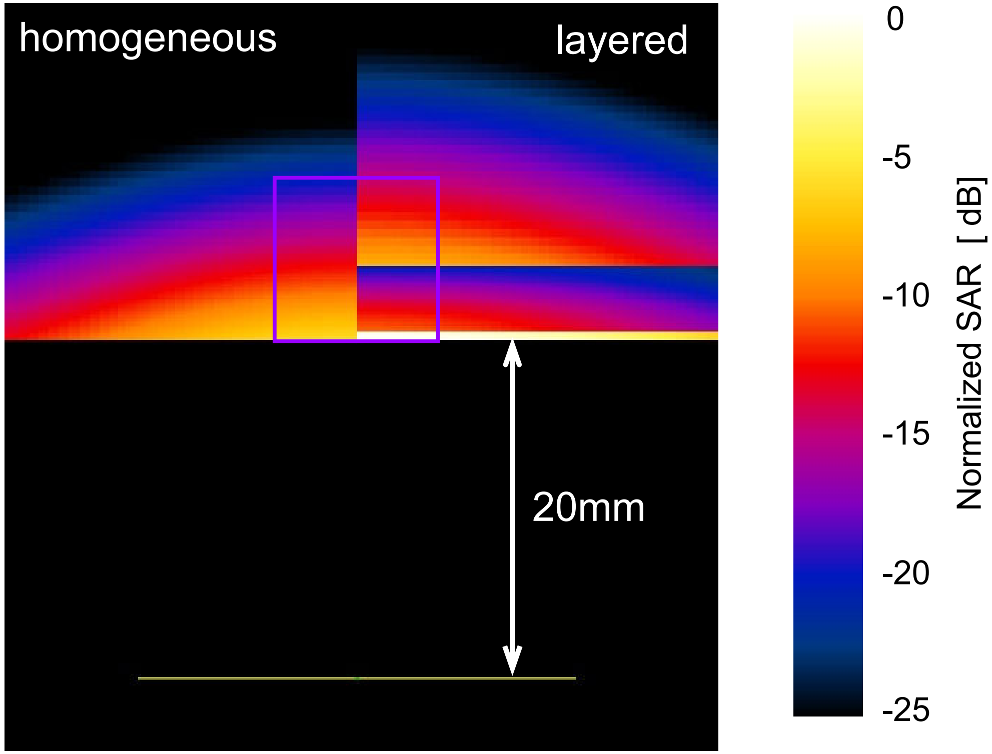
- 1g average SAR in layered and homogeneous tissue structures for a λ/2 and a λ/16 dipole antenna at 236MHz
- normalization to 1W radiated power (0dB = 1W/kg)
- SAR increase of approximately 2dB at close distances for the λ/16 dipole
- increase due to standing wave effects at an antenna distance of approximately λ/6

SAR Increase due to Near-Field Coupling of Short Antennas



- ratio of the 1g average SAR (layered vs. homogeneous) for the $\lambda/16$ dipole for frequencies from 30MHz to 900MHz tissues normalized to radiated and forward power as function of the antenna distance

SAR in a Layered Flat Phantom at 5800MHz



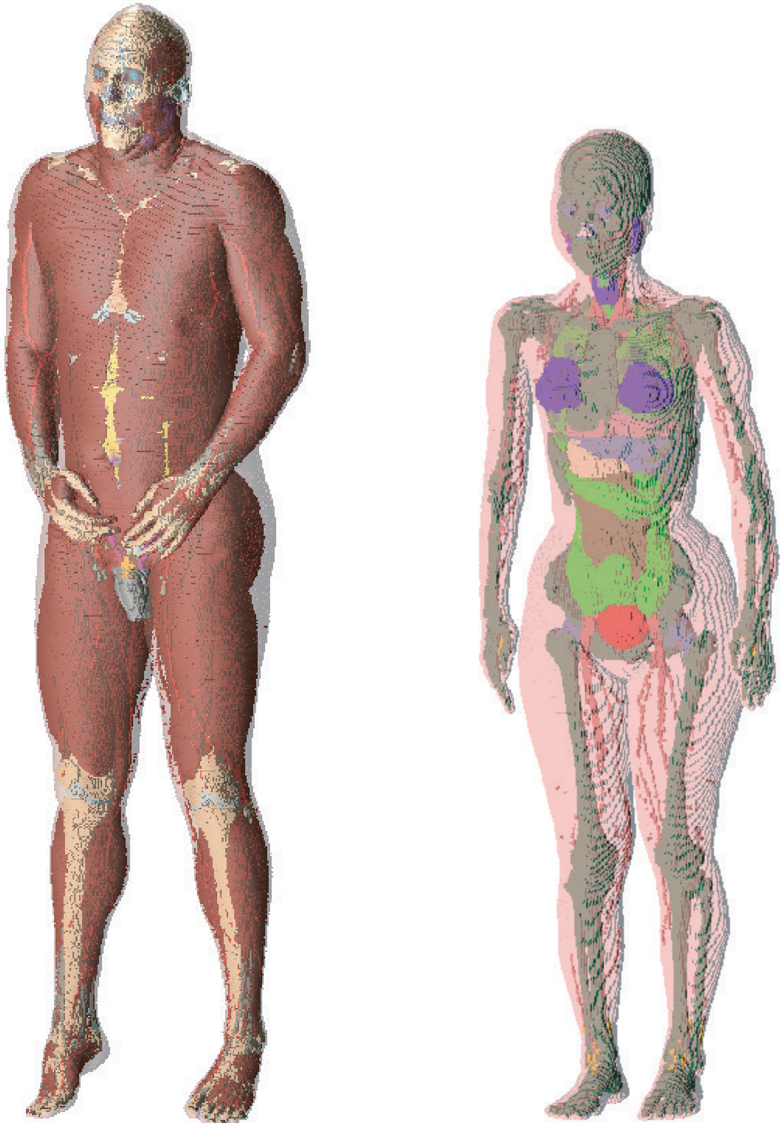
distance	1g SAR ratio
5mm	-0.9dB
10mm	+1.9dB
15mm	+2.4dB
20mm	+2.1dB

- λ/2-dipole under layered and homogeneous flat phantoms
- 0.5mm skin tissue, 3.8mm fat tissue
- far-field-like effects for distances of 10mm and above

Summary and Conclusions

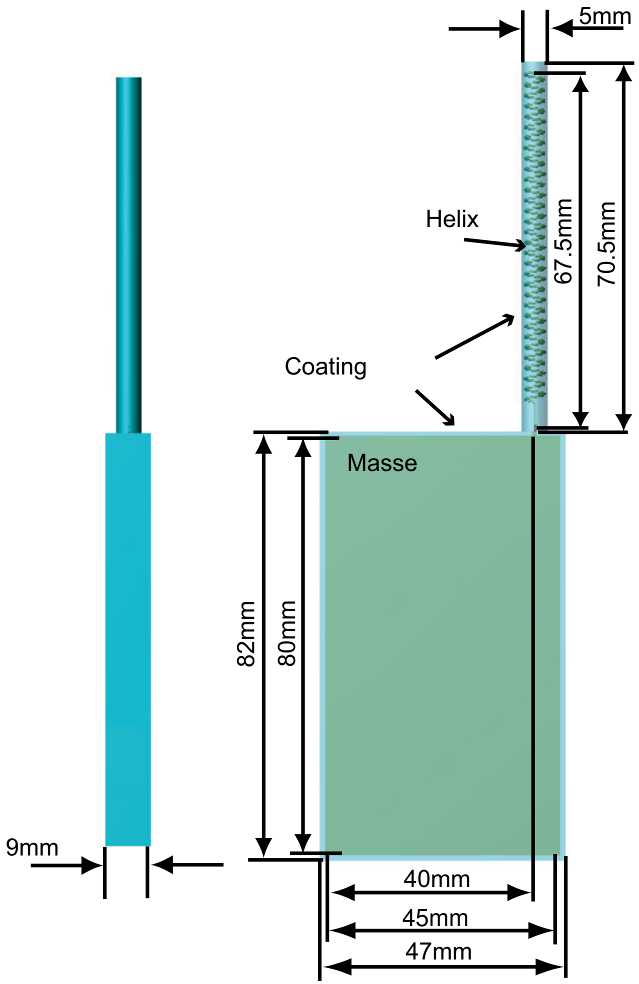
- Two different effects can lead to an increase of SAR by up to 5dB in layered anatomical tissue:
  - standing wave effects in the tissue sequence skin - fat - muscle for far field conditions and a thickness of the fat layer of approximately $\lambda/4$
  - enhanced E-field coupling for low frequencies due to low permittivity fat tissue for frequencies below 450MHz and short dipole antennas
- Tissue simulating liquids do not reproduce these effects and do not under all circumstances yield a conservative exposure estimate.
- Existing standards and procedures for the compliance testing of wireless devices operating at the ear are not affected by the presented findings.

