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NEMA STANDARDS PUBLICATION

NEMA MS 8

CHARACTERIZATION OF THE SPECIFIC ABSORPTION RATE FOR MAGNETIC RESONANCE IMAGING SYSTEMS

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NEMA Standards Publication No. MS 8-1993 (R2000)

Characterization of the Specified Absorption Rate for Magnetic Resonance Imaging Systems

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TABLE OF CONTENTS

		Page
	Foreword	i
	Introduction	i
	Scope	i
	Preamble	ii
Section 1	REFERENCES AND DEFINITIONS	1
Section 2	PULSE-ENERGY METHOD	3
Section 3	CALORIMETRY METHOD	7
Section 4	RESULTS	9

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FOREWORD

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

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].

Parameters such as bore temperature, ambient temperature, relative humidity, air flow rate, patient perspiration, and patient 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.

Determination of SAR may be done either calorimetrically or by measurements of energy per pulse. 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 gram 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.

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 which produce relatively homogeneous RF fields.

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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 governing the image quality 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.

The NEMA Magnetic Resonance subdivision has identified a set of key magnetic resonance image quality parameters. This Standard describes the measurement of one of these parameters.

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 specified in the pubished 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 image quality parameter determined using this standard is to be reported, together with the value of the parameter. Justification for the cliamed 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

1. Goldman, R.F., E.B. Green, and P.F. Iampietro, 1965, "Tolerance of Hot Wet Environments by Resting Men," *J. Appl. Physiol.*, 20(2):271-277.

2. Wyndham, C.H., N.B. Strydom, J.F. Morrison, C.G. Williams, G.A.G. Bredell, J.S. Maritz, and A. Munro, 1965, "Criteria for Physiological Limits for Work in Heat," *J. Appl. Physiol., 20(1): 27-45.*

3. Department of Health and Human Services, Food and Drug Administration. Magnetic Resonance Diagnostic Device; Panel Recommendation and Report on Petitions for MR Reclassification, Docket nos. 87P-0214/CP through 87P-0214/CP0013. Fed Reg 1988; 53(46):7575-7579.

4. Department of Health and Human Services, Food and Drug Administration. Recommendation and Report on Petitions for Magnetic Resonance Reclassification and Codification, Final Rule, 21 CFR Part 892. Fed Reg 1989; 54(20):5077-5088.

5. Adair, E.R. and L.G. Berglund, "On The Thermoregulatory Consequences of NMR Imaging," *Magnetic Resonance Imaging*, 1986, 4, 321-333.

1.2 DEFINITIONS

1.2.1 Specific Absorption Rate (SAR)

The average RF power absorbed by the object in watts divided by the mass of the object in kilograms. In this document SAR implies whole-body SAR.

1.2.2 Tip Angle

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

1.2.3 Landmark

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

1.2.4 Phantom 1

A physically small object used during the calibration of tip angles and during the determination of RF coil losses with 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 shall be physically small and compact in shape. The phantom volume shall be less than 250 milliliters. The longest dimension of the phantom shall be not more than three times the shortest dimension.

1.2.5 Phantom 2

The test object whose SAR is to be determined using the pulse-energy method.

1.2.6 Phantom 3

An annular test object designed to provide RF coil loading equivalent to that of a human.

This phantom is used with the calorimetric method of SAR measurement. It is filled with aqueous sodium chloride solution whose concentration is adjusted to yield a conductivity which produces the loading specified below. The filling solution shall also contain a doping material such as manganese chloride to shorten the relaxation properties of the solution to render it invisible in scans. The total volume of the phantom shall be less than 25 liters. The phantom shall be designed to load the same as a 50 to 90 kg human positioned for a scan within the stated tolerances.

a. Coil 3 dB bandwidth: 15%
b. Coil Impedance: 20° phase
c. Coil center frequency shift: 1% of center frequency

Annular phantom thermal properties shall be sufficient to maintain a 2°C temperature rise over ambient (in the filler material) to within 5% for 1 hour.

1.2.7 $P_{forward}$

The forward peak RF power going into the terminals of the RF coil when loaded with phantom 2.

