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Standard Practice for Computed Tomographic (CT) Examination¹

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

1. Scope*

1.1 This practice is for computed tomography (CT), which may be used to nondestructively disclose physical features or anomalies within a test object by providing radiological density and geometric measurements. This practice implicitly assumes the use of penetrating radiation, specifically X-ray and γ -ray.

1.2 CT systems utilize a set of transmission measurements made along paths through the test object from many different directions. Each of the transmission measurements is digitized and stored in a computer, where they are subsequently reconstructed by one of a variety of techniques. A treatment of CT principles is given in Guide E1441.

1.3 CT is broadly applicable to any material or test object through which a beam of penetrating radiation passes. The principal advantage of CT is that it provides densitometric (that is, radiological density and geometry) images of thin cross sections through an object without the structural superposition in projection radiography.

1.4 This practice describes procedures for performing CT examinations. This practice is to address the general use of CT technology and thereby facilitate its use.

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.* For specific safety statements, see Section 8, NBS Handbook 114, and Federal Standards 21 CFR 1020.40 and 29 CFR 1910.96.

2. Referenced Documents

2.1 ASTM Standards:²

E1316 Terminology for Nondestructive Examinations

E1441 Guide for Computed Tomography (CT) Imaging

E1695 Test Method for Measurement of Computed Tomography (CT) System Performance

2.2 NIST Standard:

NBS Handbook 114 General Safety Standard for Installations Using Non-Medical X-Ray and Sealed Gamma-Ray Sources, Energies Up to 10 MeV
ANSI N43.3 General Radiation Safety Installations Using Non-Medical X-Ray and Sealed Gamma Sources up to 10 MeV³

2.3 Federal Standards:⁴

21 CFR 1020.40 Safety Requirements of Cabinet X Ray Systems

29 CFR 1910.96 Ionizing Radiation

2.4 ASNT Documents:⁵

SNT-TC-1A Recommended Practice for Personnel Qualification and Certification in Nondestructive Testing

ANSI/ASNT-CP-189 Qualification and Certification of Nondestructive Testing Personnel

2.5 Military Standard:

¹ This practice 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 National Institute of Standards and Technology (NIST), 100 Bureau Dr., Stop 3460/1070, Gaithersburg, MD 20899-3460/20899-1070, http://www.nist.gov.

⁴ Available from Standardization Documents Order Desk, DODSSP, Bldg. 4, Section D, 700 Robbins Ave., Philadelphia, PA 19111-5098, http://dodssp.daps.dla.mil.

⁵ Available from American Society for Nondestructive Testing, 1711 Arlingate Plaza, P.O. Box 28518, Columbus, OH 43228-0518.

^ε Available from American Society for Nondestructive Testing (ASNT), P.O. Box 28518, 1711 Arlingate Ln., Columbus, OH 43228-0518, http://www.asnt.org.

*A Summary of Changes section appears at the end of this standard.

MIL-STD-410 Nondestructive Testing Personnel Qualification and Certification⁴

2.6 *AIA Standard:*

NAS-410 Certification and Qualification of Nondestructive Testing Personnel⁶

3. Terminology

3.1 *Definitions*—For definitions of terms used in this guide, refer to Terminology E1316 and Annex A1 in Guide E1441.

4. Summary of Practice

4.1 Requirements in this practice are intended to control the reliability and quality of the CT images.

4.2 CT systems are made up of a number of subsystems; the function served by each subsystem is common in almost all CT scanners. Section 7 describes the following subsystems:

4.2.1 Source of penetrating radiation,

4.2.2 Radiation detector or an array of detectors,

4.2.3 Mechanical scanning assembly, and

4.2.4 Computer system including:

4.2.4.1 Image reconstruction software/hardware,

4.2.4.2 Image display/analysis system,

4.2.4.3 Data storage system, and

4.2.4.4 Operator interface.

4.3 Section 8 describes and defines the procedures for establishing and maintaining quality control of CT services.

4.4 The extent to which a CT image reproduces an object or a feature within an object is influenced by spatial resolution, statistical noise, slice plane thickness, and artifacts of the imaging system. Operating parameters should strike an overall balance between image quality, inspection time, and cost. These parameters should be considered for CT system configurations, components, and procedures. The setting and optimization of CT system parameters is discussed in Section 9.

