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Determination of Image Uniformity
in 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.

Foreword

This standards publication is classified as a NEMA standard unless otherwise noted. It is intended for use by MRI system manufacturers, manufacturers of accessory equipment (including radio-frequency coils), and by MRI end users.

The purpose of this standards publication is to provide a standard procedure for measuring and reporting image-intensity uniformity in an MRI system.

Image uniformity refers to the ability of an MR imaging system to produce an identical signal response throughout the scanned volume when the object being imaged is homogenous. Image-intensity non-uniformity in a two-dimensional MR image of a uniform test object can be caused by a number of factors, including RF coil geometry and penetration, non-uniformity of the transmitted RF field (B_1 non-uniformity), inhomogeneity of the static magnetic field (B_0 non-uniformity), inadequacies in gradient pulse calibration or eddy current corrections, and spatial positioning of the phantom.

Image uniformity is quantified here in terms of the deviation of the image pixel intensities from the midrange value. The analysis of uniformity shall be performed over the region of interest that is typically occupied by clinical samples and not over the full available volume of the RF coil.

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:

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

This Standard measures image non-uniformity (see 1.3) to characterize the low spatial frequency non-uniformities typical of MR images. It is important to quantify image non-uniformity because it alters image contrast.

Various factors influence MR image non-uniformity such as B1 non-uniformity (both in transmit and receive), quality of B0 shim, geometric distortion, etc. Various techniques exist to correct for some forms of image nonunifomity such as RF receive coil correction algorithms.

The use of geometric distortion correction algorithms and image uniformity correction algorithms is becoming increasingly common, and in some situations necessary. Both types of corrections will alter image uniformity results reported in this standard. While it was the original intent of this standard to characterize the coil without these corrections, it is also the intent of the standard to test the coil under typical clinical conditions. Therefore the results will be reported both ways where possible.

This standard characterizes image non-uniformity qualitatively with a gray-scale uniformity map and quantitatively with simple figures of merit that analyze the range of pixel intensities relative to some measure of the average image intensity.

Scope

This document defines a method for measuring image-uniformity performance of diagnostic magnetic resonance imaging systems using single channel volume coils and performing proton imaging. This document does not address the use of surface coils, chemical shift imaging, or spectroscopy.

Image uniformity can be characterized in a number of different ways. The choice of a measurement and reporting method was guided by a desire for simplicity, accuracy, and ease of implementation on all MR systems. The peak deviation method represents a single image test that can quickly determine and report uniformity with a single number. It works best with very high SNR images. The gray-scale uniformity map image represents a single image test that can visually describe image uniformity. Both the ACR MR Accreditation Procedure method and the Normalized Absolute Average Deviation method resolve some of the image SNR issues of the peak deviation method.

Measurements are made over a volume that is representative of the region used for typical clinical studies. Due to the difficulty in handling large phantoms, it is permitted to use a test phantom that only covers 85% of the specification area.

This document does not address the use of special purpose coils (see MS 6) or coils that require multiple receiver channels for operation (see MS 9).

Section 1
DEFINITIONS

1.1 MEASUREMENT REGION OF INTEREST (MROI)

A centered, regular geometric area enclosing at least 75 percent (area) of the image of the signal producing volume of the phantom.

1.2 MEASUREMENT SUBREGION OF INTEREST (SROI)

A regular geometric area wholly enclosed within the MROI that covers approximately 0.15% of the number of image pixels (e.g. ~100 pixels for a 256x256 matrix image).

1.3 IMAGE NON-UNIFORMITY

The signal pixel intensity variations within an image that are repeatable from scan to scan.

An absence of image non-uniformity (N) is defined as N=0% and perfect image uniformity (U) is defined as U=100%. The relationship is: U = 100 – N.

1.4 NORMALIZED ABSOLUTE AVERAGE DEVIATION

A measure of uniformity defined by the average absolute deviation from the mean within the MROI, normalized with respect to the mean within the MROI.

