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.

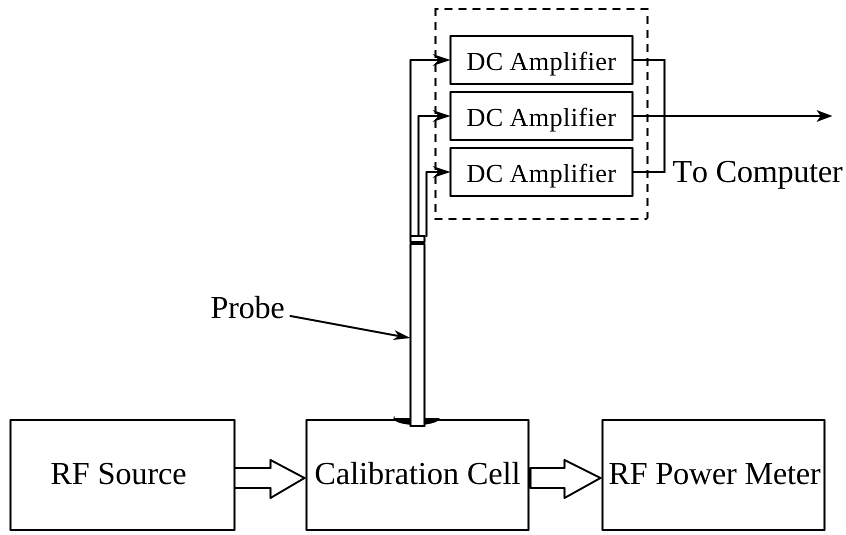
Determine E-Field from Amplified Probe Outputs

Note: Equipment must be regularly calibrated.

- RF Signal Generator - frequency range to at least 2 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,
- 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

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”.



< Free Space Calibration Setup for Amplifier Setting >

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.

- 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:

$$AS_i = \frac{Sensor\_Factor}{V_{\max_i} - DC_i} \times \cos^2 \theta_i$$

Where:

As_i : Amplifier Setting for channel i
Sensor_Factor : an arbitrary value 10.8 [mV/(mW/cm^2)]
$Vmax_i$: Maximum voltage recorded for channel i by rotation about the probe axis with the probe in a TEM cell
DC_i : DC offset of channel i (the voltage out of the transmission line with the instrumentation amplifier on and RF power off, recorded at the beginning of the probe calibration)
θ_i : Angles between the probe axis and the dipole sensor axis of channel i ($\theta_1 = \theta_2 = 45°$, $\theta_3 = 0°$ for I-beam probe, and $\theta_1 = \theta_2 = \theta_3 = 90° - 54.7° = 35.3°$ for triangular probe when the probe axis is assumed to be perpendicular to the plane of the septum inside TEM cell)

SAR from Temperature Measurement and Correlation to E-Field Probe

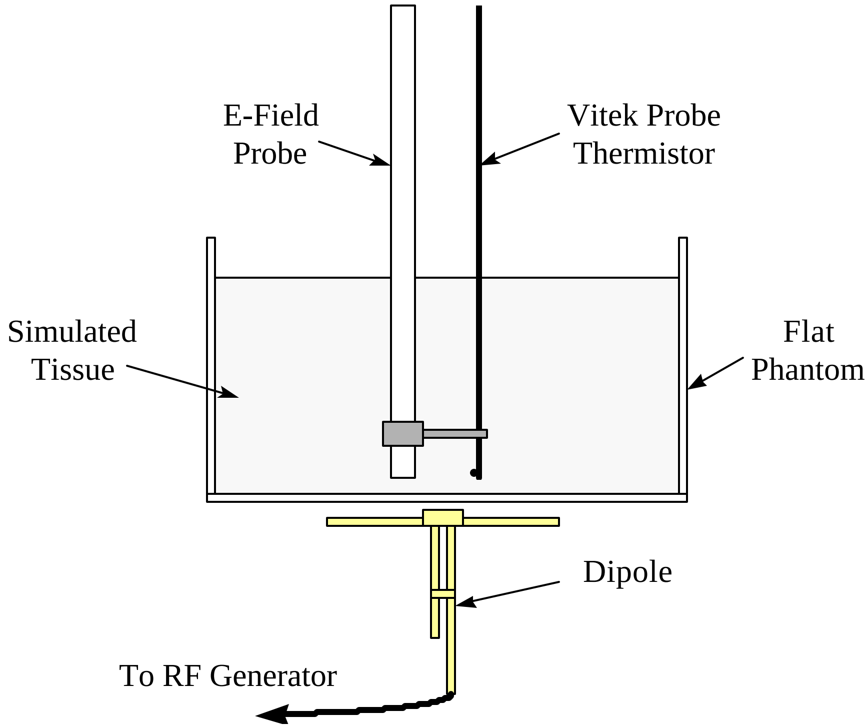
Measurement

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 a certain amount of time (generally 30 seconds) exposures at the same RF power levels used for the E-field are recorded. Care is taken to allow cooling down 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 specific heat capacity of the simulated brain tissue (approximately $c = 2.7$ joules/g/^{o}C for simulated brain tissue) 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:

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

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

Since, even at the closest practical position, the E-field sensors are at a distance ($\approx$ 3 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. (the method is described in the next section).

