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Determination of Slice Thickness in
Diagnostic Magnetic Resonance Imaging

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CONTENTS

Preamble

This standard is one in 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 ensure 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. The 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 two methods for determining slice thickness in diagnostic magnetic resonance imaging. The methods presented are essentially numerical in character and, consequently, will require the preparation and use of supplementary dedicated computer software to perform the computations.

The methods are based upon the determination of the slice profile, from which the slice thickness is obtained as the full width at half maximum (FWHM). The slice profile is obtained either by direct measurement with a thin inclined slab of signal-producing material or by numerical differentiation of the measured edge response function (ERF) from an inclined surface of a wedge immersed in signal-producing material. A correction technique is provided to compensate for errors caused by tilt of the phantom.

With the inclined slab approach, better signal-to-noise ratio (SNR) can be realized through the use of direct measurement[1]. However, the extremely thin slabs required for measurement of very thin slices are not practical to fabricate. Differentiation of the ERF degrades the SNR that is obtained for the slice profile and usually requires the averaging of several measurements but does permit measurement of thinner slices since fabrication is not limiting.

Slices of any thickness, which can provide adequate signal, may be evaluated with the wedge procedure; the slab method is suitable for thicker slices.

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:

Computer Imaging Reference Systems—Norfolk, VA
GE Healthcare, Inc.—Milwaukee, WI
Hitachi Medical Systems America, Inc.—Twinsburg, OH
Invivo—Gainesville, FL
Medipattern Corp.—Toronto, Ontario

Medtronic Navigation – Yokneam, Israel
Philips Healthcare—Bothell, WA
Siemens Healthcare, Inc.—Malvern, PA

Toshiba America Medical Systems—Tustin, CA
AllTech Medical Systems America—Solon, OH

[1] For additional information, see *MS 1, Determination of Signal-to-Noise Ratio (SNR) in Diagnostic Magnetic Resonance Imaging*.

Rationale

Slice thickness is measured along the dimension perpendicular to the slice plane and is a measure of the thickness of the anatomy projected onto the plane of the image. Since slice thickness depends on the radiofrequency (RF) pulse shape and sequencing, transmit gain, RF field homogeneity, the selection gradient, and other parameters, the slice thickness is a significant measure of the proper adjustment of a diagnostic magnetic resonance imaging system and its image quality.

Section 1

1.1 Scope

This standards publication provides a method for determining the slice thickness of proton images. Both the typical and the typically thinnest slices in routine clinical use for a particular system are determined at one location within the specification volume and only one of the three orthogonal orientations (transverse, sagittal, or coronal). Imaging types and conditions not addressed by this standard include spectroscopy, chemical shift imaging, and warped slices.

1.2 Definitions

1.2.1 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.

1.2.2 Contiguous Slices

Contiguous slices are adjacent slices for which the separation of consecutive profile centers is equal to one FWHM.

1.2.3 Edge Response Function (ERF)

The edge response function is the integral of the slice profile versus **z**, from a fixed initial value of **z** to a variable ending value of **z**.

1.2.4 Intrinsic Pixel Size

For this standard, the “intrinsic” pixel size is defined as the image domain distance **d** (in meters) such that 1/**d** (in meters^{-1}) is the span of the measured data in the Fourier domain.

1.2.5 Slice Coordinate

The slice coordinate, denoted by **z**, is the dimension perpendicular to the slice plane.

1.2.6 Slice Profile

The slice profile is conceptually a plot of magnetic resonance (MR) signal intensity perpendicular to the slice plane arising from a uniform sample that is larger than the **z** dimension to be analyzed.

1.2.7 Slice Thickness

The slice thickness is the full width at half maximum (FWHM) of the slice profile.

1.2.8 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-cm 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.

Section 2
Methods of Measurement

2.1 Scan Conditions

The following scan conditions shall be used:

a. Single spin echo at a typical clinical value of TE;
b. TR ≥ 3 T_1 in the signal-producing material;
c. Pulse sequence as used for clinical scans;
d. Slice thickness: both the typical and the thinnest in routine clinical use;
e. Multi-slice mode, with at least three slices for which the consecutive profile centers are separated by twice the nominal FWHM (not contiguous).

