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Designation: E1695 – 20

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

This standard is issued under the fixed designation E1695; 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.

This standard has been approved for use by agencies of the U.S. Department of Defense.

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) volumes. The determination is based on examination of the CT volume of a uniform cylinder of material. The spatial resolution measurement (Modulation Transfer Function) is derived from an image analysis of the sharpness at the edges of the reconstructed cylinder slices. The contrast sensitivity measurement (Contrast Discrimination Function) is derived from an image analysis of the contrast and the statistical noise at the center of the cylinder slices.

1.2 This test method is more quantitative and less susceptible to interpretation than alternative approaches because the required cylinder is easy to fabricate and the analysis easy to perform.

1.3 This test method is not to predict the detectability of specific object features or flaws in a specific application. This is subject of IQI and RQI standards and standard practices.

1.4 This method tests and describes overall CT system performance. Performance tests of systems components such as X-ray tubes, gamma sources, and detectors are covered by separate documents, namely Guide E1000, Practice E2737, and Practice E2002; c.f. 2.1, which should be consulted for further system analysis.

1.5 *Units*—The values stated in SI units are to be regarded as standard. The values given in parentheses after SI units are provided for information only and are not considered standard.

1.6 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

E1000 Guide for Radioscopy

E1316 Terminology for Nondestructive Examinations

E1441 Guide for Computed Tomography (CT)

E1570 Practice for Fan Beam Computed Tomographic (CT) Examination

E2002 Practice for Determining Total Image Unsharpness and Basic Spatial Resolution in Radiography and Radioscopy

E2737 Practice for Digital Detector Array Performance Evaluation and Long-Term Stability

2.2 *ISO Standard:*[3]

15708 NDT – Radiation Methods – Computed Tomography – Part 1: Terminology, Part 2: Principles, Equipment and Samples, Part 3: Operation and Interpretation, Part 4: Qualification

3. Terminology

3.1 *Definitions*—The definitions of terms relating to Gamma- and X-Radiology, which appear in Terminology E1316 and Guide E1441, shall apply to the terms used in this test method.

[1] This test method is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.01 on Radiology (X and Gamma) Method.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from International Organization for Standardization (ISO), ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, http://www.iso.org.

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3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *examination object, n*—a part or specimen being subjected to CT examination.

3.2.2 *phantom, n*—a part or item being used to quantify CT system performance.

3.3 *Acronyms:*

3.3.1 *CDD*—contrast-detail-diagram; see Guide E1441 for details.

3.3.2 *CDF*—contrast discrimination function; describes the influence of image noise on the detectability of a feature in an elsewhere homogeneous material neighborhood as a function of the size of this feature in voxels.

3.3.2.1 *Discussion*—It intentionally does not pay regard to unsharpness effects, as these are covered by the MTF. See Guide E1441 for details.

3.3.3 *ERF*—edge response function.

3.3.4 *LSF*—line spread function.

3.3.5 *MTF*—modulation transfer function; describes the transfer of a spatial modulation in an image signal (relative intensity variation, here by a CT system) as function of the modulation's spatial frequency.

3.3.5.1 *Discussion*—Intentionally, it does not include noise effects, as those strongly depend on scan parameters and sample materials. Noise effects are covered by the CDF. See Guide E1441 for details.

4. Significance and Use

4.1 The major factors affecting the quality of a CT image are total image unsharpness (U_T^{image}), contrast ($\Delta\mu$), and random noise (σ). Geometrical and detector unsharpness limit the spatial resolution of a CT system, that is, its ability to image fine structural detail in an object. Random noise and contrast response limit 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. In this test method, spatial resolution is quantified in terms of the modulation transfer function (MTF), and contrast sensitivity is quantified in terms of the contrast discrimination function (CDF). The relationship between contrast sensitivity and spatial resolution describing the resolving and detecting capabilities is given by the contrast-detail-diagram (CDD metric, see also Guide E1441 and Practice E1570). 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 and is a measure for system stability over time and performance acceptability.

