Fast SAR - Concept, Implementation, Results of Validation and Verification

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Motivation & Challenges

- Wireless became pervasive
  - ~0.7 billion devices 2000 (voice)
  - ~5 billion devices today (data, voice)
  - ~80 billion devices by 2020 (lifestyle, biomedical/healthcare, data, voice)

- Challenges
  - Antennas integrated into smaller and smaller devices occupying minimal volume
  - Minimal power consumption
  - Directly connected to world and to other body-mounted and implanted devices
  - Integrated wireless power transfer
  - Integrated intelligent sensors (some of them EM based)

- Technical constraints
  - SAR regulations
  - Over-the-Air (OTA) and Inside-the-Body (ITB) performance
  - EMC/EMI hostile environment

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Content

- Challenges
- Concept and Basis of SAR Standards
- Implementation, Uncertainty, and Validation of Gold Standard SAR Systems
- Implementation, Uncertainty, and Validation of Vector Array Systems
- Future of SAR Evaluations
- Conclusions
Declaration of Financial Interests or Relationships

- founder and shareholder of NFT
- founder & president of the board of ZMT
- founder & president of the board of SPEAG
- IT’IS performed research for various wireless, medical device companies, collaborations with regulators, e.g., FCC, FDA, NIST, NICT, NIM, TMC, RRA, etc.
Challenges
Challenges: Hand-Held Devices
Challenges: Body-Mounted Antennas
Challenges: Rapidly Changing Link Environment
Challenges: Tissue-Embedded Antennas (all side exposures)

- electrically small antennas
- symmetrical design desirable
- close proximity to the head and pinna
- head/pinna very variable between people
- tolerant to environment
Challenges: Implanted Antennas (Wireless Endoscopy)
Challenges: Wireless Power Transfer (strong gradient, interference w/ implants)
Concept and Basis of SAR Standards

- concept behind SAR standards
- basis of SAR standards
- the gold standard
Basis of SAR Standard: Absorption Mechanism

- Kuster and Balzano, Trans. IEEE on VT, 1992
- Kuster, BEMS, 2015
Concept Behind the SAR Standards

**issue**
- hand-held and body-worn devices expose locally
- safety limits expressed in SAR averaged over any 1g or 10g of tissue (shape cube)
- exposure is close to these limits

**objectives**
- scientifically sound, reliable, and reproducible compliance evaluation with minimal uncertainty
- minimal overestimation
- objective (devices that cause low exposures result in low exposures in the test and vice versa)
- minimal test effort

**implementation**
- phantom shape and tissue simulation liquid to warranty conservative assessment (95th percentile)
- well-defined device positions and operational conditions
- minimally disturbing measurement instrumentation calibrated to ISO17025
- smallest possible uncertainty, rigorous uncertainty assessment
- thorough and comprehensive validation
Basis of SAR Standard: Absorption Mechanism ($d < 200$ mm)

- $\text{SAR} = RF_{\text{losses}} \sim j^2/d^2$ or $\sim q^2$ (only very close to the surface)
- exposure is not directly related to the radiated power!
- strongly design dependent

\[
\text{SAR} = \frac{\sigma}{\rho} \frac{\mu \omega}{\rho \sqrt{\sigma^2 + \epsilon^2 \omega^2}} (1 + c_{\text{corr}} \gamma_{\text{pw}})^2 H_{\text{tinc}}^2
\]

in which $\gamma_{\text{pw}}$ is the plane-wave reflection coefficient for the $H_t$ field

\[
\gamma_{\text{pw}} = \frac{2 |\sqrt{\epsilon'}|}{|\sqrt{\epsilon'} + \sqrt{\epsilon_0}|} - 1
\]

$H^2 \sim j^2/d^2$
Inductive vs. Capacitive Coupling

- inductive coupling: propagating
- capacitive coupling: significant content of evanescent waves
- evanescent waves decay highly over-exponentially
SAR (dB) of Dipole: 1800 MHz @ $d = 10 \ mm$
SAR (dB) of Dipole: 1800 MHz @ $d = 2$ mm
Basis of SAR Standards: Instrumentation Requirements

