1. System Calibration

The SAR measurement system has two main components:

a) the probe, which is connected to the inputs of
b) the instrumentation amplifier whose outputs are connected through the transmission line to
c) the computer.

The system is calibrated as one unit not as individual components. If any components is modified or replaced, the system must be re-calibrated.

The system calibration is performed by two steps:

1) determination of free space E-field from amplified probe outputs in a test RF field, and
2) correlation of the measured free space E-field and the measured E-field in the medium to temperature rise in a dielectric medium.

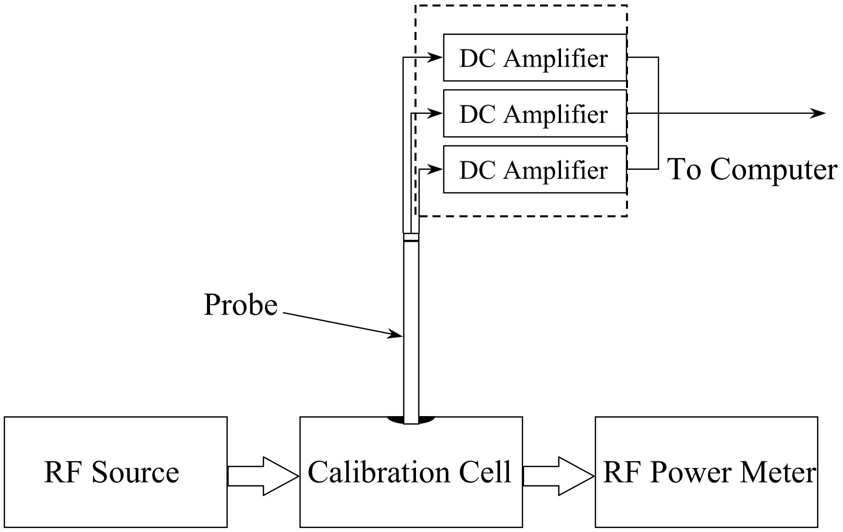
1.1 Determine E-Field from Amplified Probe Outputs

Note: Equipment must be regularly calibrated.
Warning! Observe recommended warm-up time (20 min).

- RF Signal Generator - frequency range to at least 3 GHz,
- RF Amplifier - if needed to generate the required power density in the test cell,
- Test Cell - TEM (Crawford) cell, waveguide, or other device capable of maintaining a uniform field. (Wave-guide if frequencies are above 1.0 GHz)
- RF Power Meter - capable of measuring at least 5 Watts (current calibration is mandatory!) if possible traceable to the National Institute of Standards and Technology (NIST).
- E-Field Probe (under Calibration)
- Probe Support Fixture
- Instrumentation Amplifier
- Transmission Line
- Computer Program with the Automated Calibration System Program

1.1.1 Method

Due to impedance variations in the diodes and the transmission line, and slight differences in gain between the channels of the instrumentation amplifier a normalization method was designed. The calibration method actually used is to determine the factors necessary adjust each channel of the system so its indicated output can then be equated to the RF field. These factors are referred to as "amplifier settings".



Amplifier Setting Calibration Setup

1.1.2 Measurement

Free Space Calibration of E-field probes can be performed using a TEM cell manufactured by IFI (Instrumentation for Industry, Farmingdale, NY 11735) with operating frequency at or below 1 GHz.(Wave-guide above 1 GHz)

- Connect the equipment as shown above;
- Adjust the RF generator output so that the power density inside the TEM cell is 1 mW/cm^2. (For the IFI model CC-110 cell, the correct power level is 271 mW);
- Mount the probe of the system to calibrate in the support fixture. Insert the probe through the aperture of the TEM cell. The probe handle should be at the geometric center of the aperture, i.e. midway between the septum and the upper surface, and orthogonal to the side of the cell. The sensing portion of

the probe should be located at a point halfway across the depth of the cell (volumetric center).

