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Determination of Slice Thickness in Diagnostic Magnetic Resonance Imaging

NEMA

NATIONAL ELECTRICAL MANUFACTURERS ASSOCIATION ■ 2101 L STREET, N.W., WASHINGTON, D.C. 20037

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MS 5

DETERMINATION OF SLICE THICKNESS IN DIAGNOSTIC MAGNETIC RESONANCE IMAGING

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Preamble

This is one of a series of test standards developed by the medical diagnostic industry for the measurement of performance parameters governing the image quality of Magnetic Resonance 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 the 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 subdivision has identified a set of key magnetic resonance image quality parameters. This Standard 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 to be equivalent to the NEMA standard. The validity or equivalence of the modified procedure will be determined by each reader.

Uncertainty of the Measurements

The measurement uncertainty of the image quality parameter determined using this standard 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 describes two methods for determining the 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 primary benefits, in addition to its objectivity, include improved accuracy, increased signal-to-noise ratio (SNR), reduced truncation effects due to pixel size, and an extended range of slice thicknesses which are measurable.

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 SNR can be realized through the use of direct measurement. 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.

In preparation of this Standards Publication, input of users and other interested parties has been sought and evaluated. Inquiries, comments, and proposed or recommended revisions should be submitted to the concerned NEMA product subdivision by contacting the:

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Rationale

Slice thickness is measured along the dimension perpendicular to the scan plane and is a measure of the thickness of the anatomy projected onto the plane of the image. Since slice thickness depends on the radio frequency (RF) pulse shape and sequencing, 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 of its image quality.

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Scope

This document provides a method for determining the slice thickness of proton images. Typical and thinnest slices for a particular system are determined at one location within the specification volume and at 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.

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DETERMINATION OF SLICE THICKNESS IN DIAGNOSTIC MAGNETIC RESONANCE IMAGING

Section 1
DEFINITIONS

1.1 SLICE COORDINATE

The Slice Coordinate, denoted by z, is the dimension perpendicular to the scan plane.

1.2 SLICE PROFILE

The Slice Profile is conceptually a plot of nuclear magnetic resonance (NMR) signal intensity perpendicular to the scan plane arising from a uniform sample which is larger than the z dimension to be analyzed.

1.3 SLICE THICKNESS

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

1.4 CONTIGUOUS SLICES

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

1.5 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.

1.6 BASELINE PIXEL OFFSET VALUE

The baseline pixel offset value is the pixel value for a particular machine which represents a noise-free signal level of zero.

1.7 SPECIFICATION VOLUME

The specification volume is the imaging volume over which a manufacturer guarantees that the 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. For head scans, the specification volume must include, as a minimum, a ten centimeter diameter spherical volume (dsv) centered in the RF head coil. For body scans, the specification volume must enclose, as a minimum, a 20-centimeter dsv centered in the RF body coil.

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Section 2
METHODS OF MEASUREMENT

2.1 SCAN CONDITIONS

The following scan conditions shall be used:

1. Single spin echo at a typical clinical value of TE;
2. TR ≥ 3 T1 in the signal producing material;
3. Pulse sequence as used for clinical scans;
4. Slice thickness, both typical and thinnest selectable; and,
5. Multislice mode, with at least three slices for which the consecutive profile centers are separated by twice the FWHM (not contiguous).

2.2 WEDGE METHOD OF MEASUREMENT

2.2.1 Phantom Description

The Phantom shall consist of two opposing wedges of material which emit 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 corrective procedure is described in Section 4.

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

2.2.2 Measurement Procedure

Select the acquisition and display parameters such 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 the purposes of 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

$d \leq FWHM/(5 \cdot \tan \alpha)$

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:

$$d_{RO} = \frac{1}{T \cdot \gamma \cdot G}$$

where: d_{RO} is the "intrinsic" pixel size in meters;

T is the duration of the sampling in milliseconds (i.e., the difference in time between the first sample and the last sample).

