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RF Dosimetry for Mobile Telephone Handsets

Q. Balzano, Ph.D. and C.K. Chou, Ph.D.
Motorola Florida Research Laboratories
Fort Lauderdale, Florida, U.S.A.
Presented by K. Joyner, Ph.D.

Introduction

Unlike ionizing radiation (radiation above the ultraviolet region of the electromagnetic spectrum), nonionizing radio frequency (RF) radiation (3 kHz to 300 GHz) with the same external EM field intensity in the far field can produce significantly different levels of energy absorption in an exposed body, depending on the tissue geometry and orientation [Chou et al., 1996]. In the near field, such as from exposure to the mobile telephone handsets, the energy coupling is further complicated by the phone geometry and positioning [Balzano et al., 1978; Stuchly et al., 1987; Kuster and Balzano, 1992]. Some of the radiated RF energy from the mobile phone is absorbed in the human body, and its maximum absorption is usually at the surface of the high water content tissue in the head or hand. In the United States, the Federal Communications Commission (FCC) adopted the RF exposure limits of ANSI/IEEE C95.1 [1992] and NCRP Report 86 [1986], and requires Specific Absorption Rate (SAR) evaluation of mobile handsets to determine RF exposure compliance [FCC OET65, 1997].

Recognizing the complexity of the SAR evaluation, the Institute of Electrical and Electronics Engineers (IEEE) Standard Coordinating Committee (SCC) 34 formed Sub-committee (SC) 2 in February 1997 to develop standardized protocols for wireless handset SAR certification. Officials of the Food and Drug Administration (FDA) and FCC are essential members of the SC2, working closely with about 40 international academic and industrial experts. This subcommittee is still discussing and drafting the standard. A final document is expected to be published in 2000. In this presentation, the methods used by Motorola to test the mobile phones and radios for FCC compliance are described. When appropriate, new decisions made by SCC34/SC2 are also included.

Methods and Procedures

Although SAR can be obtained either with E field or temperature measurement, the use of simulated tissue models probed with small electric field sensors is preferred for testing low power wireless devices [Balzano et al, 1995; Gandhi et al., 1996; Okoniewski and Stuchly, 1996; Watanabe et al. 1996; Meier et al., 1997]. Using temperature measurement for SAR determination requires high power exposures [Guy and Chou, 1986], therefore only the E-field probe method will be described. Basically, the SAR is measured with a computer-controlled robot used to position a miniaturized electric field probe in a human head shaped phantom filled with tissue-simulating liquid when exposed to a mobile telephone. The SAR system consists of an E-field probe, a probe holder, differential amplifiers, high impedance cables connecting the probe to the differential amplifiers and the amplifier outputs to a personal computer, the robotic arm, simulated tissue phantom, and a holder assembly for positioning the phone to the phantom.

Definition of SAR

Specific absorption rate is the time derivative (rate) of the incremental energy absorbed by (dissipated in) an incremental mass contained in a volume element of a given density. SAR is expressed in units of watts per kilogram (W/kg). *SAR* can be related to the electric field at a point by $SAR = \frac{\sigma |E|^2}{\rho}$, where σ = conductivity of the tissue (S/m), ρ = mass density of the tissue (kg/m^3), E = total RMS electric field strength (V/m). *SAR* can also be related to the increase in temperature at a point by $SAR = \frac{c\Delta T}{\Delta t}$, where ΔT = change in temperature (°C), Δt = duration of exposure (seconds), c = specific heat capacity (J kg^{-1} C^{-1}). This assumes that measurements are made under adiabatic conditions, i.e. no heat loss by thermal diffusion, heat radiation, or thermoregulation due to blood flow or sweating.

E-field Probe

Because E and H fields near mobile phones have highly variable magnitude, phase and orientation, the induced E fields inside the tissue are also complex. The E-field probe for SAR-measurements should be small and isotropic, should have a linear response between voltage and SAR, and should not perturb the RF fields significantly. To be isotropic, E-field probes consist of three orthogonally oriented short dipole antennas. Each antenna element has a diode detector, a dielectric mechanical support, a dielectric coating and high resistance leads to feed a rectified electric signal to the electronic readout device. The three dipoles can be mounted on the substrates and shaped as I-beam or triangular-beam. The triangular-beam probe works better than the I-beam probe in terms of isotropy.

