Designation: E 1695 – 95

An American National Standard

Standard Test Method for
Measurement of Computed Tomography (CT) System Performance[1]

This standard is issued under the fixed designation E 1695; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method provides instruction for determining the spatial resolution and contrast sensitivity in X-ray and γ-ray computed tomography (CT) images. The determination is based on examination of the CT image of a uniform disk of material. The spatial resolution measurement is derived from an image analysis of the sharpness at the edge of the disk. The contrast sensitivity measurement is derived from an image analysis of the statistical noise at the center of the disk.

1.2 This test method is more quantitative and less susceptible to interpretation than alternative approaches because the required disk is easy to fabricate and the analysis is immune to cupping artifacts. This test method may not yield meaningful results if the disk image occupies less than a significant fraction of the field of view.

1.3 This test method may also be used to evaluate other performance parameters. Among those characteristics of a CT system that are detectable with this test method are: the mid-frequency enhancement of the reconstruction kernel, the presence (or absence) of detector crosstalk, the undersampling of views, and the clipping of unphysical (that is, negative) CT numbers (see Air Force Technical Report WL-TR-94-4021[2]). It is highly likely that other characteristics as well can be detected with this test method.

1.4 The values stated in SI units are to be regarded as the standard. Inch-pound units are provided for information only.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*
E 1316 Terminology for Nondestructive Examinations[3]
E 1441 Guide for Computed Tomography (CT) Imaging[3]

E 1570 Practice for Computed Tomographic (CT) Examination[3]

3. Terminology

3.1 *Definitions*—The definitions of terms relating to Gamma- and X-Radiology, which appear in Terminology E 1316 and Guide E 1441, shall apply to the terms used in this test method.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *phantom*—a part or item being used to quantify CT system performance.

3.2.2 *test object*—a part or specimen being subjected to CT examination.

3.3 Acronyms:

3.3.1 *ERF*—edge response function.

3.3.2 *PSF*—point spread function.

3.3.3 *MTF*—modulation transfer function.

3.3.4 *CDF*—contrast discrimination function.

4. Significance and Use

4.1 Two factors affecting the quality of a CT image are geometrical unsharpness and random noise. Geometrical unsharpness limits the spatial resolution of a CT system, that is, its ability to image fine structural detail in an object. Random noise limits the contrast sensitivity of a CT system, that is, its ability to detect the presence or absence of features in an object. Spatial resolution and contrast sensitivity may be measured in various ways. ASTM specifies spatial resolution be quantified in terms of the modulation transfer function (MTF) and contrast sensitivity be quantified in terms of the contrast discrimination function (CDF) (see Guide E 1441 and Practice E 1570). This test method allows the purchaser or the provider of CT systems or services, or both, to measure and specify spatial resolution and contrast sensitivity.

5. Apparatus

5.1 *Disk Phantom*—The disk phantom shall be a right cylinder of uniform material conforming to the design and material requirements in Table 1 and Fig. 1. Since spatial resolution and contrast sensitivity depend on the examination task (that is, the test object and the specified CT parameters), the application requirements must be fixed before the phantom can be designed. In general, each examination task will require

