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Non-destructive testing — Radiation methods — Computed tomography —

Part 2: Examination practices

Essais non destructifs — Moyens utilisant les rayonnements — Tomographie informatisée —

Partie 2: Pratiques d'examen

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this part of ISO 15708 may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 15708-2 was prepared by Technical Committee ISO/TC 135, *Non-destructive testing*, Subcommittee SC 5, *Radiation methods*.

ISO 15708 consists of the following parts, under the general title *Non-destructive testing — Radiation methods — Computed tomography*:

— *Part 1: Principles*

— *Part 2: Examination practices*

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Introduction

Computed tomography (CT), as with conventional radiography and radioscopic examination, is broadly applicable to any material or test object through which a beam of penetrating radiation passes, including metals, plastics, ceramics, metallic/non-metallic composite material and assemblies. The principal advantage of CT is that it provides densitometric (i.e., radiological density and geometry) images of thin cross sections — "slices" — through an object. Because of the absence of structural superposition, images are much easier to interpret than conventional radiological images. CT images correspond closely to the way the human mind visualizes 3D structures than conventional projection radiology. Because CT images are digital, the images may be enhanced, analysed, compressed, archived, input as data into performance calculations, and compared with digital data from other non-destructive evaluation (NDE) modalities. CT images can also be transmitted to other locations for remote viewing.

This part of ISO 15708 describes CT procedures that can provide for non-destructive testing and evaluation. Requirements in this part of ISO 15708 are intended to control the reliability and quality of the CT images. This part of ISO 15708 is applicable for the systematic assessment of the internal structure of a material or assembly and may be used to prescribe operating CT procedures. It also provides a basis for the formation of a programme for quality control and its continuation through calibration, standardization, reference samples, inspection plans and procedures.

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Non-destructive testing — Radiation methods — Computed tomography —

Part 2: Examination practices

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1 Scope

This part of ISO 15708 gives guidelines for procedures for performing CT examinations. It is intended to address the general use of CT technology and thereby facilitate its use. This part of ISO 15708 implicitly assumes the use of penetrating radiation, specifically X-ray and γ-ray.

2 Normative reference

The following normative document contains provisions which, through reference in this text, constitute provisions of this part of ISO 15708. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of ISO 15708 are encouraged to investigate the possibility of applying the most recent edition of the normative document indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 15708-1:2002, *Non-destructive testing — Radiation Methods — Computed tomography — Part 1: Principles*

3 Terms and definitions

For the purposes of this part of ISO 15708 the terms and definitions listed in annex A of ISO 15708-1:2002 apply.

4 Summary

This part of ISO 15708 describes CT procedures which can provide for non-destructive testing and evaluation. Requirements in this part of ISO 15708 are intended to control the reliability and quality of the CT images.

CT systems are made up of a number of subsystems; the function served by each subsystem is common in almost all CT scanners. Clause 5 describes the following subsystems:

a) source of penetrating radiation;

b) radiation detector or an array of detectors;

c) mechanical scanning assembly;

d) computer system including:

   1) image reconstruction software/hardware;

2) image display/analysis system;

3) data storage system;

4) operator interface.

Clause 6 describes and defines the procedures for establishing and maintaining quality control of CT examination services.

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 shall strike an overall balance between image quality, inspection time and cost. These parameters shall be considered for CT system configurations, components and procedures. The setting and optimization of CT system parameters are discussed in clause 7.

Methods for the measurement of CT system performance are provided in clause 8.

5 System configuration

5.1 CT System configurations

Many different CT examination 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 careful analysis of the benefits and limitations of the available system components and the chosen system configuration.

5.2 Radiation sources

5.2.1 General

Whilst the CT examination 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 [i.e., X-ray tubes and linear accelerators (linacs)] 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, polychromaticity of the energy spectrum causes artifacts such as “cupping” (the anomalous decreasing attenuation toward the centre of a homogeneous object) in the image, if left uncorrected.

5.2.2 Electrical radiation generators

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.

5.2.3 Radioisotope sources

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, primarily due to inefficiency in the process whereby continuous X-rays are generated. Radioisotope sources are typically several orders of magnitude less intense that X-ray generators

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5.2.4 Synchrotron radiation (SR) sources

SR sources produce very intense, naturally collimated, narrow bandwidth, tunable radiation. Thus, CT systems using SR sources can employ essentially monochromatic radiation. With current technology however, practical SR energies are restricted to less than approximately 20 keV 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 used, SR systems can, in general, image only small (about 1 mm) objects.