5. Apparatus

5.1 *Cylinder Phantom*—The cylinder phantom shall be a right circular cylinder of uniform material conforming to the design and material requirements in Table 1 and Fig. 1. For fan beam CT apparatus with LDA, a disk-shaped phantom as described in the precedented version of this standard (cf. Test Method E1695-95) is sufficient. Standard ISO 15708-2, Table 1, provides recommendations for X-ray voltages depending on material and thickness.

6. Procedure of Measurement

6.1 The phantom shall be mounted on the CT system with the orientation of the axis of revolution of the cylinder parallel to the scan axis. The alignment shall not compromise the measurement of unsharpness. The phantom shall be placed at the center of the field of view used for the examination object. It may also be placed off center at defined and documented positions.

6.2 The data acquisition parameters shall be similar to those used for examination object scans, whereas strong cupping artifacts near the surface shall be avoided by using enough pre-filter material (two half-value layers may be appropriate) or numeric corrections, or both, during the reconstruction.

6.2.1 For fan beam CT, one slice shall be acquired and analyzed.

6.2.2 The cylinder height shall be chosen according to Table 1.

6.2.3 For cone beam CT, three slice planes shall intercept the phantom cylinder at different positions of the detector. The first shall be positioned at the center of the reconstructed volume, the second and third at 15 % from the top and bottom of the reconstructed volume under investigation. MTF and CDF shall be computed on each plane individually. Additional slice locations may be added.

NOTE 1—The opening angle of the cone beam may contribute to lower MTF values, which in turn may result in lower spatial resolution in the object under examination at these opening angles.

7. Procedure of Analysis

7.1 *Spatial Resolution*—From the CT image data, generate the composite profile of the edge of each individual cylinder slice to obtain the edge response function (ERF), as discussed below in this section. Calculate the first derivative of the ERF to obtain the line spread function (LSF). Calculate the magnitude of the Fourier Transform[4] of the LSF and normalize the results to unity at zero frequency to obtain the modulation transfer function (MTF). In detail:

7.1.1 The ERF shall be generated as follows; cf. Fig. 2:

7.1.1.1 Find the 50 % iso-surface of the disk and fit a circle to it. Its radius is r_c. Other, more advanced methods of surface detection are permitted and shall be documented.

7.1.1.2 Select the inner and outer radii, r_i and r_o of the evaluation annulus with respect to the center of the circle resulting from 7.1.1.1 that comfortably bracket the edge, that is, it should extend from top plateau level to background level.

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

7.1.1.4 Generate a table of voxel values in order of their voxel distance from the circle center.

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

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

TABLE 1 a Disk Phantom Design Requirements

NOTE 1—The cupping effect due to beam hardening should be reduced by prefilters in front of the X-ray tube or in front of the detector or by numeric corrections in the reconstruction algorithm, or both.

Material	The material, in conjunction with the diameter of the cylinder, shall be such that the phantom approximates the attenuation range of the examination object. The material should preferably be the same as that of the examination object.
Diameter	The diameter shall be such that the reconstruction of the cylinder occupies *at least 250 voxels* in diameter of the resulting image. In conjunction with the material, the diameter shall be such that the phantom approximates the attenuation range of the examination object, provided the beam hardening effects are acceptable.
Height	The height of the cylinder should cover 80 % the detector height symmetrical to the middle line at the magnification used to inspect the examination object. It may be shorter if there are means to move it across the field of view.
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. The reconstructed image may be realigned by software for evaluation.
Finish	The surface texture roughness of the curved surface shall not affect the measurement of geometrical unsharpness.

TABLE 1 b Cylinder Phantom Suggestions

NOTE 1—The circularity is recommended, assuming the diameter covers up to 1000 voxels.