4.5 Methods for the measurement of CT system performance are provided in Section 10 of this practice.

5. Significance and Use

5.1 This practice is applicable for the systematic assessment of the internal structure of a material or assembly using CT technology. This practice may be used for review by system operators, or to prescribe operating procedures for new or routine test objects.

5.2 This practice provides the basis for the formation of a program for quality control and its continuation through calibration, standardization, reference samples, inspection plans, and procedures.

6. Basis of Application

6.1 This practice provides the approach for performing CT examinations. Supplemental information covering specific items where agreement between supplier⁷ and purchaser⁸ are necessary is required. Generally the items are application specific or performance related, or both. Examples include: system configuration, equipment qualification, performance measurement, and interpretation of results.

7. System Configuration

7.1 Many different CT system configurations are possible and it is important to understand the advantages and limitations of each. It is important that the optimum system parameters be selected for each examination requirement, through a careful analysis of the benefits and limitations of the available system components and the chosen system configuration.

7.2 *Radiation Sources*—While the CT systems may utilize either gamma-ray or X-ray generators, the latter is used for most applications. For a given focal spot size, X-ray generators (that is, X-ray tubes and linear accelerators) are several orders of magnitude more intense than isotope sources. Most X-ray generators are adjustable in peak energy and intensity and have the added safety feature of discontinued radiation production when switched off; however, the polychromaticity of the energy spectrum from an X-ray source causes artifacts such as beam hardening (the anomalous decreasing attenuation toward the center of a homogeneous object) in the image if uncorrected.

7.2.1 X-rays produced from electrical radiation generators have focal spot sizes ranging from a few millimetres down to a few micrometres. Reducing the focal spot size reduces geometric unsharpness, thereby enhancing detail sensitivity. Smaller focal spots permit higher spatial resolution, but at the expense of reduced X-ray beam intensity.

⁴ Available from Aerospace Industries Association of America, Inc. (AIA), 1250 Eye St., NW, Washington, DC 20005.

⁶ Available from Aerospace Industries Association of America, Inc. (AIA), 1000 Wilson Blvd., Suite 1700, Arlington, VA 22209-3928, <http://www.aia-aerospace.org>.

⁷ As used within this document, the supplier of computed tomographic service refers to the entity that physically provides the computed tomographic services. The supplier may be a part of the same organization as the purchaser, or an outside organization.

⁸ As used within this document, the purchaser of computed tomographic services refer to the entity that requires the computed tomographic services. The purchaser may be a part of the same organization as the supplier, or an outside organization.

7.2.2 A radioisotope source can have the advantages of small physical size, portability, low power requirements, simplicity, and stability of output. The disadvantages are limited intensity and limited peak energy.

7.2.3 Synchrotron Radiation (SR) sources produce very intense, naturally collimated, narrow bandwidth, tunable radiation. Thus, CT systems using SR sources can employ essentially monochromatic radiation. With present technology, however, practical SR energies are restricted to less than approximately 20 to 30 keV. Since any CT system is limited to the inspection of samples with radio-opacities consistent with the penetrating power of the X-ray employed, SR systems can in general image only small (about 1 mm) objects.

7.3 *Radiation Detection Systems*—The detection system is a transducer that converts the transmitted radiation containing information about the test object into an electronic signal suitable for processing. The detection system may consist of a single sensing element, a linear array of sensing elements, or an area array of sensing elements. The more detectors used, the faster the required scan data can be collected; but there are important tradeoffs to be considered.

7.3.1 A single detector provides the least efficient method of collecting data but entails minimal complexity, eliminates detector cross talk and detector matching, and allows an arbitrary degree of collimation and shielding to be implemented.

7.3.2 Linear arrays have reasonable scan times at moderate complexity, acceptable cross talk and detector matching, and a flexible architecture that typically accommodates good collimation and shielding. Most commercially available CT systems employ a linear array of detectors.

7.3.3 An area detector provides a fast method of collecting data but entails the transfer and storage of large amounts of information, forces tradeoffs between cross talk and detector efficiency, and creates serious collimation and shielding challenges.

7.4 *Manipulation System*—The manipulation system has the function of holding the test object and providing the necessary range of motions to position the test object between the radiation source and detector. Two types of scan motion geometries are most common: translate-rotate motion and rotate-only motion.