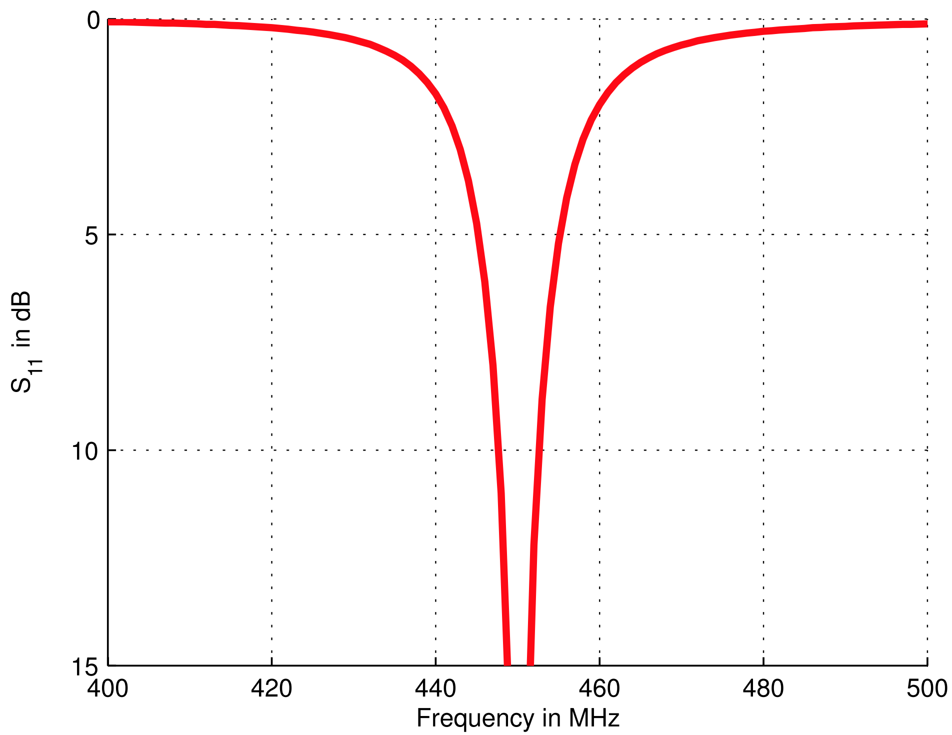
Anatomical Whole Body Models



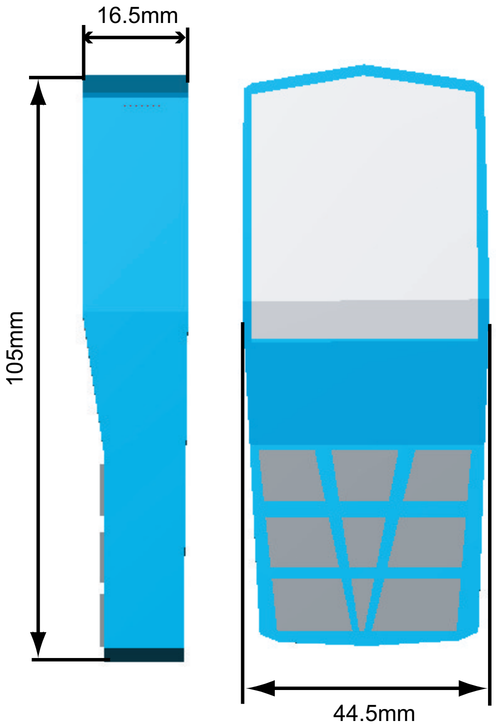
- adult male model based on cryo-section images
- 38 years old,1.80m, 90kg, 112 different tissue types
- SEMCAD compound format: 2.5D representation of slices, free positioning, rotating, etc., possible without loss of accuracy
- adult female model based on MR-images
- 22 years old, 1.60m, 53 kg, 51 different tissue types
- 2 x 2 x 2mm^3 voxel size
- models irradiated with $\lambda/2$-dipole antennas and generic models of real world devices

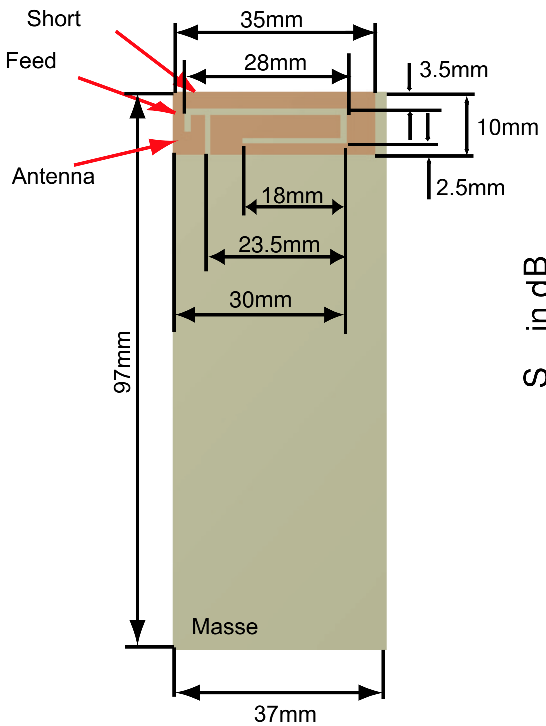
Generic Devices - Walkie Talkie for 450MHz

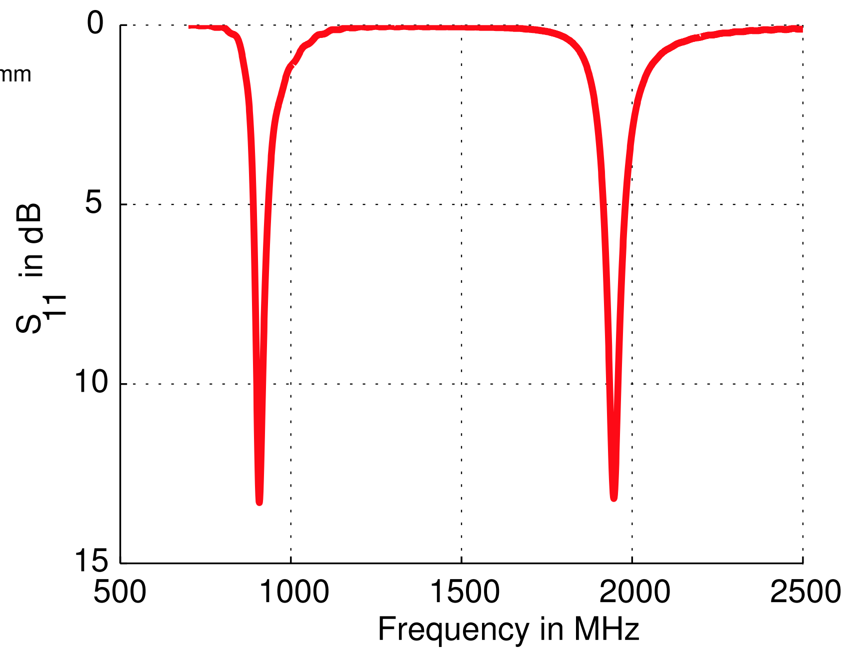




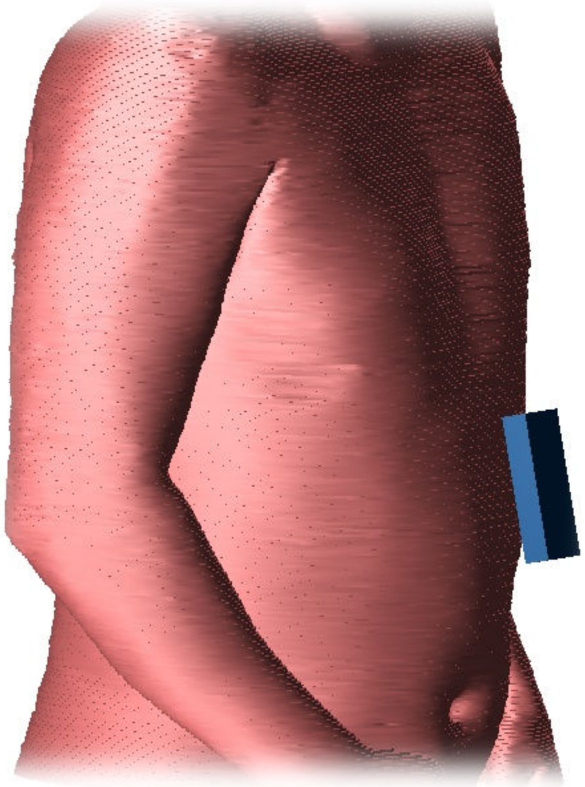
Generic Devices - Mobile Phone (900 and 1950MHz)

