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Acceptance Testing and Quality Control of Digital Radiographic Imaging Systems

The Report of AAPM Task Group 150

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Conflict of Interest Statement

The members of TG-150 listed below attest that they have no potential conflicts of interest related to the subject matter or materials presented in this document.

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List of abbreviations/acronyms

AEC: Automatic exposure control
CFR: Code of Federal Regulations
CNR: Contrast to noise ratio
CR: Computed radiography
CV: Coefficient of variation
DICOM: Digital Imaging and Communications in Medicine
DQE: Detective quantum efficiency
DR: Digital radiography
EI: Exposure Index
ERMF: Estimated Radiographic Magnification Factor
FPD: Flat panel detector
HIS: Hospital Information System
HVL: Half-value layer
IEC: International Electrotechnical Commission
IFU: Information for Use
IHE: Integrating the Healthcare Enterprise
IOD: Information Object Definition
KAP: Kerma-area product (standard terminology $P_{K,A}$)
kV: Tube voltage
LUT: Lookup table
MITA: Medical Imaging and Technology Alliance
MTF: Modulation transfer function
NEMA: National Electrical Manufacturers Association
NNPS: Normalized noise power spectrum
OID: Object-to-image distance
PACS: Picture archiving and communication system
PBL: Positive beam limitation
PMMA: Polymethyl methacrylate
QA: Quality assurance
QC: Quality control
RIS: Radiology Information System
ROI: Region of interest
SCD: Source-to-chamber distance

SDD: Source-to-detector distance
SID: Source-to-image distance
SNR: Signal-to-noise ratio
SOD: Source-to-object distance
SSD: Source-to-skin distance
TCP/IP: Transmission Control Protocol/Internet Protocol
VOI: Value of interest

Chapter 1 - Introduction

Charge: The formal charge of American Association of Physicists in Medicine (AAPM) Task Group 150 (TG-150) was "This group will outline a set of tests to be used in the Acceptance Testing and Quality Control of Digital Radiographic Imaging Systems." The task group ultimately refined the charge to cover only those tests performed by medical physicists, as tests performed by technologists are covered by AAPM Report 151.

Scope: The recommendations outlined in this report apply to all x-ray imaging systems used to acquire static projection radiographic images in digital form, without respect to the technology of acquisition; for example, flat panel digital radiography and computed radiography systems. This report does not apply to dual energy or digital tomosynthesis modes of radiographic systems, nor to digital mammographic, slot scanning radiographic, DXA bone densitometry, fluoroscopic, dental radiographic, cone-beam computed tomography, or computed tomography systems.

1.1 Background

Guidelines for the medical physics evaluation of new imaging systems that have major or incremental advances in imaging system technology must always be evaluated in the context of related preexisting guidance and technologies. This is particularly true of the guidance contained within this task group report, which builds upon the work of the AAPM Report 74 [1] and AAPM Report 93 [2]. Report 74 "Quality Control in Diagnostic Radiology" provided guidance on the performance evaluation of x-ray projection imaging (and other) systems including limited guidance on screen-film and computed radiography systems. Report 93 "Acceptance Testing and Quality Control of Photostimulable Storage Phosphor Imaging Systems" focused on the performance evaluation of computed radiography imaging systems, including receptors and readout technologies.

At the inception of TG-150, the stated goal was to provide incremental guidance for flat panel digital radiography systems, similar to that of Report 93, but primarily focused on the imaging receptor. However, as the work of the task group progressed and image receptor technology advanced, the form factor of flat panel image receptors and the standards that govern the communication of digital images evolved. In our deliberations, it became increasingly clear that the best approach would be to provide an integrated overall guidance document that described tests of all major subsystems of digital radiographic systems from the x-ray tube and generator to the diagnostic display. To achieve this goal, the task group considered each of the subsystems that comprise a digital radiographic system, namely the x-ray generator, collimator and tube assembly, scatter reduction grid, automatic exposure control (AEC), patient support, image receptor, and digital image processing, as well as network connectivity and the performance of the composite imaging system. As part of this effort, the task group identified all tests that were conducted in a traditional screen-film environment, assessed whether the tests were still relevant for digital imaging systems (flat panel or photostimulable storage phosphor based), and whether the specific test methodology needed to be modified to accommodate unique features of the digital image receptor technology. In addition, new test recommendations specific to digital radiography were also considered.

This report therefore covers tests of the following subsystems and the full imaging chain (system):

- X-ray tube and generator
- Collimator
- Anti-scatter grid
- Digital image receptor
- Automatic exposure control
- Image processing
- Acquisition display monitor
- System test

In considering the acquisition display monitor and overall imaging chain in the scope of guidance, this report relied heavily on the following AAPM task group reports:

- Online Only Report OR03 [3] (Task Group 018) "Assessment of Display Performance for Medical Imaging Systems"
- Report 4 [4] "Basic Quality Control in Diagnostic Radiology"[1]
- Report 14 [5] "Performance Specifications and Acceptance Testing for X-ray Generators and Automatic Exposure Control Devices"[1]
- Report 25 [6] "Protocols for the Radiation Safety Surveys of Diagnostic Radiological Equipment"[1]
- Report 31 [7] "Standardized Methods for Measuring Diagnostic X-ray Exposures"[1]
- Report 74 [1] "Quality Control in Diagnostic Radiology" [1]
- Report 93 [2] "Acceptance Testing and Quality Control of Photostimulable Storage Phosphor Imaging Systems"
- Report 116 [8] "An Exposure Indicator for Digital Radiography"
- Report 151 [9] "Ongoing Quality Control in Digital Radiography"
- Report 248 [10] "Interoperability Assessment for the Commissioning of Medical Imaging Acquisition Systems"
- Report 270 [11] "Display Quality Assurance"

In addition, we relied on the following standards and reports published by groups outside the AAPM:

- United States Code of Federal Regulations (CFR), 21 CFR 1020.30 and 21 CFR 1020.31 [12]
- International Electrotechnical Commission (IEC) 60336 X-ray tube assemblies for medical diagnosis - Focal spot dimensions and related characteristics [13]
- IEC 60601-2-54 Particular requirements for the basic safety and essential performance of X-ray equipment for radiography and radioscopy [14]
- IEC 62220-1-1 Determination of the detective quantum efficiency - Detectors used in radiographic imaging [15]
- IEC 62494-1 Exposure index of digital X-ray imaging systems [16]
- IEC 61267 Medical diagnostic X-ray equipment – Radiation conditions for use in the determination of characteristics [17]

As we have only reflected the highlights of the comprehensive guidance contained within these reports, we recommend medical physicists conducting performance evaluations of digital radiographic imaging systems be familiar with the contents of the publications listed above.

It should also be noted that AAPM Task Group 150 was formed to focus on the testing of digital radiography systems to be performed by a qualified medical physicist. A companion Task Group (Task Group 151) was also formed in parallel to focus on ongoing quality control testing to be performed by a technologist. The work of both committees was informed by each other's efforts. The Task Group Report 151 [9] "Ongoing Quality Control in Digital Radiography" is an essential companion report for medical physicists performing evaluations of digital radiographic imaging systems, especially for those providing oversight of the ongoing quality control of such systems.

Membership of this task group (TG-150) included imaging scientists from both industry and academia with expertise in the performance characterization of digital radiographic imaging systems, and clinical medical physicists with extensive experience testing x-ray imaging systems in the clinical environment. Industry liaisons on the committee were instrumental in our efforts to solicit information

[1]These reports are sunset i.e., considered "retired" by the AAPM.

in the form of a written survey sent at the outset of the task group to commercial manufacturers of digital radiographic imaging systems. The information obtained during that survey and in the many subsequent discussions conducted with liaisons during and outside of task group meetings was informative and key to our endeavor.

A pivotal milestone in our efforts occurred when the task group requested a new National Electrical Manufacturers Association (NEMA) standard for digital radiographic systems. NEMA/MITA (Medical Imaging & Technology Alliance) responded by promulgating Standard XR 30-2016 "X-ray Equipment for Radiography Quality Control Tools for Digital Projection Radiography" [18]. It describes digital radiography system features, which would facilitate the testing conducted by medical physicists. The development of such a standard was key to improving access to data and images required for the testing methods outlined in this report. We note that, for the majority of new commercial systems, accessing this data is far easier now than when we initiated our first discussions with vendor liaisons (when the task group was formed). Standard XR 30-2016 is available as a free download from the NEMA website, and contains the following provisions, as well as guidance for implementation:

- The equipment shall provide means to access and export original data of acquired images in a non-proprietary format to an output device. The accompanying documents shall specify the methodology for export and format of the exported data.
- If the relation of the original data to the image receptor air kerma is non-linear, e.g., logarithmic or square-root characteristic, an inverse conversion function shall be provided to enable calculation of linearized data.
- The equipment shall provide means to electronically document image processing parameters. The equipment shall provide means to export the image processing parameter sets in a compatible file format to an output device. The accompanying documents shall specify the methodology to export and the format of the exported data.

Appendix G outlines some less formal suggestions for vendors and software developers that would simplify the task of testing radiographic units.

It is important to note that the form factor of digital imaging receptors has evolved over time and current digital radiographic imaging systems may utilize:

- removeable flat panel detectors (FPD) that can be used on the patient table, in the table bucky, the wall bucky, or mounted in a mobile cassette stand, and which may use wired or wireless communication,
- fixed flat panel detectors installed in either the table or wall bucky,
- a computed radiography (CR) cassette that can be used on the patient table, in the table bucky, or the wall bucky, or mounted in a mobile cassette stand, or
- a combination of the aforementioned.

As the imaging pathway associated with each receptor configuration must be thoroughly tested in addition to the intrinsic receptor testing, it is strongly recommended that the number of imaging receptors and their type and configuration be carefully considered when planning, especially in consideration of the time allotted to complete testing.

The variety of available imaging configurations has required a consideration of the imaging receptor form factor and whether the imaging receptor can be easily tested with the grid removed when defining testing approaches. In other cases, the anti-scatter grid may be fixed in the bucky or unremovable. Also, systems with removable grids may use grids with multiple focal lengths to accommodate multiple source-to-image distance (SID) values.

The science and technology of digital radiography imaging systems is constantly evolving, and this report does not delve into this complex subject for two main reasons: any such treatment would likely become quickly obsolete, and the complexity of these systems is out-of-scope for this report.

1.2 General Observations

In assessing the differences in testing methodology between screen-film systems and digital radiography imaging systems, several generalized observations help inform the approach to testing of the latter.

- When the evaluation involves production of large quantities of x-rays, the image receptor must be protected both to ensure the physical integrity of the receptor but also to ensure subsequent test results are not compromised.
- For most tests that are receptor-based or receptor-dependent, the protocol for testing must be re-evaluated in the context of the limitations imposed by the difference in receptor characteristics and form factor.
- When the image receptor itself is being evaluated, additional specialized tests specific to the receptor technology will be required in addition to adapted historical receptor-based tests.
- Many of the receptor tests and other tests that rely on the receptor may require access to unprocessed digital data, which may or may not be easily accessed from within the conventional clinical user interface. Access to this data is a key part of the NEMA/MITA Standard XR 30-2016 [18].
- Whereas many of the traditional tests based on screen-film had target values and tolerances expressed in units of optical density, targets and tolerances for digital radiographic systems must be expressed as pixel values or some other derived indicator of receptor air kerma.
- Because many facilities no longer use computed radiographic (CR) systems, all tests can be performed without CR cassettes. For those facilities that still use CR, some tests may include an alternate procedure that uses CR cassettes as a tool.
- Several of the tests use a beam quality similar to RQA5 as defined in IEC 61267-2 [17]. This simulates the beam quality of a 70 kV beam after exiting a typical patient but with minimal scatter. This is achieved by using a 70 kV tube voltage and a beam with a half-value layer of 6.8 mm of aluminum. This can be achieved by adding approximately 21 mm of aluminum at the exit port of the collimator. Alternately, the 21 mm of aluminum may be replaced with 0.5 mm of copper and 2 mm of aluminum, with the copper between the x-ray tube and the aluminum.
- Some tests require the use of a digital “distance measurement” software tool located on the acquisition workstation, on the diagnostic review workstation, or in an external Digital Imaging and Communications in Medicine (DICOM) image reader software application. The user should take note that these tools often report the distance measurements obtained based on an assumption that the imaged object was located at a nominal distance above the image receptor. To the extent that the test object may or may not lie in this plane, the distance measurements obtained may need to be corrected using the DICOM Estimated Radiographic Magnification Factor (ERMF) for the image; see Section 4.8.4 and Appendix B for details. For example, many radiographic systems report distance measurements referenced to the patient table when the image receptor is in the table bucky. With a 100 cm SID, and an image plane 7 cm below the patient table, the ERMF is approximately 1.07. Without taking this into account, distance measurements may be 7% off. For this reason, measurements taken with the image receptor “free in air” (i.e., on the table) may be simpler to interpret, as the ERMF will almost always be 1.0 in this situation.

1.3 Barriers to Testing of Digital Radiographic Systems

Members of the task group recognized that there are several fundamental challenges when testing digital radiographic systems in the clinical environment, including the wide variety of commercial digital radiographic systems with different receptor technologies and form factors, both of which complicate the definition of standardized tests. Based on the responses to our commercial survey and other feedback, we also recognized that manufacturers often have uniquely defined protocols for calibration of their systems using techniques that are not standardized across the industry. Though individual manufacturers often include specialized quality control test acquisition and processing functions within their software, performance results obtained on one system cannot easily be compared to other systems from another manufacturer at the same facility because there is no standardized convention for the test devices used, the test methodology, or the analytical or processing methods used.

As noted in the general observations, many of the tests require access to unprocessed data that are free from the nonlinear effects of digital image processing that may confound test results. In this report, we primarily use DICOM terminology, but use IEC nomenclature when appropriate (see Figure 1/ Table 1).

Table 1: Comparison and description of IEC and DICOM image terminology

DICOM	IEC	Description
None	RAW DATA	Image data that has not been modified to correct for image receptor or system limitations.
FOR PROCESSING	ORIGINAL DATA	Image data that has been corrected for defective detector elements, nonuniformity of the x-ray field, gain and offset of pixels, etc.
FOR PRESENTATION	PRESENTATION DATA	Image data that has been processed for display and diagnostic interpretation; for example, after applying nonlinear lookup tables, image filters, etc.
None	LINEARIZED DATA	Image data whose pixel values are proportional to image receptor data.

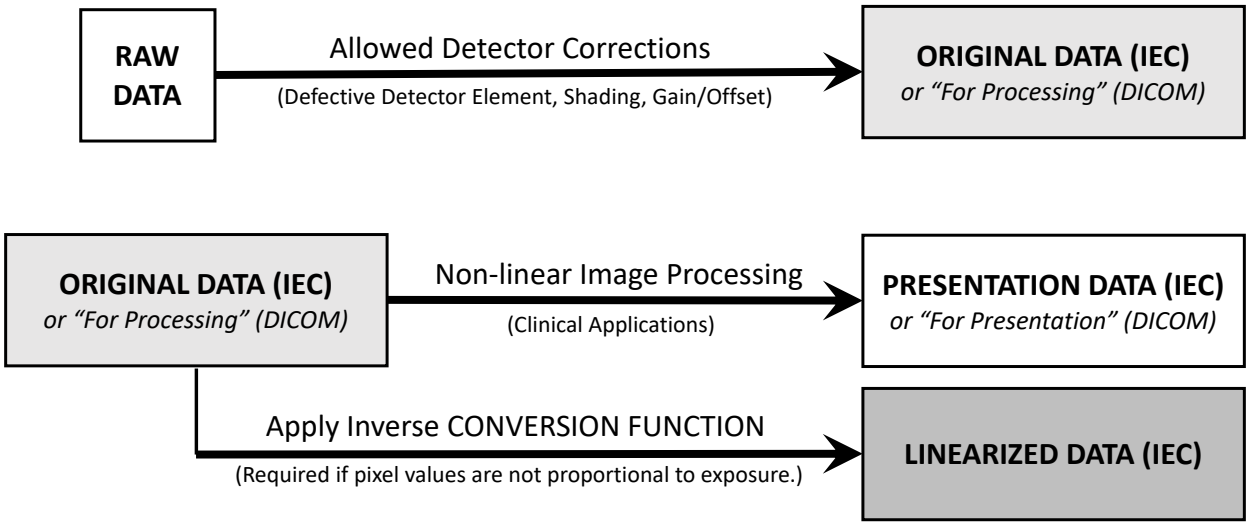

Figure 1. Generalized representation of the relationship between various digital radiography image data types as described in the IEC 62220-1-1 standard [15]. The IEC data types are shown in bold font, the equivalent DICOM presentation types are in italics. See Figure 2 of AAPM Report #116 [8] for additional information about the relationship between image data types.

Access to FOR PROCESSING data or LINEARIZED DATA is required for many objective tests, particularly advanced tests, which characterize system performance in terms of spatial frequencies; examples are the MTF(f), NNPS(f), and DQE(f). In addition, access to RAW DATA may be required to assess an image receptor for the location of and number of detector elements.

The finite time available to perform periodic testing was also recognized as an important consideration and necessitates that tests be ranked according to category and priority. Key tests should be performed first. Lower priority tests should be performed afterwards, as necessary. For acceptance testing, the physicist should prioritize tests that are needed to verify the safe and effective use of the system.

At the outset of our effort, the relative dearth of digital radiographic imaging systems in the clinical environment, the lack of standardized testing methods, and the difficulty in accessing the required image data types contributed to a relative lack of accumulated clinical expertise with these new systems. Thus, for many of the tests, the acceptable range and measurement tolerances for performance test results have not yet been established. Ideally, these tolerances should be defined based on the impact on clinical image quality; however, the correlation between imaging system performance metrics and the quality of clinical images is not well established, and establishing this relationship is beyond the scope of the current task group report. In cases where acceptance test result ranges are recommended in the task group report, they are based on values reported in the literature, trials conducted by the task group, reasonable estimates, or from comparisons to limits established for screen-film radiography or computed radiography where such comparisons are valid.

1.4 Use of Radiographic Test Tools/Objects

The intent of the task group was to avoid being prescriptive regarding the means by which testing must be performed. Rather than specifying new test devices such as quality control (QC) tools or phantoms, the task group concentrated on determining the test measurements that needed to be made and considered existing tools that could be applied to the task [19] [20]. Many of the tools that have been traditionally used for testing conventional screen-film x-ray imaging systems yield meaningful results when applied to digital radiography (DR); examples include focal spot, sector and line pair test tools. There are also several integrated test object phantoms that have been adapted to DR or were specifically designed for DR, including various commercially available test tools based on the Deutsches Institut für Normung (DIN) 6868 standard [21] [22]. In addition, there are several geometric patient-equivalent phantoms originally developed for traditional radiography that can be used with DR, namely the American National Standards Institute (ANSI) Chest, Skull, and Extremity phantoms [7], Modified ANSI Abdomen/Lumbar Spine phantom [7], the Center for Devices and Radiological Health (CDRH) Chest [7] [23] [24], Abdomen/Lumbar Spine [7] [25], and Pediatric Chest phantoms, and the American College of Radiology (ACR) radiofrequency (RF) phantom [26].

1.5 Use of Existing Vendor-Provided Automated Test Results

Several manufacturers have developed and incorporated into their own clinical systems manual, semi-automated, and fully automated test procedures, often utilizing a propriety integrated test tool phantom such as those described in the prior section and their own proprietary software. Where available, these automated test protocols may provide an alternative methodology for some of the tests described in this report, which can facilitate testing especially where the manufacturer has provided acceptance ranges for results obtained following their testing protocol.

With the publication of the guidance contained in this report, there is an opportunity for commercial manufacturers of digital radiographic imaging systems to adopt standardized test and analysis methods, which would facilitate comparisons in environments where many different makes and models of digital x-ray imaging systems are in use. The recent emergence of vendor-neutral QC database and

reporting systems would suggest that there is a trend toward more automation in the management of imaging system QC at the enterprise level. Such approaches can facilitate the work of medical physicists when there are common and comparable performance metrics being reported.

1.6 Performance Measurements in the Digital Domain

Optimization of image quality in radiography at a fundamental level could be described as "the quest for contrast." In the most general sense, image contrast can be thought of as the difference in signal between two features that differ in composition, density, and/or thickness. In screen-film systems, image contrast was relatively fixed and dependent on radiographic technique, subject contrast, film characteristics, and film processing. However, in digital radiography, electronic image processing can be applied to modify image contrast (and other characteristics), but it cannot recreate image contrast that did not exist in the original image data due either to physical subject contrast limitations or to receptor limitations.

Electronic image processing is key to the successful use of digital radiographic imaging systems for clinical purposes, and medical physicists should verify that the images provided by such systems meet diagnostic requirements. However, for the most part the performance testing of an imaging system conducted by medical physicists should be made on linear ORIGINAL DATA or LINEARIZED images (see Table 1).

The importance of using LINEARIZED images is illustrated by the following example. Consider an object that differs in attenuation from its surroundings such that the air kerma in the imaging plane behind the object is 9 μGy and the air kerma in the imaging plane of the surroundings is 10 μGy. The subject contrast is (10-9)/10 or 10%. Assuming the same efficiency of conversion, and linear conversion into a digital value, the receptor contrast is also 10%. However, for systems with a logarithmic dose response curve described by:

$$PV(AK) = C + B \log_{10}\left(\frac{AK}{AK_{ref}}\right) \tag{1}$$

where PV is the pixel value, AK is the air kerma, and C, B, and AK_{ref} are calibration constants, the receptor contrast is given by:

$$\frac{PV(10\mu Gy) - PV(9\mu Gy)}{PV(10\mu Gy)} = \frac{B \log_{10}(10/9)}{C + B \log_{10}(10/AK_{ref})} \tag{2}$$

In other words, not only is the receptor contrast not equal to the subject contrast, it also depends on the details of the dose-response curve. This is not an unfamiliar effect: recall that the characteristic function of screen-film receptors is also nonlinear, and logarithmic with respect to air kerma for a major portion of its dynamic range.

Chapter 2 - Required Resources and Prerequisites

Successful implementation or commissioning of a clinical digital radiographic imaging system and the determination of whether it is acceptable for clinical use will be contingent on many factors. The medical physicist has primary responsibility for these components of commissioning:

- compliance with the vendor's stated device performance claims,
- compliance with aspects of performance covered by local, regional, national, or international safety or practice standards and regulations, and
- verification that the system has been properly calibrated and configured for interoperability.

In addition, the medical physicist may work with the lead technologist and radiologist to ensure that the system:

- has acceptable clinical workflow and uptime, and
- is deemed by the interpreting radiologist(s) to have sufficient image quality for accurate diagnosis.

Consequently, an effective acceptance and commissioning process for digital radiographic systems requires planning and coordination among the vendor's installation and service engineers, the facility's in-house service engineers (if applicable), the medical physicist, the facility's radiologic technologists, the vendor's applications specialists, and preferably a lead radiologist for the facility. The roles and responsibilities of each, summarized here and elaborated further in Sections 2.2 and 2.3 below, should be understood as a representative and achievable optimum, but will of course vary depending on availability of personnel.

In addition, the facility's picture archiving and communication system (PACS) support personnel and other appropriate Information Technology personnel must be involved in assuring proper system interoperability, as discussed in Section 2.1 below and fully in AAPM Report 248 [10].

2.1 Site Preparation for Interoperability

For most clinical-use scenarios, the use of a DR system depends on interoperability with a host of other systems, including Radiology Information System (RIS), PACS, post-processing workstations, and clinical viewers. Nominally, interoperability might be assured by a vendor in an IHE (Integrating the Healthcare Enterprise) Integration Statement [27]. However, it is recommended that responsibility for interoperability be established through the purchasing process by requiring the vendor to agree to meet specific requirements as discussed in AAPM Report 248 [10] and that meeting these requirements is part of the criteria for acceptance of the system. Otherwise, the vendor may refer the site to its DICOM conformance statement and assume no responsibility for interoperability, leaving validation and clinical readiness assessment to the site.

Since, in most cases, the DR vendor is coming into an existing and established digital imaging environment, these contractual conditions should describe the existing environment and list those systems for which the vendor must provide interoperability. For example, these may include the following:

1. All networked devices must adhere strictly to DICOM 3.0 standards using the TCP/IP protocol. No other protocols or proprietary networking configurations of any kind will be acceptable.
2. All networked components supplied as part of this DR system, which must connect to the site's existing network, must connect via 10/100/1000-Base-T Ethernet connections, or where applicable the site's wireless network. Ethernet-connected devices must be able to operate with both 100-Base-T and 1000-Base-T connection. Actual connection rate and type will be determined in conjunction with site's Information Technology personnel.

3. The vendor must provide the site with MAC addresses for all devices to be connected to the site's network; the site will then provide Application Entity titles, IP addresses, and gateway addresses and masks. Appropriate site personnel must be able to define and modify all DICOM and network-related parameters for ALL devices.
4. Certain types of network traffic, such as frequent broadcasts, are not allowed on the site's network, and provisions to avoid them are required. Where possible (if applicable), arrangements should be made for testing of networked devices in the site's Information Technology test labs.
5. The purchase contract should specify other systems with which the vendor's provided system is expected to provide interoperability, including the PACS, RIS, Hospital Information System (HIS), 3D workstations, structured dose reporting system, etc.

Before the medical physicist begins acceptance testing, they should verify that the imaging acquisition system is able to send images to the PACS in order to permit system end-to-end testing. Ideally, the medical physicist will have direct access to the PACS for image interpretation and for interoperability testing as described in AAPM Report 248. If this direct access is not available, the medical physicist should request that a technologist with this access be assigned to assist during testing.

Many of the tests in this report require the use of FOR PROCESSING images; however, for many acquisition workstations, it is impossible to export FOR PROCESSING images directly to PACS. In those cases, the images will need to be exported from the acquisition workstation to removable media for importing to a computer with a DICOM-compliant image review application.

Finally, troubleshooting and imaging chain optimization will generally be a team effort. The medical physicist should understand the imaging subsystems and any variables that can impact the image, starting from the x-ray tube and generator through to final interpretation viewing station, and should work in coordination with clinical engineering, vendor applications and service personnel, PACS support personnel, the lead x-ray technologist, and the radiologist as necessary to identify and resolve issues during testing. Each of these individuals provides special knowledge of workflow, data flow, and possible factors that could affect image quality and information integrity at each point in the imaging chain.

2.2 Personnel – Roles and Responsibilities

2.2.1 Service Engineer

The vendor's service engineer for the site will generally be included as part of the vendor's installation team. The service engineer should be available, either in person or by phone, during physics acceptance testing and should be able to answer—or obtain answers to—questions arising during acceptance.

If the site arranged for or intends to use some level of in-house servicing, and if the vendor or contractual arrangements permit, it is valuable to have the in-house clinical engineer work with the vendor service engineer during the installation and calibration. The medical physicist may find it valuable to participate in part of this work if they are responsible for overseeing the imaging receptor calibrations post-installation.

2.2.2 Medical Physicist

The medical physicist is responsible for the performance of acceptance and annual testing of the digital radiographic imaging system and is also responsible for the oversight of the overall quality assurance program, which includes the periodic quality control monitoring tests (and calibrations) performed by technologists. The terms "physicist" or "medical physicist" in this report means a medical physicist competent to test diagnostic imaging systems as defined by regional authorities, such as the "Qualified Medical Physicist" as defined by the AAPM in the United States [28] or the "Medical Physics Expert"

as defined by the European Union [29] [30]. Since the acceptance process is the most opportune time to identify and correct issues and deficiencies, the acceptance testing should be both rigorous and thorough. The physicist should obtain and review the system technical specifications in advance of testing. This information can be obtained in the summarized technical specifications data sheet, in white papers provided by the manufacturer, and in the user manual. The IEC now requires manufacturers to provide Instructions For Use (IFU) documents; however, what is included as an Instructions for Use document is left up to manufacturers. Therefore, an Instructions for Use document will be vendor-specific, and any document such as the user manual, technical manual, operator manual, etc. may qualify as an Instruction for Use document. Additional information may also be obtained from the technical comparison studies published in the literature. Although not strictly a physics responsibility, it is quite important to obtain a copy of the system purchase order and, as a first step in acceptance, perform a system "audit": i.e., verify that the delivered system (components and accessories) is both complete and as specified. If any components are unavailable at the time of testing, the acceptance report should indicate this and specify whether follow-up testing is required.

If the facility has other units of the same model that have been previously installed, it may be possible to request that the service engineer preloads the facility's approved clinical protocols before acceptance testing. Otherwise, in some cases it may be necessary for the medical physicist to repeat some tests after applications training. This would certainly be the case for any dosimetry tests that relied heavily on clinical protocols, as the technique parameters for these protocols may have been changed or optimized by the applications specialist. It is essential to ensure that adequate time has been allotted to accommodate acceptance testing by the medical physicist and the resolution of any significant performance issues before first clinical use. The schedule should include a testing interval of a week, which includes 1–2 days for acceptance testing, plus additional days for service intervention to resolve any identified issues. Otherwise, failure to allocate sufficient time to resolve issues identified during medical physics testing might preclude patient scanning during clinical applications training, which could significantly constrain the usefulness of this training or cause delays in clinical implementation.

The medical physicist may have identified issues during testing that require service intervention, and additional issues may be identified during applications training. Therefore, follow-up service after acceptance testing and applications training may be necessary in which case additional post-service testing by the medical physicist may be required. Depending on the medical physicist's judgment, they may recommend accepting service reports as evidence of a problem being resolved, delegate the verification of the repair to an appropriately trained individual who may be either a technologist or a physicist assistant, or perform the repeat testing themselves. Repairs should be accomplished promptly, and verification of a repair should be accomplished as soon as possible but generally within 30 days or sooner depending on the severity of the repair (e.g., prior to clinical use if there is a safety issue associated with patient table, etc). Overall, based on evaluation of the system, a medical physicist should comment if the system is safe for clinical use.

2.2.3 Clinical Applications Specialist

The vendor's clinical applications specialists will generally not be available until applications training. Though the clinical application specialist nominally trains the facility's technical staff, it has become more common that they also perform additional configuration of various programmed system functions, including protocols for different exams and patient positions, image processing presets, and dose index parameters. A consequence of this process is that certain parts of physics testing may need to be repeated (at least in part) following applications configuration. These include automatic exposure control (AEC) air kerma measurements, since these will change if exam-specific AEC air kerma values ("speed" settings) and target values are adjusted.

2.2.4 Registered Radiologic Technologist

The registered radiologic technologists are the ones who will ultimately be using the system. Although their role in the acceptance process prior to applications training is generally limited, it is quite useful to perform the system equipment inventory mentioned above with a lead technologist present. This will help assure that all ancillary equipment the technologists will require, such as image receptor holders, straps, etc., are present.

2.2.5 Radiologist

Since image processing presets on modern digital systems are highly configurable, it is essential that a designated lead radiologist be available to review the appearance of processed images and verify that they match expectations as closely as possible. This should be done for at least a limited number of representative projections, such as a PA chest, an AP abdomen, an AP L-spine, and an extremity. If sample images are unavailable on the system for this evaluation, then it may need to be done in real-time during the first few clinical uses of the system.

2.3 Training

Comprehensive training of the site's personnel will generally be required for optimum and safe clinical use of digital radiography systems because of their complexity; consequently, this training is often mandated by various governmental or accrediting organizations. This training should ideally be conducted after acceptance testing but before routine clinical use of the system, should be structured, and include a sign-in sheet to facilitate documentation of attendance for the purpose of demonstrating compliance with regulations.

Maximum benefit from applications training is attained if there is a good understanding of the technology of digital radiographic systems, whose underlying science can be complex. This is particularly true for the use of dose indices to help guide proper exposures. Providing didactic education on some of these concepts prior to applications training can provide a good foundation in the basic concepts so that the applications training is more effective. This didactic education should cover the basics of digital radiographic imaging receptors and technology, the definition and use of dose indices to control patient exposures, and the specific implementation of dose management for the current system. The medical physicist is uniquely positioned to provide this education. Alternatively, educational content from the vendor can be reviewed by staff prior to applications training.

While clinical applications training is typically targeted to the technologist staff who will be using the system clinically, medical physicists may also benefit from exposure to some of the applications training curriculum, especially if they are overseeing the imaging system QA program.

Chapter 3 - Recommended Schedule of Quality Control (QC) Testing/Monitoring

The allotted time for testing will be heavily dependent on the number of digital imaging receptors being installed with the unit, the number of grids and their configuration, and whether the unit will be used with other ancillary imaging receptors such CR cassettes. Image receptor tests should be performed for each independent imaging receptor in use on the system.

Table 2 below summarizes the order and frequency of tests described in each section of Chapter 4. The order of the tests in Table 2 takes into account that the results of some tests are prerequisites for subsequent tests. The main points to consider in this regard are:

- Displayed SID and collimation dimensions should be verified before tests that rely on them are performed.
- The accuracy of the digital software calipers must be confirmed prior to performing x-ray collimated field size, focal spot, or other tests requiring accurate distance measurements within the image.
- Verification of the generator calibration and air kerma rates at multiple tube voltages are fundamental and should always be done first. Inaccurate tube voltages or air kerma rates outside expected ranges can significantly affect many remaining tests. Calibration errors should be corrected by a service engineer before testing continues.
- Proper calibration of the exposure index must be ascertained prior to its use as an image receptor exposure surrogate during AEC tests.
- Flat field tests of the image receptor should always be performed before tests requiring test object(s), to avoid the impact of transient image artifacts on the flat field tests.
- Grid misalignment can substantially affect image quality tests, AEC tests, and any tests that use the AEC, so grid alignment evaluation must precede those tests.
- Tests that require the same beam quality, such as RQA5, are generally grouped together.

The individual physicist may find it convenient to reorder and combine some of these tests; Table 2 is merely a guide.

Each test is placed in one of the following importance categories:

- **Rec: Recommended.** These are tests may be necessary to verify compliance with state or local regulations, or that Task Group 150 considers to be important for verifying adequate image quality or acceptable patient dose.
- **Opt: Optional.** Some of these tests may be useful in diagnosing problems with the equipment; others test important performance parameters that are unlikely to change after acceptance.

Table 2: Recommended order and frequency of QA tests

QA Test	Acceptance Testing	Periodic Testing	Notes
PREPARATION (See Note 1)			
Review operation manual	Rec	Opt	-
Inspect facility and verify radiation safety	Rec	Opt	-
Inventory the equipment	Rec	Opt	-
Visual inspection (collimator, patient table, cables and insulation)	Rec	Rec	-
Test of emergency stop buttons	Rec	Rec	Note 2
ACQUISITION DISPLAY MONITOR TESTS (See Note 3)			
See AAPM Report 270 for details [11]	Rec	Rec	-
SYSTEM TEST			
Determination of ERMF	Rec	Opt	Note 4
X-RAY COLLIMATOR			
Light field illuminance	Rec	Rec	-
SID indicator accuracy	Rec	Rec	Note 4
X-ray field/light field alignment	Rec	Rec	-
Collimator dial accuracy	Rec	Rec	Note 4
X-ray field/image receptor alignment	Rec	Rec	Note 4
Positive beam limitation (PBL)	Rec	Rec	Note 4
User selectable filtration	Rec	Opt	-
Off-focus radiation	Rec	Opt	-
X-RAY GENERATOR			
X-ray beam on controls/indicators	Rec	Rec	-
Tube voltage accuracy & reproducibility	Rec	Rec	-
Tube output levels	Rec	Rec	-
Air kerma reproducibility	Rec	Rec	-
Aluminum half-value layer (HVL)	Rec	Rec	-
Exposure timer accuracy & reproducibility	Rec	Rec	-
Air kerma linearity	Rec	Rec	-
Tube voltage and air kerma waveforms	Rec	Opt	-
Focal spot size	Rec	Opt	-
Spatial resolution at clinical magnification	Rec	Rec	-
Spatial resolution uniformity	Rec	Opt	-
Leakage radiation	Rec	Opt	-
SYSTEM TESTS			
Exposure index accuracy	Rec	Rec	Note 4
Displayed air kerma and kerma-area product (KAP) accuracy	Rec	Rec	-
BASIC IMAGE RECEPTOR FLAT FIELD TESTS (See Note 5)			
Pixel value/air kerma response	Rec	Opt	-
Visual inspection of flat field images	Rec	Rec	-
ADVANCED IMAGE RECEPTOR FLAT FIELD TESTS (See Note 5)			
Signal uniformity	Rec	Opt	-
Noise uniformity	Rec	Opt	-
Signal-to-noise ratio (SNR) uniformity	Rec	Opt	-
Minimum SNR	Rec	Opt	-
Dark noise analysis	Rec	Opt	-

(continued)

Table 2: Recommended order and frequency of QA tests (continued)

QA Test	Acceptance Testing	Periodic Testing	Notes
Correlated noise	Rec	Opt	-
Defective detector element detection	Opt	Opt	Note 6
BASIC IMAGE RECEPTOR WITH TEST OBJECT (See Note 5)			
Spatial resolution	Rec	Rec	-
Contrast-to-noise ratio	Rec	Rec	-
Geometric accuracy	-	-	Note 7
Ghosting/lag	-	-	Note 8
Qualitative review of test object image	Opt	Opt	-
ADVANCED IMAGE RECEPTOR TEST (See Note 5)			
Detective quantum efficiency (DQE)	Opt	Opt	Note 9
GRID			
Lateral grid alignment and detent positioning accuracy	Rec	Rec	Note 4
Grid uniformity and artifacts	Rec	Rec	Note 4
AEC			
Minimum response time	Rec	Rec	-
AEC reproducibility	Rec	Rec	-
AEC sensitivity	Rec	Rec	-
Sensitivity selector	Rec	Opt	-
Density selector	Rec	Rec	-
Cell selection	Rec	Opt	-
Cell balance	Rec	Rec	-
Tube voltage tracking	Rec	Rec	-
Patient thickness tracking	Rec	Rec	-
Field of view compensation	Rec	Opt	-
Backup timer	Rec	Rec	-
IMAGE PROCESSING			
Stability of pixel values	Rec	Rec	-
Review of image processing parameters	Rec	Opt	-
Storage of image processing test images	Rec	N/A	Note 10
Evaluation of changes to image processing	N/A	Rec	-
SYSTEM TESTS			
Patient equivalent phantom test	Rec	Rec	-
End-to-end image chain test	Rec	Opt	-
INTEROPERABILITY (See Note 11)			
DICOM Modality Worklist configuration	Rec	Opt	-
DICOM Modality Worklist information display	Rec	Opt	-
DICOM Modality Worklist information accuracy	Rec	Opt	-
RIS (procedure) code mapping	Rec	Opt	-
Image transmission test	Rec	Opt	-
Image annotation test	Rec	Opt	-
Physical measurement consistency	Rec	Opt	-
Received image appearance	Rec	Opt	-
Propagation of image annotations and orientation/laterality	Rec	Opt	-
Physical measurement consistency	Rec	Opt	-

(continued)

Table 2: Recommended order and frequency of QA tests (continued)

QA Test	Acceptance Testing	Periodic Testing	Notes
Propagation and display of image metadata	Rec	Opt	-
Proper image compression settings	Rec	Opt	-
Patient information editing	Rec	Opt	-
Downtime procedure validation	Rec	Opt	-

Notes:
Note 1: These tasks are not described in detail in this report but are self-explanatory.
Note 2: The emergency stop buttons should be tested at installation and at least annually by service engineers while performing preventative maintenance. The medical physicist should verify that this has been done.
Note 3: A minimal test of the acquisition workstation display monitor should be done at the start of testing (e.g., look at SMPTE pattern and verify that 5% and 95% squares are visible, or look at TG-18 uniform grayscale images for nonuniformity). A full assessment can be deferred to the end of testing; see Report 270 [11] for more details.
Note 4: These tests should be performed on both the table and the wall bucky, if both are present. If CR plates will be used with the system, a relevant subset of these tests should be performed for one representative CR plate.
Note 5: All image receptor tests should be performed on each flat panel detector used with the unit.
Note 6: There is no validated procedure for detecting defective detector elements. Should a validated practical procedure be published, the task group would recommend that it be performed during annual testing.
Note 7: Geometric accuracy test is recommended for storage phosphor (CR) and optically coupled systems; however, flat panel detectors are less susceptible to geometric inaccuracies, so this test is optional for those systems.
Note 8: Ghost/lag testing is recommended for storage phosphor (CR) image receptors; flat panel detectors are much less susceptible to lag so this test is optional for those systems. However, a passive ghost test is recommended for flat panel systems; this consists of examining flat field images acquired after other tests with high contrast objects in the field. It should be performed immediately after the spatial resolution test, the geometric accuracy test, or any test involving a high contrast test object.
Note 9: The DQE test, listed as an optional test, is not described in detail in this report because it is an advanced test, which requires resources that may be beyond the availability of most physicists. DQE testing is highly recommended when evaluating new imaging receptor technologies in order to characterize system performance and compare against manufacturer specifications. For those wishing to perform DQE testing, there are several papers in the literature that provide guidance [31] [32] [33] [34].
Note 10: NEMA/MITA XR-30 provides recommendations to manufacturers for features to aid in verifying the stability of image processing. These tests are recommended for those systems that are compliant with this standard.
Note 11: Interoperability tests are recommended to be performed during acceptance testing; however, these tests may be performed by someone other than a medical physicist, preferably with oversight by a physicist.

Table 3: Suggested tests to be performed after major component replacement or repair

See note before Table 2 for a description of the Importance column (Rec – recommended; Opt – optional).

Test	Importance
X-ray Tube	
Tube output	Rec
Aluminum half-value layer	Rec
Focal spot size	Rec
Spatial resolution at clinical magnification	Rec
X-ray/light field alignment	Rec
X-ray field/image receptor alignment	Rec
Off-focus radiation	Rec
X-ray Generator	
Tube voltage accuracy	Rec
Tube output	Rec
Exposure timer accuracy	Rec
Air kerma reproducibility	Rec
Air kerma linearity	Rec
Tube voltage waveform	Rec
Focal spot size	Rec

(continued)

Table 3: Suggested tests to be performed after major component replacement or repair (continued)

See note before Table 2 for a description of the Importance column (Rec – recommended; Opt – optional).

Test	Importance
Spatial resolution at clinical magnification	Rec
Leakage radiation	Rec
Collimator	
Aluminum half-value layer	Rec
Mechanical inspection	Rec
X-ray/light field alignment	Rec
Light field illuminance	Rec
Collimator dial accuracy	Rec
SID indicator accuracy	Rec
X-ray field/image receptor alignment	Rec
Positive beam limitation	Rec
User selectable filtration	Rec
Off-focus radiation	Rec
Grid	
Lateral grid alignment and detent positioning accuracy	Rec
Grid uniformity and artifacts	Rec
AEC Cells	
AEC reproducibility	Rec
Minimum response time	Rec
AEC sensitivity	Rec
Sensitivity selector	Rec
Cell selection	Rec
Cell balance	Rec
Density selector	Rec
Tube voltage tracking	Rec
Patient thickness tracking	Rec
Field of view compensation	Rec
Backup timer	Rec
Software Change	
Determination of ERMF	Opt
Exposure indicator accuracy	Opt
Target exposure indicator values	Opt
Evaluation of changes to image processing	Opt
DICOM Modality Worklist configuration	Opt
DICOM Modality Worklist information display	Opt
DICOM Modality Worklist information accuracy	Opt
RIS (procedure) code mapping	Opt
Received image appearance	Opt
Propagation of image annotations and orientation/laterality	Opt
Physical measurement consistency	Opt
Propagation and display of image metadata	Opt
Proper image compression settings	Opt
Patient information editing	Opt
Downtime procedure validation	Opt

Table 4: List of tests that may be combined, if certain conditions are met

Tests	Condition
Determination of ERMF Geometric accuracy	Grid of lines of radio-opaque material is available
Geometric accuracy (FPD only) Spatial resolution uniformity	Wire mesh is available
Collimator dial accuracy X-ray/light field alignment X-ray field/image receptor alignment	See note below
Tube voltage accuracy & reproducibility Tube output Air kerma reproducibility Aluminum half-value layer Exposure timer accuracy & reproducibility Tube voltage waveform Air kerma linearity	Solid state dosimeter with HVL and kV waveform readouts is available

Note: the x-ray/light field alignment test is most easily performed on the tabletop, and the x-ray field/image receptor alignment test must be performed in the bucky. The collimator dial accuracy test can be done on the tabletop only if the collimator displays the correct SID when the image receptor is on the tabletop. If the image receptor cannot be removed from the bucky, then all three tests may be combined.