TABLE 1 Disk Phantom Design Requirements

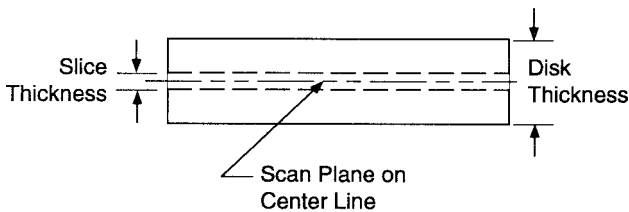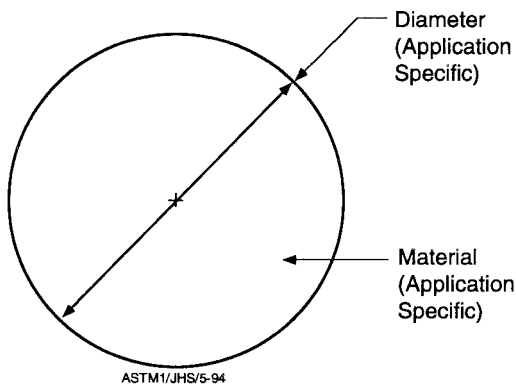|	
Material	The material, in conjunction with the diameter of the disk, shall be such that the phantom approximates the attenuation range of the test object. The material should preferably be the same as that of the test object.
Diameter	The diameter shall be such that the reconstruction of the disk occupies a significant fraction of the resulting image. In conjunction with the material, the diameter shall be such that the phantom approximates the attenuation range of the test object.
Thickness	The thickness of the disk shall be greater than the slice thickness used to inspect the test object.
Shape	The perpendicularity of the axis of revolution with respect to the surface used to mount the phantom on the CT system shall not compromise the measurement of geometrical unsharpness.
Finish	The surface texture roughness of the curved surface shall not compromise the measurement of geometrical unsharpness.

FIG. 1 Disk Phantom

a separate phantom. The diameter of the disk relative to the field of view shall be such that the reconstructed image of the disk occupies a significant fraction of the image matrix. Recommended sizes are given in Table 2. The diameter and opacity of the disk shall be such that the phantom approximates the attenuation range of the test object. If possible, the phantom should be of the same material as the test object, but the other

requirements take precedence and may dictate the selection of another material. The design of the disk phantom is a matter of agreement between the purchaser and the supplier.

6. Procedure

6.1 The phantom shall be mounted on the CT system with the orientation of the axis of revolution of the disk normal to the scan plane. The alignment shall not compromise the measurement of geometrical unsharpness. Unless otherwise agreed upon between purchaser and supplier, the phantom shall be placed at the center of the field of view used for the test object.

6.2 Unless otherwise agreed upon between purchaser and supplier, the data acquisition parameters shall be identical to those used for test object scans. The slice plane shall intercept the phantom approximately midway between the flat faces of the disk.

6.3 Unless otherwise agreed upon between purchaser and supplier, the reconstruction parameters shall be identical to those used for test object reconstructions.

6.4 Unless otherwise agreed upon between purchaser and supplier, the display parameters shall be identical to those used for test object display. It shall be verified by examination that the disk image occupies an image at least two-thirds of the image matrix. Recommended guidelines are given in Table 2.

7. Interpretation of Results

7.1 *Spatial Resolution*—From the CT image data, generate the composite profile of the edge of the disk to obtain the edge response function (ERF). Calculate the derivative of the ERF to obtain the point spread function (PSF). Calculate the amplitude of the Fourier Transform[4] of the PSF and normalize the results to unity at zero frequency to obtain the modulation transfer function (MTF).

7.1.1 Unless otherwise agreed upon between the purchaser and supplier, the ERF shall be generated as follows:

7.1.1.1 Calculate the center of mass of the disk.

7.1.1.2 Select the inner and outer radii with respect to the center of mass that comfortably bracket the edge.

TABLE 2 Suggested Measurement Parameters

Image Matrix Size (Pixels)	Disk Image Diameter (Pixels)	Maximum Tile Size (Pixels)	ERF Bin Size (Pixels)	Number of Fit Points
256	235	12	0.100	11
512	470	24	0.050	21
1024	940	48	0.025	41

[4] The Fourier Transform and Its Applications, Ronald M. Bracewell, McGraw-Hill, NY, ISBN 0-07-007013-X.

7.1.1.3 Compute the distance to the center of mass for all pixels between the inner and outer radii.

7.1.1.4 Generate a table of pixel values in order of their pixel distance from the center of mass.

7.1.1.5 Segregate the values into equal bins sized to a small fraction of one pixel. The bin size should be as small as practical without causing some bins to be empty. Recommended sizes are given in Table 2.

7.1.1.6 Average the members of each bin to obtain a table of values at constant increments from the inner to outer radius.