- **probe technology** (Bassen et al., 79, Schmid 94, Pokovic 99)
- **calibration technology** (Pokovic 99, Kühn 09, Kühn 11)
- **phantoms** - shape, tissue simulating media
  - dependence on **inner anatomy** (Hombach 96, Meier 96, Drossos 01, Christ 08)
  - dependence on **outer anatomy** (Meier 96, Schoenborn 98, Christ 05, Kuehn 09)
  - dependence on **age** (Gandhi 93, Schoenborn 98, Christ 05, Kuehn 09)
  - dependence of **ear modeling** on the psSAR (Burkhardt 00, Christ 09)
  - enhancements due to **metallic implants** (Meier 96, Kyriakou 11)
  - dependence of the **hand on head exposure** (Meier 95, Li, 11, Li 12)
  - procedure for **body-worn** devices (Christ et al. 06, Kühn et al. 09)

- **assessment procedures**
  - IEEE1528, IEC62209-1, IEC 62209-2
  - FCC KDB865664
Basis of SAR Standards: Uncertainty and Validation

- **uncertainty** assessment procedures and budget (Pokovic, 99)
- **verification** (IEEE1528, IEC62209, FCC KDB865664)
- **validation** of procedures
  - validation of SAM head - *in silico* (Beard 05, Christ 06)
  - validation of instrumentation - *in silico* compared to experimental (Meier 94, Burkhardt 98, Chavannes 98, 06, Gosselin 12, etc.)
  - inter-lab comparison of calibration with NIST (USA), NPL (UK), NICT (Japan), STUK (Finland), NIM (China), TMC/CTTL (China)
- **inter-lab repeatability**
  - inter-lab comparison with test labs: > 50 labs
Basis of SAR Standards: Non-Disturbed Phantom System

- replacement of the 7 billion human anatomies and various handheld positions with
  - one homogeneous phantom (conservative shape and media)
  - two device positions (cheek and 15° tilt)

- standard objective
  - assessment of the non-disturbed psSAR 1g and 10g
Basis of SAR Standards: Non-Disturbed Phantom System

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Basis of SAR Standards: Latest Issue

- Lee at al. in TEMC, pp 1281-84, Vol. 57 2015 points to an underestimation of SAR for bottom mounted antenna in bar-type phone model
- This is obvious and a function of the head shape
- Often devices are optimized to meet the standard
- Realistic test conditions are important
Implementation of Single Probe Systems
Requirements of IEEE 1528, IEC 62209-1/2

- detailed description of phantom (shell & media)
- minimal requirements of probe (size, sensitivity, isotropy)
- detailed definition of scanning requirements
- well-defined description of uncertainty assessment
- well-defined description of system check or verification
- well-defined validation procedure
Basis of SAR Standards: Distortion by Single Probe Systems

- distortion: minimized by the standard requirement (one probe, small tip, and normal to surface)
- psSAR: measured at sufficient points
- uncertainty: independent of location and DUT
Dosimetric Probes

- best amplitude accuracy
- optimized isotropy
- minimized cross-section
- primary calibration (ISO17025)

Size: 2.5mm
Spherical isotropy: <0.3dB
Dynamic range: <1mW/kg -> 100W/kg
Dynamic range: 10 MHz - 6 GHz
Exposure Adaptive Grids

area scan
determine maximums (within x dB)
measurement of psSAR1g and 10g in volume scans and with sufficient points
Concept of Scanning and Post Processing

- area scan to find maxima
- volume scans to assess the 1g and 10g
- only measured SAR values are used

exception
  - fast SAR for decision making only
Concept of Uncertainty Assessment

- based on GUM
- divided into uncorrelated components
- all components accessible by anybody
- uncertainty evaluation described in detail
- volume scan to assess the 1g and 10g
- only measured SAR values are used

- exception
  - fast SAR for decision making only
Single Probe System Verification

- dipole sources (CLA for $f < 300$ MHz)
- system check/verification
  - correct probe
  - correct liquid
  - correct software settings
- at flat section only
  - procedure defined in detail and optimized
  - scanning everywhere the same
  - field distortion/interference everywhere the same
Single Probe Validation

- dipole sources
- system validation
  - dynamic range
  - isotropy
  - modulation
  - spatial resolution
- at flat phantom only
  - procedure defined in detail and optimized
  - scanning everywhere the same
  - field distortion/interference everywhere the same
Standards (SAR, etc.)

