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*Characterization of the Specific Absorption Rate (SAR)
for Magnetic Resonance Imaging Systems*

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Preamble

This is one of a series of test standards developed by the medical diagnostic industry for the measurement of performance parameters related to the safety of Magnetic Resonance Imaging systems. These test standards are intended for the use of equipment manufacturers, prospective purchasers, and users alike.

Manufacturers are permitted to use these standards for the determination of system performance specifications. This standardization of performance specifications is of benefit to the prospective equipment purchaser, and the parameters supplied with each NEMA measurement serve as a guide to those factors that can influence the measurement. These standards can also serve as reference procedures for acceptance testing and periodic quality assurance.

It must be recognized, however, that not all test standards lend themselves to measurement at the installation site. Some test standards require instrumentation better suited to factory measurements, while others require the facilities of an instrumentation laboratory to assure the stable test conditions necessary for reliable measurements.

The NEMA test procedures are carried out using the normal clinical operating mode of the system. For example, standard calibration procedures, standard clinical sequences, and standard reconstruction processes shall be used. No modifications to alter test results shall be used unless otherwise specified in these standards.



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Foreword

Unless otherwise noted, this publication has been approved as a NEMA standard. It describes the test conditions and parameters that ensure accurate measurement of the Specific Absorption Rate (SAR). This Standard does not attempt to establish relationships between SAR and body temperature.

This standards publication was developed by the Magnetic Resonance Section of the National Electrical Manufacturers Association.

Section approval of the standard does not necessarily imply that all section members voted for its approval or participated in its development. At the time it was approved, the section was composed of the following members:

Computer Imaging Reference Systems – Norfolk, VA.
GE Healthcare, Inc. – Milwaukee, WI.
Hitachi Medical Systems America, Inc. – Twinsburg, OH.
Invivo – Gainesville, FL.
Medipattern Corporation – Toronto, Ontario
Medtronic Navigation – Yokneam, Israel
Philips Healthcare – Bothell, WA.
Siemens Medical Solutions, Inc. – Malvern, PA.
Toshiba America Medical Systems – Tustin, CA.
AllTech Medical Systems America – Solon, OH.

User needs have been considered throughout the development of this publication. Proposed or recommended revisions should be submitted to:

Executive Director, Medical Imaging & Technology Alliance
National Electrical Manufacturers Association
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Introduction

In magnetic resonance (MR) imaging, radiofrequency (RF) magnetic fields are used to interrogate a region of interest. These RF fields induce currents in the body, which may lead to heating. It is not considered prudent to raise the core temperature in a patient above 39.2°C (roughly a 2.2 degree rise from thermoneutral) (1,2). If patient exposure to radiofrequency magnetic fields during MR scanning is insufficient to produce a core temperature rise in excess of 1°C and localized heating greater than 38°C in the head, 39°C in the trunk, and 40°C in the extremities, RF heating is considered to be within safe levels (3,4,5,6).

Parameters such as bore temperature, ambient temperature, relative humidity, air flow rate, perspiration, and blood flow influence temperature rise in the patient. A key variable in determining patient heating potential in an MR scanner is the power absorbed per unit mass, which is the Specific Absorption Rate (SAR). An insulated slab of tissue initially at thermal equilibrium with its environment increases in temperature at a rate of approximately 1°C per hour when exposed to a SAR of 1 W/kg.

The MR scanning process applies a train of RF pulses, which have specific, calibrated tip angles. Each pulse results in some power absorption in the patient. The highest absorbed energy per pulse takes place in those patients whose cross-sectional area is greatest. The highest absorbed power (and SAR) takes place in such patients when they are exposed to the highest permitted RF duty cycle. The greater the number of images (slices/echoes) per unit time the greater the SAR. Note that scan time implies the length of time the scanner gradient or RF hardware is employed to produce an image. For example, the period over which the SAR from an echo planar scan is averaged is the entire time required to pulse the RF and gradients, not merely the pulse duration of the initial RF pulse.

There is a need to measure SAR for developing and verifying various predictive safety algorithms. To this purpose, measurements of SAR in phantoms with electrical conductivities similar to patients are important. This standard was developed to fill these needs.

Determination of SAR may be done either calorimetrically or by measurements of energy per pulse. In the calorimetric method the absorbed RF power is measured directly, while the pulse energy method measures the net power delivered to the transmit coil less the relevant losses to determine the remaining absorbed power. The pulse energy method may be used to determine SAR either in a phantom or a patient. Both methods are described in this standard; either method may be chosen. The pulse energy method permits the use of low duty cycle scans for the test. The results from either method may then be extrapolated to other scan parameters and even to other waveforms.

Local SAR measurements are important for assessing localized heating. The local average SAR is the total power divided by the exposed mass. The (spatial) peak SAR is the SAR in the highest SAR occurring in any 10 grams of tissue. While peak and local SAR levels are important in localized heating, they are difficult to measure directly in living patients. For this reason, determinations of peak and local SAR levels are beyond the scope of this document.

An addition has been made to this standard that takes into account variations in coil power loss that have been observed since the last publication of the standard. Note that the variation is higher for the relatively newly introduced 70 cm and 3T systems compared to the old standard 1.5T systems. This variation affects directly the SAR estimate because the transmit coil power loss is not constant. Additionally, the calorimetric SAR verification is affected because of the necessary step of finding the patient equivalent mass of phantom 2.

Scope

This NEMA Standards Publication describes two measurement procedures for whole-body SAR measurements, the calorimetric method and the pulse-energy method. Extrapolation of these data to patient temperature rise is beyond the scope of this document. This document does not apply to gradient (low-frequency time-varying magnetic fields) safety where nerve and cardiac excitation are the primary safety issues. Neither is it intended to apply to spatial peak or local average SAR nor does it address other factors involved with patient heating. The tests specified are only for volume RF transmit coils that produce relatively homogeneous RF fields.

Equivalence

It is intended and expected that manufacturers or others who claim compliance with these NEMA standard test procedures for the determination of image quality parameters shall have carried out the tests in accordance with the procedures in the published standards.

In those cases where it is impossible or impractical to follow the literal prescription of a NEMA test procedure, a complete description of any deviation from the published procedure must be included with any measurement claimed to be equivalent to the NEMA standard. The validity or equivalence of the modified procedures will be determined by each reader.

Uncertainty of the Measurements

The measurement uncertainty of the parameter determined using this standard is to be reported, together with the value of the parameter. Justification for the claimed uncertainty limits shall also be provided by a listing and discussion of sources and magnitudes of error.