7.1.1.7 Starting at one end of the table and iterating until the entire table has been processed, smooth the pixel values by performing a piece-wise, least-squares cubic fit to an odd number of table values and replacing the center value with that predicted by the fit. The number of values to include in the fit should be large compared to the order of the polynomial and small compared to the fine ERF structure. Recommended guidelines for the number of values to use in the fit are given in Table 2.

7.1.1.8 Determine how much of the table to include in the analysis and delete the unwanted portions of the leading and trailing tails to obtain the ERF.

7.1.2 Unless otherwise agreed upon between the purchaser and supplier, the PSF shall be generated as follows:

7.1.2.1 Starting at one end of the table and iterating until the entire table has been processed, perform a piece-wise, least-squares cubic fit to the ERF using for the fit the same number of values as were used to smooth the data (see 7.1.1).

7.1.2.2 For each fit, calculate the analytical derivative of the resultant polynomial and determine its numerical value at the center of the piece-wise window.

7.1.2.3 Generate a table of derivative values as a function of distance from the center of the disk.

7.1.2.4 Normalize the peak value of the resulting curve to unity to obtain the PSF.

7.1.3 Unless otherwise agreed upon between the purchaser and supplier, the MTF shall be generated as follows:

7.1.3.1 Calculate the Fourier Transform[4] of the PSF. The maximum frequency of the resultant transform should be at least four times the cut-off frequency of the matrix, which by definition is 0.5 line-pairs per pixel. The sampling frequency in the Fourier domain should be small enough that the transform is smooth within the frequency range of interest. A sampling frequency of 0.01, or smaller, is recommended.

7.1.3.2 Calculate the magnitude of the transform by taking the square root of the product of the transform and its conjugate.

7.1.3.3 Normalize the magnitude at zero frequency to unity to obtain the MTF.

7.1.4 Unless otherwise agreed upon between the purchaser and supplier, the MTF shall be visually displayed or plotted, or both, and the frequency at 10 % modulation quantitatively indicated. Although not mandatory, the ERF and the PSF should also be graphically presented, with the full width at half maximum of the latter quantitatively indicated.

7.2 *Contrast Sensitivity*—From the CT image data, generate a sequence of tile patterns which fit within the central region of the disk. For each pattern, calculate the mean CT value within each tile and store the result in a table specific to that pattern. For each table of results, calculate the standard deviation to obtain the standard error in the mean and store the result in a separate table in order of ascending tile size. Express each standard error in the mean as a percent of its respective ensemble average and multiply by a factor of 3 to obtain the contrast discrimination function (CDF).

7.2.1 Unless otherwise agreed upon between the purchaser and supplier, the sequence of tile patterns shall be generated as follows:

7.2.1.1 Select a circular region of interest at the center of the disk. The diameter of the region should be large enough to encompass a statistically significant number of tiles but not so large that the single-pixel noise or cupping, or both, (if present) changes appreciably over the selected region. (The two influences act in opposite directions: statistical noise decreases with increasing radius and will lower the standard error in the mean if too large a radius is chosen; whereas, cupping increases with increasing radius and will increase the standard error in the mean if too large a radius is chosen.) As a rule of thumb, these conditions will be satisfied when the diameter of the central region is about one-third that of the disk. For each new application, it is recommended that the validity of these requirements be verified empirically by monitoring the behavior of the CDF as the size of the region of interest is increased (see 7.2.3).

7.2.1.2 For tiles ranging in size from a single pixel to n^2 pixels, generate a sequence of patterns that tessellate the selected central region of the disk with a checkerboard of non-overlapping squares (see Fig. 2). (For the special case of single-pixel tiles, the requirement for non-overlapping tiles is satisfied trivially.) Terminate the sequence of patterns when the size of the tiles becomes too large to obtain a statistically significant number of tiles. It is recommended that the minimum number of tiles be on the order of 25. See Table 2 for suggested maximum tile sizes.

7.2.2 Unless otherwise agreed upon between the purchaser and supplier, the CDF shall be generated as follows:

7.2.2.1 Starting with the finest pattern of tiles and iterating until the entire sequence of patterns has been exhausted, calculate the mean value of the CT numbers within each tile and store the results in a table unique to each pattern. (For the special case of the single-pixel tiles, the calculation of means is trivial.)