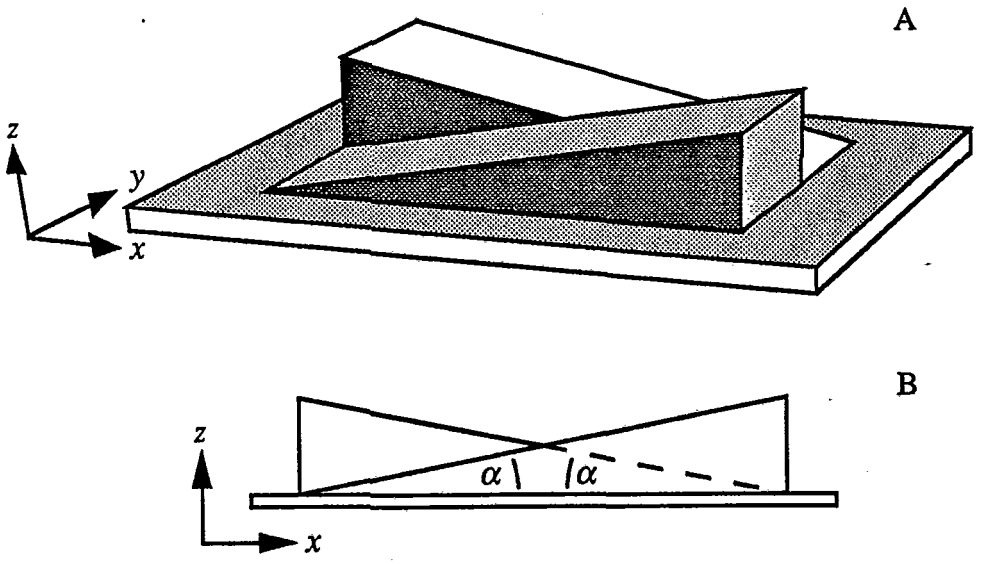


Figure 2-1
Crossed Wedge Phantom

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γ is the magnetogyric ratio in MHz/Tesla

G is the readout gradient strength in mT/m

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In the phase encoding direction, the "intrinsic" pixel size is:

$$d_{PE} = \frac{1}{2 \cdot \gamma \cdot \int G \, dt}$$

where: d_{PE} is the pixel dimension in meters;

γ is the magnetogyric ratio in MHz/T;

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.

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

Define the direction y in the scan plane, which is parallel to the inclined surface of the wedge (see Figure 2-2).

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

The ERF is obtained by plotting the image pixel intensities in the x direction.

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

$$D(X_i) = \frac{I(X_i) - I(X_{i-1})}{X_i - X_{i-1}}$$

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

Without interpolation, find the maximum of the projected slice profile D.

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

Multiply the resulting width of the projected slice profile by tan α to obtain the properly scaled slice width.

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

A slab phantom shall consist of two thin opposed 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 scan plane. The slab thickness shall be less than one-fifth of the selected slice thickness times cos α. As an example, for $\alpha = 30$ 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 corrective 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 line indicates the scan plane.