Characterization of E-field Probe: Due to the deviation from ideal probe and the variation of probe construction, it is necessary to characterize the probes to know their limits in terms of isotropy, spatial resolution, linearity and offset errors. The isotropy can be assessed within the corresponding media in a spherical bowl by rotating the probe around its axis, rotating the field polarization from normal to parallel to the incident plane (determined by the probe axis and the incident propagation vector), and varying the incidence angle from 0 to 90°, thus obtaining hemispherical receiving pattern. The spatial resolution of a probe measures its ability to discriminate two RF sources in close proximity. Due to the finite dimensions of the probe, the probe output is not related to field strength at one point but depends on the field in a certain volume around the probe sensors. Probe non-linearity is due to the diode detector used to rectify the dipole sensor voltage output. For CW and modulated fields, the non-linearity must be compensated properly according to the temporal characteristics. Offset error is the DC voltage shift even when there is no RF field. This error can be measured and compensated for in the system.

When the probe approaches the model boundary, the probe response has a sudden increase in the measured values. This boundary effect is due to the disturbance of the field from the finite size probe. With commercially available probes (3-7 mm in diameter) it is recommended that SAR not be measured through media boundaries. The actual field near the boundary can be extrapolated from the field values away from the boundary. The high resistance leads of the probe as well as the electronic circuit can pick up the unintended RF or power line frequency interference. Proper grounding and filtering must be introduced if necessary to protect the instrumentation.

SCC34/SC2 Recommended Performance Specifications: Table 1 summarizes the E-field probe performance range that is achievable with current industrial manufacturing resources. The sensors and their feed lines must be contained in a rigid, sealed, and low dielectric constant enclosure. This structure must be rigid to facilitate precision probe positioning and chemically resistant to the components of the mixtures simulating human tissue.

Table 1 E-Field Probe Recommended Specifications

Parameter	**Specification**
Frequency band:	800-2200 MHz

Sensor length:	1-2 mm
Sensor mounting geometry:	Triangular beam (preferred)
Isotropy uncertainty over hemisphere:	±15%
Spatial Resolution:	7-9 mm
Probe measurement range:	10 mW/kg - 100 W/kg
Linearity (with compensation):	±1% over measurement range
Offset error:	Less than 5 mW/kg
Probe enclosure diameter:	7 mm OD or less

Phantom Materials

Phantom tissues have been developed to simulate tissue dielectric properties for dosimetry purpose. Dielectric properties consist of dielectric constant and equivalent conductivity (S/m) which are frequency dependent, the former decreases and the later increases with frequency. Dielectric properties of tissues have been studied for several decades [Schwan and Piersol, 1954; Stuchly and Stuchly, 1990]. Data variations are large which was due to different measurement methods, temperature, freshness of tissue, etc. Recently, most RF dosimetry researchers use the comprehensive data collected by Gabriel [1996] using improved instrumentation. The information is available on the Internet and used by FCC as reference data. SCC34/SC2 has decided to use the Cole-Cole plot data as published on the Internet.

The next question is which head tissues should be considered. Currently, most mobile phone tests have been conducted with a liquid simulating the average brain gray and white matters. SCC34/SC2 has adopted a weighting function method, which will include different proportions of skin, fat, muscle, bone, gray and white matters. The exact formula is to be determined after a modeling study is completed. Before a final decision on the phantom materials, Motorola will continue to use the existing formulas (Table 2) for mixing the brain simulating liquid.

Table 2 Recipes for mixing brain-simulating liquids

Tissue	Freq. (MHz)	Water (%)	Sugar (%)	Salt (%)	Glycol* (%)	HEC* (%)	Bactericide (%)	ε	σ (S/m)
Brain	835	43.55	54.66	0.72		0.90	0.17	44.0	0.90
Brain	935	43.55	54.66	0.72		0.90	0.17	44.0	0.93
Brain	1500	54.90		0.18	44.92			41.1	1.00
Brain	1600	54.90		0.18	44.92			40.9	1.14
Brain	1800	54.90		0.18	44.92			40.3	1.35
Brain	1900	54.90		0.18	44.92			39.9	1.42

*Glycol is Diethylene Glycol Butyl Ether.
HEC is hydroxyetheylcellulose, a nonionic water-soluble polymerizing agent.

