Phantom Test Guidance for Use of the Large MRI Phantom for the

MRI Accreditation Program

Contents

Phantom Test Guidance for the ACR MRI Accreditation Program

0.0 INTRODUCTION

0.1 Overview and Purpose

This document provides information about the phantom tests that are part of the American College of Radiology Magnetic Resonance Imaging Accreditation Program. The primary purpose of this document is to enable facilities that have failed the phantom tests to understand the significance of the failure, to take steps to correct it, and to determine whether or not their corrective actions have been successful.

This document will also be useful to facilities wishing to determine whether or not they will pass the phantom tests prior to data submission, and to facilities wishing to utilize their ACR phantom for quality control and system performance testing.

We begin with an introduction in which we briefly describe the phantom and the image data acquired for the tests, introduce terminology to be used in referring to the images, and list the tests that constitute the phantom assessment portion of the accreditation process. Then we discuss each test in turn, describing how it is done, giving an acceptance criterion, naming common causes of failure, and offering advice on corrective actions that might be taken.

The acceptance criteria here are indicative of a minimum level of performance one can reasonably expect from a well-functioning MRI system. On the other hand, being minimum levels of performance, these criteria are not to be construed as indicators of typical or normal levels of performance.

Information about the phantom, phantom placement and image acquisition are given here only insofar as they are necessary to the discussion. For a more detailed treatment of these topics see the ACR document called *Accreditation Program Testing Instructions*, which is available on the acraccreditation.org website.

0.2 The Phantom

The ACR MRI phantom is a short, hollow cylinder of acrylic plastic closed at both ends. The inside length is 148 mm; the inside diameter is 190 mm. It is filled with a solution of nickel chloride and sodium chloride: 10 mM $NiCl_2$ and 75 mM NaCl. The outside of the phantom has the words “NOSE” and “CHIN” etched into it as an aid to orienting the phantom for scanning, as if it were a head.

Inside the phantom are several structures designed to facilitate a variety of tests of scanner performance. These structures will be described as the tests in which they are used in the discussion below.

0.3 The Required Images

The phantom portion of the MRI accreditation program requires the acquisition of a sagittal localizer and 4 axial series of images. The same set of 11 slice locations within the phantom is acquired in each of the 4 axial series. These images are acquired using the scanner’s head coil. The scan parameters for the localizer and the first 2 axial series of images are fully prescribed by the ACR in the scanning instructions. Therefore, we refer to them as the **ACR sequences** or **ACR images.** The third and fourth series of axial images are based on the site’s own protocols, and are referred to as the **site sequences** or **site series**. To discuss the image data it is convenient to introduce names for the different sets of images and numbering for the slice locations within the phantom.

The localizer is a 20 mm thick single-slice spin-echo acquisition through the center of the phantom, and is referred to simply as the **localizer**.

The first axial series is a spin-echo acquisition with ACR-specified scan parameters that are typical of T1-weighted acquisitions. This series is called the **ACR T1** series.

The second axial series is a double spin-echo acquisition with ACR-specified scan parameters that are typical of proton density/T2-weighted acquisitions. When analyzing data from this acquisition only the second-echo images are used. The set of second-echo images from this acquisition is called the **ACR T2** series.

The third and fourth axial series are based on the scan parameters the site normally uses in its clinical protocols for axial head T1 and T2 weighting respectively. These series are called the **site T1** and **site T2** series.

Each of the axial series has 11 required slice locations. The locations are numbered starting at the inferior end of the phantom; so, slice location 1 is at the end of the phantom labeled "CHIN." Different scanners number images differently. Regardless of how the scanner numbers the images, we always refer to them by their series name and slice location number. For example, ACR T2 slice 7 is the second-echo image of the ACR-prescribed double-echo acquisition at slice location 7.

For all 4 axial series the required slice thickness is 5 mm and the slice gap is 5 mm. Thus, the set of 11 slices spans a distance of 100 mm from the center of the first slice to the center of the last slice. (Some scanners will not allow prescription of 5 mm slices with 5 mm gaps; the MR Accreditation Program Testing Instructions explain what to do in those cases.)

Figure 1 shows a sagittal localizer with the 11 axial slice locations cross-referenced on it. There are 2 pairs of crossed 45° wedges lying in the central sagittal plane of the phantom: 1 pair at each end of the phantom. They are indicated on the image in Figure 1. Slice 1 is prescribed to be centered on the vertex of the angle formed by the crossed wedges at the inferior end of the phantom. The vertices of the 2 pairs of wedges are separated by 100 mm, and therefore slice 11 falls on the vertex at the superior end of the phantom.

The image data must be submitted to the ACR in digital form (DICOM-formatted image files written onto CD) or electronically uploaded. (*Please see the MR Accreditation Program Testing Instructions and the Instructions for Electronic Upload for detailed information on submitting images for accreditation evaluation.)*

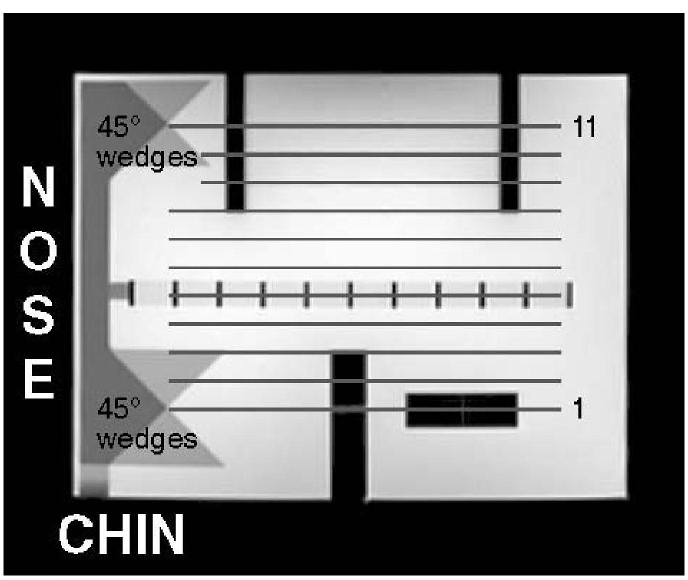

Figure 1: Sagittal localizer showing the 11 required axial slice locations and the paired 45° wedges. The words "CHIN" and "NOSE" on this image indicate the locations where those same words are etched into the phantom as an aid to orienting it for scanning as if it were a head.

0.4 The Image Analysis

For quantitative analysis the digital data are displayed on a computer image workstation capable of the basic image manipulation functions found on all scanner consoles: window and level adjustments, magnification (zoom), mean and standard deviation measurements in a region-of-interest (ROI), and length measurements. In most cases the most convenient place for a facility to make these measurements on its own data will be the scanner console or an associated image review station. However if the images are to be submitted on CD in uncompressed DICOM format or directly on-line, it is recommended to review the images in the form in which they will be submitted in order to replicate the way the data will be analyzed by the ACR reviewer.

There are 7 quantitative tests made using measurements on the digital data. They are:

1. Geometric accuracy
2. High-contrast spatial resolution
3. Slice thickness accuracy
4. Slice position accuracy
5. Image intensity uniformity
6. Percent-signal ghosting
7. Low-contrast object detectability

Each of these tests will be described in turn in the sections below. The sections are numbered to correspond with the numbering of the tests in this list.

It won't be discussed further here, but the reader should be aware that in addition to these quantitative tests the ACR data reviewers examine the images for artifacts. Artifacts that could have an adverse effect on diagnostic accuracy, and artifacts suggestive of system problems that could affect diagnostic accuracy, may result in a failure for accreditation even though the system passes the quantitative tests.

1.0 GEOMETRIC ACCURACY

1.1 What It Is

The geometric accuracy test assesses the accuracy with which the image represents lengths in the imaged subject. This is also sometimes called the geometric error test. It consists of making length measurements on the images, between readily identified locations in the phantom, and comparing the results with the known values for those lengths.

A failure means that dimensions in the images differ from the true dimensions substantially more than is usual for a properly functioning scanner.

1.2 What Measurements Are Made

Seven measurements of known lengths within the phantom are made using the display station's on-screen length measurement tool. The display window and level settings can affect the length measurements, so it is important to set them properly. For that purpose a separate ancillary procedure for adjusting the display window and level settings is provided following the main procedure.

Measurements for this test are made according to the following procedure:

1. Display the localizer. Adjust the display window and level as described below.
2. Measure the end-to-end length of the phantom as it appears in the localizer. This should be measured along a line near the middle of the phantom as shown in Figure 2.
3. Display slice 1 of the ACR T1 series. Adjust the display window and level as described below.
4. Measure the diameter of the phantom in 2 directions: top-to-bottom and left-to-right (Figure 3).
5. Display slice 5 of the ACR T1 series. Adjust the display window and level as described below.
6. Measure the diameter of the phantom in 4 directions: top-to-bottom, left-to-right, and both diagonals (Figure 4).

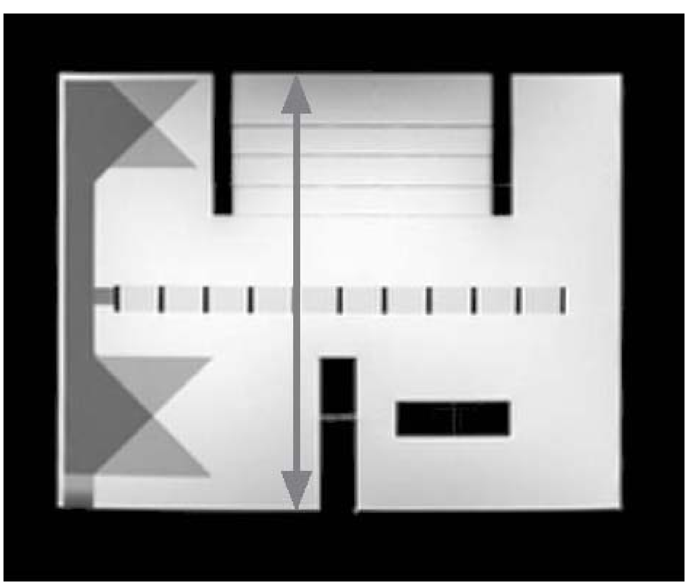

Figure 2: Localizer with end-to-end length measurement illustrated (arrow).