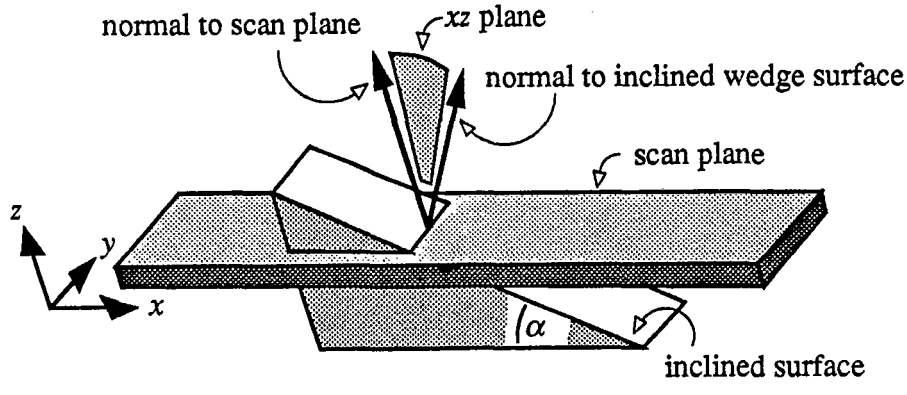


Figure 2-2
Diagram of Referenced Planes

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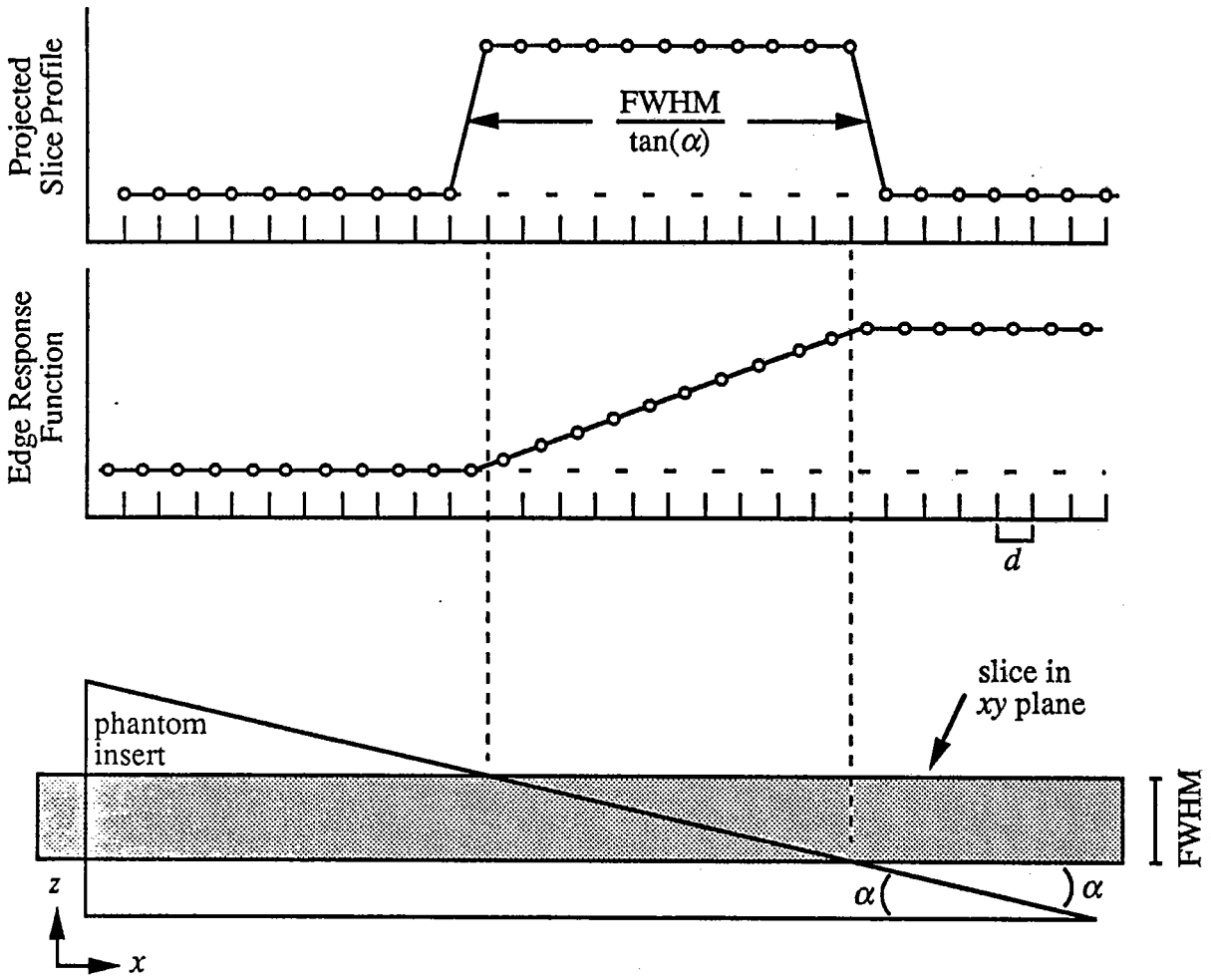