Chapter 4 - Acceptance and Performance Tests

This chapter contains detailed instructions for performing many of the tests listed in the previous chapter. However, they are ordered by category, rather than by suggested order of testing. We recommend using the tables in Chapter 3 as a guide to selecting which tests to perform and in what order.

Most tests in this section include expected performance limits. These performance limits may or may not conflict with statutory requirements written into national, state, or local regulations. Where conflicts exist, the statutory requirements take precedence. Note that some tests use action limits based on Food and Drug Administration (FDA) performance standards. However, in 2019, the FDA issued guidance allowing manufacturers to meet IEC standards in lieu of the FDA standards [35].

The foundation of any quality assurance program in digital radiography should ideally follow the vendor's recommendations regarding preventive maintenance, service and repair, and initial and periodic calibration (especially the image receptor), and include manufacturer-recommended routine quality control tests to confirm the system is operating as expected. In the case of routine QC tests, some vendors will have implemented an automated QC test acquisition interface often in conjunction with use of a specified "one shot" phantom, with meaningful PASS/FAIL criteria and tracking capabilities. However, as there can be variability in vendor guidance and support for QC testing, it may be necessary for the medical physicist to either specify the routine QC testing to be performed by technologists or supplement the manufacturer's recommendations with additional tests. The technologist's QC program should at minimum be based on the manufacturer's recommendations.

As the medical physicist is typically responsible for oversight of the imaging system's QC in digital radiography, the medical physicist performing acceptance testing should devote part of their effort to assessing the manufacturer's recommendations regarding device calibration and routine QC with particular emphasis on the methodology and resources supplied. Any additional recommendations from this assessment should be included in the acceptance test report by the medical physicist. Medical physicists are urged to consult TG-151 for additional guidance on implementing a routine digital radiography QA program.

Many of these tests require the use of a dosimeter. A dosimeter may display either air kerma or exposure, depending on the model and/or settings. These written procedures use the term "air kerma" rather than "exposure," and the term "exposure" is reserved to mean "irradiation event." The term "dosimeter sensor" is used to refer to either the ionization chamber or the solid-state dosimeter sensor, as appropriate, unless explicitly specified in any subsection of this report. In this document, the solid-state dosimeter sensor implies measurement device that does not include backscatter in measurements (thus, the solid-state dosimeter is only measuring or is only sensitive to the incident air kerma).

Many of these tests involve acquiring test images that are sent to a PACS for further analysis. It is prudent to add annotations, either using lead markers or digital annotations, to these images to avoid ambiguity during analysis.

As part of the acceptance testing, the medical physicist should take the opportunity to confirm that the site has met all radiation safety regulatory requirements related to the use of the X-ray equipment such as:

- required postings are in the use area,
- the device has been registered with the appropriate oversight authority,
- required warning labels are present on the device,
- the x-ray tube housing leakage radiation is acceptable, and
- there are personal protective devices provided for operators if the unit is a mobile x-ray system, or that the room in which the device has been installed has been properly shielded as confirmed by an approved shielding plan from the appropriate regulatory authority and that post-installation verification of installed shielding has been performed by a qualified medical (or health) physicist.

4.1 X-ray Generator Tests

Introduction

The term "x-ray generator" typically refers to the power supply that provides the x-ray tube with a quasi-constant high voltage and provides current for the cathode, as well as the control system for the power supply. This section of the report covers the testing of both the x-ray generator and the x-ray tube.

The designs of x-ray generators and tubes have not changed significantly since the introduction of the high-frequency generator in the 1980s. However, AAPM Report 14 [5] "Performance Specifications and Acceptance Testing for X-ray Generators and Automatic Exposure Control Devices" was published in 1985, before the common use of digital image receptors in the clinical setting. Many established QA and QC procedures for testing x-ray generators make use of screen-film cassettes and direct film cassettes, particularly in measurements of the focal spot size and the collimated x-ray field size. With the emergence of digital imaging, it is becoming increasingly common for facilities to have no film or CR cassette processing capability, making the use of film-based or CR-based techniques impractical. This section describes techniques for making these measurements without the use of film or CR cassettes.

Test equipment required

Except for the focal spot size and spatial resolution, all of the following tests require that the image receptor be protected from the x-ray beam. This can be accomplished either by removing the image receptor from the bucky, moving the bucky and the image receptor out of the beam, or by covering the image receptor with a lead attenuator such as a lead apron when the image receptor is fixed.

Test	Required equipment
Tube voltage (kV) accuracy and reproducibility	Noninvasive kV meter. A multimeter that can simultaneously measure kV and air kerma and can display kV or air kerma waveforms is preferred.
Aluminum half-value layer (manual measurement)	Ionization chamber with dosimeter. If an ionization chamber is not available, a solid-state dosimeter may be used if appropriately calibrated. Aluminum sheets (type 1100[2]), 0.5 mm to 2 mm thick and approximately 10×10 cm, that can be combined for thicknesses of at least 2 mm to 6 mm in steps of 0.5 mm. Test stand for holding filters.
Aluminum half-value layer (automatic measurement)	Solid-state dosimeter with automatic HVL measurement.
Exposure timer accuracy	Dosimeter capable of measuring exposure time. A solid-state multimeter capable of measuring air kerma, tube voltage, and voltage and/or air kerma waveforms is preferred.
Air kerma reproducibility Air kerma linearity Tube output	Ionization chamber with dosimeter or solid-state dosimeter.
Tube voltage and air kerma rate waveforms	A multimeter that can simultaneously measure kV and air kerma and can display kV or air kerma waveforms.
Focal spot size	Star pattern. Spatial resolution test object (e.g., bar pattern). Test stand approximately 30 cm tall. Measuring tape. Orientation marker (e.g., pen).
Spatial resolution at clinical magnification	Spatial resolution test object (e.g., bar pattern). Test stand approximately 30 cm tall.
Leakage radiation	Dosimeter capable of measuring air kerma rate. Lead sheet (3-4 mm thick). Distance measuring tape.

[2]Type 1100 aluminum is described in footnote 1 of 21 CFR 1020.30 [12].

Expected results

Table 5: Expected results for each generator test

Test	Tolerance
Tube voltage accuracy and reproducibility	Accuracy: within 5 kV or 5%, whichever is greater. Reproducibility: within 5%.
Tube output	+/– 50% from Report 25 values [6] +/– 10% from measured baseline
Aluminum HVL	Must be greater than or equal to values specified by local regulations
Exposure timer accuracy	1 millisecond (ms) for exposure times of 20 ms or less 5% for exposure times more than 20 ms
Air kerma reproducibility Air kerma linearity Tube output	Coefficient of variation should be 5% or less Milligray (mGy)/milliampere (mAs) must match to within 10% for all adjacent stations For each station, mGy/mAs should match average of all stations to within 10%.
Tube voltage and air kerma rate waveforms	Rise time to 95% of nominal within 1 ms Fall time from 95% of nominal within 1 ms Peak-peak ripple < 5% of nominal value
Focal spot size	Acceptance testing: must be less than IEC limits Annual testing: should be less than IEC limit x 1.10.
Spatial resolution at clinical magnification	Acceptance testing: N/A Annual testing: within 10% of baseline at acceptance
Leakage radiation	Acceptance testing: Leakage radiation is below the regulatory limit (< 0.88 mGy/hour at 1 m) and as per manufacturer specifications

Description of tests

4.1.1 Tube Voltage (kV) Accuracy and Reproducibility

Rationale

Tube voltage (or kV) can strongly impact patient radiation dose and image contrast. In general, image display optimization algorithms of digital radiographic systems will tend to mask kV-related changes in image contrast. In addition, a well-calibrated automatic exposure control will compensate for inaccurate or unstable tube voltage by maintaining a consistent image receptor air kerma for exposures with AEC. Thus, testing the accuracy and reproducibility of the tube voltage is important to detect problems covered up by the image processing and AEC.

Since there is a trend toward use of higher x-ray filtration with digital radiographic systems, it is important to use a kV meter that is insensitive to variations in beam quality or at least have available appropriate manual HVL-dependent corrections. If the kV meter allows firmware to be updated, be sure that the most up-to-date software is loaded.

Recommended method

Tube voltage testing is the same as for non-digital systems but with one essential difference: the image receptor must be protected from the x-ray beam to avoid burn-in. The term “dosimeter sensor” refers to a solid-state dosimeter sensor.

1. Remove the image receptor from the beam path, either by removing it from the bucky assembly or moving the bucky assembly. If the image receptor cannot be removed, ensure that the image receptor is shielded from the entire collimated beam.
2. Place the dosimeter sensor in the center of the x-ray beam on the tabletop and ensure that the orientation of the sensor relative to the anode-cathode axis is correct. The correct orientation will depend on the specific sensor model being used.

3. If possible, select an option to use an "alternate image receptor" (e.g., CR cassette) to avoid acquiring an image with each exposure.
4. Remove any added or user-selectable filtration from the beam.
5. If the kV meter has different configurations for different waveforms, kV ranges, etc., verify that the kV meter is configured appropriately for the system being tested.
6. If using a multimeter capable of displaying or recording kV waveforms, turn on the waveform feature. This information will be used for the kV waveform test (Section 4.1.7).
7. Using an exposure time about 100 ms (e.g., 10 mAs and 100 mA), measure the tube voltage for the large focal spot over a range of clinically used kV stations (at least 60 kV, 80 kV, 100 kV, and 120 kV), and for at least one kV station (e.g., 60 kV) using the small focal spot.
8. For at least one kV/mA combination, repeat the measurement at least three times to verify tube voltage reproducibility. This combination should be representative of clinical use.
9. Using a short exposure time (e.g., 1 mAs and 100 mA), measure the tube voltage at a clinically used tube voltage (e.g., 80 kV).
10. During acceptance testing, verify tube voltage accuracy for each discrete mA station at one tube voltage (for example, 80 kV); this is because discrete mA stations may have different tube voltage calibrations. If using a multimeter for these tests, this may be performed simultaneously with air kerma linearity tests.

Alternative methods

Invasive kV testing, either using step down transformers in parallel with the tube or test points in the generator circuit, can provide kV values as well as waveforms independent of any effects of the condition of the tube or collimator assembly. This is useful for troubleshooting; however, these methods are too laborious for routine QC and are therefore not recommended. Moreover, directly accessing test points in the generator circuit should not be attempted without specific training from the equipment manufacturer.

The end point kV can also be determined by x-ray spectroscopy or through interpretation of the image of a penetrometer. However, these methods are more inconvenient than commonly available kV meters, so they are also not recommended for routine QC.

Expected performance limits

Measured tube voltage accuracy within 5 kV or 5% (whichever is greater) relative to the displayed value and the reproducibility, described by the coefficient of variability, within 0.05 (5%) are expected, as with film/screen systems. In practice, high frequency generators—now by far the most used with digital radiographic systems—can be calibrated with high accuracy and operate with high precision. It is reasonable to aim for tighter tolerances when attempting to match output and performance of multiple DR systems at a single site, particularly for devices of the same model.

Potential findings

- A failure of this test may indicate inappropriate filtration or incorrect voltage calibration. Contact the service engineer to investigate.
- If the measured tube voltage for a short exposure time differs significantly from the measurement for a long exposure time, the kV waveform should be examined.

Potential pitfalls

- It is essential that the image receptor be protected from the x-ray beam during this test.
- It is important that the meter be calibrated for the tube filtration used, or that appropriate manual HVL-dependent corrections are available.
- Ensure that the orientation of the dosimeter sensor relative to the anode-cathode axis is correct. The correct orientation will depend on the specific model dosimeter being used.

- The kV measurement may be inaccurate if additional filtration is left in the beam.
- Most noninvasive meters have selectable settings for different waveform types and voltage ranges, and correct settings for current measurement conditions should be verified before each test.

4.1.2 Tube Output

Rationale

The image receptor must be removed or covered for this test. If the tube output is too high, it may indicate inadequate filtration that may result in excessive patient dose. If the tube output is too low, it may indicate an aged tube that will require longer exposures to achieve desired image receptor dose.

Recommended method

Verify that the ratio mGy/mAs calculated as part of the air kerma linearity test (Section 4.1.6) falls within the limits below.

Alternative methods

None noted.

Expected performance limits

The results should match the baseline determined during acceptance testing to within 10%.

The following table lists typical tube outputs for a high frequency generator averaged over measurements done on 10 different model radiographic units. Measured tube outputs should generally match these values to within 30%.

Table 6: Typical tube output as a function of tube voltage measured 100 cm from the focal spot

kV	mR/mAs	mGy/mAs
50	1.83	0.016
60	2.92	0.025
70	4.13	0.036
80	5.25	0.046
90	6.97	0.061
100	8.3	0.072
110	9.98	0.087
120	11.73	0.102
130	13.31	0.116
140	15.1	0.131

Potential findings

A failure of this test may indicate inappropriate filtration, incorrect mA or kV calibration, or inaccurate timing. Contact the service engineer to investigate.

Potential pitfalls

None noted.

4.1.3 Air Kerma Reproducibility

Rationale

The exposure timer accuracy (Section 4.1.5) is sensitive to inaccuracies in the length of the exposure, but is not sensitive to changes in the air kerma rate from one exposure to the next. The present test is sensitive both to variations in exposure time and in air kerma rate.

Recommended method

1. Remove the image receptor from the beam path, either by removing it from the bucky assembly or moving the bucky assembly. If the image receptor cannot be removed, ensure that the image receptor is shielded from the entire collimated beam.
2. Place the dosimeter sensor on the patient table at the center of the light field.
3. Select the manual mA mode, and set the tube voltage and mAs to typical clinically used values; for example, 80 kV and 10 mAs.
4. Acquire three to five exposures in manual mode at the same settings; record the air kerma displayed by the dosimeter for each exposure.
5. Calculate the coefficient of variation (standard deviation divided by average) for the dose measurements.

Alternative methods

None noted.

Expected performance limits

The coefficient of variation should be 5% or less.

Potential findings

A failure of the air kerma reproducibility may be a symptom of a deeper problem, and may cause invalid results for other tests. Contact the service engineer to investigate the source of the problem.

Potential pitfalls

None noted.

4.1.4 Aluminum Half-Value Layer (HVL)

Rationale

The half-value layer (HVL) characterizes the primary x-ray beam quality. The HVL is a function of the tube voltage (kV), the total filtration of the beam, and lesser factors such as the tube angle. The test is performed by determining the thickness of aluminum required to reduce the air kerma rate of the x-ray beam to half of its value. The Code of Federal Regulations (21 CFR 1020.30 (m)(1)) [12] specifies minimum values of HVL for radiographic equipment sold in the United States; many states require that x-ray machines in clinical use continue to meet these requirements. International regulatory agencies may use other criteria, e.g., total equivalent filtration is specified rather than the HVL in some European countries.

Commercially available survey instruments can determine the value of HVL with a single exposure. For routine use, the "Standard Procedure (automatic measurement)" using one of these instruments may be adopted. If using such equipment, be sure to validate the displayed HVL values by comparing to the results of the manual procedure described in this section before relying exclusively on the automatic measurement.

The "Alternative Procedure (manual measurement)" below makes use of an ionization chamber and aluminum attenuators and is the gold standard for HVL measurements. It should be used when:

- A solid-state dosimeter is not available,
- The accuracy of the solid-state dosimeter is unknown or suspect, or
- A secondary check of the solid-state dosimeter is desirable; for example, when the measurement differs from the action limit by an amount less than the uncertainty of the dosimeter.

Although the manual procedure using an ionization chamber is the gold standard, using a calibrated solid-state dosimeter that reports HVL will allow rapid measurement of HVL at multiple tube voltages. If there is reason to doubt the accuracy of these HVL measurements, or the measured values

are close to the regulatory limit, we recommend a measurement of the HVL using aluminum sheets and an ionization chamber.

When a solid-state dosimeter is not available during annual testing, we consider HVL testing to be optional if all the following conditions are met:

- Local regulations do not require annual HVL testing,
- The measured tube output and tube voltage (measured using the same kV, mAs settings, and source-chamber distance as the baseline measurements) are close to the baseline values, and
- The baseline measurement of HVL is significantly higher than the regulatory minimum.

This is because any changes in the x-ray tube and collimator that would cause a significant change in HVL would also cause a significant change in the tube output or tube voltage measurements. If any of these conditions are not met, then the HVL should be tested using the ionization chamber at the same voltage used during acceptance testing.

Standard procedure (automatic measurement)

This test may be combined with the tube output measurement to determine the HVL at multiple tube voltages.

1. Remove the image receptor from the beam path, either by removing it from the bucky assembly or moving the bucky assembly. If the image receptor cannot be removed, ensure that the image receptor is shielded from the entire collimated beam.
2. Place the solid-state dosimeter sensor on the patient table at the center of the light field. To minimize the effect of scatter, collimate the field to slightly larger than the dosimeter.
3. Take an exposure at the statutory tube voltage[3] and a standardized technique (e.g., 10 mAs and 100 ms) and record the displayed HVL.
4. Optional: repeat step 3 for multiple tube voltages, such as the maximum and minimum clinical voltages, and the most commonly used clinical tube voltages.

Alternative procedure (manual measurement)

1. Remove the image receptor from the beam path, either by removing it from the bucky assembly or moving the bucky assembly. If the image receptor cannot be removed, ensure that the image receptor is shielded from the entire collimated beam.
2. Place the ionization chamber at the center of the light field. To minimize the effect of scatter, collimate the field down to slightly larger than the ionization chamber, and if possible raise the chamber several centimeters above the table. If it is not possible to raise the chamber, place it on a lead apron to minimize backscatter.
3. Place the test stand in the light field. To minimize the effect of scatter, the stand must be capable of holding the aluminum filters at an appropriate height above the ionization chamber (e.g., at least five times longest dimension of the x-ray field); see Figure 2.
4. Acquire an exposure in manual mode at the statutory tube voltage and a standardized technique (e.g., 10 mAs and 100 ms). Record the air kerma.
5. Place varying amounts of aluminum on the test stand, and for each amount of aluminum make an exposure at the same manual mode settings as in step 4. Record the air kerma for each exposure. Adjust the amount of aluminum until recording air kerma values (using thicknesses of aluminum that differ by no more than 1 mm) above and below the target air kerma. The target air kerma is 50% of the air kerma measured with no added aluminum.

[3]The "statutory tube voltage" is the voltage at which local regulations specify a minimum HVL. In most jurisdictions in the United States, this is 80 kV.

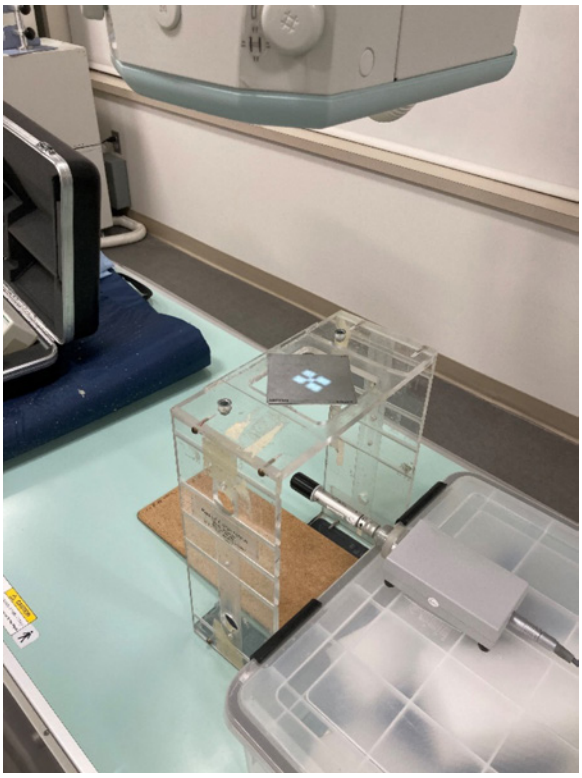

Figure 2. Setup for manual measurement of HVL using an ionization chamber and aluminum filters.

6. Use Equation 3, to calculate the HVL by interpolating the amount of aluminum required to achieve 50% of the original air kerma,

$$HVL = \frac{T_1 \ln\left(\frac{I(0)}{2I(T_2)}\right) - T_2 \ln\left(\frac{I(0)}{2I(T_1)}\right)}{\ln\left(\frac{I(T_1)}{I(T_2)}\right)} \quad (3)$$

where $I(T)$ is the measured air kerma for an aluminum thickness of T, and T_1 and T_2 are thicknesses that produce air kerma values above and below I(0)/2 (i.e. $I(T_1) > I(0)/2$ and $I(T_2) < I(0)/2$). This equation is derived in Appendix A.1.

Expected performance limits

Refer to 21CFR1020.30(m)(1) [12] for FDA limits on the HVL. Refer to state regulations for local limits.

Potential findings

The HVL may be less than the regulatory limit. This would result in a needlessly high skin dose for the patient.

Potential pitfalls

- When using the manual method, failure to adhere to the following will result in excessive scatter, which may compromise the measurement:
  1. The beam should be collimated as narrowly as possible consistent with complete beam coverage of the ionization chamber.

2. The imaging receptor must be appropriately shielded, preferably with a lead shield. (Use of low-Z material should be avoided; Z: atomic number.)
3. The ionization chamber must be separated from both the aluminum filters and the floor or patient table by a reasonably large air gap.

Note: Backscatter is less of an issue with lead-backed solid-state dosimeters.

- When using the standard procedure on a system with no manual mA mode, use AEC mode and place aluminum filters above and below the dosimeter sensor so that the total aluminum in the beam remains constant in order to maintain a constant technique for the test.
- When using a solid-state dosimeter with automatic HVL measurement, ensure that the orientation of the sensor relative to the anode-cathode axis is correct. The correct orientation will depend on the model of the dosimeter being used.
- If the exposure time is too short, the tube voltage may not have stabilized for a significant fraction of the exposure, leading to an erroneous reading.

4.1.5 Exposure Timer Accuracy

Rationale

Digital image receptors have a much wider dynamic range than screen-film systems, and so an error in the length of an exposure is less likely to have clinical impact in a digital system. However, modern generators should be capable of extremely accurate control and measurement of the length of an exposure, so an error in the exposure time is likely a symptom of equipment failure.

Recommended method

1. Remove the image receptor from the beam path, either by removing it from the bucky assembly or moving the bucky assembly. If the image receptor cannot be removed, ensure that the image receptor is shielded from the entire collimated beam.
2. Place the dosimeter sensor on the patient table at the center of the light field.
3. If using a solid-state multimeter capable of recording air kerma waveforms, turn on this feature. The recorded waveforms will be used for the air kerma waveform test (see Section 4.1.7).
4. Acquire an exposure in manual mode with a short exposure duration (≤10 ms). If the system does not allow the exposure time to be set, use a low mAs setting (~1 mAs).
5. Record the time setting (or the mA and mAs settings), the exposure time reported by the dosimeter, and the exposure time displayed on the console after the exposure (if applicable).
6. Repeat the procedure for a 100 ms and a 1000 ms exposure for both focal spots. On acceptance testing, measure and record the exposure time for additional exposure lengths; for example, at 5, 10, 25, 50, 100, 200, 500, and 1000 ms, or for all selectable options.
7. For each measurement, calculate the error in the measured exposure time relative to the settings and to the displayed exposure time.

Alternative methods

None noted.

Expected performance limits

The exposure time should be accurate to within 1 ms for exposure times of 20 ms or less, and to within 5% for exposure times of more than 20 ms. This is based on the recommendations of AAPM Report 74 [1].

Potential findings

A failure in the exposure timer accuracy may be a symptom of a deeper problem. Contact the service engineer to investigate the source of the problem.

Potential pitfalls
None known.

4.1.6 Air Kerma Linearity

Rationale
The use of manual techniques based on technique charts assumes that the air kerma is proportional to the mAs setting; this test verifies that the condition of linearity is met.

Recommended method
1. Remove the image receptor from the beam path, either by removing it from the bucky assembly or moving the bucky assembly. If the image receptor cannot be removed, ensure that the image receptor is shielded from the entire collimated beam.
2. Place the dosimeter sensor on the patient table at the center of the light field and set the collimation so the sensor is completely illuminated.
3. Set the tube voltage to the value most commonly used clinically (typically 80 kV).
4. Using the large focal spot, acquire a series of exposures in manual mode, at mAs stations ranging from the smallest available to the largest available. For each mAs station, record the displayed current-time product (mAs) and the measured air kerma. During acceptance testing, all available tube current stations should be tested; during annual testing, a subset of stations, varying by no more than a factor of two from one to the next, may be tested (e.g., 1 mAs, 2 mAs, 4 mAs, etc).
5. Using the small focal spot, acquire a series of exposures in manual mode, at mAs stations ranging from the smallest available to the largest available[4]. For each mAs station, record the displayed current-time product (mAs) and the measured air kerma. During acceptance testing, all available tube current stations should be tested; during annual testing, a subset of stations, varying by no more than a factor of two from one to the next, may be tested (e.g., 1 mAs, 2 mAs, 4 mAs, etc).
6. For each measurement, calculate and record the ratio of the air kerma to the current-time product (mR/mAs or mGy/mAs). For systems with separate controls of mA and exposure time, if the exposure timer accuracy is verified, mA may be varied to change the mAs.

Alternative methods
None noted.

Expected performance limits
According to 21 CFR 1020.31(c) [12], the ratio mGy/mAs for any two adjacent stations must match to within ±10%:

$$\left|X_2 - X_1\right| < 0.10\,(X_2 + X_1),\ where\ X_n \equiv \frac{mGy_n}{mAs_n} \tag{4}$$

or equivalently:

$$\left|X_n - \overline{X}\right| < 0.10\,\overline{X},\ \text{where}\ \overline{X} \equiv \frac{X_2 + X_1}{2} \tag{5}$$

Task Group 150 recommends that the ratio mGy/mAs for any stations should match the average over all stations $\overline{X}$ to within ±10%:

$$\left|X_n - \overline{X}\right| < 0.10\,\overline{X},\ where\ \overline{X} \equiv \sum_{n=1}^{N} X_n \tag{6}$$

[4]The maximum tube current available with the small focal spot is generally smaller than the maximum for the large focal spot.

Potential findings

The ratio mGy/mAs at very low mAs stations may differ from the remaining stations by more than ±10%. This can occur if the mAs stations have been miscalibrated; any such concerns should be referred to the service engineer.

Potential pitfalls

None noted.

Alternative methods

None noted

4.1.7 Tube Voltage and Air Kerma Rate Waveforms

Rationale

The majority of radiologic multimeters available today are capable of sampling tube voltage and air kerma rate waveforms at sufficiently high sample rates such that the waveforms may be accurately displayed for review. Inspection of tube voltage and air kerma rate waveforms is worthwhile: to help document proper performance, to reveal reasons for performance issues such as inaccurate tube voltage and reduced air kerma linearity at short exposure times, and to warn of impending problems with high voltage regulation and control of the electron beam within the x-ray tube.

Recommended method

1. Inspect the waveforms recorded during the exposure time accuracy and tube voltage accuracy tests.
2. Compare the waveforms to the expected performance section below.

Expected performance limits

The voltage and air kerma rate waveforms must meet the manufacturer's performance specifications.

If no performance specifications are available, general guidelines are as follows:

- The tube voltage should rise from zero to ≥95% of the nominal value within 1 ms of the start of the exposure and fall from 95% of the nominal value to zero within 1 ms.
- Between the time the tube voltage first reaches the nominal value and the last time it is at nominal value, the difference between the minimum and the maximum voltage should be no more than 5% of the nominal voltage. This limit applies both to kV overshoot and kV ripple.
- Any significant deviation from the voltage waveform recorded at acceptance test time should be brought to the attention of the service engineer.
- Rise and fall times of the air kerma rate waveforms should be sufficiently fast to maintain acceptable air kerma linearity for exposure times as short as 5 ms.

Alternative methods

Although more cumbersome than use of multimeters capable of waveform display, some older noninvasive kV meters, which do not display waveforms, provide a coaxial output for display of captured waveforms on an oscilloscope.

Potential findings

Examples of problems with the tube voltage and air kerma rate waveforms are presented in Figures 3–7 below. A failure of the waveform tests provides guidance on other tests to perform, such as measuring the air kerma linearity at low tube currents or at short exposure times; alternately, tube voltage waveforms can help with troubleshooting failure of other tests. In general, an x-ray generator should not be replaced in response to a tube voltage waveform failure alone, although evidence of arcing is justification for replacing the x-ray tube.

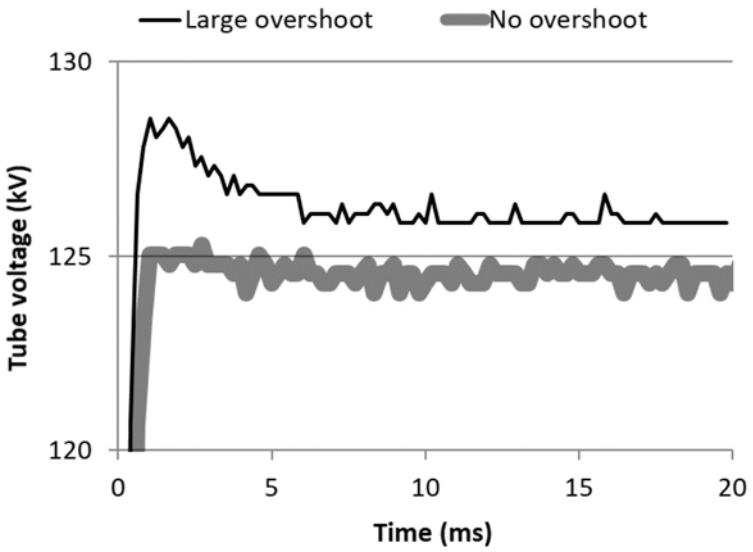

Figure 3. kV waveforms with large overshoot and no overshoot. Both waveforms are within the overshoot limit (5% of 125 kV = 6.25 kV).

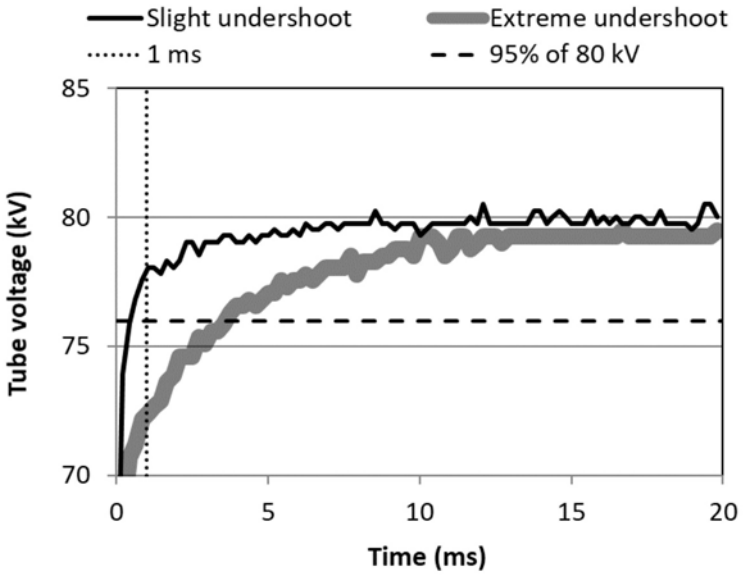

Figure 4. Two examples of tube voltage undershoot. The one with slight undershoot passes the recommended limits; the one with extreme undershoot does not.

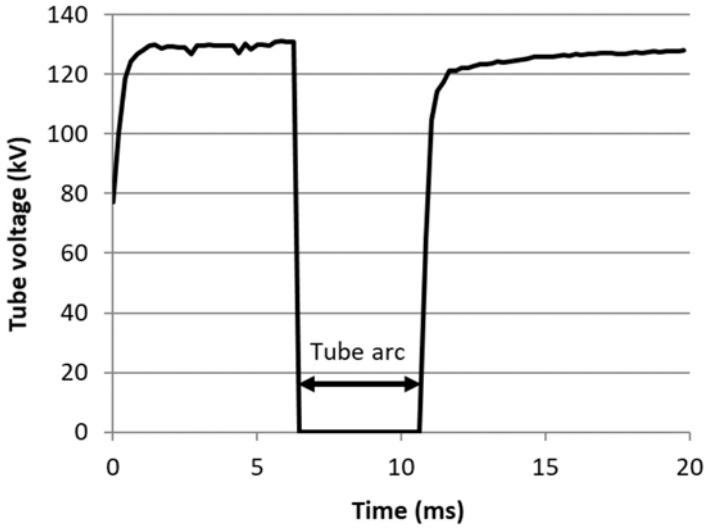

Figure 5. Example of tube arc

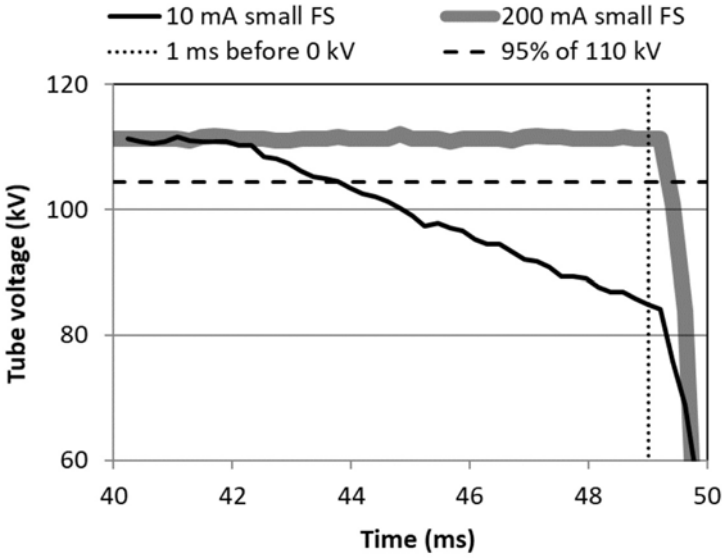

Figure 6. Two examples of the trailing edge of a kV waveform. The 200 mA waveform passes the recommended limits; the 10 mA waveform does not.

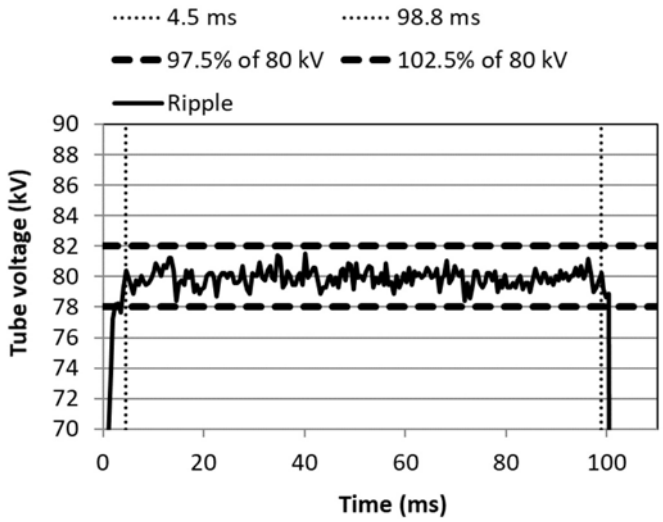

Figure 7. Tube voltage waveform with ripple limits between 4.5 and 98.8 ms of the exposure duration.

Potential pitfalls

- Some multimeters also show air kerma rate waveform along with tube voltage waveforms. Although air kerma rate waveform can exhibit shapes that significantly deviate from "flat," it is not clear that these deviations are clinically significant, so long as the total air kerma is essentially "correct," i.e., meets tube voltage accuracy and air kerma linearity requirements.
- Long voltage fall times can be caused by high capacitance in the tube voltage cable. If the cable cannot be shortened, this problem may be impossible to fix. This problem may also affect air kerma linearity.

4.1.8 Focal Spot Size

Rationale

During the acceptance test or after a tube replacement, the focal spot size should be measured using a focal spot test tool, such as a star pattern or a pinhole camera. The focal spot size affects image quality. This test requires the acquisition of at least one image of the test tool. Therefore, this test is most affected by the use of digital image receptors (due to their reduced spatial resolution relative to screen-film and direct film receptors).

The focal spot size can be measured using a star pattern [13], a slit camera [13] [36], or a pinhole camera [13] [37]. In this report, we describe the method for measuring the focal spot size using a star pattern as applied to digital image receptors, as we believe this is the most commonly used tool for this test. In addition, because digital image receptors have more limited spatial resolution than screen-film systems and the star pattern test is more sensitive to the spatial resolution of the image receptor than the other two tests, it is more important to use an appropriate geometric magnification to produce accurate results. Care must be taken in selecting the radiographic magnification to ensure that the first blur radius of the star pattern image is visible; see Table 7 for guidance.

IEC 60336:2005 [13] specifies the use of a slit camera or pinhole camera as the normative procedure, but also describes the use of star pattern test tools in an informational appendix.

Recommended method

The focal spot size in a single direction can be determined from an image of the star pattern by the equation:

$$FS = \frac{M}{M-1}\left(\frac{\pi\,\theta_{spoke}}{180}\right) D_{blur}^{OP} \tag{7}$$

where M is the radiographic magnification of the star pattern, θ_{spoke} is the angle in degrees subtended by one line of the star pattern (not the angle per line pair), and D_{blur}^{OP} is the blur diameter in the object plane, or the distance on the star pattern between the point at which the lines blur on one side of the center of the pattern and the point where the lines blur on the opposite side. If this measurement is made along a line parallel to the anode-cathode axis of the tube, it is sensitive to the width of the focal spot. If the measurement is made along a line perpendicular to the anode-cathode axis of the tube, it is sensitive to the length of the focal spot.

Note that equation (7) differs from the classic equation used with screen-film systems by a factor of M [13] [36] [37]:

$$FS = \frac{1}{M-1}\left(\frac{\pi\,\theta_{spoke}}{180}\right) D_{blur}^{IP} \tag{8}$$

The classic equation uses the blur diameter in the image plane (D_{blur}^{IP}); however, with a digital image receptor, it is more straightforward to measure the blur diameter in the object plane, as described below.

The value of θ_{spoke} is a specification provided by the manufacturer of the star pattern. Thus, the only numbers to be determined are M and D_{blur}.

This test may be performed with the system's flat panel detector. However, if another image receptor with higher spatial resolution is available, it should be used. The images may be easier to interpret with the higher resolution receptor.

1. If possible, remove the image receptor from the table bucky and place it on the patient table. If the image receptor cannot be removed, remove the grid. Grid line artifacts may interfere with the interpretation of the images.
2. Select the optimal radiographic magnification for the star pattern (see Table 7).
3. Place the star pattern on the central axis of the beam at or near the optimal radiographic magnification plane, supported by a test jig as shown in Figure 8. If the star pattern has spokes in only four quadrants, make sure that these quadrants are oriented parallel or perpendicular to the anode-cathode axis.
4. Place an orientation marker (such as a pen) alongside the star pattern to indicate the anode-cathode axis direction in the image.
5. Measure and record the actual radiographic magnification; do not rely on DICOM attributes such as "Source to Patient Distance" to determine this magnification. See "Determination of radiographic magnification" section below.
6. Collimate to a 10 cm × 10 cm field while ensuring that it is large enough to image both the star pattern and the orientation marker.
7. Acquire an image at a low tube voltage and mAs (e.g., 75 kV and 1 mAs). The technique should be fairly high to minimize image noise, but low enough that the image receptor does not saturate. If possible, set the tube current to half of the tube's rated value [13].

8. Using either a digital/electronic measuring tape or the software distance tool, measure the diameters of the spoke pattern and the blur pattern on the image.[5]
9. Calculate the blur diameter using equation (13) below.
10. Calculate the focal spot size using equation (7) above. The focal spot size in the direction parallel to the anode-cathode axis (i.e., the focal spot length) is calculated from the blur on the spokes that are perpendicular to the anode-cathode axis; the focal spot size in the direction perpendicular to the anode-cathode axis (i.e., the focal spot width) is calculated from the blur on the spokes that are parallel to the anode-cathode axis (See Figure 9 and 10 below).

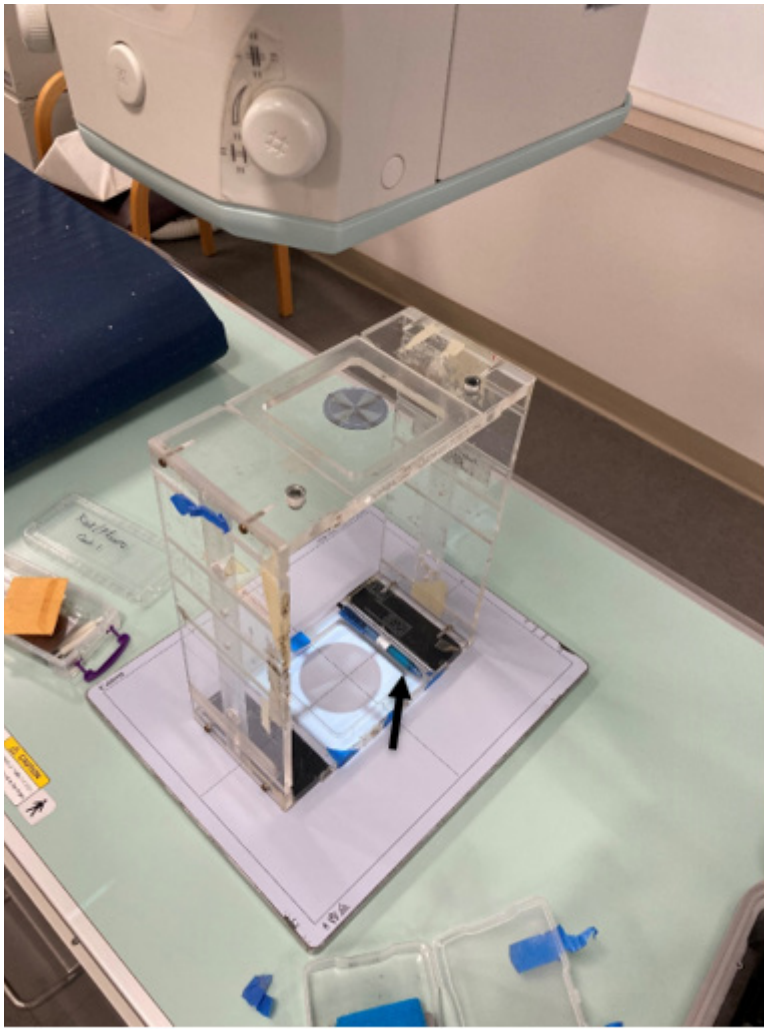

Figure 8. Setup for measuring focal spot size using star pattern. Note the pen (indicated by arrow) used to mark the anode-cathode axis. By measuring with the image receptor on the patient table, it is possible to determine the radiographic magnification precisely.

[5]The measurement of the blur diameter is largely insensitive to image processing such as edge enhancement, because it depends on finding the zero-crossing of the modulation transfer function (MTF).

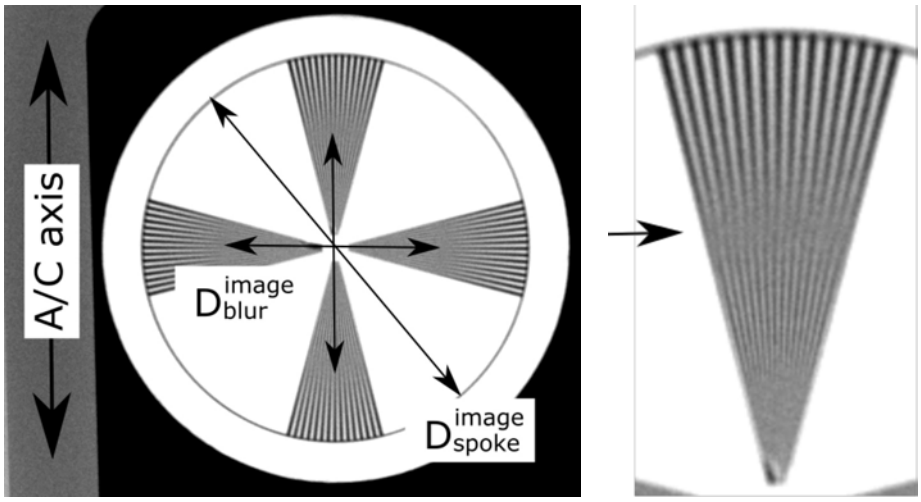

Figure 9. Star pattern image acquired at optimum magnification. Left: The blur diameter indicated by the horizontal arrow is used to measure the focal spot length; the blur diameter indicated by the vertical arrow is used to measure the width. Right: The image is enlarged to show the blur region clearly; its center is indicated by an arrow. Note that the outer lines of the pattern are dark outside the first blur region but light inside the first blur region, indicating that contrast inversion is not present.

