NEMA MS 6

CHARACTERIZATION OF SPECIAL PURPOSE COILS FOR DIAGNOSTIC MAGNETIC RESONANCE IMAGES

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Characterization of Special Purpose Coils
for Diagnostic Magnetic Resonance Images

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Preamble

This is one of a series of test standards developed by the medical diagnostic imaging industry for the measurement of performance parameters governing image quality of magnetic resonance (MR) 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 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 Section has identified a set of key magnetic resonance image quality parameters. This standards publication 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 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 equivalent to the NEMA standard. The validity or equivalence of the modified procedure will be determined by the reader.

Uncertainty of the Measurements

The measurement uncertainty of the image quality parameter determined using this standards publication 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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Foreword

This standards publication is classified as a NEMA standard unless otherwise noted. It describes a method for evaluating special purpose radio-frequency coils for use with magnetic resonance (MR) imaging (MRI) systems. These coils are used to receive signal from a limited portion of the anatomy. These include surface coils, flexible coils, pairs of coils such as Helmholtz coils, or coils that surround a specific tissue such as the knee or breast. These coils achieve good signal-to-noise performance because of their increased filling factor; in some cases, however, these coils have a nonuniform signal distribution. Both receive-only and transmit-receive coils are included. The system head and body coils are excluded. Also excluded are coils that require multiple receiver channels for operation (array coils).

The purpose of this procedure is to provide a standard means for measuring and reporting the signal-to-noise ratio (SNR) and nonuniformity of signal intensity in images acquired with special purpose coils. These quantities are helpful in evaluating the impact of system changes on performance or in demonstrating effectiveness for FDA applications.

The measurement methods have been designed for compatibility with existing NEMA methods for determining the SNR and signal intensity uniformity of head and body coil images (see MS 1 and MS 3). Evaluations are performed on images generated using standard clinical scan protocols.

This standards publication is intended for use by MRI system manufacturers, manufacturers of accessory equipment (including special purpose radio-frequency coils), and MRI end users.

This standards publication has been developed by the Magnetic Resonance Section of the National Electrical Manufacturers Association. User needs have been considered throughout the development of this publication. Proposed or recommended revisions should be submitted to:

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National Electrical Manufacturers Association
1300 North 17th Street, Suite 1847
Rosslyn, VA 22209

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:

Aurora Imaging Technologies—Wilmington, MA
Bruker Medical, Inc.—Billerica, MA
Fonar Corporation—Melville, NY
GE Medical Systems, Inc.—Milwaukee, WI
Hitachi Medical Systems America, Inc.—Twinsburg, OH
IGC Medical Systems—Milwaukee, WI
Marconi Medical Systems—Highland Heights, OH
Philips Medical Systems North America—Shelton, CT
Siemens Medical Systems, Inc.—Iselin, NJ
Toshiba America Medical Systems—Tustin, CA
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Rationale

Special purpose coils are constructed to optimize the signal-to-noise ratio (SNR) of images from a restricted volume of interest within the patient. This measurement procedure seeks to define the volume near the coil that produces a useful signal and to estimate the SNR at a reference point within that volume.

The increased signal-to-noise performance of some of these coils is accompanied by a loss of image uniformity. While image uniformity is generally a desirable goal, the reduction of signal from areas outside the region of interest can be exploited to reduce motion artifacts or to reduce image wrap-around artifacts caused by undersampling when the field of view is small. Therefore, it is appropriate to map the sensitive volume of a special purpose coil, since a simple figure of merit for uniformity can be misleading.

The SNR is a sensitive, but rather non-specific, measure of MR system performance. It can be used to assess the effect of alterations in the MR system (excluding the coil), or it can be used to compare the performance of two coils. Given that the sensitivity of many special purpose coils is spatially dependent, the assessment of the effect of alterations in the MR system can be achieved by measuring the SNR at a fixed reference point relative to the coil position. Since different coils are designed for different coil-to-tissue distances, it is not possible to fix a single reference position that is appropriate for all coil designs. The reference position selected shall approximate the position of the anatomical feature for which the coil is used. This standard allows flexibility in the choice of reference position; however, this flexibility may prevent direct comparison of different coil designs.