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 prove output voltage obtained at the same location in the phantom

$$CF_{\left[mW/g/(mW/cm^2)\right]} = \frac{SAR_t}{\Delta V_t} \times 0.0108 \qquad (\Delta V_t \text{ in volts})$$

$$CF_{\left[mW/g/(mW/cm^2)\right]} = \frac{SAR_t}{\Delta V_t} \times 10.8 \qquad (\Delta V_t \text{ in mV})$$

For historical reasons, CF is scaled by the factor 10.8 [mV/(mw/cm^2)]. (see discussion to sensor factor in Appendix B) Note, as a result of the scaling constant (10.8 [mV/(mw/cm^2)]) the dimensions of CF are [mW/g/(mw/cm^2)].

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
$\Delta T = 0.0163^oC$ (from thermistor base temperature probe)
c = 2.7 J/g/^{o}C (simulated brain tissue) 3.0 (simulated muscle tissue)
Δt = 30 sec.

The resulting SAR_t was (eq.1)
SAR_t = (2.7 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
ΔV_t = 28.5 mV (from the software acquisition screen)

The calculation of CF follows:
CF = (1.47[mW/g] / 28.5[mV]) x 10.8 [mV/(mw/cm^2)] = 0.56 [mW/g/(mw/cm^2)]

Data Acquisition Methodology

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.

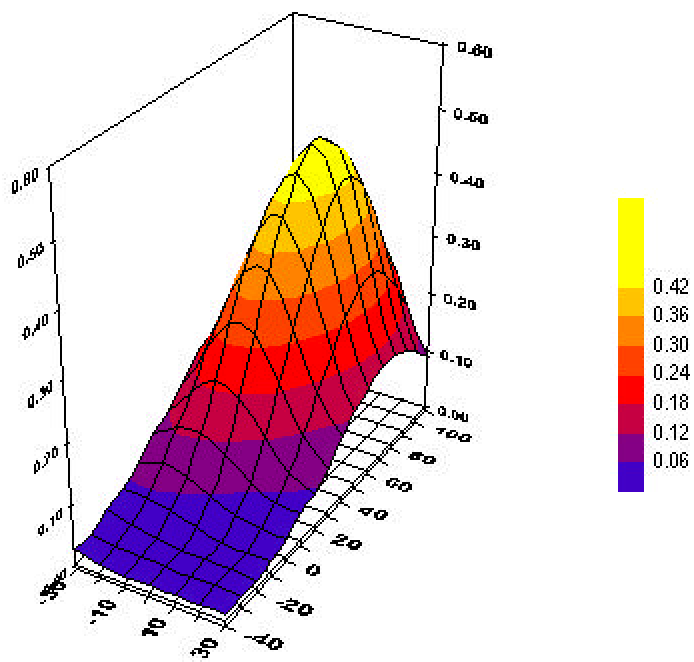
At each measurement point, the program records the output of the three channels:

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

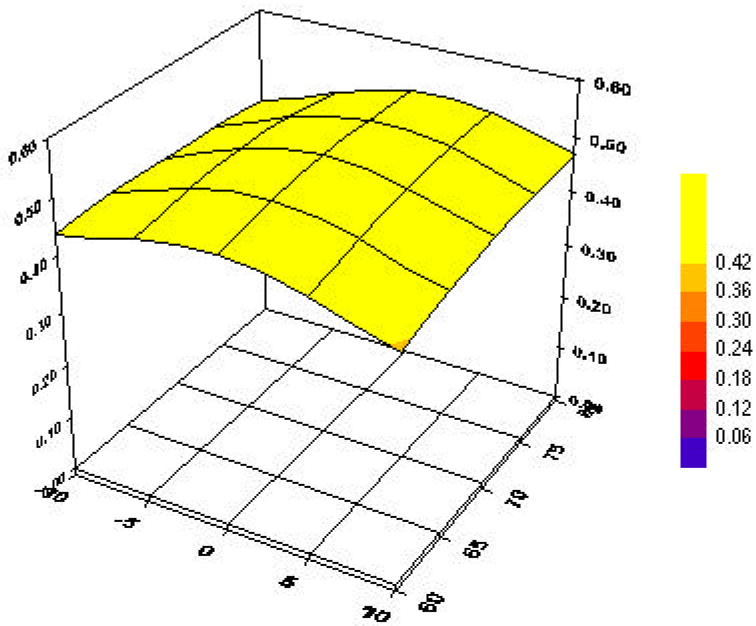
V_n = Voltmeter reading of channel n at one measurement point
E_n = Actual voltage of channel n at one measurement point
AS_n = amplifier setting of channel n
Pd_{tot} = Total probe output at one measurement point (see Appendix C)