2.2 Wedge Method of Measurement

2.2.1 Phantom Description

The phantom shall consist of two opposing wedges of a material that emits no proton signal, immersed in a reservoir of signal-producing material (see Figure 2-1). These wedges shall be used to measure slice profile while providing correction for errors of tilt (rotation about the **y**-axis). The correction procedure is described in Section 4.

The inclined surfaces of both wedges shall form an angle α with the slice plane (see Figure 2-1B).

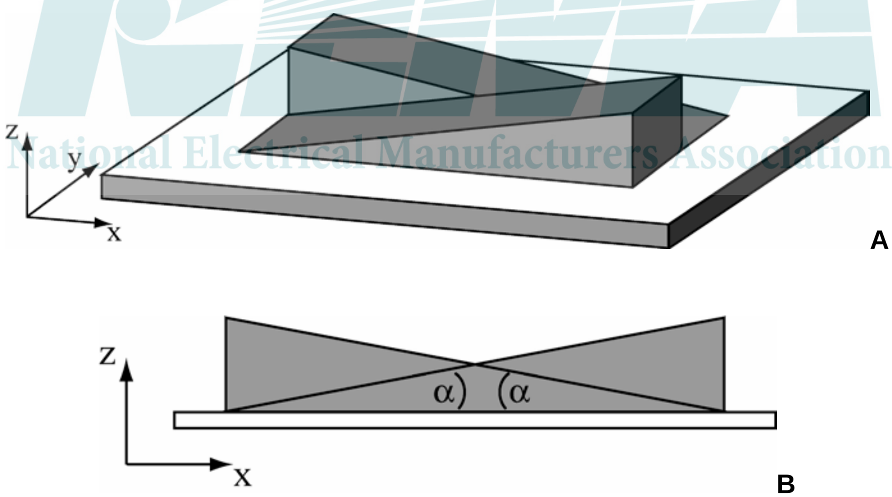

Figure 2-1
Crossed Wedge Phantom

2.2.2 Measurement Procedure

a. Select the acquisition and display parameters so that the resulting spatial resolution in the **x**-direction (see Figure 2-3) is sufficient to include at least six “intrinsic” pixels across the FWHM of the stretched (projected) slice profile. For this standard, the “intrinsic” pixel size is defined as the image domain distance **d** (in meters) such that 1/**d** (in meters^{-1}) is the span of the measured data in the Fourier domain. An example is shown in the Authorized Engineering Information below. This condition is met when:

$$d \leq \frac{FWHM}{5 \cdot \tan\alpha} \qquad \textit{Equation } 1$$

where FWHM refers to the correctly scaled (not stretched) slice profile.

For a standard two-dimensional Fourier transform imaging technique, the “intrinsic” pixel size in the readout direction is given by:

$$d_{RO} = \frac{1}{\tau \cdot \gamma \cdot G} \qquad \textit{Equation } 2$$

where:
d_{RO} is the “intrinsic” pixel size in meters,
τ is the duration of the sampling in milliseconds (i.e., the difference in time between the first sample and the last sample),
γ is the magnetogyric ratio in MHz/tesla,
G is the readout gradient strength in mT/m.

In the phase encoding direction, the “intrinsic” pixel size is given by:

$$d_{PE} = \frac{1}{2 \cdot \gamma \cdot \int G dt} \qquad \textit{Equation } 3$$

where:
d_{PE} is the “intrinsic” pixel size in meters,
γ is the magnetogyric ratio in MHz/tesla,
G is the gradient strength in mT/m of the largest phase encoding,
The integral is performed over the duration of the gradient pulse and has the units (mT*msec)/m.

Authorized Engineering Information 8-28-1991.

This example is valid for standard 2D Fourier transform imaging in which the spin echoes are sampled symmetrically, the data are reconstructed with a 2D Fourier transform, and symmetric positive and negative phase encoding steps are used. This analysis assumes that the data have not been filtered.

Authorized Engineering Information 8-28-1991.

b. Generate a magnetic resonance image from one of the three orthogonal acquisition planes (transverse, sagittal, or coronal). Only the center slice of the multi-slice acquisition shall be analyzed.

c. Define the direction **y** in the slice plane, as shown in Figure 2-2.