- Once the prescribed position is obtained, it must be maintained during the rest of the measurement. The only movement of the probe allowed is rotation on its axis to position the dipole in the plane of the E-field and, for channel 3 only, parallel to the vertical uniform field (max./min. output).
- Verify that the RF power level remains constant throughout the measurement. While the probe is being rotated through 360 degrees, software indicators will show the maximum measured on each channel.

Thus, the amplifier settings for each channel are as follows:

$$AS_1 = \frac{\left(\frac{Sensor\_Factor}{2}\right)}{V_{\max_1} - DC_1}$$

$$AS_2 = \frac{\left(\frac{Sensor\_Factor}{2}\right)}{V_{\max_2} - DC_2}$$

$$AS_3 = \frac{Sensor\_Factor}{V_{\max_3} - DC_3}$$

Where:

As_n = Amplifier Setting for channel n

Sensor Factor = an arbitrary value 10.8 mV/mW/cm^2

$Vmax_n$ = Maximum voltage recorded for channel n by rotation about the probe axis with the probe in a TEM cell (E perpendicular to the beginning of the probe axis)

DC_n = DC offset of channel n (the voltage out of the transmission line with the instrumentation amplifier on and RF power off, recorded at the beginning of the probe calibration)

1.2 SAR from Temperature Measurement and Correlation to E-Field Probe

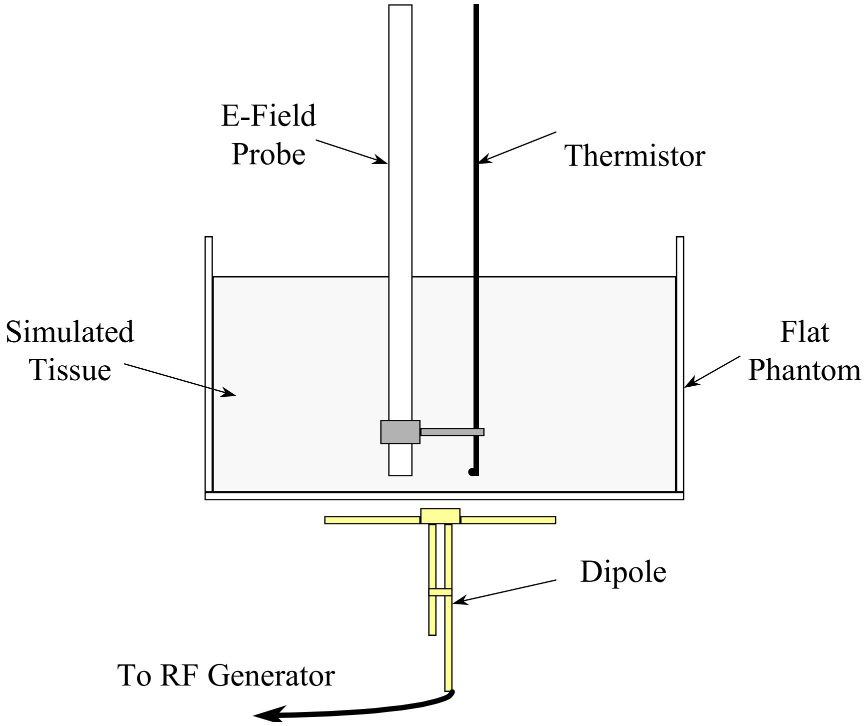
1.2.1 Measurement

A RF transparent thermistor-based temperature probe and a isotropic E-field probe are placed side-by-side in a planar phantom while both are exposed to RF energy from a half wave dipole antenna located below the phantom The E-field probe and amplifiers were previously calibrated.

First, the location of the maximum E-field close to the phantom's bottom is determined as a function of power into the dipole

Then, the E-field probe is moved sideways so that the temperature probe, while affixed to the E-field probe is placed at the previous location of the E-field probe.

Finally, temperature changes for 30 second exposures at the same RF power levels used for the E-field measurement are recorded. Care is taken to allow cooling to the original temperature and temperature stabilization between tests.