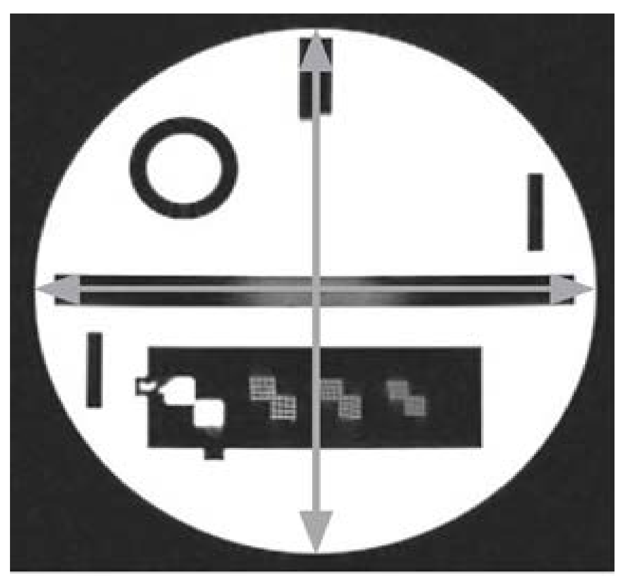

Figure 3: Slice 1 with diameter measurements illustrated (arrows).

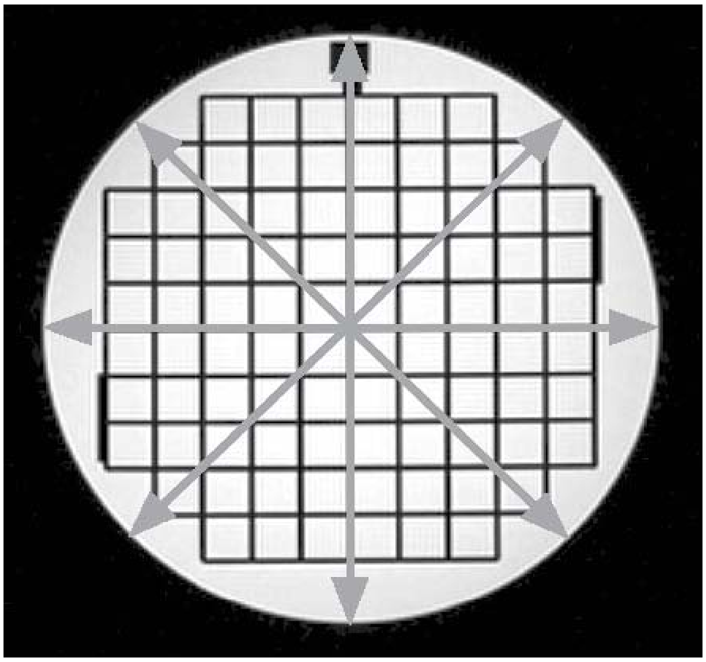

Figure 4: Slice 5 with diameter measurements illustrated (arrows).

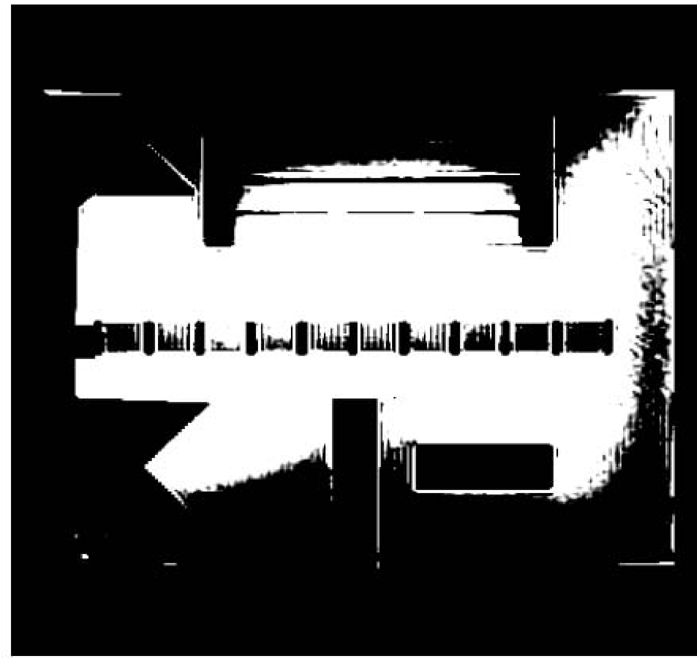

Figure 5: Sagittal locator shown with display window set to zero and level adjusted for approximate measurement of mean signal level

The display window and level settings can affect the apparent location of the edges of the phantom and thus cause errors in the length measurements. To avoid this, the measurements should be made with the display window width set to the mean signal value and the level set to a value equal to half the mean signal value of the water-only regions of the image.
On most scanners the following procedure can be used for setting the display window and level:
1. Adjust the window to its narrowest setting, which is 0 or 1 on most scanners.
2. Observe the regions of the phantom that have only water, i.e., the regions that are not partial-volumed with some of the internal structures of the phantom. These regions have the highest signal. Lower the display level until the signal in these water-only regions is all white.
3. Raise the display level until about half of the total area of the water-only regions has turned dark. This is illustrated in Figure 5 for the localizer. The level is now set to a numerical value approximating the mean signal of the water-only regions; note this value. (This is really estimating the median signal, but that will be sufficiently close to the mean for our purpose.)
4. Lower the level setting to half of the mean signal value found in step 3. Increase the window width setting to equal the mean signal value.

NOTE: Some older scanners have a numerical value of 1024 as the zero pixel intensity value. For such scanners this zero offset must be taken into account when figuring the half value of the mean signal.

1.3 How the Measurements Are Analyzed

The length measurements are compared with the known values of the distances in the phantom.

The inside end-to-end length of the phantom is 148 mm.

The inside diameter of the phantom is 190 mm.

1.4 Recommended Action Criteria

All measured lengths should be within ± 2 mm of their true values. Images submitted for accreditation will fail if any measured length differs more than +/- 3 mm from its true value.

1.5 Causes of Failure and Corrective Actions

Some MR vendors provide the ability to select gradient distortion correction at the operator console. For these systems be sure that the distortion correction option is turned on as this can cause geometric accuracy failure.

The most common cause of failure of this test is miscalibration of one or more gradients. A miscalibrated gradient causes its associated image dimension (x, y, or z) to appear longer or shorter than it really is. It can also cause slice position errors. It is normal for gradient calibration to drift over time and to require recalibration by the service engineer.

NOTE: Gradient amplifiers need time to warm up and stabilize when they are turned on. Some sites power off their scanner hardware, including gradient amplifiers, overnight. Those sites should make sure their hardware has been on at least an hour before acquiring images of the phantom.

Another possible cause of failure is use of too low an acquisition bandwidth. It is common practice on some scanners and at some facilities to reduce acquisition bandwidth to increase signal-to-noise ratio. This can be pushed to the point that the normal inhomogeneities in B_0 manifest themselves as spatial distortions in the image. On most scanners the default bandwidth for T1 acquisitions is set high enough to avoid this problem.

If the geometric accuracy test measurements fail, and the ACR T1 series was acquired at low bandwidth, try acquiring that series again at a higher bandwidth to see if the problem is eliminated.

Although uncommon, it is possible that abnormally high B_0 inhomogeneities could cause significant dimensional errors in the phantom images. Such B_0 inhomogeneities could be caused by improper adjustment of the gradient offsets, improper adjustment of passive or active magnet shims, or a ferromagnetic object such as a pocket knife or large hair clip lodged in the magnet bore. Regardless of the cause, the service engineer can then measure the magnetic field homogeneity and any inhomogeneity large enough to cause failure of the geometric accuracy test should be apparent.

2.0 HIGH-CONTRAST SPATIAL RESOLUTION

2.1 What It Is

The high-contrast spatial resolution test assesses the scanner's ability to resolve small objects when the contrast-to-noise ratio is sufficiently high that it does not play a role in limiting that ability. This is sometimes called limiting high-contrast spatial resolution.

A failure of this test means that for a given field of view and acquisition matrix size the scanner is not resolving small details as well as normal for a properly functioning scanner. However, since clinical protocols are typically adjusted to optimize high contrast resolution, if the site fails resolution for either of the ACR series, this test is then applied to the site series. The submitted images must pass for either both ACR series or both site series.

2.2 What Measurements Are Made

For this test, one visually assesses the distinguishability of individual small bright spots in arrays of closely spaced small holes. These bright spots are water-filled holes drilled in a small block of plastic called the **resolution insert**, which appears in slice 1. Before describing how to make the visual assessment of resolution using the images of the insert, it is first necessary to describe the insert in some detail.

The resolution insert

Figure 6 shows an image of slice 1 with the resolution insert identified. There are 3 pairs of not-quite-square arrays of holes in the insert. One pair of hole arrays is illustrated in Figure 7.

Note that it consists of an upper left (UL) hole array and a lower right (LR) hole array. Here right and left refer to the viewer's right and left. The UL and LR arrays share 1 hole in common at the corner where they meet. The UL array is used to assess resolution in the right-left direction, and the LR array is used to assess resolution in the top-bottom direction (anterior-posterior if this were a head).

The UL array comprises 4 rows of 4 holes each. The center-to-center hole separation within a row is twice the hole diameter. The center-to-center row separation is also twice the hole diameter. Each row is staggered slightly to the right of the one above, which is why the array is not quite square. The staggering ensures that the holes in at least one row will align exactly with the display matrix so that each hole in that row will be centered within a pixel. Holes that do not align with the display matrix will experience partial volume affects and appear to be blurred, irregularly shaped spots of signal.