Figure 2-3
Schematic Overview of the Wedge Method

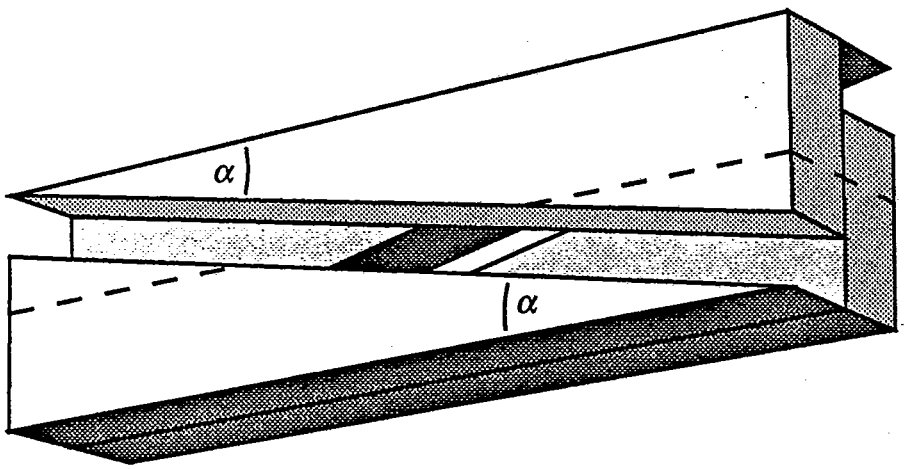


Figure 2-4
Crossed Slab Phantom

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2.3.2 Measurement Procedure

Select the acquisition and display parameters such 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 2.2.2).

Generate an image from one of the three optional acquisition planes (transverse, sagittal, or coronal). Only the center slice of the multi slice acquisition shall be analyzed.

Define the direction y in the scan plane, which is parallel to the inclined surface of the slab.

Define the direction x in the scan plane, which is perpendicular to y. Note that x forms an angle α with the inclined surface of the slab.

The stretched (projected) slice profile is the plot of pixel intensities as a function of x (see Figure 2-5).

Without interpolation, find the maximum of the projected slice profile.

Find the width of the projected slice profile at one-half of the maximum (see Figure 2-5). If necessary, use linear interpolation and correct for baseline pixel offset.

Multiply the resulting width of the projected slice profile by tan α to obtain a properly scaled slice width (FWHM).

Correct results for tilt (rotation about the y axis) as detailed in Section 4 prior to reporting results in Section 5.2.