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 and 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 request 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 SAR. Finally, the SAR is averaged over the cubic volume surrounding the peak localized SAR. This spatially-averaged SAR is reported as SAR (W/kg).

Data Extrapolation

The distance from the center of the sensor (diode) to the end of the protective tube is called the 'probe offset'. To compensate we use an exponential curve fitting method to obtain the peak surface value from the voltages measured at the distance from the inner surface of the phantom. At the point where the highest voltage was recorded, the field is measured as close as possible to the phantom's surface and every 1mm along the ` Z ` axis for a distance of 50 mm. The appropriate exponential curve is obtained from all the points measured and used to define an exponential decay of the energy density versus depth.

$$E(z) = E_0 \cdot e^{-z/d} \text{ (mV)}$$

Data Interpolation and Gram Averaging

The voltage, (1 cm) above the phantoms surface (E_{tot} 1 cm), is needed to calculate the exposure over one gram of tissue. This SAR value that estimates the average over 1 gram of tissue, is obtained by taking the integral over 1 cm^2 surface of the measured field along the exponential decay curve of the energy density with depth.

$$SAR(mW/g) = \int_{v=1g} SAR(\bullet)dv = \int_{s=1cm^2} \int_0^{1cm} E(z) \cdot \frac{CF}{SensorFactor} dzds$$

Determining the Heat Capacity of Simulated Tissue

Instruments and Materials

- Calibrated differential thermometer (Vitek or BAT-8 or equivalent)
- Two identical 500 ml containers
- A thermally insulated vessel (thick styrofoam, with a form fitting hole for one container)
- Hot and cold tap water
- Solution under test
- Hot plate
- Temperature vs. time (chart recorder, or data loger)

Method

Heat can be propagated by conduction, convection and radiation. In the case of liquids heated from below, gravity convection is the main and predominant heating mechanism of the fluid mass.

Obtain two containers that can be rapidly heated (e.g. glass or suitable plastic). Fill one container with 250 ml of water, the other with the same mass of simulated tissue. The initial temperature of the water should be the same as that of the simulated tissue ($\pm$1°C). Since we are dealing with heating by electromagnetic sources at ambient temperature, it is essential that we eliminate the chance of any direct infrared heating of the temperature sensor. To ensure this, position the tip of the sensor 2 mm from the bottom of the center of the container. Turn on the heat source and wait at least 5 minutes for its temperature to stabilize. Record the initial temperature of the water. Place the container of water 5 mm above the center of the hot plate and monitor the temperature increase.

After 30 seconds of heating, the water temperature should have increased by at least 5°C. Record the time and temperature. Remove the container from the heat source and place it in the thermally insulated vessel. Stir the liquid thoroughly and record the steady state temperature 1-2 minutes after stirring.

Repeat the above procedure using the container of simulated tissue. Ensure that the container is placed on the same area of the hot plate, is heated for the identical length of time, and the steady state temperature is recorded after the identical time interval.

Since the heat capacity of water is C_w = 1 cal/°C/g with excellent approximation (~1%) in the temperature range of interest, the heat capacity (C_s) of the solution is given by:

$$C_s = C_w \cdot \frac{\Delta T_w}{\Delta T_s}$$

where ΔT_w is the temperature increase of water and ΔT_s the temperature increase of the solution. The ration of the values, $\Delta T_w / \Delta T_s$, should be the same (within the sensivity of the thermometer) at the end of the heating and stirring. This ensures that the liquids have been uniformly heated.

Rationale

$$C \cdot \Delta T = Heat\_Flow \cdot Time = Total\_Heating\_Energy$$

If the heat flow, sample mass, and absorption (heat transfer) are the same for both liquids, then:

$$C_w \cdot \Delta T_w = C_s \cdot \Delta T_s$$

The heat flow and total heating are kept constant by using the same source for the same amount of time. If the heat transfer mechanisms for the woe liquids are about the same, with insignificant differences in convective and conductive characteristics, then any differences in temperature increase are a direct measure of the specific heat capacity, C.