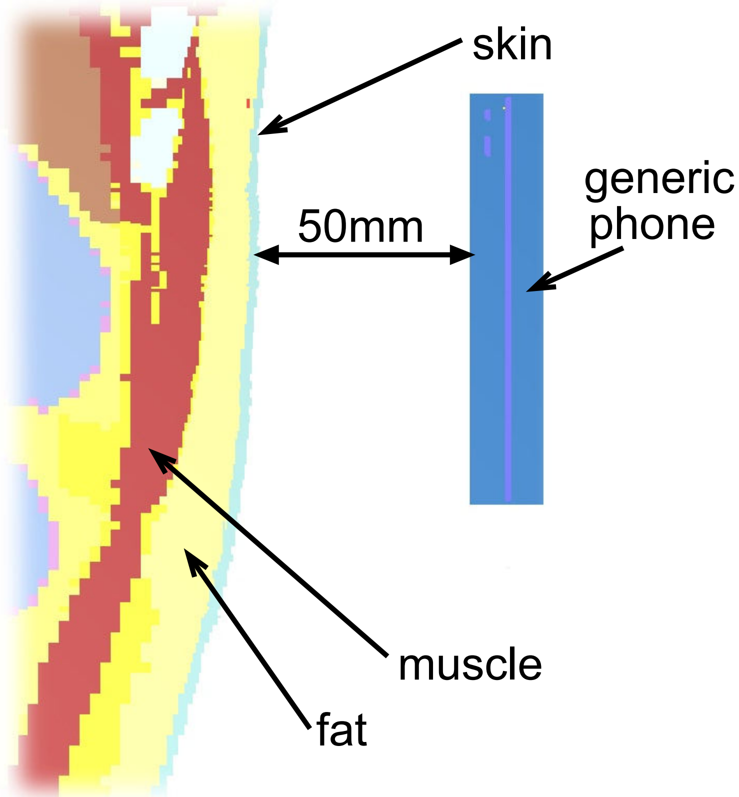






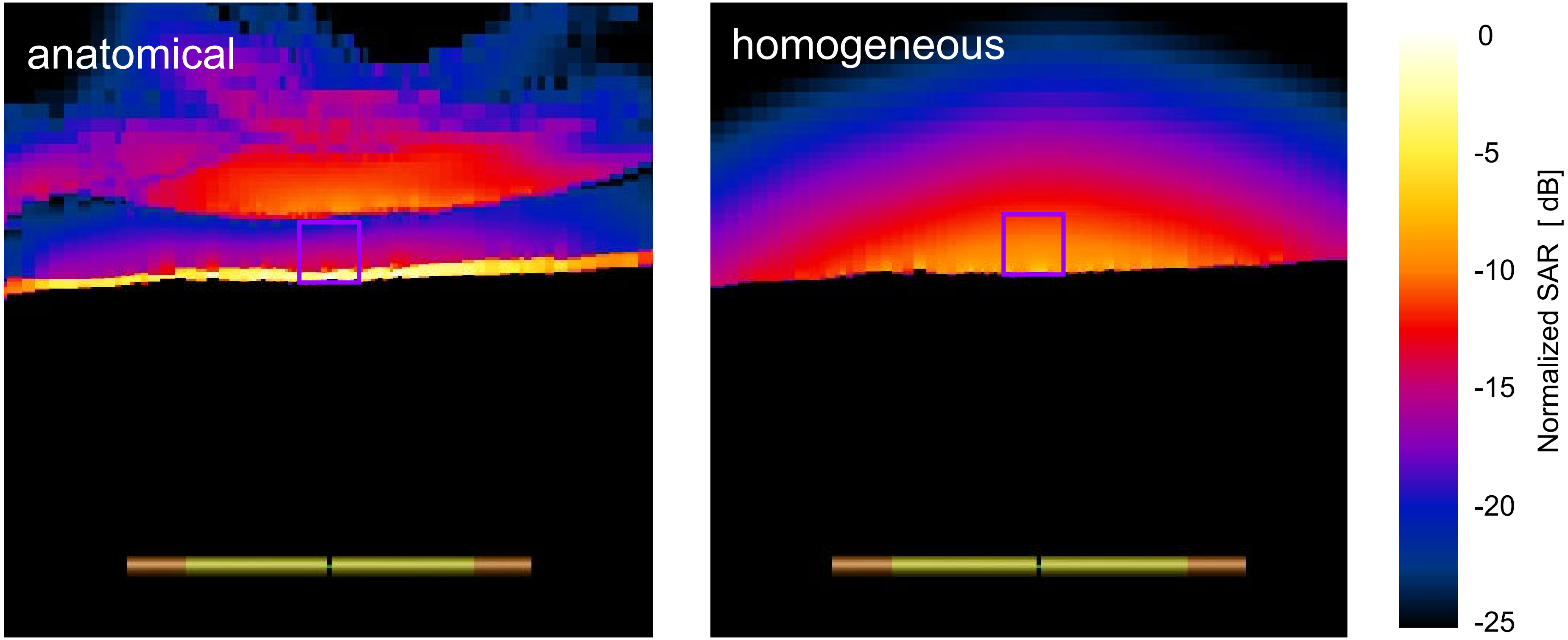
SAR in the Abdominal Region at 1800MHz





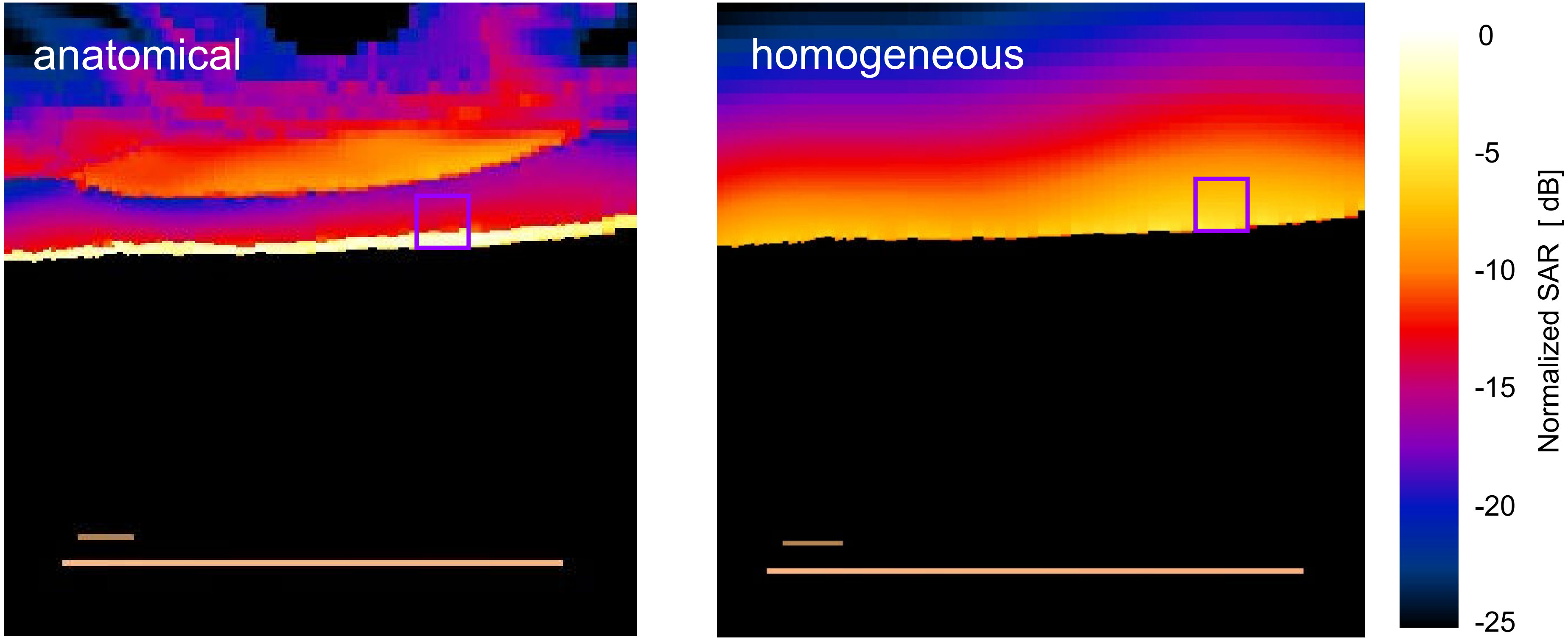
- $\lambda/2$ dipole and generic phone with integrated antenna at 50mm in front of abdomen
- tissues: skin (2mm - 3.5mm), fat (7mm - 15mm), muscle