The loading of special purpose radio-frequency coils varies substantially from patient to patient and even from exam to exam for the same patient. Because of these variations, a loading scheme is not included in this standard. Since both loaded and unloaded SNRs are sensitive to changes in the remainder of the MR system (although the loaded SNR may be more representative of clinical conditions), either shall be permitted in this measurement procedure. Loading of the phantom shall be considered when the specific hardware configuration makes the unloaded SNR less than optimally sensitive to system changes.

Special purpose radio-frequency coils that require multiple MRI system receiver channels for proper operation (commonly referred to as array coils) are not included in this standard. Due to unique SNR and image nonuniformity effects that are outside the scope of this standards publication, the characterization of array coils shall be addressed through the development of a separate NEMA standard.

Two measurement procedures are offered for SNR and image nonuniformity: primary and alternative. The primary measurement procedures may require access to MRI system software functions normally available only to the MRI system manufacturer. As a result, the alternative measurement procedures, which do not require access to these system software functions, are provided.

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Scope

This standards publication defines test methods for measuring the signal-to-noise ratio, image uniformity, and image nonuniformity of MR images produced using special purpose coils. These methods are applicable to both receive-only and transmit-receive coils. This document does not address the use of general head and body coils (see MS 1 and MS 3) or coils that require multiple receiver channels for operation (array coils).

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Section 1
DEFINITIONS

1.1 SPECIFICATION VOLUME

The specification volume is the imaging volume within which a manufacturer guarantees image performance specifications. Images or portions of images outside this volume will not necessarily meet performance specifications, but can still be useful for diagnostic purposes. For head scans, the specification volume must enclose, as a minimum, a 10 centimeter diameter spherical volume (dsv) centered in the RF head coil. For body scans, the specification volume must enclose a 20 centimeter dsv centered in the RF body coil.

1.2 REFERENCE POSITION

The reference position is a point within the specification volume normally occupied by the anatomical feature for which the coil is used.

1.3 SENSITIVE VOLUME

The sensitive volume is that volume within which the MR signal of a uniform phantom is greater than or equal to 10 percent of the MR signal measured at the reference position.

1.4 CHARACTERIZATION VOLUME

The characterization volume is a regular geometric volume selected for measurement of uniformity variations over the anatomical region for which the coil is used. The characterization volume shall contain as much of the sensitive volume as is practical, as well as the reference position.

1.5 CHARACTERIZATION AREA

The characterization area is the intersection of the image plane and the characterization volume; it shall include the reference position. The MR images that are acquired of the uniform phantom in each image plane shall include the characterization area in its entirety.

1.6 IMAGE ARTIFACT

An image artifact is an image anomaly, excluding random noise, that is not representative of the structure or chemistry of the object being scanned, or that is derived from the structure or chemistry of the object being scanned but which appears in the image at a location other than expected.

1.7 IMAGE NONUNIFORMITY

Image nonuniformity is the variation of the pixel intensities in an image of a uniform phantom that is reproducible from scan to scan.

1.8 BASELINE PIXEL OFFSET VALUE

The baseline pixel offset value is the pixel value for a particular MR system that represents a noise-free signal level of zero.

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Section 2
METHODS OF MEASUREMENT

2.1 TEST HARDWARE

2.1.1 MR Characteristics of the Signal Producing Volume

The following are the MR characteristics of the signal producing volume:

T_1 < 1200 milliseconds (at operating field strength)

T_2 > 50 milliseconds (at operating field strength)

Spin density = density of H_2O ± 20%

2.1.2 RF Coil Loading Characteristics

A loading scheme is not included in this standard. Since both loaded and unloaded SNRs are sensitive to changes in the remainder of the MR system, either shall be permitted in this measurement procedure (see Rationale).

2.1.3 Test Volume

For each selected slice, the signal-producing volume of the phantom must enclose at least the entire volume defined by the slice thickness and the characterization area for that slice. The phantom or phantom position may be changed for the second slice position.

