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Determination of Signal-to-Noise Ratio (SNR)
in Diagnostic Magnetic Resonance Imaging

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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.

Foreword

This standards publication is classified as a NEMA standard unless otherwise noted. It describes four methods to measure image signal-to-noise ratio (SNR). It is intended for use by MRI system manufacturers, manufacturers of accessory equipment (including radiofrequency coils), and by MRI end users.

The major feature of the first method is that the SNR performance of the system is evaluated using a standard clinical scan procedure. However, it should be noted that since this method involves the subtraction of two images, it can be very sensitive to system instabilities that may occur during the data acquisition process. If results are highly variable, it is advisable to perform the alternative calculation of standard deviation, described in method #1, or use methods #2, #3, or #4. These alternative methods have been designed to be less susceptible to system instabilities and can be used to determine if any variability in the SNR is due to system instability or genuinely poor SNR. Both methods are intended to measure thermal and other broadband, non-structured noise, and specifically do not address low frequency variations in an image or artifacts as defined herein.

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:

> Vice-President, Engineering Department
> National Electrical Manufacturers Association
> 1300 North 17th Street, Suite 900
> Rosslyn, VA 22209

This standards publication was developed by the Magnetic Resonance Section. 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 Magnetic Resonance 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
> Philips Healthcare—Andover MA
> Siemens Medical Solutions, Inc.—Malvern, PA
> Toshiba America Medical Systems—Tustin, CA

Rationale

Image SNR is a parameter that relates to clinical usefulness of magnetic resonance images and also is a sensitive measure of hardware performance. Experience has shown that variations in system calibration, gain, coil tuning, radiofrequency shielding, or other similar parameters are usually demonstrated by a corresponding change in image SNR.

Scope

This document defines methods for measuring the signal-to-noise ratio of magnetic resonance images obtained under a specific set of conditions, and using single-channel volume receiver coils. This document does not address the use of special purpose coils (see MS 6) or coils that employ multiple receiver channels for operation (see MS 9).

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 may not necessarily meet performance specifications, but may 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, as a minimum, a 20-cm dsv centered in the RF body coil.

1.2 SPECIFICATION AREA

The specification area is the intersection of the specification volume and the image plane.

1.3 MEASUREMENT REGION OF INTEREST (MROI)

The measurement region of interest (MROI) is a centered, regularly shaped geometric area enclosing at least 75% of the area of the image of the signal-producing volume of the phantom.

1.4 IMAGE SIGNAL

The image signal is the mean pixel value within the MROI (minus the baseline pixel offset, if any) in the original, unsubtracted image.

1.5 IMAGE NOISE

The random variations in pixel intensity in the MROI are called image noise.

1.6 IMAGE SIGNAL-TO-NOISE RATIO

The image signal-to-noise ratio is a single number obtained by dividing the image signal by the image noise.

1.7 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, if it is an anomaly derived from the structure or chemistry of the object being scanned, appears in the image at a location other than expected.

1.8 VOXEL DIMENSIONS

This parameter is composed of three elements:

a. Slice thickness – operator selected slice thickness.

b. Pixel horizontal dimension – the field of view in the horizontal direction divided by the number of data sampling points in the horizontal axis. This corresponds to the horizontal dimension of the data acquisition matrix.

c. Pixel vertical dimension – the field of view in the vertical direction divided by the number of data sampling points in the vertical axis. This corresponds to the vertical dimension of the data acquisition matrix.

1.9 REAL IMAGE

After reconstruction, the image pixels are vectors with real and imaginary parts. A phase correction is applied to the image in an attempt to rotate the noise-free signal to the real axis. The positive and negative real components of each pixel form the real image.

1.10 MAGNITUDE IMAGE

The magnitude image is formed by taking the magnitude of each complex pixel.