1.2.8. $P_{reflected}$

The peak RF power reflected from the terminals of the RF coil when loaded with phantom 2.

1.2.9 P_{other}

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

1.2.10 P_{object}

The net peak power delivered to phantom 2.

1.2.11 P_{coil}

The net peak power absorbed by the RF transmit coil for the tip angle specified.

1.2.12 $P'_{forward}$

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The forward peak RF power going into the terminals of the RF coil when loaded with phantom 1.

1.2.13 $P'_{reflected}$

The peak RF power reflected from the terminals of the RF coil when loaded with phantom 1.

1.2.14 P'_{other}

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

1.2.15 B1

The magnetic induction of the RF magnetic field used in MR imaging and spectroscopy.

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Section 2
PULSE-ENERGY METHOD

2.1 TEST HARDWARE

2.1.1 Peak power measurements shall be made either with the use of an oscilloscope whose bandwidth exceed the desired frequency by a factor of 5 or more and dual directional couplers whose directivity exceeds 30 dB, or with attenuators.

2.1.2 Phantom 1 and phantom 2 shall be provided.

2.2 HARDWARE SETUP

Connect the directional coupler, oscilloscope, and other power measurement equipment with 50-ohm coaxial transmissions lines as shown in Figure 2-1 or Figure 2-2. Ensure that the oscilloscope input is terminated in a 50-ohm impedance.

2.3 SAR MEASUREMENT PROCEDURE

2.3.1 Position phantom 1 in the scanner at isocenter.

2.3.2 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.

2.3.3 Start the scan sequence chosen for the SAR measurement. Ensure that the scan time is long enough to allow the completion of the desired measurements, or set the scanner to repeat the pulse sequence indefinitely.

2.3.4. Measure the peak-to-peak RF envelope voltages (forward, reflected, and other) for each RF pulse in the sequence, or use other means to measure the instantaneous, RF peak power levels (forward, reflected, and other if applicable).

2.3.5. Measure the power attenuation of the transmission line between the body coil and the coupler and the transmission line between the dummy load port and the oscilloscope.

2.3.6. Convert the peak-to-peak voltage measurements into peak power measurements. The peak power measured at the oscilloscope is:

$$\frac{V_{pp}^2}{8Z_0}$$

Where:

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

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

The calculated peak power at the oscilloscope shall be converted into peak power referenced to the input terminals of the RF coil by considering transmission line attenuation and directional coupler coupling constants.

For example, suppose for a quadrature RF coil that the fractional power attenuation (not in dB) of the transmission line between the body coil and the coupler is α_1 and the attenuation between the dummy load port and the oscilloscope is α_2. Then:

$$P_{forward} = P_{fm} * \alpha_1,$$

Where:

P_{fm}= forward power measured at the terminals of the oscilloscope coupler

Similarly, we have:

$$P_{reflected} = P_{rm}/\alpha_1 \text{ and}$$

$$P_{other} = P_{om}/\alpha_2$$

Where:

P_{rm}= reflected power measured at the terminals of the oscilloscope

P_{om}="other" power measured at the terminals of the oscilloscope

Note that for unmatched linear coils transmission line attenuation increases with the mismatch:

$$\alpha = \alpha_0 * (R+1)/(2*R)$$

Where:

α = actual attenuation

α_0= attenuation under matched conditions

R= standing wave ratio

2.3.7 Calculate the peak power absorbed by the unloaded coil, P_{coil}:

$$P_{coil} = P'_{forward} - P'_{reflected} - P'_{other}$$

Note that $P'_{forward}$, $P'_{reflected}$, and P'_{other} are from the experiment using phantom 1.

2.3.8 After initial measurements are made on phantom 1, they are repeated using phantom 2. Remove phantom 1 from the coil, place phantom 2 in the scanner at isocenter, and repeat steps 2.3.3 and 2.3.4. The same tip angle shall be used for Phantom 2 as was used for phantom 1.