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Section 1 References and Definitions

1.1 References

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1.2 Definitions

1.2.1 B1 and B1+

The transmit coil creates a magnetic field frequently termed B_1 . B_{1+} is the component of B_1 field that rotates in the direction of nuclear precession thus induces the flip angle oriented with respect to the B_0 field (Z axis). For the purposes of MR imaging and spectroscopy only B_{1+} is of interest and many workers in the field refer to B_{1+} as simply B_1 . However full B_1 , including the counter-rotating B_{1-} component, is required for SAR calculation purposes.

Note: the power requirements can vary depending on load for the same target B_{1+} .

1.2.2 Body Coil Current Sense

A means to sense body coil current (for example small flux loops (8), Appendix A within or close to the coil). This is used to determine variations in coil current under different loading conditions.

Note: Since the losses are proportional to the square of the currents this accounts for coil power loss variation.

1.2.3 Equivalent loading

The equivalence of the loading of the phantom and the human subject are established when the quotient of power absorbed by a phantom relative to total net input power of RF transmit coil (e.g. as determined with peak power with the same RF pulse(s)) is similar to (e.g., +/- 20%) the quotient assessed with a human subject at the designated landmark position,

$$P_{phantom_2}/(P_{phantom_2} + P_{CPL_phantom_2}) \approx P_{human}/(P_{human} + P_{CPL_human}) \quad [1]$$

The quotient may be assessed experimentally with pulse energy method, calorimetry method (for phantom only) or with simulations.

Alternatively, equivalence can be established by matching all of the following coil characteristics when comparing the phantom with a representative human subject:

- a. Coil 3 dB bandwidth: $\pm 15\%$
- b. Coil Impedance: $\pm 20\%$ magnitude, $\pm 20^\circ$ phase
- c. Coil center frequency shift: $\pm 1\%$ of center frequency

1.2.4 Equivalent mass M_{bod}

When test phantom (phantom 2 or 3) has equivalent loading of a human subject, the mass of the human subject is the phantom's equivalent mass or M_{bod} . Phantom's equivalent mass may be different from its actual mass.

1.2.5 Landmark

The landmark is the region of the body to be placed in the center of the RF coil.

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1.2.6 Phantom 1: Unloaded Tip Angle Calibration Phantom

Phantom 1 is a lossless phantom used during the calibration of tip angles in the pulse-energy and the calorimetric methods. It is used for the determination of RF coil losses of the unloaded coil using the pulse-energy method.

The phantom shall be filled with a material which can be imaged by the scanner, but whose conductivity is less than 0.003 siemens/meter. This ensures that the RF losses of the object are negligible, thus permitting the measurement of coil losses while contributing little to system losses. Phantom 1 design should limit measurement impact from any B_0 distortion. To ensure proper calibration of tip angle the relaxation properties shall be: $T1 \leq 400$ ms. See Figure 1-1a.

1.2.7 Phantom 2: Pulse-Energy Device under Test (Human or Phantom to be tested)

Phantom 2 is the test object whose SAR is to be determined using the pulse-energy method. If phantom 2 is not biological and $T1 > 400$ ms, add paramagnetic material (for example, 0.68% by weight $MnCl_2 \cdot 4H_2O$) to shorten the relaxation properties of the solution to render it invisible in scans. The phantom shall be designed to load the same as a 70 to 90 kg human positioned for a scan at the designated landmark position. The phantom may be cylindrical, with a diameter of at least 35 cm, or elliptical with long axis 40-50 cm and short axis 25-30 cm. See Figure 1-1b. The length of the phantom should be shown to effectively load the body coil.

1.2.8 Phantom 3: Calorimetric Test Phantom

Phantom 3 is a test object designed to provide RF coil loading equivalent to that of a human (see Figure 1-1c.). Loading equivalence should be established by the MR manufacturer using appropriate RF simulations or measurements. The test phantom may have various configurations:

- a. an annular shell of elliptical or cylindrical shape,
- b. similar to the phantom described in reference 7 with the addition of the doping material described below,
- c. an elliptical phantom with long axis 40-50 cm and short axis 25-30 cm. The length of the phantom should match the length of the body coil. Alternatively, a cylindrical phantom with a diameter of at least 35 cm can be used.

Phantom 3 is filled with aqueous sodium chloride solution whose concentration is adjusted to a conductivity that produces the loading specified below. The filling solution can contain a doping material such as manganese chloride (for example, 0.3% by weight MnCl₂) to shorten the relaxation properties of the solution to render it invisible in scans. Note that adding MnCl₂ will increase the conductivity of the phantom (and power deposition).

Other phantom compositions that meet the desired electrical and relaxation properties are permitted.

The phantom shall be designed to load the same as a 70 to 90 kg human positioned for a scan at the designated landmark position.

The quality of insulation is one of the key determinants in the calorimetry computation and error analysis. A minimum insulation time constant of T_c = 35,000 seconds is suggested. Please note that any finite time constant leads to underestimation of final temperature. For example, with the rate of heating corresponding to 2 watts per kilogram SAR, the temperature at the end of 1 hour of continuous heating would be underestimated by approximately 5%. Monitoring the temperature for up to 1 hour after the completion of heating may reveal poor experimental conditions, for example incomplete thermal equilibrium from inadequate stirring in Section 3.3g.

This assumes an exponential cooling, of the form:

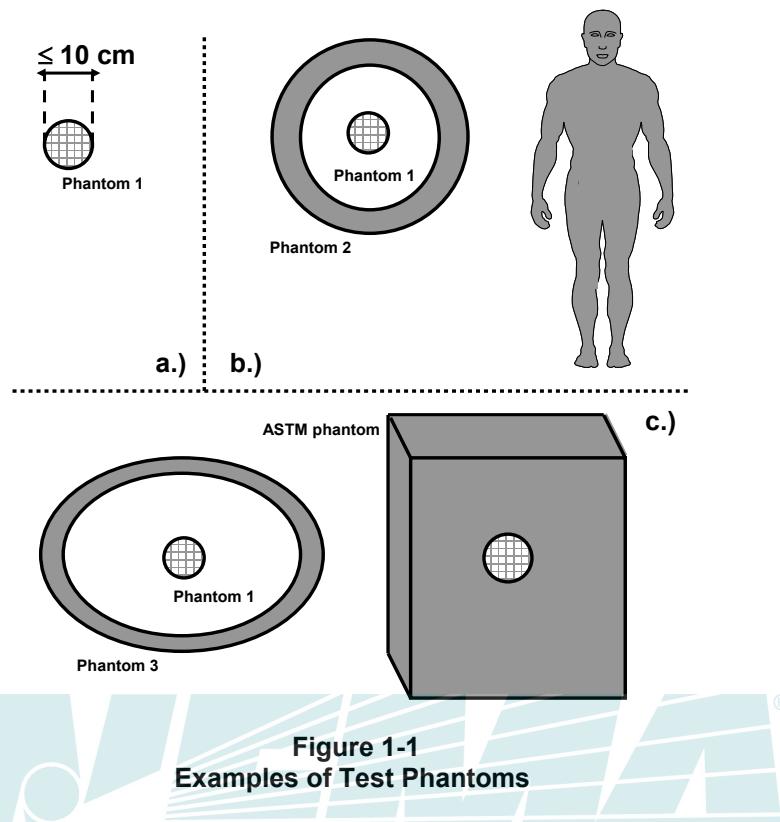
$$T = T_{ambient} + \Delta T e^{-\frac{(t-t_s)}{T_c}} \quad [2]$$