5.3 Detection system

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.

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

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.

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.

5.4 Manipulation System

5.4.1 General

The test part manipulation system has the function of holding the test object and providing the necessary range of motions to position the volume of interest between the radiation source and detector. Two types of scan motion geometries are most common.

5.4.2 Translate-rotate motion

With translate-rotate motion, the test object is translated in a direction perpendicular to the direction of and in the plane of the X-ray beam. Full data sets are obtained by rotating the test article between translations by the fan angle of the beam and again translating the part until a minimum of 180° 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 a longer scan time.

5.4.3 Rotate-only motion

With rotate-only motion, a complete view is collected by the detector array during each sampling interval. A rotate-only scan has a 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 the scan speed is important.

5.5 Computer system

CT requires substantial computational resources such as a large capacity for image storage and archival and the ability to perform numerous mathematical computations swiftly and efficiently, especially for the back-projection operation. Computational speed can be augmented by either generalized array processors or specialized back-projection hardware or both. 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 and archiving is often appropriate.

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5.6 Image reconstruction software

The aim of CT is to obtain information regarding the nature of material occupying exact positions in a test object. In current CT scanners, this information is obtained by "reconstructing" individual cross-sections (i.e., slices) 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.

The simplifying assumptions made in setting up the theory of reconstruction algorithms are:

a) cross sections are infinitely thin (i.e., they are planes);

b) both the focal spot or source and the detector elements are infinitely small (i.e., they are points);

c) the physical measurements correspond to total attenuation along the line between the source and detector;

d) 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.

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 ISO 15708-1 for a treatment of reconstruction algorithms.

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. Many methods have been devised to scan objects larger than the largest FOV for which an instrument has been designed. One technique, which also provides improved spatial resolution in specific regions of larger objects is known as region-of-interest (ROI) tomography. ROI tomography reconstructs a convex region within an object, utilizing a projection subset, on a specified sampling grid, providing higher resolution in this reduced area.

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5.7 Image display

The function of the image display is to convey derived information (i.e., 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.

Generally, CT image display requires a special graphics monitor. Television image presentation is of lower quality but may be acceptable. Most industrial systems utilize colour displays. These units can be switched between colour and grey-scale presentation to suit the preference of the viewer, but it should be noted that grey-scale images presented on a colour monitor are not as sharp as those on a grey-scale monitor. The use of colour permits the viewer to distinguish a greater range of variations in an image than grey-scale does. Depending on the application, this may be an advantage or a disadvantage. Sharply contrasting colours may introduce false, distinct definition between boundaries. While at times advantageous, unwanted instances can be corrected through the choice of colour (or monochrome) scales.

5.8 Data storage medium

Many CT examination 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 shall be chosen on the basis of these and other pertinent parameters, as agreed upon by the supplier and purchaser of CT examination services. The reproduction quality of

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the archival method shall be sufficient to demonstrate the same image quality as was used to qualify the CT examination system.

5.9 Operator interface

5.9.1 General

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 amongst 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.

5.9.2 Simple programming console interface

Here the operator types in commands on a keyboard. Whilst being less "user friendly," this type can offer the greatest range of flexibility and versatility.

5.9.3 Dedicated console

This has specific function buttons and relatively rigid data and processing features. These systems are usually developed explicitly for standardized, non-varying inspection tasks. They are designed to be "functionally hardwired" for efficient throughput for that programme. Medical CT equipment is often of this type.

5.9.4 Graphical user interface

This uses 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 interface.

5.10 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 test objects or to improve their processes as they gain experience with CT.

6 Documentation

6.1 General

The examination protocol shall cover the areas listed in 6.2 to 6.5.

6.2 Equipment qualifications

These comprise a listing of the basic system features that shall be qualified to ensure that the system is capable of performing the desired examination task.

6.3 Test object scan plan

6.3.1 General

There shall be a listing of test object scan parameters and performance measurements to be extracted from the image(s).

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6.3.2 Data acquisition parameters

A listing of radiation source and detector-related variables shall include:

a) source energy;

b) intensity, current, rad output or equivalent;

c) integration time, number of pulses or equivalent;

d) source spot size or isotope source size;

e) source filtration;

f) source collimation;

g) detector filtration;

h) detector collimation;

i) source-to-object distances;

j) source-to-detector distance;

k) detector gain factor, gain range or equivalent;

l) sampling parameters (linear increment, angular increment or equivalent);

m) number of detectors or channels;

n) scan mode (e.g. translate-rotate, rotate only);

o) calibration of detector air counts (no test object) and dark counts (no source) and frequency of calibration;

p) position of slice plane and orientation of sample.