1.5 PEAK DEVIATION NON-UNIFORMITY

The maximum absolute deviation from the midrange pixel value (2.3.2, Equation 3) expressed as a percentage.

1.6 GRAY-SCALE UNIFORMITY MAP

The percentage deviation from a midrange pixel value expressed in a gray-scale image format.

1.7 MAXIMUM SELECTABLE VOLUME

For a given scan orientation (i.e., transverse, sagittal, coronal), the volume enclosed by the maximum selectable fields of view and the planes of maximum selectable slice offset from isocenter.

1.8 SPECIFICATION VOLUME

The imaging volume over which a manufacturer guarantees image performance specifications will hold. Images or portions of images outside this volume will not necessarily meet performance specifications, but may still be useful for diagnostic purposes and require subjective judgment on the part of the diagnosing physician. For head scans, the specification volume must enclose, as a minimum, a 10 cm diameter spherical volume (dsv) centered in the RF head coil, and similarly for body scans, it must enclose, as a minimum, a 20 cm dsv centered in the RF body coil.

1.9 SPECIFICATION AREA

The intersection of the specification volume and the image plane.

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 cm 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 cm diameter circle or 85% of the specification area, whichever is larger.

2.1.2 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. Take care to select some material that does not cause undue wavelength ("dielectric resonance") effects.)

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 uniformity data shall be acquired as a single-slice scan at isocenter in each of the three orthogonal imaging planes. A typical diagnostic clinical scan sequence and reconstruction process shall be used. 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. Room and phantom temperature shall be 22 ± 4 ^{o}C;
c. TR ≥ 5XT1 of the filler material in the signal producing volume;
d. TE within the clinically selectable range;
e. The selected field of view shall not exceed 110 percent of the largest linear dimension of the RF coil in the image plane;
f. Spin echo pulse sequence (first echo);
g. Slice thickness ≤ 10 mm; and
h. Data acquisition matrix size ≥ 128x128;
i. All user selectable image filters to be disabled.

2.3 MEASUREMENT PROCEDURE

System image uniformity shall be determined by sequentially executing the following procedure:

a. Center the signal producing volume of the phantom in the RF receive coil;
b. Perform the standard clinical pre-scan calibration procedure as recommended by the system manufacturer; and
c. Execute the scan(s). Increase the number of signals averaged and/or decrease data matrix size (see 2.2h) to increase image SNR, if needed.
d. Analyze the image uniformity data as described in 2.3.2, 2.3.3, 2.3.4, or 2.3.5. Pre-processing of the image data is permitted, as described in 2.3.1.

The four measurement procedures found in this standard have different characteristics. The Peak Deviation non-uniformity measure (2.3.2) is sensitive to noise. As noise levels increase, the maximum and minimum signal levels increase and decrease respectively, lowering measured image uniformity. This method is also particularly sensitive to extreme image non-uniformities found within the image (e.g. “hot spots” near receiver coil conducting elements).

The gray-scale uniformity map method presents subtle uniformity information as an image and is not quantitative. Its strength is the spatial display of image non-uniformities.

The ACR-MRAP procedure (2.3.4) reduces the noise sensitivity of the Peak Deviation non-uniformity measure (2.3.2) by signal averaging. The ACR-MRAP procedure finds the highest and lowest small signal sub-region areas of interest (SROI) instead of single pixels. However, the ACR-MRAP procedure is still relatively sensitive to extreme image non-uniformities.

The Normalized Absolute Average Deviation method (2.3.5) reduces the noise sensitivity of the Peak Deviation non-uniformity measure by using all pixel values within the MROI and computing the average absolute deviation from the average value within the MROI. Since all pixels contribute equally to the measurement of non-uniformity, it is not sensitive to “hot spots” or surface coil signal drop-off.