Where T_{ambient} is the ambient room temperature, and final temperature of the phantom

ΔT is the temperature over ambient caused by heating

t, t_s are respectively the running time of temperature measurement and the start time when heating stopped, in seconds

Note: that the required time-span for the experimental verification depends on the available precision of the temperature measurement. Establishing the insulation time constant is a lengthy experiment. Therefore, adequacy of thermal insulation can be proven by a one-time design verification of the phantom setup. It does not require proof for every particular execution of the calorimetric SAR determination.



**Figure 1-1
Examples of Test Phantoms**

- Phantom 1. Lossless test phantom for pulse-energy coil loss determination of the unloaded coil
- Pulse-energy device under test. Acceptable test objects are a human volunteer or a loading
- Phantom, such as phantom 2, or the ASTM phantom (7). Phantom 1 might be added if necessary for the specific system to calibrate B₁₊.Calorimetric test phantom examples. Acceptable test objects are loading phantoms, such as phantom 3 in combination with phantom 1, or the ASTM phantom with doped solution (7), in combination with phantom 1, or a loading phantom alone if the manufacturer has an alternate means of calibrating B₁₊.

Regarding definitions 1.2.9 through 1.2.14 inclusively:

The definition applies for different load situations of the RF coil as well as for “peak” and “average” considerations. The following two load situations are herein of interest: 1) The “loaded case” when the RF coil is loaded with phantom 2, and 2) the “unloaded case” when the RF coil is loaded with phantom 1. Those mentioned differentiations are indicated by the following indexes “loaded”, “unloaded”, “peak” and “average” to the parameter of interest at the procedure description at section 2.

1.2.9 P_{forward_{loaded, unloaded}}

The forward RF power going into the terminals of the RF coil.

1.2.10 P_{other_{loaded, unloaded}}

The RF power absorbed or dissipated elsewhere in the system when the coil is loaded with {phantom 2 , phantom 1}. For example, in a quadrature system fed by a four-port splitter, this is the power delivered to the dummy load.

1.2.11 P_{reflected_{loaded, unloaded}}

The RF power reflected from the terminals of the RF coil when loaded with {phantom 2, phantom 1} .

1.2.12 $P_{CPL_ \{loaded, unloaded\}}$

The coil power loss (CPL) of the {loaded, unloaded} RF transmit coil; i.e., the RF power delivered to the coil that is not absorbed by the subject positioned inside the coil

1.2.13 $P_{phantom_2}$

The net {peak, average} power absorbed by phantom 2.

1.2.14 P_{human}

The net {peak, average} power absorbed by human subject.

1.2.15 Whole body Specific Absorption Rate (SAR)

The whole body SAR is the average RF power absorbed by the object in watts divided by the mass of the object in kilograms.

1.2.16 Tip Angle

The tip angle is the angle through which the macroscopic magnetization vector is nutated by an RF pulse.

1.2.17 $V_{flux_loop_loaded}$

The peak voltage from body coil flux loop when the RF coil is loaded with phantom 2, or other test object.

1.2.18 $V_{flux_loop_unloaded}$

The peak voltage from Body coil flux loop when the RF coil is loaded with phantom 1.

Section 2 Pulse Energy Method

2.1 Overview

Whole-body SAR is defined as the ratio of the absorbed RF power to the mass of the whole body. Therefore the primary task is the determination of the RF power absorbed by the subject; i.e. the loading phantom in this test. The whole-body-SAR is simple division of the absorbed RF power by the registered weight.

The Pulse Energy Method describes a procedure for measuring the RF power absorption utilizing directional couplers in the RF transmission path to the body coil.

To excite spins in an MRI experiment RF power is applied during multiple pulses. Therefore, the time average RF power is the sum of all pulse-energy-values applied during the sequence divided by the scan time.

Total pulse energy can be measured either by RF power meter with averaging capability, or via measurement of the pulse-peak-power and subsequent calculation of the pulse energy utilizing knowledge about the pulse shape. In case of rectangular shaped RF pulse the pulse energy simply results by the multiplication of the pulse-peak-power with the length of the RF pulse. ®

The pulse-peak-power can be measured either by peak reading RF power meter or an oscilloscope. The knowledge of the pulse shape could come from analysis of the pulse shape, by measurement, or from a prior knowledge of the radiofrequency waveform (e.g. from the system pulse programmer).

In order to determine the RF power absorbed by the phantom, the coil losses must be subtracted from the net power value measured at the terminals of transmit coil. The net power is the difference of the forwarded power and the reflected power at body coil.

The coil losses are determined by a separate measurement using a phantom with negligible power absorption (phantom 1). Especially at higher frequencies – e.g. as used in 3T systems – these coil losses are not constant, and the unloaded power value alone is not sufficient in order to determine the losses when transmit coil is loaded. Since the losses are proportional to the square of the current flowing in the transmit coil conductors, an additional (relative) measurement of those currents is required – for the loaded and unloaded case. The current can be measured via flux loops. In order to represent the losses due to the different currents at the individual rods and end-rings, a sufficient number flux loops should be supplied (e.g. one for each part of the transmit coil).

In the methods described here the average power being measured is for a user defined test sequence.

It is recommended to use a sequence with a regular repetitive and temporally continuous RF exposure pattern. The pulse shape used within the test sequence can be chosen arbitrarily and is recommended to adopt a high SAR sequence for measurement accuracy purposes.

