



IEEE

IEC/IEEE 62209-1528

Edition 1.1 2026-09

INTERNATIONAL STANDARD

CONSOLIDATED VERSION

Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices -

Part 1528: Human models, instrumentation, and procedures (Frequency range of 4 MHz to 10 GHz)

CONTENTS

FOREWORD	14
INTRODUCTION	17
1 Scope	18
2 Normative references	18
3 Terms and definitions	18
4 Symbols and abbreviated terms	26
4.1 Physical quantities	26
4.2 Constants	26
4.3 Abbreviated terms	27
5 Quick start guide and evaluation plan checklist	28
6 Measurement system specifications	30
6.1 General requirements for full SAR testing	30
6.2 Phantom specifications	31
6.2.1 General	31
6.2.2 Basic phantom parameters	31
6.2.3 Head phantom	33
6.2.4 Flat phantom	34
6.2.5 Device-specific phantoms	35
6.3 Influence of hand on SAR in head	35
6.4 Scanning system requirements	36
6.5 Device holder specifications	36
6.6 Characteristics of the readout electronics	37
7 Protocol for SAR assessment	37
7.1 General	37
7.2 Measurement preparation	37
7.2.1 Preparation of tissue-equivalent medium and system check	37
7.2.2 Preparation of the wireless communication DUT	38
7.2.3 DUT operating mode requirements	38
7.2.4 Positioning of the DUT relative to the phantom	40
7.2.5 Antenna configurations	58
7.2.6 Options and accessories	58
7.2.7 DUTs with alternative form factor	58
7.2.8 Test frequencies for DUTs	59
7.3 Tests to be performed for DUTs	59
7.3.1 General	59
7.3.2 Basic approach for DUT testing	60
7.4 Measurement procedure	61
7.4.1 General	61
7.4.2 Full SAR testing procedure	61
7.4.3 Drift	65
7.4.4 SAR measurements of DUTs with multiple antennas or multiple transmitters	67
7.5 Post-processing of SAR measurement data	73
7.5.1 Interpolation	73
7.5.2 Extrapolation	73
7.5.3 Definition of the averaging volume	73

7.5.4	Searching for the maxima	74
7.6	Time-period averaged SAR considerations	74
7.6.1	General	74
7.6.2	RF conducted power	74
7.6.3	Time-period averaged SAR measurement settings for SAR measurement methods	74
7.6.2	Exposure conditions and test positions	76
7.6.3	SAR measurements	76
7.6.4	Time-period averaged SAR for simultaneous transmission.....	77
7.6.6	TX factor assessment	77
7.6.7	SAR measurements	77
7.6.5	Uncertainty in TPAS evaluations.....	79
7.7	Proximity sensors considerations	79
7.7.1	General	79
7.7.2	Procedures for determining proximity sensor triggering distances.....	81
7.7.3	Procedure for determining proximity sensor coverage area.....	84
7.7.4	SAR measurement procedure involving proximity sensors	85
7.8	SAR correction for deviations of complex permittivity from targets	85
7.8.1	General	85
7.8.2	SAR correction formula.....	86
7.8.3	Uncertainty of the correction formula	87
7.9	Minimization of testing time.....	87
7.9.1	General	87
7.9.2	Fast SAR testing	88
7.9.3	SAR test reductions	93
7.10	Motion sensors considerations	105
7.10.1	General	105
7.10.2	SAR measurement procedure involving motion sensors.....	106
7.11	Devices used next to the ear during voice calls.....	106
7.11.1	General	106
7.11.2	Operating mode characteristics	107
7.11.3	Applicability criteria	107
7.11.4	Hand SAR test procedure	108
7.11.5	Duty cycle and time-averaged output power considerations for hand SAR testing	108
8	Measurement uncertainty estimation	110
8.1	General.....	110
8.2	Requirements on the uncertainty evaluation.....	111
8.3	Description of uncertainty models	111
8.3.1	General	111
8.3.2	SAR measurement of a DUT	112
8.3.3	System validation and system check measurement.....	112
8.3.4	System check repeatability and reproducibility.....	112
8.3.5	Fast SAR testing (relative measurement).....	112
8.4	Parameters contributing to uncertainty	114
8.4.1	Measurement system errors	114
8.4.2	Phantom and device (DUT or validation antenna) errors	115
8.4.3	Corrections to the SAR result (if applied).....	117

9	Measurement report	118
9.1	General.....	118
9.2	Items to be recorded in the measurement report	118
Annex A	(normative) SAR measurement system verification	122
A.1	Overview	122
A.2	System check	122
A.2.1	Purpose	122
A.2.2	Phantom set-up	123
A.2.3	System check antenna.....	123
A.2.4	System check antenna input power measurement.....	124
A.2.5	System check procedure.....	125
A.2.6	System check acceptance criteria	126
A.3	System validation.....	126
A.3.1	Purpose	126
A.3.2	Phantom set-up	126
A.3.3	System validation antennas	126
A.3.4	Input power measurement	127
A.3.5	System validation procedure.....	127
A.4	Fast SAR testing system validation and system check	129
A.4.1	General	129
A.4.2	Fast SAR testing system validation.....	129
A.4.3	Fast SAR testing system check.....	130
Annex B	(informative) SAR test reduction supporting information.....	132
B.1	General.....	132
B.2	Test reduction based on characteristics of DUT design	132
B.2.1	General	132
B.2.2	Statistical analysis overview	132
B.2.3	Analysis results	133
B.2.4	Conclusions.....	136
B.2.5	Expansion to multi-transmission antennas	136
B.3	Test reduction based on analysis of SAR results on other signal modulations	136
B.3.1	General	136
B.3.2	Analysis results	137
B.4	Test reduction based on SAR level analysis.....	138
B.4.1	General	138
B.4.2	Statistical analysis	139
B.4.3	Test reduction applicability example	142
B.5	Other statistical approaches to search for the high SAR test configurations	144
B.5.1	General	144
B.5.2	Test reductions based on a DOE	144
B.5.3	One factor at a time (OFAT) search	144
B.5.4	Analysis of unstructured data.....	144
Annex C	(informative) Measurement uncertainty of results obtained from specific fast SAR testing methods	145
C.1	General.....	145
C.2	Measurement uncertainty evaluation – contributing parameters	145
C.2.1	General	145
C.2.2	Probe calibration and system calibration drift.....	146
C.2.3	Isotropy	146

C.2.4	Probe positioning	147
C.2.5	Mutual sensor coupling	148
C.2.6	Scattering within the probe array	149
C.2.7	Sampling error	149
C.2.8	Array boundaries	149
C.2.9	Probe or probe array coupling with the DUT	149
C.2.10	Measurement system immunity / secondary reception	149
C.2.11	Deviations in phantom shape	150
C.2.12	Spatial variation in dielectric properties	150
C.2.13	Reconstruction	150
C.3	Uncertainty budget	150
Annex D (normative)	SAR system validation antennas	153
D.1	General antenna requirements	153
D.2	Standard dipole antenna	153
D.2.1	Mechanical description	153
D.2.2	Numerical target SAR values	156
D.3	Standard waveguide	158
D.3.1	Mechanical description	158
D.3.2	Numerical target SAR values	159
D.4	System validation antennas for below 150 MHz	159
D.4.1	General	159
D.4.2	Confined loop antenna	160
D.4.3	Meander dipole antenna	162
D.5	Orthogonal E-field source – VPIFA	163
D.5.1	Mechanical description	163
D.5.2	Numerical target SAR values	166
Annex E (normative)	Calibration and characterization of dosimetric (SAR) probes	167
E.1	Introductory remarks	167
E.2	Linearity	168
E.3	Assessment of the sensitivity of the dipole sensors	168
E.3.1	General	168
E.3.2	Two-step calibration procedures	168
E.3.3	One-step calibration procedure – reference antenna method	174
E.3.4	One-step calibration procedure – coaxial calorimeter method	178
E.4	Isotropy	180
E.4.1	Axial isotropy	180
E.4.2	Hemispherical isotropy	180
E.5	Lower detection limit	185
E.6	Boundary effect	186
E.7	Response time	186
Annex F (informative)	Example recipes for phantom tissue-equivalent media	187
F.1	General	187
F.2	Ingredients	187
F.3	Tissue-equivalent medium liquid formulas (permittivity/conductivity)	188
Annex G (normative)	Phantom specifications	190
G.1	Rationale for the phantom characteristics	190
G.1.1	General	190
G.1.2	Rationale for the SAM phantom	190