2.3.9 Calculate the peak power absorbed phantom 2, P_{object}:

$$P_{object} = P_{forward} - P_{reflected} - P_{other} - P_{coil}$$

Note that $P_{forward}$, $P_{reflected}$, and P_{other} are all obtained from the measurements on phantom 2, while P_{coil} is from phantom 1 (2.3.7).

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2.3.10 Calculate the energy per pulse absorbed by the object.

2.3.10.1 Integrate each of the RF waveforms in the pulse sequence and find the pulse durations of equivalent (in energy) rectangular pulses which have the same peak power levels as the actual RF pulses. This step must be repeated for each type of RF pulse in the pulse sequence (e.g., 90° pulses as well as 180° pulses). The equivalent rectangular pulses shall result in both the same peak power and in the same energy deposition as the actual pulse. The pulse duration, $W_{rectangle}$, shall be calculated from the RF pulse waveform, B1(t) normalized to its peak value, $B1_{peak}$, as follows.

$$W_{rectangle} = \int B1(t)^2 \frac{dt}{(B1^2_{peak})}$$

For example, a sinc pulse is equivalent in energy to a rectangular pulse with the same peak power and half the width of the main lobe of the sinc pulse. In Figure 3, a truncated sinc pulse ranging from -2π to 2π with a height of one is shown along with a rectangular pulse ranging from 0 to π with the same peak power. For this example, the truncated sinc pulse has 95% of the energy in the "equivalent" rectangular pulse. Note that manufacturers may employ more complex waveforms than the simple shape given here as an example.

2.3.10.2 Calculate the energy per pulse, E_i as:

$$E_i = P_{object} * W_{rectangle}$$

2.3.11 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:

$$P_{ave} = \sum_i \left(\frac{E_i}{TR}\right)$$

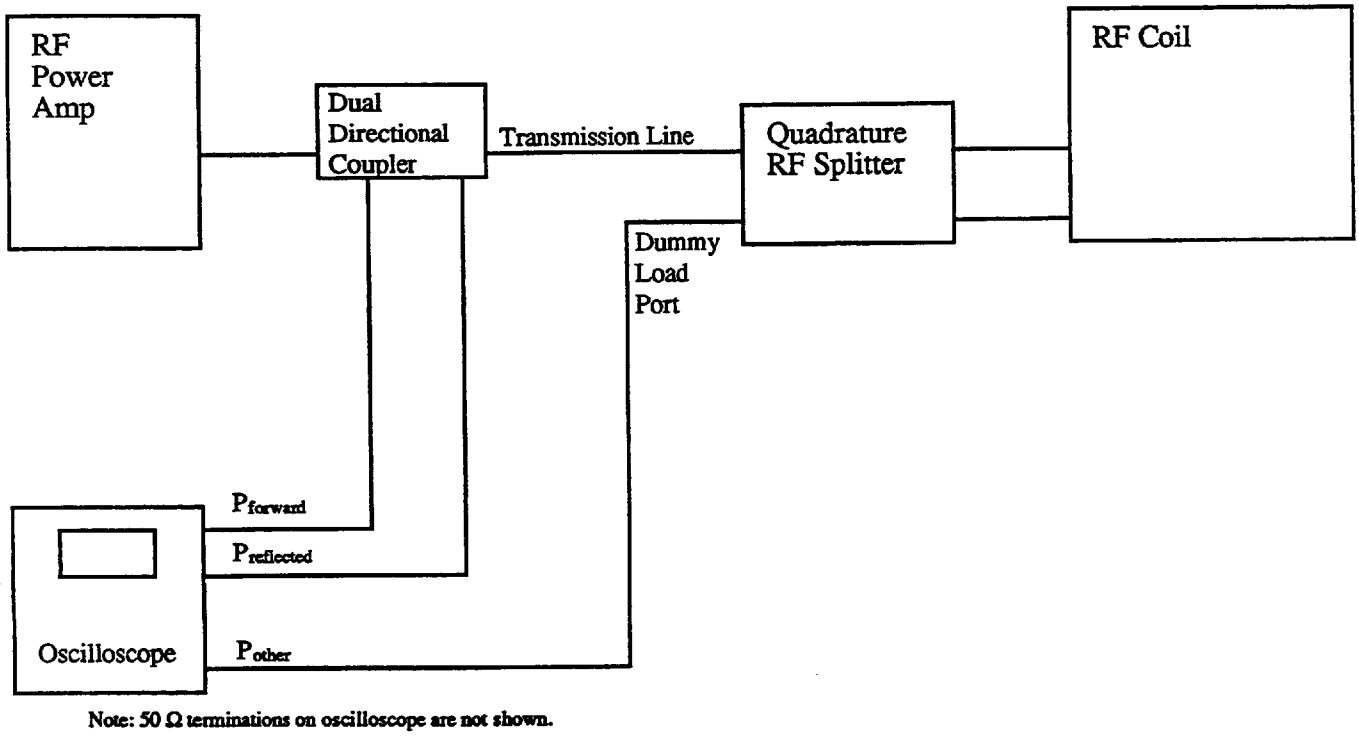
For sequences where TR is undefined (such as single-shot sequences), the total average power shall be calculated from the sum of all energies in all the pulses used in the scan divided by the total scan time, S:

$$P_{ave} = \sum_i \left(\frac{E_i}{S}\right)$$

2.3.12 Calculate the SAR for phantom 2, whose mass is M.

$$SAR = \frac{P_{ave}}{M}$$

2.3.13 The SAR shall be reported as described in 4.1.

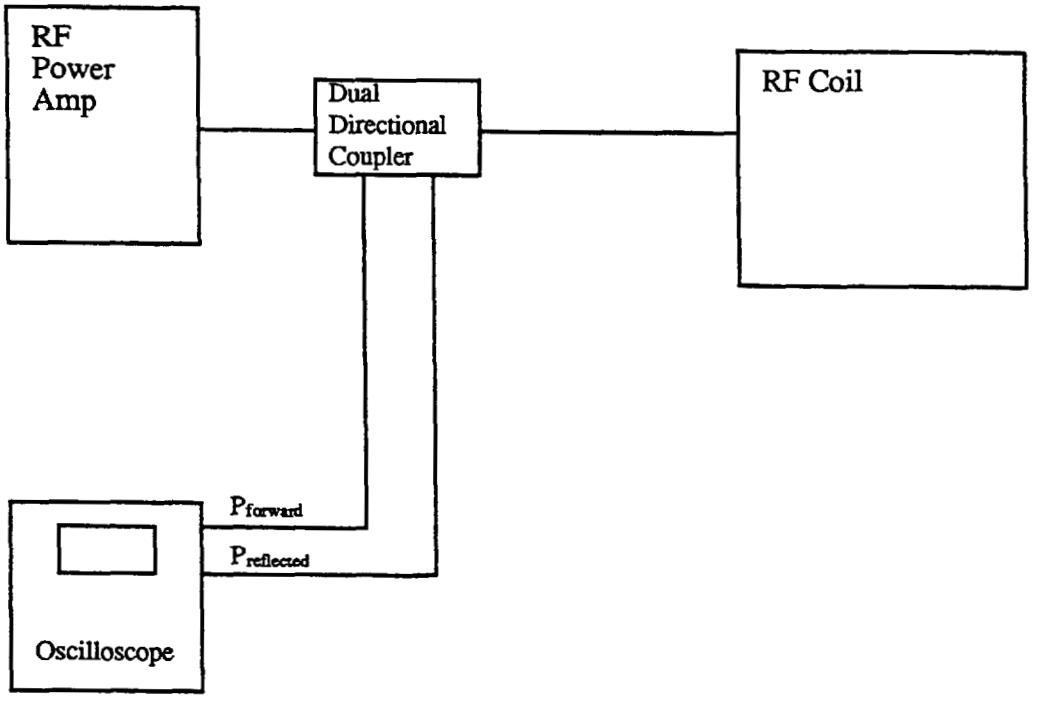


Note: 50 Ω terminations on oscilloscope are not shown.

Figure 2-1

HARDWARE SETUP FOR ENERGY PER PULSE METHOD FOR A QUADRATURE COIL

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Note: 50 Ω terminations on oscilloscope are not shown.