2.2 Test Hardware

Peak power measurements shall be made either with an oscilloscope or with an RF power meter. The bandwidth of the measuring instrument must exceed the measurement frequency by a factor of 5. Peak/average power ratio that can be measured by the instrument must be higher than 10. Sampling intervals must be lower than 10 microseconds. The RF transmission power is sampled by dual directional couplers; the directivity of the coupler must exceed 30 dB and is connected to the measurement device. See Figures 2.1, 2.2a and 2.2b. Ensure that the oscilloscope input is terminated in the characteristic impedance of the system (typically 50-ohm impedance). Note: The input of RF/microwave power meters

are typically 50-ohm impedance; (oscilloscopes with bandwidth of greater than 200 MHz can generally be configured to have 50-ohm input impedance).

The current flowing in the transmit coil shall be monitored via flux loops (see appendix A).

Phantom 1 and phantom 2 shall be provided.

2.3 Hardware Setup

Connect the directional coupler, oscilloscope or RF power meter, the flux loop(s) and other power measurement equipment with 50-ohm coaxial transmission lines as shown in Figure 2-1 or Figure 2-2a or Figure 2-2b.

If two flux loops are employed they must be placed such that they are orthogonal to each other. If the system has more than two flux loops, the loops need to be distributed evenly to get a balanced sample of the coil currents.

The possible measurement setups are illustrated in Figures 2.1, 2-2a, and 2-2b.

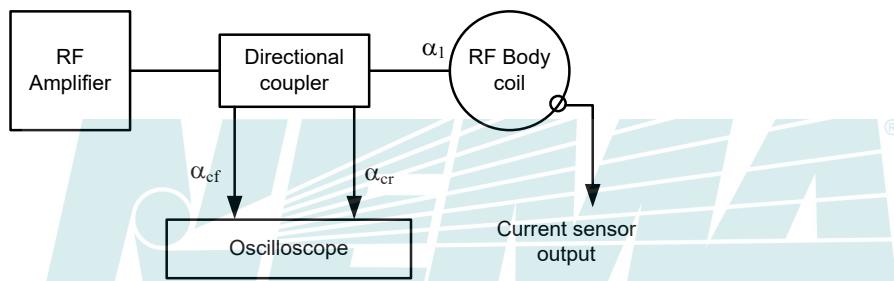


Figure 2-1 Possible arrangements for measuring radiofrequency power absorption in linear
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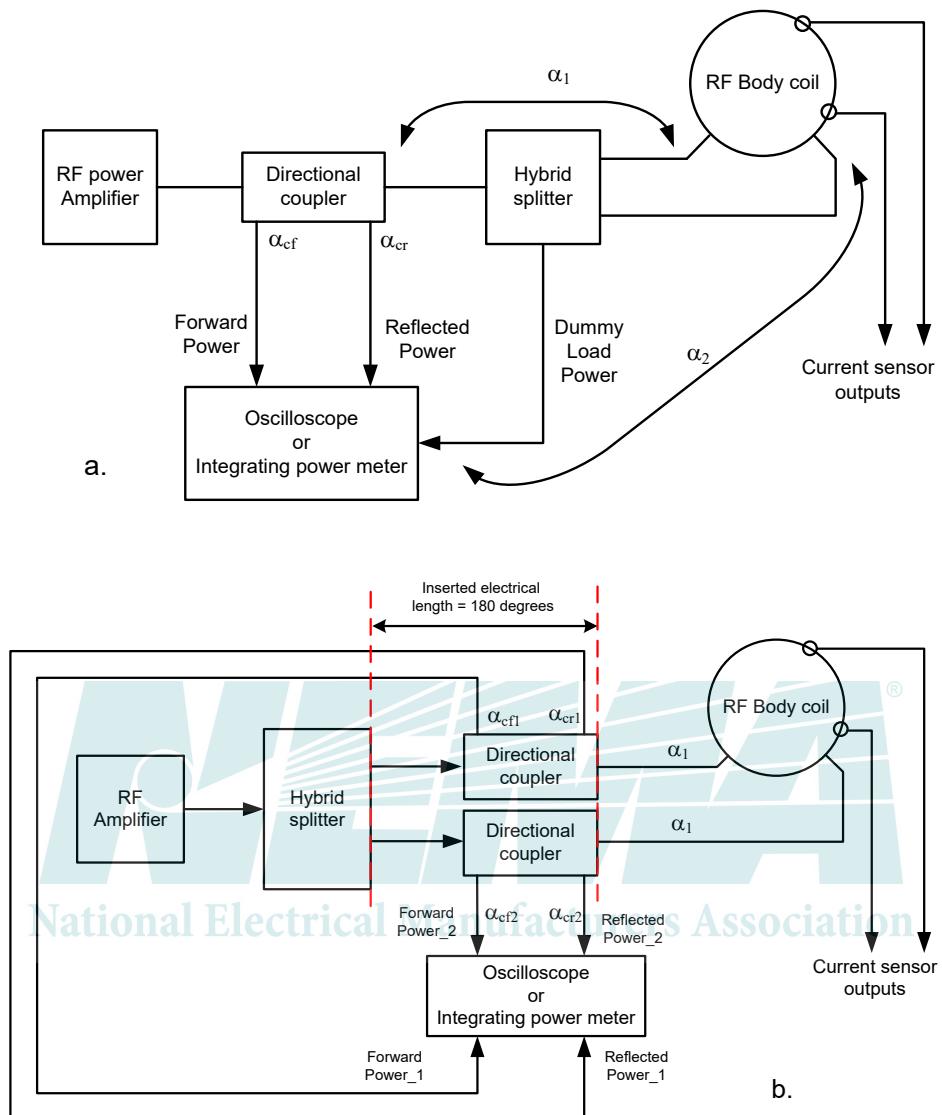


Figure 2.2 Possible arrangements for measuring radiofrequency power absorption in quadrature transmit coils

Note 1: Figure 2-2b; if the scanner already has directional couplers as standard equipment the electrical length note does not apply.

Note 2: Figure 2-2b; if directional couplers are added to make this measurement then the inserted electrical length of a directional coupler and transmission lines between the splitter and coupler should be 180 degrees to prevent changing the complex impedance seen by the splitter.

Prior to first use, it is necessary to measure the various loss constants shown in the Figures 2.1 and 2.2. In this standard measurements of loss are expressed as a fractional power attenuation (not in dB).

Measure α_1 , the attenuation between the directional coupler and the body coil; in Figure 2.2a this will include the hybrid and adjacent transmission lines. Assume the forward power attenuation introduced by the dual directional coupler and the transmission line between the coupler and the measurement device is α_{cf} , and the reflected power attenuation is α_{cr} . Measure α_2 , the attenuation between the body coil and the dummy load; this will be the sum of transmission line losses either side of the hybrid and the sample factor of the dummy load port.