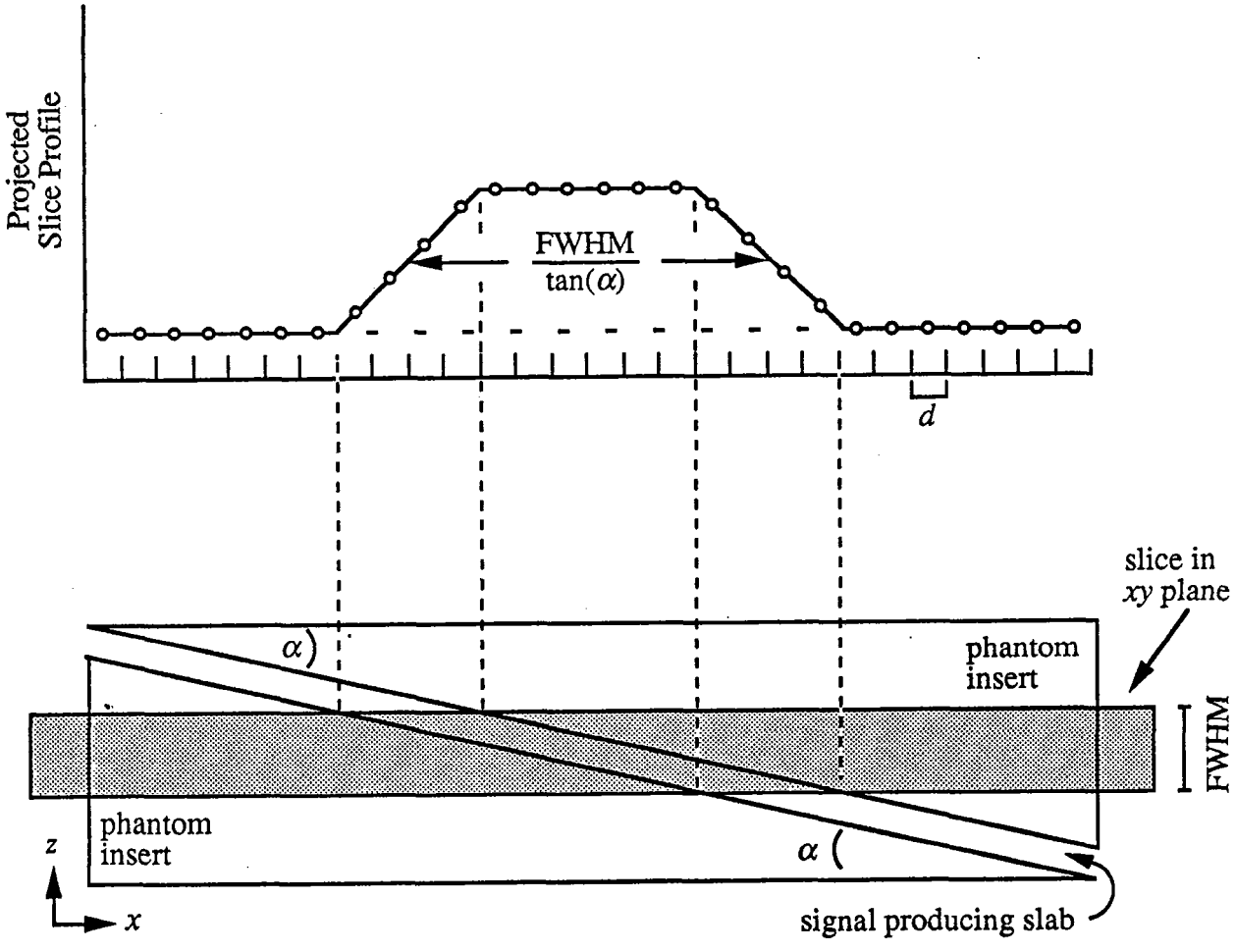


Figure 2-5
Schematic Overview of the Slab Method

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.

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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 ten. 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:

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.

To improve the SNR, form the average A of the values, $I_j(x_i)$, of the N profiles.

$$A(X_i) = \frac{1}{N} \cdot \sum_{j=1}^{N} I_j(X_i)$$

where x_i is the position along the profile.

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Section 4
CORRECTING FOR ROTATIONAL ERRORS

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

Rotation about the z axis will rotate the entire image. Rotation about the x axis will cause the slice profile to shift from one value of y to the next and will change the effected. 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 only 11.3 degrees for a 1:5 wedge, and a 1 degree rotational error about y produces a 10 percent 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.

Compute the rotational error θ of the phantom about the y axis using:

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

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

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

$$FWHM = w_1 \tan(\alpha + \theta) \qquad \text{(Equation 2)}$$

Report the FWHM and θ in Section 5.2.

Equation 1 is derived as follows:

1. Assume that the first wedge or slab makes an angle $\beta 1 = \alpha + \theta$ with the slice plane and the second wedge or ramp makes an angle $\beta_2 = \alpha - \theta$.
2. The projected slice thickness determined from the first wedge or slab will be $w_1 = FWHM/\tan(\beta_1)$ and the other wedge or slab will be $w_2 = FWHM/\tan(\beta_2)$, where FWHM is the value obtained with no rotational error.
3. The FWHM may be eliminated by forming the ratio: $(w_2 - w_1)/w_2 + w_1)$
   $= (\tan(\beta_1)-\tan(\beta_2))/(\tan(\beta_1)+\tan(\beta_2))$
   $= \sin(\beta_1 - \beta_2)/\sin(\beta_1 + \beta_2)$
   $= \sin(2\theta)/\sin(2\alpha)$ (Equation 3)
4. Equation 3 is solved for θ to give Equation 1.

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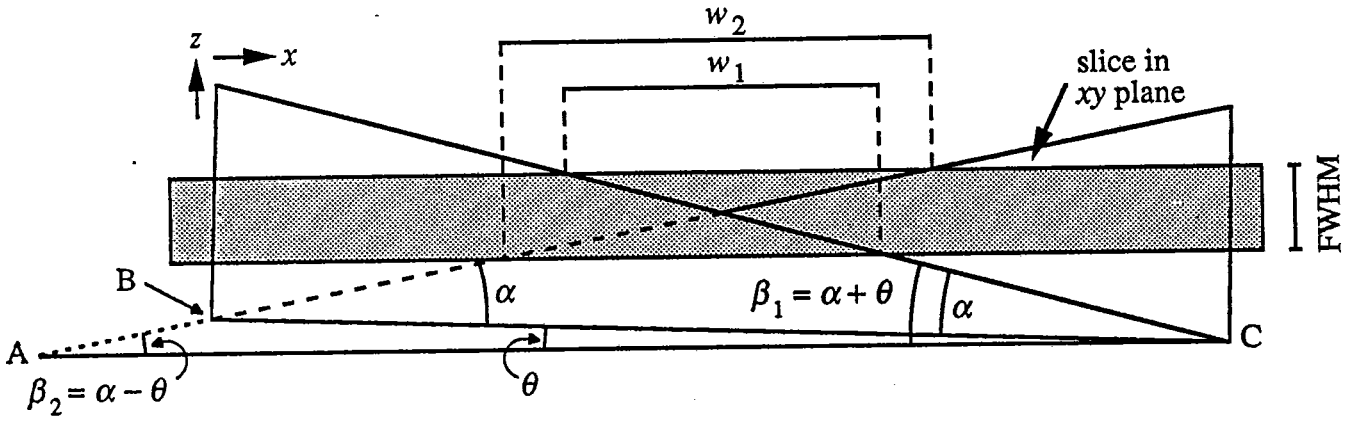