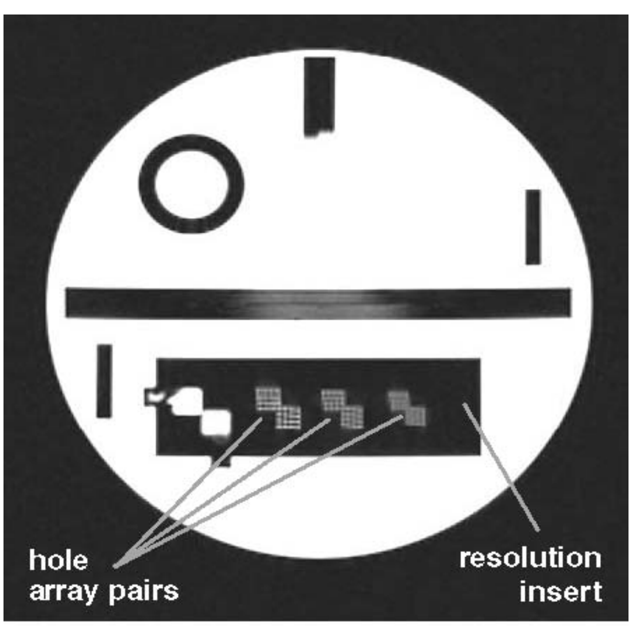

Figure 6: Slice 1 with resolution insert and hole array pairs indicated.

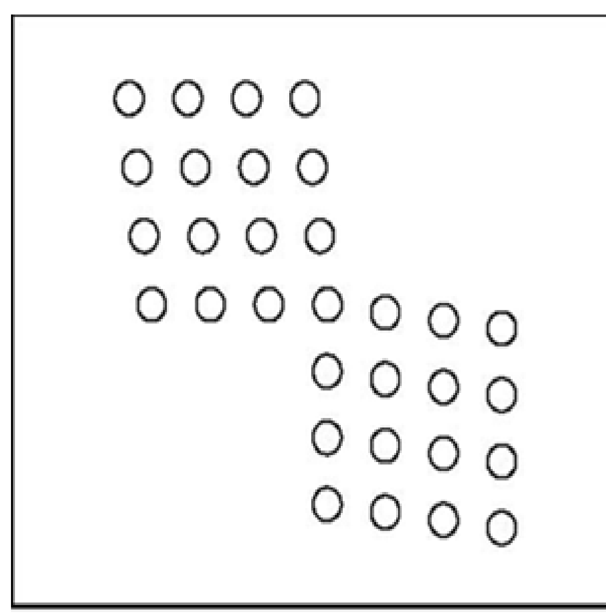

Figure 7: Illustration of 1 of the pairs of hole arrays in the resolution insert.

The LR array comprises 4 columns of 4 holes each. The center-to-center hole separation within each column and the center-to-center spacing between columns are twice the hole diameter. Each column is staggered slightly downward from the one to its left. As with the rows, staggering of columns ensures that the holes in at least one column will align exactly with the display matrix and not experience partial volume effects.

The hole diameter differs between the array pairs: for the left pair it is 1.1 mm, for the center pair it is 1.0 mm, and for the right pair it is 0.9 mm. Thus, using this insert, one can determine whether or not resolution has been achieved at each of these three hole sizes.

For this test, resolution in slice 1 of each of the 2 ACR axial series is evaluated. The following procedure is repeated for each of those series:

1. Display the slice 1 image.
2. Magnify the image by a factor of between 2 and 4, keeping the resolution insert visible in the display. This is illustrated in Figure 8.
3. Begin with the leftmost pair of hole arrays, which is the pair with the largest hole size, 1.1 mm.
4. Look at the rows of holes in the UL array, and adjust the display window and level to best show the holes as distinct from one another.
5. If all 4 holes in any single row are distinguishable from one another, score the image as resolved right-to-left at this particular hole size.

To be “distinguishable” or resolved, it is not necessary that image intensity drop to zero between the holes. To be distinguishable a single window and level setting can be found such that all 4 holes in at least one row are recognizable as points of brighter signal intensity than the spaces between them. Figure 9a shows the typical appearance of well-resolved holes.

When the hole size is comparable to the resolution in the image, groups of two or more holes in a row or column may blur together and appear as a single irregularly shaped spot of signal. In this case the holes in that row are considered unresolved. An example of this is shown in row 1 of the UL array of Figure 9b.

Figure 8: Magnified portion of slice 1 displayed appropriately for visually assessing high-contrast resolution.

Sometimes one or more holes which are distinguishable from their neighbors in their own row blur together with their neighbors in adjacent rows. This is acceptable and does not affect the scoring for the row. An example of this is shown in the second row of the UL array of Figure 9b, where the holes at each end of the row blur with their neighbors in adjacent rows.

6. Look at the holes in the LR array and adjust the display window and level to best show the holes as distinct from one another.
7. If all 4 holes in any single column are seen to be distinguishable from one another, score the image as resolved top-to-bottom at that particular hole size. The remarks made in step 5 about distinguishability of holes within rows apply here to holes within columns.
8. Move on to the pair of arrays with the next smaller hole size, and evaluate as in steps 4 through 7. Continue until the smallest resolvable hole sizes have been found for the right-to-left and top-to-bottom directions.
9. Make a note of the smallest hole size resolved in each direction; that is the measured resolution for that direction.

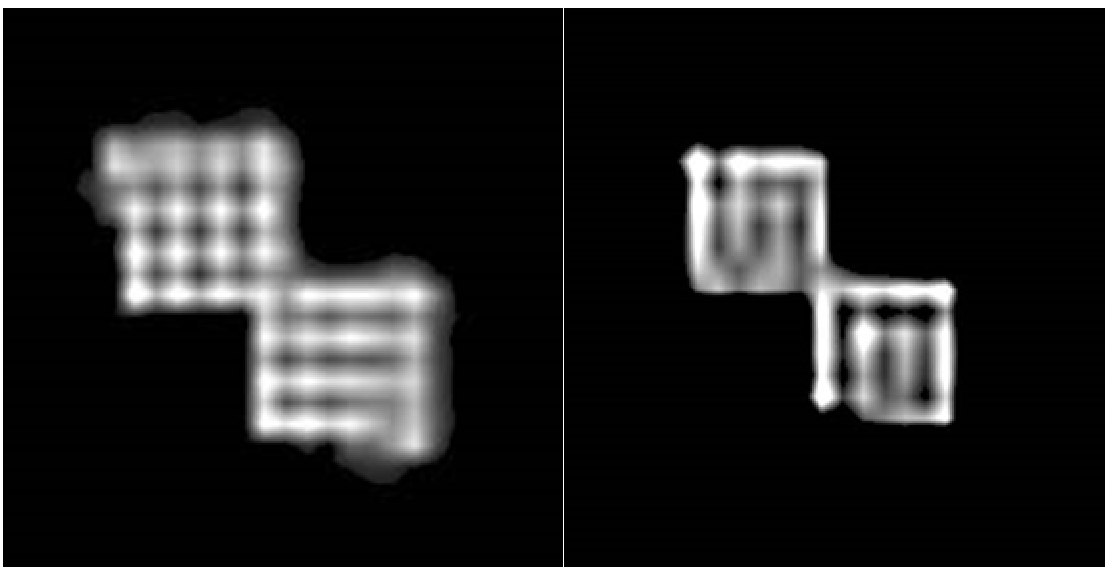

Figure 9:
(a) Typical appearance of well-resolved holes. Rows 2 through 4 of the UL array are resolved, and columns 1 through 3 of the LR array are resolved. (Rows and columns are numbered starting from the upper left corner of each array.)
(b) Example of barely resolved rows and unresolved columns. Row 2 of the UL array is resolved because all 4 holes are discernible from each other, even though the holes at either end of the row blur together vertically with their neighbors in the row below. So, the horizontal direction would be scored as resolved at this hole size. None of the columns of the LR array show more than 3 discernible spots within the column, so the vertical direction is not resolved at this hole size.

2.3 How the Measurements Are Analyzed

There is no analysis. One simply notes the measured resolution in both directions for both axial series.

2.4 Recommended Action Criteria

The field of view and matrix size for the axial ACR series are chosen to yield a resolution of 1.0 mm in both directions. The measured resolution of both axial ACR series must be 1.0 mm or better in both directions. If the resolution score for either of the ACR series is more than 1.0 mm, then evaluate the site series. If both site series can resolve 1.0 mm then the scanner passes this test. A scanner must pass on both the ACR T1 and T2 series, or on both the site T1 and T2 series. A scanner cannot pass on just one of ACR series and one site series.

2.5 Causes of Failure and Corrective Actions

Excessive image filtering can cause failure. Many types of filtering that are used to make the images appear less noisy also smooth the image, which blurs small structures. A site that has failed the high-contrast resolution test should check that any user selectable image filtering is either turned off, or at least set to the low end of the available filter settings.

Poor eddy current compensation can cause failure. The scanner's service engineer should check and adjust the eddy current compensation if this problem is suspected.

Excessive image ghosting can cause failure. The presence of excessive ghosting will be obvious elsewhere in the image if it is sufficient to cause failure of the high-contrast resolution test. Ghosting is a very nonspecific symptom of a hardware problem. In general, it is caused by instability of the measured signal from pulse cycle to pulse cycle, which can have its origin in the receiver, transmitter, or gradient subsystems. Motion of the phantom can also cause ghosting. Make sure the phantom is stable in the head coil and not free to move or vibrate. Having ruled out phantom motion, it will usually be necessary to ask the service engineer to track down and correct the cause of ghosting.

Geometric errors from gradient miscalibration, B_0 inhomogeneity and too-low acquisition bandwidth can cause failure of this test. However, it is unusual for the geometric errors to be large enough to do that. In such cases the image will usually be obviously misshapen, e.g., the circular phantom may appear elliptical or egg-shaped. If the scanner passes the geometric accuracy test, it is very unlikely that geometric error could be the cause of failure of the high-contrast spatial resolution test. On the other hand, if the scanner fails the geometric accuracy test by a large margin, then the failure of this test and the geometric accuracy test may have a common cause. Refer to section 1.5 of the geometric accuracy test for discussion of causes and corrective actions for geometric error.