With respect to the measurement with the oscilloscope it is necessary to convert the peak to peak voltages measurements into time average power values. The basic task is illustrated with Figure 2-3, while the basic method is described with equation (4) and (5) of Section 2.5.

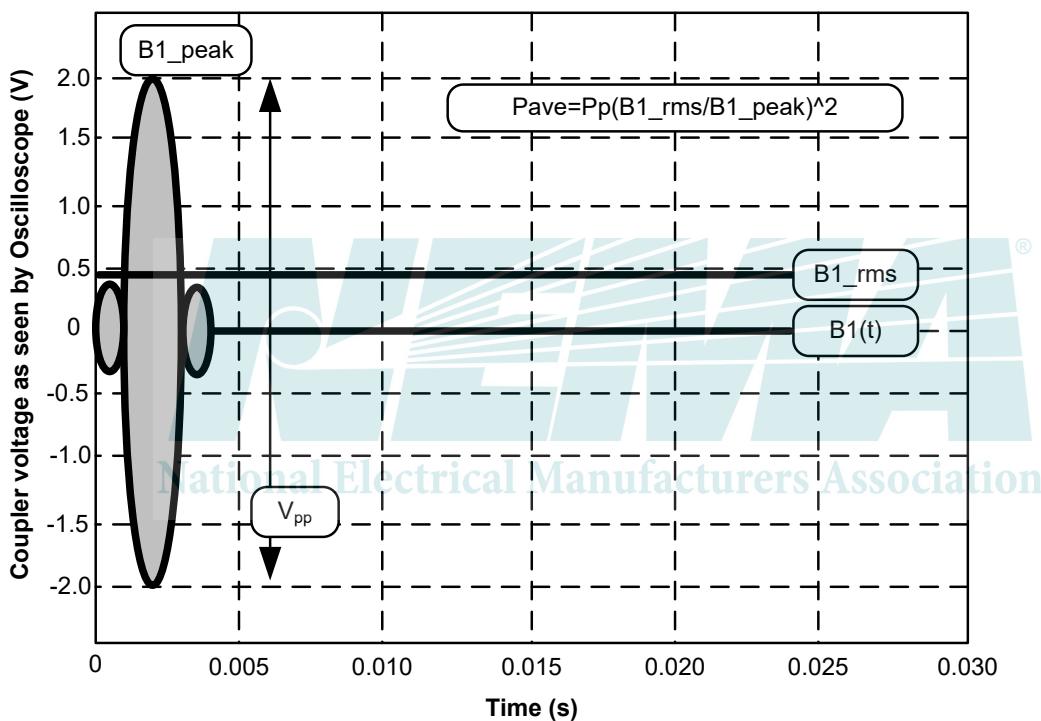


Figure 2-3
Method to Find Average Power Per TR Using Coupler Forward Power Port and an Oscilloscope Capable of Finding Peak and RMS Levels of the Waveform

2.4 General Measurement Procedure

- a. At MR console enter patient weight as either the equivalent mass of the phantom (M_{bod}) or the true mass if the test is performed on human (instead of phantom 2).
- b. Position phantom {1,2} with desired landmark at the isocenter of the scanner.
- c. Calibrate the tip angle. The standard methods (hardware and/or software) employed by each manufacturer shall be used to set the tip angle to the desired value for the type of scan selected. The same tip angle shall be used for Phantom 1 and Phantom 2 power measurements.

Note: In case of measurement with phantom 2 place phantom 1 near the center of phantom 2 to obtain tip angle calibration.

- d. Start the test sequence chosen for the measurement. Ensure that the scan time is long enough to allow the completion of the desired measurements, e.g. set the scanner to repeat the pulse sequence with a sufficiently high number.
- e. Measure and record the {peak, average} RF power (forward, reflected, and other) for the chosen test sequence.
- f. Measure the current(s) at the transmit coil via flux loops.

Note: Since only the relatively change of the current(s) with the load is of interest, this measurement can be performed with other test sequences (e.g., single RF pulse).

- g. Compute SAR as required for the particular pulse energy method used

2.5 Pulse Energy SAR Measurement Evaluation

If measurements using an oscilloscope are done, then all steps below are required. If a peak power meter is used, start at step ii.

- i. When the measurements are performed using an oscilloscope, the peak-to-peak voltage measurements must be converted into peak power measurements. The peak power, P_p , measured at the oscilloscope is:

$$P_p = \frac{V_{pp}^2}{8Z_0} \quad (1)$$

where:

V_{pp} = measured peak-to-peak voltage

Z_0 = characteristic impedance of the transmission line (and also the input impedance of the oscilloscope)

- ii. Calculating corresponding power values at input terminals of the body coil:

Irrespective of how the RF power is measured it has to be converted into power values at input terminals of the body coil. If the test is performed using RF power meter then the measurement values can be used directly for the subsequent listed equations. This is valid for the peak power values as well as for already time averaged values.

The measured peak or average power values shall be converted into corresponding peak or average power values at input terminals of the RF coil by considering transmission line attenuation and directional coupler coupling constants.

For example, the corresponding forward power, $P_{forward}$, at the input terminals of the body coil may be expressed in terms of the forward power measured at the oscilloscope or by the RF power meter, P_{fm} , (see Figures 2.1, 2.2) and attenuations α_1 , α_{cf} as:

$$P_{forward} = \frac{P_{fm} \alpha_1}{\alpha_{cf}} \quad (2)$$

Similarly, reflected power, $P_{reflected}$, and “other” power, P_{other} , at the RF coil may be expressed as:

$$P_{reflected} = \frac{P_{rm}}{\alpha_1 \alpha_{cr}} \quad (3)$$



$$P_{other} = \frac{P_{rm}}{\alpha_2} \quad (4)$$

where:

P_{fm} = forward power measured at the terminals of the {oscilloscope, RF power meter}.

P_{rm} = reflected power measured at the terminals of the {oscilloscope, RF power meter}.

- iii. Measure the peak voltage induced to the flux loop V_{flux_loop} {loaded, unloaded} during RF pulsing in order to analyze coil losses.

$$V_{losses}^2 = V_{flux_loop}^2 \quad (5)$$

If more than one flux loop is utilized, then the sum of the squared voltage values $V_{flux_loop}^2$ has to be calculated:

$$V_{losses}^2 = \sum_{i=1}^n V_{flux_loop,i}^2 \quad (6)$$

Note: the formula assumes all flex loops have the same sensitivity.