G.1.3	Rationale for the flat phantom	190
G.2	SAM phantom specifications	191
G.2.1	General SAM phantom specifications	191
G.2.2	SAM phantom shell specification	195
G.3	Flat phantom specifications.....	197
G.4	Justification of flat phantom dimensions	198
G.5	Rationale for tissue-equivalent media	201
G.6	Definition of a phantom coordinate system and a DUT coordinate system	203
Annex H (informative)	Measurement of the dielectric properties of tissue-equivalent media and uncertainty estimation	205
H.1	Overview	205
H.2	Measurement techniques	205
H.2.1	General	205
H.2.2	Instrumentation.....	205
H.2.3	General principles	205
H.3	Slotted coaxial transmission line	206
H.3.1	General	206
H.3.2	Equipment set-up	206
H.3.3	Measurement procedure	207
H.4	Contact coaxial probe	207
H.4.1	General	207
H.4.2	Equipment set-up	208
H.4.3	Measurement procedure	209
H.5	TEM transmission line.....	209
H.5.1	General	209
H.5.2	Equipment set-up	210
H.5.3	Measurement procedure	210
H.6	Dielectric properties of reference liquids	211
Annex I (informative)	Studies for potential hand effects on head SAR	214
I.1	Overview	214
I.2	Background	214
I.2.1	General	214
I.2.2	Hand phantoms	215
I.3	Summary of experimental studies	215
I.3.1	Experimental studies using fully compliant SAR measurement systems	215
I.3.2	Experimental studies using other SAR measurement systems	215
I.4	Summary of computational studies.....	216
I.5	Conclusions	216
Annex J (informative)	Skin enhancement factor	217
J.1	Background	217
J.2	Rationale	218
J.3	Simulations	218
J.4	Recommendation	219
Annex K (normative)	Application-specific phantoms	221
K.1	General.....	221
K.2	Phantom basic requirements.....	221
K.3	Examples of specific alternative phantoms.....	221
K.3.1	Face-down SAM phantom	221
K.3.2	Head-stand SAM phantom	222

K.3.3	Wrist phantom	222
K.4	Scanning and evaluation requirements.....	223
K.5	Uncertainty assessment.....	223
K.6	Reporting	223
Annex L (normative)	Fast compliance evaluations using a flat-bottom phantom with a curved corner (Uniphantom).....	224
L.1	General.....	224
L.2	Uniphantom	224
L.3	Device positions for compliance testing and definitions of handset shapes	224
L.3.1	General	224
L.3.2	Handsets with a straight form factor.....	225
L.3.3	Handsets with a clamshell form factor.....	225
L.4	Testing procedure.....	225
L.4.1	General	225
L.4.2	Handsets with straight form factors.....	225
L.4.3	Handsets with clamshell form factors	226
L.5	Uncertainty of SAR measurement results using Uniphantom	227
Annex M (informative)	Wired hands-free headset testing	228
M.1	Concept	228
M.2	Example results	229
M.3	Discussion	230
Annex N (informative)	Applying the head SAR test procedures	231
Annex O (normative)	Uncertainty analysis for measurement system manufacturers and calibration laboratories	234
O.1	Probe linearity and detection limits	234
O.2	Broadband signal uncertainty.....	235
O.3	Boundary effect	235
O.4	Field-probe readout electronics uncertainty.....	236
O.5	Signal step-response time uncertainty.....	236
O.6	Probe integration-time uncertainty	237
O.6.1	General	237
O.6.2	Probe integration-time uncertainty for periodic pulsed signals.....	237
O.6.3	Probe integration-time uncertainty for non-periodic signals	238
O.7	Contribution of mechanical constraints.....	238
O.7.1	Mechanical tolerances of the probe positioner (directions parallel to phantom surface).....	238
O.7.2	Probe positioning with respect to phantom shell surface	238
O.7.3	First-order approximation of exponential decay.....	239
O.8	Contribution of post-processing.....	239
O.8.1	General	239
O.8.2	Evaluation test functions.....	240
O.8.3	Data-processing algorithm uncertainty evaluations	242
O.9	Tissue-equivalent medium properties uncertainty.....	245
O.9.1	General	245
O.9.2	Medium density	245
O.9.3	Medium conductivity uncertainty	245
O.9.4	Medium permittivity uncertainty	245
O.9.5	Assessment of dielectric properties measurement uncertainties.....	245
O.9.6	Medium temperature uncertainty.....	247

Annex P (normative) Post-processing techniques	249
P.1 Extrapolation and interpolation schemes	249
P.1.1 General	249
P.1.2 Extrapolation schemes	249
P.1.3 Interpolation schemes	249
P.2 Averaging scheme and maximum finding	249
P.2.1 Volume average schemes	249
P.2.2 Finding the psSAR and estimating the uncertainty	250
Annex Q (informative) Rationale for time-period averaged SAR test procedure	251
Annex R (normative) Measurement uncertainty analysis for testing laboratories	252
R.1 RF ambient conditions	252
R.2 Device positioning and holder uncertainties	252
R.2.1 General	252
R.2.2 Device holder perturbation uncertainty	253
R.2.3 DUT positioning uncertainty with a specific test device holder: Type A	254
R.3 Probe modulation response	254
R.4 Time-period averaged SAR	255
R.4.1 General	255
R.4.2 TX factor uncertainty	255
R.5 Measured SAR drift	256
R.5.1 General	256
R.5.2 Accounting for drift	256
R.6 SAR scaling uncertainty	257
Annex S (normative) Validation antenna SAR measurement uncertainty	258
S.1 Deviation of experimental antennas	258
S.2 Other uncertainty contributions when using system validation antennas	258
Annex T (normative) Interlaboratory comparisons	260
T.1 Purpose	260
T.2 Phantom set-up	260
T.3 Reference devices	260
T.4 Power set-up	260
T.5 Interlaboratory comparison – procedure	261
Annex U (informative) Determination of the margin for compliance evaluation using the Uniphanom	262
U.1 General	262
U.2 Deviation of the psSAR measured using the Uniphanom from the psSAR measured using the SAM phantom	262
U.3 Determination of margin based on 95 % confidence interval	263
U.4 Examples of the determination of the margin factor	263
U.4.1 Margin for handsets with straight form factors at flat-bottom position	263
U.4.2 Margin for handsets with straight form factors (except smart phones at flat-bottom position)	265
U.4.3 Margin for smart phones at flat-bottom position	267
U.4.4 Margin for smart phones at corner position	269
U.4.5 Margin for handsets with clamshell form factors at corner position	271
Annex V (informative) Automatic input power level control for system validation	274
V.1 General	274
V.2 Operational mechanism of AIPLC	274
Annex W (informative) LTE test configurations supporting information	276

W.1	General.....	276
W.2	Study 1	276
W.3	Study 2	278
W.4	Justifications of relative standard deviations	279
Annex X (informative) Rationale for head phantom test reductions based on flat phantom SAR data.....		281
X.1	General.....	281
X.2	Rationale for SAR level threshold	281
X.3	Rationale for distance threshold.....	282
Annex Y (normative) Validation of motion sensors		284
Y.1	General.....	284
Y.2	Procedure	284
Y.3	Validation report	285
Bibliography.....		287
Figure 1 – Quick start guide.....		29
Figure 2 – Dimensions of the elliptical phantom		35
Figure 3 – Mounting of the DUT in the device holder using low-permittivity and low-loss foam to avoid changes of DUT performance by the holder material.....		37
Figure 4 – Designation of DUT reference points.....		42
Figure 5 – Measurements performed by shifting a large device over the efficient measurement area of the system including overlapping areas – in this case: six tests performed		42
Figure 6 – Test positions for body-worn devices		43
Figure 7 – Device with swivel antenna		44
Figure 8 – Test positions for body supported devices.....		46
Figure 9 – Test positions for desktop devices		48
Figure 10 – Test positions for front-of-face devices.....		49
Figure 11 – Test position for hand-held devices, not used at the head or torso		50
Figure 12 – Test position for limb-worn devices		50
Figure 13 – Test position for clothing-integrated wireless communication devices.....		51
Figure 14 – Possible test positions for a generic device		52
Figure 15 – Vertical and horizontal reference lines and reference points A and B on two example device types: a full touch-screen smart phone (left) and a DUT with a keypad (right)		54
Figure 16 – Cheek position of the DUT on the left side of SAM where the device position shall be maintained for the phantom test set-up.....		57
Figure 17 – Tilt position of the DUT on the left side of SAM		57
Figure 18 – An alternative form factor DUT with reference points and reference lines		58
Figure 19 – Block diagram of the tests to be performed		61
Figure 20 – Orientation of the probe with respect to the line normal to the phantom surface, for head and flat phantoms, shown at two different locations		65
Figure 21 – Measurement procedure for different types of correlated signals		73
Figure 29 – Example illustration of the output power characteristics of a simple TPAS implementation		77
Figure 22 – Positioning of the surfaces and edges of the DUT for determining the proximity sensor triggering distance.....		83