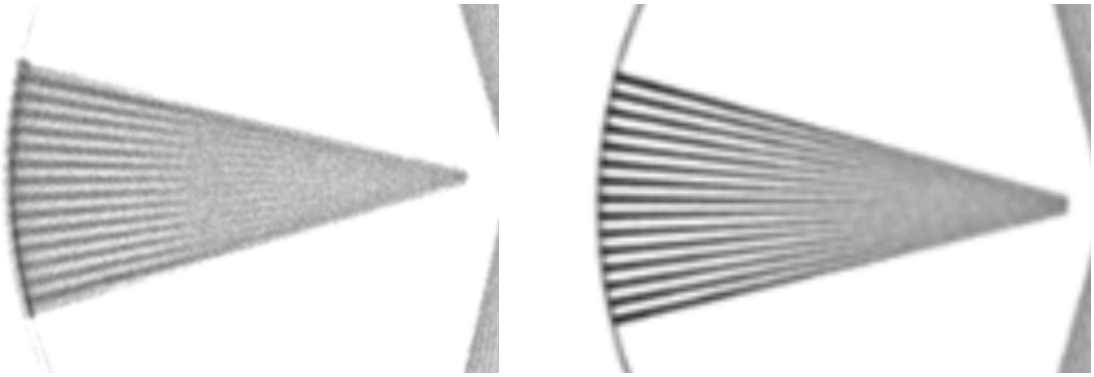

Figure 10. Images of the 1 deg star pattern with inappropriate magnification. Left: 1.2 mm focal spot at M = 2. The first zero crossing is not visible, and the bar pattern shows contrast inversion; the outermost bars are light, not dark. Right: 0.6 mm focal spot at M = 1.45. The location of the first blur region is so close to the center of the star that it is impossible to find the center of the blur region.

Selection of optimal radiographic magnification

Care must be exercised to select a test geometry and corresponding magnification (M) that will yield accurate results. If the magnification is too large, the focal spot blur occurs at too low a spatial frequency to be visualized on the image of the star pattern; this is true both for digital imaging systems and for screen-film systems. If the magnification is too small, the focal spot blur in the image is at a high enough spatial frequency that the image receptor modulation transfer function (MTF) is

effectively zero, and while an upper limit may be placed on the focal spot size, the actual size cannot be determined.

Table 7: Optimum radiographic magnification for measuring focal spot size for a star pattern with a spoke diameter of 45 mm

	Spoke Angle (deg)	0.5	1.0	1.5	2.0
Nominal FS size	Expected FS length (mm)	Optimum Radiographic Magnification			
0.6	1.2	1.20	1.49	1.96	2.89
1.2	2.4	1.09	1.19	1.33	1.49

Table 7 offers suggested radiographic magnifications for two common focal spot sizes and the spoke angles of four commercially available star patterns. At the specified magnification, the blur diameter will be equal to or less than half of the spoke diameter when the focal spot length is twice the nominal focal spot size. Table 7 is based on the following equation:

$$M_{opt} = \frac{1}{1 - \frac{\left(\frac{\pi}{360}\theta_{spoke}\right) D_{spoke}}{FS_{exp}}} \tag{9}$$

where FS_{exp} is the expected focal spot size, about twice the nominal focal spot size. This equation is derived in Appendix C, which includes a table listing the optimum magnification for a wide variety of focal spot sizes.

If the star pattern is placed object-to-image distance (OID) cm above the image receptor, the SID should be set to:

$$SID = OID\frac{1}{1 - \mathrm{M}^{-1}} = OID\frac{FS_{exp}}{\left(\frac{\pi}{360}\theta_{spoke}\right) D_{spoke}} \tag{10}$$

Table 8: Optimum source-to-image distance (SID) for measuring focal spot size for a star pattern with a spoke diameter of 45 mm for an object-to-image distance (OID) of 30 cm or 40 cm

	Spoke Angle (deg)	0.5	1.0	1.5	2.0
Nominal FS size	OID (cm)	Optimum SID (cm)			
0.6	30	183	92	61	46
1.2	30	367	183	122	92
0.6	40	244	122	81	61
1.2	40	489	244	163	122

Determination of radiographic magnification (M)

M can be determined one of two ways. The first is to use a measuring tape to measure the distance from the focal spot to the star pattern (SOD, or the source-to-object distance), and the distance from the focal spot to the image receptor (SID, or the source-to-image distance). Thus, M is calculated as:

$$M = \frac{SID}{SOD} \tag{11}$$

The magnification should always be determined this way before the image is acquired to ensure that it is close to the desired magnification. Note that the SID is the distance to the surface of the image receptor, not the surface of the patient table or the wall bucky.

Second, if an accurate software distance tool is available to measure distances on the image, then the diameter of the star pattern image D_{spoke}^{image} can be measured using the calipers, and compared to the actual diameter of the star pattern D_{spoke} measured using a ruler, digital hardware caliper, or from the manufacturer's specification). The magnification can then be calculated as:

$$M = \frac{D_{spoke}^{image}}{D_{spoke}} ERMF \tag{12}$$

where ERMF is the ratio between the actual image diameter and the measured image diameter; techniques for determining the ERMF are presented in Section 4.8.4 and Appendix B. If the image receptor is not integrated into the system (e.g., a CR cassette), the ERMF is likely to equal 1.

By calculating M using both approaches, one can assure the accuracy of the result.

Determination of D_{blur}^{OP}

Before determining D_{blur}^{OP}, the window and level of the image should be adjusted to make it as clear as possible where the lines blur out. The blur distance should be measured from the center of the first blurred region on one side of the image to the center of the first blurred region on the other. The "first blurred region" refers to the blurred region closest to the center of the pattern. If possible, the image should be zoomed to allow a more accurate determination of the center of the blur regions.

The simplest way to determine D_{blur}^{OP} is to use the software distance tool to measure the blur diameter D_{blur}^{image} and the diameter of the spoke wheel D_{spoke}^{image} on the image, and then divide D_{blur}^{image} by the apparent magnification $D_{spoke}^{image}/D_{spoke}$:

$$D_{blur}^{OP} = D_{blur}^{image} \frac{D_{spoke}}{D_{spoke}^{image}} \tag{13}$$

Equation (13) is independent of the ERMF, and can be used whether the measurements are taken using a measuring tape on the screen, a measuring tape on printed film, or the software distance tool at either the acquisition or the diagnostic workstation.

Alternative methods

The focal spot size may also be measured using a slit camera or a pinhole camera. See IEC 60336 [13], Jain et al. [37], or Rong et al. [36] for details.

Expected performance limits

The maximum permissible focal spot size in each direction (length and width) is listed in Table 9.

Potential findings

- If the focal spot size at acceptance testing is larger than the limits in Table 9, the tube is not acceptable and should be replaced.
- If the focal spot size is measured during annual testing and the focal spot size is between 100% and 110% of the limits in Table 9, the service engineer and facility should be notified that the tube is approaching end of life. If larger than 110% of the limit, image quality may be affected and the facility should consider replacing the tube.

Table 9: Maximum permissible values of focal spot dimensions for nominal focal spot values

Nominal focal spot value	**FOCAL SPOT dimensions, Maximum permissible values** mm	
f	**Width**	**Length**
0.1	0.15	0.15
0.15	0.23	0.23
0.2	0.30	0.30
0.25	0.38	0.38
0.3	0.45	0.65
0.4	0.60	0.85
0.5	0.75	1.10
0.6	0.90	1.30
0.7	1.10	1.50
0.8	1.20	1.60
0.9	1.30	1.80
1.0	1.40	2.00
1.1	1.50	2.20
1.2	1.70	2.40
1.3	1.80	2.60
1.4	1.90	2.80
1.5	2.00	3.00
1.6	2.10	3.10
1.7	2.20	3.20
1.8	2.30	3.30
1.9	2.40	3.50
2.0	2.60	3.70
2.2	2.90	4.00
2.4	3.10	4.40
2.6	3.40	4.80
2.8	3.60	5.20
3.0	3.90	5.60

NOTE For NOMINAL FOCAL SPOT VALUES 0.3 to 3.0, the maximum permissible values for the length have been adjusted with the factor 0.7 (see Appendix C).
Reprinted from Table 3 of IEC standards publication 60336 [13] with permission.

Potential pitfalls

- If the radiographic magnification is too high, the blur radius will be too large to be seen on the image of the star pattern. In this case, a second blur pattern may be seen; calculating the focal spot size on this blur pattern will result in an unrealistically small estimate of the focal spot size, see Figure 11.
- If the radiographic magnification is too low, the blur radius will be too small to be unambiguously visualized by the image receptor, see Figure 12.
- If the magnification is calculated using the software distance tool, multiply the result by the ERMF to determine the actual radiographic magnification factor.
- If the acquisition workstation does not have a zoom feature, it may be necessary to send the image to a diagnostic workstation, or export it to a USB flash drive for analysis elsewhere.

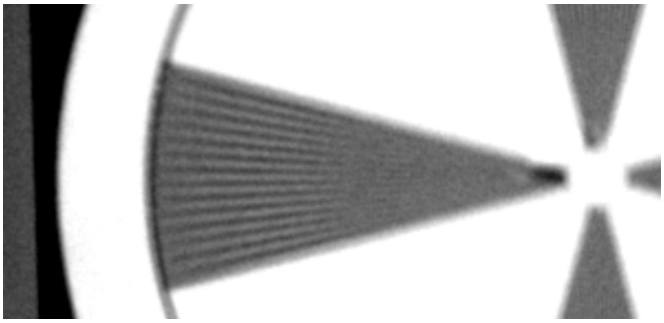

Figure 11. Star pattern acquired with too much radiographic magnification. The first blur pattern is not visible, and the outer lines of the sector are light.

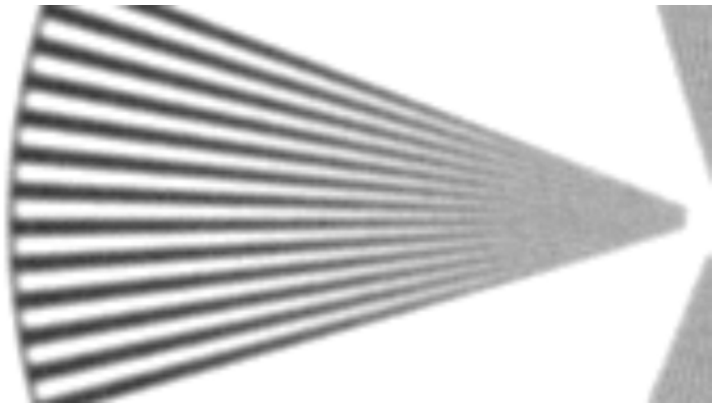

Figure 12. Star pattern acquired with too little radiographic magnification. It is difficult to unambiguously identify the center of the blur region.

4.1.9 Spatial Resolution at Clinical Magnification

Rationale

Standard spatial resolution tests are performed with minimal radiographic magnification, and are therefore insensitive to the focal spot size. The spatial resolution at clinical magnification test is performed at a clinically significant radiographic magnification, and is therefore sensitive to both the image receptor resolution and the focal spot size. [38]

As the star pattern measurement of the focal spot size may require more work than is appropriate for routine testing, it is recommended that the spatial resolution at clinical magnification test be performed during acceptance testing and annual QA/QC testing. If the test fails during annual QA/QC testing, then a star pattern measurement of the focal spot size can be made.

Recommended method

The same geometry and focal spot size must be used during annual testing as that used during acceptance testing. This test can be performed with the image receptor on the table or in the bucky; however, it is the stability of the results that are important rather than the value of the results.

1. If there is a choice of image receptors, choose the image receptor with the highest spatial resolution (e.g., orthopedic CR cassette).

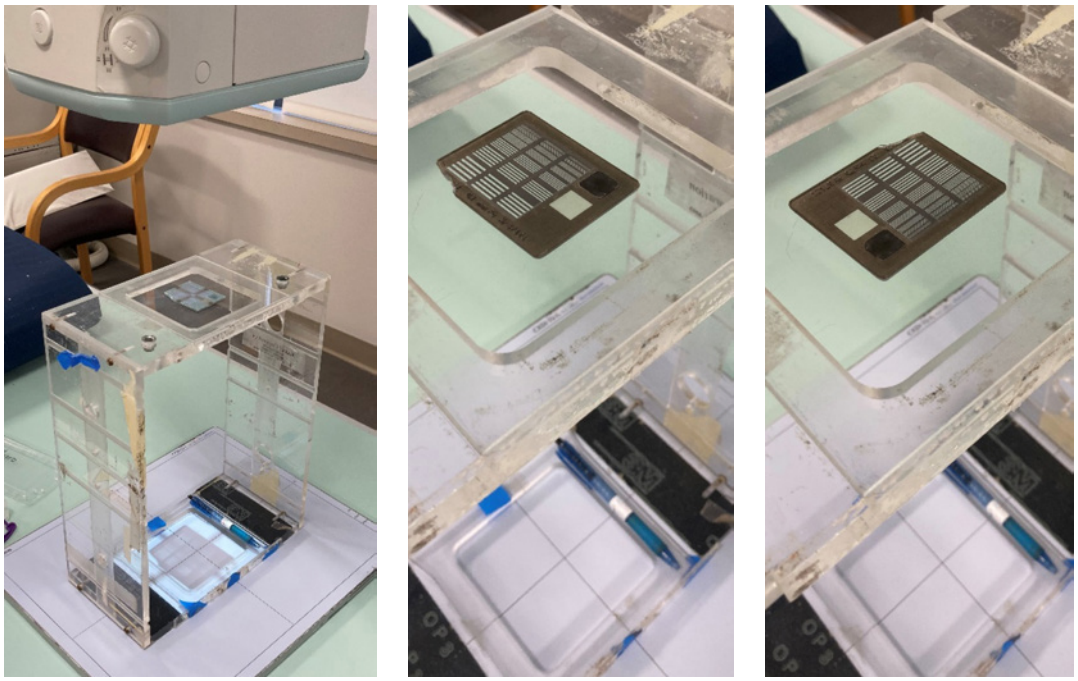

Figure 13. Setup to measure spatial resolution at clinical magnification. Center: bar patterns oriented to be sensitive to focal spot width. Right: bar patterns oriented to be sensitive to focal spot length.

2. Set the SID to the smallest value that is likely to be used clinically (e.g., 100 cm for general radiography).
3. Remove the grid if possible.
4. Place the spatial resolution test object in the center of the beam and as far from the patient support as patient anatomy is likely to be located clinically (e.g., 20–30 cm for general radiography). The test object must be parallel to the patient table (representative setup shown in Figure 13).
5. Align the test object so the lines are offset several degrees from the anode-cathode axis
6. Acquire an image of the test object (suggested technique < = 70 kV and ~10 mAs), with minimal image processing.
7. Read from the image the limiting spatial resolution at the object plane, and record it. The limiting spatial resolution is the spatial resolution at which the MTF is zero. For a test object with continuously varying spatial frequency, this is indicated by the first position where the line pairs disappear. For a test object with discrete line pair frequencies, this is indicated by the last set of resolved line pairs without contrast inversion (see Figures 14 and 15).
8. Acquire a second image with the lines approximately 90 degrees offset from the anode-cathode axis.
9. Calculate and record the radiographic magnification.
10. Calculate the limiting spatial resolution at the image plane, by dividing the object plane spatial resolution by the radiographic magnification.
11. If more than one focal spot is available, repeat steps 5 to 8 for all focal spots.

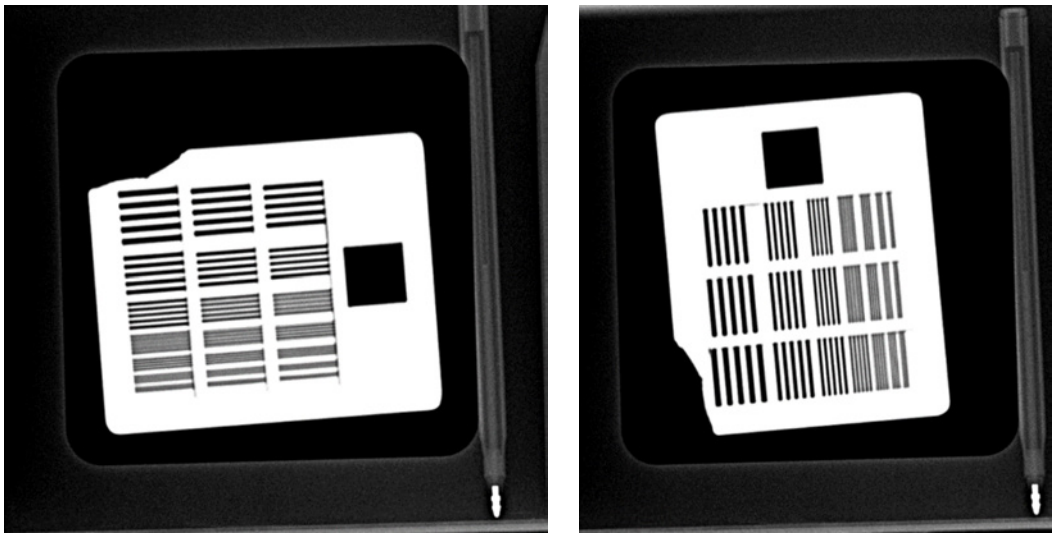

Figure 14. Radiographs of bar pattern phantom with large focal spot and M=1.67. The pen indicates the anode-cathode axis.

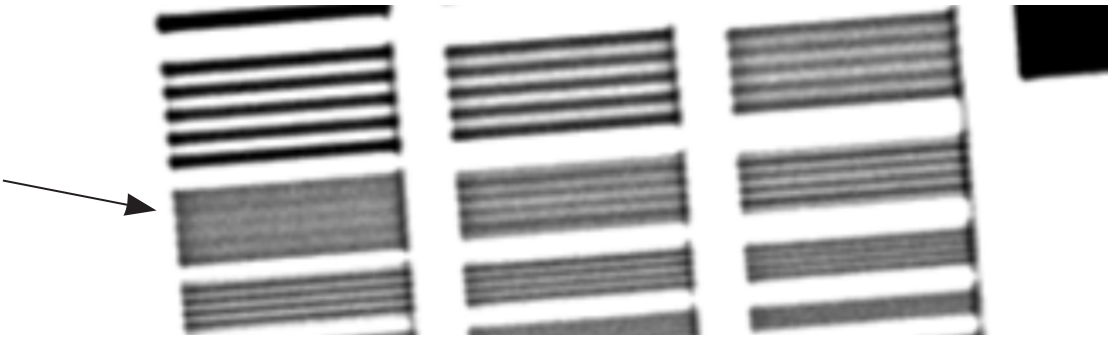

Figure 15. Closeup of Figure 14. The bar pattern closest to the limiting spatial resolution (zero crossing of the MTF) is indicated by an arrow. The next bar pattern shows clear contrast inversion.

Alternative methods

None noted.

Expected performance limits, if applicable

The measured limiting resolution should be no lower than 10% below the value determined during acceptance testing.

Potential findings

A failure of this test may indicate that the focal spot size no longer meets specifications. Measure the focal spot using a star pattern, slit camera, or similar tool (Section 4.1.8); replace the tube if the focal spot is unacceptably large.

Potential pitfalls

- The result depends on the angle (with respect to the anode-cathode axis) at which the test object is placed, which may not be the same as the angle at acceptance testing.
- Image processing with edge enhancement may affect results.
- Bar patterns past the zero crossing might be resolved; do not count patterns that display contrast inversion. See Figure 15 for an example.

4.1.10 Leakage Radiation

This test is to ensure that the x-ray equipment has adequate measures to protect the patient and staff from leakage radiation.

Recommended method

1. Remove the image receptor from the beam path, either by removing it from the bucky assembly or moving the bucky assembly. If the image receptor cannot be removed, ensure that the image receptor is shielded from the entire collimated beam.
2. Place a 3–4 mm lead sheet on the exit window of the collimator and collimate the beam to the smallest possible size.
3. Note the highest possible kV and mAs settings that correspond to the leakage technique factors. Then, select the highest kV possible and use a fraction of the maximum mAs setting for exposure (to prevent excessive loading of the x-ray tube). For example, if the maximum mAs value at maximum kV setting is 500 mAs, then a selection of 100 mAs can be made for this test.
4. Place the dosimeter at 1 m from the focal spot location marked on the x-ray tube housing.
5. Make an exposure at the selected parameters and record the air kerma value at this location.
6. Calculate the corresponding air kerma rate at the leakage technique factors using the specified mAs values.
7. Repeat this procedure at different positions at 1 m from the focal spot location marked on the x-ray tube housing.

Alternative methods

None noted.

Expected performance limits

As per CFR, the leakage radiation at 1 m in any direction from the x-ray source shall not exceed 0.88 mGy/h, and the measured value should be as per manufacturer recommendations.

Potential findings

If the measurements exceed the regulator limit or are not as per manufacturer specifications, then consult the manufacturer for service intervention.

Potential pitfalls

The exact location of the focal spot and anode within the x-ray tube insert and housing is not known. So, the 1 m distance measurements to measure leakage radiation compliance may be different.

4.2 Collimator Tests

Introduction

The main purpose of the collimator is to limit the x-ray field to the area of clinical interest. However, other aspects of system performance related to the x-ray tube/housing/collimator system are often included in collimator performance testing, and these other aspects are included here as well.

Care should be taken with digital radiography systems, as the image processing algorithm may "mask" or electronically collimate the image. Most systems provide an option for disabling the electronic mask. Some clinical systems manufactured before 2016 have these features; all systems that are compliant with the NEMA/MITA standard XR 30-2016 [18] should have these features. If the mask cannot be disabled in the FOR PRESENTATION images and the FOR PROCESSING images are available, measurements should be made using FOR PROCESSING image. If it is unclear how to disable the electronic mask, contact the vendor.

Test equipment required

Several of the following tests require the use of a lead attenuator to protect the image receptor, if the image receptor cannot be removed from the bucky assembly.

Test	Required equipment
Light field illuminance	Illuminance meter
SID indicator accuracy	Measuring tape Radio-opaque object of known size (radiographic method) Stand for radio-opaque object (radiographic method)
Collimator dial accuracy	Measuring tape (recommended method) Radio-opaque grid or ruler (alternative method)
X-ray/light field alignment	Four or more coins or radio-opaque ruler Ruler or measuring tape
X-ray field/image receptor alignment	A small coin (U.S. penny, 19 mm)
Positive beam limitation	CR cassette 4 small coins (if no CR cassette available)
User selectable filtration	Ionization chamber (alternative method only)
Off-focus radiation	Lead attenuator (~10 x10 cm) with 1–2 mm pinhole at center

Expected results

Table 10: Expected results for each collimator test

Test	Expected results
Light field illuminance	Should be >160 lux at 100 cm or maximum SID, whichever is less (21 CFR 1020.31(d)(2)(ii)).
SID indicator accuracy	Should be accurate to within 2% (21 CFR 1020.31(e)(1)).
Collimator dial accuracy	Should be accurate to within 2% of SID in each direction (21 CFR 1020.31(e)(3)).
X-ray/light field alignment	Should align within 2% of SID (21 CFR 1020.31(d)(2)(i)).
X-ray field/image receptor alignment	Distance from the center of the x-ray field to the center of the image receptor should be <2% of SID (21 CFR 1020.31(e)(1)). Distance from the crosshairs to the center of image receptor should be <2% of SID (recommendation of TG-150).
Positive beam limitation	Height and width of x-ray field must not differ from the corresponding image receptor dimension by more than 3% of the SID, and the sum of the height and width differences (without regard to sign) must not exceed 4% of the SID (21 CFR 1020.31(g)).
User selectable filtration	Selection of additional filters should reduce the tube output by approximately the expected amount.
Off-focus radiation	The width of the pre-collimator should be no more than 20% larger than the width in the collimator specifications. If the specifications are not available, the width should be no wider than 30 mm. The off-focus radiation should be no more than 20% of the total tube output.

Description of tests

4.2.1 Mechanical Inspection

Rationale

The collimator and tube housing should rotate freely but remain in the desired location when stationary. Also, high voltage and other cables should be restrained and positioned such that they do not interfere with the motion of the tube housing or collimator.

Recommended method

- Inspect the collimator/tube assembly by rotating both collimator and tube housing in all available directions, ensuring that the assembly will maintain selected angles.
- Verify that cables do not interfere with or restrict normal motion of the assembly or become trapped or pinched.

- Verify that all visible cables are appropriately shielded and secured.
- Verify that the collimator control knobs rotate freely through their full range of motion, and remain stationary when released.

Potential findings

- The collimator range of motion may be constrained by poorly placed cables.
- Collimator locks may be nonfunctional.
- Cable insulation or covers may be damaged.
- Control knobs may not be adequately tight or may be too tight.

Potential pitfalls

None noted.

4.2.2 Light Field Illuminance

Rationale

The purpose of this test is to ensure adequate illuminance of light field for x-ray field delineation when positioning a patient for a radiograph.

Recommended method

1. Turn off or minimize the room lights.
2. Set the SID to 100 cm or its maximum value, whichever is less.
3. Open the collimator fully and turn on the collimator lamp.
4. Verify that the light field shows no shadows of debris on the collimator window.
5. Measure the illuminance in the approximate center of each quadrant of the light field.
6. Calculate the average of the measurements.

Expected performance limits

21 CFR 1020.31 (d)(2)(ii) [12] specifies that the illuminance is greater than or equal to 160 lux at 100 cm SID or maximum SID, whichever is less.

Potential findings

- The lamp may not be sufficiently bright.
- Shadows in the light field may be caused by debris in the collimator window or on the mirror.
- If the measured illuminance is too low, inspect the exit window of the collimator housing for dust or other debris. If the exit window is accessible, then clean and repeat the measurement. If the exit window is not accessible, then assistance of a service engineer may be needed to clear the dust/debris.

Potential pitfalls

- For some environments, it may not be possible to obtain a measurement with room lights completely dimmed. In that instance, take an illumination measurement with the collimator lamp turned OFF and subtract that reading from measurements obtained with the collimator lamp turned ON.

4.2.3 Source-to-Image Distance (SID) Indicator Accuracy

Rationale

CFR 21 1020.31(e)(1) [12] specifies that means shall be provided to indicate the SID (source-to-image distance) to within 2 percent. The SID indicator has become an integral part of many digital systems. In addition to the integrated measuring tape that is part of many radiographic systems, there is typically an electronic display of the SID that can be used as a part of a dose-calculation system to estimate the

air kerma at a reference point relative to the image receptor. The SID indicator is also used by the PBL (positive-beam limitation) system to determine the limits on the shutter locations. Thus, an error in the SID measurement can influence the positioning of the x-ray tube relative to the patient, the extent of anatomy exposed, and the reported dose.

The SID indicator accuracy should be measured separately for the table bucky and the wall bucky. It is necessary to measure the accuracy of the integrated measuring tape only for a single bucky.

Only the recommended method explicitly includes a test of the accuracy of the integrated measuring tape. However, if the SID is verified by one of the other methods, it is straightforward to then test the accuracy of the integrated measuring tape.

Recommended method (direct measurement)

Use this method if the image plane location and the focal spot locations are both well known (i.e., to within 1 cm). It requires an external reference measuring tape.

Verify the accuracy of the SID displayed on the collimator

1. Move the tube housing to a clinically used SID (e.g., 100 cm for a table bucky, and 180 cm for a wall bucky), and record the displayed SID.
2. Use the external measuring tape to measure the distance from the focal spot to the image plane.
3. Compare the measured SID to the displayed SID.

Verify the accuracy of the integrated measuring tape

1. Use the external measuring tape to measure the distance from the focal spot to the patient table, and record the distance.
2. Pull the end of the integrated measuring tape to surface of the patient table, and record the indicated distance.
3. Compare the two measuring tape measurements.

Alternative methods (radiographic measurement)

These procedures can be used if either the location of the focal spot, the location of the image plane, or both, is not well known (i.e., to within 1 cm). The method uses radiographic images and triangulation to determine the SID. Once the SID is known, it can be compared to the calculated SID. These techniques rely on a measurement of an object size in the image, and must therefore be corrected by the ERMF.

After using one of these methods, it is useful to measure the distance from the table to the bottom of the collimator, then record the difference between the SID and this distance. In later surveys, the table/collimator distance can quickly be measured, and the recorded difference added to this to determine the SID.

Method A

Use this method if the image plane location is well known but the focal spot location is not; this may happen if the tube housing is enclosed in a shroud that cannot be removed.

1. Place a radio-opaque object of known size d (e.g., a star pattern) on the central ray between the focal spot and image receptor, at least 30 cm from the image receptor.
2. Measure the OID from the object to the image plane.
3. Acquire an image using a low-dose exposure (e.g., 70 kV and 10 mAs).
4. Measure the size D of the object in the image.
5. Calculate the SID using the following formula:

$$SID = \frac{M}{M-1} OID, \text{ where } M \equiv ERMF\frac{D}{d} \tag{14}$$

Method B

Use this method if the focal spot location is well known but the image plane is not well known; this may happen if the image receptor is hidden in a housing that cannot be opened.

1. Place a radio-opaque object of known size d (e.g., a star pattern) on the central ray between the focal spot and image receptor, at least 30 cm from the image receptor.
2. Measure the SOD from the object to the focal spot.
3. Acquire an image using a low-dose exposure (e.g., 70 kV and 10 mAs).
4. Measure the size D of the object in the image.
5. Calculate the SID using the following formula:

$$SID = \mathrm{M}\, SOD, \text{ where } M \equiv ERMF\frac{D}{d} \tag{15}$$

Method C

Use this method if neither the focal spot location nor the image plane location is well known.

1. Place a radio-opaque object of known size d (e.g., a star pattern) on the central ray between the focal spot and image receptor, at least 30 cm from the image receptor housing (i.e., the patient table or the wall bucky); see Figure 16.
2. Measure the distance Δz from the object to the image receptor housing (tabletop or wall bucky cover).
3. Acquire an image using a low-dose exposure (e.g., 70 kV and 10 mAs).
4. Measure the size D_1 of the object in the image.
5. Place the radio-opaque object onto the image receptor housing (i.e., the patient table or the wall bucky).
6. Acquire an image using a low-dose exposure.
7. Measure the size D_2 of the object in the image.
8. Calculate the SID using the following formula:

$$SID = ERMF\frac{\Delta z}{d}\frac{D_2 D_1}{D_1 - D_2} \tag{16}$$

See Appendix A for the derivation of this equation.

Method D

This variation on Method C uses two test objects in the same radiograph.

1. Place a radio-opaque object of known size d_1 (e.g., a star pattern) on the central ray between the focal spot and image receptor, at least 30 cm from the image receptor housing (i.e., the patient table or the wall bucky); see Figure 16.
2. Measure the distance Δz from the object to the image receptor housing (tabletop or wall bucky cover).
3. Place a second radio-opaque object of size d_2 on the image receptor housing.
4. Acquire an image using a low-dose exposure (e.g., 70 kV and 10 mAs).
5. Measure the sizes D_1 and D_2 of the objects in the image.
6. Calculate the SID using the following formula:

$$SID = ERMF\,\Delta z\frac{D_2 D_1}{d_2 D_1 - d_1 D_2} \tag{17}$$

See Appendix A for the derivation of this equation.

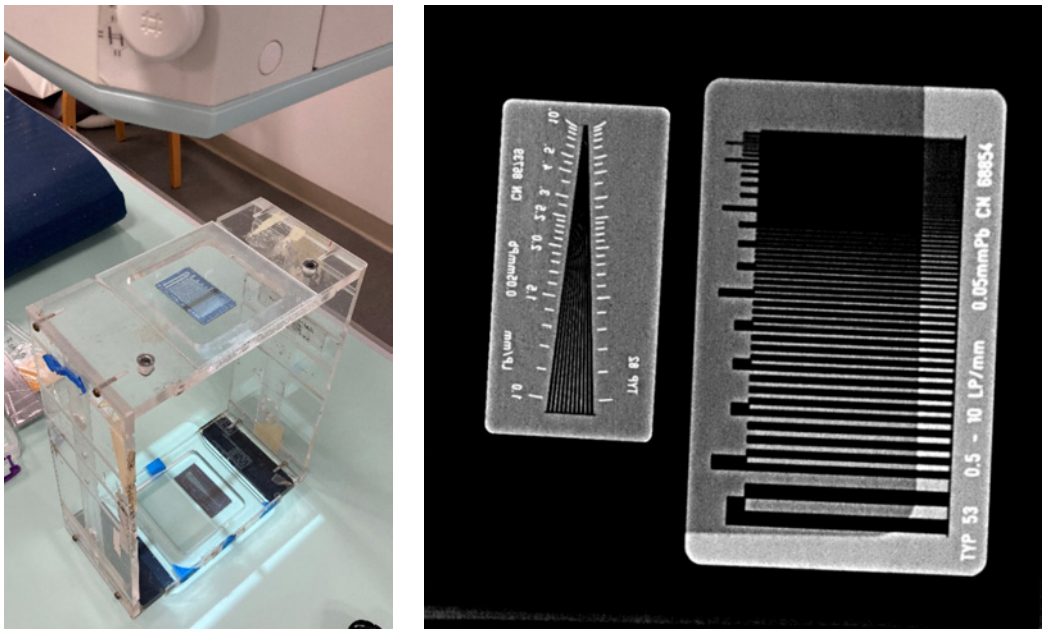

Figure 16. Measuring both focal spot location and image plane location. Left: setup with two objects at different magnification imaged simultaneously. Right: radiograph of objects.

Expected performance limits

The SID indicator should be accurate to within ± 2%.

Potential findings

- The displayed SID may be accurate at one height but not another.
- The displayed SID may be consistently inaccurate at all heights.
- The displayed SID may be accurate for the table bucky but not the wall bucky, or vice versa.

Potential pitfalls

- It is important to be aware of the calibration of the software digital calipers. See Appendix A for details.
- The focal spot marker on the tube may not be visible, or the focal spot may not be at this marker.
- SID digital indicator could be incorrect due to incorrect detent selection/placement.
- Determining the precise location of the image plane of an integrated image receptor may be difficult.
- Performing these procedures may be challenging with a wall stand.

4.2.4 X-ray Field/Light Field Alignment and Collimator Dial Accuracy

Rationale

The purpose of this test is to assess the alignment between the projected light field and the x-ray field. Large differences between the x-ray field and indicated light field may result in either anatomical cut-off, which would necessitate a repeated image, or exposing tissue outside the area of clinical interest. This test also determines the accuracy of the x-ray field size as indicated by the collimator dials and associated gauges.

Performing the collimator dial accuracy test is easiest if done on the tabletop. However, this requires that the SID displayed on the collimator matches the actual distance to the image receptor. If this is not the case, the collimator dial accuracy test must be done with the image receptor in the bucky, and can be done in combination with the x-ray field/image receptor alignment test.

The text below describes four approaches to testing the alignment.

- The recommended method uses radio-opaque objects to mark the edge of the light field, and then the software distance tool to measure the misalignment between the x-ray field and the light field.
- The first alternative method uses a plastic grid or ruler with radio-opaque lines but does not require the use of the software distance tool.
- The second alternative method uses radiochromic film to locate the edges of the radiation field and does not require the use of the image receptor.
- The last method uses commercially available electronic devices to locate the edges of the radiation field and does not require the use of the image receptor.

Recommended method

1. If possible, remove the image receptor from the bucky and place it on the patient table.
2. Set the SID to a typical clinical value such as 100 cm.
3. Collimate the light field to a clinically reasonable size at least several centimeters smaller than the image receptor; for example, 30×30 cm for a 36×43 cm image receptor.
4. Record the field size indicated on the collimator.
5. Mark the edges or corners of the visible light field using coins or the lines on a radio-opaque ruler (e.g., see AAPM Report 4 [4], and Figure 17 below).
6. Take an exposure at a low image receptor dose (e.g., 70 kV, 1 mAs).
7. In the image, use the software distance tool to measure the distance between the marked edges of the light field and the imaged x-ray field to determine the misalignment. If there is a visible penumbra, measure to the middle of the penumbra.
8. In the image, measure the height and width of the irradiated field.
9. If the image receptor is in the bucky, then multiply the measured distances by the ERMF. Note, this is more critical for the collimator dial accuracy.

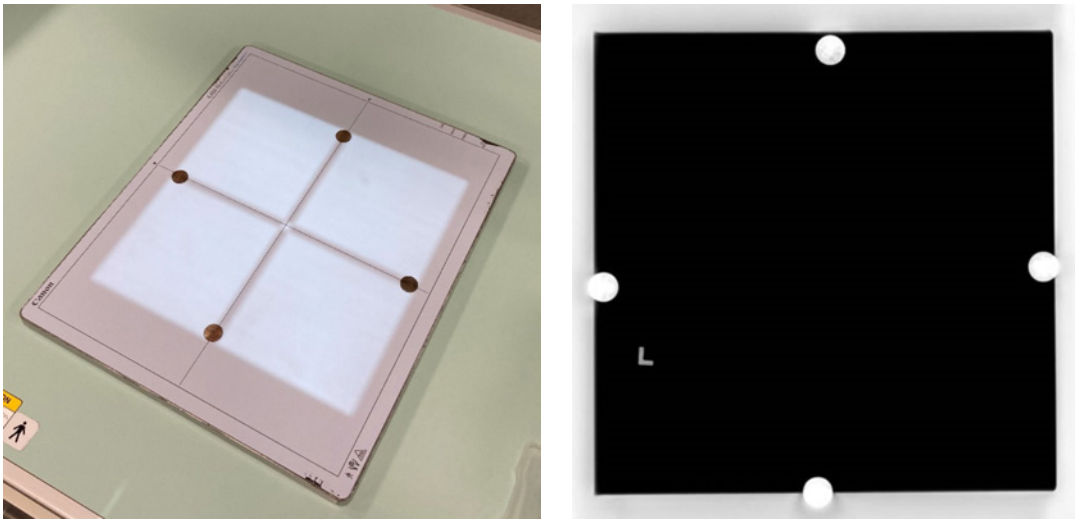

Figure 17. Measuring x-ray/light field alignment using coins and software distance tool.

Alternative method using radio-opaque test tool (grid or ruler)

1. If possible, remove the image receptor from the bucky and place it on the patient table.
2. Set the SID to a typical clinical value such as 100 cm.
3. Collimate the light field to a clinically reasonable size at least several centimeters smaller than the image receptor; for example, 30×30 cm for a 36×43 cm image receptor.
4. If using a radio-opaque grid, align the edges of the light field with lines on the grid (see Figure 18); it may be necessary to adjust the field size to match the grid.
5. If using a ruler with radio-opaque markings, place the ruler at the center of each edge of the light field, with the zero mark at the center of the ruler aligned with the edge of the light field (see Figure 19).
6. Record the field size indicated on the collimator.
7. Take an exposure at a low image receptor dose (e.g., 70 kV, 1 mAs).

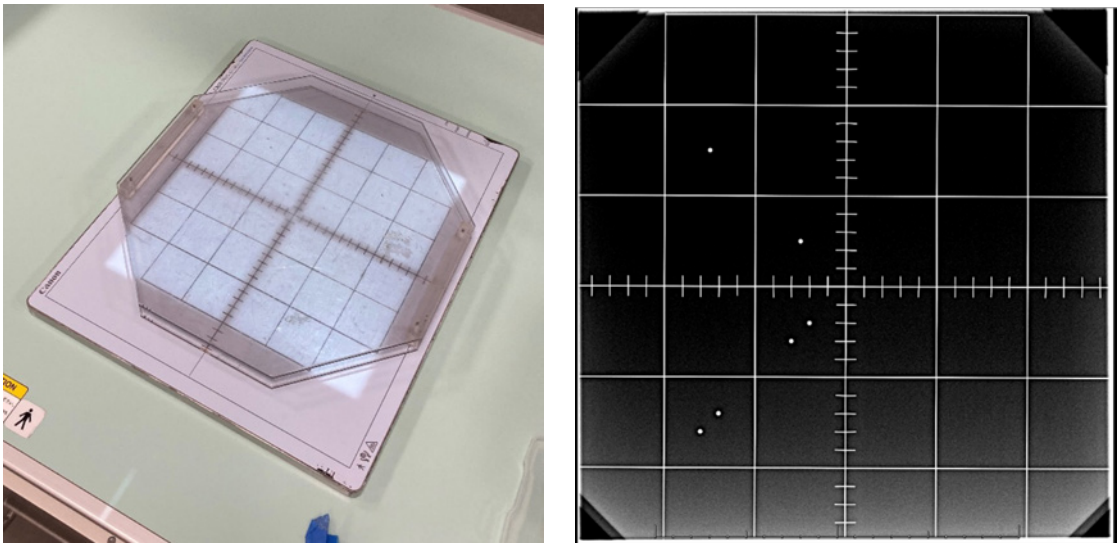

Figure 18. Measuring x-ray/light field alignment using grid of radio-opaque lines.

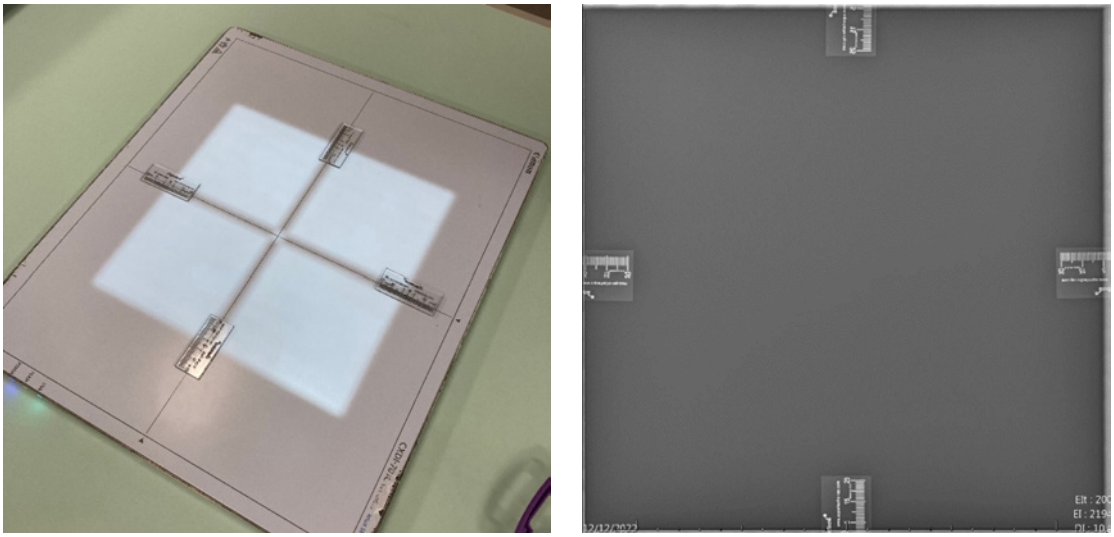

Figure 19. Measuring x-ray/light field alignment using plastic ruler.

8. In the image, use the markings on the grid to determine the field size at the grid. If the image receptor was in the bucky, multiply the field size by the actual radiographic magnification.
9. Compare the field size at the image receptor to the field size displayed on the collimator.
10. In the image, use the markings on the test tool to determine the distance between the edge of the light field and the edge of the x-ray field along each side of the field.

Alternative method using radiochromic film

1. This method uses 4 small strips of radiochromic film, approximately 2 cm × 5 cm. If small strips are not available, they may be cut from a larger piece (see Figure 20).
2. Protect the image receptor by removing it from the bucky, moving the bucky away from the radiation field, or covering the patient table with lead.
3. Set the SID to a typical clinical value such as 100 cm.
4. Collimate the light field to a clinically reasonable size; for example, 30×30 cm for a system that uses a 36×43 cm image receptor.
5. Record the field size indicated on the collimator.
6. Place a strip of film at the center of each edge of the light field, with the zero mark at the center of the strip aligned with the edge of the light field.
7. Use a measuring tape to measure the height and width of the light field; the measurements should be made between the zero marks of the film strips.
8. Take a tabletop exposure at a sufficient air kerma to darken the film; e.g., 70 kV and 250 mAs.
9. Use the markings on the film to determine the distance between the edge of the light field and the edge of the x-ray field along each side of the field.
10. Use the distances determined in step 9 and the measured size of the light field to determine the size of the x-ray field at the tabletop.
11. Compare the x-ray field size at the tabletop to the field size displayed on the collimator.

Alternative method using electronic devices

There are commercially available electronic devices that will indicate the location of the edges of the x-ray field. Follow the instructions provided with the device.