7.2.2.2 For each table of results, calculate the standard deviation of the ensemble of measurements to obtain the standard error in the mean. (For the special case of the single-pixel tiles, the standard error in the mean is equal to the standard deviation.)

7.2.2.3 Generate a table of the standard error in the mean as a function of increasing tile size, where the size of a tile is defined as the lineal dimension of its edge. Units of either pixels or length may be used, though pixels are usually easier to interpret and more convenient to apply.

7.2.2.4 Express each standard error in the mean as a percentage of the average of its respective ensemble. Multiply each result by 3 to obtain the CDF. (For a false-negative rate of 50 % (that is, for the case of threshold detectability), this
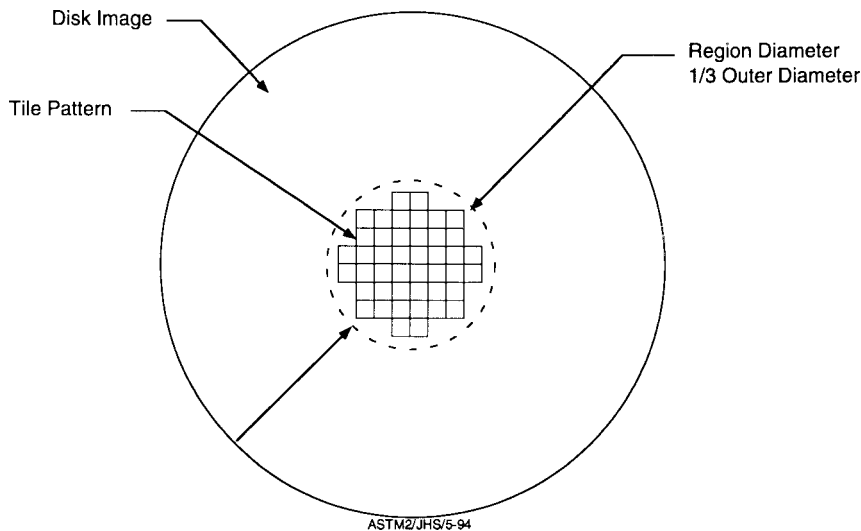
FIG. 2 Typical Tile Pattern

corresponds to a false-positive rate of 0.135 %. To select a different false-negative or false-positive rate, or both, refer to Practice E 1570.)

7.2.3 For each new application, verify that the requirements stipulated in 7.2.1.1 are satisfied by repeating the determination of the CDF for other sized regions. For a tile size one-third maximum, the CDF value will typically remain fairly constant over a range of radii from 10 % of the disk diameter to some critical radius on the order of 30 to 40 % of the disk diameter. As the radius is increased beyond this, the CDF will begin to change significantly. Unless otherwise agreed upon between the purchaser and supplier, select the largest region for which the CDF is constant to better than 5 %.

7.2.4 Unless otherwise agreed upon between the purchaser and supplier, the CDF shall be visually displayed or plotted, or both, as a function of tile size. When plotting, the convention is to present the data on a log-log graph.

8. Report

8.1 A report documenting the spatial resolution and contrast sensitivity determination should include all relevant data ac-

quisition, reconstruction, and display parameters (see Practice E 1570). The specific parameters to be documented is a matter of agreement between the purchaser and the supplier. The report shall contain at a minimum graphical presentations of the modulation transfer function and the contrast discrimination function.

9. Precision and Bias

9.1 Conformance to the requirements specified herein will produce results that are within the following tolerances:

9.1.1 *Precision*—The measured spatial resolution and contrast sensitivity will be repeatable within ± 5 %.

9.1.2 *Bias*—The measured spatial resolution and contrast sensitivity will be accurate within ± 5 %.

10. Keywords

10.1 computed tomography; contrast discrimination; contrast sensitivity; CT; geometrical unsharpness; spatial resolution