Figure 23 – Positioning of the edges of the DUT to determine proximity sensor triggering distance variations with the edge positioned at different angles from the perpendicular position.....	84
Figure 24 – Fast SAR Procedure A	91
Figure 25 – Fast SAR Procedure B	93
Figure 26 – Modified chart of Figure 19.....	98
Figure 27 – Use of conducted power for LTE mode selection, for Band 1 (1 920 MHz to 1 980 MHz) (MPR values are in dB)	101
Figure 28 – Use of conducted power for LTE mode selection, for Band 17 (704 MHz to 716 MHz) (MPR values are in dB)	102
Figure A.1 – Test set-up for the system check	124
Figure B.1 – Distribution of Tilt/Cheek.....	134
Figure B.2 – SAR relative to SAR in position with maximum SAR in GSM mode.....	138
Figure B.3 – Two points identifying the minimum distance between the position of the interpolated maximum SAR and the points at $0,6 \times SAR_{max}$	140
Figure B.4 – Histogram for D_{min} in the case of GSM 900 and iso-level at $0,6 \times SAR_{max}$	140
Figure B.5 – Histogram for random variable $Factor_{1g,1800}$	142
Figure D.1 – Mechanical details of the standard dipoles.....	155
Figure D.2 – Standard waveguide (dimensions are according to Table D.3)	158
Figure D.3 – Drawing of the CLA that corresponds to a resonant loop integrated in a metallic structure to isolate the resonant structure from the environment	160
Figure D.4 – Mechanical details of the meander dipoles for 150 MHz.....	162
Figure D.5 – VPIFA validation antenna	165
Figure D.6 – Mask for positioning VPIFAs	165
Figure E.1 – Experimental set-up for assessment of the sensitivity (conversion factor) using a vertically-oriented rectangular waveguide	172
Figure E.2 – Illustration of the antenna gain evaluation set-up	175
Figure E.3 – Schematic of the coaxial calorimeter system.....	179
Figure E.4 – Set-up to assess hemispherical isotropy deviation in tissue-equivalent medium.....	181
Figure E.5 – Alternative set-up to assess hemispherical isotropy deviation in tissue-equivalent medium.....	182
Figure E.6 – Experimental set-up for the hemispherical isotropy assessment.....	183
Figure E.7 – Conventions for dipole position (ξ) and polarization (θ)	184
Figure E.8 – Measurement of hemispherical isotropy with reference antenna.....	185
Figure G.1 – Illustration of dimensions in Table G.1 and Table G.2.....	192
Figure G.2 – Close up side view of phantom showing the ear region.....	194
Figure G.3 – Side view of the phantom showing relevant markings	195
Figure G.4 – Sagittally bisected phantom with extended perimeter (shown placed on its side as used for device SAR tests)	196
Figure G.5 – Picture of the phantom showing the central strip.....	196
Figure G.6 – Cross-sectional view of SAM at the reference plane	197
Figure G.7 – Dimensions of the flat phantom set-up used for deriving the minimal phantom dimensions for W and L for a given phantom depth D	199
Figure G.8 – FDTD predicted error in the 10 g psSAR as a function of the dimensions of the flat phantom compared with an infinite flat phantom at 800 MHz	200

Figure G.9 – Complex permittivity of human tissues compared to the phantom target properties	203
Figure G.10 – Example reference coordinate system for the left-ear ERP of the SAM phantom	204
Figure G.11 – Example coordinate system on a DUT	204
Figure H.1 – Slotted line set-up	206
Figure H.2 – An open-ended coaxial probe with inner and outer radii a and b , respectively	208
Figure H.3 – TEM line dielectric properties test set-up [85]	210
Figure J.1 – SAR and temperature increase (ΔT) distributions simulated for a three-layer (skin, fat, muscle) planar torso model.....	217
Figure J.2 – Statistical approach to protect 90 % of the population	219
Figure J.3 – psSAR skin enhancement factors	220
Figure K.1 – SAM face-down phantom	222
Figure K.2 – SAM head-stand phantom.....	222
Figure K.3 – Wrist phantom	223
Figure L.1 – Cross section of the unified phantom (Uniphantom) with its dimensions	224
Figure L.2 – Measurement positions of handsets with straight and clamshell form factors	225
Figure L.3 – Flow chart of testing procedure for handsets with straight form factors.....	226
Figure L.4 – Flow chart of testing procedure for handsets with clamshell form factors.....	227
Figure M.1 – Configuration of a personal wired hands-free headset	228
Figure M.2 – Configuration without a personal wired hands-free headset.....	229
Figure O.1 – Orientation and surface of averaging volume relative to phantom surface.....	245
Figure U.1 – Categories (classes) for comparison of the measured psSAR between the Uniphantom (SAR_{uni}) and the SAM phantom (SAR_{SAM})	262
Figure U.2 – Histogram of the deviation of the 10 g psSAR of 45 handsets with straight form factors positioned at the flat bottom of the Uniphantom.....	264
Figure U.3 – Histogram of the deviation of the 1 g psSAR of 40 handsets with straight form factors positioned at the flat bottom of the Uniphantom.....	265
Figure U.4 – Histogram of the deviation of the 10 g psSAR of 25 handsets with straight form factors positioned at the flat bottom of the Uniphantom.....	266
Figure U.5 – Histogram of the deviation of the 1 g psSAR from 20 handsets with straight form factors positioned at the flat bottom of the Uniphantom	267
Figure U.6 – Histogram of the deviation of the 10 g psSAR of 20 handsets with straight form factors or smart phones positioned at the flat bottom of the Uniphantom.....	268
Figure U.7 – Histogram of the deviation of the 1 g psSAR of 20 handsets with straight form factors or smart phones positioned at the flat bottom of the Uniphantom.....	269
Figure U.8 – Histogram of the deviation of the 10 g psSAR of 20 handsets with straight form factors or smart phones positioned at the corner of the Uniphantom	270
Figure U.9 – Histogram of the deviation of the 1 g psSAR of 19 handsets with straight form factors or smart phones positioned at the corner of the Uniphantom	271
Figure U.10 – Histogram of the deviation of the 10 g psSAR of 20 handsets with clamshell form factors at the corner of the Uniphantom.....	272
Figure U.11 – Histogram of the deviation of the 1 g psSAR of 19 handsets with clamshell form factors at the corner of the Uniphantom.....	273
Figure V.1 – Generated RF input power variations to operation time without and with application of AIPLC	274

Figure V.2 – The system block diagram of the AIPLC.....	275
Figure V.3 – Power variation characteristics by adjusting the amplifier or signal generator outputs	275
Figure W.1 – Low, middle, and high channels at 2 GHz band (Band 1)	277
Figure W.2 – RF conducted power versus 10 g psSAR	278
Figure W.3 – 1 g SAR as a function of RF conducted power in various test conditions	279
Figure X.1 – Number of test cases where the psSAR at a specified distance to the flat phantom is more than 5 % higher than the psSAR at $d = 0$ mm, and the psSAR is at least 0,2 W/kg.....	282
Figure X.2 – Distance along a representation of a planar DUT between the ERP and a point that is 10 mm from the SAM phantom outer shell.....	283
Figure X.3 – Example of a measured region (red and blue regions), where the red region indicates where all spatial-average SAR values shall be at least 5 dB below the applicable head SAR limit, per the test reduction criteria in 7.9.3.7	283
Figure Y.1 – Procedure for the validation of the power reduction	285
Table 1 – Evaluation plan checklist	28
Table 2 – Dielectric properties of the tissue-equivalent medium	32
Table 3 – Area scan parameters	64
Table 4 – Zoom scan parameters	64
Table 5 – Example method to determine the combined SAR value using Alternative 1	71
Table 6 – Root-mean-squared error SAR correction formula as a function of the maximum change in permittivity or conductivity [28].....	87
Table 7 – Threshold values $TH(f)$ used in this proposed test reduction protocol	97
Table 8 – Divisors for common probability density functions (PDFs).....	111
Table 9 – Uncertainty budget template for evaluating the uncertainty in the measured value of 1 g or 10 g psSAR from a DUT or validation antenna (N = normal, R = rectangular)	113
Table 10 – Uncertainty of Formula (8) (see 7.8.2) as a function of the maximum change in permittivity or conductivity	117
Table B.1 – The number of DUTs used for the statistical study	133
Table B.2 – Statistical analysis results of $P(\text{Tilt/Cheek} > x)$ for various x values	134
Table B.3 – Statistical analysis results of $P(\text{Tilt/Cheek} > x)$ for 1 g and 10 g psSAR	134
Table B.4 – Statistical analysis results of $P(\text{Tilt/Cheek} > x)$ for various antenna locations	135
Table B.5 – Statistical analysis results of $P(\text{Tilt/Cheek} > x)$ for various frequency bands	135
Table B.6 – Statistical analysis results of $P(\text{Tilt/Cheek} > x)$ for various device types	136
Table B.7 – Distance $D_{\min}^*$ for various “iso-level” values	140
Table B.8 – Experimental thresholds to have a 95 % probability that the maximum measured SAR value from the area scan will also have a psSAR.....	142
Table B.9 – SAR values from the area scan (GSM 900 band): Example 1	143
Table B.10 – SAR values from the area scan (GSM 900 band): Example 2	143
Table C.1 – Measurement uncertainty budget for relative SAR measurements using Class 2 fast SAR testing, for tests performed within one frequency band and modulation	151
Table C.2 – Measurement uncertainty budget for system check using Class 2 fast SAR testing	152