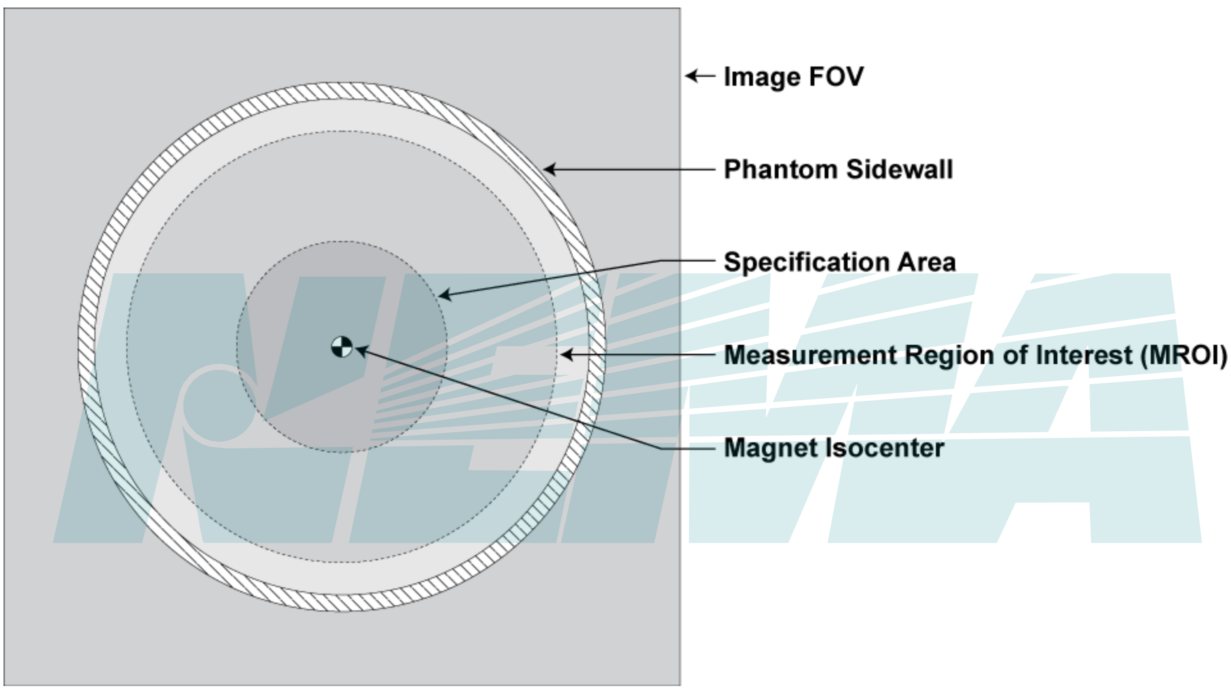

Figure 1–1
A Schematic Showing the Relative Location of Defined Terms

Section 2
METHODS OF MEASUREMENT

2.1 TEST HARDWARE

2.1.1 Size of the Signal Producing Volume

The size of the signal producing volume is determined by the thickness of the slice being imaged (per the protocol in 2.2) and the cross-sectional area resulting from the intersection of the image plane and the phantom. The size of this cross-sectional area must meet the following requirements:

a. Head specification volume: in the image plane, the phantom shall enclose, as a minimum, a 10 centimeter diameter circle or 85% of the specification area, whichever is larger.

b. Body specification volume: in the image plane, the phantom shall enclose, as a minimum, a 20 centimeter diameter circle or 85% of the specification area, whichever is larger.

2.1.2 RF Coil Loading Characteristics

In order to approximate the image noise performance that would be typically encountered in a clinical situation, the RF receive coil of interest (i.e., either head or body coil), must be electrically loaded. Loading may be accomplished by phantoms or other reproducible means. When loaded, the following electrical parameters must be the same as when a 50 to 90 kg human is positioned for a scan (within the stated tolerances):

a. Coil 3 dB bandwidth: ±15%

b. Coil impedance: ±20% magnitude, ±20° phase

c. Coil center frequency shift: ±1% of center frequency

2.1.3 MR Characteristics of the Signal Producing Volume

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

T1 < 1200 milliseconds (at operating field strength)
T2 > 50 milliseconds (at operating field strength)
Spin density = density of H_2O ± 20% (for water-based phantoms)

The phantom material, additives, and any special preparation procedures, shall be specified with the results to allow reproducibility.