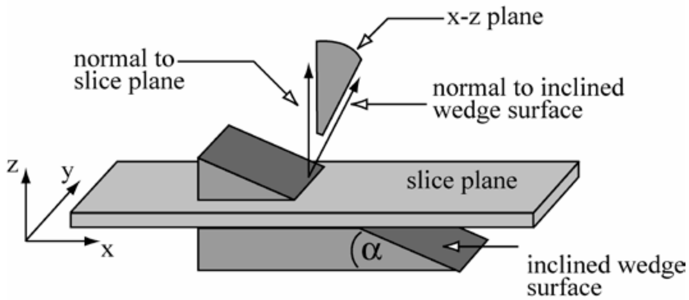

Figure 2-2
Diagram of Referenced Planes

a. Define the direction **x** in the slice plane, which is perpendicular to **y**. Note that **x** forms an angle α with the inclined surface of the wedge (see Figure 2-2).

b. Plot the image pixel intensities in the **x**-direction to obtain the ERF.

c. Differentiate the ERF with respect to **x** to obtain a stretched (projected) slice profile **D(x)** (see Figure 2-3) as shown below:

$$D(x_i) = \frac{I(x_i) - I(x_{i-1})}{x_i - x_{i-1}} \qquad \textit{Equation 4}$$

where $I(x_i)$ is the ERF value at each position x_i.