Table D.1 – Mechanical dimensions of the reference dipoles	156
Table D.2 – Numerical target SAR values (W/kg) for standard dipole and flat phantom	157
Table D.3 – Mechanical dimensions of the standard waveguide	158
Table D.4 – Numerical target SAR values for waveguides	159
Table D.5 – Numerical target SAR values for CLAs	161
Table D.6 – Mechanical dimensions of the reference meander dipole	162
Table D.7 – Numerical target SAR value (W/kg) for meander dipole	163
Table D.8 – Dimensions for VPIFA antennas at different frequencies	164
Table D.9 – Electric properties for the dielectric layers for VPIFA antennas	165
Table D.10 – Numerical target SAR values for VPIFAs on the flat phantom	166
Table E.1 – Uncertainty analysis for transfer calibration using temperature probes	170
Table E.2 – Guidelines for designing calibration waveguides	173
Table E.3 – Uncertainty analysis of the probe calibration in waveguide	174
Table E.4 – Uncertainty template for evaluation of reference antenna gain	176
Table E.5 – Uncertainty template for calibration using reference antenna	177
Table E.6 – Uncertainty components for probe calibration using thermal methods	180
Table F.1 – Suggested recipes for achieving target dielectric properties, 30 MHz to 900 MHz	188
Table F.2 – Suggested recipes for achieving target dielectric properties, 1 800 MHz to 10 000 MHz	189
Table G.1 – Dimensions used in deriving SAM phantom from the ARMY 90th percentile male head data (Gordon et al. [61])	193
Table G.2 – Additional SAM dimensions compared with selected dimensions from the ARMY 90th percentile male head data (Gordon et al. [61]) – specialist head measurement section	193
Table G.3 – Parameters used for calculation of reference SAR values in Table D.2	200
Table H.1 – Parameters for calculating the dielectric properties of various reference liquids	212
Table H.2 – Dielectric properties of reference liquids at 20 °C	213
Table J.1 – psSAR correction factors	219
Table N.1 – SAR results tables for example test results in GSM 850 band	231
Table N.2 – SAR results tables for example test results in GSM 900 band	232
Table N.3 – SAR results tables for example test results in GSM 1800 band	232
Table N.4 – SAR results tables for example test results in GSM 1900 band	233
Table O.1 – Parameters for the reference function f_1 in Formula (O.12)	241
Table O.2 – Reference SAR values from the distribution functions f_1 , f_2 , and f_3	242
Table O.3 – Example uncertainty template and example numerical values for permittivity (ϵ'_r) and conductivity (σ) measurement	247
Table S.1 – Uncertainties relating to the deviations of the parameters of the standard waveguide from theory	258
Table S.2 – Other uncertainty contributions relating to the dipole antennas specified in Annex D	259
Table S.3 – Other uncertainty contributions relating to the standard waveguides specified in Annex D	259
Table U.1 – Summary of information to determine the margin for handsets with straight form factors positioned at the flat bottom of the Uniphantom	264

Table U.2 – Summary of information to determine the margin for handsets with straight form factors, including slide-type and bar handsets (except smart phones), positioned at the flat bottom of the Uniphantom	266
Table U.3 – Summary of information to determine the margin for the smart phones positioned at the flat bottom of the Uniphantom	268
Table U.4 – Summary of information to determine the margin for smart phones positioned at the corner of the Uniphantom	270
Table U.5 – Statistical analysis results of $P(\text{Tilt/Cheek} > x)$ for various device types	271
Table U.6 – Summary of information to determine the margin for handsets with clamshell form factors positioned at the corner of the Uniphantom	272
Table W.1 – Relative standard deviation of α found in Study 1 (without MPR)	277
Table W.2 – Maximum relative standard deviation of α found in Study 2 (with MPR)	279

INTERNATIONAL ELECTROTECHNICAL COMMISSION

Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices - Part 1528: Human models, instrumentation, and procedures (Frequency range of 4 MHz to 10 GHz)

FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC document(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation.

IEEE Standards documents are developed within IEEE Societies and Standards Coordinating Committees of the IEEE Standards Association (IEEE SA) Standards Board. IEEE develops its standards through a consensus development process, approved by the American National Standards Institute, which brings together volunteers representing varied viewpoints and interests to achieve the final product. Volunteers are not necessarily members of IEEE and serve without compensation. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information contained in its standards. Use of IEEE Standards documents is wholly voluntary. *IEEE documents are made available for use subject to important notices and legal disclaimers (see <https://standards.ieee.org/ipr/disclaimers.html> for more information).*

IEC collaborates closely with IEEE in accordance with conditions determined by agreement between the two organizations. This Dual Logo International Standard was jointly developed by the IEC and IEEE under the terms of that agreement.

- 2) The formal decisions of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees. The formal decisions of IEEE on technical matters, once consensus within IEEE Societies and Standards Coordinating Committees has been reached, is determined by a balanced ballot of materially interested parties who indicate interest in reviewing the proposed standard. Final approval of the IEEE standards document is given by the IEEE Standards Association (IEEE SA) Standards Board.
- 3) IEC/IEEE Publications have the form of recommendations for international use and are accepted by IEC National Committees/IEEE Societies in that sense. While all reasonable efforts are made to ensure that the technical content of IEC/IEEE Publications is accurate, IEC or IEEE cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications (including IEC/IEEE Publications) transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC/IEEE Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC and IEEE do not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC and IEEE are not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or IEEE or their directors, employees, servants or agents including individual experts and members of technical committees and IEC National Committees, or volunteers of IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (IEEE SA) Standards Board, for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC/IEEE Publication or any other IEC or IEEE Publications.
- 8) Attention is drawn to the normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.

- 9) Attention is drawn to the possibility that implementation of this IEC/IEEE Publication may require use of material covered by patent rights. By publication of this standard, no position is taken with respect to the existence or validity of any patent rights in connection therewith. IEC or IEEE shall not be held responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patent Claims or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility.

This consolidated version of the official IEC Standard and its amendment has been prepared for user convenience.

IEC/IEEE 62209-1528 edition 1.1 contains the first edition (2020-10) [documents 106/514/FDIS and 106/520/RVD] and its amendment 1 (2026-09) [documents 106/738/FDIS and 106/747/RVD].

In this Redline version, a vertical line in the margin shows where the technical content is modified by amendment 1. Additions are in green text, deletions are in strikethrough red text. A separate Final version with all changes accepted is available in this publication.

International Standard IEC/IEEE 62209-1528 has been prepared by IEC technical committee 106: Methods for the assessment of electric, magnetic and electromagnetic fields associated with human exposure, in cooperation with the International Committee on Electromagnetic Safety of the IEEE Standards Association, under the IEC/IEEE Dual Logo Agreement.

This first edition of IEC/IEEE 62209-1528 cancels and replaces IEC 62209-1:2016, IEC 62209-2:2010, IEC 62209-2:2010/AMD1:2019 and IEEE Std 1528-2013. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) extension of the frequency range down to 4 MHz and up to 10 GHz;
- b) testing of devices with proximity sensors;
- c) application specific phantoms;
- d) device holder specifications;
- e) fast SAR testing procedures;
- f) test reduction procedures;
- g) LTE assessment procedure;
- h) revision of validation clause, including validation antennas;
- i) revision of SAR assessment procedure;
- j) time-average SAR measurement procedure;
- k) uncertainty analysis;

This publication is published as an IEC/IEEE Dual Logo standard.

This publication contains attached files in the form of the Fast SAR Wizard described in 7.9.2.2 as well as CAD files for the SAM phantom. These files are available at:

http://www.iec.ch/dyn/www/f?p=103:227:0::::FSP_ORG_ID,FSP_LANG_ID:1303,25.

These files are intended to be used as a complement and do not form an integral part of the publication.

The text of this standard is based on the following IEC documents:

FDIS	Report on voting
106/514/FDIS	106/520/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The IEC Technical Committee and IEEE Technical Committee have decided that the contents of this document and its amendment will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

INTRODUCTION

The objective of this document is to provide procedures for measuring the human exposure from devices intended to be used at a position near the human head or body. It was developed to provide procedures to evaluate electromagnetic field (EMF) exposures due to radio frequency (RF) transmitting devices used next to the ear, in front of the face, mounted on the body, operating in conjunction with other RF-transmitting and non-transmitting devices or accessories (e.g. belt-clips), or embedded in garments. The types of devices dealt with include but are not limited to mobile telephones, cordless telephones, cordless microphones, and radio transmitters in personal computers. The applicable frequency range is from 4 MHz to 10 GHz. The document defines:

- measurement system requirements (Clause 6),
- SAR measurement protocols (Clause 7),
- SAR measurement uncertainty evaluation (Clause 8), and
- reporting requirements (Clause 9).