If the properties are different from those stated above, the differences shall be noted with the results.

It shall be permitted to use oil-based or water-based phantoms. Sufficient specification of the materials used for the phantom fluid shall be provided in the report of results to allow for reproducibility of the measurement.

2.2 SCAN CONDITIONS

Image signal-to-noise ratio data shall be acquired using a typical clinical scan sequence and reconstruction process, which has not been altered in any fashion to affect the SNR results. In addition, the following scan conditions shall be used to acquire the data:

a. The phantom shall be centered in the RF receive coil.

b. The RF receive coil shall be positioned at isocenter.

c. The RF receive coil shall be electrically loaded as per Section 2.1.2.

d. The room and phantom temperature shall be 22 ± 4 °C.

e. A spin echo pulse sequence (first echo) is recommended but not required.

f. The sequence repetition time (TR) shall be ≥ 3 x T1 of the filler material in the signal-producing volume.

g. The echo time (TE) shall be within the clinically selectable range.

h. A single, transverse (axial) slice shall be acquired at isocenter.

i. The selected field of view shall not exceed 110% of the largest linear dimension of the RF coil in the image plane.

j. The slick thickness shall be ≤ 10 mm.

2.3 MEASUREMENT PROCEDURE

Important: Some of the following steps involve statistical analysis of the images. This analysis must be performed on images that have been processed by the system's standard diagnostic clinical reconstruction algorithm, but prior to any further optional modifications for display purposes (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.

2.3.1 Image Signal Determination

Image signal shall be determined by executing the following procedure:

a. Center the signal-producing volume of the phantom (head or body as appropriate) in the RF receive coil and load the coil per Section 2.1.2.

b. Perform the standard clinical pre-scan calibration procedure as recommended by the system manufacturer.

c. Perform the scan to obtain [image 1].

d. Determine the mean pixel value within the MROI. The resulting number (minus the baseline pixel offset value, if any) is called the signal S.

2.3.2 Procedures to Evaluate Image Noise

Any one of four methods shall be permitted to evaluate image noise.

The first method requires the subtraction of two signal-containing images. This method can be used for any n-channel receive system but is subject to system drift artifacts. The usage of this method is restricted to single-channel receive systems in this standard.

The second method requires the generation of an image with no NMR signal. Because the noise measurement is obtained directly from an image having no coherent signal, it is not sensitive to system drift, but it is sensitive to any mechanism that distorts the expected noise distribution. The correction factor described in this standard is appropriate only for single-channel receive systems, consistent with the scope of this standard. (With a different appropriate correction factor, this method can be used for any n-channel receive system.) This method cannot be used with any image reconstruction/processing algorithm that alters the noise characteristics of a noise-only region.

Methods 1 and 2 stipulate that the second scan shall be performed with less than 5 minutes elapsed time from the end of the first scan to the beginning of the second.

The third method produces two signal images synthetically from one scan which can then be subtracted to form a noise image. This method can be used for any n-channel receive system, but is restricted to single-channel receive systems in this standard. This method is minimally sensitive to system drift because the effective time difference between the two derived images is the sampling interval of the acquisition.

The fourth and last method is a single acquisition method. The noise is measured in a region free of visible signal artifacts outside the phantom. It is not sensitive to system drift artifacts because only one image is acquired, but the noise statistics can be distorted by signal artifacts that are not clearly visible. It can be used for any n-channel receive system, with the appropriate correction factors as noted for the second method, but this method is restricted to single-channel receive systems in this standard. This method is not compatible with any image reconstruction/processing algorithm that alters the noise characteristics of a noise-only region.

None of the methods described here is compatible with parallel imaging methods in their present form because noise in parallel imaging methods is spatially variant.