2.3.1 Pre-processing of the Image

To help minimize the effects of noise on the measurement, it shall be permitted to convolve the image I, with a nine point low-pass filter function h (m_l,m_2). The filtered image is given by:

$$S(n_1,n_2) = \frac{1}{W}\sum_{m_1=-1}^{1}\sum_{m_2=-1}^{1} h(m_1,m_2)\,I(n_1 - m_1, n_2 - m_2)$$

Where n_1, n_2 cover the range of the image.

The filter kernel is

$$\begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix} = \begin{bmatrix} h(-1,-1) & h(-1,0) & h(-1,1) \\ h(0,-1) & h(0,0) & h(0,1) \\ h(1,-1) & h(1,0) & h(1,1) \end{bmatrix}$$

and represents the product of two raised cosines in the frequency domain. The weighting factor W is given by:

$$W = \sum_{m_1=-1}^{1} \sum_{m_2=-1}^{1} h(m_1, m_2)$$

and is used to normalize the DC response of the filter in the frequency domain to unity.* If the filter is not used, S =I.

*See NEMA NU 1, *Performance Measurements of Scintillation Cameras.*

2.3.2 Peak Deviation Non-Uniformity

For pixels within the MROI, the maximum (S_{max}) and minimum (S_{min}) values are determined.

A span Δ and midrange value $\bar{S}$ are calculated as:

$$\Delta = \frac{S_{max} - S_{min}}{2} \tag{1}$$

$$\bar{S} = \frac{S_{max} + S_{min}}{2} \tag{2}$$

The ratio of Δ to $\bar{S}$ is multiplied by 100, and expressed as a percentage non-uniformity.

The Peak Deviation non-uniformity measure (N) is defined as:

$$N = 100\frac{\Delta}{\bar{S}} = 100\frac{S_{max} - S_{min}}{S_{max} + S_{min}} \tag{3}$$

The peak deviation non-uniformity measure is sensitive to image SNR. As SNR decreases, S_{max} and S_{min} diverge, lowering computed peak deviation uniformity.

2.3.3 Gray-Scale Uniformity Map

It shall be permitted to provide a gray-scale coded map of the image showing where, and by how much, departures in uniformity occur. Such a map is readily created by the following procedure:

1. Select a region of interest (ROI) on the center of the image that encloses a sufficient number of pixels to yield the desired statistical precision (e.g., 400 pixels to provide 5 percent precision), and determine its mean value. If the ROI is in a region with anomalous signal characteristics (e.g. center of high signal intensity caused by dielectric resonance) use the mean from the MROI.

2. Examine the signal from each pixel in the entire image and assign a gray level to each pixel according to the magnitude by which the signal differs from the mean value at the center ROI. Pixels with signal magnitudes differing by less than 10 percent from the mean value shall be assigned a neutral gray level. Pixels whose signals are more than 10 percent greater than the mean value, but less than 20 percent greater, shall be assigned the next lighter gray level. Pixels whose signals are more than 10 percent smaller than the mean value but less than 20 percent smaller, shall be assigned the next darker

gray level. Pixels with signals more than 20 percent greater than the mean value shall be white, and pixels with signals more than 20 percent smaller than the mean value shall be black.

3. The indicated procedure produces a five gray-level representation of the image non-uniformity with the following ranges relative to the mean value:

a. lowest signal value to –20%
b. –20% through –10%
c. –10% through +10%
d. +10% through +20%
e. +20% through to highest signal value

These five unequally sized bands visualize the location and structure of non-uniformities without showing the complex structure immediately surrounding the coil elements.

4. Display the gray-scale coded image on the monitor to readily visualize the amount, the magnitude, and the location of non-uniformities in the image. Since non-uniformity location in the image is correlated with the cause of the non-uniformity, the coded image is performance-diagnostic tool for system adjustment. Supply a copy of this coded image with the measurement report.

5. Alternatively, the gray-level representation of image non-uniformity may also be shown using the method of MS-6. A single gray level shall be assigned to all pixels in the signal producing area of the image 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 have has been corrected for baseline pixel offset, if any.