SAR Distribution in the Abdomen for the λ/2-Dipole



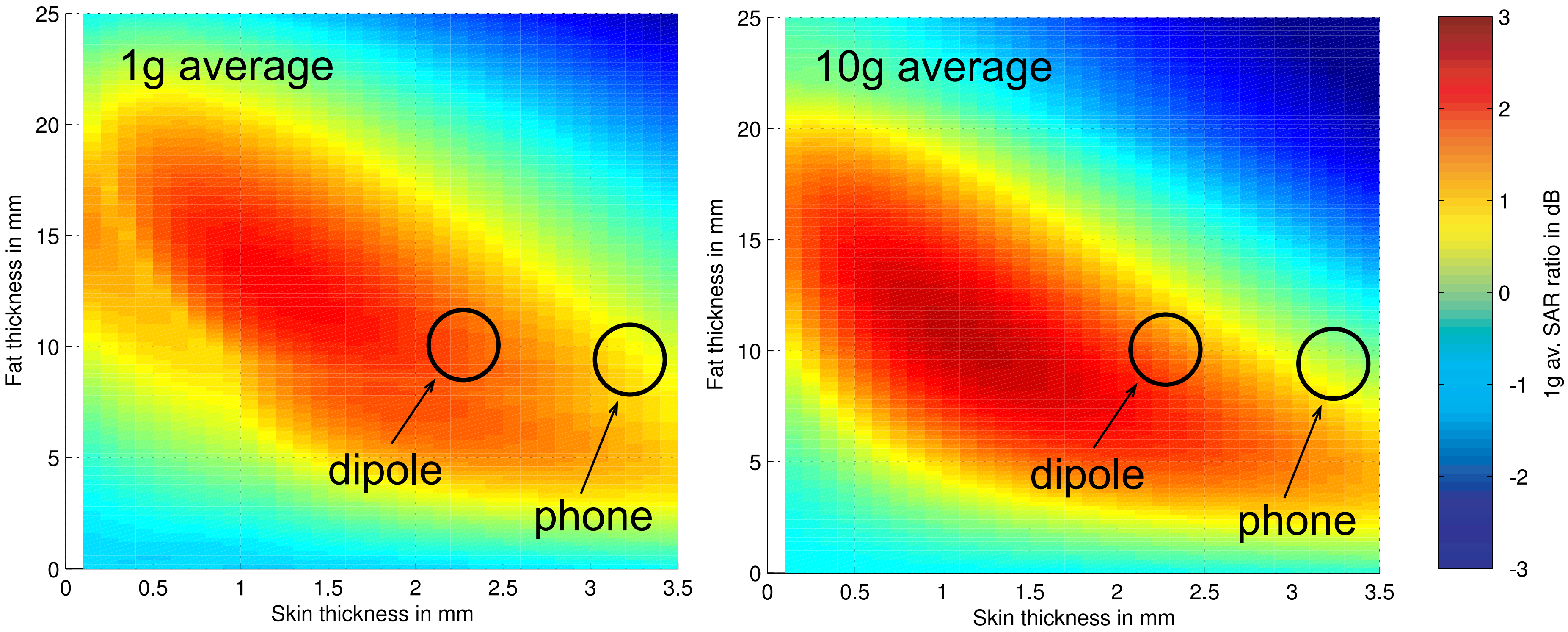
- SAR distribution at 1800MHz normalized to output power
- av. SAR ratio (anat. / hom.) of 1.6dB (1g) and 1.4dB (10g)
- skin thickness: 2.2mm, fat thickness: 10mm (approximate values)

SAR Distribution in the Abdomen for the Generic Phone



- SAR distribution at 1800 MHz normalized to output power
- av. SAR ratio (anat. / hom.) of 1.2dB (1g) and 0.6dB (10g)
- skin thickness: 3.3mm, fat thickness: 9mm (approximate values)

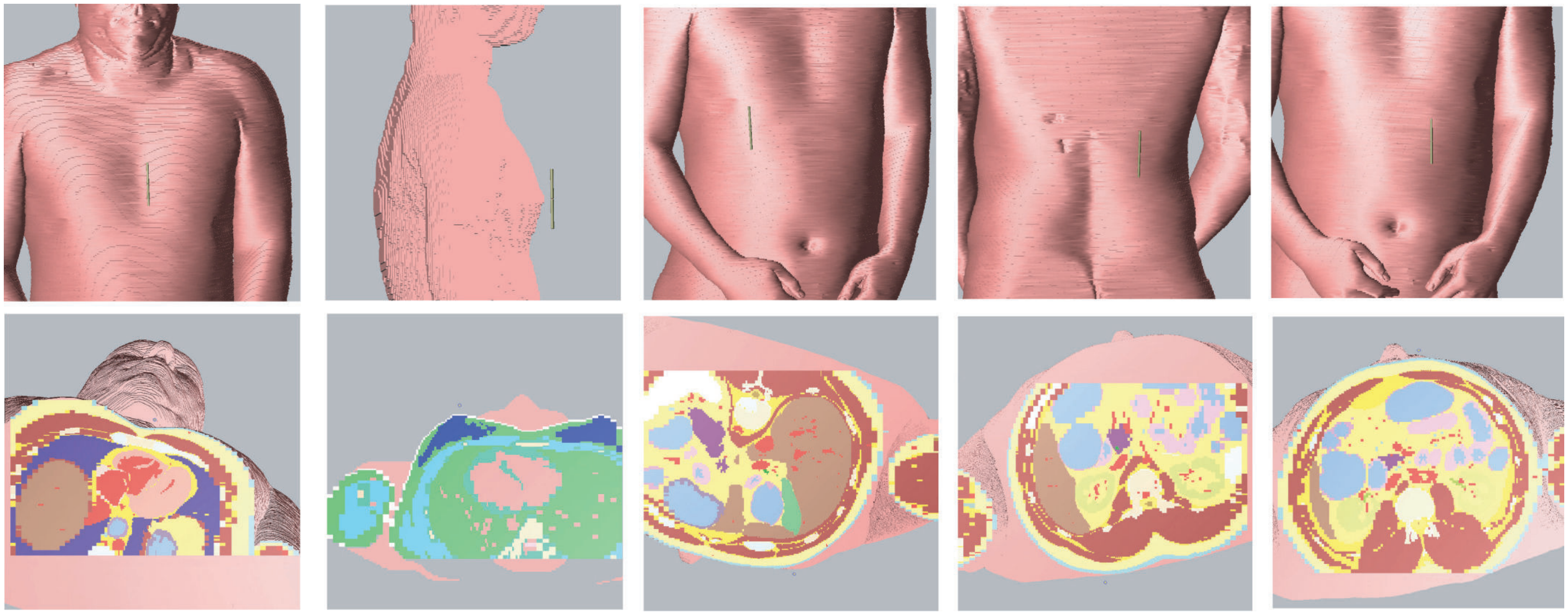
SAR for Far-Field-Like Exposure at 1800MHz