7.4.1 With translate-rotate motion, the object is translated in a direction perpendicular to the direction and in the plane of the X-ray beam. Full data sets are obtained by rotating the test object between translations by the fan angle of the beam and again translating the object until a minimum of 180 degrees of data have been acquired. The advantage of this design is simplicity, good view-to-view detector matching, flexibility in the choice of scan parameters, and ability to accommodate a wide range of different object sizes including objects too big to be subtended by the X-ray fan. The disadvantage is longer scan time.

7.4.2 With rotate-only motion, a complete view is collected by the detector array during each sampling interval. A rotate-only scan has lower motion penalty than a translate-rotate scan and is attractive for industrial applications where the part to be examined fits within the fan beam and scan speed is important.

7.4.3 In volume CT, a complete data set for the entire part is acquired in at least one rotation. This allows for much faster data acquisition, as the data required for multiple slices can be acquired in one rotation.

7.5 *Computer System*—CT requires substantial computational resources, such as a large capacity for image storage and archival and the ability to efficiently perform numerous mathematical computations, especially for the back-projection operation. Computational speed can be augmented by either generalized array processors or specialized back-projection hardware. The particular implementations will change as computer hardware evolves, but high computational power will remain a fundamental requirement for efficient CT examination. A separate workstation for image analysis and display often is appropriate.

7.6 *Image Reconstruction Software*—The aim of CT is to obtain information regarding the nature of material occupying exact positions inside a test object. In current CT scanners, this information is obtained by “reconstructing” individual cross-sections of the test object from the measured intensity of X-ray beams transmitted through that cross section. An exact mathematical theory of image reconstruction exists for idealized data. This theory is applied although the physical measurements do not fully meet the requirements of the theory. When applied to actual measurements, algorithms based on this theory produce images with blurring and noise, the extent of which depends on the quantity and quality of the measurements.

7.6.1 The simplifying assumptions made in setting up the theory of reconstruction algorithms are: (1) cross sections are infinitely thin (that is, they are planes), (2) both the source focal spot and the detector elements are infinitely small (that is, they are points), (3) the physical measurements correspond to total attenuation along the line between the source and detector, and (4) the radiation is, or can be treated as, effectively monoenergetic. A reconstruction algorithm is a collection of step-by-step instructions that define how to convert the measurements of total attenuation to a map of linear attenuation coefficients over the field of view.

7.6.2 A number of methods for recovering an estimate of the cross section of an object have evolved. They can be broadly grouped into three classes of algorithms: matrix inversion methods, finite series-expansion methods, and transform methods. See Guide E1441 for treatment of reconstruction algorithms.

7.6.3 If the test object is larger than the prescribed field of view (FOV), either by necessity or by accident, unexpected and unpredictable artifacts or a measurable degradation of image quality can result.

7.7 *Image Display*—The function of the image display is to convey derived information (that is, an image) of the test object to the system operator. For manual evaluation systems, the displayed image is used as the basis for accepting or rejecting the test object, subject to the operator’s interpretation of the CT data.

7.7.1 Generally, CT image display requires a special graphics monitor; television image presentation is of lower quality but may be acceptable. Most industrial systems utilize color displays. These units can be switched between color and gray-scale

presentation to suit the preference of the viewer, but it should be noted that gray-scale images presented on a color monitor are not as sharp as those on a gray-scale monitor. The use of color permits the viewer to distinguish a greater range of variations in an image than gray-scale does. Depending on the application, this may be an advantage or a disadvantage. Sharply contrasting colors may introduce false, distinct definition between boundaries. While at times advantageous, unwanted instances can be corrected through the choice of color (or monochrome) scale.

7.8 Data Storage Medium—Many CT applications require an archival-quality record of the CT examination. This could be in the form of raw data or reconstructed data. Therefore, formats and headers of digital data need to be specified so information can be retrieved at a later date. Each archiving system has its own specifics as to image quality, archival storage properties, equipment, and media cost. Computer systems are designed to interface to a wide variety of peripherals. As technology advances or needs change, or both, equipment can be easily and affordably upgraded. The examination record archiving system should be chosen on the basis of these and other pertinent parameters, as agreed upon by the supplier and purchaser of CT services. The reproduction quality of the archival method should be sufficient to demonstrate the same image quality as was used to qualify the CT system.