At the time this document was developed, two computational and measurement joint IEC/IEEE projects dealing with millimetre-wave power density assessment were under development, covering the frequency range from 6 GHz to 300 GHz. Hence there is an overlap of frequency between this document, which deals with SAR, and the other joint IEC/IEEE projects dealing with power density from 6 GHz to 10 GHz. The IEC/IEEE joint working group was aware of this fact and believed that it would give the flexibility of using whatever metrics suitable for the considered case of compliance assessment.

1 Scope

This document specifies protocols and test procedures for the reproducible and repeatable measurement of the conservative exposure peak spatial average SAR (psSAR) induced inside a simplified model of the head and the body by radio-frequency (RF) transmitting devices, with a defined measurement uncertainty. These protocols and procedures apply to a significant majority of the population, including children, during the use of hand-held and body-worn wireless communication devices. These devices include single or multiple transmitters or antennas, and are operated with their radiating structure(s) at distances up to 200 mm from a human head or body. This document is employed to evaluate SAR compliance of different types of wireless communication devices used next to the ear, in front of the face, mounted on the body, operating in conjunction with other RF-transmitting, non-transmitting devices or accessories (e.g. belt-clips), or embedded in garments. The applicable frequency range is from 4 MHz to 10 GHz. Devices operating in the applicable frequency range can be tested using the phantoms and other requirements defined in this document.

The device categories covered include, but are not limited to, mobile telephones, cordless microphones, and radio transmitters in personal, desktop and laptop computers, for multi-band operations using single or multiple antennas, including push-to-talk devices. This document can also be applied for wireless power transfer devices operating above 4 MHz.

This document does not apply to implanted medical devices.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62209-3:2019, *Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices – Part 3: Vector measurement-based systems (Frequency range of 600 MHz to 6 GHz).*

ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

Bibliography

- [1] IEC TR 62630:2010, *Guidance for evaluating exposure from multiple electromagnetic sources*
- [2] Drossos, A., Santomaa, V., and Kuster, N., "The dependence of electromagnetic energy absorption upon human head tissue composition in the frequency range of 300-3000 MHz," *IEEE Trans. Microwave Theory Tech.*, Nov. 2000, vol. 48, no. 11, pp. 1988–1995
- [3] ICNIRP, "International Commission on Non-Ionizing Radiation Protection guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (Up to 300 GHz)," *Health Physics*, Vol. 74, No. 4, pp. 494–522, 1998
- [4] IEEE Std C95.1-2019, *IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz*
- [5] Francavilla, M., Schiavoni, A., Bertotto, P., and Richiardi, G., "Effect of the hand on cellular phone radiation," *IEE Proceedings Microwaves, Antennas and Propagation*, Vol. 148, No. 4, pp. 247–253, Aug. 2001
- [6] Gandhi, O. P., Lazzi, G., and Furse, C. M., "Electromagnetic absorption in the human head and neck for mobile telephones at 835 and 1900 MHz," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 44, No. 10, pp. 1884–1897, Oct. 1996
- [7] Jensen, M. A., and Rahmat-Samii, Y., "Performance analysis of antennas for hand-held transceivers using FDTD," *IEEE Transactions on Antennas and Propagation*, Vol. 42, No. 8, pp. 1106–1113, Aug. 1994
- [8] Jensen, M. A. and Rahmat-Samii, Y., "EM interaction of handset antenna and a human in personal communications," *Proceedings of the IEEE*, vol. 83, no.1, pp. 7–17, Jan. 1995
- [9] Kuster, N., Kästle, R., and Schmid, T., "Dosimetric evaluation of mobile communications equipment with known precision," *IEICE Trans. Commun.*, May 1997, vol. E80-B, no. 5, pp. 645–652
- [10] Watanabe, S., Taki, M., Nojima, T., and Fujiwara, O., "Characteristics of the SAR distribution in a head exposed to electromagnetic fields radiated by a hand-held portable radio," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 44, No. 10, pp. 1874–1883, Oct. 1996
- [11] IEEE Std 1528, *Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Head from Wireless Communications Devices: Measurement Techniques*, New York: Institute Electrical and Electronics Engineers, Sep. 2013
- [12] Balzano, Q., Garay, O., and Manning, T., "Electromagnetic energy exposure of the users of portable cellular telephones," *IEEE Transactions on Vehicular Technology*, Vol. 44, No. 3, pp. 390–403, Aug. 1995
- [13] Meyer, F. J. C., Palmer, K. D., and Jakobus, U., "Investigation into the accuracy, efficiency and applicability of the method of moments as numerical dosimetry tool for the head and hand of a mobile phone user," *Applied Computational Electromagnetics Society Journal*, Vol. 16, No. 2, pp. 114–125, July 2001

- [14] Beard, B. B., et al., "Comparisons of Computed Mobile Phone Induced SAR in the SAM Phantom to that in Anatomically Correct Models of the Human Head," IEEE Transactions on Electromagnetic Compatibility, Vol. 48, No. 2, May 2006
- [15] Bit-Babik, G., "Computational comparison of SAR in SAM phantom and anatomically correct head models at 300 MHz–5.8 GHz: Summary comparison of the results," report to ICES TC34 SC1, October 2008
- [16] Kainz, W., et al., "Dosimetric comparison of the specific anthropomorphic mannequin (SAM) to 14 anatomical head models using a novel definition for the mobile phone positioning," Phys. Med. Biol., Vol. 50, pp. 3423–3445, July 2005
- [17] ISO/IEC 17025:2017, *General requirements for the competence of testing and calibration laboratories*
- [18] IEC TR 62905:2018, *Exposure assessment methods for wireless power transfer systems*
- [19] Di Nallo, C., and Faraone, A., "Effect of amplitude modulation of the CDMA IS-95 signal on SAR measurements," IEEE Transactions on Electromagnetic Compatibility, vol. 48, no. 3, pp. 552–562, August 2006
- [20] Nadakuduti, J., Kühn, S., Fehr, M., Douglas, M., Poković, K., and Kuster, N., "Effect of Diode Response of Electromagnetic Field Probes for the Measurements of Complex Signals," IEEE Transactions on Electromagnetic Compatibility, vol. 54, no. 6, pp. 1195–1204, December, 2012
- [21] IEC 106/465/INF, *Supporting Information for Amendment 1 to IEC 62209-2 Ed.1 (Document 106/460/CDV)*, 2018-07-27
- [22] Poković, K., "Advanced Electromagnetic Probes for Near Field Evaluation," Doc. Tech. Sci. Diss. ETH Nr. 13334. Switzerland, Zurich: Swiss Federal Institute of Technology, 1999
- [23] Bolomey, J. C., "Efficient near-field techniques for human exposure evaluation: Applications to mobile and fixed antennas," presented at the Electromagnetic Environment and Human Exposure Evaluation Workshop of EMC, Sorrento, Italy, 2002
- [24] Kanda, M. Y., Douglas, M.G., Mendivil, E. D., Ballen, M., Gessner, A. V. Chou, C-K., "Faster Determination of Mass-Averaged SAR From 2-D Area Scans," IEEE Transactions on Microwave Theory and Techniques, vol. 52, no. 8, pp. 2013–2020, August, 2004
- [25] Manning, M., Massey, P., "Rapid SAR testing of mobile phone prototype using a spherical test geometry," in IEE Tech. on Antenna Measurements and SAR Seminar, Loughborough, U.K., May 28–29, 2002
- [26] Merckel, O., Fleury, G., Bolomey, J.-C., "Rapid SAR measurement via parametric modeling," Proc. 5th International Congress of the European BioElectromagnetics Association (EBEA), p. 75–77, Helsinki, Finland, Sep. 2001
- [27] Merckel, O., Bolomey, J.-Ch., Joisel, A., "Near-field approach to Rapid SAR Measurement of Mobile Phones," Symp. of the Association for Measurement and Testing of Antennas (AMTA 2003), Irvine, Denver, USA, Oct. 2003