- av. SAR ratio (layered / hom.) for layered plane wave model
- good agreement with SAR increase observed in the VH model

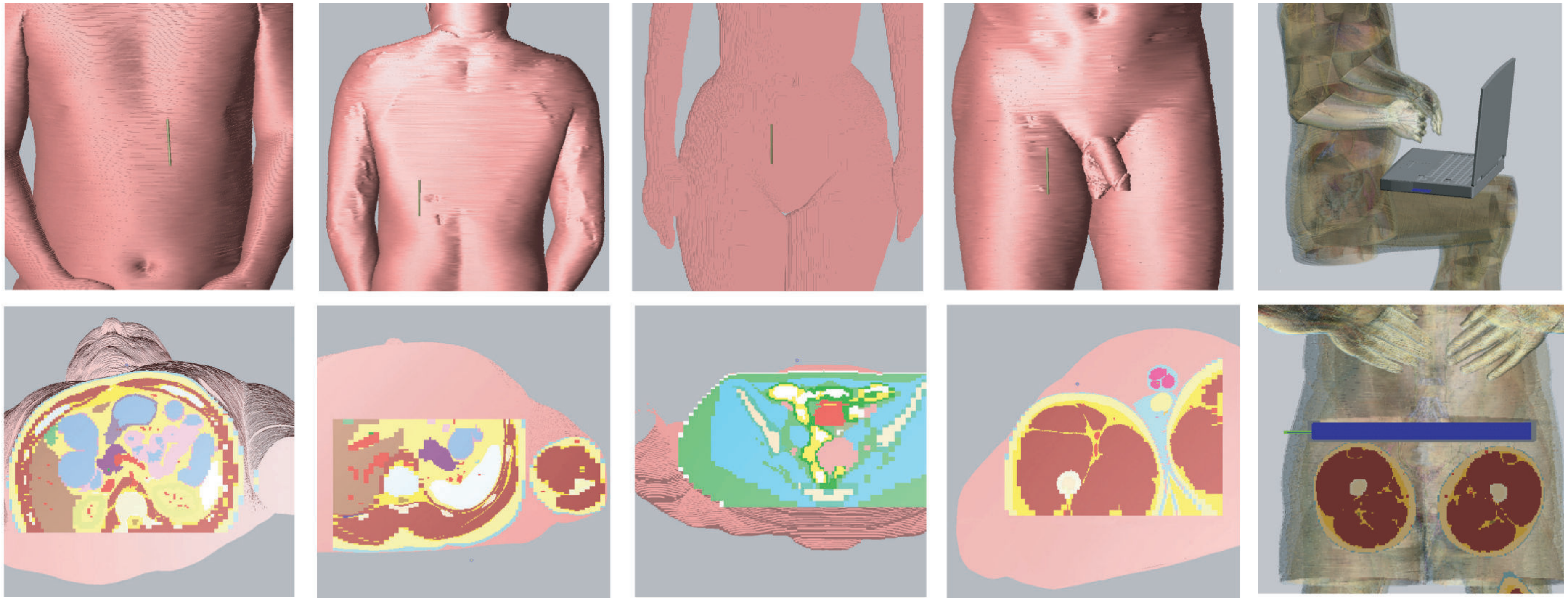
Exposed Positions I

Heart/Lung Breast Liver/Bile Kidney Intestine

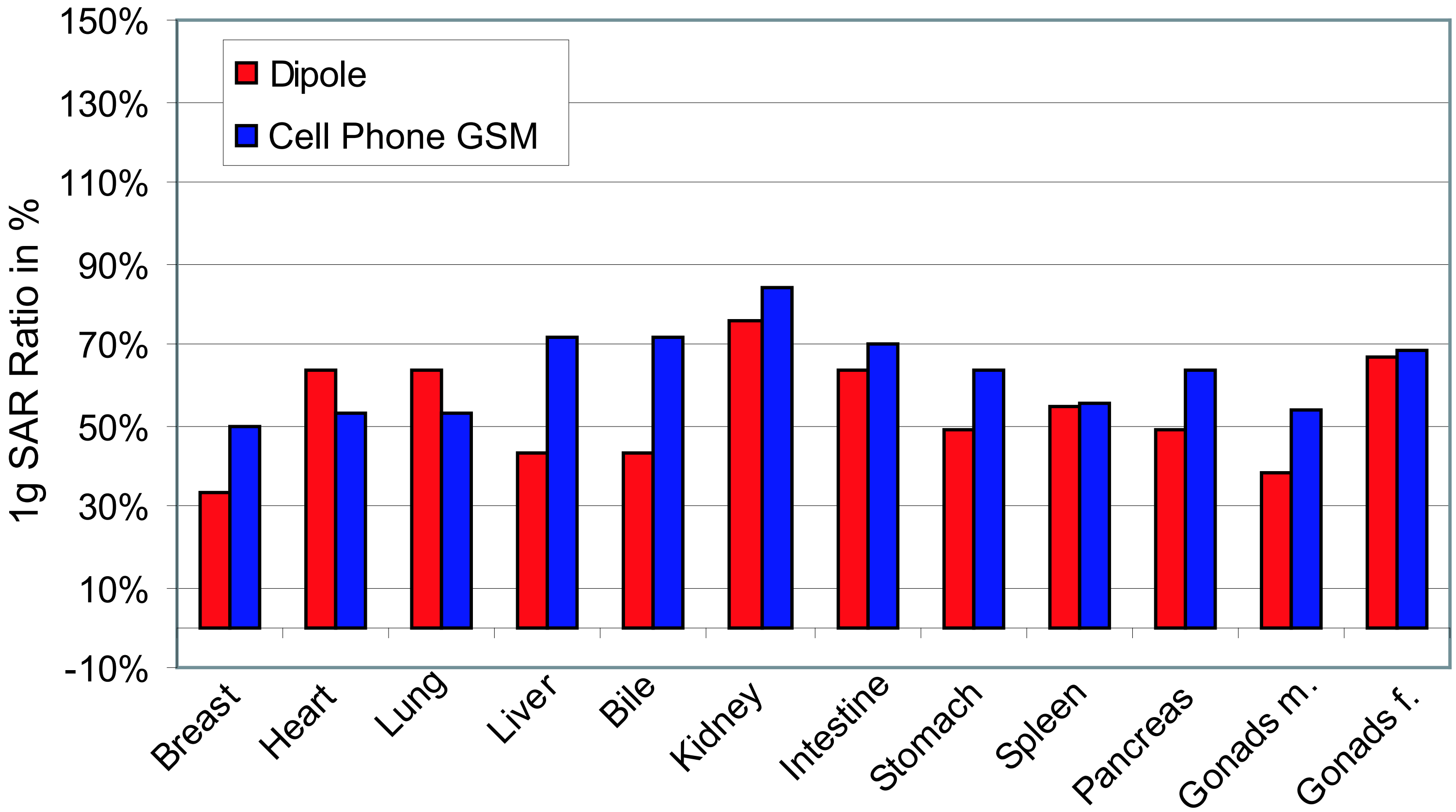


Exposed Positions II

Stomach/Pancreas Spleen Fem. Gonads Male Gonads Lap

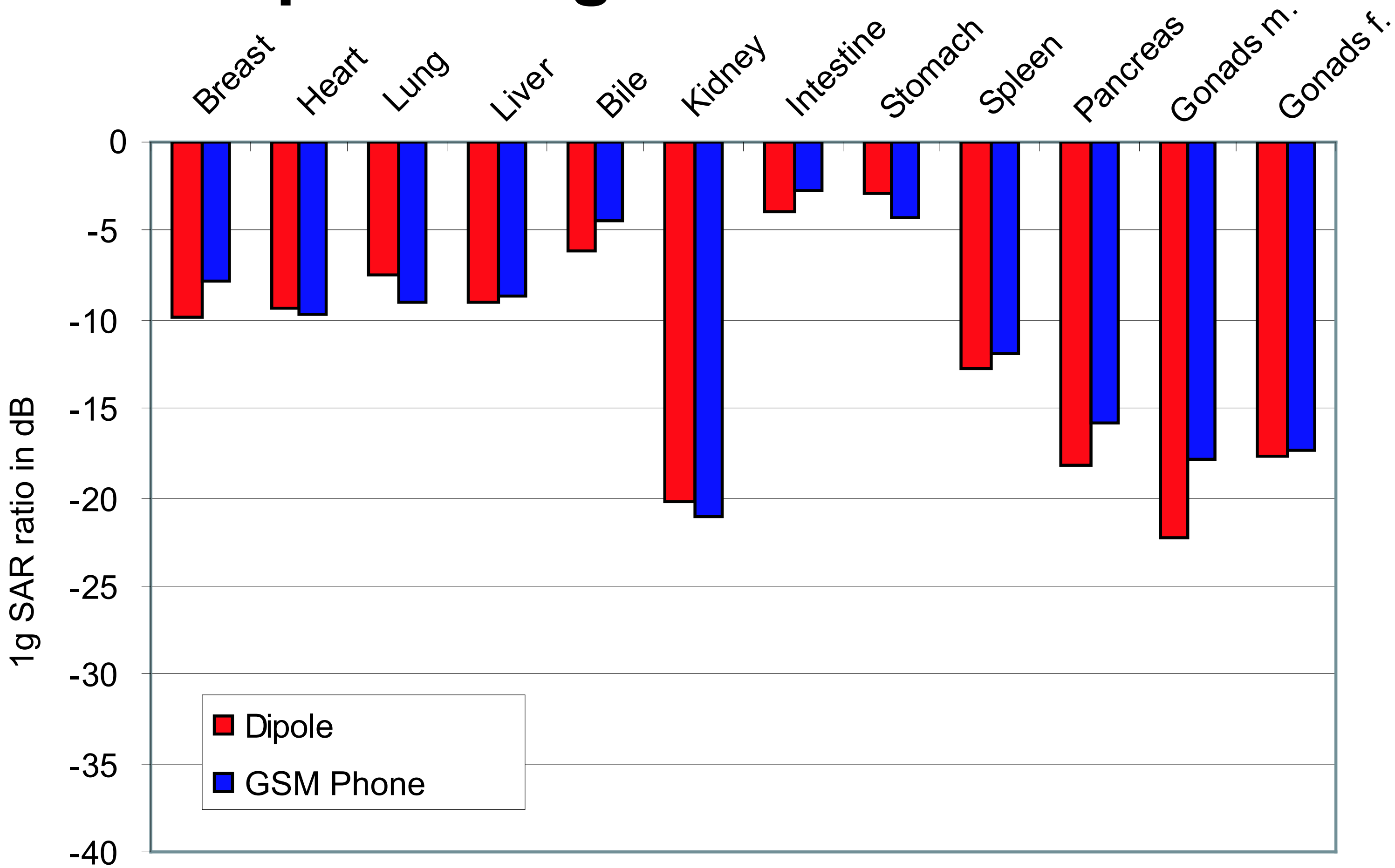


SAR Ratio Anatomical vs. Flat Phantom at 900MHz



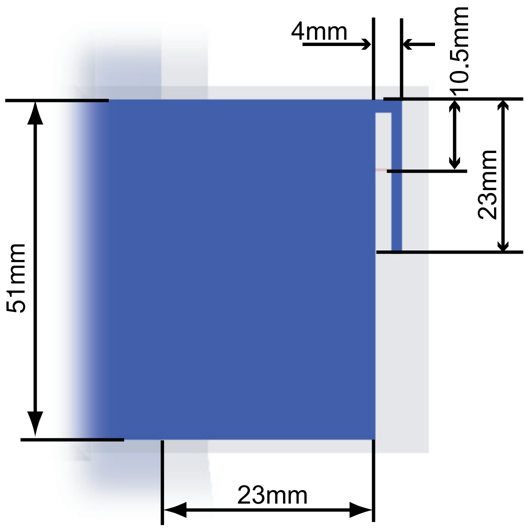
- generally conservative exposure estimation with flat phantom for both device types
- similar characteristics observed at 450MHz, 1950MHz and 5800MHz