Cylinder Diameter [mm]	Circularity [mm]
1	0.001
3	0.003
10	0.010
30	0.030
100	0.10
Materials	Diameters [mm]
Plastic (for example, Delrin)	1-100
Aluminum	1-100
Steel	1-30
Inconel	1-30

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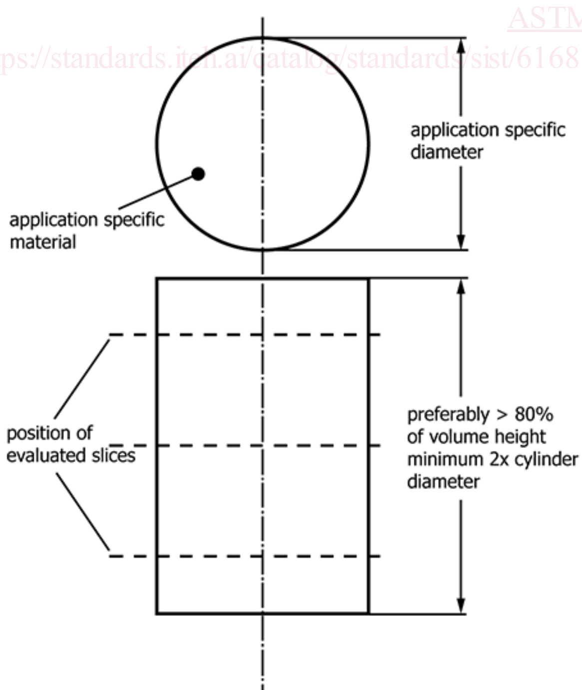

FIG. 1 Principle Drawing of the Cylinder Phantom, Not to Scale

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

7.1.1.7 Starting at one end of the table and iterating until the entire table has been processed, smooth the voxel 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 is needed to be included in the analysis and delete the unwanted portions of the leading and trailing tails to obtain the ERF.

7.1.2 The LSF 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 cylinder.

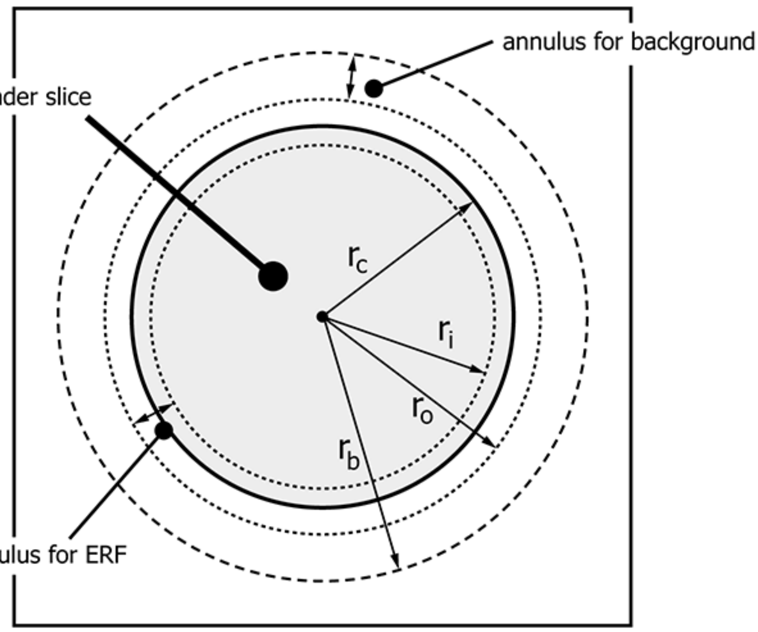

FIG. 2 Areas for Evaluation

TABLE 2 Suggested Measurement Parameters

Disk Image Diameter [Voxels]	Maximum Tile Size (CDF) [Voxels]	ERF Bin Size (MTF) [Voxels]	Number of Fit (MFT) Points
235	12	0.100	11
470	24	0.050	21
940	48	0.025	41

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

7.1.3 The MTF shall be generated as follows:

7.1.3.1 Calculate the Fourier Transform[4] of the LSF. The maximum frequency of the resultant transform should be at least four times the cut-off frequency of the matrix, which is 0.5 line-pairs per voxel. 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 lp/mm 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 (Magnitude spectrum).