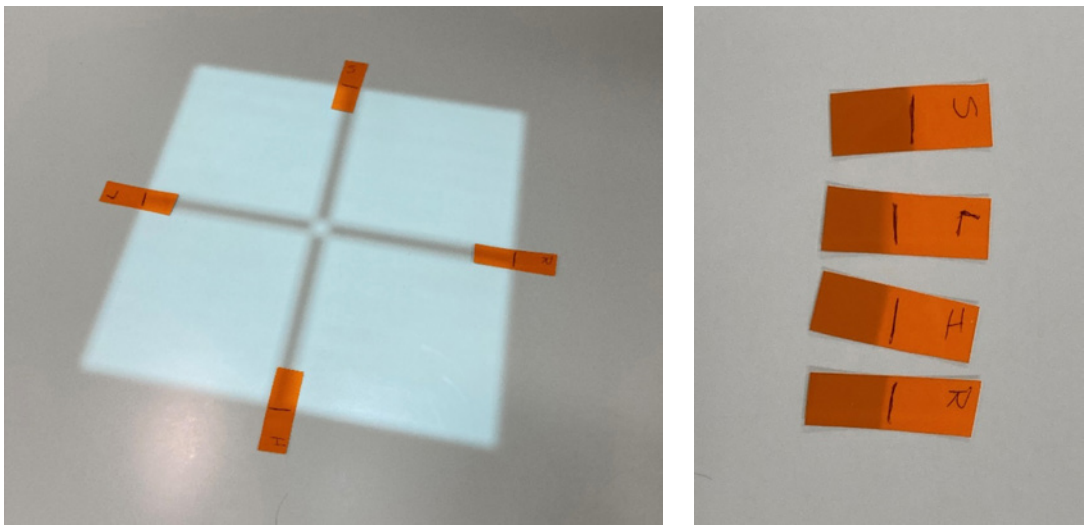

Figure 20. Measuring x-ray/light field alignment using radiochromic film.

Expected performance limits

- The total misalignment of the edges of the visually defined field with the respective edges of the x-ray field along either the length or width of the visually defined field shall not exceed 2 percent of the SID (21 CFR 1020.31(d)(2)(i) [12]).
- The actual x-ray field size at the image receptor should correspond to the indicated size within 2% of the SID in each direction at each field size tested (21 CFR 1020.31(e) [12]).

Potential findings

None noted.

Potential pitfalls

If the image receptor is in the bucky, the field size result from the standard method will be erroneous unless the correct ERMF is used. Consider an acquisition with a 100 cm SID, a nominal field size of 30 cm but an actual field size of 33 cm.; this 3% error should fail the test. If the reference plane is at the tabletop and the image receptor is 5 cm below the tabletop, the ERMF is 1.053 and the size displayed by the software distance tool is 33 cm / 1.053 = 31 cm. If the ERMF is not accounted for, the system erroneously passes the test. This is a much smaller concern for the alignment test; if the distance between the field edges is 2 cm, then a 5% error in that measurement is negligible. These complications may be avoided by performing the standard test with the imaging receptor on the tabletop.

4.2.5 X-ray Field/Image Receptor Alignment

Rationale

The purpose of this test is to verify that the central ray of the x-ray field is aligned to the center of the image receptor to avoid anatomical cutoff.

Recommended method

This procedure may be combined with the light field/x-ray field alignment test.

1. Align the x-ray tube and collimator with the image receptor using position detents. If the system provides automatic longitudinal tracking between the x-ray tube and the image receptor, engage this tracking. If the system does not provide automatic tracking, use the collimator alignment lights or laser to manually align the image receptor to the tube.
2. Turn on the field light, and place a coin on the patient support, centering it on the crosshairs.
3. Acquire an image at low technique (e.g., 70 kV, 1 mAs) with the field size at least 3 cm smaller than the image receptor in both directions.
4. Turn off automatic masking of the image on the acquisition workstation.
5. At the acquisition or PACS workstation, use a measuring tool to make a cross by drawing lines from one corner of the image to the other, in both directions. See Figure 21.
6. Draw a second cross from the corners of the x-ray field to indicate the center of the x-ray field.
7. Measure the distance between the centers of the crosses and verify that it is no larger than 2% of SID. Note: if a small coin is near the center of the image, it can be used to visually assess whether the distance between the centers exceeds the limit. The diameter of a U.S. penny is 19 mm, or 1.9% of a 100 cm SID.
8. Measure the distance between the centers of the x-ray field and the coin centered on the crosshairs, and verify that it is no larger than 2% of SID.

Alternative methods

1. Follow steps 1 to 4 above.
2. Measure the distance from the edge of the x-ray field to the edge of the image along each of the 4 sides.

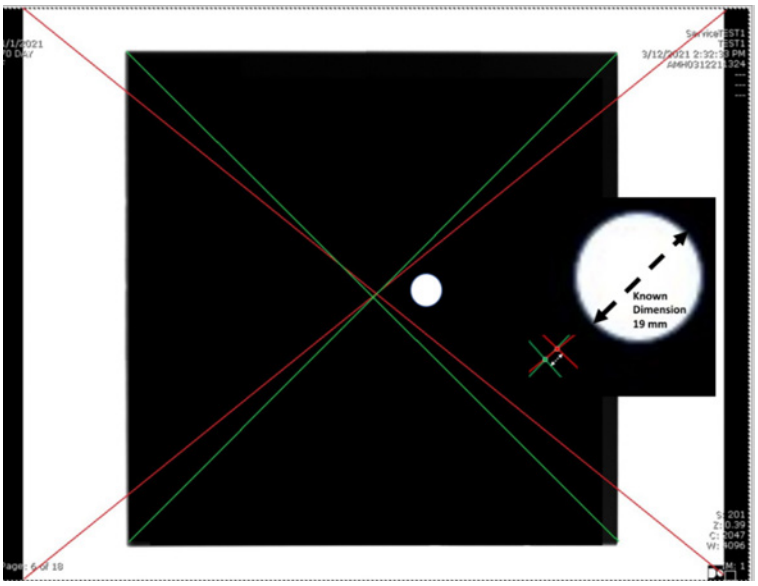

Figure 21. Illustration of the x-ray field/image receptor alignment test.

The horizontal and vertical distance between the center of the image receptor and the center of the field is given by:

$$d_x = \frac{M_L - M_R}{2} \text{ and } d_y = \frac{M_T - M_B}{2} \tag{18}$$

where M_L, M_R, M_T, and M_B are the distances between the x-ray field and the edge of the image receptor on the left, right, top, and bottom sides of the image, and the distance between the center of the field and the center of the image receptor is $\sqrt{d_x^2 + d_y^2}$.

Expected performance limits

- The center of the x-ray field should match the center of the image receptor to within 2% of the SID.
- 21 CFR does not specify a requirement for the alignment of the crosshairs with the x-ray field, but this task group suggests that they should match to within 2% of SID.

Potential findings

None noted.

Potential pitfalls

It may be impossible to identify the center of the image receptor in a system that automatically masks the image to the irradiated field.

4.2.6 Positive-Beam Limitation (PBL)

Rationale

Bucky devices use positive-beam limitation (PBL) to limit the size of the x-ray field to the active area of the image receptor. Note that not all radiographic systems are equipped with PBL. FDA regulations covering PBL are in 21 CFR 1020.31(g) [12].

If the PBL allows an excessively large field size, the region of patient anatomy exposed to radiation is higher, leading to a higher effective patient dose. A larger field size will also cause potential degradation in image contrast due to an increase in detected scatter relative to primary x-rays. On the other hand, over-restricting the field size can result in anatomical cutoff, which might require that images be repeated, resulting in higher patient exposure.

For systems using image receptors of different sizes, the PBL system uses a set of sensors in the bucky tray to determine the size of the image receptor inserted, and relays the information to the collimator control system, which restricts the x-ray field accordingly. Some systems use image receptors of a single size but allow the user to set the active area of the image receptor. In this document, the term "image area" refers to both the size of the image receptor for systems using multiple size image receptors, and the size of the active area of the image receptor for systems using a single size image receptor. 21 CFR 1020.30(b) [12] states that "In those cases where means are provided to preselect a portion of the image receptor, the term 'image receptor' shall mean the preselected portion of the device."

The PBL should be tested quantitatively at acceptance test time for each image area size, and for each SID associated with each of the detent positions used clinically ("SID detent"). Ideally, the PBL should be tested for all image area sizes at each SID detent. However, in practice, it is sufficient to test all image area sizes at one SID detent, and at all SID detents for one image area size.

During annual testing, it may be acceptable to test one image receptor size at one SID quantitatively, and the other image receptor sizes and other SIDs qualitatively.

Recommended procedure for quantitative testing

This procedure determines the maximum x-ray field size by opening the field to the maximum size allowed by the PBL, reducing the field size by a fixed amount, and then adding that fixed amount to the measured value of the x-ray field size. This allows an unambiguous measurement of the maximum x-ray field size in a single exposure, even when the x-ray field can extend past the edges of the image receptor. Reducing the field size by about 5% of SID guarantees that all 4 edges of the radiation field will be visible in the image even when:

- the x-ray field size is at its maximum allowed value (3% of SID larger than the image receptor), and
- the distance between the center of the x-ray field and the center of the image receptor is at its maximum allowed value (2% of SID).

1. Set the SID to the detent position (approx. 100 cm for the table bucky, or 180 cm for a wall bucky).
2. Place the internal image receptor in the bucky (if necessary).
3. Turn on the PBL system, and open the light field as far as it will go.
4. Reduce the size of the light field[6] by about 5% of SID in each direction (5 cm for a 100 cm SID, or 10 cm for 180 cm SID; see Figure 22).
5. Acquire an image at 70 kV and 1 mAs.
6. Turn off automasking in the image.
7. Use the software distance tool to measure the height and width of the collimated x-ray field in the image.
8. Calculate the maximum x-ray field size in the image plane using the following equation:

$$H_{max} = H_{meas} ERMF + \Delta \mathrm{H}$$
$$W_{max} = W_{meas} ERMF + \Delta W \quad (19)$$

   where ΔH and ΔW are the amounts by which the width of the light field was reduced in step 4.
9. Verify that the differences between the maximum height and width of the x-ray field match the height and width of the image receptor to within the regulatory limit (see "Expected performance limits" below).

[6]The change in size of the radiation field can be determined using the collimator SID display, a measuring tape, or an object of known size (two U.S. quarters have a combined diameter of 4.9 cm, so comprise a useful 5 cm test object).

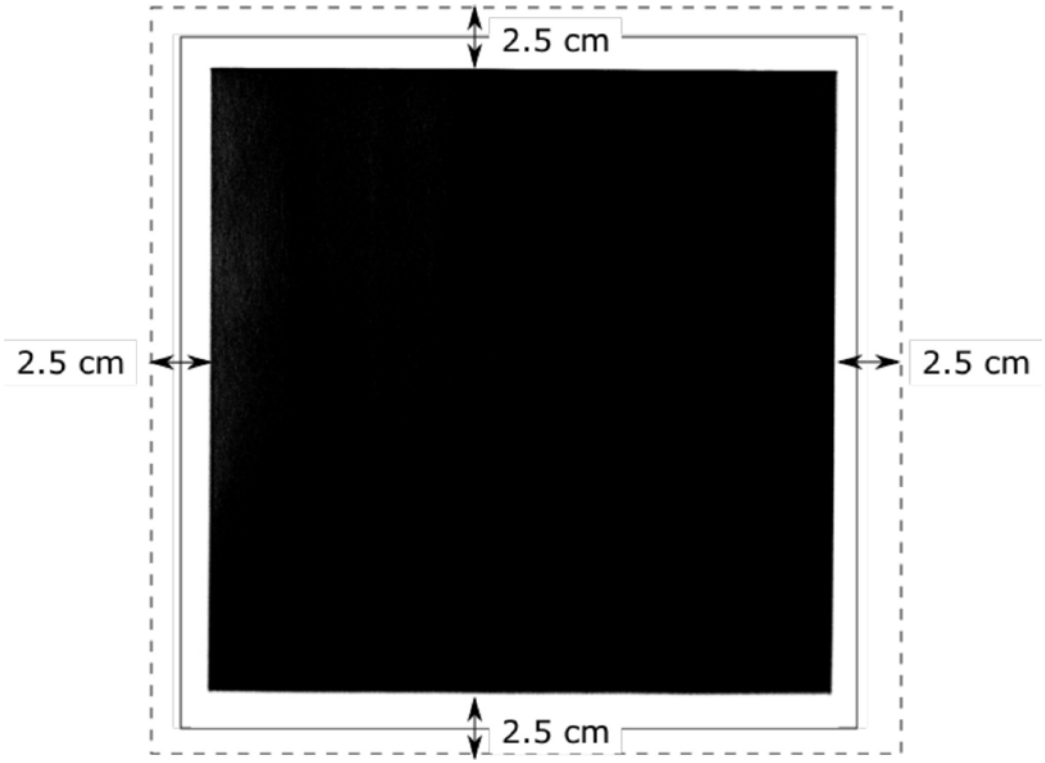

Figure 22. Radiograph showing x-ray field with field size 5 cm smaller than maximum value. The dotted line represents the maximum size of the radiation field allowed by the PBL; the solid square is the outline of the image receptor.

10. At acceptance testing, if there are multiple detents for different SIDs, test for each SID.
11. If there are two buckys, repeat for each bucky at every SID used clinically (e.g., 100 cm for table bucky, 100 cm and 180 cm for wall bucky).

Alternative method (with external image receptor)

This method uses an external image receptor larger than the receptor in the bucky. If multiple external image receptors are available but none are larger than the receptor in the bucky, then two external image receptors may be placed on the table.

1. Set the SID to the detent position (approx. 100 cm for the table bucky, or 180 cm for a wall bucky).
2. Place the internal image receptor in the bucky.
3. Place the external image receptor on the bucky surface (patient table or wall bucky cover).
4. Turn on the PBL and open the collimator as wide as possible.
5. Acquire an image at 70 kV and 1 mAs.
6. Verify that the shadows of all 4 edges of the x-ray field are visible in the image from the internal receptor. If they are not, process the image of the external image receptor, and use it to verify that the height and width of the x-ray field do not exceed the regulatory limit.

Alternative method (qualitative testing)

This may be done for each image receptor size during annual testing after verifying the PBL quantitatively for the largest image receptor size.

1. Insert a different size image receptor in the bucky, or select a different active area of the image receptor.
2. Turn on the light field, and open the collimator as far as it will open.
3. Measure the light field on the table; verify that it is close to the size of the image receptor.

Expected performance limits

The following limits are based on 21 CFR 1020.31(g) [12]. Local regulations may be stricter than this.

- The height and width of the x-ray field must not differ from the corresponding image receptor dimension by more than 3% of the SID.
- The sum of the length and width differences (without regard to sign) must not exceed 4% of the SID; that is $|H_{rad} - H_{IR}| + |W_{rad} - W_{IR}| < SID * 0.04$ where H_{rad} and W_{rad} are the height and width of the radiation field at the image receptor, and H_{IR} and W_{IR} are the height and width of the active area of the image receptor.

Potential findings

- Incorrectly calibrated collimator sensors may result in a field size that is larger or smaller than the image receptor by more than the regulatory limit.
- Failure of the collimator sensors or motors may result in a failure of the field size to change as the active area of the image receptor changes.

Potential pitfalls

- The recommended method requires that the size of the radiation field be reduced by 5 cm or 10% from its maximum. If the change in size is determined using the collimator SID display, the accuracy of the change is limited by the accuracy and precision of the SID display. For example, if the precision of the display is 0.5 cm and the displayed value is 30 cm, the actual field size may be anywhere from 29.5 cm to 30.5 cm.
- When the image receptor is in the bucky, the ERMF for a 100 cm SID is typically about 1.07; for a 43 cm image receptor, ignoring the ERMF will underestimate the x-ray field size by 7%, or 3% of SID.

4.2.7 User Selectable Filtration

Rationale

Many modern radiographic systems offer user selectable filtration, most commonly copper, that can be automatically inserted into the x-ray beam. A common configuration is selectable copper filtration amounts of 0.1, 0.2, or 0.3 mm. This test verifies that the amount of added filtration matches the selected filtration.

Recommended method

Using no added filtration, acquire an image at 80 kV using AEC. Next, insert the first amount of copper filtration and acquire an image under the same conditions. Repeat for all available thicknesses. Verify that mAs values increase as expected based on amount of filtration.

Alternative methods

Using a dosimeter, measure the air kerma 30 cm from the patient support along the central ray with an exposure at 80 kV and 10 mAs. Repeat this measurement for each available copper thickness and verify that measured air kerma decreases as expected with addition of filtration.

Table 11: Expected changes in air kerma or AEC mAs for small amounts of copper (Cu) filtration

Cu thickness (mm)	Exposure (relative to no Cu)	AEC mAs (relative to no Cu)
0.1	0.5 to 0.6	1.7 to 2.0
0.2	0.3 to 0.4	2.5 to 3.3
0.3	0.2 to 0.3	3.3 to 5.0

Expected performance limits

Changes in mAs or air kerma should reflect the relative amounts of filtration in the x-ray beam. Table 11 lists expected changes in air kerma or mAs for small amounts of copper (Cu) filtration.

Potential findings

- The filter actuators or limit switches may be inoperable.
- The control button may be inoperable.

Potential pitfalls

The performance of the AEC system should be verified before this or any test that makes use of the AEC system.

4.2.8 Off-Focus Radiation

Rationale

X-rays are emitted not only from the focal spot, but also from other areas of the anode. These off-focus x-rays both add to patient dose and reduce image contrast. Off-focus radiation is minimized by pre-collimation close to the tube exit port. The highest quality collimators include variable-width pre-collimation blades in both directions; lower quality collimators include only a fixed pre-collimator (the "lead cone"). Collimators that do not include any pre-collimation are generally considered unacceptable for clinical use.

With proper collimation, off-focus radiation can be reduced to less than 10% of the total tube output; without proper collimation, it can be as high as 30% of the total tube output.

Recommended method

1. Attach the lead attenuator to the collimator window, with the pinhole at the center of the window. Collimate the beam to slightly smaller than the lead plate, and use a low dose exposure (e.g., 80 kV, 1 mAs) to acquire an image. Measure and record the distance from the focal spot to the lead plate, and the distance from the focal spot to the image receptor.
2. If using a linear dose-response image receptor, take images at several different techniques, increasing the mAs by a factor of 2 from one exposure to the next, until reaching an image of the off-focus radiation without saturating the image receptor. If using a log dose-response image receptor, take two images with a factor of 2 or 4 change in mAs from one image to another.
3. The image produced will be an image of the focal spot surrounded by an image of the off-focus radiation. Measure the width of the off-focus radiation in the image.

The size of the pre-collimator can be calculated from:

$$W_{pre} = \frac{W_{img}}{M_{eff} - 1} \qquad M_{eff} \equiv \frac{SID - SPD}{SOD - SPD} \tag{20}$$

where W_{img} is the width of the pre-collimator in the image (Figure 23), SPD is the source-pre-collimator distance, and SOD is the source to lead plate distance. The SPD can be determined from the specifications for the collimator. The calculated width of the pre-collimator should be compared to the specifications.

Figure 23 is taken on a 35×43 cm flat panel image receptor.

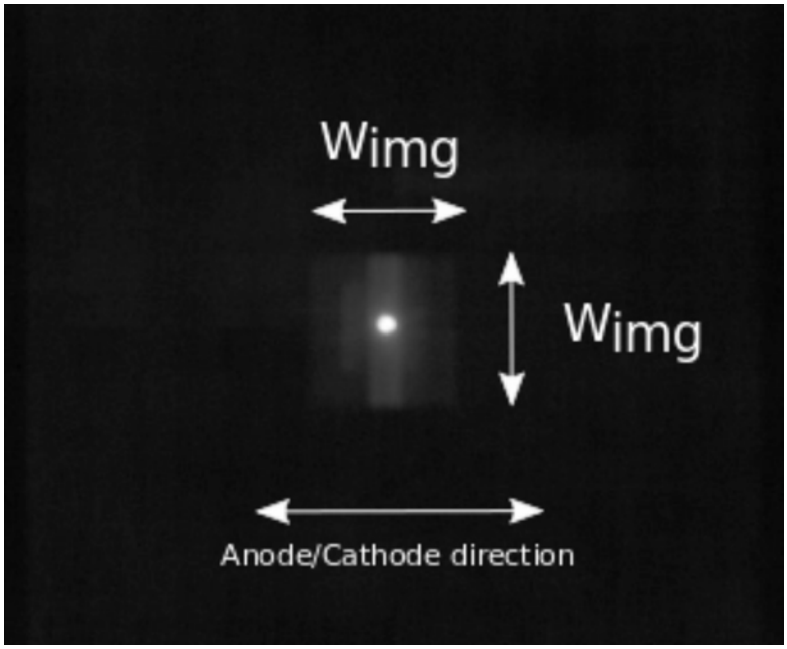

Figure 23. Image of off-focus radiation. The vertical band is caused by x-rays produced by backscattered electrons striking the tungsten track on the anode.

Alternative method

Analyze the LINEARIZED DATA image using an image analysis program such as ImageJ [39]. Calculate the sum S_{FS} of the pixel values within the central hot-spot (the image of the focal spot), and then calculate the sum S_{TOT} of the pixel values over the image of the pre-collimator (i.e., the focal spot plus the pre-collimator). If there is no well-bounded image of the pre-collimator, calculate the sum S_{TOT} over the entire image.

Calculate the fraction of the tube output due to off-focus radiation as:

$$OFR = 1 - {S_{FS}}\Big/{S_{TOT}} \tag{21}$$

Expected performance limits

The measured width of the pre-collimator should be no more than 20% larger than the width listed in the collimator specifications. If this is not available, the pre-collimator should be no wider than 30 mm.

The off-focus radiation should be no more than 20% of the total tube output.

Potential findings

If the calculated size of the pre-collimator is larger than 30 mm, or the off-focus radiation is more than 20% of the total tube output, there may be no pre-collimation.

Potential pitfalls

- If an insufficient radiographic technique or an inappropriate window/level display setting is used, or the hole in the lead plate is too small, the off-focus radiation may not be visible on the display.
- A linear dose-response image receptor may not have sufficient dynamic range to visualize the off-focus radiation without saturating the image of the focal spot.
- If a log dose-response image receptor is used, the calculated amount of off-focus radiation will be inaccurate unless the correct dose-response curve is used.

4.3 Digital Image Receptor Tests

Introduction

There is a vast array of different clinical implementations of digital x-ray image receptors and systems. Consequently, it is difficult to provide detailed instructions that will be appropriate for every eventuality. However, the tests described herein can form the basis of an appropriate QA program for most settings. In general, where a manufacturer's QC recommendations already exist, it should form the basis of QA program/QC testing of the image receptor, especially when functionally equivalent information about receptor performance is provided. These tests are intended for image receptors comprised of CCD/CMOS or flat panel technology, but have utility for other digital devices, including storage phosphor systems so long as the differences between the fundamental imaging technologies are understood by the user and the results of the tests are appropriately interpreted. Certain other imaging technologies may also have unique failure modes that may not be addressed by the tests described here. For example, see AAPM Report 93 [2] for tests specific to PSP (photostimulable storage phosphor) image receptors.

The test suite outlined here specifically assesses performance of the x-ray image receptor component of the digital imaging chain. It is not always possible to isolate this component from other system components such as the grid or automatic exposure control unit. In this situation, care should be taken when interpreting the results of these tests to ensure that any anomalous measurements are attributed to the correct component in the imaging chain. Again, close collaboration with the equipment vendor should allow efficient resolution of any performance issues identified by the recommended tests.

In general, image receptor testing for digital systems has two specific goals:

1) *Measurement of the fundamental imaging performance of the image receptor.* This includes, but is not limited to, properties such as:
   a. Sensitivity i.e., signal expected for a given air kerma with a predefined x-ray beam quality,
   b. Noise at given air kerma levels,
   c. Nonuniformity of the signal response and noise,
   d. Nonuniformity of spatial resolution across the image receptor surface,
   e. Geometric accuracy (for systems using lens or fiber-optic coupling between the phosphor and the sensing plane/CCD), and
   f. Contrast-to-noise performance for a specific "phantom."
2) *Detection of artifacts in the image that are problematic for the diagnostic interpretation of the image.* This may include, but is not limited to:
   a. Inadequately corrected defective detector elements,
   b. Correlated noise, such as that caused by ground loop pick-up or light leaks,
   c. Uncorrected image features caused by configuration changes from the system calibration conditions, either geometric or beam quality, and
   d. Residual effects such as signal ghosting or lag for DR systems or inadequate erasure for CR systems.

The tests in this section have been developed to address these two goals with a least burdensome approach to allow efficient implementation in a clinical environment. The tests comprise two main types of data acquisition:

1. Flat field images, where a series of x-ray exposures of clinically significant beam quality and image receptor dose are acquired with nothing in the beam except added beam filtration; and
2. A series of images of test objects, again acquired under well-controlled acquisition conditions, that measure the image receptor's spatial resolution and contrast-to-noise performance, as well as image retention behavior and geometric accuracy.

These acquired images are then analyzed to provide information on the imaging performance and stability of the device being tested.

The next section will outline some of the prerequisites and system configuration issues that must be addressed before testing can commence.

QC testing prerequisites and system configuration

The tests outlined here assume that the x-ray production equipment, e.g., the x-ray tube and generator, is in proper working order. In particular, the operation of the x-ray delivery system must be validated prior to the creation of baseline test results that will form the basis for ongoing QC testing. The beam output (mGy/mAs) and half-value layer or tube voltage should be measured, validated against expected values, and recorded for future reference when initial testing of the system is undertaken. In general, the tests should be performed in the configuration used for system calibration. Issues of whether the grid or other system components should be included in the calibration configuration must be addressed with the system manufacturer. Deviation from the manufacturer's specified calibration configuration can seriously affect the gain calibration process and invalidate the results of subsequent testing. Care should be exercised when aligning the x-ray beam with the image receptor prior to image acquisition; otherwise, intensity variation due to misalignment may invalidate test results.

Limitations of these QC tests

The image receptor tests described in this section are useful to establish performance benchmarks and track system operation over time. It is not recommended to use these tests as a measure of absolute system performance for the purpose of comparing different models from a single manufacturer or different manufacturers. Quantitative measurements based on image pixel values are dependent on various scaling and calibration factors and the image receptor response function. Comparing systems with different underlying pixel value representations may lead to false or misleading conclusions.

Some of these tests require specialized software; examples include correlated noise and defective detector element detection. Some modality units include software to perform these or similar tests automatically; however, independent verification based on third-party software is recommended. Task Group 150 is aware that until such software is widely available, these tests will not be practical for most physicists.

Test equipment required

Test	Required equipment
Acquisition of flat field image data	USB drive or other storage media to save and record images for further analysis, or access to images on PACS. Solid-state dosimeter or ionization chamber with dosimeter. One of the following mounted at the exit port: • Attenuator specified by manufacturer for calibration (preferred) • 21 mm aluminum block • 0.5 mm of copper and 1 mm of aluminum • 2 mm of copper
Spatial resolution	Spatial resolution target such as: • Bar pattern phantom, ideally with the lowest frequency no higher than 1/3 of the Nyquist frequency, and the highest no lower than the Nyquist frequency • Sector line pair phantom • Specialized edge device for a full pre-sampled MTF measurement
Spatial resolution uniformity	Wire mesh with the following properties: • Sufficient sampling for image receptor being tested (wire mesh spacing several times the detector element pitch) • Thickness somewhat smaller than the detector element pitch • Large enough to cover the image receptor
Contrast-to-noise ratio (aluminum sheet method)	One of the following: • Aluminum stepwedge • Single-shot phantom containing stepwedge • 4 mm aluminum filter
Contrast-to-noise ratio (contrast detail method)	Contrast-detail phantom
Geometric accuracy	One of the following: • One or more radio-opaque objects of known dimension • Test object containing grid of lines of attenuating material
Ghosting (active test method)	High contrast object such as: • 5×5 cm lead square, 1 mm or more thick • Lead-backed dosimeter

Description of flat field tests

The following sections describe:

- The acquisition of flat field image data at a variety of air kerma levels,
- Calculations to be performed on the images, and
- Analysis of the results of the calculations.

4.3.1 Acquisition of Flat Field Image Data

Rationale

A large amount of information on the imaging performance of a digital x-ray image receptor can be obtained from simple flat field images acquired under well-constrained imaging conditions. Depending on the type of testing being undertaken, i.e., whether initial acceptance testing or ongoing image quality validation, it may be appropriate to acquire a number of images at different image receptor incident air kerma levels to test the performance of the device over its typical operational range. These images can:

- provide information on the suitability of the gain/offset correction parameters the system is using and whether calibration is required,
- help identify defective detector elements and lines,
- highlight various image artifacts that can confuse clinical diagnosis,
- validate the accuracy of air kerma indicator values generated from clinical images, and
- serve as the basis for other important imaging performance metrics.

Some system manufacturers recommend the acquisition of "dark" images, i.e., images acquired with zero input radiation, to allow measurement of the inherent electronic noise levels within the image receptor. However, analysis of dark image data can be problematic because of the different ways manufacturers handle extremely low signal values. Offset subtraction arithmetic, inherent in the gain/offset correction algorithms, can result in negative pixel values. Some systems will not acquire and transmit an image without exposure to x-rays.

During the acquisition of flat field images, it is recommended that clinical image processing be deactivated or minimized if possible. The ideal image for flat field analysis is the "FOR PROCESSING" image (DICOM nomenclature) or the "ORIGINAL" data (IEC nomenclature). The system manufacturer should provide guidance to the user on how to deactivate or minimize clinical image processing, and how to obtain "ORIGINAL" data. If the clinical image processing cannot be temporarily disabled, the user must know exactly what image processing is being performed and how to reestablish this image processing configuration for future testing. Examples of "clinical" image processing are noise suppression, log exposure space conversion, edge enhancement, contrast modification, dynamic range compression, etc. Many of these are nonlinear in effect and can easily confound the results of consistency testing if their detailed processing parameters are not controlled. Unless otherwise specified, the tests in this section require the use of FOR PROCESSING images.

This task group recognizes that there is an opportunity for vendors to anticipate the clinical QC testing requirements of medical physicists conducting evaluations. Vendors could publish white paper guidelines on recommended approaches to achieve accurate results using the system, include specific guidance targeted to the medical physicist in the user manual, and incorporate test functions into their acquisition software to perform the tests described in this report.

Recommended method

Ideally, this test should be done immediately after calibration. If the manufacturer has specific instructions for acquiring flat field images for QC, follow those. Otherwise, do the following:

1. If possible, turn off all clinical image processing (see note under "Rationale" above).
2. Attach a ~21 mm aluminum block or 0.5 mm copper and 1 mm aluminum filters to the exit port of the collimator.
3. Place a lead apron on the floor to prevent backscatter.
4. Place the dosimeter on the lead apron. If it is impossible to remove the image receptor from the bucky, place the dosimeter on the entrance to the bucky, and remove the anti-scatter grid if possible.
5. Set the SID to 180 cm, or the highest possible value, whichever is smaller.
6. Open the collimator to about a 10 cm × 10 cm field and take an exposure at 80 kV using a technique in the range 10–50 mAs.
7. Divide the mAs by the air kerma and record the result.
8. Repeat steps 5 and 6 at 60, 100, and 120 kV.
9. Remove the dosimeter, and place the image receptor on the floor in its place. To minimize the heel effect, the image receptor should be oriented with its short axis parallel to the tube's anode-cathode axis.
10. Turn off the PBL, and open the collimation wide enough that the x-ray field extends at least 1 cm past the image receptor on all sides.
11. Acquire flat field images at 80 kV for minimum of three different air kerma values (low, medium, and high as mentioned in Table 12). Use the ratio calculated in step 7 to determine the mAs required for the desired air kerma.
12. At the medium level, acquire flat field images at 60, 100, and 120 kV.
13. Save the images, either to an external storage media or an image server.

Table 12: Recommended air kerma levels for flat field image data sets

Level	Description
Medium	This is the air kerma typically seen in clinical use; this is described in IEC 62220-1-1 as the "normal" level. The value depends on the model of the image receptor, but it is typically ~3–5 μGy (0.3–0.5 mR).
Low	An air kerma ~ 0.3125 * the medium level (i.e., medium level/3.2)
High	An air kerma ~ 3.2 * the medium level
Calibration (optional)	The air kerma used for system calibration according to manufacturer specifications.
Maximum	The maximum air kerma within the image receptor's specified operating range.

These levels have been chosen to reflect the signal ranges that the image receptor is exposed to during typical clinical use of the system, and are based on recommendations from IEC standard 60220-1 [15]. The only purpose of testing the maximum clinically useable air kerma recommended by the manufacturer is to detect artifacts that may appear in heavily overexposed but not saturated images.

Note: if any of the flat field analysis tests fail, it is advisable to repeat the tests under the calibration conditions. Failure under calibration conditions warrants service intervention.

IMPORTANT: Moderately high-dose exposures of high contrast objects such as solid-state dosimeter sensors can produce ghost artifacts that may take minutes or hours to decay, possibly affecting subsequent test results. Avoid taking such high-level exposures whenever possible, and minimize the number of such images at the medium level.

Additional notes

In situations where the benchmark performance is being determined and validated against manufacturer specifications, it is recommended that flat field exposure acquisition is done immediately after the system has been fully calibrated, and without changing the geometric configuration of the image receptor or x-ray source [40]. Thus, it is preferable that the physicist coordinate with the vendor service engineer to be present during initial calibration of the image receptor. This should be possible during acceptance testing, but may be impractical for periodic testing. This test will then provide the most accurate measurement of the image receptor's imaging capabilities.

In situations where the image receptor is calibrated at a variety of beam quality settings, flat field images should be acquired for analysis at each of the different beam quality settings.

For systems that are frequently used with widely varying kilovoltages but are only calibrated at a single beam quality configuration, it may be informative to acquire a single image at a representative air kerma value for high and low tube voltage settings that are different from the calibration tube voltage. Because of the variability of the x-ray tube heel effect at different tube voltage settings, this may introduce nonuniformities in the resulting flat field images that must be interpreted carefully.

Potential findings

The images will be used in the tests described in Section 4.3.2 "Flat field image analysis."

Potential pitfalls

- Some manufacturers follow calibration protocols that do not employ any level of beam filtration that results in an x-ray spectrum very different from spectra encountered during clinical operation of the equipment. Multiple authors have reported energy dependence of various digital image receptors [41] [42] [43] [44]. Employing filtration such as 0.5 mm copper + 1 mm aluminum as recommended by AAPM Report 93 [2] for flat field tests may provide more clinically relevant information on image receptor behavior.
- Nonuniform irradiation of the image receptor can confound the flat field image analysis. There are several solutions to this problem. When the x-ray tube heel effect is not removed by a gain correction procedure (e.g., in photostimulable storage phosphor systems), it is recommended that the flat field image be acquired using two 50% mAs exposures: one with the receptor

rotated by 180 degrees. This process helps reduce the exposure nonuniformity caused by the heel effect (AAPM Report 93 [2]). For digital image receptors that do not allow a split exposure, two separate images can be acquired with 180-degree image receptor rotation and then summed using a software application such as ImageJ [39] to produce a flat field image with heel effect cancelled out. However, keep in mind that many digital image receptors have a heel effect compensation "built-in" to the gain correction. The gain correction should exactly compensate for heel effect if the flat field image is acquired under image receptor calibration conditions, including the same image receptor orientation. A large source-to-image distance (SID) will minimize nonuniformity from the heel effect, but this SID may not represent the conditions of calibration or the conditions of clinical use.

4.3.2 Flat Field Image Analysis

Many of the following tests would be expedited by using automated image QC software. It is beyond the scope of this task group to enumerate the specific products currently available, but we encourage manufacturers of digital radiographic imaging systems to implement automated analysis tools that can facilitate the overall work of the medical physicist during acceptance testing, and the performance of this test in particular.

Rationale

Flat field image analysis allows calculation of the image quality metrics that will be used to quantify the imaging performance of the image receptor. The characteristic signal and noise levels should be determined for a number of regions of interest (ROIs) distributed across the image receptor surface for each of the flat field images acquired at the different air kermas.

The flat field image analysis generates a collection of signal and noise values corresponding to each ROI. A single characteristic image signal ($\bar{S}_{IR}$) and a single characteristic image noise value ($\bar{N}_{IR}$) can be determined from the collection of individual ROI pixel value means and ROI pixel value standard deviations by calculating the mean of the ROI pixel value means and the mean of the ROI pixel standard deviations (Figure 24). Once the signal and noise characteristics have been determined for the images acquired at different air kerma values, a number of image quality metrics can be calculated and tested against pass/fail thresholds. These include eight metrics described in the following sections:

- Pixel value/air kerma response
- Signal uniformity
- Noise uniformity
- Signal-to-noise ratio uniformity
- Minimum signal-to-noise ratio
- Defective detector element detection
- Correlated noise
- Detective quantum efficiency

Recommended method

1. If specialized software is developed or purchased for this purpose (recommended), then define small ROIs (~1 to 2 cm square) that are contiguous or overlapping to cover the entire surface of the image receptor (Figure 24). The exact dimensions and locations of ROIs can be aligned with the preamplifier/readout circuit layout for the specific image receptor under test (if this information is available from the manufacturer) to achieve the maximum benefit. ROIs matched to chip boundaries make tests more sensitive to nonuniformities caused by differences in chip characteristics (e.g., gain and offset).
2. If the calculation is being done manually, then define at least 5 ROIs (~2×2 cm) located at the center and close to the 4 edges of the image receptor surface (Figure 24).

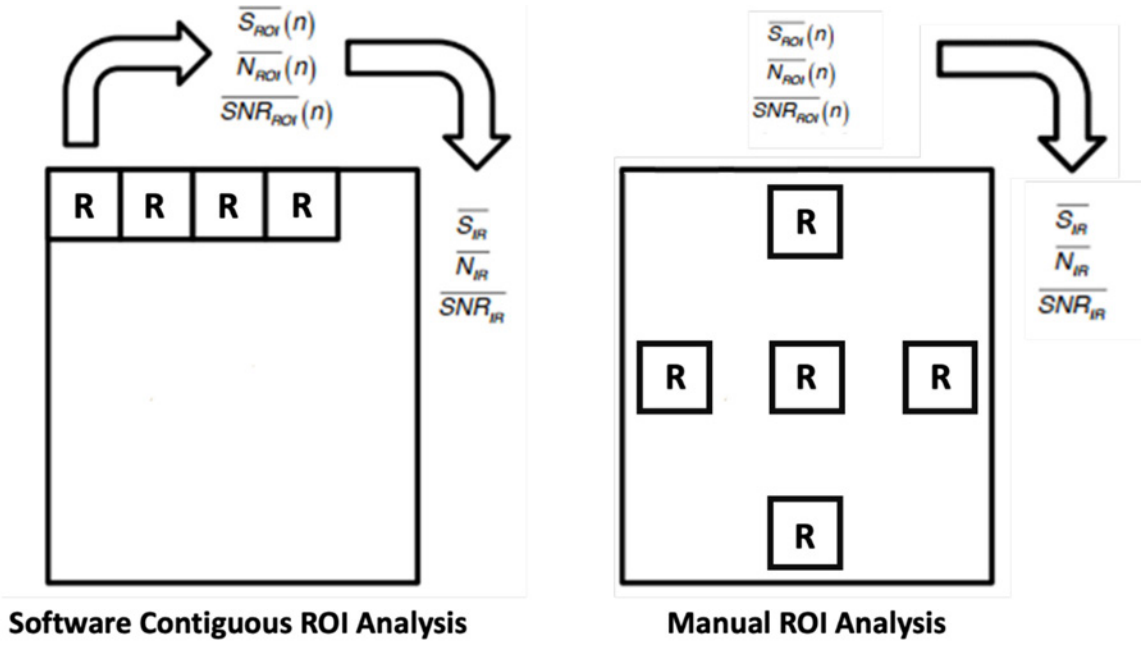

Figure 24. Determination of average properties of receptor from average properties of a collection of ROIs. Left: ROIs placed automatically by dedicated software. Right: ROIs placed manually.

3. For each of the ROIs, calculate the average pixel value ($\overline{S_{ROI}}$), the pixel standard deviation (SD_{ROI}), and the signal-to-noise ratio (SNR_{ROI}). These are the "local statistics:"

$$\overline{S_{ROI(n)}} = \frac{1}{N_{pixels}} \sum_{k=1}^{N_{pixels}} S_k \tag{22}$$

$$SD_{ROI(n)} = \sqrt{\frac{1}{N_{pixels} - 1} \sum_{k=1}^{N_{pixels}} \left(S_{pixel} - \overline{S_{ROI(n)}} \right)^2} \tag{23}$$

$$SNR_{ROI(n)} = \overline{S_{ROI(n)}} \Big/ SD_{ROI(n)} \tag{24}$$

4. Calculate the average for each of the quantities; these are the "global statistics:"

$$\overline{S_{IR}} = \frac{1}{N_{ROIs}} \sum_{n=1}^{N_{ROIs}} S_{ROI(n)} \tag{25}$$

$$\overline{N_{IR}} = \sqrt{\frac{1}{N_{ROIs}} \sum_{1}^{N_{ROIs}} SD^2_{ROI(n)}} \tag{26}$$

$$\overline{SNR_{ROI}} = \frac{1}{N_{ROIs}} \sum_{1}^{N_{ROIs}} SNR_{ROI(n)} \tag{27}$$

where N_{ROIs} is the number of regions of interest.

Expected performance limits

The local and global statistics calculated with equations 22–27 do not have specific performance limits. These values are used to calculate performance metrics in the following sections. Limits for each individual test are found in their respective sections. If general standards are available, they will be listed; otherwise manufacturer specific performance limits may be used.

Potential findings

Potential findings for each image quality metric are provided in each of the following sections.

Potential pitfalls

- Defective pixels within the ROI area have the potential to lead to ambiguous results. One way to minimize these errors is through the use of the median filter operator. Another approach is to detect and eliminate from analysis anomalous pixels before calculating the ROI signal and noise values.
- Variations in the signal background (e.g., inverse square law dependent exposure variation or the heel effect) will cause the pixel standard deviation to be larger than the actual noise. This effect is likely to be small for small ROIs, but can be significant if using an ROI that contains most or all of the image. Additional corrections can be applied to achieve a more uniform flat field image for analysis. Approaches to make these corrections include:
  - Acquire a second image at the same air kerma and beam quality as the image to be tested, and subtract the two images. The resulting image should include only statistical noise, but this noise will be elevated in magnitude by the subtraction, and important correlated image features (i.e., artifacts) that should be analyzed may be removed or suppressed.
  - Acquire a high exposure, low noise image and divide the image to be tested by this image. This will remove slowly varying background, but it may remove or suppress important undesirable image features (i.e., artifacts) that should be analyzed in another test, and it will add noise from the high exposure image to the image to be tested.
  - Apply a high-pass filter to the image to be tested. This will result in an underestimate of the noise by suppression of low frequency noise, and will not correct well for errors in the nonuniformity correction.
  - For software that automates the analysis, it is useful to fit a two-dimensional function[7] to the image, and then subtract the fitted function from the pixel values. This will remove any slowly varying background without affecting the noise or the noise nonuniformity.

4.3.3 Pixel Value/Air Kerma Response

Rationale

This test characterizes image receptor response (i.e., the pixel value/air kerma response function) by plotting the characteristic image signal value, $\overline{S}_{IR,}$ versus the exposure value from the images acquired at different air kerma values (low, medium, high, and calibration). If the image receptor response is linear with exposure, then the slope of this curve is the sensitivity, and characterizes the image receptor response. In situations where the image receptor response is nonlinear, it may be sufficient to ensure that the signal value is as expected for the different air kerma levels over a "reasonable" extent of the image receptor response curve. This test does not necessarily require any linear or polynomial fitting to the data but may take the form of ensuring that a specific exposure results in an appropriate corresponding signal value in the image. This can be performed in either the linear or log exposure domain; that is, the signal value changes either linearly or logarithmically with exposure. If advanced imaging system performance analysis (e.g., DQE) is to be performed, then it will be necessary to linearize the

[7] For example, a two-dimensional quadratic function:
$= C_0 + C_1x + C_2y + C_3x^2 + C_4xy + C_5y^2$

exposure domain of images used in the evaluation. The image receptor response function determined in this step can be used for this linearization. See Appendix D of this report for more information about image exposure domains. Depending on the details of the flat field gain correction applied to the image, the image receptor response test may reflect changes in the inherent sensitivity of the image receptor or only give information on the accuracy of the exposure index that is reported.

Recommended method

Results of calculations from Sections 4.3.1 and 4.3.2 are used.

Plot $\overline{S}_{IR}$ values versus incident air kerma obtained from the different air kerma flat field images. The values used should be from the central ROI, or several ROIs covering the central 10% of the area of the detector (IEC 62494-1) [16].