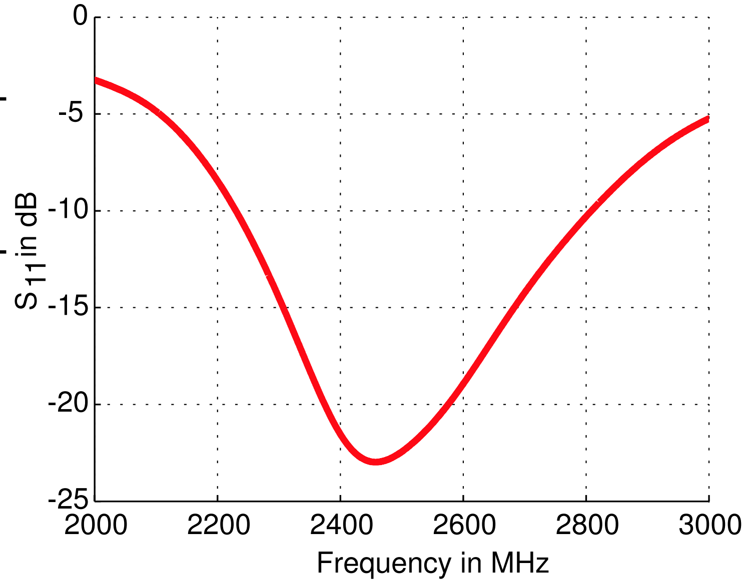
SAR Ratio Exposed Organ vs. Flat Phantom at 900MHz



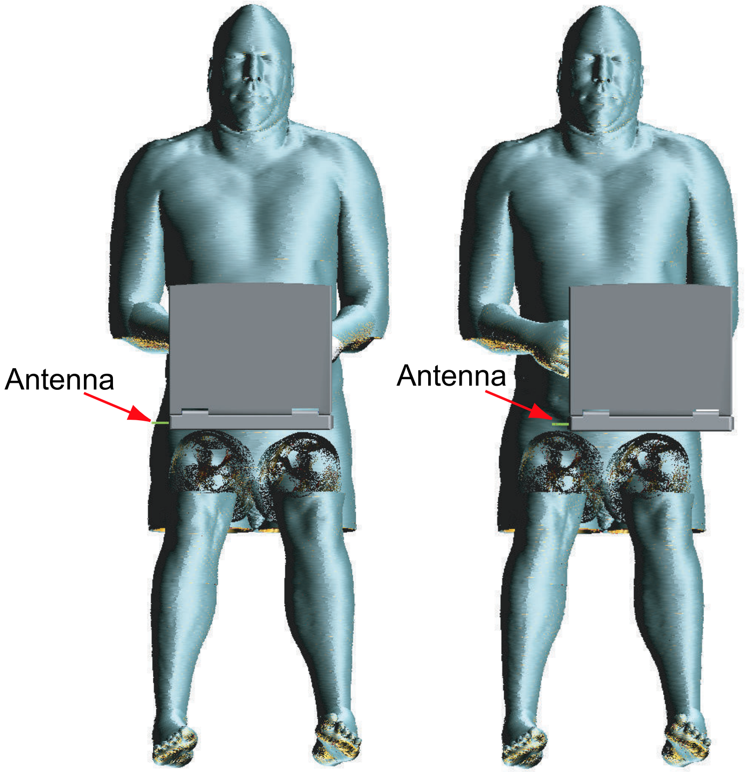
- significantly lower SAR in the inner organs due to attenuation of the body tissue
- exposure mainly dependent on position of the organ in the body

Generic Devices - Laptop with WLAN Card (2450MHz)





Exposure to the Antenna of a WLAN Card (2450MHz)



- sitting Visible Human model
- thighs and shanks separated and rotated, original body mass retained
- SAR in the thigh and in the gonads assessed for 2 different positions of the laptop
- SAR in the gonads more than 35dB below value in flat phantom