- iv. From measurement with phantom 1 calculate the peak power absorbed by the unloaded coil (i.e., the losses), $P_{CPL_unloaded}$:

$$P_{CPL_unloaded} = P_{forward_unloaded} - P_{reflected_unloaded} - P_{other_unloaded} \quad (7)$$

Note that $P_{forward_unloaded}$, $P_{reflected_unloaded}$, and $P_{other_unloaded}$ are from the experiment using phantom 1.

- v. Calculate the losses given at the measurement using phantom 2:

$$P_{CPL_loaded} = P_{CPL_unloaded} * \left(\frac{V_{losses,2}^2}{V_{losses,1}^2} \right) \quad (8)$$

Note that $V_{losses,\{1,2\}}^2$ is from the experiment using phantom {1,2}.

- vi. Calculate the peak power absorbed by phantom 2, $P_{phantom_2}$:

$$P_{phantom_2} = P_{forward_loaded} - P_{reflected_loaded} - P_{other_loaded} - P_{CPL_loaded} \quad (9)$$

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- vii. Calculate the energy (per pulse or for the entire repetition time) absorbed by the object.

If your peak power meter has power averaging capabilities, skip this step. Otherwise, find B_{1rms} for the waveform over the desired time interval (pulse width, TR, or other appropriate averaging window). This shall be done from the oscilloscope display of coupled power or from prior knowledge of the radiofrequency waveform (from the system pulse programmer). B_{1rms} may be expressed as:

$$B_{1rms} = \sqrt{\frac{\int_{-\tau}^{\tau + \Delta\tau} B_1^2(t) dt}{\Delta\tau}} \quad (10)$$

where $\Delta\tau$ is the interval of interest (pulse width of the radiofrequency pulse or else the TR period).

Note: this equation does not consider the summation required when two or more different RF pulses are used.

- viii. Calculate the energy (per pulse, or TR, or other appropriate period), E_i as:

$$E_i = P_{phantom_2_i} \frac{B_{1rms_i}^2 \Delta\tau_i}{B_{1peak_i}^2} . \quad (11)$$

Note: that index i counts all the RF pulses.

- ix. Calculate the total average power, P_{ave} , absorbed by the object. The total average power for sequences with well-defined pulse repetition times (TR) is the sum of all the energies in all the pulses per repetition divided by TR:

$$P_{ave} = \frac{\sum E_i}{i} . \quad (12)$$

For sequences where TR is undefined (such as single-shot sequences), TR in equation 14 shall be considered the total scan time.

- x. Calculate the SAR for phantom 2, whose mass is M:

$$SAR = \frac{P_{ave}}{M} . \quad (13)$$

Where M either is the equivalent mass of the phantom (M_{bod} , please refer to definition 1.2.4) or M refers to the weight of the human the test is performed with. Please note, that "M" must have been registered before start of this test measurement. The SAR shall be reported as described in 4.1.

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Section 3 Calorimetry Method

3.1 Test Hardware

- a. Phantom 1 (if needed for MR B_{1+} calibration) and phantom 3 shall be provided. Proof for equivalence of loading of the phantom and a typical human body at the respective landmarks shall be provided by simulations and/or measurements.
- b. A temperature measurement system accurate to within 0.1°C over the range of 15°C to 45°C shall be provided. The system will be used to make initial and final measurements of temperature. Acceptable examples are fiber-optic temperature sensors, thermistor-based temperature sensors, and thermocouple temperature sensors.

3.2 Hardware Setup

- a. Place the temperature measurement hardware in a convenient location remote from the magnet to permit measurement of phantom filler temperature quickly before and after scanning. This will prevent inaccuracies due to the static magnetic field.
- b. Position phantom 3 at isocenter in the RF body coil before the scan.
- c. The number of acquisitions for the scan shall be adjusted to yield a scan sufficiently long to create a temperature rise at least 20 times greater than the error of the temperature measurement system.

Note: for an aqueous solution, a 1-hour exposure to an SAR of 1 W/kg will result in an average temperature rise of 0.86°C ($0.0143^{\circ}\text{C}/\text{minute}$), assuming no thermal losses. There is a trade-off between accuracy gained in a large temperature rise and accuracy lost in heat losses.

3.3 SAR Measurement Procedure

- a. Equilibrate Phantom 1 (if used) and Phantom 3 in the magnet bore. Turn the air flow off.
- b. Stir the phantom filler material.
- c. Measure the initial temperature, T_i , of the phantom by inserting a temperature sensor into the filler material.

Note: The initial bore temperature should not differ from T_i by more than 1°C .

- a. Position the phantom 3 in the MR scanner at isocenter and place phantom 1 (if needed) centrally within it.
- b. Calibrate the tip angle. The standard methods (hardware and/or software) employed by each manufacturer shall be used to set the tip angle to the desired value for the type of scan selected.
- c. Scan with enough acquisitions to ensure the desired measurement accuracy (cf. 3.2.c).
- d. Measure the final temperature, T_f , of the filler solution of phantom 3. Invert the phantom several times, or stir sufficiently so that filler solution has uniform temperature.

If it is necessary to continue the scanning (heating) after an interruption, any heat loss during the break time must be accounted for in the error analysis. Additionally the break time must be subtracted from the total time so that a corrected total scan time is used in equation (17).

- a. Calculate the energy, E (in Joules), absorbed by the phantom 3 in terms of the mass, M, of the filler (in kilograms) and the specific heat capacity, c, of the filler fluid in Joules/(kilogram °C). Note that if the product of the mass, M_s , and specific heat capacity, c_s of the empty phantom shell is more than 10% of the product of the mass and specific heat capacity of the filler fluid, then in equation (16) "M c" shall be replaced by "(M c + $M_s c_s$)".

$$E = M c (T_f - T_i) . \quad (19)$$

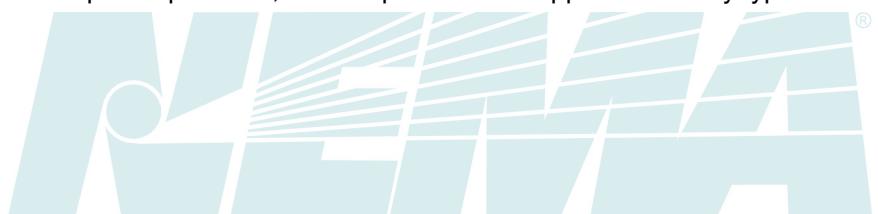
- a. Calculate the average power during the scan in Watts from the scan time, τ , in seconds.

$$P = \frac{E}{\tau} . \quad (20)$$

- b. Calculate the actual SAR measured:

$$SAR = \frac{P}{M_{bod}} . \quad (21)$$

For systems with multi-port capabilities, the test procedure is applicable to any typical drive setting.