Expected performance limits

According to IEC 62494-1 [16], the calculated sensitivity or average signal values, $\overline{S}_{IR}$, should be within +/− 20% of the expected value/values determined at acceptance/commissioning or defined by the manufacturer.

If the detector has a linear dose-response function, air kerma should match a linear fit to the pixel value to within the exposure reproducibility of air kerma.

Potential findings

- The air-kerma/signal curve may not have the shape specified by the manufacturer.
- The signal amplitude may be above or below the values specified by the manufacturer.

Potential pitfalls

None noted.

4.3.4 Signal Uniformity

Rationale

Nonuniformity metrics can be divided into local (Eq. 28) and global (Eq. 29) measurements. Local nonuniformity is determined from the difference in signal value between a ROI's characteristic signal level, $\overline{S}_{ROI(i)}$, and the characteristic signal levels from neighboring ROIs. This difference is expressed as a percentage of the characteristic signal value for the whole image, $\overline{S}_{IR}$:

$$NU^{S,local}_{ROI(i)} = \frac{\overline{S}_{ROI(i)} - \left\langle \overline{S}_{ROI(j)} \right\rangle_{j \text{ near } i}}{\overline{S}_{IR}} \tag{28}$$

The global nonuniformity is calculated by determining the maximum difference between the largest and smallest values of the characteristic signal levels from the individual ROIs, $\left(\max\left(\overline{S}_{ROI(\mathrm{i})}\right)\right.$ and $\left.\mathrm{in}\left(\overline{S}_{ROI(\mathrm{i})}\right)\right)$, expressed as a percentage of the characteristic signal value for the whole image:

$$NU^{S,global} = \frac{\max\left(\overline{S}_{ROI(\mathrm{i})}\right) - \min\left(\overline{S}_{ROI(\mathrm{i})}\right)}{\overline{S}_{IR}} \tag{29}$$

Recommended method

Results of calculations from Section 4.3.2 (Flat Field Image Analysis), specifically from equations (22) and (25), are used.

Calculate the local and global nonuniformity for the flat field images from equations (28) and (29).

Expected performance limits

- For a given flat field image, the local nonuniformity will be less than or equal to the global nonuniformity.
- Compare the calculated local and global signal nonuniformity to the determined at acceptance/commissioning or defined by the manufacturer.

Potential findings

Excessive nonuniformity may indicate incorrect image receptor calibration.

Potential pitfalls

- If the relative position of the tube and image receptor have changed since calibration, it is possible that nonuniformities in the x-ray field, rather than image receptor properties, can dominate the measurement of the global nonuniformity. A change in SID will change the inverse-square effect, and a change in orientation will aggravate the heel effect. This is particularly an issue for portable DR systems where the image receptor is not fixed in place with respect to the x-ray source. This may require recalibration of the image receptor prior to the testing described here, and with the test images acquired without the image receptor being moved between calibration and acquisition.
- Alternative methods for removing x-ray field nonuniformity and fixed pattern noise from the flat field are presented in Potential pitfalls of Section 4.3.2 (Flat Field Image Analysis) above. However, care should be exercised in evaluation of the subtracted image because correlated noise patterns may be removed by the subtraction operation.
- Manufacturer may not supply relevant criteria for signal nonuniformity.

4.3.5 Noise Uniformity

Rationale

As with the signal nonuniformity, the global and local noise nonuniformity can be determined and tested in a similar manner by using the individual ROI characteristic noise value, $\overline{N}_{ROI(i)}$. One should remember that, unlike signal nonuniformity, problems with noise nonuniformity cannot be "corrected" by the gain/offset correction procedure. This has the following consequences:

- The global and local noise nonuniformity failure limits are necessarily different than the appropriate tolerance for signal nonuniformity.
- Noise nonuniformity may be a more sensitive test for problems with image receptor blocks than signal nonuniformity.

Recommended method

Results of calculations from Section 4.3.2 (Flat Field Image Analysis), specifically from equations (23) and (26), are used.

Calculate the local and global noise nonuniformity for the acquired flat field images using the following equations:

$$NU^{N,local}_{ROI(i)} = \frac{N_{ROI(i)} - \left\langle N_{ROI(j)} \right\rangle_{j \text{ near } i}}{\overline{\mathrm{N}_{IR}}} \tag{30}$$

$$NU^{N,global} = \frac{\max\left(\mathrm{N}_{ROI(\mathrm{i})}\right) - \min\left(\mathrm{N}_{ROI(\mathrm{i})}\right)}{\overline{\mathrm{N}_{IR}}} \tag{31}$$

Expected performance limits

The noise nonuniformity values should be compared to manufacturer specifications, if they exist. Otherwise, they should be compared to results from acceptance testing or previous periodic testing.

Potential findings

- A defective image receptor block may have a large local noise nonuniformity.

Potential pitfalls

- Even with an image receptor with perfectly uniform noise performance, exposure nonuniformity from the heel effect can inject a substantial amount of nonuniformity in the noise profile across the image receptor surface. The magnitude of the nonuniformity from the heel effect depends on the details of the x-ray tube and the distance to the image receptor, and is geometrically dependent on the orientation of the image receptor with the anode-cathode axis during calibration and test image acquisition. This has an impact on the "acceptable" level of noise nonuniformity on different clinical systems.
- Manufacturer may not supply relevant criteria for noise nonuniformity behavior.

4.3.6 Signal-to-Noise Ratio (SNR) Uniformity

Rationale

The global and local signal-to-noise ratio (SNR) nonuniformity can be determined in a similar manner as signal and noise nonuniformity. Both local and global SNR nonuniformity are expressed as a percentage of the characteristic SNR for the image receptor, $\overline{SNR_{IR}}$.

Recommended method

Results of calculations from Section 4.3.2 (Flat Field Image Analysis), specifically from equations (24) and (27), are used.

Calculate the local and global signal-to-noise nonuniformity (SNR) for the acquired flat field images using the following equations:

$$NU_{ROI(i)}^{SNR,local} = \frac{SNR_{ROI(i)} - \left\langle SNR_{ROI(j)} \right\rangle_{j \text{ near } i}}{\overline{SNR_{IR}}} \tag{32}$$

$$NU^{SNR,global} = \frac{\max\left(SNR_{ROI(i)}\right) - \min\left(SNR_{ROI(i)}\right)}{\overline{SNR_{IR}}} \tag{33}$$

Expected performance limits

The calculated local and global SNR nonuniformity is less than a specified threshold determined at acceptance/commissioning or as defined by the manufacturer.

Potential findings

None.

Potential pitfalls

Manufacturer may not supply relevant criteria for SNR nonuniformity behavior.

4.3.7 Minimum Signal-to-Noise Ratio

Rationale

In addition to SNR nonuniformity, it is also important to evaluate the SNR of the image receptor on an absolute basis. It is more important to evaluate the minimum SNR, $\overline{SNR}_{ROI(i)min}$, from the different ROI values than the average SNR, $\overline{SNR}_{IR}$, of the image receptor. The limit for the minimum SNR of an image receptor at a specific air kerma should be provided by the manufacturer and validated at system acceptance/commissioning. At high air kerma levels, the SNR should be dominated by the incident photon flux and the image receptor DQE. At low air kerma levels, the SNR may be dominated by electronic noise.

Recommended method

Results of calculations from Section 4.3.2 (Flat Field Image Analysis), specifically equation (24), are used.

Determine the minimum value of the SNR ($\min(SNR_{ROI(n)})$).

Expected performance limits

The minimum SNR should be no less than the value specified by the manufacturer, and no less than 90% of the minimum SNR measured during acceptance testing.

Potential findings

A loss of SNR at low air kerma levels implies an increase in the electronic noise.

Potential pitfalls

Manufacturer may not supply relevant criteria for minimum SNR behavior.

4.3.8 Defective Detector Element Detection

Rationale

During detector calibration, the flat panel digital radiographic system software generates a map of defective (unresponsive or over- or under-responding) detector elements often referred to as a "bad pixel map." A more accurate description is that this is a "defective detector element map." During image data acquisition, the pixel values for the defective detector elements are generated by interpolating the values of neighboring pixels. Manufacturers generally specify the maximum number of allowable bad pixels, and these may be counted by periodic vendor-supplied QC tests. However, an independent test is desirable to verify that the number of bad pixels is below the specified maximum.

Recommended methods

No reliable methods of detecting bad pixels independent of manufacturer-supplied tests is known to the task group. This continues to be a high priority topic for research.

4.3.9 Correlated Noise

Rationale

In addition to anomalously behaving individual detector elements, groups of detector elements can exhibit subtle correlated behavior that can manifest as distracting image artifacts. This is particularly true of elements along the same vertical or horizontal line. The human visual system is extremely sensitive to linear correlations of this type. It is the correlation, rather than the magnitude of the signal difference, that makes the artifact visible. These artifacts can manifest as rows or columns with values systematically above or below from their neighbors due to offset or gain errors. The pixels involved in the correlation may easily pass the "Defective detector element detection" test, but the resulting artifact can be clearly visible. This type of correlated noise can be "stationary" in an image receptor, i.e., it remains in the same location in different images, or it may appear to move in location from image-to-image. The latter is typically caused by external influences such as electromagnetic or microphonic interference, while the former is typically associated with aspects of the electrical connections within the image receptor. However, there are a myriad of reasons for this type of artifact, and it is not always possible to identify the root cause. Flat field images acquired in Section 4.3.1 are used to identify correlated noise.

Recommended method A

An effective method for identifying line correlated noise that is aligned with either of the pixel raster axes is to project a line profile along each axis by averaging all the pixels along each row or column (see Figure 25):

$$P_n^{row} = \frac{1}{N_{rows}} \sum_m S_{n,m} \qquad P_m^{col} = \frac{1}{N_{cols}} \sum_n S_{n,m} \tag{34}$$

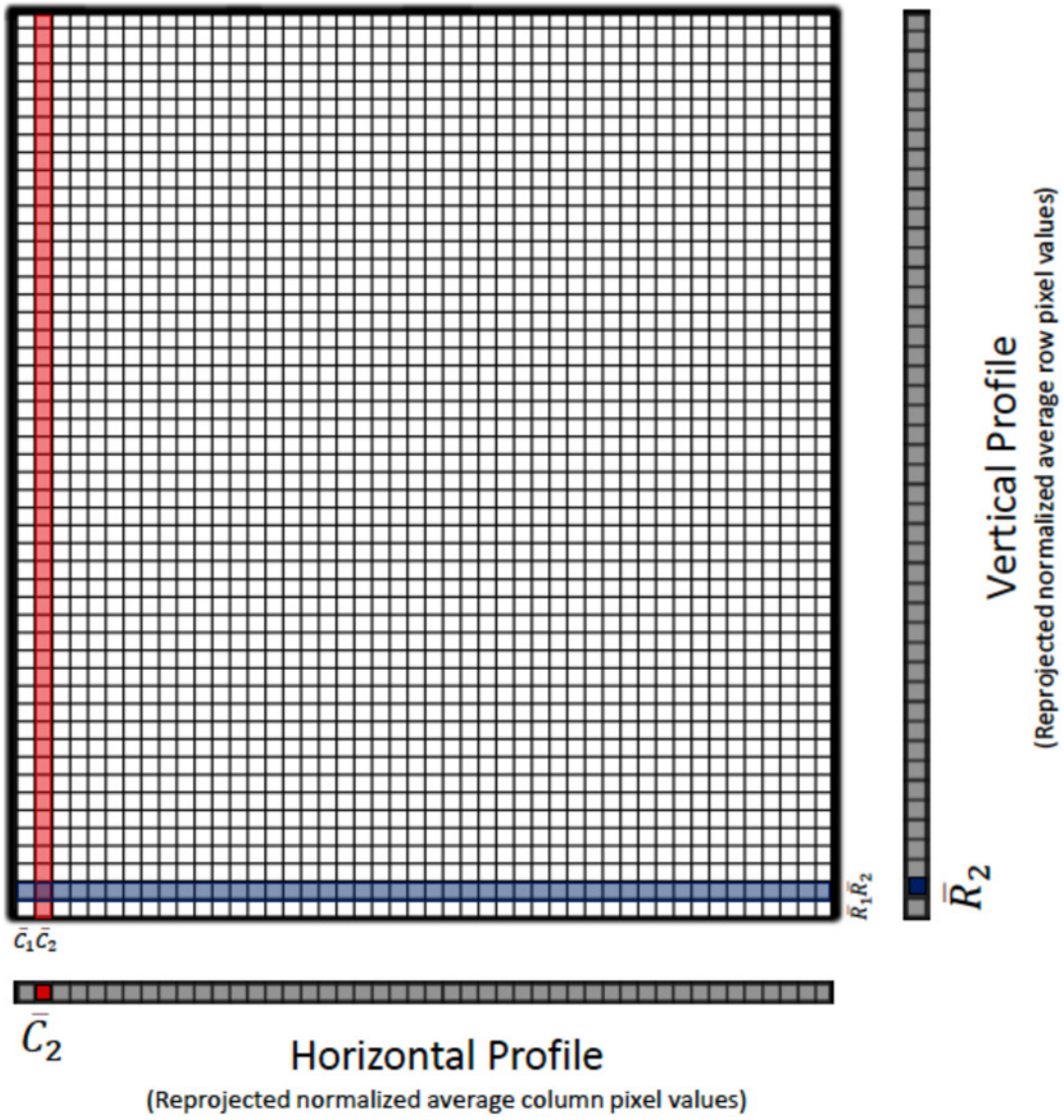

Figure 25. Illustration of concepts of horizontal and vertical profiles.

This process tends to reduce the stochastic component of the pixel signal levels and enhances the correlated component of the pixel signals. Rows or columns with anomalously low or high pixel values can be detected by calculating the difference between each value in the profile and the average of its neighbors:

$$D_n^{row} = P_n^{row} - \frac{P_{n-1}^{row} + P_{n+1}^{row}}{2} \quad D_n^{col} = P_n^{col} - \frac{P_{n-1}^{col} + P_{n+1}^{col}}{2} \tag{35}$$

Global vertically or horizontally correlated noise can be detected by calculating the standard deviation of the row profile or the column profile:

$$SD_{row} = \sqrt{\frac{1}{N_{row} - 1} \sum_n \left(P_n^{row} - \overline{P_{row}}\right)^2}$$

$$SD_{col} = \sqrt{\frac{1}{N_{col} - 1} \sum_n \left(P_n^{col} - \overline{P_{col}}\right)^2} \tag{36}$$

and comparing them to the average pixel noise $\overline{N_{IR}}$ calculated using equation (26) in Section 4.3.2 (Flat Field Image Analysis). For completely uncorrelated noise, these would be related as:

$$SD_{row} = \frac{1}{\sqrt{N_{rows}}}\overline{N_{roi}} \qquad SD_{col} = \frac{1}{\sqrt{N_{cols}}}\overline{N_{roi}} \tag{37}$$

Values of SD_{row} or SD_{col} well in excess of these predictions would indicate the presence of correlated noise.

Recommended method B

Another type of pixel correlation is caused by slight differences in offset, gain, or noise associated with the readout integrated circuits. This can manifest itself as subtle signal differences between readout/control chips, noise amplitude or texture differences, edge effects at chip boundaries, or other features confined to the pixels connected to the anomalous electronic integrated circuit component. This can appear in the direction of the readout control chips or the signal readout chip. Such artifacts can be identified by judicious choice of the size and location of the ROIs analyzed in the signal and noise nonuniformity tests described above. Summation of rows and columns within the confines of these boundaries will provide the most sensitive test of structured nonuniformities. For example, an image receptor consisting for four tiled quadrants should be tested by summing rows and columns within each quadrant. Statistically significant differences in mean signal values within or between quadrants indicate potential image artifacts.

Expected performance limit

The appropriate limits for clinically allowable correlated noise and line artifacts are currently unavailable, and further studies are required to establish the limits.

Potential findings

- Global correlated noise may indicate electronic interference, or noise in the readout circuits.
- Anomalously high or low columns may indicate a need for recalibration.

Potential pitfalls

Performing these tests requires specialized software that may not be available.

4.3.10 Detective Quantum Efficiency

Rationale

Detective quantum efficiency (DQE) evaluation is considered an optional test for commissioning and quality assurance in the field. However, DQE evaluation is recommended when assessing new imaging receptor technologies if the appropriate expertise and testing resources are available.

DQE is a measure of the contrast-to-noise ratio of the image receptor as a function of spatial frequency, and requires knowledge of the modulation transfer function (MTF) and the noise power spectrum (NPS) at a known photon fluence. Therefore, measurements of the MTF using test object images and the NPS using flat field images can be used to determine the DQE of the image receptor as a function of spatial frequency. This calculated metric provides enhanced information on the signal-to-noise performance of the image receptor versus that obtained from the minimum signal-to-noise ratio described in Section 4.3.7. While the DQE provides more information than the simple large-area SNR described above, its accurate measurement is time-consuming and can require custom phantoms for evaluation of frequency-dependent modulation transfer function, MTF(f), filters for modification of beam quality, and software to complete the calculations. DQE evaluations can be further complicated for clinical systems where the grid cannot be easily removed for testing.

Recommended method

Specifications for the measurement of this performance metric are found in IEC standard 62220-1 [15]. Several researchers have also published techniques for measuring DQE outside the industrial environment [31] [32] [33] [34].

Expected performance limit

The measured DQE should be within a predetermined percentage of the expected DQE value determined at acceptance/commissioning or provided by the manufacturer.

Potential findings

- Loss of DQE at low air kerma may be caused by an increase in electronic noise.
- Loss of DQE at high air kerma may be due to a decoupling between the scintillator and the photodiode array.

Potential pitfalls

In general, DQE measurement requires careful attention to detail, and results obtained in field measurements (i.e., in the clinical environment) may not be directly comparable to similar measurements made under more controlled conditions in a laboratory. A discrepancy in image receptor performance that would affect the DQE should also be evident using the other ROI-based tests described above.

4.3.11 Dark Noise Test

Rationale

The dark noise test is designed to assess contributions to image noise that arise in the absence of a radiation source—hence the reference to "dark." The dark noise is dominated by electronic noise from the electrical components of the imaging system, typically in the detection and readout electronics of the image receptor, and can affect clinical images where the incident air kerma to the detector is very low.

The dark noise test is considered an optional annual test but should be acquired at acceptance to establish that the imaging receptor is not defective. This acquisition will also establish a baseline reference image depicting typical detector dark noise for comparison purposes if the dark noise test is performed in the future during troubleshooting.

Recommended method

1. If the image receptor can be removed from the bucky, remove it and bring it into the shielded control booth if possible; otherwise, position it as far from the x-ray tube as possible and position it behind an in-room moveable shield.
2. If the image receptor cannot be removed from the bucky, orient the x-ray tube away from the image receptor and drape the image receptor housing with a lead apron.
3. Close the collimator completely.
4. Select the lowest kV and lowest mAs setting available on the system and acquire an image.
5. View the FOR PROCESSING image on the acquisition workstation. Draw a region of interest and record the mean and standard deviation of the pixel values. If a FOR PROCESSING image cannot be viewed, use a test protocol with minimal processing and evaluate the image qualitatively.
6. For acceptance testing, record the values as a baseline. For annual testing, compare the values to the baseline values.

Recommended method for CR cassettes

1. Perform a deep erasure of an unused CR plate.
2. Within ten minutes, read the CR plate again.
3. Calculate the average and standard deviation of the pixel value of the image read.

This is separate from the lag test that is performed when a high contrast object is imaged and then the plate is re-read to assess the extent of image lag/ghosting.

Expected performance limits

Using a FOR PROCESSING image, the average and standard deviation of the pixel values measured during annual testing should be within a predetermined percentage relative to the baseline values.

Using a FOR PRESENTATION image, the appearance of the image seen during annual testing should mimic the appearance at acceptance testing.

Potential findings

A significant increase in the dark noise since acceptance testing may represent an increase in the electronic noise. Contact the service engineer to investigate.

Potential pitfalls

- If the system fails to take an image, it may be set to use the AEC system. If this happens, try again using a manual technique.
- If the pixel values are proportional to air kerma, the expected pixel value is zero. However, the system may truncate negative values, leading to a non-zero result comparable to the standard deviation of the pixel values.
- If the pixel values are not proportional to air kerma, it may be difficult to interpret the meaning of the average pixel value.
- If the image is a FOR PRESENTATION image, the image appearance and the average and standard deviation of the pixel values may depend on the details of the image processing.
- Quantitative interpretation of the mean and standard deviation may be difficult to interpret; the values determined from a low-level flat field FOR PROCESSING image may be more meaningful.
- For wireless detectors that rely on communication with the main acquisition computer for readout, care should be taken to ensure that when the receptor is shielded from the radiation beam, either by removing it to the control booth or by shielding it in room, that the line of sight from the imaging receptor to any telemetry readout systems is adequate to allow the image to be acquired.
- For CR cassettes, the pixel value of the FOR PROCESSING image may have a logarithmic response to air kerma. Electronic noise is an additive effect, so it is unclear how the standard deviation at zero air kerma would relate to that at low air kerma in the clinical range.

4.3.12 Visual Inspection of Flat Field Images

Rationale

While it is possible for software to detect many different artifacts that can appear in an image, it is impossible to guarantee that all artifacts are detected. Artifact identification software is only as good as the understanding of the artifacts it has been designed to catch. It is therefore recommended that a visual inspection of at least one of the acquired images be performed. For this visual inspection, acquired flat field images from Section 4.3.1 are used.

Recommended method (Method A)—using DICOM viewing software and diagnostic quality monitor

- Display a flat field image in the DICOM viewer on a diagnostic quality monitor using a 1-to-1 mapping of image pixels to display pixels. If a diagnostic monitor is not available, use the acquisition workstation monitor.
- Adjust the window/level settings to those typical of clinical use. Appendix E provides some suggestions for selecting the settings.
- Search the image for artifacts. Excessive panning and scanning should be avoided, since this can lead to observer fatigue and areas of the image being missed.

Recommended method (Method B)—using laser film printer and diagnostic quality lightbox

- Display a flat field image on the acquisition workstation or any computer with a DICOM viewer.
- Adjust the window/level settings to those typical of clinical use. Appendix E provides some suggestions for selecting the settings.
- Print the image to a diagnostic quality film printer.
- View the image on a diagnostic quality lightbox, and search the image for artifacts.

Potential findings

If an artifact is found using clinical window/level settings, work with a radiologist to review clinical images to determine if the artifact is clinically significant.

Potential pitfalls

- If the window setting is too narrow, clinically insignificant artifacts will be obvious.
- If the window setting is too wide, or the level setting is inappropriate, clinically significant artifacts may be hidden.
- It may be difficult to review the entire image while panning the image at 1-to-1 mapping.
- Printing to a film printer with inappropriate calibration will cause issues similar to viewing on a softcopy monitor with the wrong window/level settings.

Descriptions of test object tests

In addition to flat field images, several tests can be performed by acquiring images of phantoms or test objects to provide additional information on image receptor performance. These tests are listed in the following sections.

4.3.13 Spatial Resolution

Rationale

Specific phantoms can be used to measure the spatial resolution of the image receptor in quantitative terms, i.e., the frequency-dependent modulation transfer function, MTF(f), or in qualitative terms, such as the limiting spatial resolution in visually resolvable line pairs per mm. MTF(f) evaluation from the image of a specially designed edge or slit phantom requires sophisticated analysis software. Also, this evaluation is prone to numerous experimental and analysis effects that can reduce its accuracy and reproducibility in a clinical environment. MTF(f) evaluation is defined in IEC standard 62220-1 [15].

As an alternative to complete MTF(f) measurements, the spatial resolution of the image receptor can be evaluated by inspecting the image of a high contrast bar pattern placed on the image receptor surface, i.e., contact radiograph. The resulting image can be evaluated visually, or if software tools are available, a quantitative assessment of the modulation in the image can be generated (see Appendix F for an example method of quantitative assessment of a bar pattern phantom image). The image of the bar pattern is a discrete representation of the square wave response function of the image receptor, and is directly related to the MTF over a limited range of spatial frequencies, i.e., frequencies greater than $f_{Ny}/3$ [45] [46]. Quantitative evaluation is recommended as a robust and practical test that can identify more subtle changes in resolution than a qualitative visual evaluation.

Test equipment required

High contrast resolution test object (bar pattern phantom) with a range of bar pattern frequencies (frequencies no narrower than 1/3 of the Nyquist frequency to the Nyquist frequency).

Recommended method A—qualitative evaluation

1. If possible, remove the anti-scatter grid before performing this test; the presence of an anti-scatter grid may affect the results.
2. Align the bar phantom along one axis of the image receptor at a slight angle relative to the axes to avoid interference (Moire) patterns between the bars and the image receptor matrix. Alternatively, the bar phantom can be placed at 45 degrees to the pixel raster and a single image acquired.
3. Acquire an image of the bar pattern under predefined beam quality and image receptor exposure conditions, such as the calibration condition or the medium exposure condition of the flat field tests (see Section 4.3.1; use the same conditions for periodic testing as were used during acceptance evaluation, e.g., same SID, same focal spot selection, etc.).
4. Either analyze the images using appropriate software (recommended), view and evaluate them on a diagnostic quality display with at least 1-to-1 pixel mapping between the image receptor and the display, or print them out for inspection using a diagnostic film printer.
5. Record out the highest visible bar pattern frequency that shows modulation, but which does not show aliasing.

Recommended method B—quantitative evaluation using bar pattern

1. Follow steps (1) through (4) of Recommended method A.
2. Select two line-pair frequencies in the bar pattern, and measure/calculate the MTF for those bar pattern groups using the Coltman method described in Appendix F. One bar group should be the closest frequency available in the test pattern that is below the image receptor's Nyquist frequency ($f_{Ny} = 1/(2d)$, where d = pixel spacing), and the other should be approximately 1/3 of the Nyquist frequency.
3. Record the MTF of these two frequencies.

Alternative methods

There are several peer-reviewed publications describing various ways to measure MTF, using either a slit, an edge, or other test object (e.g., [32] [47] [48] [49] [50] [51]).

Expected performance limits

The spatial resolution should be no less than that determined during acceptance testing or specified by the manufacturer.

Potential findings

The unit may not provide the required spatial resolution, which may be caused by electronic binning, or improper DR panel installation.

Potential pitfalls

- Great care is needed when visually evaluating the images to ensure consistency of results. Changes in viewing conditions can make subtle differences in resolution difficult to appreciate.
- Because this test is performed at a magnification of 1, it is not sensitive to variations in the focal spot size.

4.3.14 Spatial Resolution Uniformity

Rationale

A number of mechanisms can degrade the spatial resolution of an image receptor at localized areas of the image receptor. Therefore, it would be desirable to measure the variation of spatial resolution over the entire area of the image receptor rather than just at a limited region. One method to achieve this goal is to make a high exposure image of a wire mesh, like the type historically used to check screen-film

contact. If the wire mesh pitch and diameter are chosen carefully to avoid aliasing with the pixel pitch of the image receptor, an evaluation of the standard deviation of the resulting signal within an ROI gives an indication of the local spatial resolution. To make this a robust method, the ROI size must be chosen carefully, again dependent on the pixel pitch of the image receptor, to prevent phase effects distorting the results. The main idea of this approach is that if the images are taken at a high enough exposure, the dominant effect that determines the standard deviation within an ROI is the signal difference caused by the attenuation of the wire, and not the inherent quantum or electronic noise in the image.

An alternative approach to identifying changes in the nonuniformity of the spatial resolution across the surface of the image receptor can be obtained from the results of the noise and SNR nonuniformity tests. Mechanisms that cause spreading of signal information across neighboring pixels, i.e., blur or loss of spatial resolution, will generally cause a reduction in the standard deviation of the pixel values within this region. This would cause an increase in noise nonuniformity and/or an increase in SNR nonuniformity within the region affected by the signal spread.

Test equipment required

Wire mesh phantom

Recommended method A—visual evaluation

1. Remove grid, if possible.
2. Place wire mesh phantom on, or as close as possible to, the image receptor.
3. Acquire image with medium level air kerma (for medium level air kerma, refer to Section 4.3.1).
4. Evaluate the image for differences in spatial resolution, i.e., if there are any visibly identifiable regional differences in the image of the wire mesh pattern across the entire image.

Recommended method B—with analysis software

1. Follow steps (1) to (3) of Recommended method A.
2. Transmit the images to a computer with appropriate image analysis software.
3. Calculate the local and global noise nonuniformity of the image using equations (30) and (31).

Recommended method C—using manual analysis

1. Remove grid, if possible.
2. Place wire mesh phantom on, or as close as possible to, the image receptor.
3. Acquire image with calibration dose.
4. Using a DICOM viewer, calculate and record the pixel standard deviation for 2×2 cm ROIs at the center and 4 corners of the image.
5. Calculate the local and global noise nonuniformity of the image using equations (30) and (31) (Section 4.3.5).

Expected performance limits

The global and local noise nonuniformities should be no higher than those measured at acceptance testing.

Potential findings

If a system is "sharp," i.e., high spatial resolution, the contrast of the wires will be high and the standard deviation will be large. If the resolution degrades, the contrast of the wires will reduce and the standard deviation will reduce. Consequently, an ongoing measure of the standard deviation within ROIs distributed across the image of the wire mesh will indicate the nonuniformity of spatial resolution across the surface of the image receptor.

Potential pitfalls

- It is likely that some acquisition systems do not have a uniform spatial resolution across their surface, e.g., some lens-based CCD systems. These systems would require a record of the resolution variation measured at acceptance as the baseline, and subsequent tests would assess the deviation from this set of values.
- Although the wire mesh test was a well-established method for evaluating resolution loss due to gaps in screen-film contact, experience with the methods described above applied to digital radiography systems is very limited at the present time. The sensitivity to detect subtle changes in spatial resolution is currently unknown, as is the impact of aliasing on the test results. Extensive testing of the methodology needs to be undertaken before their use can be recommended. Therefore, these methods are being included as optional tests.

4.3.15 Contrast-to-Noise Ratio (CNR)

Rationale

Image receptor CNR can be measured by imaging an appropriately designed aluminum step phantom or other object whose contrast spans the useful exposure range for a given image receptor under specified imaging conditions. The test object can be as simple as a set of aluminum filters, or as complex as the DIN 6868 standard phantom for digital radiography or various commercial phantoms provided by digital radiography manufacturers and QA specialty companies. Software could identify the contrast patches and automatically calculate the CNR for each step. Alternatively, the CNR can be determined manually.

A test related to CNR is contrast detail determination. Contrast detail testing is typically performed by imaging a phantom with an array of holes of varying depth and diameter. The test is to then determine the smallest diameter hole that is detectable with a given contrast.

Test equipment required

- ~21 mm aluminum block or ~ 0.5 mm thick copper filter; and then equipment as per the method selected from below.

Stepwedge method

A stepwedge test object; that is, one of the following:

- Aluminum stepwedge
- Commercial single-shot QC phantom containing a stepwedge

Aluminum filter method

4 mm aluminum sheet, approximately 10×10 cm

Contrast detail method

Contrast detail phantom

Recommended method (stepwedge)

1. Place the stepwedge test object on the image receptor housing, ensuring that the orientation of the steps is perpendicular to the anode-cathode axis.
2. Acquire an image of the stepwedge using the conditions recommended by the manufacturer of the test object. If there are no specified conditions, cover the exit port of the tube housing with an attenuator (~21 mm aluminum block or ~0.5 mm copper filter), and acquire an exposure at the low exposure level described in Table 12.
3. For each step of the stepwedge, calculate the mean and standard deviation of the pixel values.
4. Calculate the background mean pixel value of an ROI in a flat region adjacent to the stepwedge.

5. Calculate the contrast for each stepwedge by subtracting the mean pixel value in the wedge from the mean pixel value in the adjacent background.
6. Divide the contrast by the noise value for each step to determine the CNR as follows:

$$CNR_n = \frac{\overline{PV_n} - \overline{PV_{back}}}{SD_{back}} \tag{38}$$

where CNR_n and $\overline{PV_n}$ are the CNR and mean pixel value for step n, and SD_{back} and PV_{back} are the standard deviation and mean pixel values of the background ROI.

7. Record the CNR.

Alternative method (aluminum filter)

Follow the instructions for the recommended method, but using a 4 mm thick aluminum filter, measure a single ROI inside the filter and a single ROI adjacent to the filter.

Alternative method (contrast-detail phantom)

1. Acquire images with contrast detail phantom.
2. Record the smallest holes visible for each contrast row.
3. Plot contrast values vs. hole size to document current receptor performance.

Expected performance limits

See manufacturer specifications for the test object, if they exist. Otherwise, contrast/ratio values should be within 10% of the values measured at baseline.

Potential findings

If the measured contrast/ratio values are more than 10% lower than values measured at baseline, contact the image receptor manufacturer for corrective action.

Potential pitfalls

- During annual testing, the measurement conditions must be identical to the baseline conditions or the comparison to baseline will be compromised.
- While the contrast/detail test can provide very useful information on system performance, a test regime that requires visual determination of limiting contrast for certain diameter features typically requires significant effort, both with respect to a viewer's time as well as with respect to controlling viewing conditions, in order to generate stable, reproducible results. This can be avoided by using automated scoring software that can remove observer variability from the evaluation [52][53].

4.3.16 Geometric Accuracy

Rationale

Some digital image receptors, such as photostimulable storage phosphor systems and image receptors that use lens coupling or fiber optic reducers or couplers in their image path, may not have an isotropic linear relationship between position on the phosphor and pixel location. This may manifest as curvature of linear objects in the image, or a variation in length measurements with different positions or orientations of objects in the image. For these image receptors, it is necessary to measure the geometric accuracy of the image.

Flat panel detectors are significantly less susceptible to these issues. However, manufacturing defects could introduce errors at boundaries between detector modules. For this reason, we recommend performing this test during acceptance testing if an appropriate test object is available.

A secondary purpose of this test is to determine whether the bucky entrance (patient tabletop or wall bucky shroud) is the reference plane of the software distance tool.

Test equipment required

One of the following:

- An object or objects of known dimensions placed at various locations on the image receptor (not used for flat panel detector).
- A test object containing a grid made of lines of radio-opaque material.

Recommended method for flat panel detectors

1. Place the image receptor in the table bucky.
2. Place the test object containing a grid made of lines of radio-opaque material (see Figure 26) on the patient table.
3. Acquire an image at 80 kV with appropriate mAs to attain acceptable image quality without saturation. If the phantom has minimal attenuation, such as the phantom in the left of Figure 26, then 1 mAs should be sufficient. If a phantom with a significant thickness of acrylic is used, then a relatively higher technique is necessary.
4. Inspect the image to verify that the lines are straight and perpendicular to each other.
5. If the acquisition workstation has a software distance tool, measure the distance between two objects that are a known distance apart, and compare the measurement to the actual distance.

Note: the spatial resolution uniformity test could be combined with this test by using a wire mesh for the test object.

Recommended method for other image receptors

1. Place the object or objects into the beam path (on or above the image receptor).
2. Acquire an image at 80 kV with appropriate mAs to attain acceptable image quality without saturation.
3. Measure the known dimensions of the objects within the images using the software distance tool.
4. Verify that the dimensions are independent of the position of the object in the image.
5. Compare the measured dimension to the actual size of the test object.

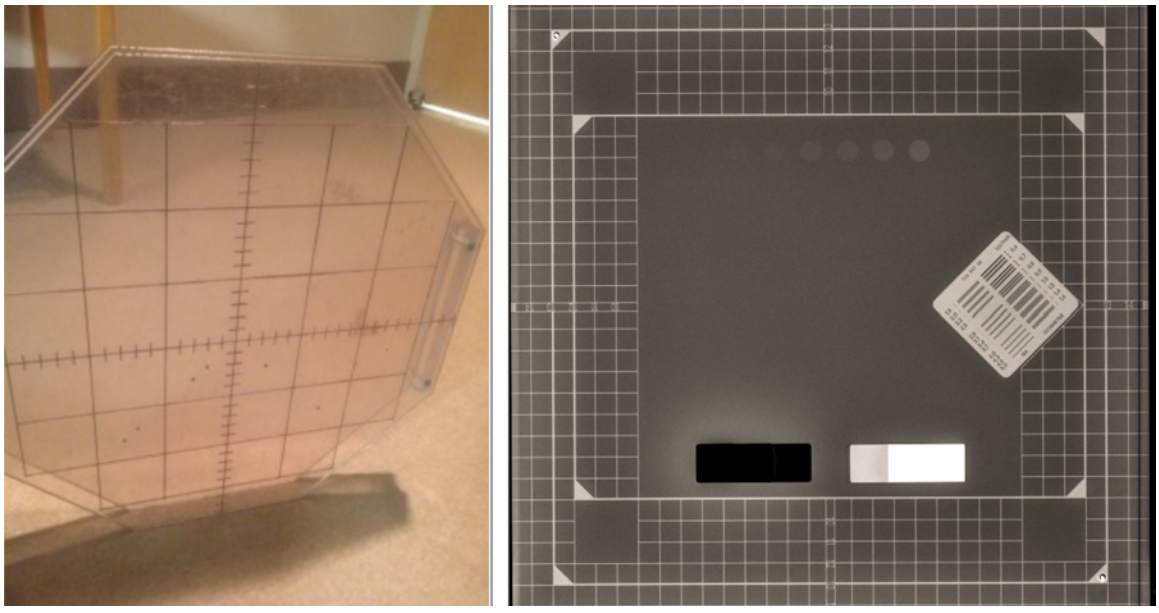

Figure 26. Two different test objects with grids of radio-opaque lines.

Expected performance limits

- All lines in the grid should be straight, evenly spaced, and perpendicular to each other.
- Measurements of object in the image should agree with the real dimensions to the precision of the displayed results, after correcting for radiographic magnification and the ERMF (if applicable).
- There should be no discontinuities along test object borders.
- If the test object is at the reference plane for the software distance tool, the measured size of the test object should match the actual size to within 1%.

Potential findings

- Flat panel detectors may show discontinuity at the borders between detector blocks.
- The feed direction and the laser scan direction in CR may demonstrate different distance calibrations.
- Other image receptor types, such as optically coupled systems, are likely to suffer from geometric distortion.
- The reference plane may be at a different position/distance from the focal spot.

Potential pitfalls

- In situations where the object to be imaged cannot be placed directly on the surface of the image receptor, the calculation of object size from the image must include the appropriate magnification factor.

4.3.17 Ghosting

Rationale

For many types of digital image receptors, image ghosting or lag should be tested. Improper erasure of CR plates, excessive exposure of stationary lead markers, and repeated "small-field" collimation with DR systems are some of the real-world clinical conditions that can cause artifacts due to signal carry-over (i.e., ghosting or lag) in the image receptor. Testing of ghosting and lag in a clinical setting requires clear definition of the testing protocol for consistent, meaningful results, e.g., see Appendix A of IEC 62220-1 for one description of a lag and ghosting test protocol [15]. **Extreme care should also be taken to ensure that this test does not induce problematic ghosting or lag into a correctly functioning image receptor. For this reason, the alternate procedure (passive test) should be used for DR systems.** Residual ghost images of high contrast objects can persist for long periods – therefore, such tests of ghosting should be performed late in the workday, or else before a weekend, to allow a sufficiently long period for residual signal decay.

Recommended method (active test)

This test should be done only with CR image receptors.

1. Place the high contrast object in the field.
2. Expose at 80 kV and the medium exposure level as defined in Section 4.3.1 (Acquisition of flat field image data; Table 12).
3. Process the CR cassette.
4. Expose the CR cassette to a flat field acquisition under the same conditions as step (2).
5. Process the CR cassette and view the processed image using a clinical window/level setting, and verify that the outline of the high contrast object is not visible.

Alternative method (passive test)

This test is to be performed after one or more of the high contrast test object image receptor tests, such as spatial resolution or geometric accuracy.

1. Remove the test object.
2. Acquire a flat field image under the same conditions used with the test object.
3. View the image using a clinical window/level setting and verify that the test object is not visible in the flat field image.

Expected performance limits

No evidence of the high contrast object in the second exposure.

Potential findings

Evidence of the presence of the high contrast object in the second exposure can be used to assess the degree of ghosting, also known as "multiplicative" lag, present in the image receptor. A second image acquired at another specified time after the first image, but without applied x-rays, i.e., a "dark" image, can be used to assess the degree of lag, also known as "additive" lag, within the image receptor.

Potential pitfalls

In some digital image receptors, the acquisition of meaningful "dark" data is problematic, due to the addition/subtraction/truncation of very low signal values performed by some raw image data acquisition processing approaches. It is therefore crucially important to understand the processing applied to very low signal images before performing lag or dark image analysis. In the absence of this information, or when access to unmodified dark image data is not possible, it is probably sufficient to assess the ghosting level in the image receptor using x-ray exposure images alone.

4.3.18 Conclusions

The image acquisitions and analyses described above provide a broad evaluation of a digital image receptor's performance for comparison to its prior performance, for example, at system acceptance, or for comparison to performance experienced at other installations of similar equipment.

The tests require acquisition of a limited number of "flat field" images—approximately four to eight images—and a small number of images of custom phantoms—approximately two to four images depending on whether resolution nonuniformity and ghosting/lag analysis are desired. All images must be acquired under well-controlled conditions of exposure.

Most of the tests describe pass/fail limits in terms of percentage differences from the predetermined baseline performance levels. Due to the large variability in currently available clinical system capabilities, it is not possible to specify absolute threshold limits that would be widely applicable across different systems and manufacturers. The preferred situation would be that individual system manufacturers provide their customers with expected test performance values for their systems that can be used as the basis for acceptance testing and ongoing monitoring of quality control.

4.4 Automatic Exposure Control Tests

Introduction

The purpose of automatic exposure control (AEC) systems is to deliver calibrated, reproducible exposures to the image receptor across a wide range of technical factors, patient sizes, and anatomical views. Poor AEC performance may result in patient overexposure, poor quality clinical images, or repeating of images. Specific aspects of AEC performance are considered in this section. There are several important considerations when evaluating AEC systems. These include attenuating phantom material and thickness, scatter conditions (air gap size and field size), the anti-scatter grid, and how the exposure index (EI) is calculated by the imaging system.

Test equipment required

Test	Required equipment
AEC reproducibility Cell balance Density selector Sensitivity selector	Any of the following: • Standard phantom (25×25 cm or 30×30 cm acrylic sheets combined to achieve a 20 cm thickness) • ~21 mm aluminum block • 2 mm copper filter • 0.5 mm copper and 2 mm aluminum filters
Cell selection	3 to 4 mm thick aluminum attenuator, approximately 10×10 cm
Minimum response time	Solid-state dosimeter with exposure time readout Note: the post-exposure time display on the console may be used if such a dosimeter is unavailable
AEC sensitivity	• Ionization chamber with dosimeter or solid-state dosimeter with sensitivity to ≤1 μGy (0.1 mR) • Any tools specified by the manufacturer
AEC sensitivity (alternative procedure)	• Ionization chamber with dosimeter or solid-state dosimeter with sensitivity to ≤1 μGy (0.1 mR) and wide angular acceptance • 15×15 cm or larger lead blocker • Standard phantom (25×25 cm or 30×30 cm acrylic sheets combined to achieve a 20 cm thickness)
Tube voltage tracking Field of view compensation	Standard phantom (25×25 cm or 30×30 cm acrylic sheets combined to achieve a 20 cm thickness)
Patient thickness tracking	Acrylic phantom (25×25 cm or 30×30 cm, in sheets that can combine to 10, 15, 20 and 25 cm thicknesses)
Backup timer	• Lead attenuator 3 mm thick or greater • Lead apron

Expected results

Table 13 summarizes the expected results from each test; these results are provided to assist interpretation of test results for those instances when a manufacturer's published specification is not available. **When a manufacturer's published specification is available, that criteria should be used to assess the test result**.

4.4.1 Key Information

Attenuating phantom material

The beam should be attenuated using an approximate tissue equivalent material such as water or polymethyl methacrylate (PMMA) located in the same position as the patient (i.e., on the table, or in contact with the wall stand). This is to ensure that the spectral and scatter characteristics of the radiation beam are similar to those encountered clinically.

Table 13: Expected results for each AEC test

Test	Expected results
AEC reproducibility	The coefficient of variation should be < 5%.
Minimum response time	The minimum response time should be < 3 ms.
AEC sensitivity	Image receptor dose should match expected value to 15%.
Density selector	Exposure time or mAs should change by 15–25% between adjacent steps.
Sensitivity selector	Change in exposure time or mAs should match manufacturer specifications to within 5%.
Cell selection	The AEC must be controlled by the selected cell.
Cell balance	The exposure time or mAs for each cell and combination should match the center cell to within 15%.
Tube voltage tracking	The image receptor dose for each tube voltage should be within 25% of the average over all tested voltages.
Patient thickness tracking	The image receptor dose for each tube voltage/thickness combination tested should be within 25% of the average over all tested combinations.
Field of view compensation	The exposure time or mAs should remain constant to within 10% over the range of fields of view tested.
Backup timer	If the exposure does not terminate after the regulatory mAs limit (600 mAs for ≥ 51kV, 2000 mAs for < 51kV), clinical use of the system must terminate until it is repaired.

