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Characterization of Phased Array 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 (MRI) 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 phased array radio-frequency coils used with MRI systems. Phased array coils consist of multiple transmit/receive and/or receive-only coil elements that are used to detect signals from a limited portion of the anatomy. The output of each coil element, or combined set of elements, is connected to the input of an independent receiver chain that is part of a set of multiple receiver chains. Examples of phased array coils are surface coils, flexible coils, pairs of coils such as Helmholtz coils, or coils that surround a specific anatomical region as well as combinations of these coils. Phased array coils achieve good signal-to-noise performance because of their increased filling factor and the simultaneous use of smaller, higher signal-to-noise receive coil elements. In some cases, however, these coil elements (both transmit and receive-only) have a nonuniform signal distribution.

The purpose of this procedure is to provide a standard means for measuring and reporting the signal-to-noise ratio (SNR), uniformity, and nonuniformity of signal intensity in images acquired with phased array 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, body, and special purpose coil images (see MS 1, MS 3, and MS 6). 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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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
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Rationale

Phased array 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 active elements of the phased array coil that produce useful signal and to estimate the SNR at a reference point or region within that volume.

Phased array coils that consist of volume coil elements may provide a uniform signal response over the sensitive volume, and therefore in this standard may be measured and characterized using methods similar to those used for volume coils such as a head or body coil.

For some sub-coils used in the construction of a phased array coil, the increased signal-to-noise performance may be 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 wrap-around artifacts caused by undersampling when the field of view is small. Therefore, it is appropriate to map the sensitive volume of a phased array surface coil element, since a simple figure of merit for uniformity can be misleading. In this standard, surface coil elements of a phased array may be measured and characterized using the methods prescribed for special purpose coils.

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 some phased array 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 phased array sub-coils are designed for different coil-to-tissue distances, it is not possible to fix a single reference position that is appropriate for all sub-coils. The reference position selected shall approximate the position of the anatomical feature for which the selected sub-coil is used. This standard allows flexibility in the choice of the reference position or region. This flexibility may, however, prevent direct comparison of different coil designs.

The loading of phased array 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 specific hardware configurations make the unloaded SNR less than optimally sensitive to system changes.

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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 phased array coils. These methods are applicable to both receive-only and transmit-receive phased array coils. Coils that do not make use of multiple transmit/receive or multiple receive-only coil elements, such as single channel linear or quadrature coils, have been addressed in other NEMA standard publications. (See MS 1, MS 3, and MS 6.)

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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 cm diameter spherical volume (dsv) centered in the RF head coil. For body scans, the specification volume must enclose a 20 cm 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 sub-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 sub-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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1.9 PHASED ARRAY COILS

Phased array coils consist of multiple transmit/receive and/or receive-only coil elements that are used to detect signals from a limited portion of the anatomy. The outputs from the receiver chains are digitized, saved, and processed to produce a composite or combined resultant image covering the entire anatomic region of interest.

1.10 SUB-COILS

A sub-coil is an independent imaging element of a phased array coil structure. The output of the sub-coil is connected to an independent receiver chain or combined together with another sub-coil by analog means and then connected to an independent receiver chain.

1.11 PHASED ARRAY – SURFACE SUB-COILS

A phased array comprised of surface sub-coils has elements whose individual sensitivities are spatially dependent and therefore are not expected to produce a uniform signal intensity in the region of interest. Signal-to-noise performance for this type of phased array coil is measured at a single reference position within the region of interest.

1.12 PHASED ARRAY – VOLUME SUB-COILS

A phased array consisting of volume sub-coils has elements whose individual sensitivities are not spatially dependent and therefore are expected to produce a uniform signal intensity in the region of interest.

1.13 PHASED ARRAY – SURFACE AND VOLUME SUB-COIL COMBINATIONS

A phased array consisting of surface and volume sub-coils has some individual sub-coils whose sensitivities vary spatially and others that do not.

1.14 COMBINED IMAGE OR IMAGE COMBINATION

Combining the outputs of the independent receiver chains produces a combined image. Image combination can be accomplished by convolution of the complex temporal data (pre-FFT or raw data), or by combining post-processed (post-FFT) image data sets, using sum-of-squares or addition of image pixel data.

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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 Signal Producing 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 (see Section 2.2.4).

2.2 SELECTION OF MEASUREMENT GEOMETRY

2.2.1 Characterization Volume and Reference Position

In general, phased array coils allow different combinations of active receiving sub-coils to be used simultaneously. For each typical sub-coil set (or mode), select a characterization volume. Consider the restrictions on phantom size (see Section 2.1.3) before selecting the characterization volume. Consider the restrictions on slice position (see Section 2.2.4) before selecting the reference position. For volume sub-coils, the characterization volume shall be the specification volume.