Pixels in the signal producing area of the image having intensities:

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

are assigned the next brighter gray level.

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. Pixels in the highest intensity bin are assigned to white.

A similar procedure is applied to pixels with intensities less than S x (1 – F). S x (1 – F). The gray level bins in this case 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.

2.3.4 ACR MR Accreditation Program (ACR-MRAP) Uniformity

In order to reduce the influence of image SNR on the analysis of image uniformity S_{max} and S_{min} can be measured over a small subregion of interest (SROI), wholly enclosed within the MROI, that covers approximately 0.15% of the number of image pixels (e.g. ~100 pixels for a 256x256 matrix image). For pixels within the MROI, the maximum (S_{max}) and minimum (S_{min}) values are determined as follows:

1. set the window width to a narrow band and adjust the window level so that a small region of the highest signal intensity within the MROI is isolated. Position the SROI in the high intensity region and the average within that SROI is $S_{max.}$

2. set the window width to a narrow band and readjust the window level so that a small region of the lowest signal intensity within the MROI is isolated. Position the SROI in the low intensity region and the average within that SROI is $S_{min.}$

Compute image non-uniformity using the same method as 2.3.2 Peak Deviation Non-uniformity:

$$PIU = 100x \left(1 - \frac{(S_{max} - S_{min})}{(S_{max} + S_{min})}\right) \qquad (4)$$

Enter this value in the column labeled “Percent Image Uniformity” of the MRI Equipment Performance Evaluation Data Form (*Appendix A*), for that coil.

2.3.5 Normalized Absolute Average Deviation Uniformity

In order to reduce the influence of image SNR on the analysis of image uniformity all pixels within the MROI will be used to compute image uniformity.

1. Compute the average pixel intensity within the MROI.
2. Compute the absolute deviation or difference of each pixel within the MROI from the average of the MROI. This statistical measure is called the Absolute Average Deviation (AAD) and is a measure of spread, or variability, within a data set.
3. To normalize the AAD, divide by the average signal within the MROI.
4. NAAD is computed as:

$$NAAD = 100\left(1 - \frac{1}{N\overline{Y}} \sum_{i=1}^{N} (|Y_i - \overline{Y}|)\right) \qquad (5)$$

Where

Y_i is the individual pixel value in the MROI,

$\overline{Y}$ is the mean of all pixels in the MROI,

$|Y_i - \overline{Y}|$ is the absolute deviation for pixel *i* and

N is the total number of pixels in the MROI.

If using low SNR images (SNR below 50), the NAAD measure can be noise compensated by computing the NAAD term in a background noise region:

$$NAAD_c = 100(1 - \frac{1}{\overline{Y}N}\sum_{i=1}^{N}(|Y_i - \overline{Y}|) + \frac{1}{\overline{Y}n}\sum_{j=1}^{n}(|Y_{bj} - \overline{Y}_b|)) \quad (6)$$

Where the “b” subscripts indicate the measurement is taken in an “n” pixel background region free of artifacts and signal.

NAAD is based on a statistical measure of spread or variability called the Absolute Average Deviation (AAD). For more information see the NIST/SEMATECH e-Handbook of Statistical Methods, *http://www.itl.nist.gov/div898/handbook/.*

Section 3
SOURCES OF ERROR AND REPORTING OF RESULTS

3.1 SOURCES OF ERROR

The following sources of error shall be discussed and reported:

- Uncertainty due to SNR limitations
- Image artifacts
- Other errors

The peak deviation uniformity measure requires high image SNR for accurate measurements. Verify that image SNR is sufficient.