Conway et al. [25] [24] attempted to evaluate effects of attenuator material on AEC calibration. They determined that while a similar image receptor signal can be achieved with water (20 cm), PMMA (20 cm), aluminum (2 cm), or copper (0.2 cm), the spectrum transmitted by 0.2 cm of copper is significantly harder than the spectrum transmitted by 20 cm of water or PMMA. In addition, the metal attenuators cannot adequately evaluate the AEC's response to the changing beam conditions reaching the image receptor as kV, patient size, beam size or other conditions change.

Certain tests in this section can be done using 25×25 cm or 30×30 cm sheets of PMMA that are 2.5 cm thick and that can be combined to achieve total thicknesses ranging from 2.5 cm to 30 cm. A somewhat more compact alternative is a phantom consisting of both PMMA and aluminum sheets: 7.5 cm (3 inches) of PMMA plus 1.6 mm (1/16") of aluminum (both 25×25 cm) is equivalent to 10 cm of tissue. Using up to nine 2.5 cm (1 inch) thicknesses of PMMA plus three 1.6 mm (1/16") aluminum sheets, patient thicknesses of up to 30 cm can be simulated. While a mixed PMMA/aluminum phantom is thinner than a comparable PMMA-only phantom, it is not significantly lighter. Section 1.4 of this report lists several standard patient-equivalent phantoms.

X-ray exposures reaching the image receptor

Radiographs are formed by x-rays exiting the patient, which have passed through the patient support, scatter removal grid, and AEC assembly. Measurements of air kerma made in front of the patient support (e.g., at tabletop) must be corrected for attenuation of the patient support and the energy- and scatter-dependent transmission characteristics of the anti-scatter grid. Although the (nearly) air-equivalent AEC cells, located between the grid and the image receptor, are exposed to the same beam conditions as the image receptor, its energy-dependent response will in general differ from that of the image receptor. To provide proper image receptor dose for all beam energies, the AEC must use various algorithms together with available information (e.g., selected kV and measured air kerma rate) to adjust for image receptor energy response. The test metric often used here is image receptor dose as estimated by the exposure index.

Exposure index (EI) calculation

When using the EI as a surrogate for image receptor dose, it is important to understand how EI is calculated. The EI reported for a clinical image is generally derived by segmenting the image and analyzing the histogram of the image pixel values. Both segmentation and histogram analysis algorithms are manufacturer-dependent. These algorithms might fail on images of uniform phantoms; if so, EI values calculated from images of uniform phantoms may not accurately reflect the true image receptor dose. If possible, a "service test" or "medical physics test" mode, designed to avoid this limitation, or a protocol specifically intended for EI calculation should be used. These modes generally calculate the EI using a specific area, often the center, of the image receptor, and do not expect to "see" a clinical pattern of exposure. It is also important to verify proper EI calibration of the system (see Section 4.8.2 Exposure indicator accuracy below) prior to performing those AEC tests that use EI.

Use of pixel value as a test metric

It may be impossible in some circumstances to use the EI or other exposure indicator as a surrogate for the image receptor dose. For example, on some systems the image segmentation commonly fails with flat field images, making the exposure indicator meaningless. Others may display a proprietary exposure index with an unclear relationship to image receptor dose; others may display the deviation index but not the EI. In these circumstances, it may be practical to use the average pixel value in a region of interest as a surrogate for image receptor dose. However, care must be taken to ensure that the pixel value truly represents image receptor dose. This is most likely to be the case when the image is a FOR PROCESSING image with a linear dose response. However, it may still be possible in such a system that the FOR PROCESSING image has undergone some preliminary scaling, which might have affected the dynamic range of pixel values if the magnitude of the rescaling depends on the image receptor dose.

In those situations where the image receptor dose must be inferred from image average pixel values, a prerequisite is to verify the relationship between pixel values and dose by acquiring a series of measurements with fixed beam quality and varying tube current or exposure time. Alternately, it is possible to use a stepwedge phantom whose transmission under specified beam conditions is known; plotting the pixel value vs. step transmission can provide a quick test of the linearity of the pixel values. However, such a test should be done using two different air kermas to verify that the scaling does not depend on average image receptor dose.

General testing instructions

The tests described in this section require the x-ray tube to be properly aligned to the image receptor with source-to-image distance (SID) set to the nominal focal distance of the grid or, if used clinically at a different distance, set to the most commonly used SID with that receptor. Detents, if available and accurate, should be used to position the tube; the detent positions are tested as part of the grid alignment test (Section 4.5.1 below). This properly aligned and positioned tube setup will be referred to in the following as the "standard setup." A 20 cm thickness (or equivalent) of the phantom material used is referred to here as the "standard phantom." When used, the x-ray field should be adjusted to just cover the base of the phantom (area of the phantom covering the surface of the image receptor).

- Several tests use reported mAs or exposure time. Some generators may report mAs values with accuracy compromised by rounding, particularly for low mA values. If so, the product of mA and the reported exposure time may be more accurate estimate of mAs.
- A dosimeter used to measure air kerma may be used as an independent indicator of AEC reproducibility.
- If using a dosimeter, ensure that neither the dosimeter nor the dosimeter cable overlap the AEC cells or are in close proximity to the AEC cells, such that the AEC response and/or the accuracy of measured air kerma is impacted.

Description of tests

4.4.2 AEC Reproducibility

Rationale

The purpose of this test is to verify that reproducible exposures are delivered by the AEC system.

Recommended method

1. Set the field of view to cover the entire image receptor.
2. Place the dosimeter sensor well away from the center but within the x-ray field. (It may be possible to conduct this test by using the reported EI values instead of measuring the air kerma, but the use of a dosimeter sensor for air kerma measurements is recommended; see discussion about EI calculation in the previous section, 4.4.1).
3. Place 21 mm of aluminum or a combination of 0.5 mm of copper and 2 mm of aluminum at the exit window of the collimator.
4. Set 80 kV and select an mA that yields an exposure duration >10 ms.
5. Select all available AEC cells.
6. Obtain at least three exposures, recording the reported mAs and air kerma of each.
7. Determine the coefficient of variation (CV) of the measured values.

Alternative method

The standard PMMA phantom may be used in place of the metal filters.

Expected performance limits

The coefficient of variation for measured values should be < 5%.

Potential findings

A failure of the AEC system may reflect an underlying component failure, inadequate calibration, or be symptomatic of a broader failure. Consult the service engineer or refer the issue to the service organization for follow-up and repair.

Potential pitfalls

- Causes of exposure fluctuation not arising from malfunctioning of the AEC itself can contribute to AEC reproducibility test values that exceed 5%. As an example, kV drifts or fluctuations of only 2–3 kV can result in significant fluence fluctuations at the image receptor. These ancillary factors must be ruled out before attributing a failed AEC reproducibility test to a failure in the AEC system itself.
- Some systems have more than three AEC cells, but allow only three to be selected at one time. For such a system, repeat the test as necessary to ensure that each AEC cell is tested at least once.
- If using a dosimeter, the stability and accuracy of the dosimeter may impact interpretation, especially if care is not taken in the placement of the dosimeter relative to the AEC cells.

4.4.3 Minimum Response Time

Rationale

An AEC may need to terminate the exposure after a very short time for optimum results. For example, a PA chest radiograph made at 120 kV and maximum mA (often auto-selected) on a thin patient may require only 1–3 ms for proper exposure. The purpose of this test is to determine the minimum (reproducible) response time of the AEC system. Care should be taken to ensure that all subsequent tests conducted have a resultant exposure time that is greater than the minimum response time of the AEC system.

Recommended method

1. Turn off the PBL and open the collimators to cover the entire image receptor; this is to prevent burn-in of the collimator shadows.
2. Start with the lowest selectable voltage, the large focal spot, and the highest selectable (large focal) mA.
3. With no added attenuation (filter or phantom), select all AEC cells and acquire an exposure.
4. Record the displayed exposure time. If the system does not display the exposure time, divide the displayed mAs value by the tube current (in mA) to get the exposure time (in seconds).
5. Increase the tube voltage by 10 kV increments until the exposure time no longer decreases.
6. At the tube voltage where the exposure time did not decrease, repeat the measurement twice more, and calculate the coefficient of variation of the three exposures.
7. If the coefficient of variation is >0.05, then decrease the tube voltage by 10 kV and take three more exposures.
8. Repeat step 6 until the coefficient of variation is < 0.05.
9. The shortest achievable time with a coefficient of variation < 0.05 is the minimum response time.

Expected performance limits

Minimum response time should be ≤ 3 ms for high frequency generators or 12 phase generators. For a single-phase generator, the minimum response time should be 8.3 ms (or a single pulse). 21 CFR 1020.31(a)(3)(ii) [12] requires that the minimum response time for "field emission equipment rated for pulsed operation" (i.e., single phase generator) be no less than 2 pulses (16.6 ms), and for all other equipment shall be no less than 1/60 sec (16.6 ms) or the time required for 5 mAs, whichever is greater.

Potential findings

An AEC minimum response time exceeding the expected performance limit, or minimal achievable times within limits but with excessive variance in reproducibility, could limit adequate AEC performance for thinner patients and/or high kV/high mA exposures.

Potential pitfalls

None noted.

4.4.4 AEC Sensitivity

Rationale

The purpose of this test is to verify that the benchmarked cell (typically center) delivers the desired calibrated dose to the image receptor. The exposure indicator displayed on the acquisition workstation is used to determine the dose to the image receptor, so the test in Section 4.8.2 "Exposure indicator accuracy" must be done before this test.

In this report, we use the term "exposure index" to refer specifically the exposure indicator as defined by IEC 62494 [16], and "exposure indicator" to mean either the exposure index, or a vendor-defined quantity that indicates the air kerma at the image receptor.

Recommended method

Test methods should follow the manufacturer's protocol and test conditions, if provided. If multiple sensitivity, speed or image receptor dose selections are available, the one setting recommended and calibrated for the image receptor should be selected for this test.

Alternative methods (if vendor recommendations are not available)

Alternative method A

1. Set the field of view to cover the entire image receptor.
2. Place the dosimeter sensor well away from the center but within the x-ray field.
3. Place 21 mm of aluminum or a combination of 0.5 mm of copper and 2 mm of aluminum at the exit window of the collimator.
4. Make an AEC exposure using a clinical protocol and note the resulting mAs and exposure indicator. If the deviation index is displayed, record its value.

Alternative method B

Follow Alternative method A, but use the standard PMMA phantom centered in the x-ray field, and adjust the field size to cover the bottom of the phantom (at 40" SID, this is approximately 27×27 cm for a 25×25 cm phantom or 32×32 cm for a 30×30 cm phantom).

Expected performance limits

- When determined using the manufacturer's specified procedures, the exposure indicator should agree with the manufacturer's specification.
- If the system conforms to the IEC EI/DI standard (IEC 62494-1 [16]), then the resulting EI should approximately equal the target exposure index, and the deviation index should be approximately zero.

Potential findings

- The dose to the image receptor under AEC control may not match manufacturer specification, or may not match the value recorded during acceptance testing.
- The displayed exposure indicator may not correctly indicate the dose to the image receptor.

Potential pitfalls

An image receptor dose determined using manufacturer conditions must be compared to the appropriate manufacturer specification, rather than to the displayed EI. This is because the displayed EI may incorporate corrections to account for the differences between the calibration beam conditions and clinical beam conditions.

4.4.5 Density Selector

Rationale

The purpose of this test is to verify that the "+/− density" selection steps (if available) provide appropriate changes in the resulting mAs or exposure time.

Initial tests and tests after a major AEC repair should include all density selections. Subsequent tests may be optionally limited to two steps in either direction.

Recommended method

1. Set the field of view to cover the entire image receptor.
2. Place the dosimeter sensor well away from the center but within the x-ray field.
3. Place 21 mm of aluminum or a combination of 0.5 mm of copper and 2 mm of aluminum at the exit window of the collimator.
4. Use a clinically representative kV, e.g., 80 kV for a table bucky and 120 kV for a wall bucky, and select an mA that provides an exposure duration >10 ms for the lowest density selection to be tested.
5. Make an AEC exposure for each selectable density step and note reported mAs or exposure time for each. Note: for annual testing, test only the density steps commonly used by technologists.
6. Determine mAs or exposure time for each density step as a percent of that for "Normal" or "0" density.

Alternative methods

- Air kerma measured using a dosimeter sensor within the x-ray field may be used for comparisons instead of mAs. Be sure that neither the dosimeter sensor nor its cable is close enough to the AEC cells to affect them.
- The standard PMMA phantom may be used in place of the metal filtration; in this case, the field of view should be barely smaller than the base of the phantom.

Expected performance limits

The change per step should meet manufacturer specifications. If specifications are not available, the mAs or exposure time should change by 15–25% between adjacent steps. During annual testing, compare the results to the baseline established during acceptance tests.

On some systems, the specified change in mAs is too small to result in a change in displayed mAs. For these systems, it is necessary to use air kerma measurements to quantify the result of changing the density selector settings.

Potential findings

A change of 15–25% per step is typical for most AECs. Situations do occur in which step changes are significantly less than 15%, or even in which adjacent steps yield essentially the same exposure time; this latter circumstance would be especially concerning on a system that had only one density step outside the range -1 to +1 as there would be no effective way of changing density using the density selection. If a test fails, it is useful to contact the manufacturer to obtain guidance on expected behavior as some systems may be intentionally configured or designed such that they are unable to meet the 15–25% density step criteria. Before doing so, it is recommended to understand how the facility typically uses density control in normal clinical operations since that will enable a more constructive dialogue and negotiation for corrective action with the vendor.

It is also recommended to review clinical protocols that utilize density selection. For instance, a clinical protocol set with a default density selection of -2 may be indicative that the clinical technique is not optimized or that the AEC needs to be recalibrated so that the full range of density adjustment is available for this protocol.

Potential pitfalls

None noted.

4.4.6 Sensitivity Selector

Rationale

Some generators designed with or for DR allow the user to select alternate sensitivities ("speeds") or image receptor doses. Older generators used with CR or retrofitted with DR may have two or more sensitivity or "speed" selections (although these were originally intended for use with different speed screen-film combinations). The purpose of this test is to verify that AEC sensitivity is varied appropriately based on the sensitivity selector setting.

Recommended method

The test procedure is the same as for "Density Selector" described above, substituting other sensitivity speed or image receptor dose selections for density selections.

Expected performance limits

The selected sensitivity setting should deliver the manufacturer's expected EI as referenced to baseline setting. For example, for a baseline setting of "400," the mAs delivered at the 200 setting should be 2x that at the 400 setting. This should be true to within +/− 5% of expected mAs.

Potential findings

- The EI values do not change with a change in the sensitivity setting.

Potential pitfalls

- Older generators with multiple "speed" selections intended for multiple screen-film combinations may have only one selection intended and calibrated for clinical use. Other selections may be calibrated identically to the clinical setting, or may be not be properly calibrated at all.
- Some systems have sensitivity or speed selections preprogrammed for each exam and view, but only changeable in a protocol editing function available when logged in as an administrator or service user. If so, a "test exam" or "physics exam" protocol should be created and clearly labeled for this test. A view should be added to this "test" protocol for each sensitivity or speed selection to be tested, and programmed with identical settings except the different sensitivity or speed selection. The test protocol should then be saved, with the test proceeding as above.

4.4.7 Cell Selection

Rationale

This test verifies that the cell selected at the console is the only cell that influences the mAs selection. This is done by covering each individual AEC cell in turn with an aluminum attenuator, and then taking an exposure with the covered cell selected and another exposure with the covered cell not selected.

Recommended method

All exposures should be AEC exposures taken at the lowest possible tube voltage, preferably less than 50 kV.

1. With no attenuation in the beam, select all three AEC cells, take an AEC exposure, and record the mAs.
2. Cover all three AEC sensors with 2 mm of aluminum, take a second AEC exposure, and record the mAs (see Figure 27). This mAs should be approximately twice the value recorded in step 1.
3. Cover the left AEC cell with an aluminum attenuator that is 2 mm thick and approximately 10×10 cm (see Figure 27).

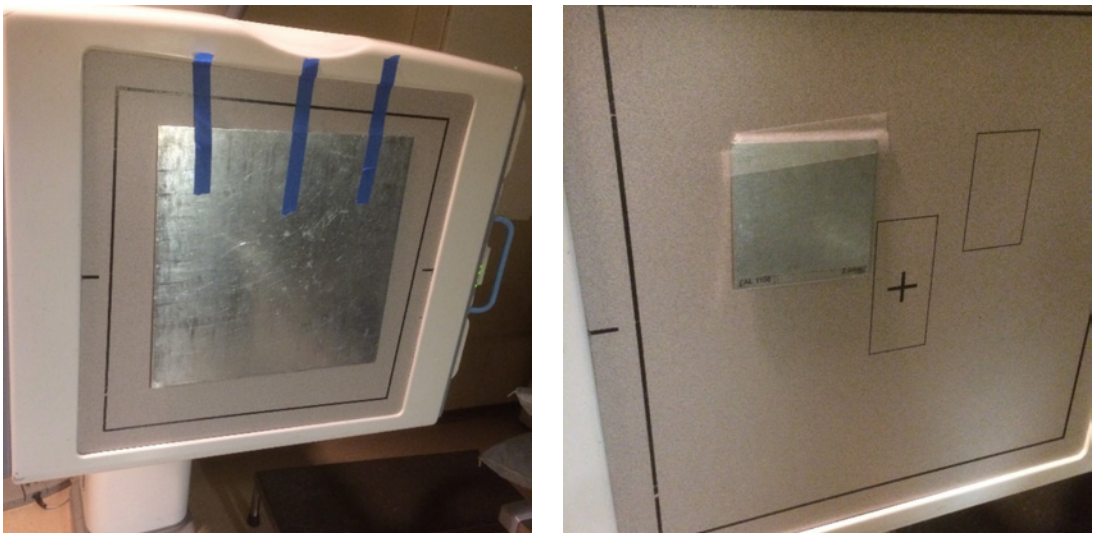

Figure 27. Setup for testing cell selection.

4. Deselect the right and center AEC cells so that only the left cell is selected, then take an exposure and record the mAs. It should be approximately the same value as that recorded in step 2.
5. Deselect the left AEC cell and select the right and center cells, then take an exposure and record the mAs. It should be approximately the same value as that recorded in step 1.
6. Repeat steps 3 through 5, covering the right and center AEC cells in turn. In all cases, the mAs when the covered cell is selected should be approximately the same as that record in step 2, and the mAs when the covered cell is not selected should be approximately the same as that recorded in step 1.

Alternative methods

None.

Expected performance limits

When the active cell is covered, the mAs should be close to the value when all cells are covered. When the active cell is uncovered, the mAs should be close to the value when all cells are uncovered. "Close" in this situation means within 30% of the difference between the covered mAs and the uncovered mAs.

Potential findings

Although not common, incorrect wiring or incorrect cell selection programming can occur, leading to incorrect cell or cells being selected at the console.

Potential pitfalls

- If a high tube voltage is used, thicker attenuations must be used or the results may be ambiguous.
- Although upright receptors usually provide templates representing cell location, table receptors do not (although some collimator templates may project cell positions onto the table, these are not always accurate and will depend on SID for the lateral cells). Judgment must be used in positioning the aluminum blockers, using the light-projected crosshairs and the cell locations on the wall receptor as a general guide.

4.4.8 Cell Balance

Rationale

The purpose of this test is to verify that all individual cells and combinations of cells deliver the desired receptor dose.

Recommended method

1. Set filtration, SID, and tube voltage to the manufacturer's calibration conditions. If these are not available, use the following:
   a. Add metal filters to the exit window of the collimator (e.g., 21 mm of aluminum or 0.5 mm of copper and 2 mm of aluminum).
   b. Open the collimators to cover the entire image receptor.
   c. Remove the grid if possible.
   d. Set the SID to a clinical detent position.
   e. Set the tube voltage to 70 kV.
2. Select one AEC cell, acquire an image, and record the mAs.
3. Repeat step 2 for each AEC cell, and for each clinically used combination. Typically, these include left and right cells, and all three cells.
4. For each cell and each combination, calculate and record the fractional deviation of the mAs from the mAs for the center cell.

Alternative methods

- If the system displays an exposure indicator proportional to detector dose (e.g., the IEC exposure index), that may be used instead of mAs.
- The measured air kerma may be used instead of mAs. The dosimeter probe would need to be placed well away from the AEC sensors.
- A PMMA or other patient-equivalent phantom may be used instead of the aluminum or copper, with the following caveats: a) unequal scatter fields sensed by center vs. lateral cells generally produce some differences unrelated to cell response; and b) proper phantom centering is critical, particularly for smaller (i.e., 25×25 cm) phantoms. It is recommended that during acceptance testing, the test first be performed with the collimator-mounted aluminum or copper attenuator to allow accurate comparison to the manufacturer specifications, followed by a patient-equivalent phantom test.

Expected performance limits

Use manufacturer specifications if they are available. Otherwise, the expected results will depend on the manufacturer's calibration scheme. Most manufacturers balance AEC cells equally; if so, results (mAs or exposure time) for each cell or cell combination should be within +/− 15% of that for the center cell. If the manufacturer uses an unbalanced calibration[8], then results should be within +/− 15% of specified relative sensitivities.

Potential findings

Changes in individual cell response over time, or problems with electronics that combine signals when using more than one cell, can create significant differences in relative responses.

[8] For example, to compensate for the different transmissions through the lungs and the mediastinum, the sensitivity of the center cell may be higher than the left and right cells.

Potential pitfalls

- If the grid is left in place, improper tube position relative to the grid focal axis can significantly affect results, particularly for the lateral cells. This includes incorrect SID and off-center misalignment.
- The precision of the measurement is affected by the precision of the displayed mAs. This effect can be minimized by using a lower tube voltage.
- When using a PMMA phantom, the difference in scatter/primary ratio for the left/right cells relative to the center cell can affect the cell balance measurements. Using a metal attenuator at the collimator window reduces the impact of scatter on the measurements.

4.4.9 Tube Voltage Tracking

Rationale

The energy dependence of digital image receptors generally differs from that of AEC cells; this requires the AEC to be properly calibrated to compensate for energy response. The purpose of this test is to verify that the AEC properly controls the image receptor air kerma over the clinically relevant kV range used with the image receptor.

The tube voltage tracking and patient thickness tracking tests can be combined if time permits; see Section "4.4.10 Patient Thickness Tracking" below.

Recommended method

1. Using the standard phantom and standard setup, set a field size to just cover the base of the phantom.
2. Select the center cell and acquire images at all clinically used tube voltages; some suggestions are presented in Table 14.
3. Record the EI for each exposure. If the system does not display an exposure index, record the manufacturer-specific exposure indicator.

Since scatter reaching the image receptor increases more steeply with increasing kV under the center of the phantom, it is recommended that this test be performed using the center cell. Energy compensations for all the AEC cells is generally identical. However, if it is known that energy compensation is set separately for each cell, then lateral cells should also be tested, at least during initial testing.

Alternative methods

Combine this test with "Patient Thickness Tracking" in Section 4.4.10 below.

Expected performance limits

EI (or other metric) maintained to within ±25% of the average, or manufacturer specifications. If using a manufacturer-specific exposure indicator, the acceptable range of the indicator should correspond to a ±25% variation of image receptor dose.

Potential findings

Improperly or inadequately calibrated AECs may under- or over-compensate for energy, leading to higher image receptor dose at lower kVs and lower image receptor dose at higher kV, or vice versa. Older generators used with CR or retrofitted with DR may be equipped with AECs designed for screen-film energy response.

Table 14: Suggested voltages for tube voltage tracking tests related to AEC tests

Bucky	Tube voltages (kV)
Table and/or wall stand used for chests and abdomens or orthopedics	60, 80, 100, 120
Wall stand used only for chests	80, 100, 120, 140 (if applicable)

Potential pitfalls

The most common reason AEC systems fail to meet performance specification is inadequate compensation for tube voltages under 70 kV. However, AECs are rarely used below 70 kV. Although AECs should be able to meet manufacturer specifications at acceptance testing, performance criteria for annual tests may be relaxed somewhat at 60 kV.

4.4.10 Patient Thickness Tracking

Rationale

The energy spectrum reaching the image receptor depends on patient thickness, corresponding differences in energy-dependent absorption, and amounts of scatter. Different energy dependences of digital image receptors relative to that of AEC cells require the AEC to be properly calibrated to compensate for patient thicknesses. The purpose of this test is to verify that the target EI (or other image or image quality metric, e.g., signal-to-noise ratio, average pixel value, or pixel value standard deviation) is maintained under AEC for the range of kVs used for the specified image receptor.

Recommended method

1. Using the standard setup, center a 10 cm (4") thickness of the phantom material used and set a field size to just cover the base of the phantom.
2. Select the center cell and acquire an image at 80 kV (table) or most common clinical kV (upright).
3. Record the exposure index.
4. Repeat for remaining thicknesses and tube voltages (see Table 15).

Since scatter reaching the image receptor increases more steeply with increasing phantom thickness under the center of the phantom, it is recommended that this test use the center cell.

Expected performance limits

EI (or other metric) maintained to within ±25% of the average, or manufacturer specifications.

Potential findings

The most common issue found with thickness tracking is poor short-time compensation for the thin (10 cm) phantom, particularly at higher kVs. Although the AEC's minimum response time may contribute to this problem for very short exposure times, it may be observed at times significantly exceeding the minimum response time. If a repeated thin phantom test with a lower mA yields similar results, the problem more likely lies with patient thickness compensation rather than short-time compensation.

Potential pitfalls

Note short-time compensation vs. patient thickness tracking discussed in "Potential findings" above.

Table 15: Suggested voltages for combined testing of tube voltage and patient thickness tracking related to AEC tests

Thickness of PMMA	Tube voltage
10 cm	60 kV, 80 kV
15 cm	60 kV, 80 kV, 100 kV
20 cm	80 kV, 100 kV, 120 kV
25 cm	100 kV, 120 kV

4.4.11 Field of View Compensation

Rationale

The purpose of this test is to verify that the AEC system demonstrates acceptable exposure constancy with changes in x-ray field of view.

Recommended method

1. Place the standard phantom on the bucky, centered over the image receptor.
2. With the x-ray tube at detent, collimate the field to 20×20 cm.
3. Select the center AEC cell.
4. Take an AEC exposure at the tube voltage used for AEC calibration or at 80 kV, and record the mAs.
5. Increase the field size by 5 cm in both dimensions, take another AEC exposure, and record the mAs.
6. Repeat step 5 until the field is larger than the top of the phantom.

Alternative methods

None.

Expected performance limits

The recorded mAs should remain constant to within +/− 10% as the field of view is changed.

Potential findings

As the field of view is increased, the amount of scatter (and thus scatter-to-primary ratio) seen by the AEC cell and image receptor increases. The resulting mAs expected to decrease moderately, since the increased scatter reaching the AEC and image receptor results in reduced primary x-rays for a properly functioning AEC. Also, the higher scatter-to-primary ratio somewhat decreases the effective beam energy, and this change may not be compensated for by the AEC's normal compensation strategies.

Potential pitfalls

The +/− 10% limit may be exceeded based on system configuration and use. A relatively wider limit may be acceptable, provided a qualified medical physicist has documented a justification for this change.

4.4.12 Backup Timer

Rationale

The purpose of this test is to verify that in the event of malfunction or technical error, the exposure is terminated within an acceptable time.

Recommended method

1. Close the collimator as tightly as possible.
2. Turn on the alignment light, and cover the exposed region of the image receptor with ~3 mm of lead.
3. Cover the entire image receptor with lead apron.
4. Select an AEC technique using the center AEC cell, a low kV (between 51 and 60 kV), and a large focal spot.
5. If the backup mAs or backup time is user selectable, select the longest possible backup mAs (or time) and record this maximum mAs (or mA × time).
6. Take an AEC exposure and record the exposure time. If it appears that the backup time was not reached (i.e., no visual or audible alarm and no reset required), repeat with lower kV and/or thicker blocker.
7. Verify that there is a visible indication that the backup timer has been reached, and that it is impossible to take further exposures without resetting the backup timer.

Expected performance limits

The following is based on 21 CFR 1020.31(a)(3)(iii)-(iv). [12].

- For tube voltages greater than or equal to 51 kV, the preset backup mAs must be ≤ 600 mAs, or must be ≤ 60,000 (kV*mAs) divided by the tube voltage. For example, if the tube voltage is 80 kV, then it must be less than 60,000 kV*mAs/80 kV, i.e., 750 mAs.
- For tube voltages less than 51 kV, the backup mAs must be ≤ 2000 mAs.
- The AEC exposure must terminate at an mAs less than or equal to the preset backup mAs, with a visual (and optionally, audible) indication of backup timer activation, and with a manual reset required before further AEC exposures can be acquired.

Potential findings

Use of any AEC system that fails to terminate an exposure within 600 mAs, or other preset backup mAs <600, must be discontinued until repaired.

Potential pitfalls

- Generators often provide kV-dependent maximum backup mAs at values < 600 (for ≥ 51 kV). As long as the AEC terminates exposures within the preset mAs, and a backup mAs >600 cannot be selected, the performance is acceptable.
- Some generators may quickly terminate an exposure if no signal is detected. kV may need to raised, or blocker thickness reduced, to allow the exposure to continue until the backup time is reached.
- If there is insufficient shielding of the image receptor and the backup timer fails, there is a possibility of introducing a ghost artifact.

4.5 Scatter Rejection Grid Tests

Introduction

An important aspect of image quality is the reduction of scatter at the image receptor. While several methods can be used to reduce the scatter, thereby increasing contrast and decreasing noise, the most common method is employing scatter rejection grids.

While scatter rejection grids will generally add to the image quality, several potential concerns arise, which may lead to artifacts, nonuniformities, and unwarranted increases in the dose to the patient. Several authors have detailed various methodologies to characterize grid performance and validate manufacturer claims [54] [55] [56] [57] [58]; here the focus is not optimization, but validation of uniform grid performance and appropriate lateral alignment with the x-ray tube.

Test equipment required

Test	Required equipment

Grid alignment and detent positioning accuracy (AEC method, Exposure indicator method, Pixel value method)	• Measuring tape
	• One of the following:
	  ○ ~21 mm aluminum block
	  ○ 2 mm copper sheet
	  ○ ~20 cm of acrylic (25×25 cm or larger)

Grid alignment and detent positioning accuracy (Plastic ruler method)	• Measuring tape • Thin 50 cm ruler

Grid uniformity	• One of the following:
	  ○ ~21 mm aluminum block
	  ○ 2 mm copper sheet
	  ○ ~20 cm of acrylic (25×25 cm or larger)

Expected results

This table summarizes the expected results from each test. In all cases, manufacturer specifications supersede these values.

Table 16: Expected results for each anti-scatter grid test

Test	Expected results
Grid alignment and detent positioning accuracy	The air kerma at detent should be no more than 5% higher than the minimum air kerma, or the distance from detent to the position of maximum air kerma is no more than 1.5% of SID.
Grid uniformity	Artifacts should not be visible when using a near-clinical window setting. Measurements of linearized pixel values in the left and right ROIs should match the center to within 20%.

Description of tests

4.5.1 Grid Alignment and Detent Positioning Accuracy

Rationale

A common source of grid cutoff is a lateral off-centering due to a mispositioned transverse detent. If so, the detent will not be properly positioned over the focal line of the grid. Since many DR systems have removable grids, proper transverse detent positioning can be checked via a physical measurement.

This procedure can only be used if it is possible to override the tube detent interlock. Procedures for doing this will vary from one model to another; on some systems it may not be possible to override the interlock at all.

Some exams may use parallel grids, for example, full-length spine exams or mobile radiographic systems. This test does not apply to such grids.

Recommended method (AEC method)

This procedure determines the tube position at which the exposure time of an AEC acquisition is minimized; this is the position at which the focal spot is closest to the grid focal axis.

1. Center the tube to the bucky using the transverse detent, with the SID equal to the grid focal length.
2. Place an attenuator (~21 mm aluminum block or 1–2 mm copper sheet) over the middle AEC cell.
3. Turn off the PBL system (if present); if the PBL system is turned on, off-detent exposures might be disabled.
4. Acquire an exposure at 80 kV using the AEC with only the middle cell. The tube output should be low enough that the exposure time is between 100 ms and 400 ms.
5. Record the exposure time.
6. Move the tube approximately 1 cm laterally toward the support tower (Figure 28).
7. Acquire another AEC exposure, and record the position and the exposure time.
8. Repeat steps 6 through 7 until the exposure time is longer than at detent.
9. Return the tube to the lateral detent.
10. Repeat steps 6 through 7, moving the tube in 1 cm increments away from the support tower until the exposure time is longer than at detent.
11. Return to detent, then acquire and record another exposure.
12. Compare the exposure time at detent to the minimum of the other exposure times.

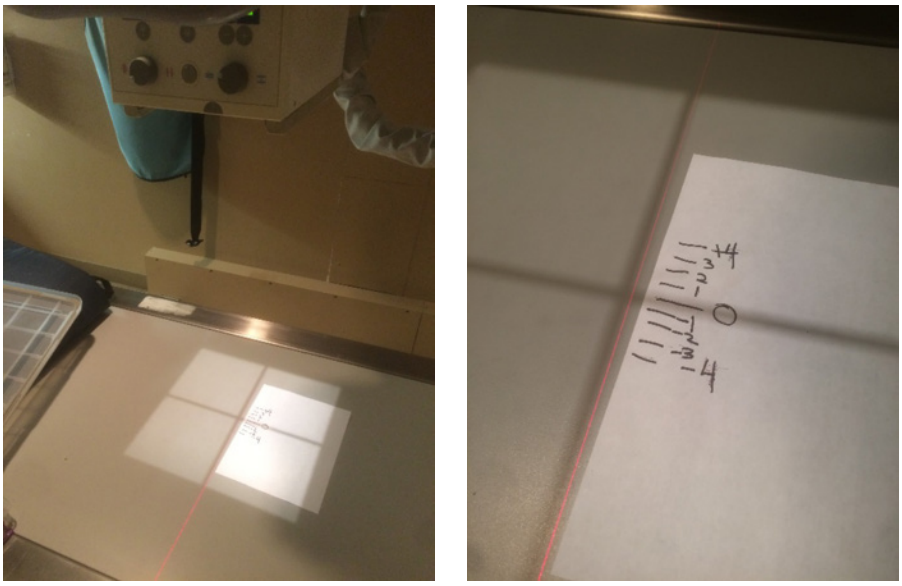

Figure 28. Setup for measuring grid alignment using the recommended method.

Alternative method A (Exposure indicator method)

If testing an older system that does not have an AEC installed, but which has an air kerma surrogate available (that is, a quantity related to air kerma such as an exposure indicator), follow the method above with the following changes:

1. Use fixed exposures (e.g., 80 kV and 1 mAs with ~21 mm aluminum filtration).
2. If the surrogate (i.e., exposure indicator) increases with increasing air kerma, look for the maximum of the air kerma surrogate rather than the minimum of the exposure time. If the surrogate decreases with increasing air kerma, look for the minimum of the surrogate.

Alternative method B (Pixel value method)

For systems without AEC and without an appropriate air kerma surrogate available, this variation on method A will work provided that it is possible to accumulate multiple exposures into a single image (e.g., using a CR cassette), or to measure pixel values in the FOR PROCESSING image at the acquisition workstation or at a diagnostic workstation.

1. Adjust the collimation so the beam at the image receptor is about 2 cm wide in the transverse direction, and is full width in the longitudinal direction[9].
2. Move the tube transversely approximately 10 cm from detent.
3. Take an exposure at fixed low-dose technique (e.g., 80 kV and 1 mAs).
4. Shift the tube transversely about 5 cm toward the detent.
5. Repeat steps 3 and 4 for five total exposures; do not move the image receptor between exposures. The third exposure should be at detent (Figure 29).
6. Position the tube at detent, change the collimation so it is approximately 5 cm wide in the transverse direction and 10 cm wide in the longitudinal direction.
7. Reduce the mAs by 20%, and take a sixth exposure. This reference exposure will be used to determine the scaling of the dose response function.

[9]The longitudinal direction is the cranial-caudal (head-foot) direction in both the wall and table bucky. This assumes that the focal axis of the grid is in the longitudinal direction. The transverse direction is perpendicular to the longitudinal one.

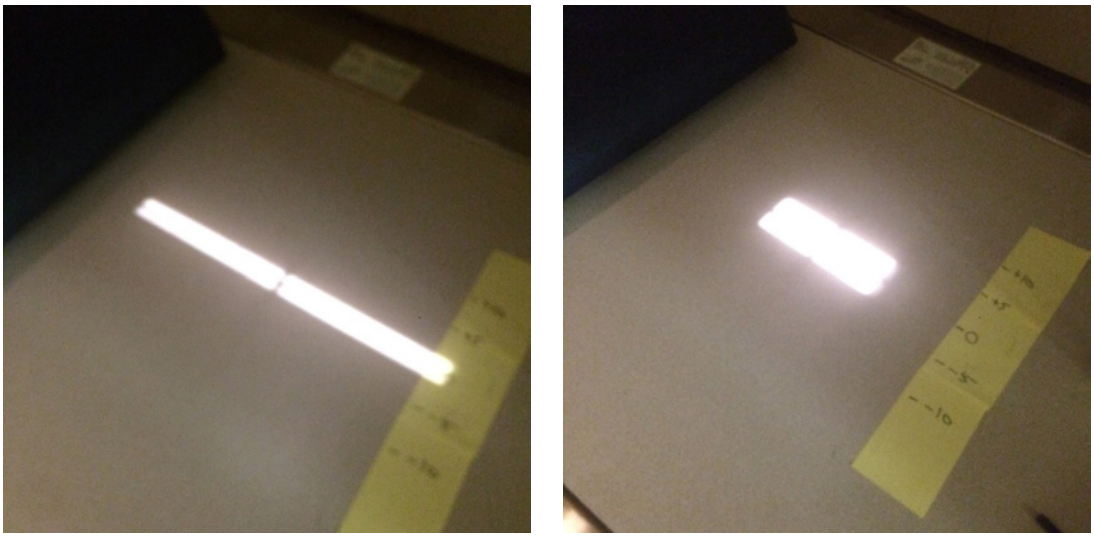

Figure 29. Setup for alternative method B for checking grid alignment. Left: the measurement taken at detent with a 2 cm wide collimation. Right: the reference measurement taken at detent with a 5 cm wide collimation.

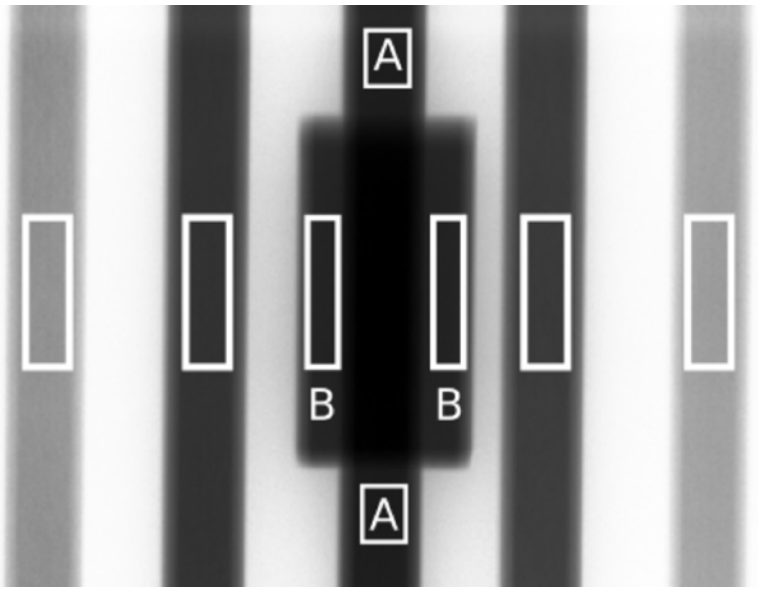

Figure 30. Radiograph used for alternative method B for checking grid alignment. The caudal-cranial axis is top to bottom. Regions A are at detent at full air kerma; Regions B are at detent but at 20% reduced air kerma. Measurements in Regions A are averaged to minimize the heel effect; measurements in Regions B are averaged to account for variations in the grid transmission.

8. Measure the average pixel value in an ROI near the center of each strip of exposed cassette. For the two exposures at detent, avoid the area that has been double exposed. See Figure 30.
9. Determine which strip was exposed with the highest grid transmission (i.e., had the highest image receptor air kerma). The focal spot was closest to the grid focal axis when this strip was exposed.

10. If the strip with the highest transmission is not the strip exposed at detent, then calculate the ratio between the image receptor air kerma at maximum transmission (AK_{max}) and the image receptor air kerma at detent (AK_{det}) using the following formula:

$$\frac{AK_{max}}{AK_{det}} = 1 + (C_0 - 1)\frac{PV_{max} - PV_{det}}{PV_{ref} - PV_{det}} \quad (39)$$

where PV_{det} is the average pixel value when the tube was at the detent, PV_{max} is the average pixel value in the strip with the maximum transmission, and PV_{ref} is the average pixel value in the reference strip (the one acquired with a 20% reduction in mAs; mAs_{ref} is the technique used to expose the reference strip). This equation is derived in Appendix A.2.

Alternative method C (Plastic ruler method)

If none of the methods above are practical, then use the following procedure.

Note: While this test is sensitive to errors in the relative positioning of the grid and the focal spot, it assumes that a line from the focal axis of the grid to the center of the grid is perpendicular to the table. Thus, it is not sensitive to errors in grid manufacture, and will give erroneous results if the grid and the table are not parallel to each other.

Note: This test requires a commercially available tool containing two beads in vertical alignment and separated by some distance. When the tool is placed on the table, and a radiograph of the tool shows the two beads superimposed, then the tool is located directly below the focal spot; i.e., it locates the ray that is perpendicular to the table that passes through the focal spot.

1. Center the tube to the bucky using the transverse detent.
2. Use a focal spot alignment tool to determine the position on the table that is directly below the focal spot.
3. Using a tape measure or 50 cm plastic ruler, measure the distance from the center of the tool to table front edge (Figure 31a).
4. Pull out or eject the grid. Tape one end of a thin 50 cm plastic ruler to the center line of the grid, with the other end extending past the front end of the table (Figure 31b).
5. Replace the grid and note the distance from the center of the grid to the front edge of the table (Figure 31c).
6. Compare the distance measured from the table location below the focal spot to the table front edge to that measured from the center of the grid to the table front edge to determine alignment.

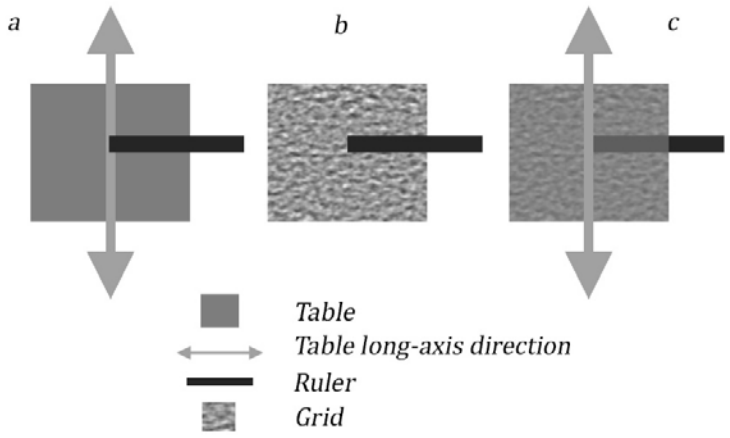

Figure 31. Grid/x-ray tube alignment setup. a) The initial measurement performed from the detent light-field center of the x-ray tube to the center of the focal spot tool. b) Fix the thin ruler to the grid with one end at the grid center. c) Insert the grid and then check that grid center and light-field center are within 1 cm of each other.

Expected performance limits

Recommended method (AEC method)

Verify that the exposure time at detent is no longer than 1.05 times the shortest of the other exposures.

Alternative method A (Exposure indicator method)

Verify that the air kerma surrogate at detent corresponds to an air kerma no less than 0.95 times the maximum of the air kerma values at other positions.

Alternative method B (Pixel value method)

Verify that the distance from detent to the position of maximum exposure is no more than 1.5% of the SID.