7.1.3.3 Normalize the magnitude at zero frequency to unity (100 % at MTF for zero spatial frequency) to obtain the MTF.

7.1.4 The MTF shall be visually displayed or plotted, or both, and the frequency at 10 % modulation (MTF_{10}) quantitatively indicated for each evaluated slice indicating its distance to the detector center (in direction to the rotation axis). Although not mandatory, the ERF and the LSF should also be graphically presented, with the full width at half maximum of the LSF quantitatively indicated. (The LSF, in particular, may indicate distortions of the X-ray source.)

7.2 *Contrast Sensitivity:*

7.2.1 *Background Correction*—Define a second annulus (see Fig. 2) which will be used to determine the background level (air) μ_{air} by averaging all n voxel values within this annulus. Let $d(x)$ be the distance of a voxel x to the center of the cylinder slice, $R = \{x \mid r_o < d(x) \leq r_b\}$ the voxels in the annulus, and $n = \#R$ the respective number of voxels.

$$\mu_{air} = \frac{1}{n} \Sigma_{x \epsilon R}\, x \tag{1}$$

Subtract the average background μ_{air} from all voxel values x in the region of interest defined in 7.2.2.

7.2.2 *Contrast Discrimination Function*—From the CT image data, generate a sequence of tile patterns of tiles T_i of size D^* (=1,2,3,…), so that T_i contains $n = D^* \cdot D^*$ numbers of voxels, n being the number voxels in a single tile; see Fig. 3. The tile pattern shall fit within the central regions of the individual cylinder slices. For each pattern, calculate the mean voxel value μ_i of all now background corrected voxel values x (cf. 7.2.1) within each tile