Flat Phantom, Thermistor and E-Field Probe

The following simple equation relates SAR to the initial temperature slope:

$$SAR \cdot \Delta t = c \cdot \Delta T \qquad \text{(eq.1)}$$

In (eq.1) Δt is the exposure time (30 sec.), c is the heat capacity of the simulated brain tissue (typically c = 2.7 joules/^{o}C/g) and ΔT is the temperature increase due to the RF exposure. SAR is proportional to $\Delta T/\Delta t$, the initial rate of tissue heating , before thermal diffusion takes place.

From (eq.1) it is possible to quantify the electric field in the simulated tissue by equating the thermally-derived SAR to the E-field:

$$SAR = \frac{|E|^2 \cdot \sigma}{\rho} \text{ (eq.2)}$$

where σ is the simulated tissue conductivity and ρ its density; typically ρ = 1.25 g/cm^3 for simulated brain tissue.

Since, even at the closest practical position, the E-field sensors are at a distance (≈ 4 mm) from the surface of the phantom shell, the field in the simulated tissue near the shell surface must be calculated. To do so, data are obtained as the probe is moved vertically, from the surface of the planar phantom.

The field attenuation is recorded and extrapolated to obtain the $|E|^2$ value at the surface of the phantom, where the maximum SAR is located. This method has given highly repeatable results.

Field attenuation in simulated tissue and result of data extrapolation. Note the surface is at Z' = -0.4cm and the position 1 cm from the surface is at Z' = 0.6 cm.

Determination of SAR Conversion Factor (CF)

The conversion factor scales the E-field in terms of the thermally-derived SAR. It is the quotient of SAR_t, the SAR determined from temperature measurements in the flat phantom, and ΔV_t, the E-field probe output voltage obtained at the same location in the phantom

$$CF_{[mW/g]} = \frac{SAR_t}{\Delta V_t} \cdot 0.0108 \qquad (\Delta V_t \text{ in volts})$$

$$CF_{[mW/g]} = \frac{SAR_t}{\Delta V_t} \cdot 10.8 \qquad (\Delta V_t \text{ in mV})$$

For historical reasons, CF is scaled by the factor 10.8 mV. (see discussion to sensor factor in Appendix B) Note, as a result of the scaling constant (10.8 mV) the dimensions of CF are mW/g.

The temperature E-field correlation is illustrated below (for simulated brain tissue) for an example in which the thermal quantities were,

RF power input = 0.5 W
$\Delta T = 0.0163^{o}C$ (from thermistor base temperature probe)
$c = 2.7\ J/g/^{o}C$ (simulated brain tissue) 3.0 (simulated muscle tissue)
$\Delta t = 30$ sec.

The resulting SAR_t was (eq.1)

$SAR_t = (2.7 \text{ x } 0.0163) / 30 = 1.47$ mW/g

In this case the output of the E-field probe when at the same position as the thermistor probe was

$\Delta V_t = 28.5$ mV (from the software acquisition screen)

The calculation of CF follows:

CF = (1.47 / 28.5) x 10.8 = 0.56 mW/g

2. Data Acquisition Methodology

2.1 E-Field Measurement

The probe calibration must be current before starting measurements. Instrumentation amplifier batteries must be charged. This can be monitored by observing DC offset voltages. A daily log of the DC offset voltages should be kept for this purpose.

Measurements in the phantom are automatically calculated for each location by summation of the three dipole outputs. Because each dipole produces an output voltage proportional to the square of the electric field component along the dipole, the sum of dipole voltages represents the RMS values for the total electric field. Thus, taking into consideration the amplifier settings and the DC offset voltages, the total electric field strength at a measurement location is as follows. See Appendix C. Pd_{tot} is labeled by the software as measure of values (volts). The SAR for calculations that are derived from the measure of values are discussed below.