2.2.2 Measurement Region-of-Interest (MROI)

Phased array coils consisting of sub-coils that do not produce a uniform signal response over the specification volume (surface sub-coils) may be measured and characterized using either of the two methods (primary and alternate) described in NEMA Standard MS 6 *"Characterization of Special Purpose Coils for Diagnostic Magnetic Resonance Images"* (see Rationale). Accordingly, for surface sub-coils, the MROI shall be a 7 x 7 pixel square area of the image centered at the reference position. The mean signal intensity value in this MROI shall be used as the numerator of the SNR. For the alternate measurement procedure for image nonuniformity, the rectangular area denoted as the ROI shall enclose at least 75% of the characterization area.

Phased array coils consisting of sub-coils that do produce a uniform signal response over the specification volume (volume sub-coils) may be measured and characterized using the methods described in NEMA Standards MS 1 *"Determination of Signal-to-Noise Ratio (SNR) in Diagnostic Magnetic Resonance Images"* and MS 3 *"Determination of Image Uniformity in Diagnostic Magnetic Resonance Images"* (see Rationale). Accordingly, for volume sub-coils, the MROI shall consist of a centered, regular geometric area enclosing at least 75% of the characterization area.

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2.2.3 Noise Evaluation Area

For volume sub-coils, the noise evaluation area shall be the MROI. For surface sub-coils, image noise shall be evaluated within a regular closed geometric area comprising the 49 pixels of the MROI plus at least 72 additional pixels, as described in MS 6 for the primary SNR measurement procedure. For the alternate SNR measurement procedure, the minimum required noise evaluation area is equivalent in size but located in a signal and artifact free area of the image with uniform noise distribution.

2.2.4 Slice Positions

For surface sub-coils, nonuniformity measurements shall be performed in two orthogonal planes, as described in MS 6. SNR is evaluated in one of these planes. Both planes must pass through the reference position.

For volume sub-coils, image uniformity data shall be acquired as single slice scans through the center of the coil (not necessarily at isocenter) in each of the three orthogonal imaging planes. SNR is evaluated in one of these planes.

In all cases, the slice positions shall be indicated on the drawing that accompanies the measurement results (see Section 3).

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 signals from multiple coils.

Some of the steps in the measurement procedure involve statistical analysis of the images. This analysis must be performed on images that have been processed by the system's standard 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 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 $22 \pm 4^\circ$ 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 MEASUREMENT PROCEDURE

As previously indicated (see Section 2.2.1), the first step in characterizing phased array coil SNR and image uniformity is to select the individual sub-coil, or set of sub-coils, that is to be activated in the region normally occupied by the anatomical feature for which the sub-coil, or set of sub-coils, is used. More than one set of measurements (SNR and uniformity) may be required depending on the size and number of coil elements, and the range of anatomic features covered by the phased array coil (e.g. cervical-thoracic-lumbar [CTL] coil).

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Once the individual sub-coil or set of sub-coils is selected, the SNR may be measured by following the procedure in NEMA Standard MS 6 for surface sub-coils or MS 1 for volume sub-coils. One of the slice positions described in Section 2.2.4 is to be selected for the SNR measurement. In order to save time, one of the images recorded during this procedure can also be evaluated for nonuniformity according to MS 6 for surface sub-coils or MS 3 for volume sub-coils.

By repeating the SNR and uniformity measurements for each sub-coil, or set of sub-coils simultaneously activated or deactivated, the performance effects of nearest-neighboring sub-coils or alternate neighboring sub-coils may be evaluated. This can also be done by comparing combined post-processed images to individual uncombined images.

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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 image SNR for each phased array sub-coil combination:

- Main magnetic field (B_0) direction
- Position of the phased array coil with respect to the gradient isocenter
- Position of the characterization volume with respect to the coil structure
- Size and shape of the 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 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 for each phased array sub-coil combination shall be reported. Indicate which method was used to characterize SNR, primary or alternative (NEMA Standard MS 6), or method 1 or method 2 (NEMA Standard MS 1).

3.2 REPORTING OF NONUNIFORMITY

3.2.1 Geometric Information

A dimensioned drawing (or drawings) showing all of the information requested in Section 3.1.1 must accompany the statement of image nonuniformity for each phased array sub-coil combination. In addition, the drawing(s) shall indicate the position relative to the phased array coil of the field of view of the gray-scale contour map described in NEMA Standard MS 6 or MS 3 (as appropriate) or of the ROI described in MS 6 (alternate procedure).

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3.2.2 Data Acquisition Parameters

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

3.2.3 Nonuniformity Results

The uniformity or nonuniformity results shall be reported in a fashion consistent with the method by which they were obtained.

For phased array volume sub-coils, the integral uniformity may be quoted or a gray-scale coded contour map may be provided as described in NEMA Standard MS 3.

For surface sub-coils, the signal contour map described in NEMA Standard MS 6 shall be provided if the primary measurement procedure was followed. This contour map shall be annotated to show the reference position and the dimension scale. If the alternate measurement method was used, a table of the nonuniformities N1 through N17 shall be provided.

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