Appendix A. *Definition of Amplifier Setting and Other Terms*

Related to Sensor Calibration

The initial sequence of probe calibrations steps performed with SAR determinations produces the factors used in scaling probe output voltage to RF power density. For historical reasons all probes factors are compared to a factor 10.8 mV per mW/cm^2 that was typical of a prototype probe, but is in fact an arbitrary ure. The factor of 10.8 mV/ mW/cm^2 is known as the sensor factor, but does not change. To calibrate a probe, each channel is assigned an amplifier setting. This factor is obtained from the maximum probe output voltage measured during probe calibration. This probe output voltage is corrected for any DC offset of the instrumentation amplifier, usually a very small amount.

During calibration, for probe with I-beam cross-section, the channel 3 is aligned parallel to the E-field, but each of the channel 1 and 2 dipoles are at 45° to the direction of the field, resulting in outputs one half as large. Thus, the amplifier settings for each channel are as follows:

$$AS_i = \frac{Sensor\_Factor}{V_{\max i} - DC_i} \times \cos^2 \theta_i$$

Where:

As_i : Amplifier Setting for channel i
Sensor_Factor : an arbitrary value 10.8 [mV/(mW/cm$^{2)}$]
$Vmax_i$: Maximum voltage recorded for channel i by rotation about the probe axis with the probe in a TEM cell
DC_i : DC offset of channel i (the voltage out of the transmission line with the instrumentation amplifier on and RF power off, recorded at the beginning of the probe calibration)
θ_i : Angles between the probe axis and the dipole sensor axis of channel i (θ_1 = θ_2 = 45°, θ_3 = 0° for I-beam probe, and $\theta_1 = \theta_2 = \theta_3$ = 90° – 54.7° = 35.3° for triangular probe when the probe axis is assumed to be perpendicular to the plane of the septum inside TEM cell)

Appendix B. *Note on Units and Various Calibration Factors*

Three calibration factors, already defined, are used in the process of obtaining electric field strengths and SARs. This note shows how the units applicable to each are consistent and produce suitable units for the final quantities. The units Pd_{tot} are also discussed.

<u>Sensor Factor</u> is a numerical constant fixed by the properties of a particular probe used in the past. It represents the voltage output from a probe placed in a flux density of 1 mW/cm^2.

$$Sensor\_Factor = 10.8\left(mV/(mW/cm^2)\right)$$
$$Sensor\_Factor = 0.0108\left(V/(mW/cm^2)\right)$$

<u>Amplifier Setting</u> (AS) is a calibration factor that reflects the probe and amplifier properties. The values of AS for each channel are computed by the software. The data for the values of each AS are obtained when the E-field probe is rotated for maximum output from the probe channels while in a TEM cell with a field strength of 1 [mW/cm^2]. The AS values are shown on screen and in the output as Amplifier Channel Settings.

For a simple example, assume only channel 3 of the probe had a non-zero output. If CF = 0.56 (mW/g/V), AS_3 = 0.375 and E_3 = 350 mV, the SAR at this location is:

$$SAR = E_3 \cdot AS_3 \cdot \frac{CF}{Sensor\_Factor}$$

$$SAR = 0.350 \cdot 0.375 \cdot \frac{0.56}{0.0108} = 6.81\,[mW/g]$$

The appearance of the Sensor Factor in the denominator for the SAR calculation effectively cancels the introduction of the same scaling constant (10.8) used in making the calculation of CF. See above for discussion of the units for AS and Sensor Factor.

The numerical scaling for CF is based on the TEM cell measurement where a test flux density of 1 mW/cm^2 was used. This flux density corresponds to an electric field strength in the TEM cell of 0.614 V/cm, or the squared value of 0.377 V^2/cm^2 (E^2). For historical reasons, CF is defined in terms on an intermediate scaling constant for a particular probe which produced an output of 10.8 mV in the TEM cell when the field strength was 0.614 V/cm.

The units of the total output of the probe, Pd_{tot} are mV. In physical terms, the probe voltages are developed in diodes and represents an electric field squared (V^2/m^2) and equivalently a power density (W/kg). Therefore, Pd_{tot} is physically appropriate for measurement of SAR. To obtain the power density corresponding to Pd_{tot} perform the following calculation:

$$SAR = Pd_{tot} \times \frac{CF}{Sensor\_Factor}$$

,or to show the units explicitly,

$$SAR(mW/g) = Pd_{tot}(mV) \times \frac{CF\left(mW/g/(mW/cm^2)\right)}{Sensor\_Factor\left(mV/(mW/cm^2)\right)}$$