3.0 SLICE THICKNESS ACCURACY

3.1 What It Is

The slice thickness accuracy test assesses the accuracy with which a slice of specified thickness is achieved. The prescribed slice thickness is compared with the measured slice thickness.

A failure of this test means that the scanner is producing slices of substantially different thickness from that being prescribed. This problem will generally not occur in isolation since the scanner deficiencies that can cause it will also cause other image problems. Therefore, the implications of a failure are not just that the slices are too thick or thin, but can extend to things such as incorrect image contrast and low signal-to-noise ratio.

3.2 What Measurements Are Made

For this test the lengths of two signal ramps in slice 1 are measured for both axial series.

The ramps appear in a structure called **the slice thickness** insert. Figure 10 shows an image of slice 1 with the slice thickness insert and signal ramps identified. The 2 ramps are crossed: one has a negative slope and the other a positive slope with respect to the plane of slice 1. They are produced by cutting 1 mm wide slots in a block of plastic. The slots are open to the interior of the phantom and are filled with the same solution that fills the bulk of the phantom.

The signal ramps have a slope of 10 to 1 with respect to the plane of slice 1, which is an angle of about 5.71°. Therefore, the signal ramps will appear in the image of slice 1 with a length that is 10 times the thickness of the slice. If the phantom is tilted in the right-left direction, one ramp will appear longer than the other. Having crossed ramps allows for correction of the error introduced by right-left tilt, and the slice thickness formula provided in the next section takes that into account.

For each axial series, the length of the signal ramps in slice 1 is measured according to the following procedure:

1. Display slice 1, and magnify the image by a factor of 2 to 4, keeping the slice thickness insert fully visible on the screen.

2. Adjust the display level so that the signal ramps are well visualized. The ramp signal is much lower than that of surrounding water, so usually it will be necessary to lower the display level substantially and narrow the window.

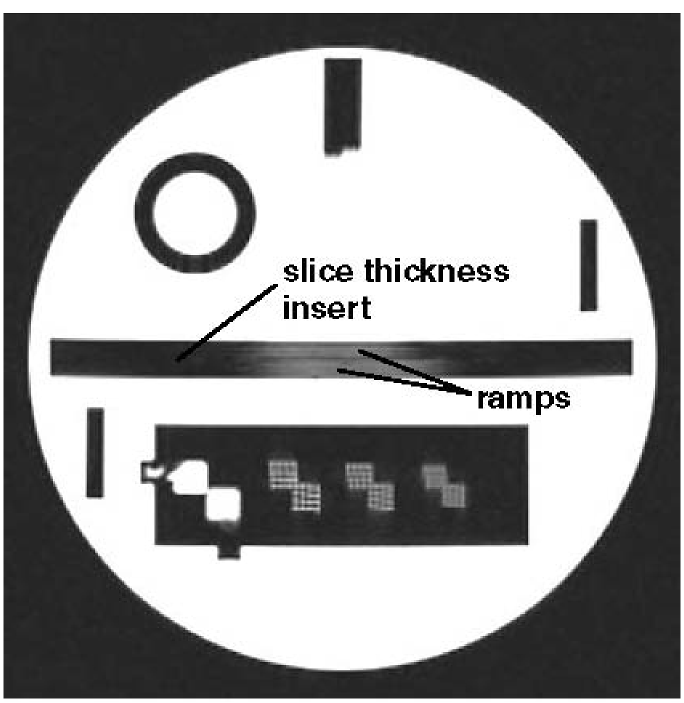

Figure 10: Slice 1 with the slice thickness insert and signal ramps indicated.

3. Place a rectangular ROI at the middle of each signal ramp as shown in Figure 11. Note the mean signal values for each of

these 2 ROIs, and then average those 2 values together. The result is a number approximating the mean signal in the middle of the ramps. An elliptical ROI may be used if a rectangular one is unavailable.

NOTE: When making these measurements be careful to fully cover the widths of the ramp with the ROIs in the top-bottom direction, but not to allow the ROIs to stray outside the ramps into adjacent high- or low-signal regions. If there is a large difference—more than 20%—between the signal values obtained for the 2 ROIs, it is often due to one or both of the ROIs including regions outside the ramps.

4. Lower the display level to half of the average ramp signal calculated in step 3. Leave the display window set to its minimum.

NOTE: Some scanners use a pixel value of 1024 as the zero signal level. For those scanners it is necessary to take that into account when calculating the mean signal in step 3, and when setting the display level to half that mean here in step 4. The goal is to set the display level to a numerical value that corresponds to a signal that is half the mean signal of the middle of the ramps.

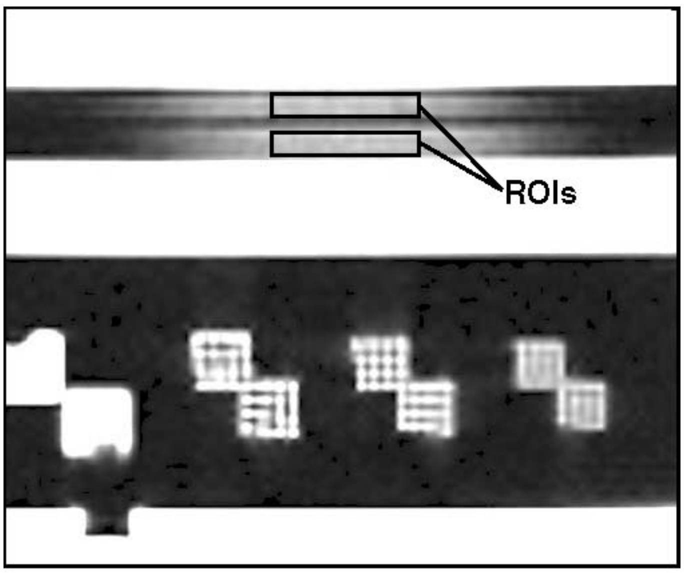

Figure 11: Magnified region of slice 1 showing slice thickness signal ramps with ROIs placed for measuring average signal in the ramps.

5. Use the on-screen length measurement tool of the display station to measure the lengths of the top and bottom ramps. This is illustrated in Figure 12. Record these lengths. They are the only measurements required for this test.

Often there are horizontal striations in the signal intensity of the ramps that cause the ends to appear scalloped or ragged. The striations are a manifestation of truncation (Gibbs) artifact, and are normal. In this case one must estimate the average locations of the ends of the ramps in order to measure the ramp lengths. Figure 12 is an example of this problem and how the measurements should be made. Estimating the ends of the ramps introduces a source of error, but a millimeter of error in the ramp length measurement corresponds to only a tenth of a millimeter error in the slice thickness, so the errors introduced are small in effect.

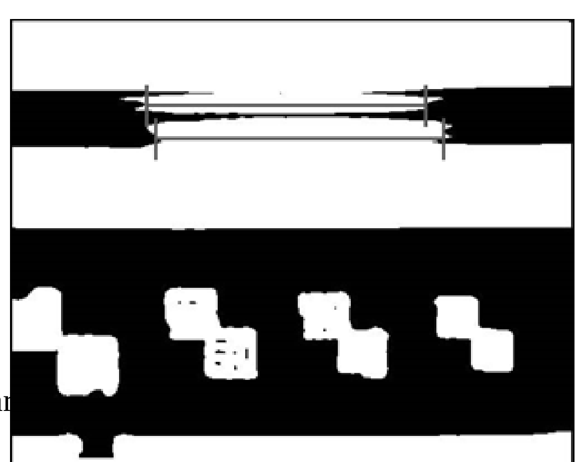

Figure 12: Magnified region of slice 1 showing slice thickness signal ramps. The display window is zero and the level is half the average signal level of the ramps. The length measurements for the ramps are shown on the image (gray lines).

3.3 How the Measurements Are Analyzed

The slice thickness is calculated using the following formula:

$$\text{slice thickness} = 0.2 \times (\text{top} \times \text{bottom})/(\text{top} + \text{bottom})$$

where top and bottom are the measured lengths of the top and bottom signal ramps. For example, if the top signal ramp were 59.5 mm long and the bottom ramp were 47.2 mm long, then the calculated slice thickness would be

$$\text{slice thickness} = 0.2 \times (59.5 \times 47.2)/(59.5 + 47.2) = 5.26 \text{ mm.}$$

3.4 Recommended Action Criteria

For both ACR series the measured slice thickness should be 5.0 mm ± 0.7 mm. Errors greater than +/-1.0 mm fail. If the thickness error for either ACR series is greater than +/-1.0 mm, then evaluate the site series. If slice thickness for both site series is 5.0 mm +/-1.0 mm, then the scanner passes this test.

3.5 Causes of Failure and Corrective Actions

Radiofrequency (RF) amplifier nonlinearity can cause distorted RF pulse shapes and failure of this test. On many scanners the service engineer must empirically calibrate the RF power amplifier for linearity. If this calibration were lost or done incorrectly, it could possibly cause failure of this test.

Distorted RF pulse shapes can also arise from malfunctions anywhere in the high power RF portion of the transmitter, i.e., in the RF power amplifier, the cables and RF switches that convey power from the amplifier to the transmitter coil, or in the transmitter coil itself.

Extremely bad gradient calibration or poor gradient switching performance can also cause failure of this test.

All of these possible causes for failure require corrective action by the service engineer.

4.0 SLICE POSITION ACCURACY

4.1 What It Is

The slice position accuracy test assesses the accuracy with which slices can be prescribed at specific locations utilizing the localizer image for positional reference.

A failure of this test means that the actual locations of acquired slices differ from their prescribed locations by substantially more than is normal for a well-functioning scanner.