Figure 2-2

HARDWARE SETUP FOR ENERGY PER PULSE METHOD FOR A LINEAR COIL

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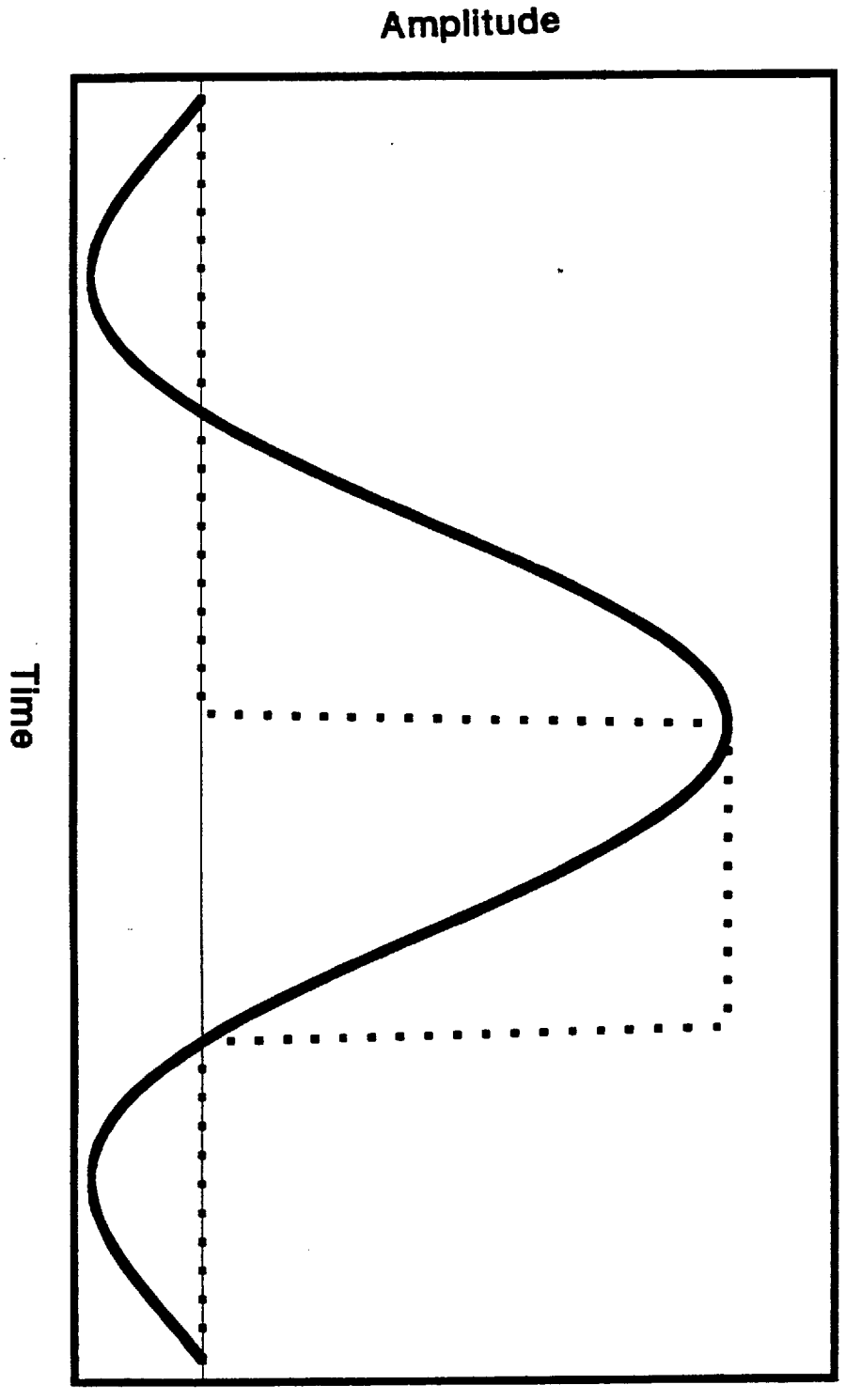


Figure 2-3
SINC AND ENERGY EQUIVALENT RECTANGULAR PULSE

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Section 3
CALORIMETRY METHOD

3.1 TEST HARDWARE

3.1.1 Phantom 1 and phantom 3 shall be provided.

3.1.2 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. It is not necessary for the system to be immune to RF interference from a scanner nor from temperature artifacts induced by the static magnetic field. Acceptable examples are fiber-optic temperature sensors, thermistor-based temperature sensors, and thermocouple temperature sensors.