- [28] Douglas, M.G., Kanda, M.Y., Luengas, W.G., Ballen, M., Babij, T.M. and Chou, C-K., "An Algorithm for Predicting the Change in SAR in a Human Phantom due to Deviations in its Complex Permittivity," IEEE Transactions on Electromagnetic Compatibility, 2007, vol. 51, no 2, May 2009
- [29] Douglas, M.G., and Chou, C-K., "Enabling the Use of Broadband Tissue Equivalent Liquids for Specific Absorption Rate Measurements," IEEE Electromagnetic Compatibility Symposium, July 2007
- [30] Kuster, N. and Balzano, Q., "Energy absorption mechanism by biological bodies in the near field of dipole antennas above 300 MHz," IEEE Transactions on Vehicular Technology, Vol. 41, No. 1, pp. 17–23, Feb. 1992
- [31] Bit-Babik, G., Faraone, A., Ballen, M. and Chou, C-K., "Sensitivity of the Spatial-Average Peak SAR to the Dielectric properties of Media Used for Compliance Testing in the Frequency Range 0.3 – 3 GHz," Antennas and Propagation Society International Symposium Digest, Vol. 3, pp. 722–725, June 2002
- [32] IEC 62479:2010, *Assessment of the compliance of low-power electronic and electrical equipment with the basic restrictions related to human exposure to electromagnetic fields (10 MHz to 300 GHz)*
- [33] Derat, B., "Experimental Study on the Relationship between Specific Absorption Rate and RF Conducted Power for LTE Wireless Devices," Proc. European Microwave Conf., Paris, France, Sep. 2015
- [34] IEC 62311:2019, *Assessment of electronic and electrical equipment related to human exposure restrictions for electromagnetic fields (0 Hz to 300 GHz)*
- [35] ISO/IEC Guide 98-1:2009, *Uncertainty of measurement – Part 1: Introduction to the expression of uncertainty in measurement*
- [36] Onishi, T. and Uebayashi S., "Influence of phantom shell on SAR measurement in 3-6 GHz frequency range," IEICE Trans. Commun., vol., E88-B, no. 8, pp. 3257–3262, 2005
- [37] Niskala, K., "Multimode SAR test reduction," Final report, IEC MT1 meeting, Tokyo-Japan, May 2014
- [38] Schiavoni, A., Francavilla, M., Forigo, D., Deplano, M., "A Procedure to Reduce the Qualification Time in SAR Compliance Tests," BEMS 2005, June 2005
- [39] Francavilla, M., "Time reduction in SAR compliance of GSM/UMTS mobile phones," BEMS 2011, Halifax, Canada, June 2011
- [40] Montgomery, D.C., Design and Analysis of Experiments (4th edition), New York: John Wiley and Sons. (1997)
- [41] IEC/IEEE 62704-1:2017, *Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communications devices, 30 MHz to 6 GHz – Part 1: General requirements for using the finite-difference time-domain (FDTD) method for SAR calculations*
- [42] IEC 60154-2, *Flanges for waveguides – Part 2: Relevant specifications for flanges for ordinary rectangular waveguides*

- [43] IEEE Std C95.3-2002, *IEEE Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields With Respect to Human Exposure to Such Fields, 100 kHz–300 GHz*
- [44] Loader, B., "Computer Simulation of WR159 Waveguide against a Flat Dielectric Phantom at 5.2 GHz and 5.8 GHz," NPL Report DEM EM 008, 2007
- [45] Choi, D.-G., Kim, K.-H., Choi, J.-H., "New Numerical Target SAR Values and an Optimized Flat Phantom for SAR Validation Test in the 150 MHz Band," IEICE TRANS. COMMUN., Vol. E98-B, No. 7, July 2015
- [46] Kim, K.-H., Jang, J.-D., Chung, S.-Y., and Gimm, Y.-M., "A Study on the Meander-Type Dipole Antenna for SAR Validation Test at 150 MHz Band," Proceedings of 2016 URSI AP-RASC (Asia-Pacific Radio Science Conference), pp. 911–913, August 21–25, 2016, Grand Hilton Seoul Hotel, Seoul, Korea
- [47] Kim, K.-H., Choi, D.-G., Gimm, Y.-M., "Automatic RF Input Power Level Control Methodology for SAR Measurement Validation," Journal of Electromagnetic Engineering and Science, Vol. 15, No. 3, pp. 181–184, Jul. 2015
- [48] Meier, K., Burkhardt, M., Schmid, T., and Kuster, N., "Broadband calibration of E-field probes in lossy media," IEEE Trans. Microwave Theory Tech., Oct. 1996, vol. 44, no. 10, pp. 1954–1962
- [49] Person, C., Tanné, G., Ahlonsou, L.N, Ngounou, C., and Grangeat, C., "New reference antennas for SAR probe calibration in tissue equivalent liquid," Millennium Conference on Antennas and Propagation, AP2000, Davos, Switzerland: April 9–14, 2000
- [50] Kuster, N., and Balzano, Q., "Experimental and numerical dosimetry," in Kuster, N., Q. Balzano, and J. C. Lin, eds., Mobile Communications Safety, New York: Chapman & Hall, pp. 13–64, 1997
- [51] Jokela, K., Hyysalo, P., and Puranen, L., "Calibration of specific absorption rate (SAR) probes in waveguide at 900 MHz," IEEE Trans. Instrumen. Meas., Apr. 1998, vol. 47, no. 2, pp. 432–438
- [52] Magee, J. W., "Molar heat capacity (Cv) for saturated and compressed liquid and vapor nitrogen from 65 to 300 K at pressures to 35 MPa," Journal of Research of the National Institute of Standards and Technology, Vol. 96, No. 6, pp. 725–740, Nov./Dec. 1991
- [53] Poković, K., Schmid, T., and Kuster, N., "Robust setup for precise calibration of E-field probes in tissue simulating liquids at mobile communication frequencies," in Proceedings ICECOM '97. Dubrovnik, Croatia, Oct. 12–17, 1997, pp. 120–124
- [54] EIA RS-261-B: 1979, Rectangular Waveguides (WR3 to WR2300)
- [55] Person, C., Ahlonsou, L.N, and Grangeat, C., "New test bench for the characterization of SAR measurement probes used in tissue equivalent liquids," Bioelectromagnetics Society 22nd Annual Meeting, Munich Germany, June 11–16, 2000
- [56] Ishii, N., Sato, K., Hamada, L., Watanabe, S., "Gain calibration in near-field region of antenna in tissue-equivalent liquid for SAR assessment," 2008 Asia-Pacific Symposium on Electromagnetic Compatibility, Singapore, pp.112–115, May, 2008
- [57] Loader, B. G, Gregory, A.P., and Bownds, D., "Coaxial artefact standard for specific absorption rate 100 kHz to 400 MHz," Progress in Electromagnetic Research Symposium (PIERS), 23–27 March, 2009, Beijing, China

- [58] Faraone, A., McCoy, D.O., Chou, C.K., and Balzano, Q., "Characterization of miniaturized E-field probes for SAR measurements," IEEE Intl. Symp. Electromag. Compat., Washington, DC, 2000, pp. 749–754
- [59] Fukunaga, K., Watanabe, S., Wake, K. and Yamanaka, Y., "Time dependence of tissue-equivalent dielectric liquid materials and its effect on SAR," EMC Europe Symp., Sorrento, Italy, Sep. 2002
- [60] Loader, B. G., Gregory A.P., Mouthaan, R., "Formulation and properties of liquid phantoms 1 MHz to 10 GHz," NPL Report TQE 9, June 2017
- [61] Gordon, C.C., Churchill, T., Clauser, C.E., Bradtmiller, B., McConville, J.T., Tebbetts, I., and Walker, R.A., "1988 Anthropometric Survey of U.S. Army Personnel: Methods and Summary Statistics," Technical Report NATICK/TR-89/044, U.S. Army Natick Research, Development and Engineering Center, Massachusetts: Natick, Sep. 1989
- [62] Lee, A.K., and Pack, J.K., "Effect of head size for cellular telephone exposure on EM absorption," IEICE Trans. Commun., Mar. 2002, vol. E85-B, no. 3, pp. 698–701
- [63] Lee, A.K., Choi, H.D., Lee, H.S., and Pack, J.K., "Human head size and SAR characteristics for handset exposure," ETRI J., Apr. 2002, vol. 24, no. 2, pp. 176–179
- [64] Leisten, O., Vardaxaglou, Y., Schmid, T., Rosenberger, B., Agboraw, E., Kuster, N. and Nicolaidis, G., "Miniature dielectric-loaded personal telephone antennas with low user exposure," Electron. Lett., Aug. 20, 1998, vol. 34, no. 17, pp. 1628–1629
- [65] Schönborn, F., Burkhardt, M., and Kuster, N., "The difference of EM energy absorption between adults and children," Health Phys., Feb. 1998, vol. 74, no. 2, pp. 160–168
- [66] Keshvari, J., Kivento, M., Christ, A., and Bit-Babik, G., "Large scale study on the variation of RF energy absorption in the head & brain regions of adults and children and evaluation of the SAM phantom conservativeness," Physics in Medicine & Biology, 61(8), 2991, 2016
- [67] Hirata, A., Ito, F., and Laakso, I., "Confirmation of quasi-static approximation in SAR evaluation for a wireless power transfer system," Physics in Medicine and Biology, vol. 58, p. N241, 2013
- [68] Laakso, I., Shimamoto, T., Hirata, A., and Feliziani, M., "Quasistatic Approximation for Exposure Assessment of Wireless Power Transfer," IEICE Transactions on Communications, vol. E98.B, pp. 1156–1163, 2015
- [69] Gabriel, S., Lau, R.W., and Gabriel, C., "The dielectric properties of biological tissues: 3. Parametric models for the dielectric spectrum of tissues," Phys. Med. Bio., 1996, vol. 41, no. 11, pp. 2271–2293
- [70] Christ, A., Klingeböck, A., Samaras, T., Goiceanu, C., and Kuster, N., "The dependence of electromagnetic far-field absorption on body tissue composition in the frequency range from 300 MHz to 6 GHz," IEEE Transactions on Microwave Theory and Techniques, vol. 54, no. 5, pp. 2188–2195, May 2006
- [71] Christ, A., Samaras, T., Klingeböck, A., and Kuster, N., "Characterization of the electromagnetic near-field absorption in layered biological tissue in the frequency range from 30 MHz to 6000 MHz," Physics in Medicine and Biology, vol. 51, no. 19, October 2006