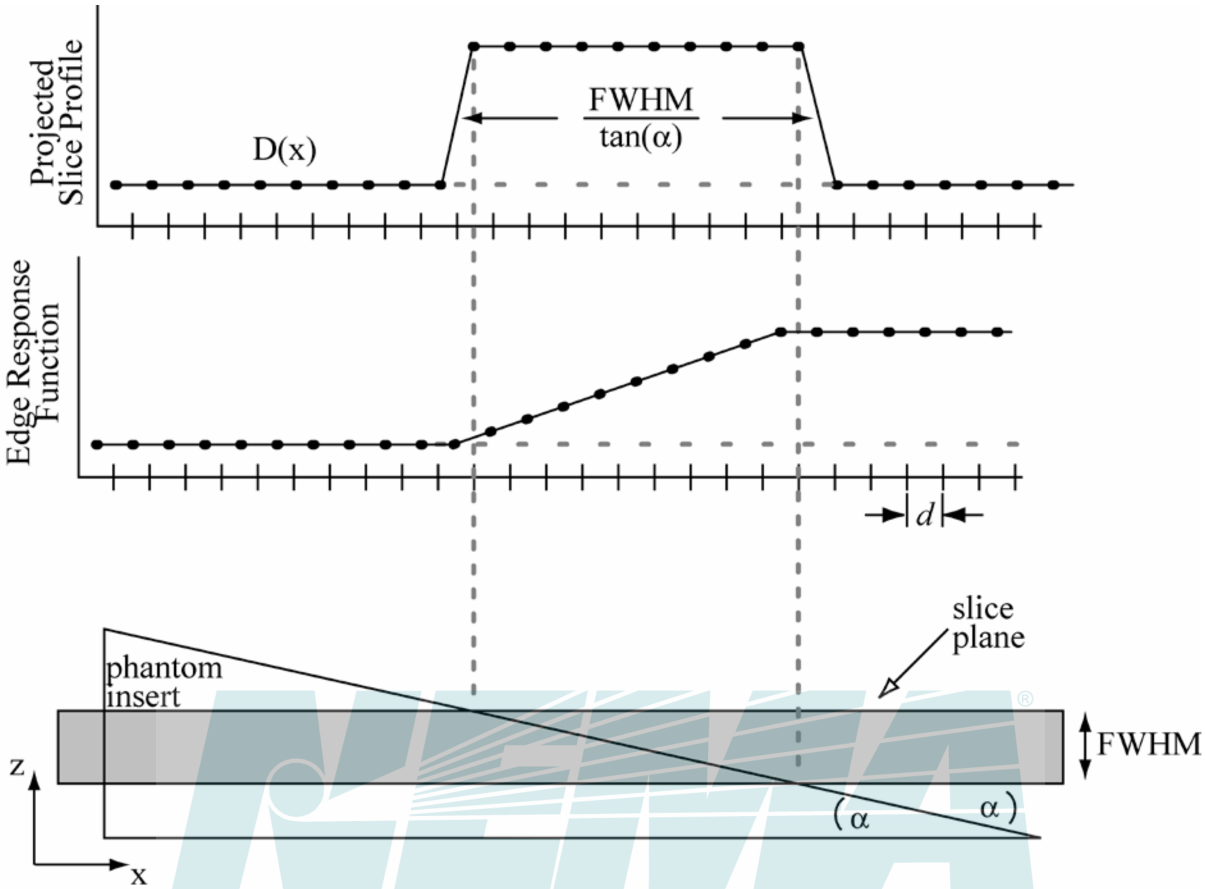

Figure 2-3
Schematic Overview of the Wedge Method

a. Find the maximum of the projected slice profile **D(x)**.

b. Find the width of the projected slice profile at one half of the maximum, using linear interpolation if necessary (see Figure 2-3).

c. Multiply the resulting width of the projected slice profile found in step 8 by tan (α) to obtain the properly scaled slice thickness (FWHM).

d. Correct the results for tilt (rotation about the **y**-axis) as detailed in Section 4, before reporting results in Section 5.2.

2.3 Slab Method of Measurement

2.3.1 Phantom Description

The slab phantom shall consist of two thin opposing inclined slabs of signal-producing material enclosed by inert material (see Figure 2-4). The inclined surfaces of both slabs shall form an angle α with the slice plane. The slab thickness shall be less than one-fifth of the selected slice thickness times cos α. As an example, for α = 30 degrees and a selected slice thickness of 10 mm, the slab thickness shall be less than 1.73 mm. These thin slabs shall be used to measure slice profile while providing correction for errors of tilt (rotation about the **y**-axis). The correction procedure is described in Section 4.

A liquid or other signal-producing material fills the gaps between the phantom inserts to form the crossed slabs. The dashed lines indicate the slice plane.

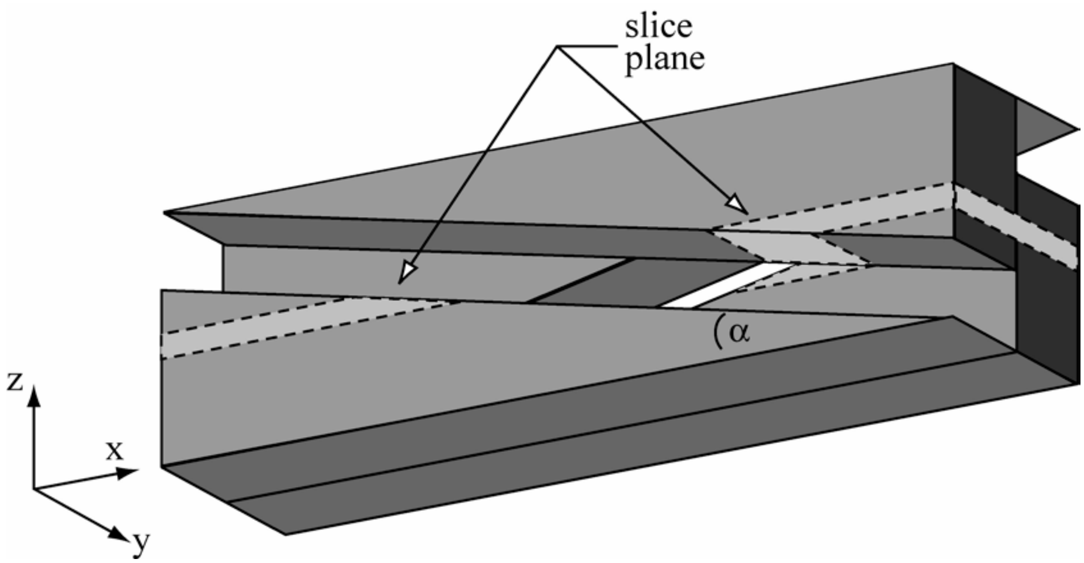

Figure 2-4
Crossed Slab Phantom

2.3.2 Measurement Procedure

a. Select the acquisition and display parameters so that the resulting spatial resolution in the **x**-direction (see Figure 2-5) is sufficient to include at least six "intrinsic" pixels across the FWHM of the stretched (projected) slice profile, as described for the wedge method (see Section 2.2.2).

b. Generate a magnetic resonance image from one of the three orthogonal acquisition planes (transverse, sagittal, or coronal). Only the center slice of the multi-slice acquisition shall be analyzed.

c. Define the direction **y** in the slice plane, as shown in Figure 2-4.

d. Define the direction **x** in the slice plane, which is perpendicular to **y**. Note that **x** forms an angle α with the inclined surface of the slab (see Figure 2-5).

e. Plot the image pixel intensities in the **x**-direction to obtain the stretched (projected) slice profile (see Figure 2-5).