$$\mu_i(D^*) = \frac{1}{n} \Sigma_{x \epsilon T_i}\, x \tag{2}$$

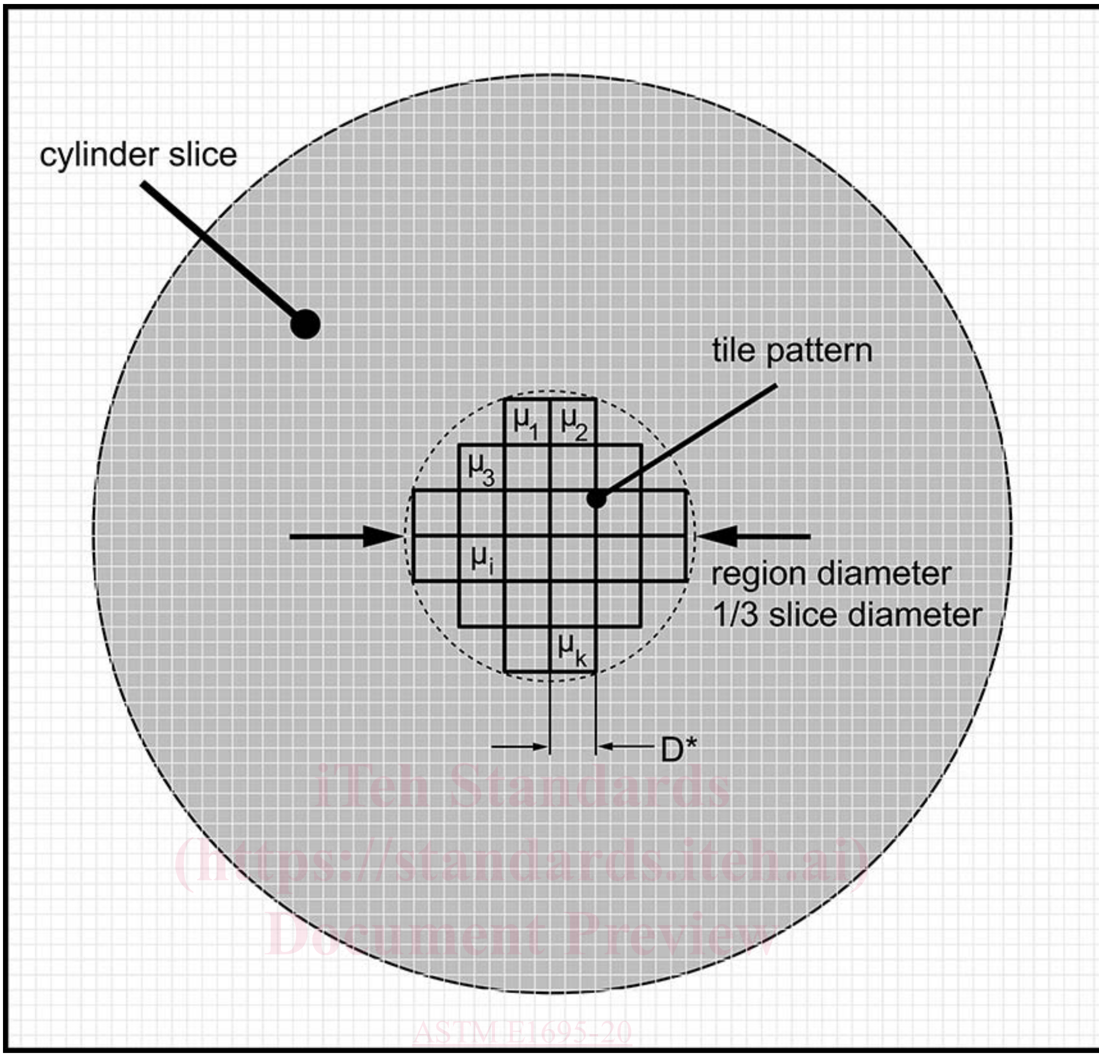
and store the result in a table specific to that pattern. For each table of results, calculate the standard deviation of the $\mu_i(D^*)$ to obtain the standard error in the mean, and store the result in a separate table in order of ascending tile size. The CDF (contrast discrimination function) value for a tile size D^* is computed by dividing the standard deviation σ_m of all (μ_i) by the mean of (μ_i) for that tile size D^* expressed as percent:

$$CDF(D^*) := 100\ \% \cdot \frac{1}{\bar{\mu}(D^*)} \sigma_m(D^*), \text{where} \tag{3}$$

$$\bar{\mu}(D^*) = \frac{1}{k} \Sigma_{i=1}^{k}\, \mu_i(D^*) \quad \text{and} \tag{4}$$

$$\sigma_m(D^*) = \sqrt{\frac{1}{k-1} \Sigma_{i=1}^{k} (u_i\,(D^*) - \bar{\mu}(D^*))^2} \tag{5}$$

k being the total number of tiles of tile size D^*. Go on by incrementing D^* according Table 2. An example is given in Annex A1.



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NOTE 1—For tiles ranging in size D^* from a single voxel to $n = D^{*2}$ voxels, generate a sequence of patterns that tessellate the selected central region of the cylinder with a checkerboard of non-overlapping squares of size D^*. 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 is about 25. See Table 2 for suggested maximum tile sizes. The tile pattern covers about one third of the cylinder slice in diameter. In each tile there is an average voxel value $\mu_i\ (D^*)$.

NOTE 2—In this specific example, there are k = 24 tiles T_i of size D^* = 3, containing n = 9 voxels.

FIG. 3 Creating Tile Pattern for the CDF Determination

7.2.3 Ideally, with a pure statistical noise, the CDF would be proportional to $\frac{1}{D^*}$ (standard error in the mean), so that its log-log plot would be a straight line with a slope of (-1).