Figure 4-1
Angle Definitions for Rotational Correction

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

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Section 5
SOURCES OF ERROR AND REPORT OF RESULTS

5.1 SOURCES OF ERROR

The following sources of error shall be discussed and reported:

1. Uncertainty due to SNR limitations;
2. Interpolation error;
3. Truncation error due to pixel dimensions;
4. Errors due to ramp or wedge angle, or non-planarity;
5. Rotational errors;
6. Errors due to image nonuniformity; and
7. Other errors and overall error.

5.2 REPORT OF RESULTS

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

1. FWHM results obtained for typical and thinnest values of the selected slice thickness;
2. For every FWHM reported, a representative plot of the properly scaled slice profile;
3. Angle α of wedge or slab;
4. Accuracy claimed for each value quoted;
5. TE, TR, T_1, T_2, number of signals averaged (NSA), selected slice thickness, and pulse sequence used;
6. Acquisition matrix size and pixel size.
7. Field of view;
8. RF coil(s) used for transmission and reception;
9. Filtering, if used;
10. Other relevant parameters needed to assure repeatability; and,
11. Sources of error including y axis rotational error θ.

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The purpose of NEMA Standards, their classification and status are set forth in certain clauses of the NEMA *Standardization Policies and Procedures* manual and are referenced below:

Purpose of Standards

National Electrical Manufacturers Association Standards are adopted in the public interest and are designed to eliminate misunderstandings between the manufacturer and the purchaser and to assist the purchaser in selecting and obtaining the proper product for their particular needs. Existence of a National Electrical Manufacturers Association Standard does not in any respect preclude any member or nonmember from manufacturing or selling products not conforming to the standard.

(Standardization Policies and Procedures, p. 1)

Definition of a Standard

A standard of the National Electrical Manufacturers Association defines a product, process or procedure with reference to one or more of the following: nomenclature, composition, construction, dimensions, tolerances, safety, operating characteristics, performance, rating, testing, and the service for which they are designed.

(Standardization Policies and Procedures, p. 2)

Dimensions

Where dimensions are given for interchangeability purposes, alternate dimensions satisfying the other provisions of the Standards Publication may be capable of otherwise equivalent performance.

(Standardization Policies and Procedures, p. 8)

Categories of Standards

National Electrical Manufacturers Association Standards are of three classes:

1. NEMA Standard, which relates to a product, process or procedure commercially standardized and subject to repetitive manufacture, which standard has been approved by at least 90 percent of the members of the Subdivision eligible to vote thereon;
2. Suggested Standard for Future Design, which may not have been regularly applied to a commercial product, but which suggests a sound engineering approach to future development, which standard has been approved by at least two-thirds of the members of the Subdivision eligible to vote thereon.
3. Adoptive Standard, which is adopted in whole or in part from the standards of another organization, either domestic, regional, or international.

(Standardization Policies and Procedures, pp 7 & 16)

Authorized Engineering Information

Authorized Engineering Information consists of explanatory data and other engineering information of an informative character not falling within the classification of NEMA Standard or Suggested Standard for Future Design, which standard has been approved by at least two-thirds of the members of the Subdivision eligible to vote on the standard.

(Standardization Policies and Procedures, pp. 7 & 16)

Official Standards Proposal

An Official Standards Proposal is an official draft of a proposed standard which is formally recommended to an outside organization(s) for consideration, comment and/or approval, and which has been approved by at least 90 percent of the members of the Subdivision eligible to vote thereon. *(Standardization Policies and Procedures, pp 7 & 16)*

Identification of Status

Standards in NEMA Standards Publications are identified in the foreword or following each standard as "NEMA Standard" or "Suggested Standard for Future Design." These indicate the status of the standard. These words are followed by a date which indicates when the standard was adopted in its present form by the Association.

The material identified as "Authorized Engineering Information" and "Official Standards Proposal" is designated similarly.

July 17, 1990

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