Alternative method C (Plastic ruler method)

Verify that the distances of step 3 and 5 agree to within 1.5% of SID.

Potential findings

- The grid installed in the table bucky may be tilted.
- The wall stand assembly may not have been installed at the correct orientation.
- Tube detents may be located at incorrect positions.
- The grid focal axis may be misplaced relative to the grid due to a manufacturing error.

Potential pitfalls

- Radiographic methods (all but the plastic ruler method): All exposures must be taken with the same field size. This requires that if PBL is turned off for any exposure, it must be turned off for all exposures.
- Exposure indicator method: This test requires that a physicist understands the nature of the "air kerma surrogate." For example, if the surrogate is calculated using a segmentation/histogram algorithm, it may fail for flat field acquisitions. In addition, it may not be proportional to air kerma.
- Pixel value method: This test requires that a physicist understands the nature of the pixel values. They must be a known function of image receptor dose, unaffected by image processing parameters.
- Exposure indicator or Pixel value method (when using CR cassette): The delay between image acquisition and CR cassette readout should be as consistent from one acquisition to another as possible to minimize variation in latent image decay.
- Plastic ruler method: This method will give misleading results if the grid is not parallel to the table.

4.5.2 Grid Uniformity – Artifacts and Off-Focal Misalignment

Rationale

To determine if grid defects are present and appropriate, grid focal distance is used.

Recommended procedure

1. Position attenuator on the collimator faceplate or on the patient support, as appropriate. Note that the use of a large air gap will minimize the effect of any imperfections in the attenuator on the image.
2. For CR, use the largest cassette size available for the bucky or cassette-holder. For DR, select the largest field of view available.
3. Set the SID to the clinically used value/focus distance for the grid being evaluated.
4. Make an exposure using the clinical technique for an average-sized abdominal radiograph, either AEC or manual.

5. For qualitative evaluation, view the image using a narrow window and clinical image processing (including any grid removal processing) to locate any imperfections in the grid. Then, set the look-up-table window to a near-clinical value to determine if these imperfections produce a visible artifact. See Appendix E for suggestions on how to select a near-clinical window setting.
6. For quantitative evaluation, measure the average pixel amplitude in three ROIs in a linearized image – in the center, and left and right sides. A line connecting the ROIs should be perpendicular to the anode-cathode axis and the grid line direction; otherwise the heel effect may lead to erroneous results. If it is impractical to use a linearized image, linearize the average pixel amplitude measurements.
7. Calculate the relative difference of the mean pixel values in the left ROI compared to the central ROI, and in the right ROI compared to the central ROI:

$$\frac{PV_{left}}{PV_{center}} - 1, \quad \frac{PV_{right}}{PV_{center}} - 1 \tag{40}$$

Expected performance limits

- Artifacts should not be visible when using a near-clinical window setting.
- If the absolute value of the relative differences of the linearized image measurements (step 7 above) is greater than 20%, sources of nonuniformity should be investigated.[10]

Potential findings

- Grid is used at incorrect focal distance. Verify specification on grid itself or from manufacturer specifications. Acquire images at different SIDs and compare maximum ROI deviation/average to see if a different SID improves nonuniformity.
- Grid is upside down.
- Grid is damaged or dented. Examine grid surface.
- There are artifacts in the grid itself.
- Some configurations may not be able to meet 20% nonuniformity control limit, even under optimum conditions (such as a wide focal range grid used at the multiple SIDs). If so, clinical requirements should be reviewed and if necessary, a higher control limit may be set.

Potential pitfalls

For CR, the regional response nonuniformity of the imaging plate and/or the additional nonuniformity introduced during the readout process may complicate evaluation of grid response. Comparison of images acquired with different cassettes with different readout orientations can be helpful in differentiating reader-introduced nonuniformities. In addition, comparison of images acquired with and without the grid may also be helpful.

4.6 Image Processing Constancy Tests

Introduction

All digital radiography systems employ some form of image processing to optimize specific image receptor characteristics and to enhance image quality. These image processing methods are usually unique to the vendor product, and detailed technical information related to the processes used by the vendor is often proprietary. Therefore, medical physicists and other users will not have access to the software's technical specifications, limiting the end-user's ability to test whether these processes are

[10] The action limit 20% is equivalent to the amount of primary beam attenuation for an 8:1 grid with 1 inch of lateral defocussing. See Table 8-4 in Christensen, 4th Edition [65].

functioning properly or have been altered or corrupted. In addition, many service representatives from the vendors do not have a good working knowledge of the image processing methods or the parameters that modify their function.

There are many different reasons image processing can fail on clinical patient images that are not related to the image processing methods setup by the vendor but are related instead to the exposure technique set by the technologist and the patient position and body habitus. Therefore, determining if the image processing is functioning correctly can be a difficult task and the best that can be done is to attempt to determine if the image processing has changed over time.

The tests described below (Sections 4.6.2 and 4.6.3) are very sensitive to any change in the image processing parameters or algorithms but require access to information on the modality unit that is often not readily accessible. However, the test in Section 4.6.1 includes a simple image processing test that can be applied to any system, but which is not as thorough. For routine annual testing, the test in Section 4.6.1 should be sufficient; however, one of the other tests should be performed periodically as part of a protocol review program, and may be performed if the annual test indicates a change in the image processing.

Expected results

Table 17 summarizes the expected results from each test. In all cases, manufacturer specifications supersede these values.

Description of tests

4.6.1 Stability of Pixel Values

Rationale

The mean and standard deviation of pixel values of the processed image in a flat region of the image are sensitive to beam quality and air kerma, but also to image processing parameters. Changes in the image processing parameters or algorithms may be detected by measuring these values during annual testing and comparing them to baseline values.

Ideally, the mean and standard deviation should be measured in a flat region near the center of the image under low scatter conditions; this minimizes the effect of a slowly varying background on the noise measurement.

Recommended method

1. Attach a ~21 mm aluminum block or 0.5 mm copper filter to the exit port of the collimator, and place a stepwedge phantom in the center of the imaging field of view.
2. Place the image receptor in the table bucky.
3. Set the SID to a typical clinical value (e.g., 100 cm).
4. Select a commonly used clinical protocol.
5. If taking a baseline measurement (e.g., during acceptance testing), acquire an image using an AEC exposure, and record the tube voltage and mAs used. If taking a follow-up measurement (e.g., during annual testing), acquire an image using a manual exposure and the same clinical protocol selection, tube voltage, and mAs used for the baseline measurement.

Table 17: Expected results for each image processing test

Test	Expected results
Stability of pixel values	The follow-up measurements should be similar to those taken during baseline measurements.
Review of image processing parameters	The image processing parameters should match the values of the last approved configuration exactly.
Comparison of FOR PROCESSING images	The newly processed images should be exactly equal to the baseline processed images.

6. Measure and record the mean and standard deviation of the pixel value in the clinically processed image in a small (~ 1 cm × 1 cm) region near the center of each step in the image of the stepwedge phantom.
7. Compare the mean and standard deviation values to those recorded at baseline.
8. Repeat for several commonly used clinical protocols.

Expected performance limits

The measurements taken during follow-up measurements should be substantially similar to those taken during baseline measurements.

Potential findings

A substantial difference in the mean or standard deviation values may indicate a change in the image processing parameters, or a change in the image processing algorithm. If so, a protocol review may be warranted. A consistent shift in the measured values may be indicative of calibration or tube output issues.

Potential pitfalls

The follow-up measurements must be taken under the same conditions as the baseline measurements, or the results may be meaningless. A change in generator, tube, or image receptor performance will also affect the measurement, so this test should be done after confirming consistent performance of other subsystems.

4.6.2 Review of Image Processing Parameters

Rationale

Each vendor product will have a methodology to configure the image processing specific to their system. These methodologies usually allow optimization of the image processing for different physician viewing preferences. Once the image processing is configured, the parameters that define this processing need to be stored so they can be used on all clinical cases. This is a baseline configuration for the image processing.

The limited information available to the end user constrains options for meaningful testing in the field. Therefore, the recommendations in this section focus on methods to determine whether the image processing has changed from a baseline configuration. If changes are found, the system should have a back-up of the baseline configuration available to allow the service engineers to restore the previous configuration if applicable. The configuration changes may have occurred as a part of the protocol optimization process.

Testing requirements

Image processing parameters are used by algorithms or software procedures to change the presentation of digital images into the desired appearance. The acquisition system stores these parameter sets and uses them on all clinical images that are sent for review and storage. This is the baseline configuration. Systems that are compliant with NEMA/MITA Standards Publication XR 30-2016 [18] will have the capabilities to export the image processing parameters. For these systems, the vendor must document the methodology for export and format of the exported data. For systems that do not meet the requirements of NEMA/MITA XR 30-2016, the image processing parameters may be available, but how to access these values will need to be determined by working with the vendor service engineers.

Procedure

To determine if changes have occurred in image processing since acceptance, or the last approved modification, the image processing parameters stored in the system must be compared to values from the previous accepted version of the image processing parameters. This requires that at acceptance, or when any change in the image processing parameters occurs, these values must be exported and stored

either with the system or in a location that is readily available at the time of testing. This exported and stored image processing parameters set will be designated the *Baseline Image Processing Parameters* for the purposes of this document.

Expected performance limits

If no change has occurred in the image processing parameters since the last approved configuration, the current stored baseline configuration on the system must be identical to the values in the *Baseline Image Processing Parameters*. A simple comparison of all values between these datasets can be done to make this determination. Any deviation in these values should be investigated to determine the cause.

Potential findings

If any deviations found are valid, the *Baseline Image Processing Parameters* file should be replaced with the current stored baseline configuration. If the change cannot be validated, then the *Baseline Image Processing Parameters* should be used to replace the baseline configuration on the system.

No changes in the image processing parameters should occur without the review and approval by a radiologist or a person of authority at the site. Therefore, even if it is found that the current baseline configuration does not match the *Baseline Image Processing Parameters,* the decision to replace must only be done under the approval either of the radiologist or of their designee at the site.

4.6.3 Comparison of FOR PRESENTATION images

Storage of test images

Every digital image processing system should have a set of representative clinical images permanently stored on the system or exported in a location that is readily available at the time of testing. This set of images should be acquired by the image receptor system type (e.g., detection material, CR, DR, etc.) that is associated with the image processing system, and they should be generic, de-identified images from actual human subjects, i.e., patients, not phantom or synthetic images. If there is more than one image receptor type associated with the image processing system, the images should be clearly designated to indicate which image receptor type acquired the images.

The stored image set should be in DICOM *FOR PROCESSING* (i.e., IEC ORIGINAL data) format with no processing applied except that required to account for image receptor and x-ray system limitations as allowed in IEC 62220-1-1:2015 [15]. This *FOR PROCESSING* image set will be designated "*FOR PROCESSING Test Images*" for the purposes of this document. These *FOR PROCESSING Test Images* will be used initially as the baseline set at acceptance and for customization of the image processing for each site and to determine subsequently if changes have occurred in the current image processing configuration. The approach can also incorporate site-specific clinical images when customizing the image processing, and these can also be archived on the system for later comparison. In this case, the site-specific images should be clearly distinguished from the original *FOR PROCESSING Test Images*, although the site-specific images can be used on their own for all testing recommendations in this document.

In addition to the *FOR PROCESSING Test Images,* the system should have a set of images that have the current site-approved *Baseline Image Processing Parameters* applied to the *FOR PROCESSING Test Images*. This set of images will be designated "*Baseline FOR PRESENTATION Test Images*" for the purposes of this document. This set of images should be used as the standard to determine whether any changes to the image processing have occurred since the original configuration or the last approved change in image processing was made by the site.

Both the *FOR PROCESSING Test Images* and *FOR PRESENTATION Test Images* should be exported and stored either with the system or in a location that is readily available at the time of testing in a DICOM-compliant format and on media such as a flash drive or other electronic storage media.

Procedure

To determine if changes have occurred in the image processing parameters since the last approved modification, the system must be able to reprocess the *FOR PROCESSING Test Images* by applying the parameters in the current baseline configuration used on clinical patient images. The new dataset created in this procedure will be designated "*Current FOR PRESENTATION Test Images*" for the purposes of this document. The *Current FOR PRESENTATION Test Images* will be compared to the stored *Baseline FOR PRESENTATION Test Images* by subtracting the images and displaying the result. This subtraction procedure and the review of the resultant images do not need to be performed on the acquisition system.

Expected performance limits

If no change has occurred in the image processing parameters since the last approved configuration, the resultant subtracted images should have a zero value everywhere. If there is a non-zero result, it can be assumed there was a change and the reason for the change would need to be investigated.

If the purpose of the evaluation is to review how image processing parameters can be optimized, the analysis may require more image manipulation procedures, e.g., region of interest statistical analysis or other qualitative and quantitative assessments. Therefore, it is desirable to have some image manipulation capabilities on the system, although analysis of the exported images can be done using an external image processing software system, e.g., ImageJ [39] or other software.

4.7 Acquisition Display Monitor Tests

Introduction

Physicists should be aware of the impact that image display has on the use of digital radiography systems, and they should include tests of image display as part of quality control and acceptance testing.

The primary concept that guides display choice, settings, and quality control is the consistent presentation of images. Without the consistent presentation of images, modifications made at the DR system to improve image appearance may not improve image appearance in the reading room. In the worst case, technologists may modify acquisition settings or image processing to compensate for a poor acquisition unit display, resulting in poor image quality for the radiologist.

For technologists to see a relevant representation of what is being sent to a radiologist, the acquisition unit display should match the radiologist's display in luminance response, luminance ratio, and environmental lighting. If this cannot be achieved, a clinical practice should be aware of the impact this has on a technologist's ability to correct or optimize image processing and be able to adjust their utilization and workflow accordingly.

List of settings and tests

Two documents provide guidance for selection, settings, and quality assurance for DR acquisition workstation displays: the ACR-AAPM-SIIM (Society for Imaging Informatics in Medicine) Technical Standard (2017) [59], and the AAPM Task Group 270 Report (2019) [11]. We defer to these documents for details on selection, calibration, and quality control testing of DR acquisition display monitors.

Conclusions

In addition to the guidance provided in the referenced documents, some general strategies can be employed for managing radiographic acquisition displays to better serve a clinical practice:

- Be knowledgeable about the luminance ratio and response of radiologists' diagnostic displays in order to support consistency in image presentation, and to be aware of how the acquisition units may show images differently.
- Perform regular testing and establish the conditions under which a monitor will need to be replaced. Display luminance, calibration, and uniformity may change with age, making it necessary to set an acceptable range of display properties to determine when a display is no

longer appropriate for the setting and task. Some DR displays are integrated into system consoles, which makes replacement difficult. This should be considered before making a recommendation to replace the display.
- Improve viewing conditions by moving the system to better ambient lighting, tilting the display to adjust for better viewing angle and reflections, or shielding the display from ambient light.
- Avoid additional protective screens or be aware of how they may affect image display.

4.8 System Tests

System tests will evaluate the configuration and integrated functions of all subsystems under standard conditions of acquisition in the clinical setting. They provide data on patient radiation exposure for comparison to applicable regulatory limits and/or published reference values, and for verification of proper dose reporting.

Test equipment required

Test	Required equipment
Patient equivalent phantom test	Patient-equivalent phantom such as: • CDRH Luc-Al Adult Chest Phantom [7] [23] [24] with Image Quality Test Tool • CDRH Luc-Al Abdomen Phantom [7] [25] with Image Quality Test Tool • ANSI Chest phantom [13] • Modified ANSI Abdomen/Lumbar spine phantom [13] • ACR RF Phantom [26] Calibrated dosimeter
Exposure indicator accuracy	Ionization chamber with dosimeter or solid-state dosimeter Noninvasive kV voltage divider 0.5 mm copper filter Alternate: 21 mm thick aluminum 1100 filter Aluminum 1100 filter set, combinable to up to 11 mm in 1 mm increments
Determination of ERMF (Method A)	Imaging workstation with a software distance tool
Determination of ERMF (Method B)	Access to DICOM metadata
Determination of ERMF (Method C)	Imaging workstation with a software distance tool, and radio-opaque test object of known size (e.g., star pattern)

Expected results

Table 18 summarizes the expected results from each test. In all cases, manufacturer specifications supersede these values.

Table 18: Expected results for each system test

Test	Expected results
Patient equivalent phantom test	The image processing parameters should match the values of the last approved configuration exactly. The calculated entrance skin exposure must be lower than reference value for same clinical anatomy and view.
Exposure indicator accuracy	The exposure indicator must be accurate to within 35%; it should be accurate to within 20%.
Determination of ERMF	None; this test determines the value(s) of ERMF to be used in other tests.

Description of tests

4.8.1 System Test Using Patient Equivalent Phantom

Rationale

Verify the following:

- Modality Worklist Management
- DICOM store
- Value of interest (VOI) lookup table (LUT)
- DICOM header values
- Exposure indicator reporting
- Entrance skin exposure
- System image quality

Recommended method (using solid-state dosimeter)

This procedure should be followed for at least three different clinically used protocols, such as abdomen, chest, and extremity.

1. Schedule a test patient for an appropriate examination in the facility RIS.
2. Select the test patient examination from the modality worklist at the DR acquisition station.
3. If the protocol requires the use of the bucky, make sure that the image receptor and correct grid are in the bucky.
4. Place the patient equivalent phantom over the image receptor.
5. Position the dosimeter sensor in the beam on top of the phantom; if testing an AEC protocol, make sure that it is not over the AEC cells.
6. Perform the examination using the selected protocol.
7. If using a phantom with embedded test objects, inspect the image on the display at the acquisition station, score according to the instructions for the phantom, and record the results.
8. Record any displayed/measured x-ray parameters and dosimetric values (kV, mAs, exposure indicator, air kerma, dose area product, etc). The incident air kerma value is indicative of the entrance skin exposure given the dosimeter sensor is on top of the phantom.
9. Measure and record the mean and the standard deviation of the pixel values in a uniform region near the center of the image.
10. Add one or more annotations to the image.
11. Transmit the image to the PACS.
12. View the image on a PACS review station.
13. If using a phantom with embedded test objects, inspect the image on the display at the diagnostic station, score according to the instructions for the phantom, and record the results.
14. Record any dosimetric values displayed on the diagnostic station.
15. Verify that the following are displayed properly on the diagnostic station:
    a. Dosimetric values
    b. Annotations
    c. Patient name and ID
    d. Exam date and time

    Note: these values will not be displayed on the diagnostic workstation unless they are included both in the DICOM metadata and the PACS is configured to display them.
16. Measure the mean and standard deviation of pixel value in a central, uniform portion of the image. Note as baseline value.

The following steps are optional:

17. If the diagnostic workstation cannot display DICOM metadata, export the image to a DICOM viewer.
18. Inspect the DICOM header to determine whether the attributes listed in Table 19 and Table 20 and in the system's DICOM Conformance statement are present.

Alternative method (using ionization chamber)

Perform the recommended procedure, with the following changes:

1. Before each exposure, place the ionization chamber approximately halfway between the phantom and the focal spot, and record the source-to-chamber distance.
2. Record the air kerma for each exposure.
3. Perform inverse-square correction of exposure measurement to simulated skin entrance plane, $((SDD/SSD)^2)$ to estimate the entrance skin exposure.

Measurements using the technique above include some contribution from the phantom scatter. If a more accurate free-in-air measurement is desired, perform the following additional steps:

1. After each exposure, remove the phantom and repeat the exposure using the same mAs and kV used for the phantom exposure; if the phantom exposure used an AEC protocol, a manual mA mode must be used for this test.
2. Record the air kerma for the exposure.
3. Perform inverse-square correction of exposure measurement to the phantom surface (simulated skin entrance plane), $((SDD/SSD)^2)$ to estimate the entrance skin exposure.

Note: if testing multiple clinical protocols with the same kV, SID, and phantom, this measurement need be done only once, and can be used to calculate the entrance skin exposures for other protocols.

Expected performance limits

- Calculated entrance skin exposure must be lower than published reference value (e.g., by practice parameters/technical standards of the American College of Radiology, etc.) for same clinical anatomy and view.
- If a phantom containing objects such as meshes or contrast/detail objects is being used, the image quality should meet the specifications for the phantom.
- Exposure indicator must be displayed at acquisition station and on PACS review station.
- The mean and standard deviation of the pixel values should not vary significantly from the baseline measurement. Because the meaning of the pixel values may vary from model to model, the interpretation of "vary significantly" is left to the professional judgment of the physicist.

Table 19: Clinically useful DICOM attributes

(The values in the "Required" column are adapted from the definition of the DX IOD Module in DICOM Part 3.3, section A.26 [60], specifically for FOR PRESENTATION images.)

Tag	Attribute	Required
(0018,1411)	Exposure Index	Optional
(0018,1412)	Target Exposure Index	Optional
(0018,1413)	Deviation Index	Optional
(0028,1050)	Window Center	Required if VOI LUT Sequence is not present
(0028,1051)	Window Width	Required if Window Center is present
(0028,3010)	VOI LUT Sequence	Required if Window Center is not present
(0028,3002)	LUT Descriptor	Required if VOI LUT Sequence is present
(0028,3006)	LUT Data	Required if VOI LUT Sequence is present

Potential findings

The following set-up or procedural problems could cause erroneous results in the system test:

- Modality worklist not configured for intended examinations.
- Images do not successfully transfer to PACS.
- Images transferred as incorrect DICOM modality object.
- Image transferred in undesired presentation state (FOR PROCESSING vs. FOR PRESENTATION).
- Image transferred with undesired digital image processing or VOI LUT.
- Images are not properly RIS-verified, i.e., "orphans" or "broken studies" on PACS.
- Entrance skin exposure in excess of reference value.
- Dosimetric values not displayed on acquisition station or PACS review station.
- Dosimetric values at PACS review station do not match values displayed on acquisition workstation.
- Changes in the mean and standard deviation of the pixel values may indicate that the image processing parameters have changed.

Potential pitfalls

- Improper positioning of patient equivalent phantom with respect to AEC cells.
- Incorrect selection of active AEC cell.
- Incorrect selection of scatter reduction grid.
- Incorrect selection of pre-patient filtration.
- Improper collimation of x-ray field to phantom.
- Unexpected segmentation of the digital image of the phantom.

4.8.2 Exposure Indicator Accuracy

Rationale

The primary procedure is used to test the displayed exposure index on systems compliant with IEC 62494-1 [16]. This IEC standard, based on the recommendations of AAPM Report 116 [8], defines a standard exposure indicator proportional to image receptor dose.

The alternative method is to be used with systems that display a parameter related to image receptor dose but which are not compliant with IEC 62491-1, for reasons that may include the following:

- The indicator is not proportional to image receptor dose (e.g., "S" values are typically inversely proportional to image receptor dose).
- The indicator may be affected by user adjustable image processing.
- The indicator is based on beam conditions that do not match those of IEC 62491-1.

The correct calibration of EI is especially important on systems that display a deviation index indicator (e.g., red/green number values for deviation from target EIs). Without proper EI calibration, these may be counterproductive by causing technologists to acquire unneeded repeats, make incorrect adjustments, or ignore the indicator entirely.

Some systems that need to be configured to display the IEC 62494-1 exposure index may not have been configured to do so at the time of installation. The task group recommends that such systems be configured to display the exposure index before the first clinical use.

Recommended method

This procedure is based on IEC 62494-1 [16] , which requires the following radiation quality:

- A half-value layer of 6.8 +/− 0.3 mm of aluminum.
- Added filtration of either 21 mm aluminum or 0.5 mm of copper and 2 mm aluminum.
- An x-ray tube voltage in the range 66–74 kV.

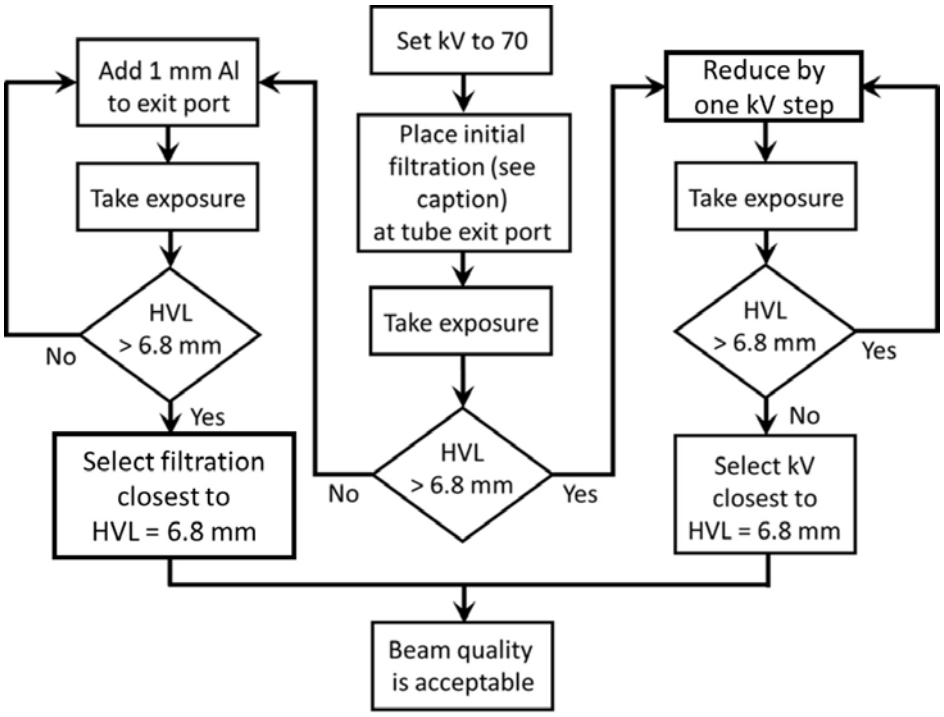

Figure 32. Flowchart for establishing acceptable beam quality for exposure index verification using a solid-state dosimeter. Initial filtration is 21 mm aluminum or 0.5 mm copper plus 2 mm aluminum.

These conditions approximate beam quality RQA5 (IEC 61627 [17]), which uses a peak kilovoltage of 70 kV, and an HVL of 6.8 mm aluminum. Achieving this precisely in the field may be impractical, so the present procedure determines the amount of filtration required to generate a beam with an HVL ~6.8 mm aluminum at 70 kV, or the lowest tube voltage that generates a beam with HVL ~6.8 mm with the available filtration.

Figure 32 is a flowchart that illustrates the procedure for establishing an acceptable beam quality.

If a solid-state dosimeter sensor that measures HVL is not available, use the first alternative method below and the flowchart shown in Figure 33.

The term "dosimeter sensor" is used to refer to the solid-state dosimeter sensor.

1. Remove the image receptor from the beam path, either by removing it from the bucky assembly or moving the bucky assembly. If the image receptor cannot be removed, ensure that the image receptor is shielded from the entire collimated beam.
2. Use a noninvasive kV voltage divider without any added filtration to determine the nominal tube voltage that produces the beam with measured kilovoltage closest to 70 kV.
3. Attach a 0.5 mm copper or 21 mm pure aluminum filter to collimator exit port.
4. Set the nominal tube voltage to the value determined in step 2 above.
5. Using narrow beam geometry and low scatter conditions, measure the x-ray beam HVL with an appropriate dosimeter sensor (see Figure 34).
6. If HVL is less than 6.8 mm aluminum, the beam is too soft; advance to step 9.
7. If HVL is greater than 6.8 mm aluminum, the beam is too hard; advance to step 12.
8. If HVL is equal to 6.8 mm aluminum, the beam quality is acceptable; advance to step 15.
9. Add 1 mm of aluminum to the collimator, to no more than a total of 25 mm of aluminum or 0.5 mm of copper and 4 mm aluminum.

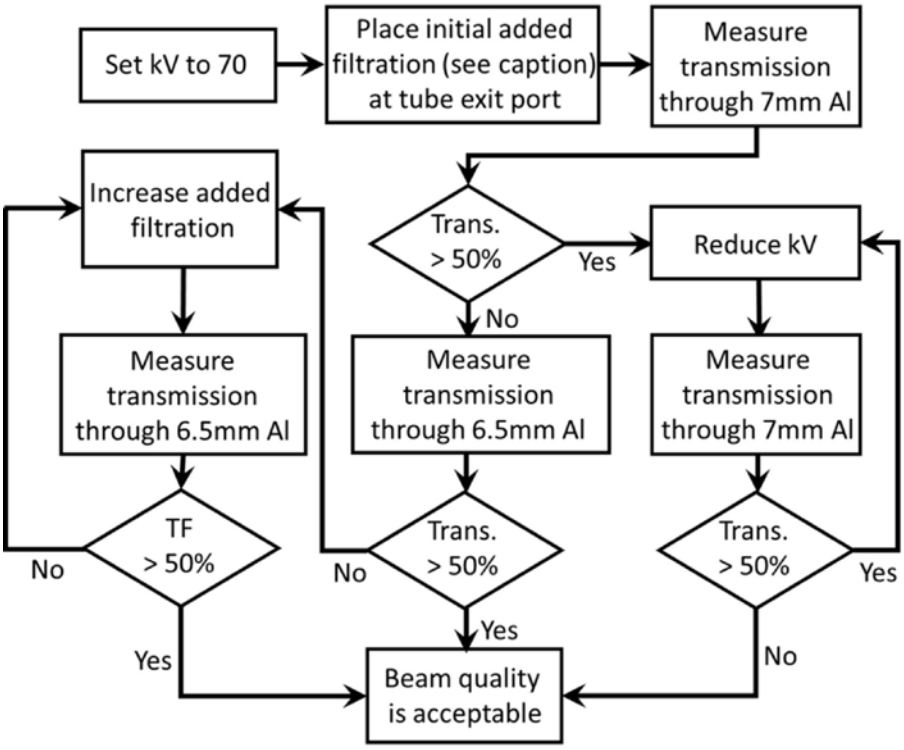

Figure 33. Flowchart for establishing acceptable beam quality for exposure index verification using an ionization chamber. Initial filtration is 21 mm aluminum or 0.5 mm copper plus 2 mm aluminum (Trans.: transmission).

10. Use the dosimeter to measure the HVL of the beam.
11. If HVL is less than 6.8 mm, repeat step 9. Otherwise, select the filtration that results in the HVL closest to 6.8 mm and advance to step 15.
12. Reduce the tube voltage by one kV step to no less than 66 kV.
13. Use the dosimeter to measure the HVL of the beam.
14. If HVL is greater than 6.8 mm, repeat step 12. Otherwise, select the tube voltage that results in the HVL closest to 6.8 mm and advance to step 15.
15. If the image receptor can be removed from the bucky, place lead shielding on the floor to minimize backscatter, and place the receptor on the lead (see Figure 34 below). Otherwise, remove the anti-scatter grid if possible.
16. Set the tube housing at the highest SID possible.
17. Place the dosimeter sensor as shown in Figure 34.
18. Using the tube voltage settings and additional filtration determined above, and a time-current product of about 2.5 mAs, acquire a full-field exposure of the image receptor (collimate to the outside edges of the image receptor), and record the air kerma.
19. Calculate the air kerma at the image receptor (if appropriate, multiply by the estimated transmission through the table and through the grid).
20. Calculate the time-current product values required to expose the image receptor using an air kerma of approximately 4.5 μGy, 9 μGy, and 18 μGy (i.e., 0.5 mR, 1.0 mR, and 2.0 mR). Record these time-current product values, and the calculated air kerma at the image receptor for each value.
21. Remove the dosimeter sensor from the beam.

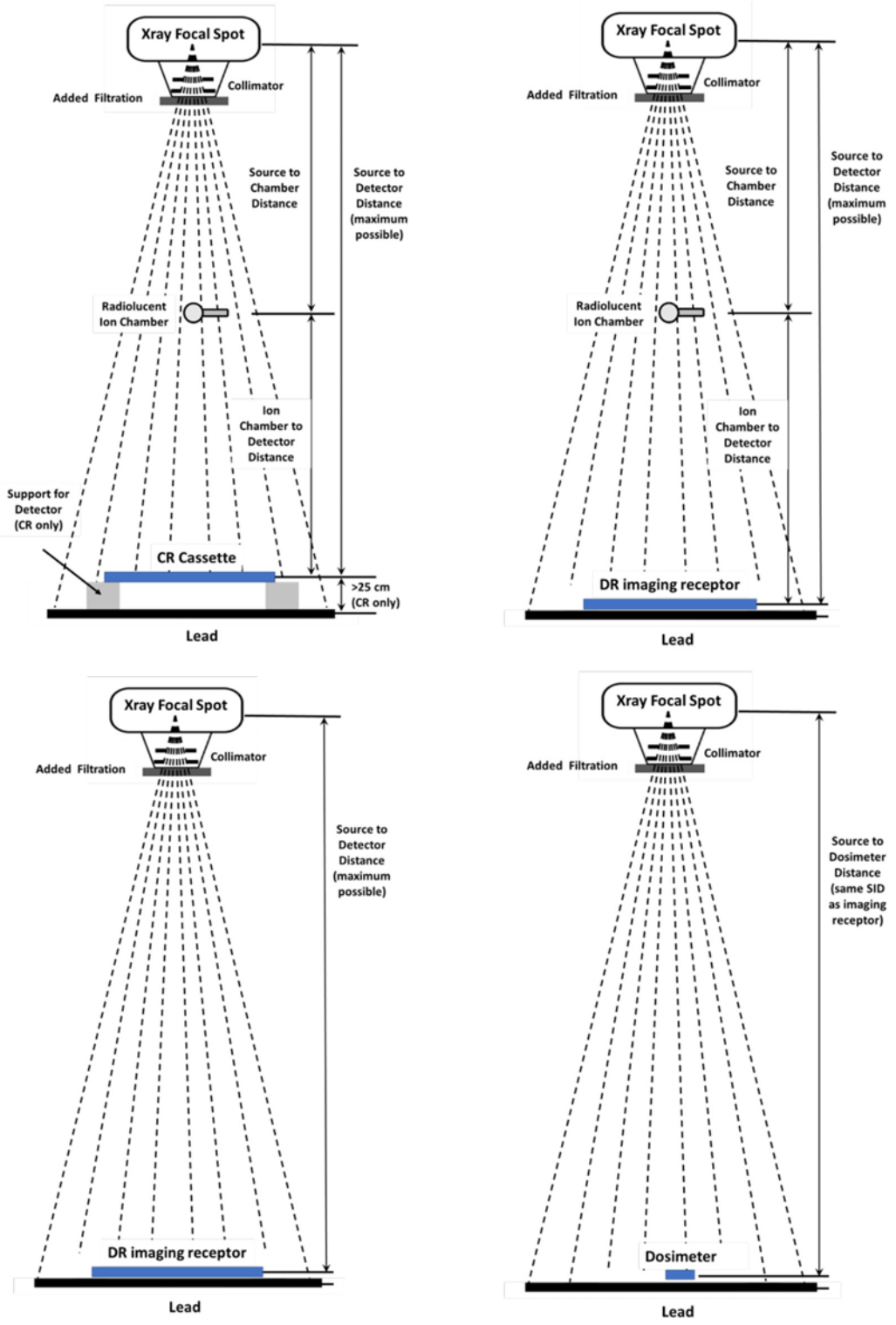

Figure 34. Geometry of exposure index validation test using ionization chamber (above) and lead-backed solid-state dosimeter sensor (below) on patient table (adapted from Figure 3, AAPM Report 116 [8]).

22. Expose the image receptor at each of the three time-current product values, and record the displayed exposure index and deviation index. Use processing appropriate for flat field image analysis, if available.
23. If the system has separate exposure index calibrations for different positions (e.g., in table bucky, on tabletop, in chest bucky – Figure 35), repeat the procedure for each receptor position, starting at step 15.
24. If the system has two image receptors, repeat the procedure for the second image receptor, starting at step 15.

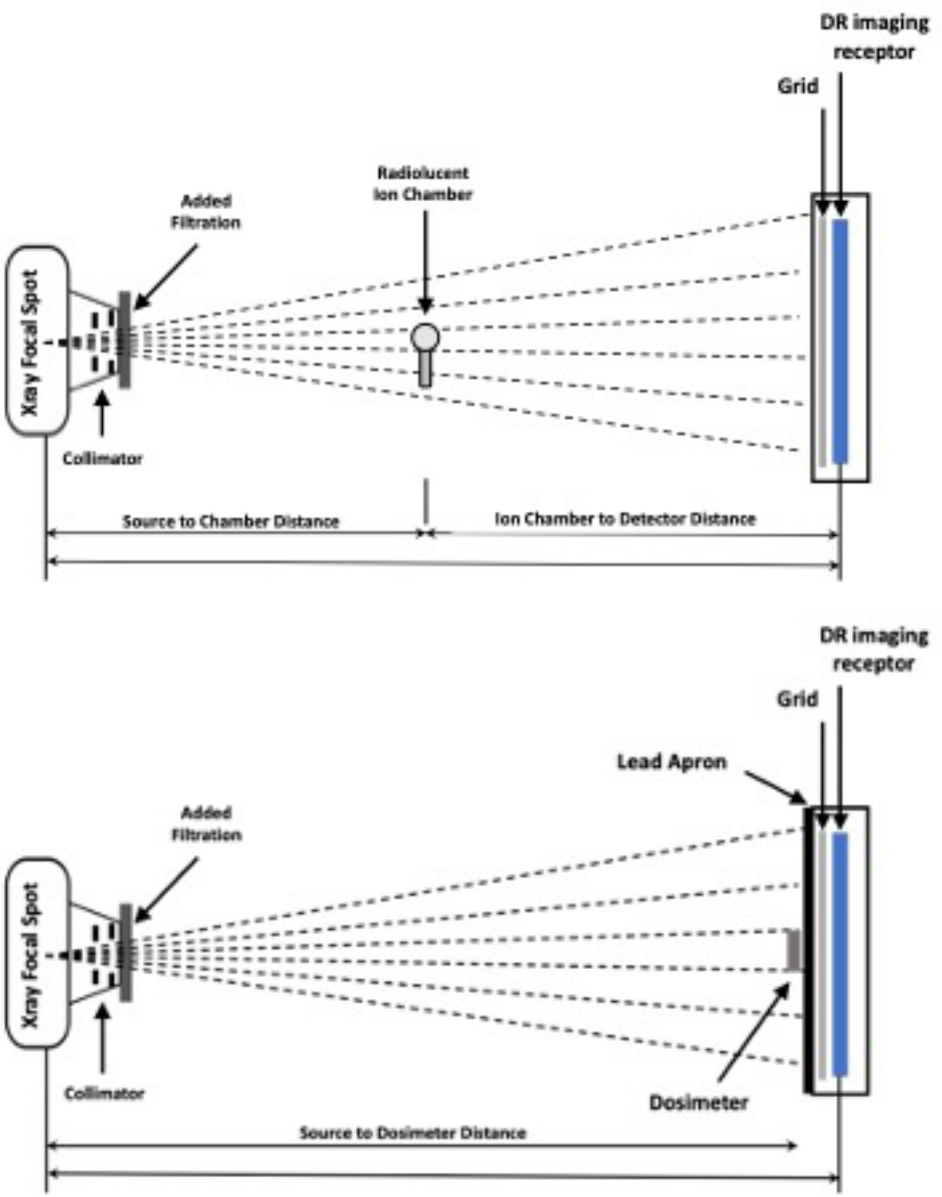

Figure 35. Geometry of exposure index validation test using ion-chamber (above) and solid state dosimeter sensor (below) with wall bucky (adapted from Figure 3, AAPM Report 116 [8]). Please refer to step 15 in the recommended method to follow the other steps, e.g., removing the grid (grid is shown in this figure to only indicate the location of the grid).

Alternative method using an ionization chamber

When using an ionization chamber, it is not necessary to determine the HVL; it is only necessary to determine if the HVL is between 6.5 mm and 7.0 mm. The method is similar to the recommended method except that after changing the tube voltage or filtration, measure the transmission through either 6.5 mm or 7.0 mm of aluminum as follows:

1. Place the ionization chamber on the patient table, and using narrow beam geometry, take an exposure at the present tube voltage and filtration and record the air kerma.
2. Place a 6.5 mm or 7.0 mm stack of aluminum filters on the ionization chamber.
3. Take a second exposure and record the air kerma.
4. Divide the air kerma from the second exposure by the first exposure to determine the transmission. Follow the steps in the flowchart of Figure 33 until the beam quality is acceptable.
5. Then follow steps from the recommended method (step 15 onwards).

Note: For calculating the air kerma at the image receptor using an ionization chamber, the ionization needs to be placed in the center of the beam (Figures 34 and 35), approximately halfway between the focal spot and the image receptor. The recorded air kerma at the image receptor is then calculated using the inverse-square correction ($(SCD/SID)^2$) and if applicable, then multiplying this by the estimated transmission through the table and through the grid.

Alternative method for annual testing

Follow the recommended method, or alternative method using an ionization chamber, but using the filtration and tube voltage determined at baseline, and using a single time-current product value.

Alternative method (for systems not compliant with IEC 62494)

In systems that are not compliant with IEC 62494, the exposure indicator may be calibrated to a beam condition specified by the vendor. For these systems, the indicator should be tested using the vendor-specified beam condition.

Expected performance limits

- Exposure indicator value should agree with exposure measurement within +/− 35% or to within manufacturer specifications, whichever is stricter [14]. However, it is commonly possible to achieve 20% accuracy.
- The ratio of exposure index to mAs should be constant to within 10% for the three air kerma levels.
- The deviation index should change by ~3 as the air kerma is doubled.

Potential findings

Incorrect dose reporting by the system secondary to:

- Incorrect calibration of image receptor sensitivity or gain
- Nonconforming implementation of IEC 62494-1:2008-08

Potential pitfalls

- Some x-ray tube and collimator assemblies already have sufficient inherent filtration such that the HVL at 66 kV with 0.5 mm copper is greater than 6.8 mm aluminum. These systems must be tested at a lower tube voltage range specified by AAPM TG-116, or less copper attenuation should be used.
- The calculation of the exposure index is based on anatomical segmentation of the image, and an analysis of the histogram of pixel values in the ORIGINAL data. This analysis may fail for a flat field image.

- Some manufacturers apply corrections to the exposure indicator that are not consistent with IEC 62494.
- If the image receptor cannot be removed from the table, it may not be possible to find specified transmissions through the table or grid that match these beam conditions.
- Older DR systems may not report an exposure indicator conforming to the IEC standard. In these cases, the traditional exposure can be converted into the new values. However, the conversion can introduce systematic error if there are differences between the traditional calibration conditions of exposure and the TG-116 beam conditions.

4.8.3 Displayed Air Kerma and Kerma-Area Product (KAP/$P_{K,A}$) Accuracy

Rationale

The exposure indicator accuracy test above refers to an indication of the air kerma at the image receptor. Some radiographic systems also display the air kerma at a reference point and/or the air kerma area product (KAP); these are associated with the air kerma entering the patient rather than the air kerma exiting the patient.

Recommended method

The procedure for measuring air kerma and KAP accuracy is described in Section 3.1 of AAPM Report 190 [61].

Expected performance limits

According to AAPM Report 190, the IEC and FDA specify tolerances of +/− 35% for the accuracy of air kerma and KAP displays for fluoroscopic systems. For radiographic systems, it is reasonable to expect these values to be accurate to within +/− 35%.

4.8.4 Determination of Estimated Radiographic Magnification Factor (ERMF)

Rationale

The goal of this test is to determine the value and behavior of the Estimated Radiographic Magnification Factor (ERMF). This value is used in multiple other tests.

Digital radiographic systems often have a software distance tool that can be used to calculate the distance between two points in the image. On some systems, this distance is the actual physical distance between the detector elements; for example, objects 100 pixels apart in an image acquired on an image receptor with 0.2 mm detector element pitch are reported as being 20 mm apart.

On other systems, the distance is referenced back to a nominal object plane. This is done by dividing the distance in the image plane by the ERMF. For example, if the source-to-image distance (SID) is 100 cm, and the nominal object plane is 80 cm from the x-ray source, the ERMF would be (100 cm)/(80 cm) = 1.25. In the example above, if the ERMF were 1.25, the software distance tool would report a distance of 20 mm/1.25 = 16 mm. The ERMF should be greater than or equal to 1.

The ERMF may have a fixed value, or it may have a value that depends on the SID. Alternately, the system may allow the user to calibrate distances by entering the physical distance between two fiducial markers in the image.

For many radiographic systems, the ERMF is equal to 1 when the image receptor is not in the bucky; when the image receptor is in a bucky, the reference plane is the entrance plane of the bucky (i.e., the surface of the patient table for the table bucky, or the surface of the bucky shroud for the wall bucky). A typical ERMF value is therefore approximately 1.07 for the table bucky, and 1.03 for the wall bucky.