7.2.4 For each new application, verify that the requirements stipulated in 7.2.2 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 cylinder diameter to some critical radius on the order of 30 to 40 % of the cylinder diameter. As the radius is increased beyond this, the CDF will begin to change significantly. Select the largest region for which the CDF is constant to better than 5 %.

7.2.5 The CDF shall be visually displayed or plotted, or both, as a function of tile size D^*. 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 which influence the MTF and CDF measurement (see Table 3 and Table 4). The report shall contain graphical presentations of the modulation transfer function MTF and the contrast discrimination CDF function; see Fig. 4 and Fig. 5. Visualizations of ERF and LSF are recommended and useful for system analysis; see Fig. 6.

9. Interpretation

9.1 *Indication of CT System Flaw or Change*—In general, a change of the MTF indicates change of image unsharpness U_T^{image} in the CT slice image. Namely, the MTF_{10} value corresponds to the basic spatial image resolution SR_b^{image} and

TABLE 3 Reporting of Measurement Parameters

Tube setting	Tube brand/name
	kV
	mA
	Spot size
Pre or intermediate filters, or both	Material
	Thickness
	Position (tube or detector, or both)
Setup geometry	
	SDD
	SOD_{CT}
	ODD_{CT}
	Cone opening angle
Detector	Detector brand/name
	Input screen area
	Gain
	Pixel size
	$SR_b^{detector}$
	SNR and PV in free beam area
	Fluorescence screen material if used
	Detector front cover material
	Detector front cover thickness
	Frame time
	Frame number
	Detector equalization procedure
Reconstruction procedure	Name of algorithm (for example, FDK)
	Spatial filters (for example, Hanning)
	Corrections (for example, cupping, beam length)
	Geometric correction of axis position/ angle
Test object	Shape: Rod
	Material
	Density if known
	Diameter
	Length

TABLE 4 Reporting of Results

Spatial resolution	Plot MTF [%] vs spatial frequency [lp/mm] with Nyquist frequency
	Plot ERF [%] vs distance from edge [mm or µm]
	Plot LSF [%] vs distance from edge [mm or µm]
	Spatial Frequency at 10% MTF (MTF_{10}) [lp/mm]
	Spatial Frequency at 10% MTF (MTF_{10}) [line/voxel]
	SRb for MTF_{10} [mm or µm]
	Nyquist frequency (1/(2 ΔV)) [lp/mm]
Contrast Sensitivity	Plot CDF [%] vs tile size D* [voxel]
	1/CDF (1) = CNR in cylinder slice
	CNR_N =88.6 µm SNR/ (2 MTF_{10})
	CDF (1) [%], Tile size D for D*=1 [mm or µm]
	CDF (2) [%], Tile size D for D*=2 [mm or µm]
	CDF (3) [%], Tile size D for D*=3 [mm or µm]
	CDF (4) [%], Tile size D for D*=4 [mm or µm]
	CDF (5) [%], Tile size D for D*=5 [mm or µm]

the total image unsharpness U_T^{image} (these quantities are described for 2-D radiographs in Practice E2002) in the CT slice image:

$$U_T^{image}[\mu m] = \frac{1\ lp}{MTF_{10}\left[\frac{lp}{\mu m}\right]} \quad \text{and} \quad SR_b^{image}[\mu m] = \frac{1\ lp}{2 \cdot MTF_{10}\left[\frac{lp}{\mu m}\right]} \tag{6}$$

A variation of the CDF typically reflects a change in the noise spectrum or in the contrast detection of the CT system. To illustrate that, some examples are given below.

9.1.1 *Example A: Variation of Flux and Focal Spot Size*—Typically, in microfocus systems, the focal spot size may depend on the power because it is adapted to the acceptable target load. That implies that an increase in contrast sensitivity (lower CDF) may deteriorate MTF_{10}. The below diagrams show MTF and CDF for otherwise identical scans at three different powers (see Fig. 7). CDF(1) roughly follows the inverse square root of the tube current. MTF_{10} decreases as expected with the increasing nominal focal spot size.