6.3.3 Image reconstruction parameters

A listing of image reconstruction variables shall include:

a) type of reconstruction (i.e, normal, zoom, annular, limited-angle and so forth);

b) conditioning of X-ray absorption measurements, reconstruction algorithm, view pre-processing, beam-hardening corrections, non-linearity corrections;

c) reconstruction diameter (field of view);

d) reconstruction pixel size, slice thickness or equivalent;

e) linear sampling intervals (if appropriate);

f) reconstruction matrix size;

g) pixel size and coordinates;

h) position orientation/size (for zoom).

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6.3.4 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, shall include the following:

a) provisions for displaying a quantized colour bar or grey scale to assist in this operation;

b) method used for adjusting the monitor and ensuring that the full range of colours or shades of grey are properly displayed;

c) the transformation from CT number to colour or grey scale look-up table (LUT);

d) upper and lower limits on the range of CT numbers displayed (or the equivalent description in terms of a range or “window” about an average value or “level”);

e) if a non-linear display technique is used, a description of the histogram equalization or log transformation.

6.3.5 Image analysis

Digital image analysis techniques used to manipulate, alter or quantify the image for the purpose of CT examination shall be documented. The documentation shall also include the following:

a) accept-reject criteria — a listing of accept/reject criteria;

b) performance evaluation — a listing of the qualification tests and the intervals at which applied.

6.4 Image archiving requirements

There shall be 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 re-evaluation or repetition of the CT examination. The listing shall specify the data types (i.e., raw data, image data, 16-bit, 8-bit, specially processed images etc.) along with format or medium be used. Data compression format shall also be listed.

6.5 Examination record data

The examination record shall contain sufficient information to allow the CT examination test to be re-evaluated or duplicated. Examination record data shall be recorded simultaneously with the CT examination image and may be in writing or a voice narrative in order to provide the following minimum data.

a) The CT examination system designation, test date, operator identification, operating turn or shift and other pertinent test and customer data.

b) Specific test part data as to part number, batch, serial number etc (as applicable),

c) Test part orientation and examination site information (i.e., scan height, slice thickness etc.) relative to system co-ordinates or by reference to unique test part features.

NOTE Slice planes can be annotated with respect to a preview radiogram.

d) System performance monitoring by recording the results of the prescribed CT examination system performance monitoring tests, as set forth in clause 8, at the beginning and end of a series of CT examinations, not to exceed the interval set forth for system performance monitoring.

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7 System set-up and optimization

7.1 CT optimization

In addition to the required flaw sensitivity, an examination set-up shall take into consideration the expected distribution of anomalies, an acceptable rate of false negatives (i.e., past defects) and an acceptable rate of false positives (normal data mistaken for an anomaly). The following attributes should be considered when developing a CT examination set-up for a group of test objects.

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

b) Examination requirements: spatial resolution, contrast sensitivity, slice thickness, time.

c) System operation: system control, safety, calibration functions, scanning procedure.

d) Interaction with programme flow: e.g., concurrent data acquisition and review, automatic acquisition sequencing, archiving, automatic anomaly recognition, data output for statistical process control.

e) Part Handling: logistics for loading and unloading the test specimen as well as the design and use of any associated fixturing.

NOTE The expected distribution of anomalies will define the region of the test object to be examined. The test object may be held at an angle to reduce the radiation path length or the complexity of the reconstruction.

7.2 Source set-up

7.2.1 General

Caution is advised against the application of documents developed for projection radiography. Except at very high energies, mass attenuation differences between materials (i.e., signal contrasts) tend to decrease as the mean X-ray energy is increased whereas X-ray production and penetrability (i.e., signal levels) tend to increase under the same conditions. 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 (SNR) ratio. 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.

7.2.2 Scattered radiation

Unless suitable measures are taken to reduce the effects of scatter, it will reduce contrast over the whole image or parts of it and produce cupping 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.

7.2.3 Source collimation

It is good practice, wherever possible, to 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 part and also the amount of scattered radiation produced.

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7.2.4 Filters

A radiation source often contains X-rays of differing energies. The use of 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 trade-off is clearly required, and some filtration is generally 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. 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.