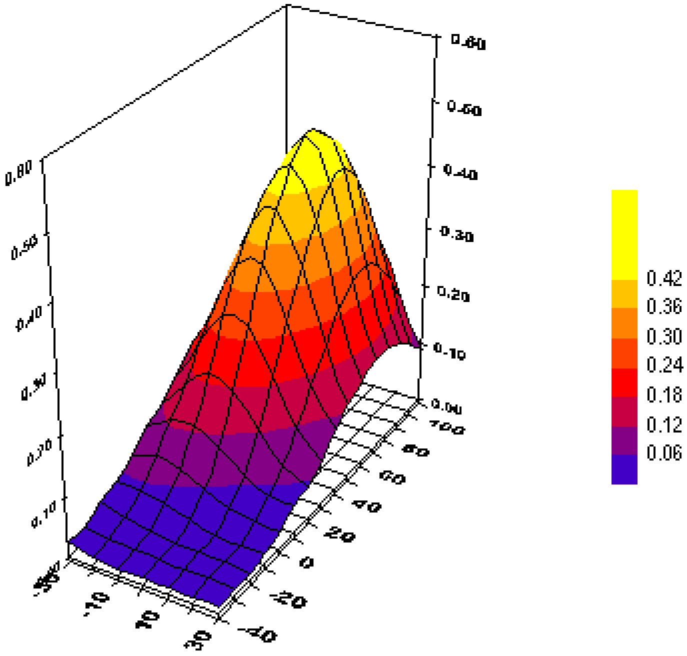
At each measurement point, the program records the output of the three channels:

$E_1 = V_1 - DC_1$
$E_2 = V_2 - DC_2$
$E_3 = V_3 - DC_3$
$Pd_{tot} = (E_1 \times AS_1) + (E_2 \times AS_2) + (E_3 \times AS_3)$

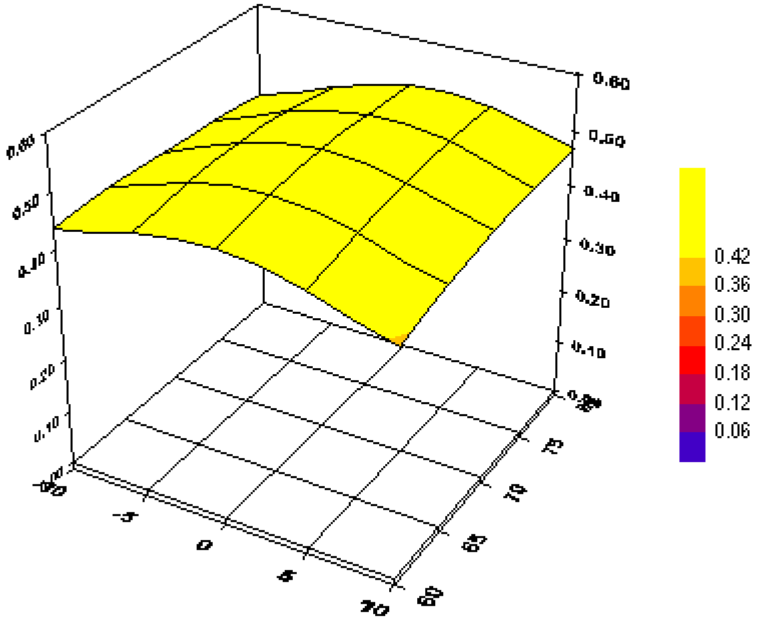
V_n = Voltmeter reading of channel n at one measurement point
E_n = Actual voltage of channel n at one measurement point
AS_n = amplifier setting of channel n
Pd_{tot} = Total probe output at one measurement point (see Appendix C)

2.2 SAR Measurement

The goals of the measurement process are to scan the phantom over a selected area in order to find the region of highest levels of RF energy. Then, to obtain a single value for the peak spatial average of SAR over a volume that would contain one gram (in the shape of a cube) of biological tissue (brain or muscle). The test procedure, of course, measures SAR in the simulated tissue.



The software requests the user to move the probe to locations at two extreme corners of a rectangle that encloses the area to be scanned. An arbitrary origin and the spatial resolution for the scan are also specified. Under program control, the scan is performed automatically by the robot-guided probe.



Next, using a higher spatial resolution, the robot guides the probe through locations with the highest SARs. Finally, the SAR is averaged over the cubic volume surrounding the peak localized SAR. This spatially-averaged SAR is reported as SAR (W/kg).