7.9 Operator Interface—The operator interface determines much of the function of the rest of the CT system. The control panel and image display system are the two significant subsystems affected. The control software, hardware mechanisms, and interface to a remote data workstation if applicable, are among those controlled by this interface. Override logic, emergency shutdown, and safety interlocks are also controlled at this point. There are three types of operator interfaces.

7.9.1 A simple programming console interface, where the operator types in commands on a keyboard. While being less “user friendly,” this type can offer the greatest range of flexibility and versatility.

7.9.2 The dedicated console with specific function buttons and relatively rigid data and processing features. These systems are usually developed explicitly for standardized, nonvarying examination tasks. They are designed to be “functionally hardwired” for efficient throughput for that program. Medical CT equipment is often of this type.

7.9.3 A graphical user interface employing a software display of the menu or windowing type with means such as a pointing device for entering responses and interacting with the system. This approach has the advantage of being able to combine the best features of the other two types of operator interfaces.

7.10 Automation—A variation among CT systems is the extent to which users can create, modify or elaborate image enhancement or automated evaluation processes. The level of sophistication and versatility of a user command language or a “learning mode” is an important consideration for purchasers and suppliers who expect to scan a variety of objects or to improve their processes as they gain experience with CT.

8. Documentation

8.1 Documentation of the examination protocol shall cover the following:

8.1.1 *Equipment Qualifications*—The following system features shall be included:

8.1.2 *Test Object Scan Plan*—A listing of test object(s), scan parameters and performance measurements to be extracted from the image(s).

8.1.2.1 *Data Acquisition Parameters*—A listing of radiation source and detector-related variables include the following:

- (1) Source energy,
- (2) Intensity, current, Rad output or equivalent,
- (3) Integration time, number of pulses or equivalent,
- (4) Source spot size or isotope source size,
- (5) Source filtration,
- (6) Source collimation,
- (7) Detector filtration,
- (8) Detector collimation,
- (9) Source-to-axis distances,
- (10) Source-to-detector distance,
- (11) Detector gain factor, gain range, or equivalent,
- (12) Sampling parameters (linear increment, angular increment or equivalent),
- (13) Number of detectors or channels,
- (14) Scan mode, that is, translate-rotate or rotate only,
- (15) Calibration of detector air counts (no test object) and dark counts (no source) and frequency of calibration, and
- (16) Position of slice plane and orientation of sample.

8.1.2.2 *Image Reconstruction Parameters*— A listing of expected image reconstruction variables including:

- (1) Type of reconstruction (that is, normal, zoom, annular, limited-angle, and so forth),
- (2) Conditioning of X-ray absorption measurements; reconstruction algorithm, view pre-processing, beam-hardening corrections, non-linearity corrections,
- (3) Reconstruction diameter (field of view),
- (4) Reconstruction pixel size, slice thickness or equivalent,
- (5) Linear sampling intervals (if appropriate),
- (6) Reconstruction matrix size,

- (7) Pixel size and coordinates, and
- (8) Position orientation/size (for zoom).

8.1.2.3 *Image Display Parameters*—A listing of the techniques and the intervals applied for standardizing the video image display as to brightness, contrast, focus, and linearity, which includes the following:

- (1) Provisions for displaying a quantized color bar or gray scale to assist in this operation.
- (2) Method used for adjusting the monitor and ensuring that the full range of colors or shades of gray are properly displayed.
- (3) Transformation from CT number to color or gray scale look-up table (LUT).
- (4) Upper and lower limits on the range of CT numbers displayed (or the equivalent description in terms of a range about an average value).
- (5) If a nonlinear display technique, like histogram equalization or log transformation is used, describe the method.

8.1.2.4 *Image Analysis*—Digital image analysis techniques used to manipulate, alter, or quantify the image for the purpose of CT examination must be documented. The documentation shall include the following:

8.1.2.5 *Accept-Reject Criteria*—A listing of accept/reject criteria.

8.1.2.6 *Performance Evaluation*—A listing of the qualification tests and the intervals at which they are applied (see 10.2).

8.1.3 *Image Archiving Requirements*—A listing of the requirements for preserving a historical record of the examination results. The listing may include examination images along with written or electronically recorded alphanumeric or audio narrative information, or both, sufficient to allow subsequent reevaluation or repetition of the CT examination. The listing ~~should~~ shall specify data types (that is, raw data, image data, 16-bit, 8-bit, specially processed images, and so forth) along with the format or medium used. Data compression ~~format also should~~ format, if applicable, shall be listed.