- IEC 62209
- FCC KDB 865664 ...
- IEEE 1528
- ANSI-C63.19
- IEC 62232
- EN 50385
- EN 50383:2010
- EU Directive RED 2014/53/EU
- AS/NZS 2772-2:2011
- ARIB STD T-56 3.1
- IS16133
- DT-IFT-007-2015
- etc.

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Single Probe Systems ARE The Gold Standard

- primary calibration ISO17025 calibration of probe
- probe does not distort the field to be measured
- same accuracy everywhere (\(\geq 1\) mm from surface)
- scanning adaptive (corresponds to more than 300’000 probe location)
- measures the 1g and 10g psSAR w/o approximation
- uncertainty budget and procedure defined in detail
- can be independently validated (all components accessible by the user)
  - probe
  - data acquisition
  - phantom shell
  - tissue simulating liquid

- most accurate system possible
Other Advantages of Single Probe System

- < 4 MHz to > 6 GHz
- adaptive to any phantom
- disadvantage until now: measurement time 10 – 20 minutes per scan
Latest Developments in Single Probe Systems

faster, automated, easier-to-use
Concept DASY6: Same Hardware -> Compatible w/ All Standard

FaceDown, Wrist, etc. compatible with any half-size phantom

TwinSAM, ELI, etc. compatible with any full-size phantom

Generic Mounting Board

Trolley easy-to-move positioner
Concept DASY6: Optimized & Accelerated Movements

- mother scan (every few weeks or when phantom is exchanged)

- ultra-fast scan
  - time: ~10s
  - output: 1g, 10g of volume scan equivalent (when the scan confirms that same pattern has been measured before; applies only when antenna and band are the same)

- area scan
  - time: 3× faster than traditional system with surface detection
  - output: max location, 1g, 10g (fast SAR algorithm; MOTOROLA to be replaced with next release)

- volume scan (verified)
  - time: 30% faster than DASY52
  - output: 1g, 10g, decay etc.
Concept DASY6: Integration of Base-Station Emulators

- Rohde & Schwarz CMW500
- Rohde & Schwarz CMU200
- Anritsu MT8820C
- Keysight (Agilent) E5515C/E 8960 (V6.2))
- Python interface enables the user to program and control base-station emulators and other hardware
Compatible to any New Phantom: FaceDown, Head-Stand, Wrist, etc.
Concept DASY6: Intelligent Software

- optimized workflow
- minimal user interaction
- accelerated movements (full compliance 3 - 10 times faster)
- reconstruction based on vector array system (more reliable than MOTOROLA algorithm)
- expert systems for any standard always updated to the latest requirements for base-station integration (automated switching of channels and linearization verification, etc.)
- full access via Python
- advanced auto-reporting
Concept of Vector Array Systems

- large number of sensors that acquire in parallel or sequentially
- array is 2D or 3D (planar or conformal to the surface)
- field is reconstructed in 3D by Maxwell-equation-based expansion functions (PWE)
First Generation of Array Systems for QA

- iSAR Flat, Unified Head, Quad by SPEAG (Switzerland)
- SARLITE by SATIMO (France)
- QuickSAR by EM-Safety (South Korea)
- SARA C by IndexSAR (United Kingdom)

-target QA, not compliance testing
What Changed in the Last Years

- more communication systems: GSM, UMTS, LTE, WLAN
- multiple bands
- more antenna, dynamic antenna tuning, MIMO
- user conditions: proximity sensors, wrist phantoms
- 10× to 100× more test conditions
- need for much faster systems in compliance testing
2nd Generation of Array Systems for Compliance Testing