4.2 What Measurements Are Made

For this test the differences between the prescribed and actual positions of slices 1 and 11 are measured. These measurements are made for the ACR T1 and T2 series.

Recall from the introduction that slices 1 and 11 are prescribed so as to be aligned with the vertices of the crossed 45° wedges at the inferior and superior ends of the phantom respectively (Figure 1). On slices 1 and 11 the crossed wedges appear as a pair of adjacent, dark, vertical bars at the top (anterior side) of the phantom. Figure 13 shows slices 1 and 11 with the vertical bars of the crossed wedges indicated.

For both slice 1 and slice 11, if the slice is exactly aligned with the vertex of the crossed wedges, then the wedges will appear as dark bars of equal length on the image. By design of the wedges, if the slice is displaced superiorly with respect to the vertex, the bar on the observer's right (anatomical left) will be longer (Figure 14a). If the slice is displaced inferiorly with respect to the vertex, the bar on the left will be longer (Figure 14b).

Measurements are made for slices 1 and 11 of the ACR T1 and ACR T2 series. Use the following procedure for each image:

1 Display the slice. Magnify the image by a factor of 2 to 4, keeping the vertical bars of the crossed wedges within the displayed portion of the magnified image.

2 Adjust the display window so the ends of the vertical bars are well defined—not fuzzy. This will mean using a fairly narrow display window. The display level setting is not critical, but should be set to a level roughly half that of the signal in the bright, all-water portions of the phantom.

3 Use the on-screen length measurement tool to measure the difference in length between the left and right bars. The length to measure is indicated by the arrows in Figure 14.

If the left bar is longer, then assign a minus sign to the length. For example, if the bar length difference is 5.0 mm and the left bar is longer, then record the measurement as –5.0 mm.

In total there are 4 length measurements.

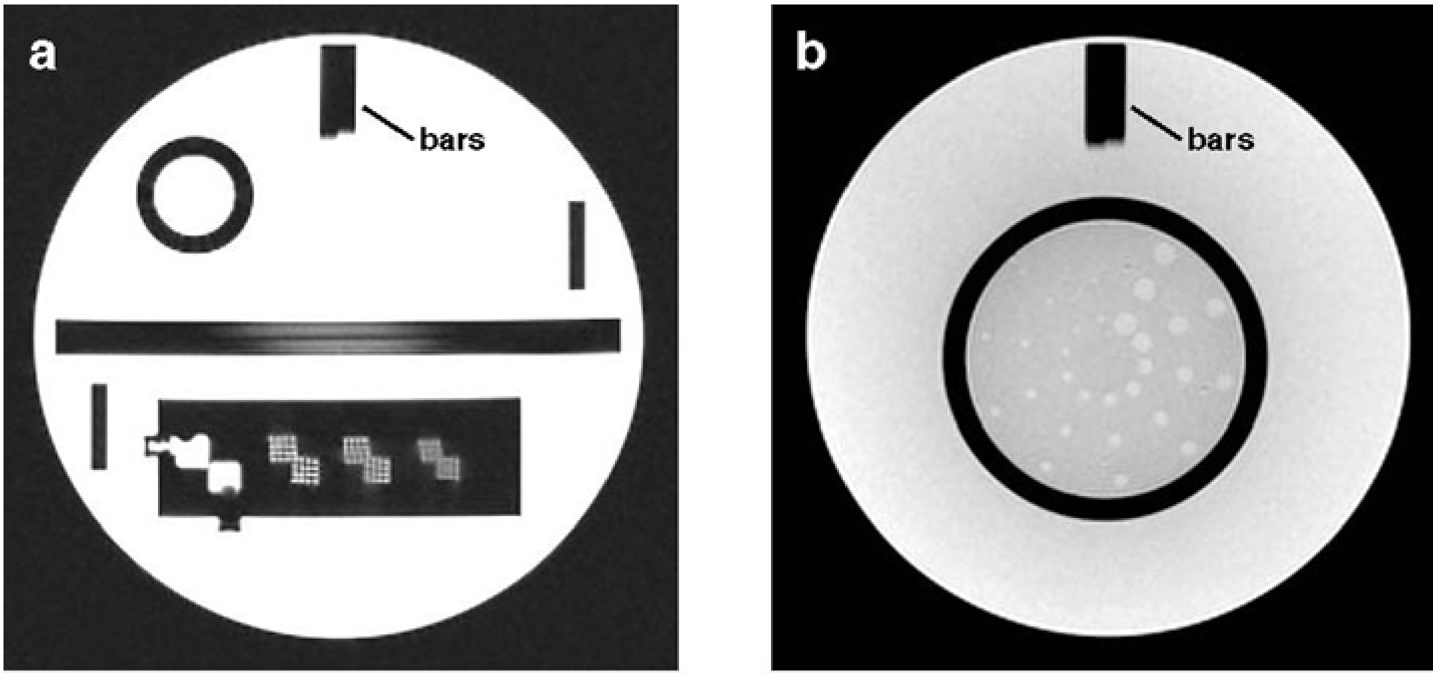

Figure 13: Images of slice 1 (a) and slice 11 (b) with the pairs of vertical bars from the 45° crossed wedges indicated. On these images the length difference between the right and left bars is small and typical of well-positioned slices.

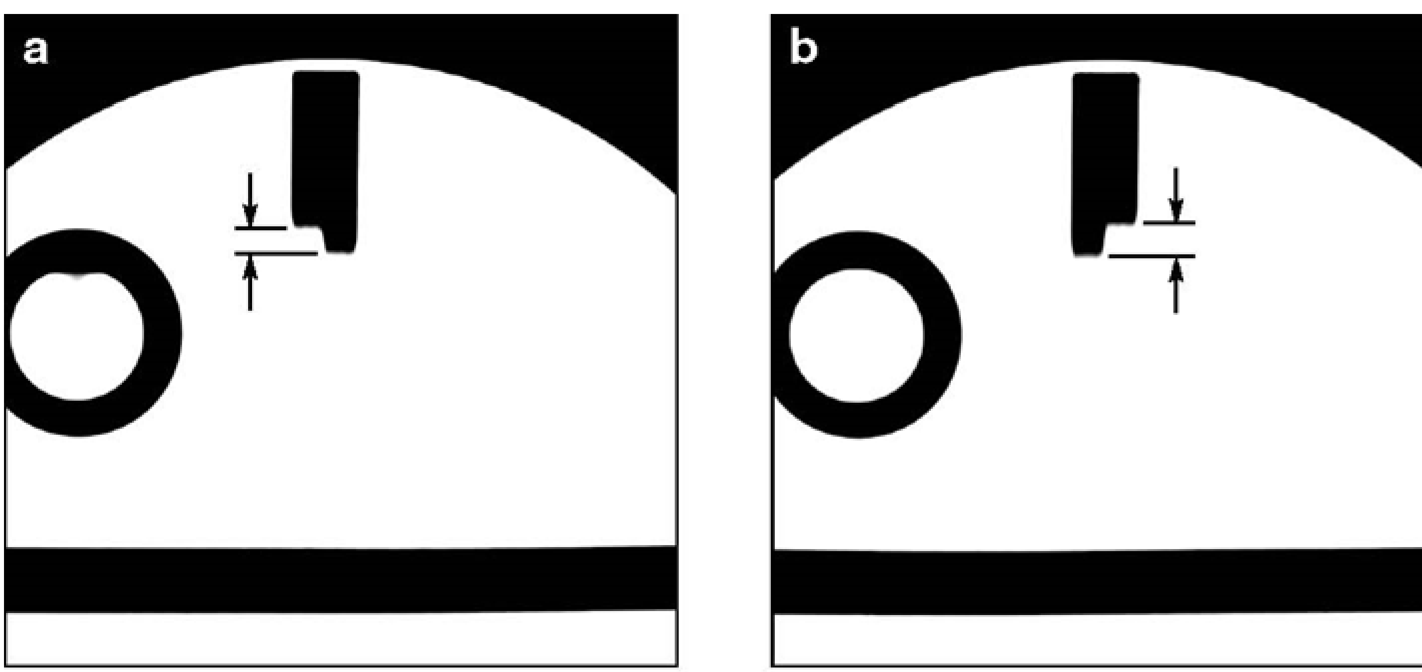

Figure 14: Images of slice 1 illustrating measurement of slice position error. The arrows indicate the bar length difference measurement that is to be made.

(a) The bar on the right is longer, meaning the slice is mispositioned superiorly; this bar length difference is assigned a positive value.
(b) The bar on the left is longer, meaning the slice is mispositioned inferiorly; this bar length difference is assigned a negative value.

4.3 How the Measurements Are Analyzed

This test requires no analysis of the measurements. The action criteria are specified in terms of limits on the bar length difference measurements.

However, because the crossed wedges have 45° slopes, the bar length difference is twice the actual slice displacement error. For example a bar length difference of –5.0 mm implies the slice is displaced inferiorly by 2.5 mm from the vertex of the crossed wedges.

4.4 Recommended Action Criteria

The absolute bar length difference should be 5 mm or less, but up to 7 mm is acceptable.

As explained in section 7.5, a bar length difference of more than 4 mm for slice 11 will adversely affect the low-contrast object detectability score. So, although 5 mm is acceptable for this test, it is advisable to keep the bar length difference to 4 mm or less.

4.5 Causes of Failure and Corrective Actions

An error by the scanner operator in the prescription of the slice locations can cause a failure. This is probably the most common cause of failure of this test. This type of error will be evident when the axial images are cross-referenced on the localizer: slices 1 and 11 will not be aligned with the crossed-wedge vertices on the localizer image. Other causes of failure do not show up as slice position error on the cross-referenced images. It is important to prescribe the slices as carefully as possible since errors introduced here can add to other sources of error and push an acceptable level of performance to an unacceptable level.

Many scanners shift the patient table position in the inferior-superior direction to place the center of a prescribed stack of images at gradient isocenter. This table shift occurs after the localizer is made, and thus error in the table positioning mechanism leads to slice position error. If the bar length difference for slices 1 and slice 11 are the same in sign and similar in magnitude, this type of table positioning error may be the cause.