8.1.4 *Examination Record Data*—The examination record ~~should~~ shall contain sufficient information to allow the CT examination to be reevaluated or duplicated. Examination record data should be recorded simultaneously with the CT image and may be in writing or a voice narrative, providing the following minimum data:

8.1.4.1 The CT system designation, examination date, operator identification, operating turn or shift, and other pertinent examination and customer data,

8.1.4.2 Specific test object data as to part number, batch, serial number, and so forth (as applicable),

8.1.4.3 Test object orientation and site information (that is, scan height, slice thickness, and so forth) relative to system coordinates or by reference to unique test object features. Slice planes can be annotated with respect to a preview radiogram, and

8.1.4.4 System performance monitoring by recording the results of the prescribed CT system performance monitoring tests, as set forth in Section 10, at the beginning and end of a series of CT examinations, not to exceed the interval set forth in 8.1.2.6 for system performance monitoring.

9. CT System Setup and Optimization

9.1 *CT Setup*—In addition to the required flaw sensitivity, an examination setup should consider the expected distribution of anomalies, an acceptable rate of false negatives (that is, passed defects) and an acceptable rate of false positives (normal data mistaken for an anomaly). The following attributes should be considered when developing a CT setup for a group of test objects:

9.1.1 Specimen (size, weight, and composition factors that determine the source accelerating potential and the mechanical handling equipment requirements),

9.1.2 Examination requirements (spatial resolution, contrast sensitivity, slice thickness, time),

9.1.3 System operation (system control, safety, calibration functions, scanning procedure),

9.1.4 Interaction with program flow (for example, concurrent data acquisition and review, automatic acquisition sequencing, archiving, automatic anomaly recognition, data output for statistical process control), and

9.1.5 Part handling (logistics for loading and unloading the test object and the design and use of any associated fixturing).

9.2 *Source Setup*—Caution is advised against applying practices developed for projection radiography. Except at very high energies, mass attenuation differences between materials (signal contrasts) tend to decrease as the mean X-ray energy is increased; whereas, X-ray production and penetrability (signal levels) tend to increase under the same condition. Therefore, the optimum source energy for a given part is not determined by the lowest possible X-ray energy that provides adequate penetration but rather by the X-ray energy that produces the maximum signal-to-noise ratio (SNR). When a part consists of a single material or several materials with distinct physical density differences, the best SNR may be obtained at a high source energy. In such cases, the decreased image noise at higher energies is more important than the increased contrast at lower energies. When chemically different components have the same or similar physical densities, the best discrimination of materials may be obtained at a low source energy. In such cases, the increased contrast at lower energies is more important than the decreased image noise at higher energies.

9.2.1 Unless suitable measures are taken to reduce the effects of scattered radiation, it will reduce contrast over the whole image, or parts of it, and produce beam hardening artifacts. Scattered radiation is most serious for materials and thicknesses that have high X-ray absorption, because the scattering is more significant compared to the primary image-forming radiation that reaches the detector through the specimen.

9.2.2 Source collimation can limit the cross section of an X-ray beam to cover only the area of the test object that is of interest in the examination. This reduces the radiation dose to the object and the amount of scattered radiation produced.

9.2.3 A radiation source often contains X-rays of differing energies. The use of source filtration will preferentially remove the

low-energy content of the X-ray spectrum. However, filtration decreases the total number of photons, which reduces the amount of available signal and may increase the noise in the image. A tradeoff is clearly required, and some filtration generally is found to be useful. The amount of filtration depends on the source spectrum and the nature and size of the test object. Filtration can be mounted near the source or the detector. Filters are generally used to combat beam hardening artifacts (see 9.5.1). The influence of scattered radiation can be addressed with filtration by reducing the number of more readily scattered low-energy photons. Filtration used to reduce scattered radiation is typically more effective if placed in front of the detector as opposed to placement at the source.

9.3 *Spatial Resolution*—The spatial resolution of a CT system is a function of the source focal spot size, the width of any detector apertures (linear detector arrays), and the source-to-detector and source-to-center of rotation distances. Many CT systems permit the spatial resolution to be adjusted by allowing the user some degree of control over some or all of these parameters. Refer to Guide E1441 for a more thorough discussion of the interactions between these different variables. The mechanical accuracy of the positioning subsystem also can limit spatial resolution but the supplier of CT services typically has no control over this aspect of the system operation.