3.2 REPORTING OF RESULTS

3.2.1 Scan Parameters

The following scan parameters, and any other parameters necessary to repeat the measurement, must accompany the statement of the image uniformity (N or U) or the gray scale uniformity map:

Parameter	Dimension
Phantom filler T1	milliseconds
Phantom filler T2	milliseconds
Phantom filler specific conductance (or phantom filler composition)	siemens per meter
Pixel bandwidth	Hz per pixel
Receiver channel 3dB bandwidth	kHz
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	….
Receive/Transmit coil(s) used	…
Phantom dimensions	millimeters
MROI size	millimeters
Scan plane	Ax./Sag./Cor.
Signal to Noise Ratio	…
Type of pulse sequence used and other relevant acquisition parameters	…
Type of signal filters used (time and/or image domain)	…
Statement of geometric distortion correction algorithm	…
Statement of RF receive coil correction algorithm	…
Software version	…

Annex A
CHANGES TO STANDARD

A.1 CHANGES TO MS 3-1989 RESULTING IN MS 3-2003

A.1.1 Summary

It is emphasized that the peak deviation (integral) uniformity measure is sensitive to the signal to noise level (SNR) of the image. Reduced data acquisition matrix size and increased number of signal averages can be used to improve SNR.

The method for measuring “integral uniformity” is derived from the Gamma Camera standard. It has been renamed to peak deviation uniformity for MRI purposes. Additionally, the meaning of uniformity versus non-uniformity has been clarified.

Changes were made to the gray-scale uniformity map technique to reflect improvements in transmit/receive coil designs. The small ROI mean definition can produce a skewed mean value which consequently will alter the gray scale.

A.1.2 Changes to introduction

- "Notice and Disclaimer" section added.
- Rationale section expanded.
- Scope section expanded. The operating scope of the various uniformity measurement methods is described. The reason why undersized specification regions are permitted is also explained.

A.1.3 Section 1

- Voxel dimension definitions deleted. Definition too simplistic and not relevant to this standard.
- Definition of image non-uniformity vs uniformity added.
- Renaming of Integral Uniformity measure to Peak Deviation Uniformity measure. The original concept of Integral Uniformity was borrowed from the Gamma Camera standard.

A.1.4 Section 2

- Spin density requirement wording changed to reflect emergence of higher field units beyond 1.5T.
- (+/-) removed from Equation 3.
- Limitations of peak deviation method described.
- Limitations to matrix size to avoid impact of ringing artifact on uniformity measurement.
- Gray Scale Uniformity Map method changed to permit the mean to be computed from the ROI or MROI. This alternate way of computing the mean is necessary to avoid particularly high or low signal intensity regions which might be at the center of the image (e.g. a bright signal region resulting from dielectric resonance effects).

A.1.5 Section 3

- Section 3 added to be consistent with the other NEMA standards.
- Require the reporting of rf coil or geometric distortion correction algorithms. These algorithms may alter image uniformity.

A.1.6 Annex A

Annex A added to highlight changes between versions of this standard

A.2 CHANGES TO MS 3-2003 RESULTING IN MS 3-2008

This standard has been brought forward in the normal review cycle to coordinate changes with other standards related to image SNR and uniformity measurements (MS-1, 3, 6, 9).

A.2.1 Pertaining to Scope

To make this standard consistent with the structure of all other related standards, this standard will cover single channel volume coils exclusively.

A.2.2 Pertaining to Section 1

New definitions added for new measurement methods

A.2.3 Pertaining to 2.3.3 Gray-Scale Uniformity Map

This standard has been modified to permit the gray-scale map definition of MS-6 for added flexibility.

A.2.4 Pertaining to 2.3.4 ACR MR Accreditation Program (ACR-MRAP) Uniformity

The ACR-MRAP method for uniformity determination is now permitted as another method for reducing the impact of SNR on uniformity measures.

A.2.5 Pertaining to 2.3.5 Normalized Absolute Average Deviation Uniformity

Section 2.3.5 is now permitted as another method for reducing the impact of SNR on uniformity measures. It is intended to cover and extend the method in IEC 62464-1: 2007.

A.3 Changes to MS 3-2008 resulting in MS 3-2013

There are no technical changes.

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