2.2 SELECTION OF MEASUREMENT GEOMETRY

2.2.1 Characterization Volume and Reference Position

In the case of a multiple-use coil, select one typical use. Select a characterization volume for the coil. Select a reference point for the coil. Consider the restrictions on phantom size (see Section 2.1.3) before selecting the characterization volume and reference point.

2.2.2 Measurement Region-of-Interest (MROI)

The MROI is a 7 x 7 pixel square area of the image centered at the reference position. The mean signal intensity value of this MROI shall be used as the numerator of the SNR. In addition, a preliminary calculation of the SNR within this region shall be used to select pixels for the noise calculation.

2.2.3 Noise Evaluation Area

Image noise shall be evaluated within a regular closed geometric area comprising the 49 pixels of the MROI plus at least 72 additional pixels. The shape of the noise evaluation area shall be chosen to ensure that at least 121 pixels have relatively high signal intensity values within the signal image (see Section 2.4, item g). The simplest noise evaluation area would be an 11 x 11 pixel square area that is centered on the reference position (see Figure 2-1), although certain coils require a more complex geometry to ensure that all of the pixels meet the signal intensity value requirement (see Figure 2-2).

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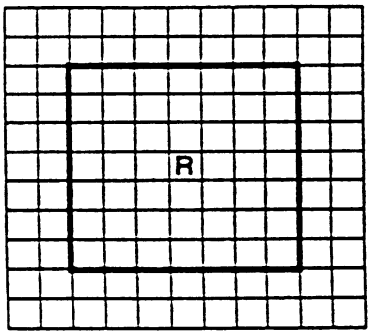


Figure 2-1
SIMPLEST GEOMETRY OF NOISE EVALUATION AREA

NOTE — Figure 2-1 shows the simplest geometry for the noise evaluation area. An 11 x 11 pixel square is centered on the reference position R. The outlined 7 x 7 pixel square is the MROI. The noise evaluation area contains 121 pixels, the minimum required by this standard, so every pixel must meet the intensity value requirement of Section 2.4, item g.

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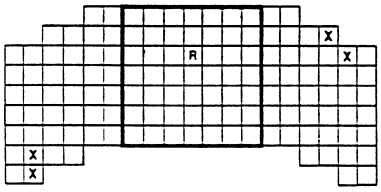


Figure 2-2
COMPLEX GEOMETRY OF NOISE EVALUATION AREA

NOTE — The geometry of Figure 2-1 is not always suited to every coil type. Figure 2-2 shows a more complex geometry. The noise evaluation area consists of 133 pixels. In this example, some of the pixels do not meet the intensity value requirement (the pixels that do not meet the requirement are identified with 'X') and are not included in the standard deviation (noise) calculation. Since more than 121 pixels do meet the requirement, a valid data set for noise evaluation is provided.

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2.2.4 Slice Positions

Nonuniformity measurements are performed in two orthogonal planes. SNR is evaluated in one of these planes. Both planes must pass through the reference position, since the purpose of the measurement is to demonstrate the falloff of signal away from the coil structure. This also facilitates measurement of the distance between the coil and the reference position on the images. For most surface coils, the slice planes shall be orthogonal to the plane of the coil and shall include the central axis of the coil (see Figure 2-3). For elliptical surface coils, one plane shall include the major axis of the ellipse, and the other shall include the minor axis of the ellipse. For cylindrical coils, one plane shall be perpendicular to the cylinder axis. Coils shall be located as near to their normal operating position in the magnet as is practical. In all cases, the slice positions shall be indicated on the drawing that accompanies the measurement result (see Section 3).