2.3.2.1 Method 1

The second image [image 2] is acquired under precisely the same conditions as the first. No system adjustment or calibration shall be performed between scans.

a. Calculate a pixel-by-pixel difference image (hereafter referred to as [image 3]) as follows:

[image 3] = [image 1] – [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 that are allowed on the particular scanning system.

b. Determine the standard deviation SD of the pixel values within the MROI on [image 3]:

$$SD = \left[\frac{\sum_{i=1}^{n} \sum_{j=1}^{m_i} \left(V(i,j) - \overline{V} \right)^2}{\sum_{i=1}^{n} (m_i) - 1} \right]^{\frac{1}{2}} \qquad \text{Equation 1}$$

Where:

$\overline{V}$ is the average pixel value in [image 3]
V(i,j) is the pixel value in [image 3]
i index spans the read encode direction
j index spans the phase encode direction

The MROI spans a maximum of n read points in the image and m_i denotes the variable number of phase encode points possible in a regularly shaped MROI.

c. The method of calculating the standard deviation can affect the result. Temporal instability of the MR imager can give rise to artifacts in the subtracted image which increase the standard deviation. These artifacts normally have low spatial frequency, and their effect on the calculation of the standard deviation can be sharply reduced by evaluating the successive differences between the adjacent points in [image 3].

$$SD = \left[\frac{\sum_{i=1}^{n} \sum_{j=1}^{m_i - 1} \left(V(i, j+1) - V(i, j)\right)^2}{2 \sum_{i=1}^{n} (m_i - 1)} \right]^{\frac{1}{2}} \qquad \text{Equation 2}$$

d. Temporal stability can be evaluated by comparing the result of Equation 2 and Equation 1. In the absence of temporal instabilities, the two measures of SD should be nominally the same. With increasing temporal instability the results of both Equation 1 and Equation 2 will increase, but the results of Equation 1 will increase more rapidly. Since both measures of SD involve a difference operation [image 3], the image noise measurement must be corrected as follows:

$$\text{imagenoise} = \frac{SD}{\sqrt{2}} \qquad \text{Equation 3}$$

2.3.2.2 Method 2

A noise scan image is acquired with the phantom in its original position and with no RF excitation. In this situation, it is permitted to decrease TR and accelerate the noise scan acquisition. Ensure that the bandwidth, matrix size and number of signal averages are held constant. Ensure that the MR system does not automatically change other relevant parameters as a result of the above changes.

a. Ensure that the output from the transmitter is such that no NMR signal is generated upon execution of the noise scan. It shall be permitted to turn off the RF amplifier or otherwise suppress the RF excitation.

b. Ensure that the system receiver attenuation (or gain control) and any scaling of the image reconstruction are identical to that of the first scan.

c. Except for TR, the noise image is acquired under the same conditions as [image 1]. No system adjustment or calibration shall be performed between the scans.

d. Determine the standard deviation, SD, of the pixel values within the MROI on the noise image using Equation 1.

e. If a magnitude image is evaluated, the image noise will not be Gaussian distributed, but rectified to a Rician distribution. The change of noise distribution must be compensated for as the SNR measure assumes the noise is Gaussian distributed. For a single-channel system the correction factor is:

$$\text{imagenoise} = \frac{SD}{0.66} \qquad \text{Equation 4}$$

The factor of 0.66 $\left(\cong \sqrt{(4-\pi)/2}\right)$ accounts for the Rayleigh distribution of the noise in the magnitude image. (Henkelman, R. M. 1985, Medical Physics, 12, 232-233.)

If a real image is evaluated, the image noise is:

$$imagenoise = SD \qquad \text{Equation 5}$$

2.3.2.3 Method 3

As noted above, system drift can adversely affect the determination of image noise statistics by the subtraction of two images acquired serially. System drift becomes more pronounced as the time interval between data measurements increases. Method 3 reduces the time interval between measurements to the minimum possible, virtually eliminating contaminated noise statistics. This method uses a single, special image acquisition, but ultimately results in two signal images that are subtracted as in Method 1. Implementation of this method requires access to the raw k-space data.

a. Acquire an image with a read direction field of view that is twice as large as the field of view used in Method 1 or 2. Center the phantom within that field of view. Simultaneously, double the read direction matrix size. On some MRI units, this can be accomplished by doubling the read and phase matrix size, then reducing the phase encode direction matrix size with a 50% rectangular field of view. Maintain the same bandwidth used in Methods 1 and 2, if possible. If it is necessary to maintain the same total sampling time and same TE, double the acquisition bandwidth.