- cSAR3D by SPEAG
- ART-MAN by ART-FI
- other system in developments
  - SATIMO
  - THESS
  - IndexSAR
Concept of Array Systems

- large number of sensors that acquire in parallel or sequentially (metal or dielectric)
- array is 2D or 3D (planar or conformal to the surface)
- field is reconstructed in 3D by Maxwell-Eq-based basis functions (PWE)
Distortion by Array Systems

- distortion: significant but compensated as much as possible
- psSAR: estimated due to advanced field reconstruction
- validity: uncertainty/scattering/reconstruction is source dependent, difficult to assess
Issues: Vector Array Systems

- large number of fixed probes (> 1000 sensors)
  - calibration of > 1000 sensors
- but still very sparse probe density
  - tricks to overcome under-sampling problems
- more or less distorts the field to be measured
  - compensation required
- estimation of field distribution anywhere in the head to assess peak spatial SAR
  - standard PWE equivalent expansion techniques
  - advanced maxwell-eq-based basis functions
- most uncertainty sources are correlated and source dependent
  - source dependent uncertainty
  - uncertainties cannot be independently verified as in Part 1/2

- vector array systems are black box systems
Example: ART-MAN (http://www.art-fi.eu/technology)
Example: cSAR3D (www.speag.com)
Example: cSAR3D (www.speag.com)
Solution to Overcome the Inherent Issues (IEC 62209-3)

- system performance requirements
- technology based uncertainty assessment
- validation of performance independent of technology
- validation of uncertainty independent of technology
- performance is the only criteria for acceptance or rejection of systems
All About Performance (IEC 62209-3)

- psSAR1g and 10g up to 10 W/kg for head and body exposures
- dynamic range for CW: 0.01 – >100 W/kg
- frequency: 30 – 6000 MHz
- any modulation
- any DUT
- with an uncertainty of <±30% (state of the art: <21/24%) with respect to the non-disturbed phantom
- otherwise special considerations are required
Concept of Uncertainty, Verification & Validation

- **uncertainty**
  - list of uncertainty sources to be considered
  - the significance and the best method to assess the uncertainty depend on the technology
  - global methods to assess and combine these uncertainties are specified
  - method technology dependent but must be rigorously documented; the uncertainty components can be assessed based on theoretical considerations or numerically

- **verification**
  - quick and easy test to make sure that all component are working
  - gives correct results
  - technology dependent but guidance provided

- **validation**
  - independent of input from the manufacturer/vendors
  - must be comprehensive, i.e., include the characteristics of all current and future devices
  - experimental validation must include the minimum set of sources sufficient to detect any underestimated uncertainties

- confirmation by round-robin testing
Uncertainty Sources I

- calibration uncertainty
- post-processing
- backscattering from the sensor array
- scattering within the array
- mutual coupling between the sensors
- coupling with the device under test
- signal pickup of the transmission lines

- geometrical deviations from the nominal location of the sensor
- sensor locations with respect to each other
- amplitude uncertainty as a function of amplitude and modulation
- phase uncertainty as a function of amplitude and modulation
- amplitude drifts
- phase drifts

- amplitude noise
- phase noise
- under-sampling
- array boundaries
- amplitude and phase of the basis functions
- reconstruction algorithm for any potential induced field distribution
Uncertainty Sources II

- integration uncertainty
- phantom shell uncertainty
- test sample positioning
- device holder
- output power drift
- linearity
- detection limits
- modulation response
- readout electronics
- response time

- integration time
- RF ambient – noise
- RF ambient – reflections
Concept of Validation Section

- independent of technology and design
- well-defined sources to test full range of SAR distributions
  - operational frequencies (700 – 6000 MHz)
  - modulations (CW, GSM, WCDMA, LTE, etc.)
  - polarizations (normal and parallel to phantom surface)
  - phantom coupling (capacitive and inductive coupling)
  - power levels (SAR1g from 0.1 to 10 W/kg)
  - distribution (3 dB radius from 5 to 50 mm)
  - single and multiple peaks
  - phantom locations
- calibration of sources
  - ISO/IEC 17025
  - uncertainty < 20% ($k = 2$)
  - both numerical and experimental target values