- [72] Kangas, I., and Hyttinen, J., "Thermal Simulations for Anatomical Human Models, Part III of Dielectric properties for Tissue Simulating Liquids Study: Extension and Validation Covering a Frequency Range from 30 MHz to 6 GHz," Technical Report, Tampere University of Technology, April 22, 2016
- [73] Christ, A., et al. "The Virtual Family—development of surface-based anatomical models of two adults and two children for dosimetric simulations," *Physics in Medicine & Biology*, vol. 55, no. 2, p. N23, 2009
- [74] Poković, K., Christ, A., Samaras, T., Douglas, M., Kuster, N., "Methods and Instrumentation for Reliable Experimental SAR Assessment at 6 – 10 GHz," The joint annual meeting of the Bioelectromagnetics Society and the European BioElectromagnetics Association, Hangzhou, China, June 5–9, 2017
- [75] Chou, C.-K., Chen, G.W., Guy, A.W. and Luk, K.H., "Formulas for preparing phantom muscle tissue at various radiofrequencies," *Bioelectromag.*, 1984, vol.5, pp. 435–441
- [76] Von Hippel, A., *Dielectric Materials and Applications*. Cambridge: MA: MIT Press, 1954
- [77] Blackham, D.V., and Pollard, R.D., "An improved technique for permittivity measurements using a coaxial probe," *IEEE Trans. Instrumen. Meas.*, Oct. 1997, vol. 46, no. 5, pp. 1093–1099
- [78] Gabriel, C., Chan, T.Y.A, and Grant, E.H., "Admittance models for open ended coaxial probes and their place in dielectric spectroscopy," *Phys. Med. Biol.*, 1994. vol. 39, no.12, pp. 2183–2200
- [79] Pournaropoulos, C.L., and Misra, D.K., "The co-axial aperture electromagnetic sensor and its application in material characterization," *Meas. Sci. Tech.*, 1997, vol. 8, pp. 1191–1202
- [80] Arai, M.J., Binner, G.P., and Cross, T.E., "Estimating errors due to sample surface roughness in microwave complex permittivity measurements obtained using a coaxial probe," *Electron. Lett.*, Jan. 19, 1995, vol. 32, no. 2, pp. 115–117
- [81] Bao, J.Z, Swicord, M.L., and Davis, C.C., "Microwave dielectric characterization of binary mixtures of water, methanol, and ethanol," *J. Chem. Phys.*, Mar. 12, 1996, vol. 104, no. 12, pp. 4441–4450
- [82] Clarke, R.N., Gregory, A.P., Hodgetts, T.E., and Symm, G.T., "Improvements in coaxial sensor dielectric measurement: relevance to aqueous dielectrics and biological tissue," in *Microwave Aquametry: Electromagnetic Wave Interaction With Water-containing Materials*, A. Kraszewski, ed., New York: IEEE Press, 1996, pp. 279–297
- [83] Mosig, J.R., Besson, J.C.E, Gex-Fabry, M., and Gardiol, F.E., "Reflection of an open-ended coaxial line and application to non-destructive measurement of materials," *IEEE Trans. Instrumen. Meas.*, 1981, IM-30, pp 46–51
- [84] Nevels, R.D., Butler, C.M., and Yablon, W., "The annular slot antenna in a lossy biological medium," *IEEE Trans. Microwave Theory Tech.*, 1985, MTT-30, pp 314–319
- [85] Toropainen, A., Vainikainen, P., and Drossos, A., "Method for accurate measurement of complex permittivity of tissue equivalent liquids," *Electron. Lett.*, 2000, vol. 36, no. 1, pp. 32–34
- [86] Hill, N.E., Vaughan, W.E., Price, A.H., and Davies, M., *Dielectric Properties and Molecular Behaviour*, London: Van Nostrand Reinhold, 1969

- [87] Gabriel, S., Lau, R. W., and Gabriel, C., "The dielectric properties of biological tissues: II. Measurement in the frequency range 10 Hz to 20 GHz," *Physics in Medicine and Biology*, Vol. 41, No. 11, pp. 2251–2269, 1996
- [88] Kaatz, U., "Complex permittivity of water as function of frequency and temperature," *J. Chem. Engin. Data*, 1989, vol. 34, no. 4, pp. 371–374
- [89] Gregory, A.P. and Clarke, R.N., "Tables of the Complex Permittivity of Dielectric Reference Liquids at Frequencies up to 5 GHz," NPL Report MAT 23, Materials Division, Teddington, England: National Physical Laboratory, Revised Jan 2012, ISSN 1754-2979
- [90] Rocher, F., Julien, T., Derat, B., "Impact of a Hand Phantom on the Measured Average SAR," presentation to ICES TC-34 committee, December 11, 2008
- [91] Bit-Babik, G., Summary and Review of the SAM Study Phase III, April 2012
- [92] Derat, B., Gabriel, S., Faraone, A., "Hand effect measurement interlab: final report," presentation to IEC MT 62209, August 2011
- [93] Derat, B., Gabriel, S., Faraone, A., "Hand effect measurement interlab: Conclusions of the study," presentation to IEC MT 62209, Dec 2011
- [94] Christ, A., "Analysis of the exposure of the hand and its impact on the absorption in the heads of cell phone users," presentation to IEC MT 62209, January 2013
- [95] Kuster, N., Douglas, M., "Proposal for inclusion of the hand for IEC 62209," IEC MT 62209 meeting, Thessaloniki Greece, June 2013
- [96] Douglas, M., Bucher, C., Ofli, E., Derat, B., Gabriel, S., Kuster, N., "Investigation of the influence of the Hand on Head SAR," IEC MT 62209 meeting, Newbury UK, March 2010
- [97] Douglas, M., Kuster, N., "Summary of two studies of hand effect on SAR in head," IEC MT 62209 meeting, Brisbane Australia, June 17, 2012
- [98] Li, C-H., Douglas, M., Ofli, E. Derat, B. and Kuster, N., "Investigation of the influence of the Hand on Head SAR," report to IEC PT 62209 MT-1, April, 2010
- [99] Nesterova, M., Review of Head-Hand Studies between 1997-1999, April 2012
- [100] Kivento, M., Keshvari, J., "Hand effect during the use of real mobile phones," Jan 2013
- [101] Park, G. B., Joyner, K., Jang, J. D. "Modified DUT Holder for SAR Measurement," IEC 62209 MT1 Meeting Turin, 11–13 Sept. 2012
- [102] Joyner, K., Jang, J.D., Park, G.B., Park, Y. H., "2nd Modified DUT Holder for SAR measurement," IEC 62209 MT1 Meeting, Ft Lauderdale, 22–24 Jan. 2013
- [103] Joyner K., "The Case to Exclude the Hand," IEC 62209 MT1 Meeting, Newbury, 7–9 May 2013
- [104] Monebhurrin, V., Wong, M. F., Gati, A., Wiart, J., "Study of the influence of the hand on the specific absorption rate evaluation of mobile phones," in *Proc. URSI*, Istanbul, Aug. 2011