9.1.2 *Example B: Detector Performance*—Variation of detector calibration quality simulates a change in detector performance. The diagram in Fig. 8 shows the CDF of cylinder slices of identical scans with good and mediocre quality detector correction (that is, equalization of pixel response), as well as without detector correction (equalization of pixel response). Reducing the number of frames in gain and offset image by a factor of 10 causes a slight change of the CDF. Switching off all corrections, including defect pixel correction, causes a dramatic effect of a factor 2 to 10. In this case, the missing correction affects more the detectability of the larger features.

9.2 *Indications of Improper Measurement*—The test method may be disturbed by inappropriate data quality or by unnoticed change in the procedure. There must be a sufficient number of voxels at acceptable noise at the edge of the cylinder slice (see Table 1), and there must not be excessive beam hardening (cupping effect) present in the slice. Further, the procedure should be carried out precisely following the documentation according to Table 3 and Table 4. Below typical indications of improper measurements are described.

9.2.1 *Excessive Beam Hardening (Cupping Effect)*—Excessive beam hardening can be identified from over shots in the MTF and ERF or an asymmetrical baseline of the LSF; see Fig. 9 and Fig. 10. This may be improved by stronger pre-filtering or by using a cylinder of smaller diameter. The strong cupping might also affect the measurement of the CDF in the inner part of the disk by adding low frequency noise.

9.2.2 *Excessive Noise*—Excessive noise or an insufficient number of evaluated voxels (Table 1) will be identified by a wiggly and irreproducible MTF.

9.2.3 *Wrong use of Data Processing or Reconstruction Parameters*—Data processing such as reconstruction filters, beam-hardening correction, use of scatter correction techniques, and image filtering may affect and distort the results. Therefore, the use of these functions and procedures should be documented accurately (see Table 3) and be used in a consistent and reproducible way.

10. Precision and Bias

10.1 *Precision* was determined following Practice E691 by evaluation measurement by various implementations of the algorithm described in Sections 6 and 7.

10.2 *Bias (trueness)* cannot be directly determined because there is no accepted more accurate reference value, so it was estimated as required by Practice E177, 10.2.2. MTF values were compared to unsharpness measurements according to Practice E2002 (in the projection and in the CT volume). To estimate CDF bias, the CDF value was compared with CNR measurements.

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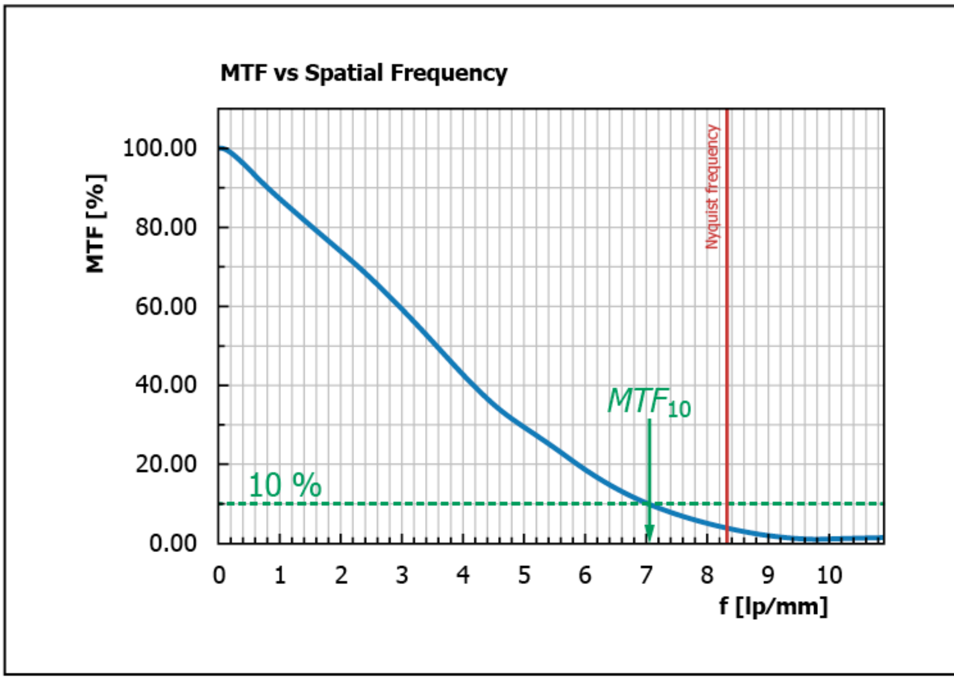