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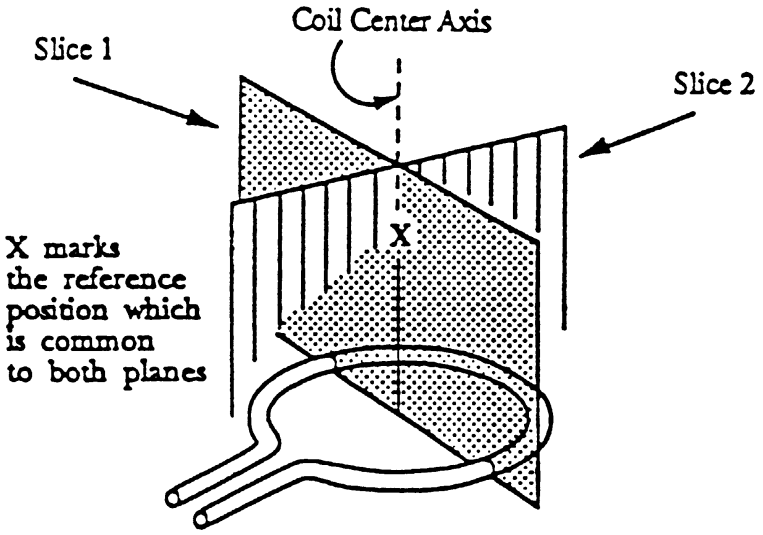


Figure 2-3
SLICE POSITIONS FOR A SURFACE COIL

2.3 SCAN CONDITIONS

Imaging shall be performed using a typical clinical scan sequence. Images shall be reconstructed by a procedure that yields a pixel value proportional to the MR signal value from the corresponding voxel.

IMPORTANT: No algorithm which compensates for nonuniformity shall be employed. This requirement is not intended to exclude algorithms that combine the signals from multiple coils.

Some of the following steps involve statistical analysis of the images. This analysis must be performed on images which have been processed by the system's typical diagnostic clinical reconstruction algorithm, but prior to any further modification for display purpose (e.g., interpolation, filtering). All such user-selectable filters shall be disabled. If this is not possible, the filter employed shall be noted in the results (see Section 3). The images to be analyzed shall be substantially free of image artifacts, other than image nonuniformity due to spatial variations in the sensitivity of the special purpose coil.

The field of view for each image must encompass the characterization area for the selected image plane.

In addition, the following scan conditions shall be used to acquire data:

Room and phantom temperature shall be 22 ± 4° C.
$TR \leq 5 \times T_1$ of filler material in the signal-producing volume.
TE within clinically selectable range.
Spin echo pulse sequence (first echo).
Slice thickness ≤ 10 mm.
Square pixel encoding.

2.4 PRIMARY MEASUREMENT PROCEDURE FOR SNR

Special purpose coil SNR is determined by sequentially executing the following procedure. The images recorded during this procedure can additionally be evaluated for nonuniformity.

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a. Position the signal-producing volume relative to the special purpose coil as prescribed in Sections 2.1.3 and 2.2.4. One of the two slice positions described in Section 2.2.4 is selected for the SNR measurement.
b. Perform the standard clinical pre-scan calibration procedure as recommended by the system manufacturer.
c. Execute two scans sequentially with less than 5 minutes elapsed time from the end of the first scan to the beginning of the second (image 1 and image 2). No system adjustment or calibration shall be performed between the scans.
d. Determine the mean pixel value within the MROI (as defined in Section 2.2.2) on image 1. The resulting number (minus any baseline pixel offset value) shall be called the image signal (S).
e. Calculate a pixel-by-pixel signed difference image (hereafter referred to as image 3) as follows:

$$[\text{image 3}] = [\text{image 1}] - [\text{image 2}]$$

NOTE—The image subtraction process must avoid overflow and underflow errors that could result from the generation of any pixel values that are outside the range of maximum and minimum pixel values allowed on the particular scanning system.

f. Calculate the standard deviation within the MROI of the subtracted image (image 3). This value is divided by the square root of two to give the preliminary image noise estimate (P).
g. Examine those pixels in image 1 which fall within the noise evaluation area (as defined in Section 2.2.3) and reject any pixels that have signal intensity values less than 5 x P (adjusting for any baseline pixel offset). At least 121 pixels must remain in image 3 that are artifact-free and contain a uniform noise distribution. Otherwise, an imaging protocol having greater SNR must be chosen, or a larger noise evaluation area must be defined. The coordinates of these pixels are the valid noise pixels.