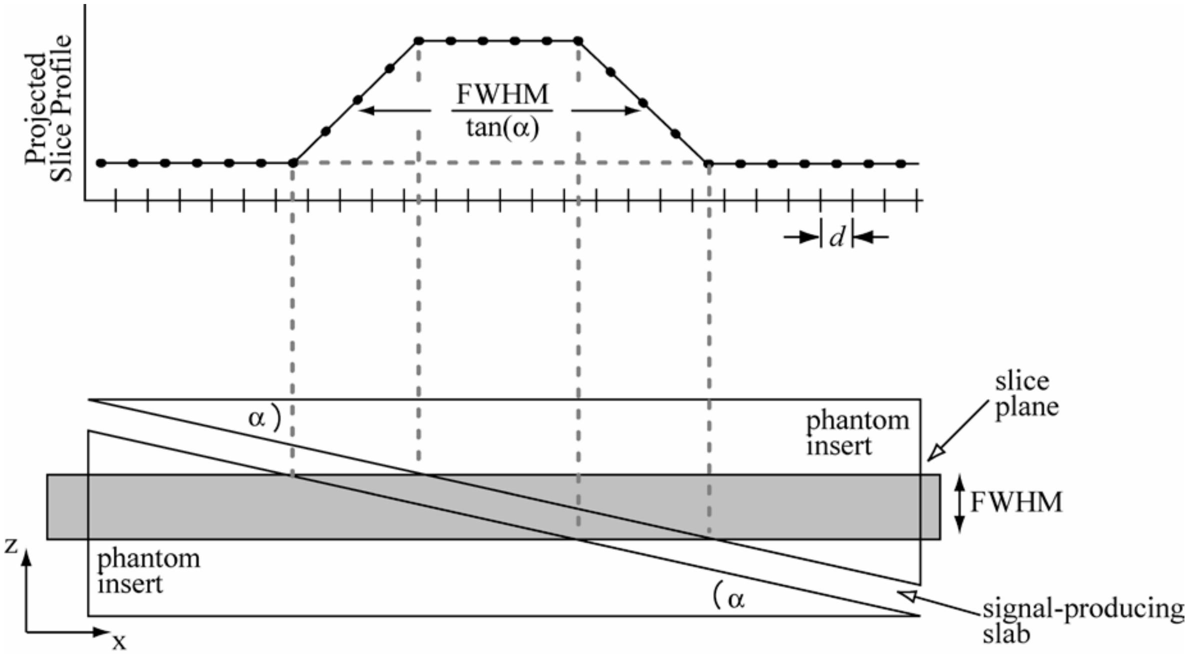

Figure 2-5
Schematic Overview of the Slab Method

Only one of the two crossed slabs is shown. For purposes of illustration, a thicker slab is shown than would be permitted by this standard, so the projected slice profile is distorted.

a. Find the maximum of the projected slice profile.

b. Find the width of the projected slice profile at one half of the maximum. If necessary, use linear interpolation and correct for baseline pixel offset.

c. Multiply the resulting width of the projected slice profile found in step 7 by tan (α) to obtain the properly scaled slice thickness (FWHM).

d. Correct the results for tilt (rotation about the **y**-axis), as detailed in Section 4, before reporting results in Section 5.2.