Many of the tests described in this report rely on measurements taken on the image, so information of the ERMF is important in analyzing test results. This information may also be important to communicate to the physicians who use the system.

There are several DICOM attributes that are related to the ERMF; these attributes are listed in Appendix B. Few systems will include all of these attributes in the image, so it is important to know how to calculate the ERMF from partial data. Furthermore, the attributes are not implemented correctly in all systems [62], so it is prudent to not only examine the attributes for consistency, but also measure the radiographic magnification factor independently.

Note that the wall bucky and the table bucky will generally have different values of the ERMF.

Test equipment required

Test method	Required equipment
A (Recommended method)	Imaging workstation with a software distance tool
B	Access to DICOM metadata
C	Imaging workstation with a software distance tool, and radio-opaque test object of known size (e.g., star pattern)

Recommended method

This procedure requires that the image be read on an acquisition workstation with a software distance tool or a PACS workstation, and knowledge of the exact image receptor width (or alternately, the matrix size and detector element pitch).

1. Using the table bucky, acquire an image under the following conditions:
   a. SID set to standard clinical value (e.g., 100 cm).
   b. PBL turned off.
   c. Collimators opened to extend the x-ray field several centimeters past the image receptor.
   d. Low exposure (e.g., 70 kV, 0.5 mAs).
2. At the acquisition workstation, use the software distance tool to measure the width of the entire image.
3. Divide the physical width of the image receptor by the measured image width; this is the ERMF.
4. Repeat for another SID, for a tabletop exposure, and for the wall bucky, to determine if the ERMF is dependent on the SID or the image receptor location.

Alternative method A

This method can be used if:

- the Geometric Accuracy test (Section 4.3.16) verified that the reference plane is at the entrance to the bucky,
- the SID test verified that the displayed SID is accurate, and
- the SID test verified that the integrated measuring tape indicates the correct source-to-object distance (SOD).

Procedure

1. Place the image receptor in the bucky.
2. Record the displayed SID.
3. Use the integrated measuring tape to determine the SOD to the bucky entrance (patient tabletop or wall bucky cover).
4. The ERMF is the radiographic magnification at the bucky entrance:

$$ERMF = \frac{SID}{SOD} \tag{41}$$

Alternative method B

This procedure requires access to the DICOM header.

1. Set the SID to a standard value (e.g., 100 cm), and acquire an image using the table bucky.
2. Read the DICOM header. Some systems allow access to the DICOM header at the acquisition workstation. Others may require sending the image to PACS. In this case, it may be more efficient to determine the ERMF after collecting data at the exam room; however, this precludes analyzing any test results that require the ERMF while taking data.
3. Use the DICOM data to calculate the ERMF for this SID using the procedures described in Appendix B. Repeat for another SID, for a tabletop exposure, and for the wall bucky, to determine if the ERMF is dependent on the SID or the image receptor location.

Alternative method C

The ERMF may be estimated radiographically. This can be done to verify that the DICOM value of ERMF is being used properly, or to determine the ERMF if the DICOM header is not available.

1. Use a low technique (e.g., 70 kV, 0.5 mAs) to acquire an image of a radio-opaque object of known size D_{actual} at a known radiographic magnification M, and then use the software distance tool at the acquisition workstation to measure the diameter $D_{displayed}$ of the object in the image.
2. Multiply the diameter of the object by the actual radiographic magnification to determine the physical image diameter (Figure 36):

$$D_{image} = D_{actual} M \tag{42}$$

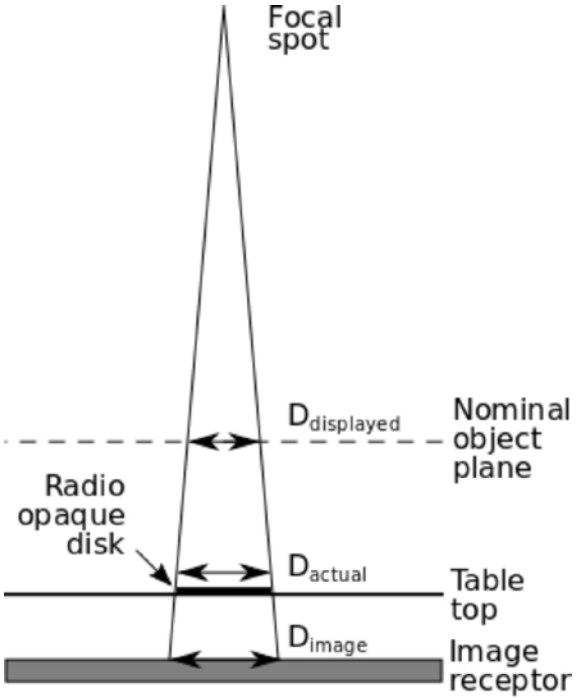

Figure 36. ERMF calculation using radio-opaque test object of known size.

3. Calculate the ERMF according to the equation:

$$ERMF = \frac{D_{image}}{D_{displayed}} = M\frac{D_{actual}}{D_{displayed}} \quad (43)$$

Expected performance limits

- The ERMF should be consistent with manufacturer specification. However, the primary purpose of this test is to determine the value of the ERMF used by the system.
- When using a flat panel detector in a bucky, the reference plane is often the top of the patient table or the entrance surface of the wall bucky.
- When using a CR cassette, or a flat panel detector out of the bucky, the ERMF is usually 1.0.

Potential findings

- The ERMF may have a fixed value, it may depend on a fiducial measurement on the image, or it may depend on SID or the image receptor location (table bucky, tabletop, wall bucky). The DICOM attribute "Pixel Spacing Calibration Type" (0028,0402) indicates whether the ERMF is based on a fiducial measurement or geometry.
- The DICOM attribute values may not be filled consistently and appropriately; this is particularly true of older systems [62].

Potential pitfalls

- If using the recommended method, make sure to measure the entire image width. It also requires knowledge of the actual active image receptor size.
- It may be difficult or impossible to access the DICOM headers at the acquisition workstation or at the diagnostic workstation.
- The radiographic approach requires that the geometric magnification be known, and therefore that the positions of the focal spot and the image plane be known accurately.

4.9 Interoperability Tests

Introduction

For most radiology practices, the functionality of a digital radiography acquisition unit extends beyond the acquisition console and depends on interoperability with a host of other systems: RIS, PACS, post-processing software, and clinical viewers. Interoperability might be assured by a vendor in an IHE Integration Statement [27], and perhaps contractually agreed to as part of a purchase. Alternatively, the vendor may assume no responsibility for interoperability and leave validation to the end user to ensure that the equipment is ready for clinical use[11]. In either case, it is wise to understand what might go wrong, what the risks are, and what aspects of interoperability are desirable to validate as part of equipment acceptance testing. The goal of the acceptance testing can be viewed in two parts:

1. To ensure that the equipment meets or exceeds the specifications provided by the manufacturer as part of the purchase process.
2. To validate that a system is ready for clinical use.

[11] Example from the DICOM conformance statement for GE XRd (DR unit) [66].

"**Validation** - Testing the complete range of possible interactions between any GE device and non–GE devices, before the connection is declared operational, should not be overlooked. Therefore, the **user** should ensure that any non–GE provider accepts full responsibility for all validation required for their connection with GE devices. This includes the accuracy of the image data once it has crossed the interface between the GE imaging equipment and the non–GE device and the stability of the image data for the intended applications. Such a validation is required before any clinical use (diagnosis and/or treatment) is performed. It applies when images acquired on GE imaging equipment are processed/displayed on a non-GE device, as well as when images acquired on non-GE equipment are processed/displayed on a GE console or workstation."

Often, it is the role of a physicist to have the final approval regarding both of these acceptance testing goals.

Deciding which system aspects should be evaluated during acceptance testing, and how, should be made based on addressing real risks to interoperability, to confirm purchase contract specifications, to protect the electronic environment to which the system connects, or to promote efficient clinical integration, patient safety, and quality of care. Some tests listed in AAPM Report 150 and AAPM Report 248, if not routinely used in acceptance testing, may be used for troubleshooting.

Troubleshooting and optimizing the imaging chain may require a team effort on the part of the physicist, service engineer, PACS system administrator, and technologist. Each of these individuals will have special knowledge of the workflow, the data flow, and the possible factors that could affect image quality and information integrity at different points in the imaging chain. The medical physicist should understand the variables that can affect the image between acquisition and display, and know where to go for additional assistance in order to isolate the source of image quality or information integrity problems.

Description of tests

AAPM Report 248 [10] covers the details of interoperability testing of all modalities. Please refer to Report 248 for recommendations.

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Chapter 6 - Glossary

Term	Definition
Acquisition display monitor	The display at the radiographic unit on which images are displayed immediately after acquisition.
ERMF	DICOM Estimated Radiographic Magnification Factor (ERMF). The distance between two pixels reported by the software distance tool (see below) is the distance at the image plane divided by the ERMF. See Section 4.8.4 and Appendix B for details.
Detector element	A single element in the image receptor array, typically corresponding to a single image pixel. These are sometimes referred to as "dels" in the literature, or less frequently "dexels."
Grid cutoff	Excess attenuation of the primary x-ray beam by the anti-scatter grid caused by misalignment.
Lateral direction	The horizontal direction parallel to the short axis of the patient table.
Longitudinal direction	The direction parallel to the long axis of the patient table.
Software distance tool	A distance measurement tool incorporated into the acquisition or diagnostic workstation software.
Baseline Image Processing Parameters	The set of approved image processing parameters.
Current Image Processing Parameters	The set of image processing parameters currently installed on the system.
FOR PROCESSING Test Images	A set of FOR PROCESSING images used to test image processing parameters.
Baseline FOR PRESENTATION Test Images	A set of FOR PRESENTATION images generated from the FOR PROCESSING Test Images using the Baseline Image Processing Parameters.
Current FOR PRESENTATION Test Images	A set of FOR PRESENTATION images generated from the FOR PROCESSING Test Images using the Current Image Processing Parameters.

Appendix A - Derivation of Equations

A.1 Aluminum Half-Value Layer (HVL) - Equation (3)

This equation is used to determine the HVL of a beam using the measured air kerma $I_n = I(T_n)$ for three thicknesses of added aluminum in the beam: $T_0 = 0mm$, T_1 mm, and T_2 mm.

The exposure at a thickness of aluminum close to HVL is:

$$I(T) = \frac{I_0}{2} exp(a(HVL - T)) \tag{44}$$

where *I(0)* is the air kerma without added aluminum (*T=0mm*) and *a* is an unknown constant. This equation can be written as:

$$a(HVL - T) = ln\left(\frac{2\,I(T)}{I_0}\right) \tag{45}$$

Given measurements at two thicknesses, we have two equations and two unknowns (*a* and *HVL*):

$$a(HVL - T_1) = ln\left(\frac{2\,I_1}{I_0}\right) \tag{46}$$

$$a(HVL - T_2) = ln\left(\frac{2\,I_2}{I_0}\right) \tag{47}$$

By subtracting these equations, we can determine *a*:

$$a = \frac{1}{T_2 - T_1} ln\left(\frac{I_1}{I_2}\right) \tag{48}$$

This can be substituted into equation (45), so:

$$ln\left(\frac{I_1}{I_2}\right)(HVL - T_1) = (T_2 - T_1) ln\left(\frac{2\,I_1}{I_0}\right) \tag{49}$$

This can be solved for HVL:

$$\text{HVL} = T_1 + (T_2 - T_1) ln\left(\frac{2\,I_1}{I_0}\right) / ln\left(\frac{I_1}{I_2}\right) \tag{50}$$

This can be rewritten as:

$$\text{HVL} = \frac{T_2 ln\left(\frac{2\,I_1}{I_0}\right) - T_1 ln\left(\frac{2\,I_2}{I_0}\right)}{ln\left(\frac{I_1}{I_2}\right)} \tag{51}$$

A.2 Grid Alignment and Detent Positioning Accuracy - Equation (39)

Suppose that three manual mAs measurements are taken using a grid as follows:

1. On detent with technique mAs_0 at air kerma AK_{det}, producing pixel value PV_{det}.
2. On detent with technique mAs_{ref} at air kerma AK_{ref}, producing pixel value PV_{ref}.
3. Off detent with technique mAs_0 at air kerma AK_{det}, producing pixel value PV_{off}.

Since the reference exposure is taken in the same position as the detent exposure, the grid transmission should be the same, so the air kerma of the two exposures is related as:

$$C_0 \equiv \frac{AK_{ref}}{AK_{det}} = \frac{mAs_{ref}}{mAs_{det}} \tag{52}$$

The derivative of the air kerma with respect to pixel value is approximately:

$$\frac{dAK}{dPV} \cong \frac{AK_{ref} - AK_{det}}{PV_{ref} - PV_{det}} = \left(C_0 - 1 \right) \frac{AK_{det}}{PV_{ref} - PV_{det}} \tag{53}$$

The air kerma for the off-detent exposure is:

$$\begin{aligned} AK_{off} &= AK_{det} + \frac{dAK}{dPV}\left(PV_{off} - PV_{det}\right) \\ &= AK_{det}\left(1 + \left(C_0 - 1\right)\frac{PV_{off} - PV_{det}}{PV_{ref} - PV_{det}}\right) \end{aligned} \tag{54}$$

So the ratio of the off-detent air kerma to the on-detent air kerma, and thus the ratio between the grid transmission at the two positions, is:

$$\frac{AK_{off}}{AK_{det}} = 1 + \left(C_0 - 1\right)\frac{PV_{off} - PV_{det}}{PV_{ref} - PV_{det}} \tag{55}$$

A.3 Determining the Focal Spot and Image Plane Location

The precise location of the focal spot and the image plane can be determined by acquiring two images of a known size at two different heights above the patient support at a known distance apart.

The actual radiographic magnification of an object at distance SOD_1 from the source is:

$$M_1 = \frac{SID}{SOD_1} = ERMF\frac{D_1}{d_1} \tag{56}$$

where D_1 is the image size measured by the distance software tool, and d_1 is the actual object.

The radiographic magnification of the second object at a second distance $SOD_2 = \mathrm{SOD}_1 + \Delta z$ is:

$$M_2 = \frac{SID}{SOD_1 + \Delta z} = ERMF\frac{D_2}{d_2} \tag{57}$$

These two equations can be combined to determine the values of the two unknowns, SID and SOD_1:

$$SID = \mathrm{ERMF}\,\Delta z\frac{D_2 D_1}{d_1 D_2 - d_2 D_1} \qquad SOD_1 = \Delta z\frac{d_1 D_2}{d_1 D_2 - d_2 D_1} \tag{58}$$

If a single object is used, or two objects with the same size d, this is:

$$SID = ERMF\frac{\Delta z}{d}\frac{D_2 D_1}{D_2 - D_1} \qquad SOD_1 = \Delta z\frac{D_2}{D_2 - D_1} \tag{59}$$

Appendix B - DICOM Estimated Radiographic Magnification Factor

The digital caliper calibration in DICOM images is determined by the "Pixel Spacing" attribute (0028,0030), which is the number of millimeters per pixel. This is related to the detector element pitch through the nominal radiographic magnification, more formally known as the Estimated Radiographic Magnification Factor (or ERMF). To convert distance measurements made with the software distance tool back to the image plane, it is necessary to multiply them by the ERMF.

Possible ways to determine the nominal radiographic magnification from the DICOM attributes include:

- Use the value of (0018,1114) "Estimated Radiographic Magnification Factor."
- Divide (0018,1110) "Distance Source to Detector" by (0018,1111) "Distance Source to Patient."
- Divide (0018,1164) "Imager Pixel Spacing" by (0028,0030) "Pixel spacing."
- Divide (0018,7022) "Detector Element Spacing" by (0028,0030) "Pixel spacing." Warning: if multiple detector elements are binned into a single pixel, this will give a result too large by the bin ratio.
- Divide (0018,2010) "Nominal Scanned Pixel Spacing" by (0028,0030) "Pixel spacing."

B.1 DICOM Attributes

The following table lists various DICOM attributes related to the nominal radiographic magnification.

Table 20: DICOM attributes related to the ERMF

Tag	Name
(0018,1110)	Distance Source to Detector
(0018,1111)	Distance Source to Patient
(0018,1114)	Estimated Radiographic Magnification Factor
(0018,1164)	Imager Pixel Spacing
(0018,2010)	Nominal Scanned Pixel Spacing
(0018,7022)	Detector Element Spacing
(0028,0030)	Pixel Spacing
(0028,0402)	Pixel Spacing Calibration Type[12]
(0029,0404)	Pixel Spacing Calibration Description[12]

The meanings of each of the attributes listed above are as follows [60]:

B.1.1 Distance Source to Detector

This is the SID measured in millimeters.

B.1.2 Distance Source to Patient

DICOM PS3.3 [60] lists this as the distance from the source to the table. Depending on the vendor's implementation, this may or may not be the distance to the reference plane.

B.1.3 Estimated Radiographic Magnification Factor

This is the radiographic magnification at the reference plane.

[12] The Pixel Spacing Calibration Type and Pixel Spacing Calibration Description describe how the distance calibration was determined, and have no direct effect on the pixel spacing calibration.

B.1.4 Imager Pixel Spacing

This is the physical distance between the centers of adjacent detector elements times the pixel binning; this is never to be adjusted to account for geometric magnification. The DICOM standard states that this is "measured at the front plane of the image receptor." This may differ from the Detector Element Spacing attribute; for example, if the data from multiple detector elements are binned into a single pixel, the Imager Pixel Spacing will be larger than the Detector Element Spacing. The Task Group is unaware of any radiographic systems that bin pixels.

B.1.5 Nominal Scanned Pixel Spacing

This is used only in Secondary Capture series. It is the distance between samples on the medium being scanned. It may be present in DICOM images from systems installed before the Digital X-ray (DX) IOD was introduced in 1998 [63].

B.1.6 Detector Element Spacing

This is the physical distance between the centers of adjacent detector elements. It is not to depend on geometric magnification nor detector binning.

B.1.7 Pixel Spacing

This is the pixel pitch at the reference plane, presumably in the patient.

B.1.8 Pixel Spacing Calibration Type

This describes how the ERMF was determined, and has the following possible values:

- GEOMETRY - ERMF is based on known or assumed geometric magnification.
- FIDUCIAL - ERMF is based on measurement in the image of an object of known size.

B.1.9 Pixel Spacing Calibration Description

This is a free text description of the pixel spacing calibration type, and may include details of the inputs to the calibration.

Appendix C - Optimal Magnification for Focal Spot Measurements

The blur radius in the image plane of a star pattern with a radiographic magnification M is well known to be:

$$D_{blur}^{IP} = \frac{FS(M-1)}{\theta_{rad}} \tag{60}$$

where θ_{rad} is the spoke angle in radians; this is half the angular period of the spokes. The blur diameter in the object plane is then:

$$D_{blur}^{OP} = \frac{FS(M-1)}{M\,\theta_{rad}} \tag{61}$$

A reasonable value for the optimal magnification M_{opt} is one where the focal spot blur diameter D_{blur}^{OP} will be half the spoke pattern diameter D_{spoke}, given the expected focal spot size FS_{exp}:

$$M_{opt} = \frac{1}{1-\left(\frac{\theta_{rad}}{2}\right)\frac{D_{spoke}}{FS_{exp}}} \tag{62}$$

In this case, the largest focal spot size that can be unambigously measured is twice the expected focal spot size, $FS_{max} = 2\,FS_{exp}$.

Star pattern spoke angles are typically specified in degrees, so equation (62) can be written as:

$$M_{opt} = \frac{1}{1-\left(\pi\frac{\theta_{spoke}}{360}\right)\frac{D_{spoke}}{FS_{exp}}} \tag{63}$$

Note that for very small focal spot sizes, equation (63) evaluates to a negative number. This indicates that there is no magnification at which the blur diameter will be equal to or greater than half the spoke diameter.

IEC 60336 [13] specifies the largest acceptable focal spot length and width for a variety of nominal focal spot sizes. For most of these, the largest acceptable length is twice the nominal focal spot size, so a reasonable value of FS_{exp} is twice the nominal size.

Table 21 lists the optimum magnification for a variety of focal spot sizes and spoke angles for a star pattern with a spoke diameter of 45 mm.

Often the star pattern is placed on a mount that determines OID, the distance from the star pattern to the image receptor. The SID is then adjusted to achieve the desired magnification. Since the magnification is given by:

$$M = \frac{SID}{SOD} = \frac{SID}{SID-OID} \tag{64}$$

The desired SID is:

$$\mathrm{SID} = \mathrm{OID}\,\frac{1}{1-M^{-1}} = \mathrm{OID}\left(\frac{360}{\pi\,\theta_{spoke}}\right)\frac{FS_{exp}}{D_{spoke}} \tag{65}$$

Table 22 lists the optimum SID for selected focal spot sizes and OID values.

Table 21: Optimum radiographic magnification for measuring focal spot size for a star pattern with a spoke diameter of 45 mm and an expected focal spot size twice the nominal size

A value of 5.00 in the table indicates that the result of equation (63) is either negative or greater than 5.

	Spoke Angle (deg)	0.5	1.0	1.5	2.0
	Spoke Diameter (mm)	45	45	45	45
Nominal FS size	Expected FS length (mm)	Optimum Radiographic Magnification			
0.1	0.2	5.00	5.00	5.00	5.00
0.2	0.4	1.96	5.00	5.00	5.00
0.3	0.6	1.49	2.89	5.00	5.00
0.4	0.8	1.33	1.96	3.79	5.00
0.5	1.0	1.24	1.65	2.43	4.66
0.6	1.2	1.20	1.49	1.96	2.89
0.7	1.4	1.16	1.39	1.73	2.28
0.8	1.6	1.14	1.33	1.58	1.96
0.9	1.8	1.12	1.28	1.49	1.77
1.0	2.0	1.11	1.24	1.42	1.65
1.2	2.4	1.09	1.19	1.33	1.49
1.5	3.0	1.07	1.15	1.24	1.35
1.75	3.5	1.06	1.13	1.20	1.29
2.0	4.0	1.05	1.11	1.17	1.24
2.25	4.5	1.05	1.10	1.15	1.21
2.5	5.0	1.04	1.09	1.13	1.19
2.75	5.5	1.04	1.08	1.12	1.17
3.0	6.0	1.03	1.07	1.11	1.15

Table 22: Optimum SID for measuring focal spot size for a star pattern with a spoke diameter of 45 mm and typical values of OID

A value of "Min" indicates that the minimum possible SID should be used.

	Spoke Angle (deg)	0.5	1.0	1.5	2.0
	Spoke Diameter (mm)	45	45	45	45
Nominal FS size	Object-Image Distance (cm)	Optimum SID (mm)			
0.1	30	Min	Min	Min	Min
0.3		92	46	Min	Min
0.6		183	92	61	46
1.2		367	183	122	92
0.1	40	Min	Min	Min	Min
0.3		122	61	Min	Min
0.6		244	122	81	61
1.2		489	244	163	122

Range of measurable values

The largest focal spot size that can be measured unambiguously is that which produced a blur diameter equal to the spoke diameter (see equation (61)):

$$D_{spoke} = \frac{FS_{max}(M-1)}{M\,\theta_{rad}} = FS_{max}\frac{M-1}{M}\frac{180}{\pi\,\theta_{spoke}} \tag{66}$$

This upper limit to the measurable focal spot size is:

$$FS_{max} = D_{spoke}\frac{M}{M-1}\frac{\pi\,\theta_{spoke}}{180} \tag{67}$$

There is a lower limit to the size of the focal spot that can be unambiguously measured; this limit is constrained by the spatial resolution of the image receptor. To unambiguously measure the focal spot size, it is necessary to visualize the spoke patterns at frequencies above the blur frequency. The image plane spatial frequency of the spoke pattern on a circle of diameter D^{IP} is:

$$f = \frac{1}{D^{IP}\theta_{rad}} \tag{68}$$

If the limiting spatial frequency of the image receptor is f_{max}, then for any focal spot at any magnification, the spoke pattern will not be visible inside an image plane circle of diameter D^{IP}_{min}:

$$D^{IP}_{min} = \frac{1}{f_{max}\theta_{rad}} \tag{69}$$

The blur diameter needs to be larger than this value, which is the case only if:

$$FS > FS_{min}, \quad FS_{min} \equiv \frac{1}{f_{max}(\mathrm{M}-1)} \tag{70}$$

Equation (70) is obtained by combining (60) and (68).

The range of focal spots that can be measured at magnification M are:

$$\frac{1}{f_{max}(M-1)} < FS < D_{spoke}\frac{M}{(M-1)}\frac{\pi\,\theta_{spoke}}{180} \tag{71}$$

C.1 Example

For example, a 1.2 mm focal spot can be expected to have a length of 2.4 mm (the IEC limit). If using a star pattern with a 1° spoke angle and spoke pattern with a diameter of 45 mm, the optimal magnification would be:

$$M_{optimal} = \frac{1}{1-\left(\frac{\pi}{360}\right)\frac{45\text{ mm}}{2.4\text{ mm}}} = 1.195 \tag{72}$$

If the star pattern is mounted 30 cm from the image receptor, the optimal SID is:

$$\mathrm{SID} = 30\,\frac{1}{1-1/1.195} = 183\text{ cm} \tag{73}$$

If the detector resolution were 2.5 lp/mm, then the minimum and maximum measurable focal spot sizes would be:

$$FS_{min} = \frac{1}{2.5(1.195-1)} = 2.05\text{ mm} \qquad FS_{max} = 45*\frac{1.195}{(1.195-1)}*\pi*\frac{1}{180} = 4.81\text{ mm} \tag{74}$$

Appendix D - Image Exposure Domain Conversions

When performing some of the tests described in Chapter 4, it is essential to understand the data space that the image data is represented in. The most common examples of these are either a *linear* exposure domain or a *logarithmic* exposure domain, although other exposure domain definitions are possible.

In a *linear* exposure domain, the pixel values in the image (PV_{linear}) are linearly related to image receptor radiation dose D_{det}:

$$PV_{linear} = C_{offset} + C_{sensitivity} D_{det} \tag{75}$$

where C_{offset} is the pixel value at zero image receptor dose, and $C_{sensitivity}$ is the change in pixel value for a unit change in image receptor dose.

In many systems, the image data are represented in a domain where the values are proportional to the log_{10} of the input air kerma (Ref. AAPM Report No. 93, Table 15, page 60, 2006). One example of such a transformation is shown here:

$$PV_{log} = C_{log} * \log_{10}\left(\frac{D_{det}}{D_0}\right) + C_0 \tag{76}$$

where C_0 is the desired pixel value at the calibration dose D_0, and C_{log} is the change in the pixel value for a factor of 10 change in the image receptor dose. For example, the choice $C_{log} = 1024$, $C_0 = 2048$, and D_0=10 μGy would allow for a 10 μGy dose to lie in the center of a 12 bit output (0 to 4095), with a 4 decade dynamic range (0.1 μGy to 1000 μGy). The exact details of this log conversion vary dramatically between manufacturers.

The use of a logarithmic exposure domain has a number of advantages for display of a medical image including the fact that the representation of a given signal contrast is independent of the underlying signal level. This is particularly important when displaying clinical images with a wide range of signal levels, such as a standard chest radiograph. The visibility of a nodule of a given contrast will translate to a fixed difference in code value in the log exposure domain, irrespective of whether the nodule is in a high or low signal region, e.g., in the lung or mediastinum. For example, at a low dose level, quantization error can visibly affect the image produced by a linear domain image receptor but has a negligible effect on the image produced by a logarithmic domain image receptor. This aids significantly in the efficient presentation of the clinical information to the viewer.

Ideally, an image receptor would use a logarithmic amplifier to process the analog signal before digitization; this would provide the full benefits of the log exposure domain. Alternately, an image receptor may digitize a linear signal, and then apply a logarithmic LUT to the resulting pixel values. This would cause a loss of information; the log-domain values would be sparsely populated at low air kerma values (i.e., not all integer values would be used), while multiple linear-domain pixel values would be mapped into a single log-domain value at high air kerma values.

Care must be taken when converting from one exposure domain to the other. For example, at very low dose levels, a unit change in the pixel value in the log-exposure domain will correspond to change of much less than 1 in the linear exposure domain; this conversion would result in a loss of information if using integer math. Similarly, at very high levels, a unit change in the linear-exposure domain will correspond to a change of much less than 1 in the log exposure domain. Thus, when linearizing a log-exposure image for quantitative analysis, it is better to convert to floating point values than to integer values.

Other issues that the reader should bear in mind when determining the exposure domain of their acquired images include the fact that certain types of image viewing workstations can invert the data range, i.e., low exposure results in high pixel values and high exposure results in low pixel values (e.g., monochrome1 versus monochrome2 photometric interpretation variants). In addition, some worksta-

tions that provide ROI analysis tools, i.e., that report pixel means and standard deviations, calculate these values based on the *displayed* values of the pixels rather than the inherent values of the pixel data. This means the resulting mean and standard deviation can be changed by modifying the window/level setting of the image. This type of data should not be used for the QA/QC analysis described in this document.

Appendix E - Window and Level Setting for Visual Inspection of Flat Field Images

E.1 Background and Justification

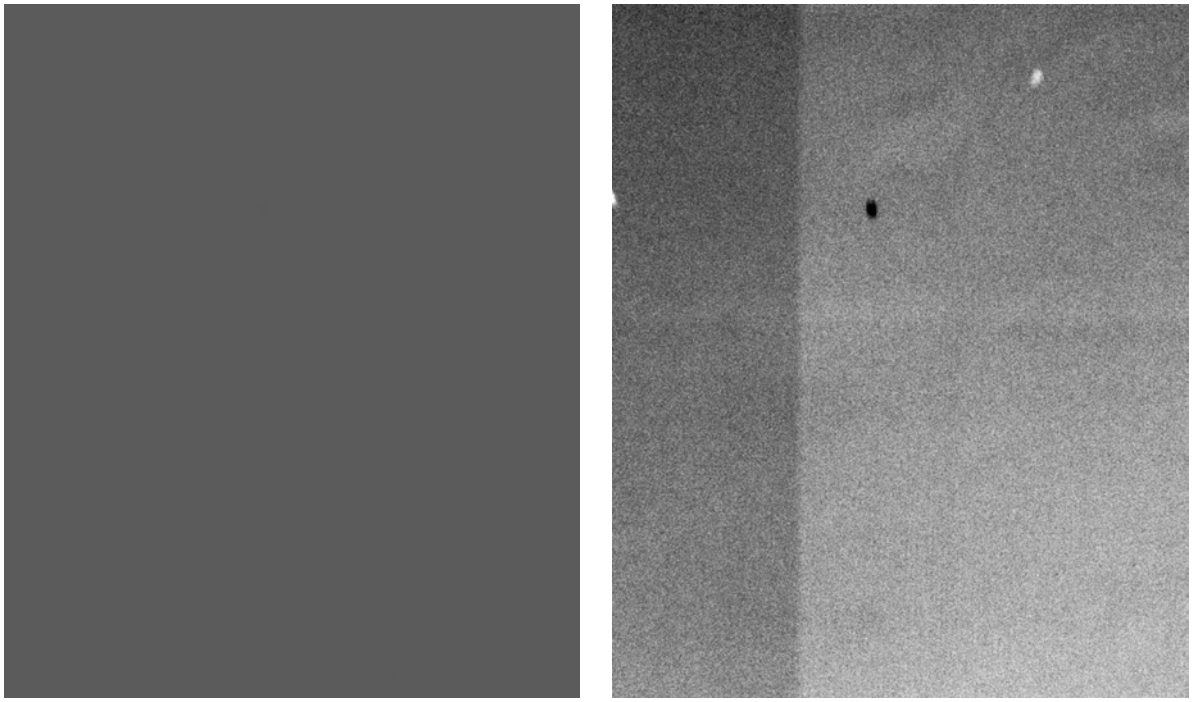
There are two goals for inspecting flat field images for artifacts. The first goal is to locate and identify artifacts; the second is to determine if the artifacts are clinically significant.

It is useful to review the Mammography Quality Standards Act (MQSA) guidance on artifact evaluation. Although written specifically for mammographic screen-film systems, the following provides pragmatic guidance for artifact evaluation in general:

- Not all artifacts can be totally eliminated. It may be helpful to use the concept of ALARA (as low as reasonably achievable) when attacking artifacts. If they can be easily eliminated, they should be. If the artifact is difficult or expensive to eliminate and is subtle (not mimicking or obscuring clinical information), it may be tolerable. The medical physicist should consult with the interpreting physician as to whether the artifact is tolerable. Tolerances for artifacts should be lower with new imaging equipment.

The images in Figure E1 illustrate the issues. The image on the left, showing the full range of pixel values, shows absolutely no features. The image on the right is of the same data, but with an extremely narrow LUT window. Artifacts are plainly visible; however, this window is so narrow that it will show image features invisible in an image with a clinical window.

The goal of this Appendix is to provide simple methods for determining window and level settings for a flat field image such that artifacts that are barely visible may be barely visible in a clinical image.



WW = 4096, WL = 2048 WW = 23, WL = 1456

Figure E1. Effect of window and level settings on artifact visualization

E.2 Procedure A

E.2.1 Detailed Procedure

This procedure is useful only if the system can produce an image with a known dose-pixel value relationship, such as linear or log-linear. If this is not the case, use Procedure B below.

1. Acquire a flat field image under the desired conditions.
2. Turn off all image processing parameters (edge enhancement, etc.).
3. Set the LUT level equal to the average pixel value.
4. If the image can be displayed as a log-linear image with the pixel value/dose relationship $PV = A + B \log_{10}(D)$, then set the LUT width equal to $B\ log_{10}(16) = B * 1.2$.
5. If the image can be displayed as a linear image with the pixel value/dose relationship $PV = C * D$, then set the LUT width equal to $PV_{avg} * 0.36$.
6. Evaluate the image for artifacts.

E.2.2 Theory of Procedure A

The goal of the above procedure is to display the image such that the contrast at the center of the display LUT is similar to the contrast in a high-contrast screen-film system. Tests at University of Wisconsin[13] have determined empirically that for a log-linear image, this implies a dynamic range of approximately 16:1.

Suppose that D_0 is the image receptor dose that corresponds to the average pixel value PV_0. If the pixel value/dose relationship of the image is $PV = A + B\ log_{10}(D)$, then the difference between the pixel value for $D = \frac{D_0}{4}$ and the pixel value for $D = 4\ D_0$ would be $B\ log_{10}(16)$; so the LUT window and level for a log-image should be:

$$W_{Log} = B \log_{10}(16) = 1.2B \tag{77}$$

To determine the desired window for an image with a linear dose curve, consider the relationship between the pixel value, the digital driving level (*DDL*), and the LUT window (*W*) and level (*L*) for an 8 bit display:

$$DDL = 128 + 256^{(PV - L)} \Big/ W \tag{78}$$

For a log-dose image, the differential relationship between the *DDL* and the image receptor dose *D* at dose D_0 using an LUT window W_{Log} is:

$$\frac{dDDL}{dD} = \frac{dDDL}{dPV} * \frac{dPV}{dD} = \frac{256}{W_{Log}} * \frac{B}{D_0 \ln(10)} = \frac{256}{B \log_{10}(16)} * \frac{B}{D_0 \ln(10)} \tag{79}$$

or finally:

$$\frac{dDDL}{dD} = 256 \frac{\ln(16)}{D_0} \tag{80}$$

For a linear-dose image with $PV{=}C\ D$ using an LUT window W_{Lin}, the differential relationship is:

$$\frac{dDDL}{dD} = \frac{dDDL}{dPV} * \frac{dPV}{dD} = \frac{256}{W_{Lin}} * C \tag{81}$$

[13] AAPM Task Group 150 meeting minutes, 26 Nov 2017

These two derivatives determine the displayed image contrast. To have the same displayed contrast for a linear-dose image as for a log-dose image:

$$256\frac{\ln(16)}{D_0} = \frac{256}{W_{Lin}} * C \tag{82}$$

so the window for a linear-dose image should be:

$$W_{Lin} = \frac{D_0 C}{\ln(16)} = 0.36\, P_{avg} \tag{83}$$

E.3 Procedure B

Use this procedure if it is impossible to determine the pixel value/dose relationship of the image.

E.3.1 Detailed Procedure

1. Acquire a flat field image under the desired conditions, using either of the following techniques:
   a. AEC technique using the highest image receptor dose (lowest "sensitivity" setting for example) used clinically.
   b. Manual technique with mAs set for approximately 2 mR at the image receptor.
2. Turn off all image processing features (edge enhancement, etc.).
3. Measure the pixel average and standard deviation in a flat, featureless section of the image.
4. Set the LUT level equal to the average pixel value.
5. Set the LUT window equal to 30 times the pixel standard deviation.
6. Evaluate the image for artifacts.

E.3.2 Justification of Procedure B

The image receptor noise at clinically useful image receptor doses should be approximately the same from one image receptor to another (to within a factor of 2). Experience at Mayo Clinic has shown that artifacts that are not visible when using a window of 30 times the noise are not visible in clinical images[14]. This is independent of the dose-response curve of the images, including any linear processing that has taken place between image acquisition and image storage.

[14] Private communication, Alisa Walz-Flannigan to David Gauntt, Dec 8, 2017.

Appendix F - Coltman Method for the Quantitative Assessment of MTF from a Bar Pattern Image

F.1 Rationale

While the spatial resolution of an imaging system can be evaluated by a qualitative assessment of the bar pattern image, it is highly recommended that a quantitative method is employed to make the assessment more robust and reproducible. One such method is described below (Coltman 1954 [64], Droege 1982 [45]).

F.2 Procedure

An image of a bar pattern phantom is obtained under specified beam quality and air kerma conditions. The air kerma is high enough that the relative image noise is much lower than the amplitude of the signal modulation in the highest frequency bar pattern to be measured. The bar should be aligned almost, but not exactly, parallel to the rows or columns of the image receptor.

Using a suitable software tool, extract the average signal and standard deviation of the appropriate ROIs (see Figure F1 and Figure F2 for one possibility where 2 lp/mm and 4 lp/mm frequency will be measured). It is important to ensure that the highest frequency analyzed is lower than the Nyquist frequency of the pixels on the image receptor. For this example, an image receptor with 50 μm sampling (and hence a 10 lp/mm Nyquist frequency) was used.

Some care should be exercised in the location of the ROI within the sections of the bar pattern image. The length should be at about half of the length of the bars, and the width should be approximately equal to the period of the bar pattern. An ROI that starts in the peak of one bar and ends in the trough of another may give a misleading result.

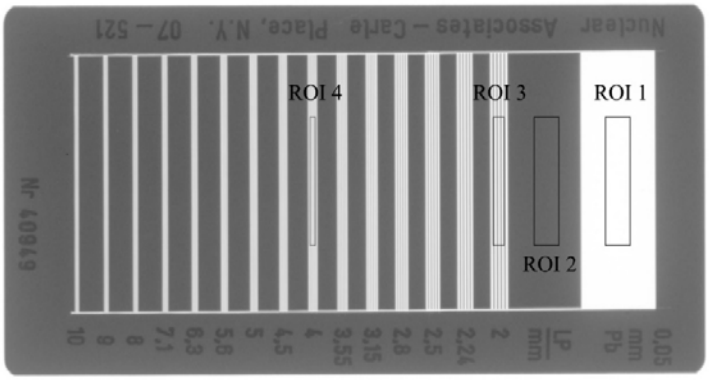


Figure F1. Image of line-pair test object

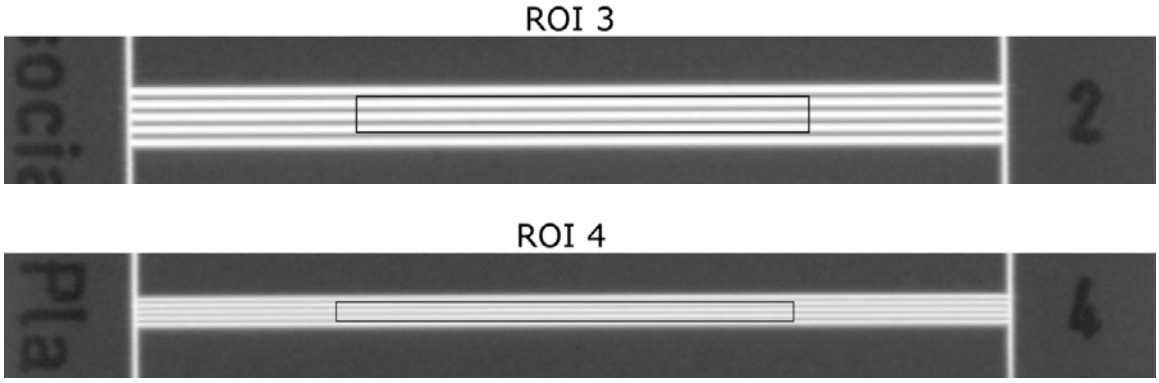


Figure F2. Closeup of ROI 3 and ROI 4

A measure of the MTF of the system at the chosen spatial frequencies can then be evaluated from the following equations:

$$MTF_{ROI3} = \frac{SD_{ROI3}}{|AVG_{ROI2} - AVG_{ROI1}|} \times 222$$
$$MTF_{ROI4} = \frac{SD_{ROI4}}{|AVG_{ROI2} - AVG_{ROI1}|} \times 222 \quad (84)$$

The 222 factor in the above equations is equal to $\frac{\pi\sqrt{2}}{2} \times 100\%$. (Droege 1982 [45]). This equation is valid only for spatial frequencies above $f_C/3$, where f_C is the cutoff frequency $\left(MTF(f) = 0 \text{ for all } f > f_C\right)$. At lower frequencies, the 3rd harmonic of the bar pattern contributes to the standard deviation measurement.

F.3 Potential Pitfalls

- MTF calculations are accurate only for spatial frequencies above $f_c/3$.
- The results will be inaccurate if the ROI extends outside a bar pattern.
- The results will be inaccurate if the measurements are not taken on a linearized image.

Appendix G - Suggestions for Vendors and Software Developers

The following are some suggestions for both for manufacturers of radiographic equipment and developers of QA software that have been suggested by task group members.

G.1 Manufacturers

Inverse conversion function

The inverse conversion function should be made readily available. IEC 62494-1 [16] explicitly requires the vendor to define the inverse conversion function for any system that provides exposure index values; this function relates pixel value in the ORIGINAL DATA to air kerma under the IEC-defined calibration conditions. While this is required to be defined, it is not always made readily available to the physicist. It would be helpful to routinely include this data in the technical reference manual, or a similar document provided to the end user. Making this information available on a website would be particularly helpful, as user documentation is not always easily found at a facility or available to offsite consulting medical physicists.

Image receptor performance specifications

Provide specified typical and maximum or minimum values for the image receptor quantities defined in Section 4.3 of this report.

Image receptor detector block size

For image receptors comprised of tiled detector blocks, make the matrix size of detector element blocks readily available to the user; this will aid setting the ROIs in QA software.

External landmarks to identify focal spot and image plane locations

Provide fiducial marks for the image plane and the focal spot that are easily accessible during routine testing. While tube housings invariably have the focal spot location marked, they are often covered in shrouds that hide the location mark. Similarly, a mark to indicate the location of the surface of the image receptor in the table bucky and the wall bucky, or a label specifying the distance from the bucky surface to the image receptor surface will help in verifying the SID value and in calculating radiographic magnification.

Acquisition workstation user interface

The user interface at the acquisition workstation should always have the following tools easily accessible to the medical physicist.

- Distance software tool (digital caliper) with display of ERMF.
- Display of pixel mean and standard deviation in an ROI.
- Ability to pan images and magnify (zoom) up to a factor of 10x.
- Ability to view image at a 1:1 scale (1 pixel on the monitor corresponds to 1 detector element).
- Ability to display the SMPTE or TG-18 test pattern on the workstation monitor.
- Ability to review DICOM metadata for physics test images.
- Ability to review the defective detector element map.
- Ability to review the offset calibration map.
- Ability to review gain calibration map.

G.2 Offline Image Analysis Software Features

Most image analysis software applications contain tools that would be useful in implementing recommendations of this report, such as:

- Tools for displaying the mean and standard deviation of pixel values in an ROI.
- Tools for displaying the distance between two points on an image.

- Ability to zoom and pan images.
- Ability to adjust window and level settings.

We would suggest that the following tools would also be useful.

- Provide tools for linearizing the pixel values of images with a known dose-response function.
- Implement calculation of the image receptor quantities defined in Section 4.3.2 (Flat Field Image Analysis) of this report.
- Allow the user to define a matrix of ROIs of a specified size for use in the calculations of Section 4.3.2 (Flat Field Image Analysis).
- Provide a tool for calculating the pre-sampled MTF of a detector based on both the tilted edge and tilted slit techniques.
- Display the ERMF of displayed DICOM images.