NOTE — In absolute value images, the noise in regions with significant signal has a Gaussian distribution, while the noise in non-signal-containing areas has a Rayleigh distribution. In order to make this procedure valid for both real and absolute value images, noise shall be evaluated only in those areas containing significant signal. This is accomplished by making a preliminary image noise estimate (see Section 2.4 item f) based on the MROI and then identifying in the original, unsubtracted image those pixels within the noise evaluation area that have intensities of at least five times the preliminary image noise estimate.

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h. Determine the standard deviation (SD) of the pixels in image 3 that have the coordinates of the valid noise pixels.
i. Calculate the SNR as follows:

$$\text{SNR} = \frac{S\sqrt{2}}{SD}$$

2.5 ALTERNATE MEASUREMENT PROCEDURE FOR SNR

The SNR of a special purpose coil can alternatively be determined by sequentially executing the following procedure. The image recorded during this procedure can additionally be evaluated for nonuniformity.

a. Position the signal-producing volume relative to the special purpose coil as prescribed in Sections 2.1.3 and 2.2.4. One of the two slice positions described in Section 2.2.4 is selected for the SNR measurement.
b. Select a field of view (FOV) such that the image contains a signal- and artifact-free area with uniform noise distribution that is at least equivalent to the noise evaluation area defined in Section 2.2.3. The minimum required noise evaluation area (NEA) can be calculated from:

$$\text{NEA} = \frac{11 \times 11 \times \text{FOV} \times \text{FOV}}{N_F \times N_P}$$

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Where:

N_F and N_P are the number of pixels in the frequency and phase encoding directions, respectively.

FOV is the field of view.

c. Perform the standard clinical pre-scan calibration procedure as recommended by the system manufacturer.
d. Execute one scan and determine the mean pixel value within the MROI. The resulting number shall be called the image signal (S). The MROI can be defined as in Section 2.2.2 or alternatively should contain an equivalent area, given by:

$$\text{MROI} = \frac{7 \times 7 \times \text{FOV} \times \text{FOV}}{N_F \times N_P}$$

e. Adjust the window level of the image so that potential image artifacts (ghosting, etc.) become visible. Measure the standard deviation (SD) of the noise contained in a signal free area of the image. The area must be at least of the size as defined in step b and must be artifact free.
f. Calculate the SNR as follows:

$$\text{SNR} = 0.655 \frac{S}{SD}$$

NOTE —The factor 0.655 arises because, in absolute value images, the noise in regions with significant signals has a Gaussian distribution, while the noise in non-signal-containing areas has a Rayleigh distribution.

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2.6 PRIMARY MEASUREMENT PROCEDURE FOR IMAGE NONUNIFORMITY

Special purpose coil image nonuniformity is determined by sequentially executing the following procedure. It shall be permitted to evaluate for nonuniformity one of the two images recorded for the SNR measurement to reduce measurement time. Steps a through d are repeated for each of the two scan planes.

a. Position the signal-producing volume relative to the special purpose coil as prescribed in Sections 2.1.3 and 2.2.4.
b. Perform the standard clinical pre-scan calibration procedure as recommended by the system manufacturer.
c. Perform the scan.
d. Image nonuniformity shall be determined by manipulation of the resulting image to produce a contour map. A single gray level shall be assigned to all pixels having intensity values (I) such that:

$$S \times (1 - F) < I \leq S \times (1 + F)$$

Where:

S is the mean pixel value within the MROI (as defined in Section 2.2.2) minus any baseline pixel offset value.

F is a fraction with a fixed value of 0.1 that specifies the width of a histogram bin.

I is the intensity value that has been corrected for baseline pixel offset, if any.

Pixels having intensities:

$$S \times (1 + F) < I \leq S \times (1 + 2 \times F)$$

are assigned the next brighter gray level.

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This process is continued, with each gray level including pixels for which I is:

$$S \times (1 + n \times F) < I \leq S \times (1 + (n+1) \times F),\ n = 1, 2, 3 \ldots$$

until all pixels brighter than S have been assigned a gray level.

A similar procedure is applied to pixels with intensities less than S x (1 - F). The gray level bins are defined by:

$$S \times (1 - (n+1) \times F) < I \leq S \times (1 - n \times F),\ n = 1, 2, 3 \ldots$$

until all pixels darker than S have been assigned a gray level. Pixels in the lowest intensity bin are assigned to black.