b. Save the raw k-space, time domain data. Introduce the following data decimation process in the read direction: split out all even number index data points in the read direction into data file “even” and all the remaining odd number index data points in the read direction into data file “odd” Magnitude reconstruct these two decimated data sets. Since every other data point is in the same data file, the sampling rate has been cut in half and the read direction field of view size has been reduced by the same factor of two. The field of view, and number of image data points, should now equal that collected in Methods 1 and 2.

c. Now we have two images where the time difference between the two images is effectively the time between samples; there is almost no drift between the two images. Subtract images as in Method 1:

   [new image 3] = [new image 1] – [new image 2]

d. Compute the signal MROI mean S in both [new image 1] and [new image 2] and average together.

e. Compute SD in the same measurement MROI region as in step d, but in [new image 3]. This is equivalent to step b. in Method 1.

f. Since Method 3, step c. computed the difference of images, it is necessary to divide the SD by √2. This is equivalent to step d. in Method 1. If the bandwidth of acquisition was doubled in step a, it is necessary to scale the results to be equivalent to Method 1 and 2. In this case, divide SD by another factor of √2.

g. Optionally, the alternate standard deviation computation (Method 1, step c) can be applied to [new image 3], but this should not be necessary.

2.3.2.4 Method 4

As noted above, system drift can adversely affect the determination of image noise statistics by the subtraction of two images acquired serially. Another solution is to compute the SNR from a single magnitude reconstructed image. The signal S is computed as before, but the noise SD measurement is computed from a background region of the image well removed from the phantom and in a region free of any visible artifacts. There are measurement risks associated with this SD determination: subtle non-visible artifacts will skew the SD measurement, image post-processing may alter the SD and some image post-processing methods may mask out the entire background region making it impossible to measure the noise SD. In addition, when acquiring images at high bandwidths the non-uniformity of the receiver sub-system frequency response may produce different noise statistics on either side of the image (high positive vs low negative frequencies). Therefore, it is recommended that the statistical measurements from the four corners be averaged together. It is necessary to ensure that these factors are not present when using this method.

a. Determine the mean pixel value within the MROI. The resulting number (minus the baseline pixel offset value, if any) is called the signal S.

b. Draw a noise MROI in a background region of the image well removed from the phantom and any visible artifacts. The projections of the noise MROI in both the read and phase direction must be well removed from the signal producing phantom. This requirement places the noise MROI in the corner of the image. This may require a larger FOV than used in the other methods to provide sufficient space for a reasonably sized MROI. [1000 pt minimal, but more points better to get more consistent results]

c. There are two methods for determining the noise SD in the MROI described in step b. Since a magnitude image is being evaluated, the image noise will not be Gaussian distributed, but rectified to a Rayleigh distribution, assuming no extraneous bias is present. Therefore, the noise SD is estimated either from the SD or mean of the Rayleigh distribution, suitably corrected to the equivalent expected Gaussian distribution. If the SD of the Rayleigh distribution is measured, the correction factor for a single-channel image is:

$$\text{imagenoise} = \frac{SD}{0.66} \qquad \text{Equation 6}$$

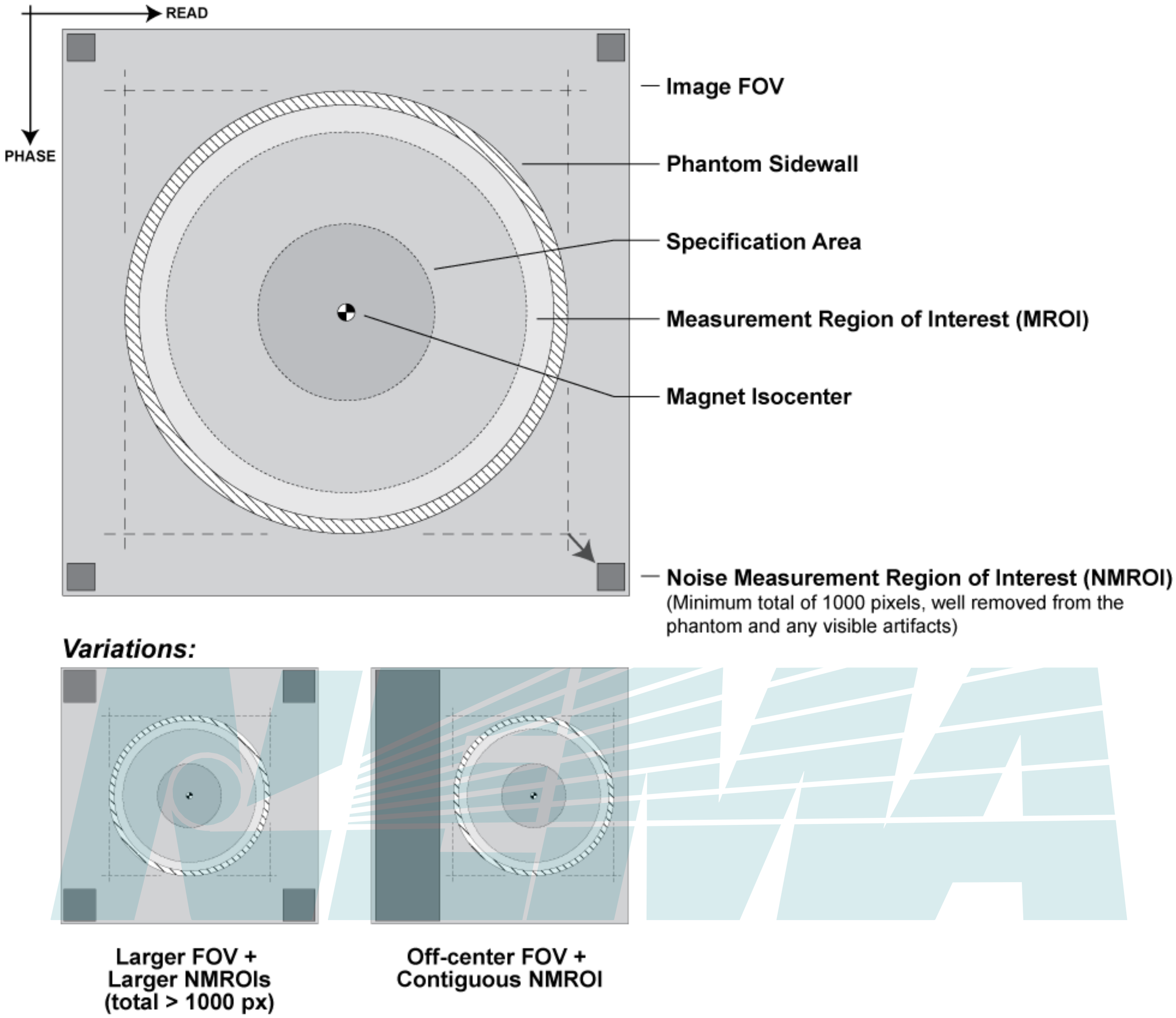

Figure 2–1
A Schematic Showing Example Background
Noise Measurement Region Locations for Method 4

2.3.3 Procedure to Determine SNR

The SNR is determined by:

$$SNR = \frac{S}{imagenoise} \qquad \text{Equation 7}$$

Section 3
RESULTS

3.1 REPORTING OF RESULTS

3.1.1 Geometric and Phantom Information

The following information must accompany the statement of the image SNR.

- Main magnetic field (B_0) direction
- Position of the coil with respect to the gradient isocenter
- Position of the specification volume with respect to the coil structure
- Size and shape of specification volume
- Size and shape of phantom and phantom fluid specification including chemical contents of phantom, T1, T2, and any preparation steps
- Position of the slice within the specification volume and resulting specification area
- Position and shape of the MROI within the specification volume
- Size and shape of the noise evaluation area and its relationship to the MROI
- Geometric information for the phantom used and specification of the phantom materials and additives used

Several of the above listed items may be best shown in a dimensioned drawing.