Section 4 Results

4.1 Reporting SAR Results

- a. State the method used (pulse-energy or calorimeter).
- b. State the measured values of SAR for each object and pulse sequence used.
- c. For the pulse-energy method, the following parameters shall be reported for both measurements with phantom 1 and phantom 2. In case of the peak power measurement the peak power values have to be reported at the measurement result section. In case of RF power meter measurements the average power values have to be reported at the measurement result section.

Parameter	Dimension
Measurement parameter section	
RF Waveform	-
Pulse Parameters	-
Tip Angle(s)	Degrees
Equivalent Rectangular Pulse Duration ($W_{\text{rectangle}}$) (for each pulse type of the test sequence)	microseconds
TR	milliseconds
Equivalent Mass of Phantom 2	Kilograms
Measurement result section	
Unloaded case	
P_{forward}	Watts
$P_{\text{reflected}}$	Watts
P_{other}	Watts
Flux loop value(s)	Voltage
$P_{\text{CPL_unloaded}}$	Watts
Loaded case	
P_{forward}	Watts
$P_{\text{reflected}}$	Watts
P_{other}	Watts
Flux loop value(s)	Voltage
$P_{\text{CPL_loaded}}$	Watts
SAR calculation	
Absorbed Average Power by Object/Phantom 2 (P_{ave})	W
Measurement uncertainty	%
Measured SAR	W/kg
Predicted SAR	W/kg
Is Predicted SAR \geq Measured SAR – Measurement uncertainty?	Y/N

- a. The following parameters shall be reported for the calorimetry method.

Parameter	Dimension
Measurement parameter section	

RF Waveform Description	-
Repetition Time (TR)	milliseconds
Echo Time (TE)	milliseconds
Number of Slices	-
Number of Echoes	-
Total Scan Time	Seconds
MR Tip Angle Employed in Study	Degrees
Phantom 3 Heat Capacity*	J/K
Phantom 3 insulation time constant*	Seconds
Phantom 3 Equivalent Mass (M_{bod})*	Kg
Measurement result section	
Initial Phantom Temperature	°C
Post Phantom Temperature	°C
Time gap of Post temperature measurement to end of rf exposure	Seconds
Final Phantom Temperature (1 hour later)*	°C
Corrected Post RF Phantom Temperature	°C
SAR calculation	
Absorbed Energy by Phantom 3	J
Absorbed Power by Phantom 3	W
Uncertainty of "Absorbed Energy by Phantom 3" determination.	%
Measured SAR	W/Kg
Predicted WB SAR	W/Kg
Is Predicted SAR ≥ Measured SAR – Measurement uncertainty?	Y/N

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[*] Phantom 3 characteristics can be considered constant by design. A design verification report is sufficient to provide these values. In this case, the "final phantom temperature (1 hour later)" is not necessary.

- The error for the calorimetry measurement to consider is mainly given by the error of the single temperature measurement values (initial and post). Due to the final insulation quality the measured temperature value post the RF heating is in principal lower than it would be using infinite good insulation. This systematic error however can be corrected by consideration of the phantom heat capacity and conductance and the time point the post temperature is measured after the end of the rf exposure.
- List any other parameters required to ensure repeatability.
- State the accuracy, type, and location (during the measurement) of all measurement devices.
- Analyze the errors and expected accuracy of the experiment according NIST Technical Note 1297 (9), If NIST methodology is used, select an appropriate coverage factor. Report the applied coverage factor.

- e. Consider the following table of possible sources of uncertainty as appropriate:

Calorimetry Error Assessment
Accuracy of temperature sensor
Insulation time constant
Heat capacity of phantom including container
Ambient temperature variability
M _{bod}

Pulse Energy Error Assessment
Accuracy of fractional power attenuation values ($\alpha_{\{1,2, cf, cr, \dots\}}$)
Accuracy of “inserted electrical length” determination.
Directivity and coupling of directional couplers
Accuracy of power measurement values
Accuracy of current sensor(s)
Remaining uncertainty of power loss determination due to placement of the current sensor(s).
M _{bod}

- f. Compare system predicted SAR and measured SAR

Appendix A

Basic Flux Loop Design

A loop of wire, shielded from electric field effects, has induced within an e.m.f. proportional to the rate of change of the enclosed magnet field (Φ).

The Instantaneous voltage is:

$$V = - d\Phi / dt \quad [A1]$$

Assuming uniform field over the small flux loop and that the B field is perpendicular to the plane of the loop area:

$$V_{loop} = \text{loop_area} * (dB/dt) \quad [A2]$$

For a 1 inch (25.4mm) diameter loop at 64 MHz ($\lambda \approx 4.7\text{m}$) and assuming a reference field $25\mu\text{T}$, the peak voltage is:

$$\begin{aligned} V_{loop} &= \pi r^2 B (2\pi f) \\ &= \pi (0.0127^2) (25 \cdot 10^{-6}) (2\pi 64 \cdot 10^6) \\ &= 5.1 \end{aligned} \quad [A3]$$

Figure 1A shows a simple 1" diameter flux loop. The loop size is a balance being large enough to be easy to manufacture, small compared with wavelength (λ) and still large enough to pick up enough voltage.



Figure A1

Representative Small 1" Flux Loop Coil

Notes:

- a. Placing the shield break at the half-way point around the loop improves performance as this makes the integral of the net induced voltage to ground zero.
- b. It is necessary to maintain very good screening of the signal from the loop so that current in the shield does not affect the measured voltage. A cut at the half way point will ensure the induced voltage from E field from both sides cancel each other.
- c. It is desirable to include a balun near the flux loop to minimize the shield current, particularly if the flux loop is in a high electric field region of the transmit coil.
- d. The inner conductor is connected to the outer shield at the base of the loop.
- e. A better flux loop can be produced using printed circuit technology, such as schematically represented in Figure A2, with:
 - 1.better consistency between samples, and
 - 2.easier addition of termination of matching components.

Body coil flux loop shown twice life size.