3.2 HARDWARE SETUP

3.2.1 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.

3.2.2 Position phantom 3 at isocenter in the RF body coil before the scan.

3.2.3 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.

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°C/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

3.3.1 Equilibrate the phantom in the magnet bore with air flow turned off.

3.3.2 Measure the initial temperature of the bore of the MR scanner and the initial temperature of the scan room.

3.3.3 Remove the phantom from the bore and invert three times to stir the filler material.

3.3.4 Measure the initial temperature, T_i, of the phantom by inserting a temperature sensor into the filler material. The initial bore temperature should not differ from T_i by more than 1°C.

3.3.5 Quickly replace the phantom (phantom 3) in the MR scanner at isocenter and place phantom 1 centrally within it.

3.3.6 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.

3.3.7 Scan with enough acquisitions to ensure the desired measurement accuracy (cf. 3.2.3).

3.3.8 Remove the phantoms from the bore and measure the final temperature, T_f, of the filler solution of phantom 3 after inverting the phantom three times.

If $T_f - T_i \leq 2.0$°C, the experiment can be continued by replacing the phantom in the bore and restarting the scan. The measurement delay time must be subtracted from the total time to assure accuracy.

3.3.9 Measure the final bore and the final scan room temperatures. If the scan room or bore temperature changes by more than 0.5°C/hour then the experiment should be repeated under more stable conditions.

3.3.10 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, c, of the filler fluid in joules/(kilogram°C).

$$E = M*c*(T_f - T_i).$$

3.3.11 Calculate the average power during the scan in watts from the scan time, τ, in seconds.

$$P = E/\tau$$

3.3.12 Calculate the actual SAR of the phantom filler material from:

$$SAR = P/M$$

3.3.13 Calculate the apparent SAR, SAR_{app}, using:

$$SAR_{app} = P/M_{bod}$$

Where:

M_{bod} =mass of a body which phantom 3 simulates (assuming that the validity of the simulation has been independently verified)

3.3.14 Report results as specified in 4.1.

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Section 4
RESULTS

4.1 REPORTING SAR RESULTS

4.1.1 State the method used (pulse-energy or calorimeter).

4.1.2 State the measured values of SAR for each object and pulse sequence used. For the calorimetry method, state the SAR of both the phantom and the apparent SAR of the object which was measured.

4.1.3 For the pulse-energy method, the following parameters shall be reported for each pulse in the pulse sequence measured for both phantom 1 and phantom 2.

Parameter	Dimension
Peak Forward Power	watts
Peak Reflected Power	watts
Peak Coil Loss Power	watts
Other Peak Power Lost	watts
RF Waveform	-
Pulse Parameters	-
Tip Angle(s)	degrees
Accuracy of Power Measurement Equipment	%
Equivalent Rectangular	-
Pulse Duration ($W_{rectangle}$)	microseconds
TR or S	milliseconds
Mass of Phantom 2	kilograms

4.1.4 The following parameters shall be reported for the calorimetry method.

Parameter	Dimension
Initial Phantom Temperature	°C
Final Phantom Temperature	°C
Initial Bore Temperature	°C
Final Bore Temperature	°C
Initial Scan Room Temperature	°C
Final Scan Room Temperature	°C
Phantom 3 Mass	kilograms
Phantom 3 Simulated Mass (M_{bod})	kilograms
Phantom Volume	liters
Phantom Dimensions	meters
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

4.1.5 List any other parameters required to ensure repeatability.

4.1.6 State the accuracy, type, and location (during the measurement) of the temperature measurement system if the calorimetry method is selected.

4.1.7 Analyze the errors and expected accuracy of the experiment.

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