Liquid tissue equivalent materials can be characterized with a slotted line [Chou et al., 1984], or a coaxial probe technique [Burdette et al., 1980; Gabriel et al., 1996]. Due to the lower uncertainty of the slotted line method (1%) than the probe technique (5%), Motorola prefers to use the slotted line method. Liquids should be characterized periodically (daily or weekly) to ensure the intended dielectric parameters are maintained within the tolerance limits (±5% around the target values) and excessive evaporation has not occurred.

Phantom model

SCC34/SC2 has agreed to use an anthropomorphic human head and neck for the mobile phone SAR certification. The size and shape of the head will follow the 90 percentile data published in 1988 on more than 2000 US Army service personnel. The compressed ear spacing was decided to be 10 mm from the head surface. A CAD file will be made from this head model and it will be available on the Internet. A less than 2-mm thick fiberglass shell model (at the measurement location) can be made from this mold. The fiberglass dielectric constant should be less than 5 and conductivity less than 0.01 S/m. FCC requires that both sides of the head are tested to count for the asymmetric antenna locations relative to the ears, therefore a right and a left model are necessary. Liquid head simulating tissue for the proper testing frequency will fill the fiberglass model at least 10 cm deep at the site with maximum SAR. There will be no hand holding the phone. The reasons for the large head, homogenous tissue liquid and no hand are that these conditions give the worst cases [Watanabe et al., 1996; Kuster et al., 1997; Schönborn et al., 1998], and the procedures are simplified. Whether the ear should be lossy or lossless is to be determined in the next committee meeting on June 15-16, 1999. In either case, it is impossible to measure the SAR in the ear due to its anatomical structure and the size of the E-field probe. Currently, Motorola uses a large man model with a 4-mm thick ear shaped lossless dielectric material (6 mm from the brain liquid to the contacted phone).

SAR Determination

Motorola has used two systems for SAR measurements, which are available from IDX (Portland, Oregon) and DASY (Zurich, Switzerland). They both are computer-controlled robotic system with E field probes for SAR scans in the liquid phantom.

System Calibration: The system must be calibrated first in free space and then in the liquid to be tested. The free space calibration is done in a TEM cell with a known field strength. DC drifts are taken care of during this calibration. Next, the calibration will have to be done for each tissue simulating liquid in a rectangular box and operating frequency with a half wave dipole antenna underneath. Since the calibration must be done in a field with a gradient identical to that of the target tissue, the location of the calibration point in the probe (e.g., probe tip, probe sensor centers, etc.) must be indicated. A SAR conversion factor is obtained by measuring the temperature rise in the liquid phantom with known specific heat.

Mobile Phone Positioning: Attaching the phone to the phantom model, Motorola currently uses a three point contact position for the cell phone tests. The earphone is in touch with the ear and the third contact point is the cheek. FCC is considering revising it to: either 80 degrees from the outer angle versus the line through both ears, or touching the cheek. Before the final decision is made by the SCC34/SC2, Motorola will continue with the existing practice. The phone is set for the maximum RF power output.

SAR Scan: The robot scans the phantom over a selected area to find the region of the highest RF field. Then, using a higher spatial resolution, the robot finds the location with the highest SAR.

Data Extrapolation and Interpolation: Due to the construction of the E-field probe and the boundary effect, it is necessary to extrapolate the SAR to the liquid-fiberglass interface. To accomplish this, the field is measured as close as possible to the hot spot near the surface and the probe is retracted every 5-mm for 5 cm. The average slope is obtained from the three data points nearest the surface and to define an exponential decay with depth. To obtain the 1-gram average SAR, the extrapolated voltage reading at the surface and the interpolated voltage reading at 1 cm inside the phantom surface are averaged and the SAR conversion factor applied.

Compliance Determination: Taking into consideration the battery slump during the SAR test, maximum SAR is calculated for maximum telephone output power. This final SAR number is compared with 1.6 W/kg for the uncontrolled environment primarily for the general population and 8 W/kg for the controlled environment for occupational applications, as specified by the FCC.

Conclusions:

SAR measurement is a complicated procedure. The uncertainty is estimated to be about 30%. Differences in dielectric properties of the simulated tissue, size and geometry of the phantom shell, as well as the positioning of the phone relative to the model, can make big differences in the final SAR results. The IEEE SCC34/SC2 is working on a standard to define the various parameters. When all test laboratories use the same set of parameters, the variations can be reduced. Even so, the complexity of the measurement still limits only specialized laboratories to conduct the tests. It takes time to learn the many details of the SAR measurements.

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