7.2.5 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-centre 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. See ISO 15708-1 for a more thorough discussion of the interactions between these different variables. The mechanical accuracy of the positioning subsystem can also limit spatial resolution but the supplier of CT examination services typically has no control over this aspect of the system operation.

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 size; 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 other considerations such as scatter sensitivity.

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7.3 Image quality

7.3.1 Contrast sensivity

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:

a) source intensity;

b) the integration/counting time allowed for each individual measurement;

c) the size of the detector resolution aperture (linear detector array);

d) the size of the detector slice thickness aperture (linear detector array);

e) the source-to-detector distance;

f) the amount of filtration used (see ISO 15708-1 for a more thorough discussion of the interactions between these different variables).

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 14 % transmission (i.e., where the typical product of thickness and linear attenuation coefficient equals 2). This value is the result of the balance between less relative contrast at higher

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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.

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 an 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 inspection tasks; users should rely on tests if they wish to determine the optimal voltage for a particular inspection. Because of substantial differences in detection characteristics, experience with X-ray film radiography should not be used to predict optimal settings for CT examinations.

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7.3.2 Artifacts

7.3.2.1 General

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. See ISO 15708-1 for a more thorough discussion. 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 examination task shall be clearly specified.

7.3.2.2 Beam hardening

Beam hardening artifacts (the anomalous decreasing attenuation toward the centre of a homogeneous object) are most common to systems using 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 shall 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.

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 test 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 real. Instead, if it decreases, the first density measurement may have been affected by a beam hardening artifact.

7.3.2.3 Edge artifacts

Generally, an edge artifact manifests itself as a streak arising from a long straight edge. It is caused by the inability of the CT system to properly handle the sudden change in signal level that occurs at high contrast boundaries. Such streaks may be reduced by any technique that can mitigate the rate of change at the offending boundary or can correct the raw data to compensate for measurement inaccuracies. Methods for lowering the contrast include imbedding the object being scanned in a second medium, e.g. water or sand, and increasing the source energy. Methods involving the use of special software typically incorporate the use of prior knowledge about the part and the application of a non-linear correction to the data. If edge artifact suppression techniques are used, the specifics of the method used shall be well documented in order to permit duplication.

7.3.2.4 Ring artifacts

Generally, a ring artifact manifests itself as circular streaks around the centre of rotation of the object under examination. It is caused by differences in detector response during the data acquisition process, and is exacerbated by the beam-hardening non-linearities. These artifacts are typically found in rotate-only type scan

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geometries. Ring artifacts may be reduced by data correction algorithms applied to the raw data to compensate for these differences in detector response. Like edge artifact correction algorithms, methods involving the use of special software typically incorporate the use of prior knowledge about the part and the application of a non-linear correction to the data. If ring artifact suppression techniques are used, the specifics of the method employed shall be well documented in order to permit duplication.

7.3.3 Speed of the examination process

For a given spatial resolution and contrast sensitivity requirement, there shall be a source capable of emitting the requisite number of photons per unit time. Since the number and configuration of detectors is usually fixed, it may not be possible to simultaneously accommodate resolution, contrast and throughput demands with the available equipment.

Examples of linear array CT system adjustments to provide adequate signals at the detector for reconstruction and optimize the speed of the examination process include:

a) allow more time for each individual measurement, increasing the overall examination time;

b) open the slice-thickness aperture plates which will provide better signal or contrast sensitivity while reducing defect sensitivity to anomalies that do not extend through the slice plane;

c) open the resolution aperture plates, which will also provide better signal but will reduce the spatial resolution of the examination;

d) a combination of these adjustments to meet the overall examination needs.

7.3.4 Reconstruction matrix size

The reconstruction matrix size governs the number of views and data samples in each view that has to be acquired. The higher the resolution, the smaller the pixel size and the larger the pixel matrix for a given region of interest on the test object. The reconstruction matrix size affects the number of scans and length of time necessary to examine a test object.

7.3.5 Slice thickness

Thicker slices provide better signal-to-noise ratio (SNR) if the other scan parameters are unchanged. Alternatively, faster scans are possible without sacrificing SNR by acquiring thicker slices. Thicker slices, while increasing contrast sensitivity to features extending through the slice, decrease defect sensitivity to anomalies that do not extend through the slice.