A particularly bad gradient calibration or poor B_0 homogeneity can cause failure of this test. In this case the problem also will usually be apparent as a failure or near failure of the geometric accuracy test.

Sometimes a failure of this test is an unfortunate combination of two or three of the problems just mentioned— inaccurate slice prescription, error in the table positioning mechanism, and poor gradient calibration or B_0 homogeneity—with none of the problems in itself being sufficiently bad to cause a failure on its own. Therefore, if no one thing seems to be responsible for causing a failure of this test, try having the service engineer shim B_0, recalibrate the gradients, and check the table positioning mechanism for excessive play. Then acquire a new image data set prescribing the slices as carefully as possible.

5.0 IMAGE INTENSITY UNIFORMITY

5.1 What It Is

The image intensity uniformity test measures the uniformity of the image intensity over a large water-only region of the phantom lying near the middle of the imaged volume and thus near the middle of the head coil.

Head coils for clinical use have fairly uniform spatial sensitivity near the middle of the coil when loaded as typical for a human head. Failure of this test means that the scanner has significantly greater variation in image intensity than is normal for a properly functioning system. Lack of image intensity uniformity indicates a deficiency in the scanner, often a defective head coil or problem in the radio-frequency subsystems.

5.2 What Measurements Are Made

For this test the high- and low-signal levels within a large, physically uniform, water-only region of the phantom are measured. This is done for the ACR T1 and T2 series.

For each of the 2 series, the measurements are made according to the following procedure:

1. Display slice location 7.
2. Place a large, circular region-of-interest (ROI) on the image as shown in Figure 15. This ROI should have an area of between 195 cm^2 and 205 cm^2 (19,500 to 20,500 mm^2). This ROI defines the boundary of the region in which the image uniformity is measured. Although the mean pixel intensity inside this ROI is not needed for the uniformity test, it is used in the percent signal ghosting test (section 6.0), so it should be noted.

   Set the display window to its minimum, and lower the level until the entire area inside the large ROI is white. The goal now is to raise the level slowly until a small, roughly 1 cm^2 region of dark pixels develops inside the ROI. This is the region of lowest signal in the large ROI.
   Sometimes more than one region of dark pixels will appear. In that case, focus attention on the largest dark region.
   It can happen that rather than having a well-defined dark region, one ends up with one or more wide, poorly defined dark areas or areas of mixed black and white pixels. In that case, make a visual estimate of the location of the darkest 1 cm^2 portion of the largest dark area.
3. Place a 1 cm^2 circular ROI on the low-signal region identified in step 3. Figure 16a shows what a typical image looks like at this point.
   Record the mean pixel value for this 1 cm^2 ROI. This is the measured low-signal value.
   If there is uncertainty about where to place the ROI because there is no single obviously darkest location, try several locations and select the one having the lowest mean pixel value.
4. Raise the level until all but a small, roughly 1 cm^2 region of white pixels remains inside the large ROI. This is the region of highest signal.

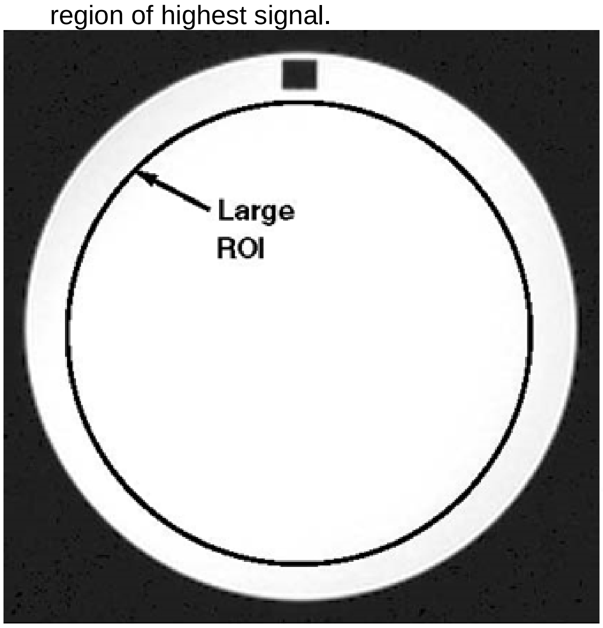

Figure 15: Image of slice 7 illustrating size and placement of the large, 200 cm^2 ROI that defines the boundary inside which image uniformity measurements are made.

Sometimes more than 1 region of white pixels will remain. In that case, focus attention on the largest white region.
It can happen that rather than having a well-defined white region, one ends up with 1 or more diffuse areas of mixed black and white pixels. In that case, make a best estimate of the location of the brightest 1 cm^2 portion of the largest bright area.

5. Place a 1 cm^2 circular ROI on the high-signal region identified in step 5. Figure 16b shows what a typical image looks like at this point.
   Record the average pixel value for this 1 cm^2 ROI. This is the measured high-signal value.
   If there is uncertainty about where to place the ROI because there is no single obviously brightest location, try several locations and select the one having the highest mean pixel value.

NOTE: Some display workstations have ROI tools that report the maximum and minimum pixel values within an ROI. It is tempting to use these as high and low signal values. However, we advise against it. Due to the presence of noise in the image, using the maximum and minimum pixel values introduces systematic overestimation of the high signal and underestimation of the low signal. This systematic error can be significant, and biases the test toward failure.

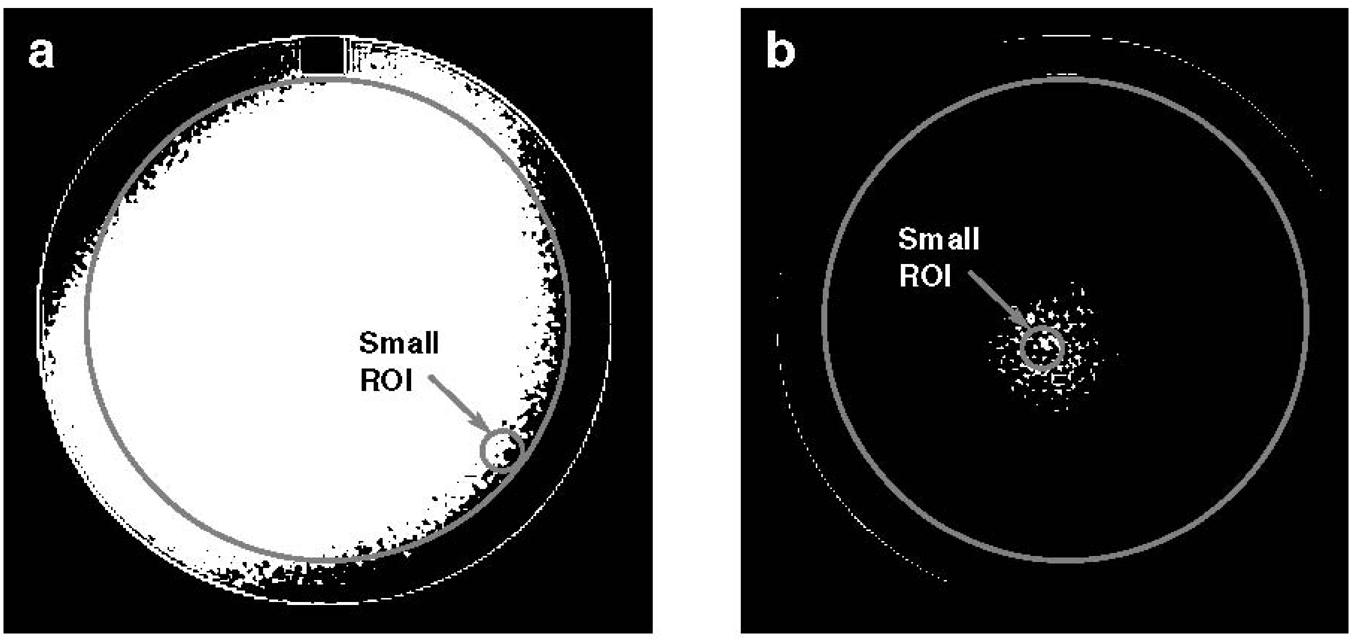

Figure 16: Image of slice 7 showing windowing of the image and placement of small, 1 cm^2 ROIs for image uniformity measurements.

5.3 How the Measurements Are Analyzed

The measured high- and low-signal values for each of the ACR series are combined to produce a value called percent integral uniformity (PIU). Use the following formula to calculate PIU:

PIU = 100 x (1 – { (high – low)/(high + low) }).

In this formula high is the measured high-signal value and low the measured low-signal value.

(a) Example of windowing and ROI placement for measurement of the low-signal value. In this case the proper location for placement of the small ROI is not entirely clear. The guidance given in step 3 above has been followed. The ROI has been placed at what is visually estimated to be the largest 1 cm^2 dark area within the large ROI.
(b) Example of windowing and ROI placement for measurement of the high-signal value. Following the guidance in step 5 above, the ROI has been placed at what is visually estimated to be the largest 1 cm^2 bright area inside the large ROI.

5.4 Recommended Action Criteria

For MRI systems with field strengths less than 3 Tesla, PIU should be greater than or equal to 87.5% and will fail if less than 85%. PIU for 3T systems should be greater than or equal to 82.0% and will fail if PIU is less than 80%.

5.5 Causes of Failure and Corrective Actions

When scanning the phantom it is important to center it in the head coil. If the phantom is closer to one side of the head coil than another, one can expect uneven image intensities and potentially a failure of this test. This problem occurs most often with poor centering in the anterior-posterior (AP) direction. It may be necessary to remove some of the normal patient head support or add some cushioning, or both, to get the phantom centered AP. Poor centering may be evident in the images. Another indicator that centering may be a problem is the appearance of bright spots in the image where the phantom is too close to the coil's conducting elements. If the scanner seems to be working well, and making ghost-free head images with the usual amount of signal-to-noise ratio, poor phantom-centering may be the cause of failure.