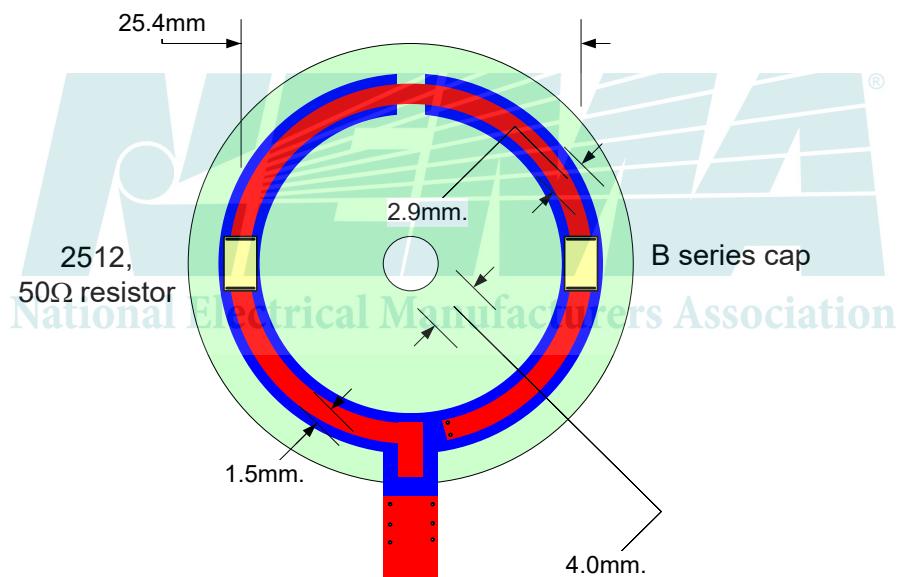
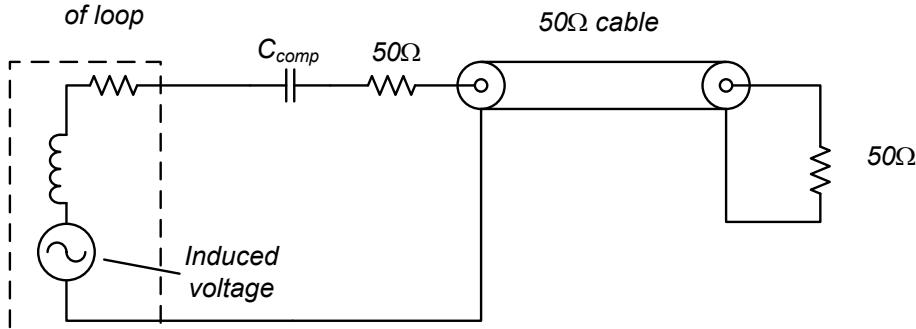


Figure A2
Schematic of a Printed Circuit Board Flux Loop

The flux loop has some self-inductance and small radiation impedance.

*Self inductance and
radiation resistance
of loop*

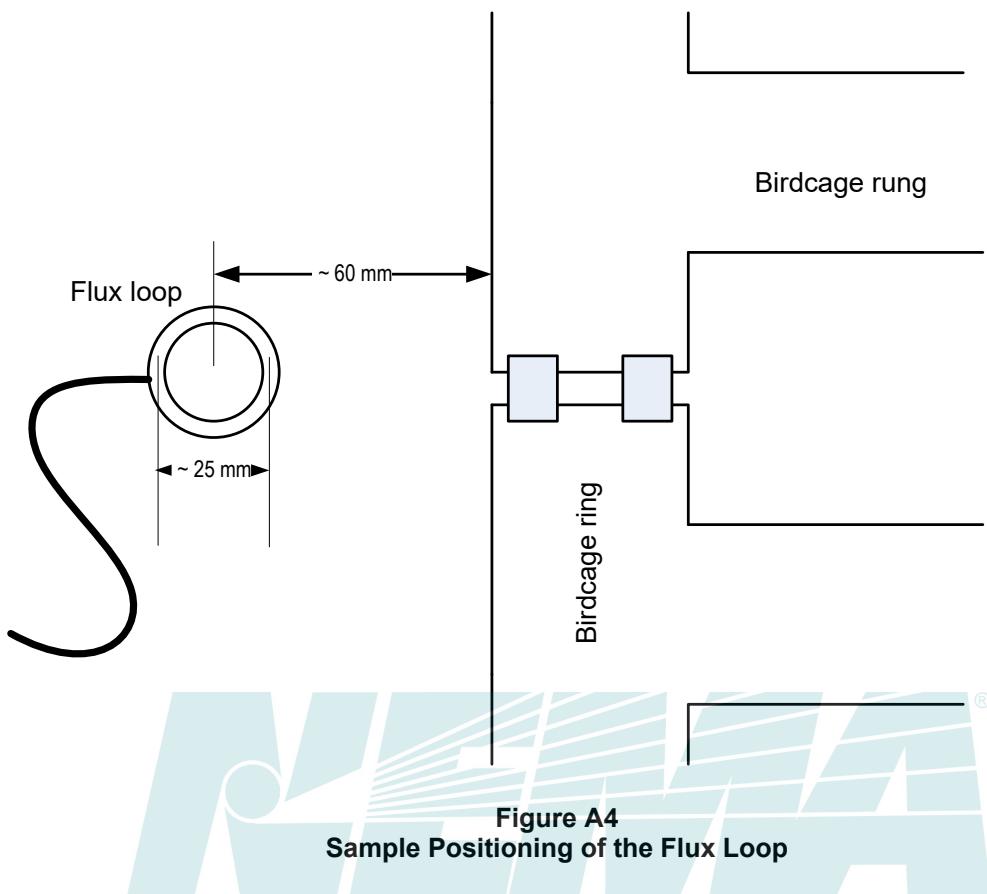


*Equivalent circuit of
flux loop*

Figure A3
Equivalent circuit representing the elements of a flux loop and cable

- a. The reactance of the self-inductance is not zero and a capacitor may be included. The inclusion of a 50Ω resistor allows the loop to have a good match in a 50Ω system. (Double terminated system is more robust against transmission line mismatches.)
- b. The expected voltage at a 50Ω terminated oscilloscope will be half of the calculated [eqn. A3] voltage.
- c. Cable losses should be taken into account.
- d. The flux loop can be positioned between the rungs of a birdcage, or spaced from the end-ring, in each case the loop is co-planer with the birdcage pcb; as shown below in Figure A4.

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Appendix B Document Changes

This standard has been significantly revised. In general changes were made to clarify the measurement methods and to make them easier for use by those who are not MR manufacturers:

- a. Methods updated to consider the impact of B_1 uniformity
- b. A new method added using power meters
- c. Additional details on experimental method
- d. Additional definitions, clarification of existing definitions
- e. Clarifying phantom requirements
- f. Additional details on error analysis

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