7.3.6 Linear detector system

For linear detector systems, slice thickness is set by the X-ray optics of the system. It is a function of the object position (i.e, the magnification of the scan geometry) and the effective sizes (normal to the scan plane) of the focal spot of the source and the acceptance aperture of the detector. The effective size of the focal spot is determined by its physical size and any source-side collimation. The effective size of the detector aperture is determined by the active size of the sensor and any detector-side collimation. The maximum thickness is achieved with the maximum effective focal spot size and the maximum effective acceptance aperture. The minimum thickness is achieved with the minimum permitted focal spot size and the minimum permitted effective acceptance angle.

7.3.7 Area detector system

For area detector systems, slice thickness is determined by software. The slice thickness can be defined before image reconstruction by averaging neighbouring detector rows (in an arbitrary orientation) or after image reconstruction by averaging adjacent slice planes.

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7.4 System operation

All control functions as well as the interface to a remote data workstation are controlled from the operator console. Override logic, calibration procedures, emergency shut-down and other safety related operations are all controlled at this point. Written procedures intended to provide safe operating instructions for the CT system shall be located at the operator console and implemented by system operators or used to train new operators. The following subjects shall be addressed.

— **Safety**: identify all hazards and safe operating procedures that apply, including federal regulations, state/local regulations, posting of area, personnel monitoring, positioning table lock-out and area evacuation.

— **Normal system power-up procedure** (if applicable).

— **X-ray tube warm-up procedure**.

— **Transport and loading of test objects**.

— **Calibration procedures**: electronic calibration, mechanical calibration and others, as applicable.

— **Scanning procedure**: digital radioscopy (preview radiogram) may be used before scanning in order to quantify test object height and visually assess radioscopic image quality. When imaging a test object for the first time, rescanning at several different system configurations is often typical. The machine operator shall be proficient at the following: scan protocol editing, record keeping and performance measurements.

— **Shutdown procedure**.

— **System maintenance**: coolants, lubricants, X-ray system, positioning table, computer system and others, as applicable.

7.5 Interaction with programme flow

The complete examination procedure may include concurrent data acquisition and review, automatic acquisition sequencing, archiving, automatic anomaly recognition or data output for statistical process control. These factors can affect the software designed to keep track of the images, the parameters recorded with the image, data compression algorithms etc. Facility interface requirements to other operations shall be established early.

8 Performance measurement

8.1 Performance parameters

Initially, CT examination system performance parameters shall be determined and monitored regularly in order to ensure consistent results. The best measure of total CT system performance can be made with the system in operation, utilizing a test object under actual operating conditions. Performance measurements involve the use of a simulated test object (also known as a test phantom) containing actual or simulated features that shall be reliably detected or measured. A test phantom can be designed to provide a reliable indication of the CT system's capabilities. Test phantom categories currently used in CT and simulated features to be imaged can be classified as noted in Table 1. Performance measurement methods shall be agreed upon agreement by the purchaser and supplier of CT examination services.

8.2 Performance measurement intervals

System performance measurement techniques shall be standardized so that performance measurement tests may be readily duplicated at specified intervals. The CT examination system performance shall be evaluated at sufficiently frequent intervals, as may be agreed upon by the supplier and user of CT examination services, in order to minimize the possibility of time-dependent performance variations.

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8.3 Placement of a simulated test object or test phantom

The simulated test object or test phantom shall be placed for examination in the same position as that used with the actual object in order to ensure that subtle effects such as object-related scatter and edge-induced artifacts are, as much as practical, realistically mimicked.

8.4 CT examination techniques

The CT scan parameters, radiation beam energy, intensity, source spot size (or isotope size), display parameters, image processing parameters, manipulation scan plan, scanning speed and other system variables, utilized for the performance measurement shall be identical to those used for the actual examination of the test object.

Table 1 — Test phantom categories

Phantom type	Detectable features
Resolution	Holes Squares Line pairs (or grids) Edges (for MTF calculations)
Contrast	Signal-to-noise ratio in a uniform material Small density variation Various solids Liquids with different contrast agents
Slice thickness	Pyramids Cones Columnar row of beads Slanted sheets Spiral slits
Geometry accuracy	Hollow cylinders Matrix of calibrated holes Simulated test object
Artifacts	Uniform density test object

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8.5 Detection or measurement with a simulated test object or test phantom

The test phantom may be an actual test object with known features that are representative of the range of features to be detected or may be fabricated to simulate a suitable range of representative features. Alternatively, the test phantom may be a one-of-a-kind or few-of-a-kind reference test object containing known characteristics that have been verified independently. Test phantoms containing known, natural features (internal defects, density variations, or spatial irregularities) are useful on a single-task basis, but are not universally applicable. Where standardization among two or more CT examination systems is required, a duplicate manufactured test phantom can be used. Test phantoms shall approximate the test object as closely as is practical, being made of the same material with similar dimensions and features in the CT examination region of interest. If the CT examination is to be for imperfections, manufactured test phantoms shall include features, at least as small as those that shall be reliably detected in the actual test objects, in locations where they are expected to occur in the actual test object.