Image ghosting can cause image intensity variations and hence failure of this test. Ghosting sufficient to cause failure of this test will be readily apparent in the image, and likely will cause failure of another test such as percent-signal ghosting (section 6.0). Ghosting is a very nonspecific symptom of a hardware problem. In general, it is caused by instability of the measured signal from pulse cycle to pulse cycle, which can have its origin in the receiver, transmitter, or gradient subsystems. Motion of the phantom can also cause ghosting. Make sure the phantom is stable in the head coil and not free to move or vibrate. Having ruled out phantom motion, it will usually be necessary to ask the service engineer to track down and correct the cause of ghosting.

Phased array head coils naturally produce images that are less uniform due to the smaller coil elements as compared to quadrature coils. Be sure to apply the vendor's intensity correction to the ACR T1 and T2 series if they were acquired using a multi-channel phased array coil. The correction goes by different names depending on vendor (SCIC, PURE, CLEAR, Normalize, and Pre-scan normalize are some examples).

Degraded image intensity uniformity can result from failure of components in the head coil, and from failure of the mechanisms for inductive decoupling of the body coil from the head coil. In these cases the images usually become noticeably lower in signal-to-noise ratio, i.e., they usually appear more grainy. A service engineer is required to diagnose and correct these problems.

6.0 PERCENT-SIGNAL GHOSTING

6.1 What It Is

The percent-signal ghosting test assesses the level of ghosting in the images. Ghosting is an artifact in which a faint copy (ghost) of the imaged object appears superimposed on the image, displaced from its true location. If there are many low-level ghosts they may not be recognizable as copies of the object but simply appear as a smear of signal emanating in the phase encode direction from the brighter regions of the true image. Ghosting is a consequence of signal instability between pulse cycle repetitions. For this test the ghost signal level is measured and reported as a percentage of the signal level in the true (primary) image.

Ghosts are most noticeable in the background areas of an image where there should be no signal, but usually they overlay the main portions of the image as well, altering the true image intensities. A failure of this test means that there is signal ghosting at a level significantly higher than that observed in a properly functioning scanner.

6.2 What Measurements Are Made

For this test, measurements are made on slice 7 of the ACR T1 series. Using the workstation's ROI tool, 5 intensity measurements are made: the average intensity in the primary image of the phantom, and the average intensity in the background at 4 locations outside of the phantom. The ROIs are placed as shown in Figure 17.

The phase encode shadow of an object in an image is the area of the image that is swept out by translating the object along the phase encode direction. Ghosts of an object can only fall in its phase encode shadow. Since the background ROIs are placed along the 4 edges of the field-of-view, 2 will be in the phantom's phase encode shadow and 2 will not. So, 2 of the background ROIs will sample the ghost signal and 2 will be free of ghost signal. It is necessary to have the 2 ghost-free background ROIs to serve as a control on the mean background intensity, which can be affected by several factors, most notably noise.

The procedure for making these measurements is:

1. Display slice 7 of the ACR T1 series.
2. Place a large, circular ROI on the image as shown in Figure 17. This ROI should have an area of between 195 cm^2 and 205 cm^2 (19,500 to 20,500 mm^2). The ROI should be approximately centered on the phantom, but should not include any of the small dark square that appears at the top of the phantom on this slice.

   Record the mean pixel value for this ROI.

   If the workstation cannot produce a circular ROI, a square ROI may be used. The area of the square ROI should be between 130 cm^2 and 140 cm^2 (13,000 to 14,000 mm^2).

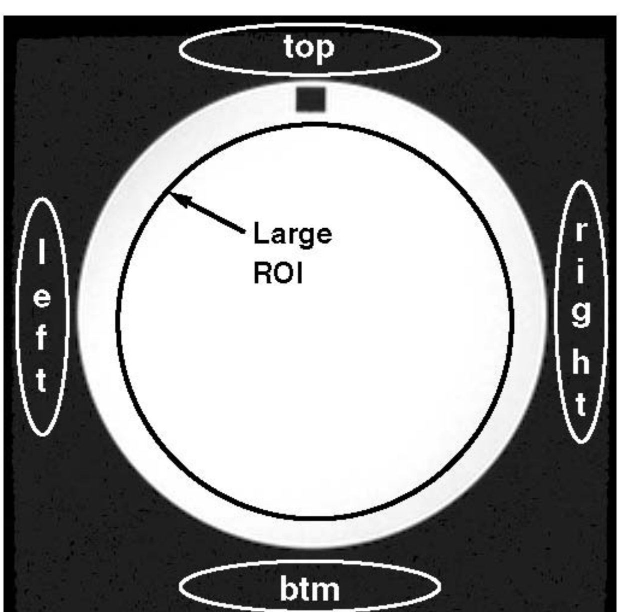

Figure 17: Image of slice 7 illustrating ROI placement for percent-signal ghosting measurements.

3. Place elliptical or rectangular ROIs along, but not immediately against, the 4 edges of the field of view, as shown in Figure 17.

   The ROIs should have a length-to-width ratio of about 4:1, and a total area of about 10 cm^2 (1000 mm^2). We will refer to these ROIs as they are labeled in Figure 17: top, bottom, left, and right.

   Record the mean pixel value for each ROI, keeping track of which value goes with which ROI.

   It is important not to place the background ROIs against the edges of the phantom or against the edges of the field of view (FOV), but centered between the edges of the phantom and FOV. If the phantom is off center in the FOV, it may be necessary to reduce the width of some of the ROIs in order to fit them between the phantom and the edge of the FOV. Reduce the ROI width as necessary to fit, and increase the length to maintain an approximately 10 cm^2 area; the top and right ROIs in Figure 17 are examples of this.

   If the workstation cannot produce an elliptical ROI, a rectangular ROI of approximately the same size may be used.

6.3 How the Measurements Are Analyzed

The value for the ghosting, as a fraction of the primary signal, is calculated using the following formula:

$$\text{ghosting ratio} = \left| \left((\text{top} + \text{btm}) - (\text{left} + \text{right}) \right) / \left(2 \times (\text{large ROI}) \right) \right|$$

where top, bottom, left, right, and large ROI are the average pixel values for the ROIs of the same names. The vertical bars enclosing the right-hand side of the equation mean to take the magnitude of the enclosed value.

6.4 Recommended Action Criteria

The ghosting ratio must be less than or equal to 0.025 (2.5%). Images submitted for accreditation will fail if the ratio exceeds 0.030 (3.0%).

6.5 Causes of Failure and Corrective Actions

Ghosting can be caused by motion or vibration of the phantom during the acquisition. Make sure the phantom is securely positioned in the head coil and not free to move.

Ghosting is a nonspecific symptom of a hardware problem. In general, it is caused by instability of the measured signal from pulse cycle to pulse cycle, which can have its origin in the receiver, transmitter, or gradient subsystems. Having ruled out phantom motion, it will usually be necessary to ask the service engineer to track down and correct the cause of ghosting.

Scanners with non-digital receivers (mostly scanners designed before 1990) are prone to a kind of ghost called quadrature receiver imbalance ghost, or receive quadrature ghost. This type of ghost is not caused by instability of the measured signal from pulse cycle to pulse cycle, but by imbalance of the quadrature channels of the analog receiver. This ghost is usually easy to distinguish from other types of ghosting because there will only be one ghost and it will be a reflection of the primary image through the origin. For example, the receive quadrature ghost of an object in the lower left corner of the image will appear in the upper right corner at an equal distance from the image center. Receive quadrature ghosting is corrected by balancing the receiver's quadrature channels, which can be done by the service engineer.

7.0 LOW-CONTRAST OBJECT DETECTABILITY

7.1 What It Is

The low-contrast object detectability test assesses the extent to which objects of low contrast are discernible in the images. For this purpose the phantom has a set of low-contrast objects of varying size and contrast.

The ability to detect low-contrast objects is primarily determined by the contrast-to-noise ratio achieved in the image, and may be degraded by the presence of artifacts such as ghosting.

Scanners at different field strengths differ widely in their contrast-to-noise ratio performance, and clinical protocols are typically adjusted to take these differences into account. Therefore, in addition to the ACR series, this low-contrast object detectability test is applied to the site series. Most scanners can pass the test on the ACR series, but it is sufficient for a scanner to pass on both site series.

A failure of this test means the images produced by the scanner show significantly fewer low-contrast objects than most properly functioning clinical scanners. Further, this deficiency holds even when the site's own clinical protocol is employed.

7.2 What Measurements Are Made

Measurements are made for the ACR and the site's series. The low-contrast objects appear on 4 slices: slices 8 through 11. In each slice the low-contrast objects appear as rows of small disks, with the rows radiating from the center of a circle like spokes in a wheel. Each spoke is made up of 3 disks, and there are 10 spokes in each circle. Figure 18 shows slice 11 with the circle of 10 spokes indicated.

All the disks on a given slice have the same level of contrast. In order, from slice 8 to slice 11, the contrast values are 1.4%, 2.5%, 3.6%, and 5.1%. All the disks in a given spoke have the same diameter. Starting at the 12 o'clock position and moving clockwise, the disk diameter decreases progressively from 7.0 mm at the first spoke to
1.5 mm at the tenth spoke.

The low-contrast disks are actually holes drilled in thin sheets of plastic mounted in the phantom at the locations of the 4 slices. Since the contrast is derived from the displacement of solution from the slices by the plastic sheets, the contrast is independent of pulse sequence, TR, flip angle, and field strength.
The measurements for this test consist of counting the number of complete spokes seen in each of the 4 slices. This is done for each of the 4 axial series.

Use the following procedure to score the number of complete spokes seen in a slice:

1. Display the slice to be scored. It helps to start with slice 11, which has the highest contrast objects.
2. Adjust the display window width and level settings for best visibility of the low-contrast objects. This will usually require a fairly narrow window width and careful adjustment of the level to best distinguish the objects from the background.
3. The task now is to count the number of complete spokes. Begin counting with the spoke having the largest diameter disks; this spoke is at 12 o'clock or slightly to the right of 12 o'clock, and is referred to as spoke 1. Count clockwise from spoke 1 until a spoke is reached where 1 or more of the disks is not discernible from the background.