3.1.2 Data Acquisition Parameters

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

Table 3–1

Parameter	Dimension
Pixel bandwidth	Hz per pixel
Voxel dimensions	millimeters
Receiver channel 3dB bandwidth	kHz
Phantom filler specific conductance (or phantom filler composition)	Siemens per meter
Phantom dimensions	millimeters
Sequence repetition time (TR)	milliseconds
Echo delay time (TE)	milliseconds
Number of signals averaged (NSA)	….
Data acquisition matrix size	….
Field of view	millimeters
Pulse sequence name	….
Software version	….
Receive/Transmit coil(s) used	…
Statement of geometric distortion correction algorithm	…
Statement of RF receive coil correction algorithm	…
Type of signal filters used (time and/or image domain)	…
Scan room temperature	ºC
Phantom temperature	ºC

3.1.3 SNR Results

The SNR value computed in Section 2.3.3 shall be provided.

3.1.4 Reconstruction Parameters

List the reconstruction parameters selected in Section 2.3.

3.1.5 Additional Data

Provide the following additional data:

a. Method used to evaluate noise.

b. If Method 1, equation used to calculate standard deviation (Equation 1 or Equation 2).

c. If Method 3, indicate whether the bandwidth was doubled.

d. If Method 4, equation used to calculate standard deviation (Equation 4 or Equation 6).

e. The method of conformance to the RF loading characteristic stated in Section 2.1.2.

3.1.6 Repeatability Data

Provide other relevant information that ensures repeatability.

3.1.7 Sources of Error

Provide a description of the potential sources of error.

Appendix A
AN ALTERNATIVE MEASURE OF NOISE STANDARD DEVIATION

Computing the standard deviation of a magnitude reconstructed noise region and applying an appropriate correction factor to eliminate the bias of the magnitude operator is not necessarily the most stable method. The squared operation in the standard deviation computation tends to be sensitive to artifacts, even when the artifacts are not visible. This sensitivity to artifacts tends to increase the standard deviation, and lower the computed image SNR. This standard permits an alternative calculation of the image noise levels. Instead of using the standard deviation of a background region, compute the mean of the exact same region and apply an appropriate correction factor:

$$image\ noise = \frac{Mean}{1.25} \qquad \text{Equation 8}$$

The factor of 1.25 is the appropriate single-channel correction factor [Henkelman, R. M. 1985, Medical Physics, 12, 232-233.]. One indirect assessment of the quality of the noise statistics is determined by computing the measured Mean/SD of the noise MROI statistics. For a single-channel system, the ratio should be 1.2533 / 0.6551 = 1.91, [Henkelman, R. M. 1985, Medical Physics, 12, 232-233.] when the ratio of the corrected SNR values should be 1.0. Small deviations of a couple of percent may be considered acceptable. The appropriate correction factors and associated ratio for images with more than one channel are found in MS-9.

Appendix B
CHANGES TO STANDARD

B.1 CHANGES TO MS 1-2001 RESULTING IN MS 1-2008

Those NEMA MR standards pertaining to SNR and uniformity measurements have been slightly restructured to consider the coil geometry as noted in the section **Scope**. In addition, new measurements methods have been added to this standard that provide benefits in certain situations as noted in the **Foreword** and section **2.3.2 Procedures to Evaluate Image Noise**. Aspects of the section “Test Hardware” related to the phantom have been updated to be more consistent between all standards and consider the practical implementation of higher field strength units. Figures have also been added to clarify the definitions and intent of the standard.

B.1.1 Pertaining to 2.1.3 MR Characteristics of the Signal Producing Volume

Spin density requirements for the phantom have been eliminated. With the advent of high field scanners (e.g. 3T) the use of materials other than water may be preferable (e.g. oil) due to wavelength effects.

B.1.2 Pertaining to 2.2 Scan conditions, step e.

The sequence TR requirement has been adjusted to bring it in line with the IEC MRI performance standard and permit the use of fast sequences.

B.1.3 Pertaining to Appendices

To improve the quality of the noise statistics, Appendix A permits an alternative method of measurement in methods #2 and #4.

B.2 Changes to MS 1-2008 resulting in MS 1-2013

There are no technical changes.

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