Where features are internal to the test object, it is permissible to produce the test phantoms in sections. Ultimately, the ability of a given CT system to image structural details at the level dictated by the inspection application can be definitively and visually confirmed only by scanning a representative part known to contain features or flaws, or both, of the required size.

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A test phantom manufactured as a simple cylinder of the same material as the actual test object is recommended for the spatial resolution and signal-to-noise ratio (SNR) measurements. The size of the cylinder shall be representative of the characteristic attenuation of the test object to be examined. A cylinder made of denser material than the test object can be made much smaller than the reconstruction diameter and has the advantage of providing a measure of the modulation transfer function (MTF) as a function of position. If, however, it is too small to support the SNR measurement, a separate test phantom may be required to obtain representative results. A cylinder of same or comparable density as the test object can be made comparable in size to the reconstruction diameter and has the advantage of serving double duty for the MTF and SNR measurements. However, it also limits the amount of knowledge that can be obtained about MTF variations within the CT reconstruction. The cylinder diameter cannot exceed the reconstruction diameter.

8.6 Quantitative measurement of CT system performance

8.6.1 General

The extent to which a CT image reproduces the object is dictated largely by the competing influences of the spatial resolution, the statistical noise and the artifacts of the imaging system. Each of these aspects is discussed briefly in 8.6.2 to 8.6.5 and in 8.7. A more complete discussion can be found in ISO 15708-1. Quantitative performance measurements should be performed using the system parameters and sample placement described in 8.3 and 8.4.

8.6.2 Spatial resolution

The spatial resolution characterizes the ability of a CT system to image fine structural detail. It is best quantified by a measurement of the line-spread function (LSF) of the system or, equivalently, by the modulation transfer function (MTF), the frequency-space representation of the LSF. The recommended method is to determine the MTF by computing the amplitude of the Fourier transform of the LSF. The LSF is obtained by calculating the derivative of the profile of the edge of a cylindrical test phantom. The size of the cylinder to be used or the method of computation is a matter of agreement between the supplier and purchaser of CT examination services. If the spatial resolution varies significantly over the field of view, it is recommended that a small cylinder be used to make multiple measurements at a number of regularly spaced locations near the periphery and at one or more locations near the centre. If the spatial resolution is fairly uniform, it is recommended that a cylinder large enough to provide a representative sampling of the periphery of the field of view be used to make a single measurement. Figure 1 illustrates one acceptable method of obtaining the MTF from the image of a simple cylinder. The use of a cylinder [Figure 1a)] is preferred because, once its "centre of mass" is determined, profiles perpendicular to the cylinder edge may be readily extracted. Many non-overlapping profiles can be computed, aligned, concatenated and smoothed to reduce system and quantization noise on the edge-response function (ERF). See Figure 1b). The LSF is estimated by taking the discrete derivative of the ERF (Figure 1c) and its discrete fourier transform (FT) is taken to obtain the MTF (Figure 1d). Note that by convention, the height of the MTF is normalized to unity and plotted in spatial-frequency units of linepairs per millimetre (lp/mm). Linepair gauges may be used to directly confirm the MTF at discrete points.

8.6.3 Signal-to-noise ratio (SNR)

The SNR can be characterized by selecting a featureless region in the reconstructed image and determining the average and standard deviation for all CT numbers in the region. The test object to be imaged, test object location within the reconstruction diameter, test slice location, region location and the region size is a matter of contractual agreement. The ratio of the average deviation to the standard deviation is used as an SNR measurement. If a test phantom rather than the test object to be evaluated is used for the SNR measurement, it is recommended that a cylinder approximating the attenuation of the part be employed. The region of the reconstructed image selected for SNR measurement should be a homogenous area within the test object or test phantom containing a reasonable number ($>$ 100) of pixels. The noise in a reconstructed image does have positional dependence, especially near the edges of an object. Extremely large areas should not be used and care should be exercised in the selection of location so that positional variations in SNR do not mask variations reflective of real changes in sensitivity.

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