SAR Measurement
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Introduction
Magnetic resonance (MR) imaging and spectroscopy both use radio frequency (RF) magnetic fields. Unfortunately, patients may absorb a portion of the transmitted RF energy. RF safety concerns include whole-body and localized heating. High core body temperatures may be life-threatening. For local transmit coils, an additional concern is preventing burns. Heating depends on ambient temperature, RF power deposited per unit mass, relative humidity, airflow rate, blood flow, and patient insulation. Specific absorption ratio, SAR, is the power absorbed per unit mass. SAR serves as a crude measure of heating potential. It is essential for patient safety to limit whole-body and localized temperatures to appropriate levels. National and International safety standards appropriately limit SAR.

MR scanners conservatively predict SAR when pulse sequences are prescribed for patients. The SAR predictions may be based on previously acquired measurement data. The National Electrical Manufacturer’s Association (NEMA) has developed standards for measuring whole-body SAR (MS-8) and for measuring local SAR (MS-10). Methods of measurement and estimation of SAR are described below.

Effect of B1 Calibration
RF power deposition levels are affected by the strategy used for calibrating the tip angle. To minimize SAR and to ensure tip angles are not overdriven it is possible to limit standing wave peaks to ninety degrees. This approach may limit shading. Another prescan strategy would be to set the root-mean-square (rms) value of the tip angles across the slice to ninety degrees. Prescan may be designed to return maximum signal across the slice. Adiabatic fast passage pulses saturate at 180 degrees even with increasing B1. Such pulses are useful but increase SAR.

Whole-body SAR Measurement - Pulse Energy Method
The Pulse-Energy Method of NEMA MS-8 (Figure 1) describes measurement of RF energy deposition. It is possible with long repetition periods to play out very low SAR pulse sequences for the purposes of data acquisition. The current required to produce a given calibrated tip angle for a rectangular pulse is constant, independent of the load in the RF coil. The energy required to achieve the tip angle in a lossless phantom is the coil loss. In general, the energy required to produce the tip angle depends on the coil loss and on the conductivity and geometry of the load and on the tip angle and pulse width. The forward power less the reflected, and (in the case of quadrature coils) the power to the dummy load results in the net power absorption in the patient (or other load) and the power absorbed by the RF transmit coil.

It is necessary to first calibrate transmission line and directional coupler losses and attenuation constants. Care must be taken to ensure that the total electrical length through each set of the additional couplers and additional transmission lines between the RF connector and the RF coil (Figure 1) including any intervening hardware such as a T/R switch. Ensure the additional transmission line/coupler electrical lengths are each integer multiples of 180° ± 5°. Otherwise, measurements may be compromised.

1. Measure losses at the magnet frequency of the transmission lines (see Figure 1) used between the directional couplers and the oscilloscope (first ensuring all transmission lines and scope impedances are 50 ohms).
2. Measure the attenuation factors (in decibels) for forward (\(\alpha_{fwd}\)) and reflected (\(\alpha_{refl}\))power and the coupler directivity (what portion of the forward power shows up as reflections in a system terminated in 50 ohms). Ideally, couplers should have sufficient directivity to avoid compromising measurements from the unintended channel. Insertion losses should be low enough to prevent compromising the system, and coupled port attenuations should permit samples sufficiently small to avoid compromising the system and sufficiently large to prevent confounding from shield currents.
3. Measure (at magnet frequency) total electrical lengths and attenuations in decibels (\(\alpha_1\) and \(\alpha_2\)) through the combined transmission line/coupler addition between the RF connector and the RF coil (Figure 1) including any intervening hardware such as a T/R switch. Ensure the additional transmission line/coupler electrical lengths are each integer multiples of 180° ± 5°. Otherwise, measurements may be compromised.
4. Adjust pulse parameters to avoid pulse stretching for all the measurements.
5. Place a small phantom that does not load the coil near the coil center.
6. Prescribe a one location (S=0, I=0), axial scan with the desired pulse (here a 1 ms wide rectangular pulse is assumed) with a flip angle of 90° and a repetition time (TR) of about 500 msec (to keep average SAR low). Run tip angle calibration. Modify the tip angle from 90 to 180. In manual prescan, scan at the TR. This is the pulse that will be used for all remaining measurements. Note the rectangular equivalent width of this pulse.