The resulting images shall be labeled to indicate physical dimensions.

2.7 ALTERNATE MEASUREMENT PROCEDURE FOR IMAGE NONUNIFORMITY

The image nonuniformity of a special purpose coil can alternatively be determined by sequentially executing the following procedure. It shall be permitted to use the image recorded for the SNR measurement for the nonuniformity evaluation to reduce measurement time. Steps a through d are repeated for each of the two scan planes.

a. Position the signal-producing volume relative to the special purpose coil as prescribed in Sections 2.1.3 and 2.2.4.
b. Perform the standard clinical pre-scan calibration procedure as recommended by the system manufacturer.
c. Perform the scan.
d. Define a rectangular characterization area denoted as the ROI, entirely containing 17 SROIs that have 7 x 7 pixel square areas (see Figure 2-4). Determine the mean signal intensities S1 through S17 at the locations defined as follows:

S1: Central SROI.
S2: Top of the ROI, vertically displaced from S1.
S3: Half distance between S2 and S1, displaced vertically.
S4: Bottom of the ROI, vertically displaced from S1.
S5: Half distance between S4 and S1, displaced vertically.
S6: Far left side of the ROI, horizontally displaced from S1.
S7: Half distance between S6 and S1, displaced horizontally.
S8: Far right side of the ROI, horizontally displaced from S1.
S9: Half distance between S8 and S1, displaced horizontally.
S10: Far top left corner of the ROI, displaced diagonally.
S11: Half distance between S10 and S1, displaced diagonally.
S12: Far bottom left corner of the ROI, displaced diagonally from S1.
S13: Half distance between S12 and S1, displaced diagonally.
S14: Far top right corner of the ROI, displaced diagonally.
S15: Half distance between S14 and S1, displaced diagonally.
S16: Far bottom right corner of the ROI, displaced diagonally from S1.
S17: Half distance between S16 and S1, displaced diagonally.

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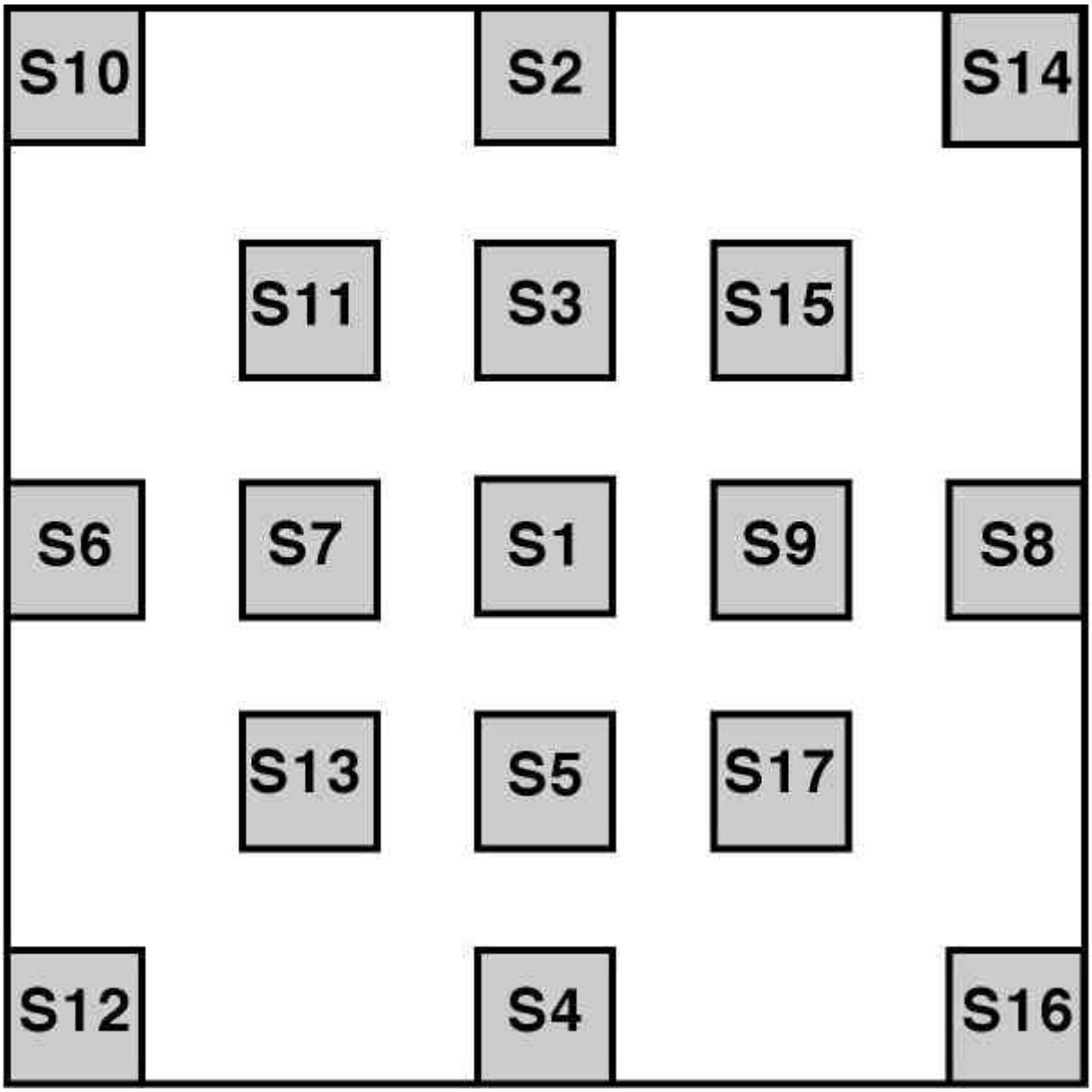