9.3.1 Test object positioning can affect spatial resolution. Because of the extended sizes of the source spot and the active detection elements, the effective width of a measurement ray varies along its path from source to detector. This is reflected in a variation with object position of spatial resolution in images computed from measurements with such rays. The simplest approximation to the minimum effective ray width for a source spot size S and a detector active aperture size A separated by a distance L is approximately $AS/(A + S)$, and occurs at a location $LS/(A + S)$ from the source.

NOTE 1—If source and aperture differ substantially in size, this minimum is located close to the smaller; this is the case for a microfocus source and for high resolution detector systems. Optimal spatial resolution can usually be obtained by placing the object as near as possible to this position, but different tasks and object sizes should be checked experimentally.

NOTE 2—The best placement for spatial resolution may not be optimal for efficient use of detectors or for such other considerations as scatter sensitivity.

9.4 *Contrast Sensitivity*—Contrast sensitivity is affected by the noise in an image and is a strong function of the total number of photons detected. Most CT systems permit the contrast sensitivity to be adjusted by allowing some degree of control over parameters affecting the number of detected photons. At a given energy, the most important factors are: (1) source intensity, (2) the integration/counting time allowed for each individual measurement, (3) the size of the detector resolution aperture (single detector or linear detector array), (4) the size of the detector slice thickness aperture (linear detector array), (5) the source-to-detector distance, and (6) the amount of filtration employed. Refer to Guide E1441 for a more thorough discussion of the interactions between these different variables.

9.4.1 Contrast sensitivity is also a function of the energy of the photons comprising the X-ray beam. For a fixed number of X-ray photons incident on a uniform composition object, the contrast sensitivity would generally be best if they have an energy which typically gives 13 % transmission (that is, where the typical product of thickness and linear attenuation coefficient equals two). This value is the result of the balance between less relative contrast at higher transmissions and more noise at lower transmissions. This exact result depends on the restrictions stated (fixed number of photons, uniform object composition, modest dynamic range), and should not be applied blindly to other situations.

9.4.1.1 The optimal acceleration voltage for CT contrast sensitivity, for CT images made with X-ray generators, is not a simple calculation. Because a given current in a X-ray generator at a voltage produces more photons at all energies (up to the end-point energy) than would the same current at a lower voltage, there is a potential for better results at the highest voltage possible. Whether this potential is realized in a particular case depends on whether the advantages of greater photon production efficiency will be overcome by the lower current typically required to meet wattage limits for a given spot size, or by saturation effects in the detection system. Different results have been reported for different systems and examination tasks; users should rely on tests if they wish to determine the optimal voltage for a particular examination. Because of substantial differences in detection characteristics, experience with X-ray film radiography should not be used to predict optimal settings for CT examinations.

9.5 *Image Artifacts*—Artifact content is one of the more difficult aspects of image quality to control or quantify. Artifacts can be viewed as correlated noise because they form fixed patterns under given conditions and are often the limiting factor in image quality. Mitigating their effects is best done by removing or reducing the cause that gave rise to them, a task that in many instances may not be feasible or practical. In some cases, it may be possible to reduce artifacts through the application of specialized software. Refer to Guide E1441 for a more thorough discussion (also see 10.7). The use of special procedures or software, or both, to verify the existence (or absence) of artifacts or reduce the influence of artifacts on the CT task must be clearly specified.

9.5.1 Beam hardening artifacts (the anomalous decreasing attenuation toward the center of a homogeneous object) are most common to systems employing polychromatic X-ray sources. A mathematical correction at some stage in the reconstructive process can be very effective, and many systems allow the option of applying such a correction. Many different approaches have been developed, and some systems offer a choice of options. If a beam hardening correction is used, the specifics of the method employed must be well documented in order to permit duplication. Beam hardening can also be reduced by going to higher source energies or filtering the low-energy content of the incident radiation, or both.

9.5.1.1 A short laboratory procedure to verify the existence of a beam hardening artifact is as follows: If a high apparent density near the surface of a test object is suspect, place a second object adjacent to the first and rescan. Part of the first object is now in the interior of the “paired object.” If the apparent density of the suspect surface does not decrease, the measured high density is