Section 3
Improving the Accuracy of Results

To obtain reliable results, the SNR of the slice profile (defined to be the signal value at the slice maximum divided by the standard deviation at the slice maximum) must be larger than 10. In general, the SNR from a single acquisition will be too low, whether obtained by the wedge or slab method. The SNR shall be increased by taking (averaging) more acquisitions (which increases the time required for the measurements) or by averaging N profiles as follows:

a. Select **N** positions in the **y**-direction, where **N** is a number chosen to provide satisfactory SNR at each position x_i of the profile.

b. Correct for in-plane rotation about the z-axis by registering each profile to a common point or rotating the phantom.

c. To improve SNR, form the average **A** of the values $\mathbf{I}_j(x_i)$ of the **N** shifted profiles:

$$A(x_i) = \frac{1}{N} \cdot \sum_{j=1}^{N} I_j(x_i) \qquad \textit{Equation } 5$$

where x_i is the position along the profile.

Section 4
Correcting for Rotational Errors

There are three possible rotational errors, one at each of the three coordinate axes that can lead to errors in the slice thickness determination.

Rotation about the **z**-axis will rotate the entire image. If multiple ERF are averaged together from one slice to improve SNR, the individual ERF will not be in the same location, further blurring the edge. Rotation about the **x**-axis will cause the slice profile to shift from one value of **y** to the next and will change the effective alpha (α). Provisions shall be made to detect these errors by providing landmarks in the phantom and either prevent them with special positioning devices or correct them by repositioning.

Greater errors result from rotation around the **y**-axis since this directly changes the wedge or slab angle α. For example, α is 11.3 degrees for a 1:5 wedge and a 1-degree rotational error about **y** produces a 10% error in α and the slice thickness. This error is corrected by evaluating the projected slice thicknesses (w_1 and w_2, see Figure 4-1) of the two opposed slabs or wedges.

a. Compute the rotational error θ of the phantom about the **y**-axis using:

$$\theta = \frac{\sin^{-1}\left[\frac{(w_2 - w_1)\sin(2\alpha)}{(w_2 + w_1)}\right]}{2} \qquad \textit{Equation } 6$$

where α is the angle between the inclined surface of the wedge or slab and the base (line BC, see Figure 4-1) of the phantom.

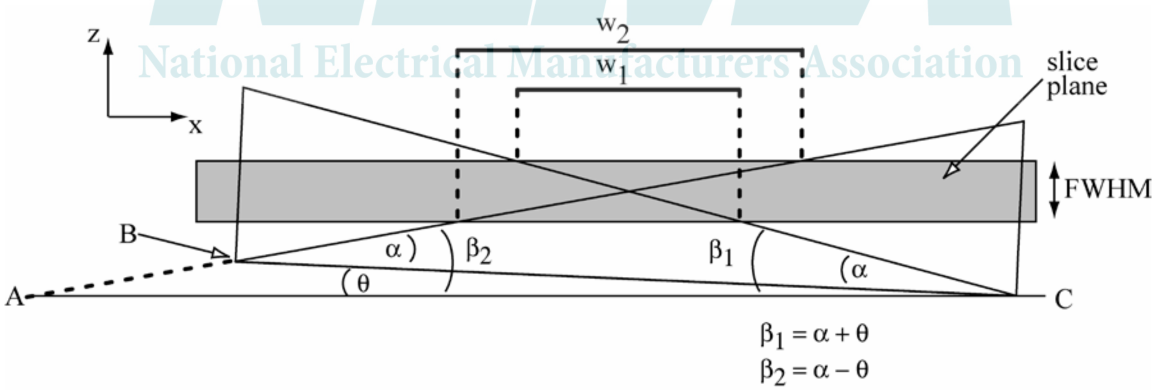

Figure 4-1
Angle Definitions for Rotational Correction

In this example, the base (line BC) of a double wedge phantom is rotated about the **y**-axis by an angle θ from the slice plane (parallel to line AC). The two inclined wedge surfaces now make angles β_1 and β_2 with respect to the slice plane.

b. The corrected and scaled slice thickness (FWHM) is then:

$$FWHM = w_1 \tan(\alpha + \theta) \qquad \textit{Equation } 7$$

c. Report the FWHM and angle θ in Section 5.2.