Phantom	Position	1g SAR [W/kg]	10g SAR [W/kg]
Flat Phantom		15,9	8,7
Visible Human	symmetrical (Pos. 1)	0,66	0,41
Visible Human	Antenna above thigh (Pos. 2)	15,6	9,9
Visible Human	Antenna above thigh (Pos. 2), distance increased by 2mm	13,7	9,2

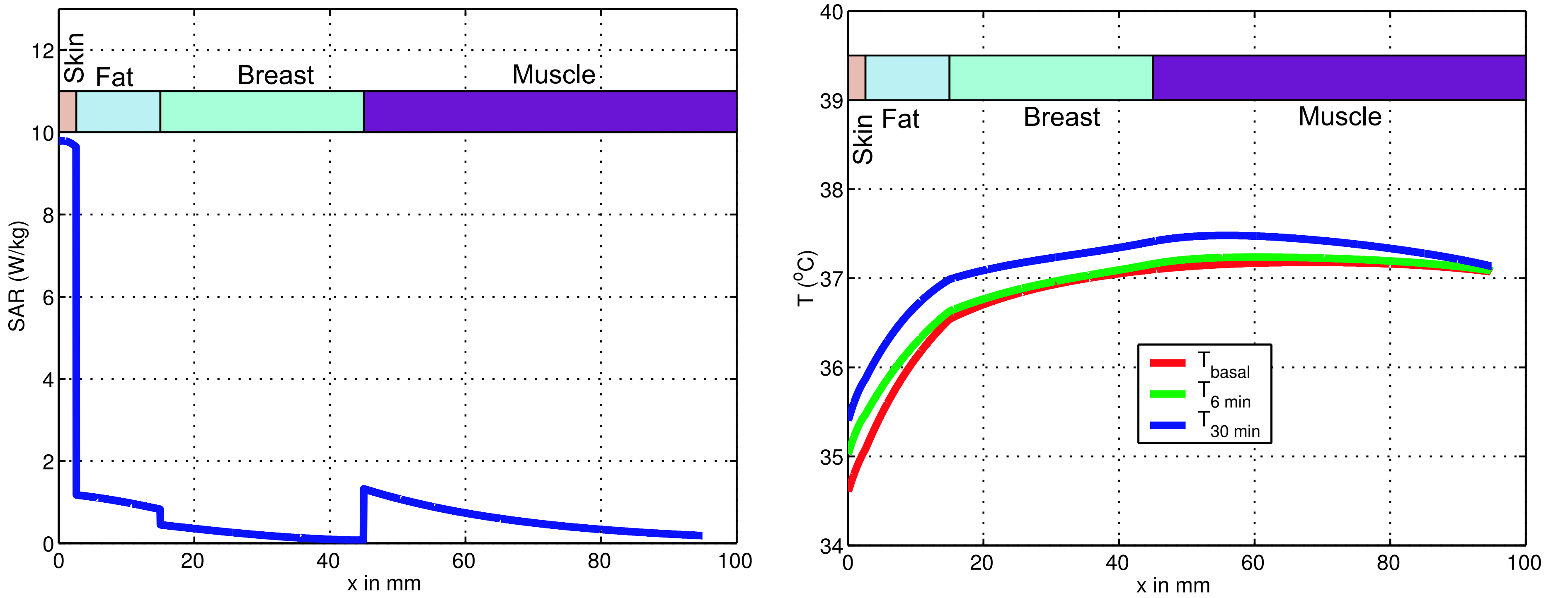
Summary - Exposure of the Body

- The exposure of the human body and its inner organs to radiation from dipole antennas and generic models of real world devices was assessed at various locations.
- The results confirm the findings of the theoretical analysis: For frequencies of 450MHz and above, the conservative assessment of the SAR is possible for near-field-like exposure. In the far-field, standing wave effects could be observed which are not reproduced by homogeneous phantoms.
- The evaluation of the exposure of the inner organs showed that the attenuation of the fields penetrating the body is the most relevant factor. Although the number of available anatomical models is too small to for a detailed uncertainty analysis, the findings of the theoretical evaluation show, that the maximum SAR occurs close to the body surface.

Thermal Worst-Case Analysis of a Generic Body Model

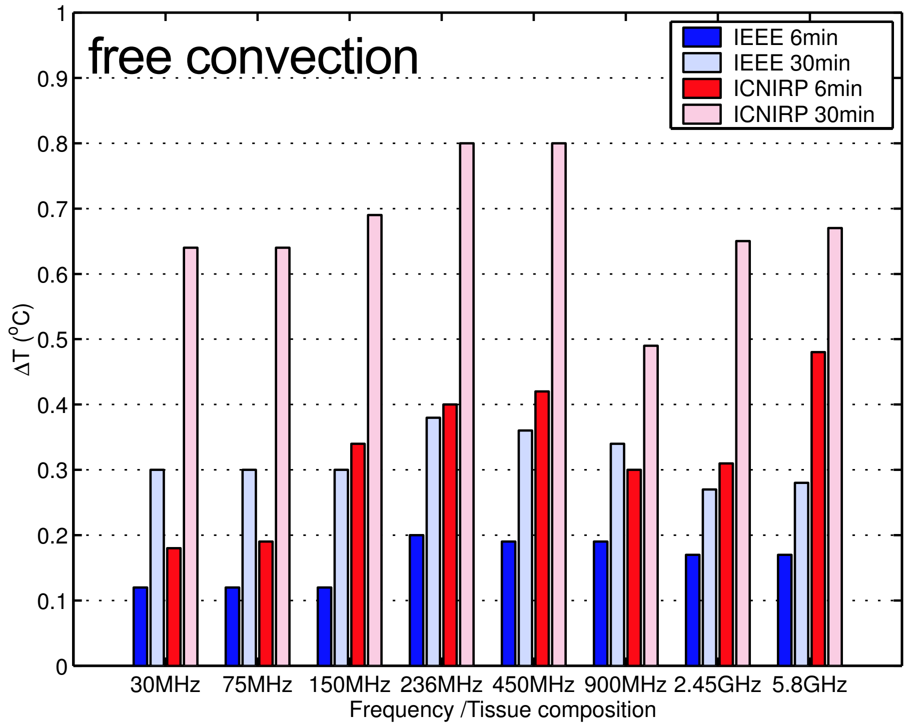
- The temperature increase in anatomical worst-case tissue compositions, as discussed previously, is assessed using the 1D Pennes equation.
- The incident power is scaled to a peak spatial-average SAR to the exposure limits of 1.6W/kg (1g) and 2.0W/kg (10g).
- The temperature increase is calculated for free convection and insulation (adiabatic conditions) after an exposure time of 6min and 30min (steady state).

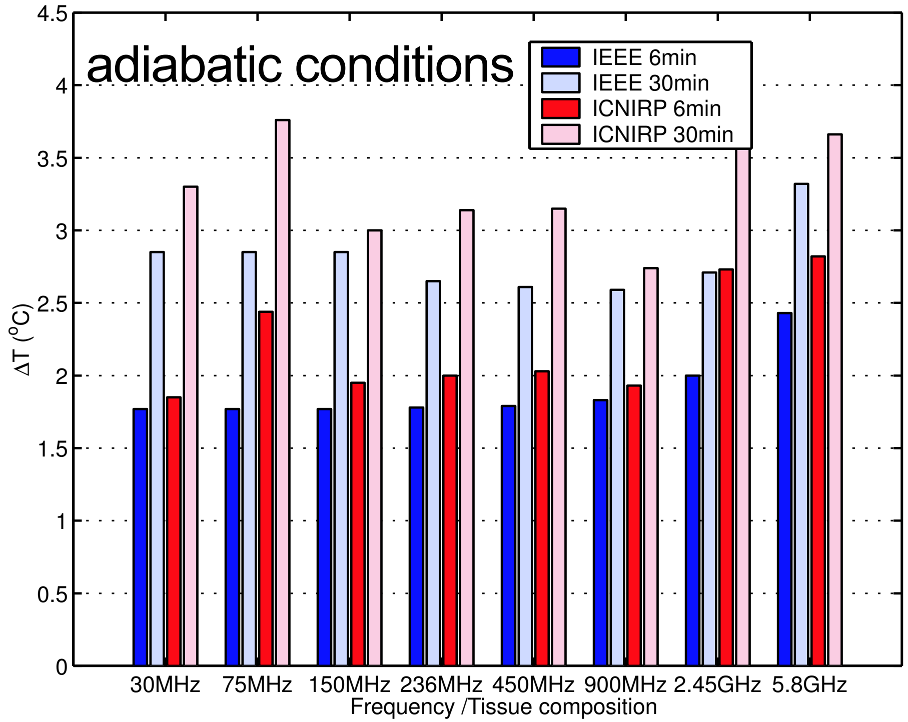
SAR and Temperature Distribution at 450MHz