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Inductive Coupling Sources: Dipoles
Capacitive Coupling Sources: Vertical PIFA (VPIFA)

VPIFA-750, VPIFA-835, VPIFA-1950, and VPIFA-3700

+/-3.85mm
Sources

- dipole antennas, as defined in IEC 62209-1, Annex G
- PIFAC-900, PIFAC-1950, PIFAC-2450, PIFAC-3700
- PIFAE-835, PIFAE-1950, PIFAE-2450, PIFA-3700, PIFAE-5200
- VPIFA-750, VPIFA-835, VPIFA-1950, VPIFA 3700
- multi-peak generic phone sources
- source sensitive to backscattering from sensor array
- numerical and experimental target values wherever possible
# Minimal Set of Modulations

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<td>LTE-TDD (SC-FDMA, 1 RB, 20 MHz, QPSK)</td>
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</table>
Validation Points Flat
Validation Points Head

A -60 / 40 / -7.08
B 25 / 40 / -12.06
C 60 / 22.5 / -11.38
D -15 / 0 / 0
E 35 / 0 / -4.77
F 85 / 0 / -19.11
G 25 / -40 / -12.54
H 60 / -22.5 / -8.14
I 120 / -35 / -43.82

EUT 80 x 160

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<th>f1 [MHz]</th>
<th>P1 [dBm]</th>
<th>b1 [MHz]</th>
<th>P2 [dBm]</th>
<th>Mod UID</th>
<th>Loc Pos Data</th>
<th>d [m]</th>
<th>PsAR 1g</th>
<th>PsAR 10g</th>
<th>Uloc (k=2)</th>
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<td>5</td>
<td>27.26</td>
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<td>0.8 dB</td>
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</table>
Example Vector Array Evaluation: Flat Phantom
cSAR3D Flat 1g(o)/10g(◊): All Dipoles/All Frequencies ($N = 515$, $\sigma = 5\%$)
cSAR3D Flat (95% range): All Dipoles/All Frequencies ($N = 515$, $\sigma = 5\%$)
cSAR3D Flat (1950 MHz) for psSAR1g: 95% range
Example Vector Array Evaluation: Head Right Phantom
cSAR3D Right Head (95% range): All Dipoles/All Frequencies ($N = 748$, $\sigma = 10\%$)
cSAR3D Right Head (1950 MHz): 95% range
Performance for Capacitively Induced Fields (Vertical PIFA)
cSAR3D 10g (2* STDEV): PIFA

![Graph showing average deviation (dB) vs. frequency (MHz) for various PIFA models.](image-url)
Conclusions
# Summary: Single Probe vs. Vector Array Systems

<table>
<thead>
<tr>
<th></th>
<th>Single Probe Systems</th>
<th>Vector Array Systems</th>
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<tbody>
<tr>
<td>Standard Compatibility</td>
<td>all standards</td>
<td>IEC 62209-3 only</td>
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<td>Government</td>
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<tr>
<td>Comparability</td>
<td>excellent (all components well-defined)</td>
<td>moderate to good (manufacturer defined)</td>
</tr>
<tr>
<td></td>
<td>minutes</td>
<td>seconds</td>
</tr>
<tr>
<td>Test Time</td>
<td>~20% (well defined)</td>
<td>~&gt;30% (manufacturer)</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>~10%</td>
<td>&lt;10%</td>
</tr>
<tr>
<td>Repeatability</td>
<td>standard</td>
<td>manufacturer defined</td>
</tr>
<tr>
<td>Verification</td>
<td>standard</td>
<td>comprehensive source set needed (standard)</td>
</tr>
<tr>
<td>Validation</td>
<td>complex / wet</td>
<td>simple / dry</td>
</tr>
<tr>
<td>maintenance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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