Figure 2-4
ROI FOR IMAGE NONUNIFORMITY MEASUREMENT

e. Calculate the nonuniformities N1 through N17 using:

$$N_n = \frac{|S_n - S_1|}{|S_n + S_1|} \quad n = 1,2,3, \ldots 17$$

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Section 3
REPORTING OF RESULTS

3.1 REPORTING OF SNR

3.1.1 Geometric Information

A dimensioned drawing (or drawings) showing the following geometric information must accompany the statement of the image SNR:

- Main magnetic field (B_0) direction
- Position of the special purpose coil with respect to the gradient isocenter
- Position of the characterization volume with respect to the coil structure
- Size and shape of characterization volume
- Position of the slice within the characterization volume
- Position of the MROI within the characterization volume (this also defines the reference position)
- Size and shape of the noise evaluation area and its relationship to the MROI

3.1.2 Data Acquisition Parameters

The following data acquisition parameters must accompany the statement of the image SNR:

Parameter	Dimension
Phantom filler T_1	milliseconds
Phantom filler T_2	milliseconds
Pixel bandwidth	Hertz per pixel
Voxel dimensions	millimeters
Sequence repetition time (TR)	milliseconds
Echo delay time (TE)	milliseconds
Number of signals averaged (NSA)	….
Data acquisition matrix size	….

A description of the coil loading, if used, shall be provided. If it was not possible to turn off all user-selectable filters (see Section 2.3), the filter that was used shall be noted. In addition, any other parameters required to ensure repeatability shall be reported.

3.1.3 SNR Results

The SNR value computed in Section 2.4, item i or Section 2.5, item f shall be provided.

3.2 REPORTING OF NONUNIFORMITY

3.2.1 Geometric Information

A dimensioned drawing (or drawings) showing all of the information described in Section 3.1.1 must accompany the statement of image nonuniformity. In addition, the drawing(s) shall indicate the position relative to the special purpose coil of the field of view of the contour map described in Section 2.6, item 4 or the ROI described in Section 2.7, item d.

3.2.2 Data Acquisition Parameters

The parameters listed in Section 3.1.2 must accompany the image nonuniformity results.

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3.2.3 Nonuniformity Results

For the primary measurement procedure, the contour map described in Section 2.6, item d shall be provided. This contour map shall be annotated to show the reference position and the dimension scale.

If the alternate measurement procedure described in Section 2.7 is used, a table of the results described in Section 2.7, item e shall be provided.

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