NOTE 1—In this example, the result for the spatial resolution of the CT system is MTF_{10} =7.06 lp/mm. For this scan, the detector, SR_b was 215 µm, the focal spot size was 60 µm at a magnification of 3.33. Guide E1000 predicts MTF_{10} = 6.90 lp ⁄mm without further influence. The Nyquist frequency is 8.33 lp/mm.

FIG. 4 Example of Visualization for MTF

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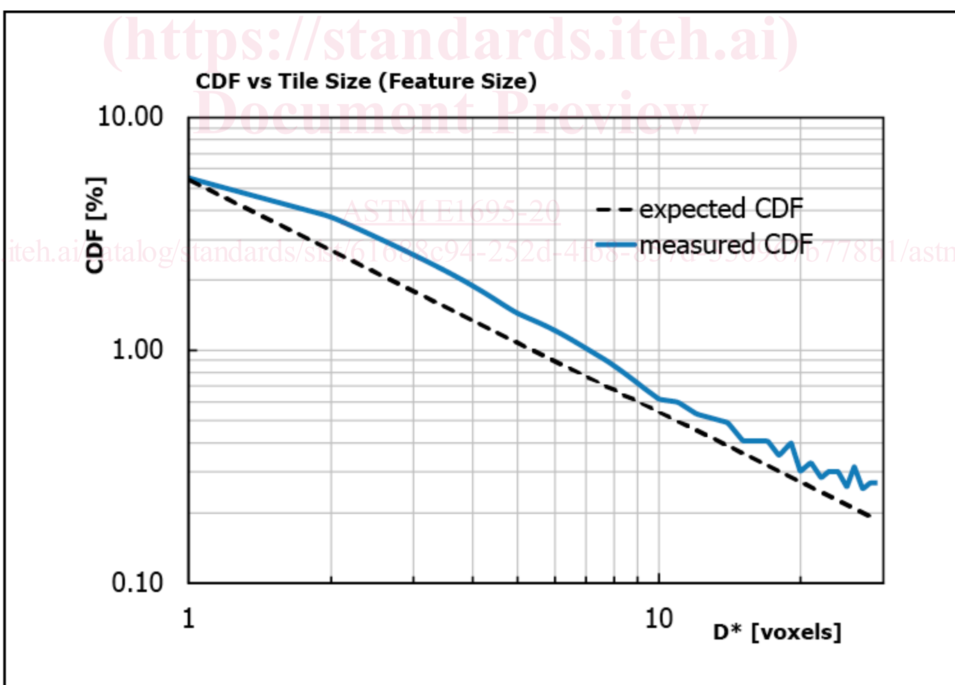

NOTE 1—For an ideally statistical noise, the CDF would be a line with slope (-1) dashed line. In this example, the noise for features sizes between 2 and 120 voxels is higher than ideally expected.

FIG. 5 Example of CDF Visualization

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

10.3.1 The measured MTF_{10} *(measured unsharpness in line pairs per mm)* will be repeatable within (1s) ± 5 %.

10.3.2 The measured MTF_{10} *(measured unsharpness in line pairs per mm)* will be true within (1s) ± 7 %.

10.3.3 The measured CDF *(contrast discrimination function)* will be repeatable within (1s) ± 10 %.