7. Start manual prescan/scan TR, and take the following peak-to-peak measurements with the oscilloscope: \( V_{\text{fwd}} \) for the coupler following the power amplifier. Peak power, \( P_p \) (either forward or reflected) may be expressed in terms of the peak to peak voltage, \( V_{pp} \), and the total attenuation, \( \alpha \), in decibels as:

\[
(1a.) \quad P_{p, \text{fwd}} = \frac{V_{pp, \text{fwd}}^2}{400} \left( 10^{\frac{0.1(\alpha_{\text{fwd}} - \alpha)}{10}} \right) .
\]

\[
(1b.) \quad P_{p, \text{refl}} = \frac{V_{pp, \text{refl}}^2}{400} \left( 10^{\frac{0.1(\alpha_{\text{refl}} + \alpha)}{10}} \right) .
\]

Note that the peak reflected power has been attenuated going to and returning from the transmit coil.

8. Convert voltage measurements to power. Note: For a 180 degree rectangular pulse of pulse width, \( \tau \), the energy absorbed is the absorbed peak power times \( \tau \). For the coupler near the power amplifier:

\[
2. \quad W_{\text{forward}} = \tau P_{p, \text{fwd}} \quad \text{and}
\]

\[
3. \quad W_{\text{reflected}} = \tau P_{p, \text{refl}} .
\]

9. Calculate the coil loss in terms of joules per standard pulse. First let forward power be the sum of the two forward power measurements and let reflected power be the sum of the two reflected power measurements. Coil loss, \( W_{\text{coil}} \), may be expressed in terms of the pulse width (in seconds) as:

\[
4. \quad W_{\text{coil}} = (W_{\text{forward}} - W_{\text{reflected}}) .
\]

Note that it is conservative to simply set coil loss = 0 joules/standard pulse. If this is done the coil loss measurement requirement goes away. The estimated absorbed power in patients will then be somewhat overestimated.

**Whole-body SAR Measurement - Calorimetry Method**

An alternative method of measuring whole-body SAR is to measure temperature rise in an appropriate phantom over a period sufficient to obtain good signal to noise on the temperature measurement. Knowledge of specific heat, \( C \), permits conversion of temperature rise (\( \Delta T \)) over time, \( t \), with mass, \( M \), into SAR (assuming no thermal losses):

\[
5. \quad \text{SAR} = \frac{C \Delta T}{t} .
\]

**Local SAR Measurement**

Localized heating may result when induced current is constrained to flow through a small cross section perhaps due to boundary conditions (such as the presence of a conductor). Current density increases locally. Heating potential increases with the square of current density. NEMA MS-10 describes how to prepare and test phantoms with electrical properties similar to muscle. MS-10 also describes how the product of the specific heat, \( C \), near the non-conductive temperature sensor and the early rate of localized heating is the local SAR (assuming specific heat is known):

\[
6. \quad \text{SAR}_{\text{local}} = C \frac{dT}{dt} .
\]
MS-10 also describes means of estimating local SAR both from closed form approximations and from numerical methods. Figure 2 shows one possible experimental arrangement.

**SAR for Non-Proton Nuclei**

Assume $\gamma$ is the magnetogyric ratio for a given nuclear species. Then the energy, $W$, deposited per pulse depends on the square of the RF tip angle, $\theta$, the square of the static field strength, $B_0$, and inversely on RF pulse width, $\tau$, and a waveform factor, $\eta$:

\[
\theta = \eta \gamma B_0 \tau \Rightarrow SAR \propto W \propto \tau \omega^2 B_0^2 \theta^2 \frac{\gamma^2 B_0}{(\eta \gamma \tau)^2} = \frac{B_0^2 \theta^2}{\eta^2 \tau}.
\]

Note that for a given field strength and RF waveform, SAR is independent of nuclear variety! It is important to recognize that SAR decreases as pulse width increases.

**Effect of Landmark**

The geometry of the patient may change with landmark. For this reason SAR also may change with landmark. Note that patients landmarked near the eyes in a body coil load the coil about half as much as when the landmark is on the umbilicus. Worst-case landmarks may be used to conservatively bound SAR calculations.

**Conclusions**

Both local and whole-body SAR may be measured using the methods described in NEMA MS-8 and MS-10. These measurements may be used to conservatively limit SAR for MR exams.

**References**

9. IEC 60601-2-33, second edition, Medical Electrical Equipment - Part 2: Particular Requirements for The Safety of Magnetic Resonance Equipment for Medical Diagnosis , International Electrotechnical Commission (IEC)*, 3, rue de Varemble, P.O. Box 131, CH - 1211 Geneva 20, Switzerland (In the United States, copies of this standard can be obtained from the American National Standards Institute (ANSI), 11 West 42nd Street, New York, NY 10036), (2002).
Figure 1 Configurations for measuring radiofrequency power absorption in quadrature transmit coils. Note in (b) that the inserted electrical length of a directional coupler and transmission lines between the splitter and coupler should be 180° to prevent changing the complex impedance seen by the splitter.

Figure 2 Local SAR measurement setup for a local transmit coil.