The number of complete spokes counted is the score for this slice. Record the score.

A spoke is complete only if all 3 of its disks are discernible. Count complete spokes, not individual disks.

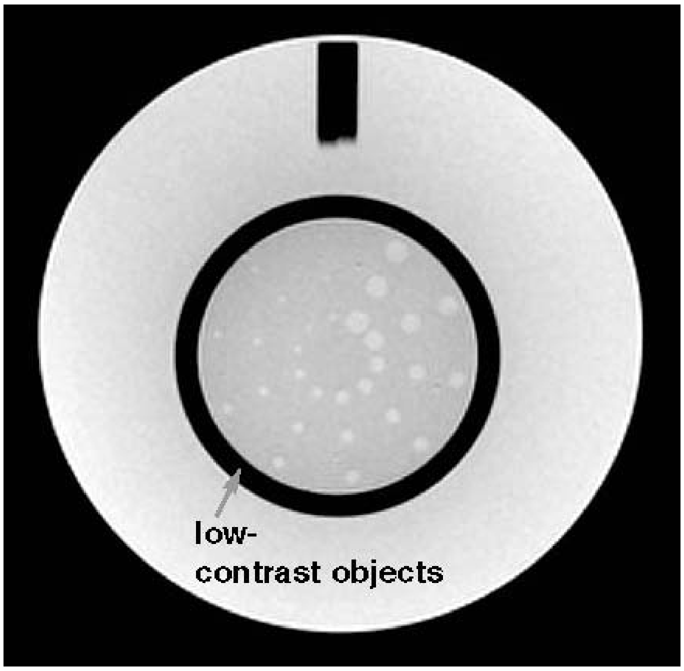

Figure 18: Image of slice 11 showing the circle of low-contrast objects for the low-contrast object detectability test.

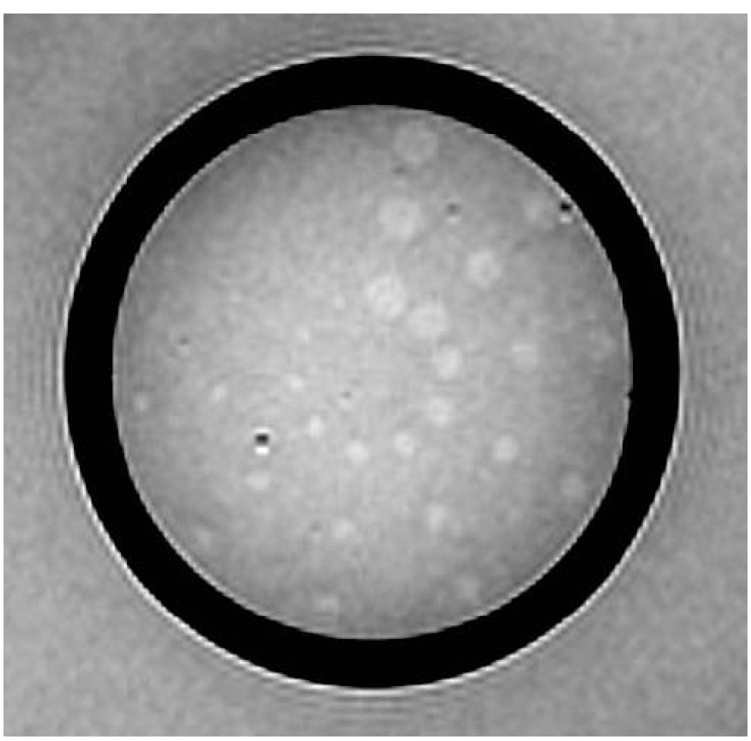

Figure 19: Image of slice 8, magnified and cropped, showing the circle of low-contrast objects. This image would be scored as showing 9 spokes.

As an example, Figure 19 shows an image of slice 8 on which less than all 10 spokes are complete. The score for this image is 9 complete spokes.

Sometimes there will be a complete spoke of smaller size following a spoke that is not complete. Do not count it. Stop counting at the first incomplete spoke.

Disks on the threshold of discernibility can present a difficult scoring decision. They may appear ragged or misshapen; that is OK. The question is whether or not there is some sort of smudge or spot at the known location of the disk which is different enough from the background that one can say with a reasonable degree of confidence that there is something really there. In making this decision it can be helpful to look at areas where there are no disks in order to gauge the fluctuations in intensity from noise and artifacts that might mimic a barely discernible disk. A disk that looks no different than the brighter background noise fluctuations would not be deemed discernible.

Most scanners greatly exceed the minimum passing score given in the action criteria section below. In most cases it isn't necessary to spend time pondering difficult decisions on barely visible disks; just score the test conservatively and revisit the scoring in the unlikely event the final score is below passing.

7.3 How the Measurements Are Analyzed

For each series, sum the number of complete spokes scored on each slice.

For example, if the ACR T2 series scored 3 spokes in slice 8, 5 spokes in slice 9, 9 spokes in slice 10, and 10 spokes in slice 11; the total score for the ACR T2 series would be 3 + 5 + 9 + 10 = 27.

7.4 Recommended Action Criteria

For scanners with field strength of less than 3T, both ACR series should have a total score of 9 spokes, but must have at least 7 to pass. If either ACR series fails this test, then evaluate the site series. If the LCD score for both site series is at least 7, then the scanner passes this test.

For 3T scanners, both ACR series must have a total score of 37 spokes to pass. If the score for either ACR series fails, then evaluate the site series. If the score for the site series is at least 37, then the scanner passes this test.
A scanner can pass on either the ACR T1 and T2 series or on the site T1 and T2 series. A scanner cannot pass on just one of the ACR series and one of the site's series.

7.5 Causes of Failure and Corrective Actions

The most frequent cause of failure is incorrectly positioned slices. Slices 8 through 11 must fall close to their proper locations within the phantom in order for the thin plastic sheets that create the low-contrast objects to do their job. If a slice is mispositioned by more than 2 mm there will be substantial reduction in the contrast of the low-contrast objects in that slice. The easiest way to check if this is a problem is to look at slice 11. Recall from section 4.0 (Slice Position Accuracy) that the bar length difference of the crossed 45° wedges on slice 11 is twice the slice position error. So, make sure the bar length difference is less than 4.0 mm on slice 11. If it is not, reacquire the images with adjustments to the slice prescription as needed to bring the crossed-wedge bar length difference in slice 11 to less than 4.0 mm.

Failure of this test can be caused by the phantom being tilted. A tilted phantom leads to parts of the slices being out of their proper location, and therefore to the same sort of problem as just described for incorrectly positioned slices. In this regard tilt (rotation) about the inferior-superior axis of the phantom is not a problem, but tilt about the other 2 axes can be. Tilt about the right-left axis will be readily apparent on the localizer. If the phantom doesn't look square with the edges of the field of view on the localizer, it should be repositioned before continuing to acquire data. The nonmagnetic bubble level that accompanies the phantom can be used to level the phantom in the head coil to avoid this kind of tilt. Tilt about the anterior-posterior axis is harder to see on the images. It can often be detected as right-to-left fade of structures that should be uniformly partial-volumed across an axial slice. The best way to avoid this kind of tilt is to carefully align the phantom squarely in the head coil. The alignment lights may be helpful for this, but they themselves are often poorly aligned.

Some scanners do not allow specification of 5 mm slices with 5 mm gaps. In such cases it is not possible to acquire all of the required slice locations in a single acquisition. The Site Scanning Instructions included with the accreditation materials give guidance on allowable alternative acquisitions. Sites that cannot specify 5 mm slices with 5 mm gaps must be especially alert to the potential for mis-positioned slices adversely affecting the low-contrast object detectability test.

Ghosting artifacts can affect the ability to see low-contrast objects and cause a failure of the test. If ghosting is the cause of failure, it should be apparent on inspection of the images. Make sure the phantom is stable and can't move or vibrate during image acquisition. If ghosting is still a problem, then the service engineer should be asked to find and correct the cause. On some scanners, a small but noticeable amount of ghosting is normal on conventional T2 spin-echo acquisitions and fast spin-echo acquisitions. If in doubt whether the ghosting seen is normal, ask the service engineer to perform the manufacturer's diagnostic tests that relate to signal stability and ghosting.

If the images are free of ghosts, and the slices are positioned accurately, then a failure of this test is most likely due to inadequate signal-to-noise ratio (SNR) in the image. Ask the service engineer to check that the scanner's SNR performance is within manufacturer specifications.

8.0 ADVICE AND RECOMMENDATIONS

Make sure the service engineer has a few weeks of warning to check the system and make everything right before acquiring images for accreditation.

The scanner hardware should be powered up for at least an hour before acquiring data for accreditation. This advice is primarily aimed at sites that power off their scanners overnight.

Position the phantom near the center of the head coil. This may not be where the patient head normally rests. Line up the center mark etched on the phantom with the center of the coil along the inferior-superior direction. Also make sure the phantom is centered in the coil right-left and anterior-posterior. This helps with image uniformity.

Use cushions and padding as necessary to stabilize the phantom against motion to avoid ghosting artifacts.

As explained in section 7.5, it is important to make sure that slices 8 through 11 lie as close as possible to their proper locations in the phantom, and that the phantom is closely aligned with the principal axes, not tilted.

Be sure when making measurements for the ACR T2 series to evaluate the second echo images. Because of the way slices are numbered on many scanners, it is easy to mistakenly make the measurements on the first echo images.

A small bubble of a few cubic centimeters cm_3 is deliberately left in the phantom by the manufacturer to allow for thermal expansion of the solution. Avoid shaking the phantom as it causes the bubble to break up into smaller bubbles which may adhere to structures within the phantom where they may interfere with scoring the tests.