Equation 6 is derived as follows:

a. Assume that the first wedge or slab makes an angle $\beta_1 = \alpha + \theta$ with the slice plane, and the second wedge or slab makes an angle $\beta_2 = \alpha - \theta$.
b. The projected slice thickness determined from the first and second wedges or slabs will be, respectively:

$$w_1 = \frac{FWHM}{\tan(\beta_1)} \qquad Equation\ 8$$

$$w_2 = \frac{FWHM}{\tan(\beta_2)} \qquad Equation\ 9$$

where
FWHM is the value obtained with no rotational error.

c. The FWHM may be eliminated by forming the ratio:

$$\frac{(w_2 - w_1)}{(w_2 + w_1)} = \frac{\tan(\beta_1) - \tan(\beta_2)}{\tan(\beta_1) + \tan(\beta_2)}$$

$$= \frac{\sin(\beta_1 - \beta_2)}{\sin(\beta_1 + \beta_2)}$$

$$= \frac{\sin(2\theta)}{\sin(2\alpha)} \qquad Equation\ 10$$

d. **Equation 10** is solved for θ to give **Equation 6**.

Section 5
Sources of Error and Reporting of Results

5.1 Sources of Error

The following sources of error shall be discussed and reported:

a. Uncertainty due to SNR limitations;
b. Interpolation error;
c. Truncation error due to pixel dimensions;
d. Errors due to wedge or slab angle;
e. Errors due to wedge or slab non-planarity;
f. Rotational errors;
g. Errors due to image non-uniformity;
h. Other errors or overall errors.

5.2 Reporting of Results

The report of results shall contain, at a minimum, the following items:

a. FWHM results obtained for the selected slice thickness;
b. For every FWHM reported, a representative plot of the properly scaled slice profile;
c. Angle α of the wedge or slab;
d. Accuracy claimed for each value quoted;
e. The following data acquisition parameters:

Parameter	**Dimension**
Phantom filler T_1	milliseconds
Phantom filler T_2	milliseconds
Sequence repetition time (TR)	milliseconds
Echo delay time (TE)	milliseconds
Number of signals averaged (NSA)	….
Data acquisition matrix size	….
Pixel dimensions	millimeters
Selected slice thickness	millimeters
Selected pulse sequence	….

f. RF coil(s) used for transmission and reception;
g. Filtering, if used;
h. Other relevant parameters needed to ensure repeatability;
i. Sources of error including **y**-axis rotation error θ**.**

Annex A
Changes to Standard

A.1 Changes to MS 5-1991 (reaffirmed 1996) resulting in MS 5-2003

A.1.1 Summary

The committee has elected to maintain the standard in current form with minor revisions. There was a discussion about expanding the standard to produce a complete slice profile in addition to the slice thickness measurement.

The desire to include a complete slice profile was motivated by proposals from the IEC to introduce slice profile measurements. The committee elected not to include the slice profile measurement at this time because the IEC's proposals had not been finalized at the time of this revision.

A.1.2 Changes to Introduction

The Disclaimer section replaced by the new "Notice and Disclaimer" section.

Rationale section modified to note the impact of transmit gain on slice thickness.

Scope section modified to define the two test points as "typical and typically thinnest slices" vs. "typical and thinnest slices" because the newer gradient systems are capable of producing two-dimensional slice thicknesses which are never used clinically. The wording change also reflects the range of MR system configurations and their different clinical uses. The remainder of the document was updated accordingly.

Various formatting changes throughout the document to bring standard in line with new NEMA requirements. Some of these formatting changes required slight changes to the text.

A.1.3 Section 2

Sections 2.2.2 and 2.3.2, step 3. The **y-**direction is not parallel to the inclined surface. Phrase removed. Reference the diagram for clarity.

A.1.4 Section 2

Section 2.2.2, step 7 and elsewhere. The phrase "without interpolation" with regard to finding the maximum of the slice profile is confusing. The intent of the phrase was to eliminate the possibility that the edge ringing artifact produces the maximum of the slice profile. The user should select the maximum of the slice profile, not the maximum of an image artifact.

A.1.5 Section 2

Minor revisions to figures artwork for clarity.

A.1.6 Section 3 and 4

Slight changes to emphasize the need to prevent or correct for any rotations that distort the slice profile.

A.1.7 Section 4

Minor revisions to figure artwork for clarity.

A.1.8 Annex A

Annex A added to highlight changes between versions of this standard.

A.2 Changes to MS 5-2003 resulting in MS 5-2010

Minor editorial changes

A.3 Changes to MS 5-2010 resulting in MS 5-2015

Minor editorial changes
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