- [105] Monebhurrin, V., Wong, M. F., Gati, A., Wiart, J., "Numerical and experimental investigations of the influence of the hand on the specific absorption rate evaluations of mobile phones," in Proc. 33rd Annual Meeting of the Bioelectromagnetics Society, Halifax, June 2011
- [106] Monebhurrin, V., "Influence of the hand on the specific absorption rate assessments of mobile phones," *Microwave Optical Technology Letters*, 54, 3, 2012, pp. 654–656
- [107] Monebhurrin, V., "Study of the influence of a CTIA hand phantom on the specific absorption rate measurements of mobile phones," in Proc. BioEM 2013, Thessaloniki, June 2013
- [108] Francavilla, M. and Schiavoni, A., "Effect of the Hand in SAR Compliance Tests of Body Worn Devices," *Applied Computational Electromagnetic Society Conference*, Verona, Italy, March 21, 2007
- [109] Li, C.H., Douglas, M., Ofli, E., Chavannes, N., Balzano, Q., Kuster, N., "Mechanisms of RF Electromagnetic Field Absorption in Human Hands and Fingers," *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 7, pp. 2267–2276, July 2012
- [110] Li, C.H., Douglas, M., Ofli, E., Derat, B., Gabriel, S., Chavannes, N., Kuster, N., "Influence of the Hand on the Specific Absorption Rate in the Head from a Mobile Phone," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 2, pp. 1066–1074, February 2012
- [111] Li, C.-H., Ofli, E., Chavannes, N., and Kuster, N., "Effects of hand phantom on mobile phone antenna performance," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 9, pp. 2763–2770, Sep. 2009
- [112] CTIA, "CTIA test plan for wireless device over-the-air performance, revision 3.7.1," CTIA Wireless Association, Feb. 2018
- [113] Greiner, T.M., "Hand Anthropometry of US Army Personal," *Army Natick Research Development and Engineering Center, Technical Report Natick/TR-92/011*, Dec. 1991
- [114] Tilley, A.R., and Henry Dreyfuss Associates, "The Measure of Man and Woman: Human Factors in Design," Wiley, Dec. 31, 2001
- [115] Buchholz, B., Armstrong, T.J. and Goldstein, S.A., "Anthropometric data for describing the kinematics of the human hand," *Ergonomics* vol. 35, no. 3, pp. 261–273, 1992
- [116] Bugbee, W.D., and Botte, M.J., "Surface Anatomy of the Hand: The Relationships Between Palmar Skin Creases and Osseous Anatomy," *Clinical Orthopaedics and Related Research*, 296, 122–126, 1993
- [117] Derat, B., "Impact of the hand on the averaged SAR in the head: simulation of a CAD phone model," presentation to IEC PT62209 MT-1, April 22, 2009
- [118] Pelosi, M., Franek, O., Knudsen, M. B., Christensen, M., and Pedersen, G. F., "A grip study for talk and data modes in mobile phones," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 4, pp. 856–865, Apr. 2009
- [119] Pelosi, M., Franek, O., Pedersen, G.F., Knudsen, M., "User's Impact on PIFA Antennas in Mobile Phones," *IEEE 69th Vehicular Technology Conference*, Barcelona, Spain, 26–29 April 2009

- [120] Wu, T., Lin, X., Yang, J., Zhao, C., Zhang, C. and Shao, Q., "TD-SCDMA Mobile Phone's SAR Measurement about OTA Hand Phantom," Progress in Electromagnetics Research Symposium, Xi'an, China, March 22–26, 2010
- [121] Pradier, A., Colas, O., Celin, P., Sarrebourse, T., Laudru, D., Wong, M.-F., Fouad Hanna, V., Wiart, J. "Evaluation of the Specific Absorption Rate Induced by the Handset Close to the Body," in BEMS 28th Annual Meeting, 2006
- [122] Diller, K.R., Adapting adult scald safety standards to children (2006) J Burn Care Res 27: 314–22
- [123] Gemperle, F., Kasabach, C., Stivoric, J., Bauer, M., and Martin, R., *Design for Wearability*, Techn. Rep. [online]. Carnegie Mellon University, PA (USA) [viewed 2019-07-16], Available at <https://www.cs.cmu.edu/~15-821/READINGS/PAPERS/gemperle1998.pdf>
- [124] Douglas, M., Bit-Babik, G., Nadakuduti, J., Faraone, A., and Chou, C-K., "Modeling of SAR in the User for Body-Worn Wireless communication devices, " Proc. 29th Annual Meeting of the Bioelectromagnetics Society (BEMS 2007), Kanazawa, Japan, June 11–15, 2007
- [125] Taylor, J.R., An Introduction to Error Analysis: The Study of Uncertainties In Physical Measurements. 2nd ed. Sausalito, CA: University Science Books, 1997
- [126] Evans, S., and Michelson, S.C., "Intercomparison of dielectric reference materials available for the calibration of an open-ended probe at different temperatures," Meas. Sci. Tech., Dec. 1995, vol. 6, no. 12, pp. 1721–1732
- [127] Jenkins, S., Hodgetts, T.E., Clarke, R.N., and Preece, A.W., "Dielectric measurements on reference liquids using automatic network analysers and calculable geometries," Meas. Sci. Tech., July 1990, vol. 1, no. 7, pp. 691–702
- [128] Migliore, M.D., "Partial self-calibration method for permittivity measurement using truncated coaxial cable," Electron. Lett., July 20, 2000, vol. 36, no. 15, pp. 1275–1277
- [129] Nyshadam, A., Sibbald, C.L, and Stuchly, S.S., "Permittivity measurements using open-ended sensors and reference liquid calibration – an uncertainty analysis," IEEE Trans. Microwave Theory Tech., Feb. 1992, vol. 40, no. 2, pp. 305–314
- [130] Press, W.H., Flannery, B.P., Teukolsky, S.A., and Vetterling, W.T., *Numerical Recipes in FORTRAN 77: The Art of Scientific Computing*, New York: Cambridge University Press, 1992
- [131] Fieguth, P.W., Karl, W.C., Willsky, A.S., and Wunsch, C., "Multi-resolution optimal interpolation and statistical analysis of TOPEX/POSEIDON satellite altimetry," IEEE Trans. Geosci. Remote Sens., Mar. 1995, vol. 33, pp. 280–292
- [132] Lancaster, P., and Salkauska, K., *Curve and Surface Fitting: An Introduction*. New York: Academic Press, 1986
- [133] Ferreira, P.J.S.G., "Non-iterative and fast iterative methods for interpolation and extrapolation," IEEE Trans. Sig. Proc., Nov 1994, vol. 41, pp. 3278–3282
- [134] Ford, C., and Etter, D.M., "Wavelet basis reconstruction of nonuniformly sampled data," IEEE Trans. Circuits Sys. II: Analog Dig. Sig. Proc., Aug. 1998, vol. 45, no. 8, pp. 1165–1168

- [135] Ustuner, K.F., and Ferrai, L.A., "Discrete splines and spline filters," *IEEE Trans. Circuits Sys.*, July 1991, vol. 39, no. 7, pp 417–422
- [136] ISO 10012:2003, *Measurement management systems – Requirements for measurement processes and measuring equipment*
- [137] EA-2/07 (rev.01), *EAL Strategy to Achieve Comparability of Results in Calibration and Testing*, Mar. 1997
- [138] ISO/IEC 17043:2010, *Conformity assessment – General requirements for proficiency testing*
- [139] Onishi, T., et. al, "LTE SAR measurement consideration," IEC TC106 MT1 meeting in Turin, Sept. 2012
- [140] Onishi, T., "Considerations on SAR measurement for recent trend of the usages and new technologies," 7th European Conference on Antennas and Propagation (EuCAP) 2013, March 2013
- [141] Onishi, T., "Investigation on SAR measurement procedure using SAM and Flat phantoms for LTE handsets," IEC TC106 MT1 meeting in Ottawa, Sept. 2013
- [142] Hinkley, D.V., "On the ratio of two correlated normal random variables," *Biometrika*, Vol. 56, No. 3, pp. 635–639, Dec. 1969
- [143] IEC TR 63424-1:2024, *Validation of dynamic power control and exposure time-averaging algorithms - Part 1: Cellular network implementations for SAR at frequencies up to 6 GHz*
- [144] Shimizu, Y., and Nagaoka, T., "Report of Hand SAR Measurement Using Commercially Available Smartphones," presentation to IEC/IEEE JWG14, February 24, 2025
- [145] Douglas, M., Ofli, E., and Kuster, N., "Investigation of Hand Grip and Hand Exposure During Voice Call Using a Mobile Phone," *Proc. BioEM Annual Meeting*, Oxford, UK, June 2023
- [146] Persson, T., Törnevik, C., Larsson, L.E., and Lovén, J., "Output power distributions of terminals in a 3G mobile communication network," *Bioelectromagnetics*, 33(4), 320-325, 2012
- [147] Joshi, P., Ghasemifard, F., Colombi, D., and Törnevik, C., "Actual output power levels of user equipment in 5G commercial networks and implications on realistic RF EMF exposure assessment," *IEEE Access*, 8, 204068-204075, 2020
- [148] Vermeeren, G., Verloock, L., Aerts, S., Martens, L., and Joseph, W., "In situ assessment of uplink duty cycles for 4G and 5G wireless communications," *Sensors*, 24(10), 3012, 2024
- [149] Douglas, M., Jain, N., Kochali, B., and Kuster, N., "Electromagnetic Exposure from Wireless Devices as Function of Distance," *Proc. Of the XXXVth General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS)*, Sapporo, Japan, August 2023 (IEEE)