- worst case tissue composition for 450MHz: frontal female thorax
- 6 min of exposure time is not sufficient for temperature convergence of inner tissues

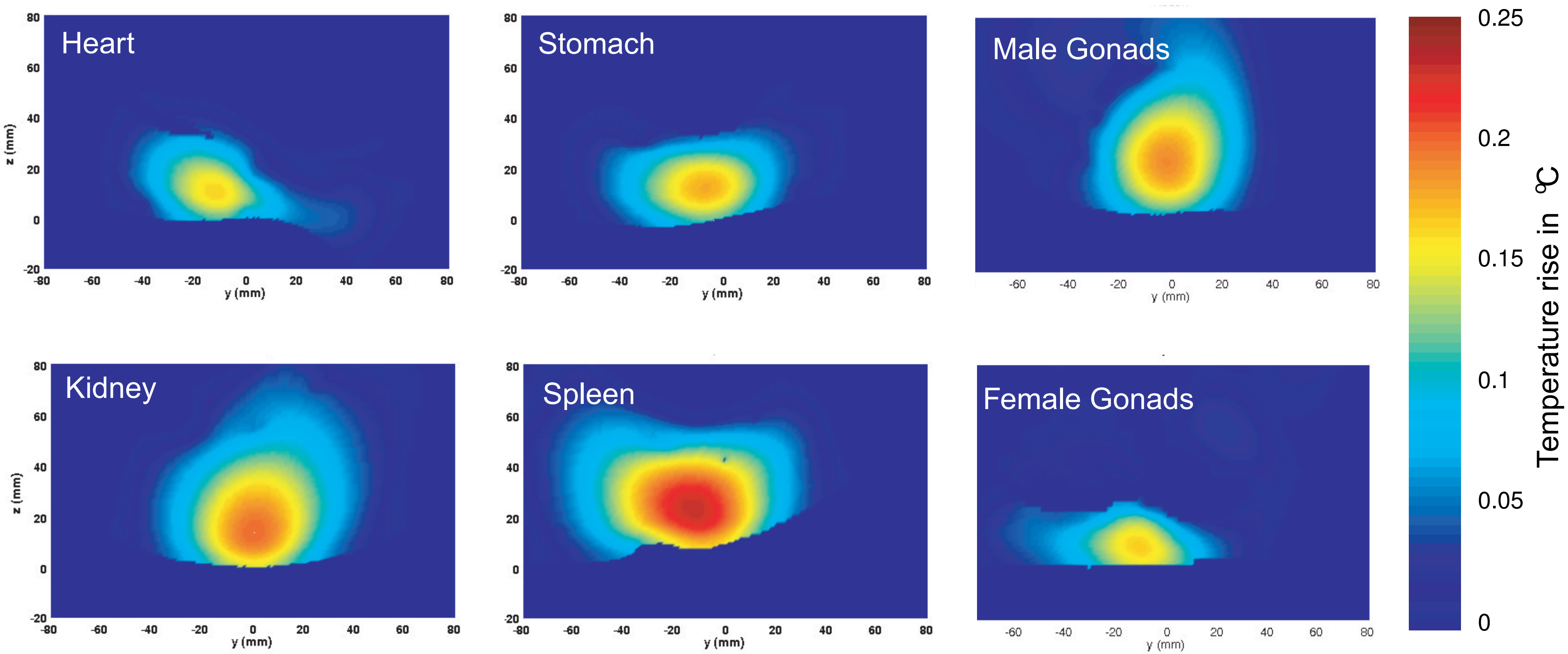
Worst Cases - Free Convection and Insulation





- steady state never reached after 6min exposure time
- 1g exposure limits more conservative than 10g limits
- thermoregulation mechanism (not considered) may counteract high temperature increase for adiabatic conditions

Temperature Increase in the Anatomical Models



- temperature increase due to irradiation with a λ/2-dipole at 450MHz at 10mm distance
- 10g Peak Spatial Average SAR of 2W/kg, free convection, 40min exposure time

Temperature Increase for Free Convection

Exposed Position	Whole Body ΔT [°C]	Whole Body Position	Organ ΔT [°C]	Organ Position	ΔT [°C]	Position
Heart	0,16	Muscle, 12 mm below the surface	0,04	Pericardium		
Stomach Pancreas	0,18	Muscle 13 mm below the surface	0,08	Stomach	$< 0,01$	Pancreas
Spleen	0,23	Muscle 15 mm below the surface	0,03	Spleen		
Kidney	0,20	Connective Tissue 14 mm below the surf.	$< 0,01$	Cortex of the Kidney		
Male Gonads	0.21	Muscle, 21mm below the surface	$< 0,01$	Penis	$< 0,01$	Testicles
Female Gonads	0.17	SAT, 7 mm below the surface	0,016	Ovary	0.037	Uterus

Temperature Increase for Adiabatic Conditions

Exposed Position	Whole Body		Organ			
	ΔT [°C]	Position	ΔT [°C]	Position	ΔT [°C]	Position
Heart	0,23	Muscle, 8 mm below the surface	0,05	Pericardium		
Stomach Pancreas	0,26	Muscle 10 mm below the surface	0,11	Stomach	< 0, 01	Pancreas
Spleen	0,31	Connective Tissue 13mm below the surf.	0,04	Spleen		
Kidney	0,28	Connective Tissue 14 mm below the surf.	< 0, 01	Cortex of the Kidney		
Male Gonads	0.26	Muscle, 22mm below the surface	< 0, 01	Penis	< 0, 01	Testicles
Female Gonads	0.17	Skin, 2 mm below the surface	0,02	Ovary	0.04	Uterus

Summary - Thermal Exposure

- For worst-case tissue composition and exposure conditions, the 1g averaging limit result in a lower temperature rise than the 10g averaging limit.
- The obstruction of heat transfer from the tissue to the environment leads to a temperature rise of more than 3.5ºC (maximum in the skin), irrespective of the frequency. This temperature rise is up to 5 times larger than that observed for free convection.
- In the anatomical model, the temperature increase is lower. A maximum of 0.23ºC occurred for free convection and 0.31ºC for adiabatic conditions. The maximum increase always occurs close to the surface. A significant increase of the temperature of the inner organs was not observed.

Conclusions

- Two effects in anatomical tissue can lead to an increase of the SAR of the body in comparison to tissue simulating liquids:
  - increased penetration of reactive near-field components at frequencies below 450MHz for electrically small antennas
  - standing wave effects for far-field-like exposure
- Under these conditions, the SAR averaged in a cubical volume can easily exceed the value for tissue simulating liquid by more than 3dB (5.5dB have been observed). If the averaging volume consists of contiguous tissue (e. g., skin layer with high local SAR), the liquids can underestimate the SAR by 8dB.
- No particularly high exposure could be observed for the deeper body tissues and inner organs. The relevant factor for their exposure is their distance from the surface of the body.
- Existing standards for the compliance testing of wireless devices operated at the head of the user are not concerned by the findings of this study.

Conclusions

- However, the observed effects must be considered for the standards for body mounted devices, e. g., by introducing a frequency and distance dependent correction factor. A suggestion has already been proposed to the respective working groups of IEC TC 106 and ICES TC34 SC2.
- The induced temperature increase due to exposure with a 10g SAR of 2W/kg can reach up to 3.5°C under worst-case conditions (1D-Modell, adiabatic boundary conditions, maximum Absorption, no thermal regulation). An increase of 0.8°C was observed for free convection.
- In the anatomical model, a significantly lower increase has been observed (0.23°C for free convection, 0.31°C for adiabatic conditions). The maximum temperature increase occurs close to the body surface. The increase of the temperature of the inner organs is negligible if the SAR is within the exposure limits.