

Performance evaluation of computed radiography systems

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Recommended methods to test the performance of computed radiography (CR) digital radiographic systems have been recently developed by the AAPM Task Group No. 10. Included are tests for dark noise, uniformity, exposure response, laser beam function, spatial resolution, low-contrast resolution, spatial accuracy, erasure thoroughness, and throughput. The recommendations may be used for acceptance testing of new CR devices as well as routine performance evaluation checks of devices in clinical use. The purpose of this short communication is to provide a tabular summary of the tests recommended by the AAPM Task Group, delineate the technical aspects of the tests, suggest quantitative measures of the performance results, and recommend uniform quantitative criteria for the satisfactory performance of CR devices. The applicability of the acceptance criteria is verified by tests performed on CR systems in clinical use at five different institutions. This paper further clarifies the recommendations with respect to the beam filtration to be used for exposure calibration of the system, and the calibration of automatic exposure control systems. © 2001 American Association of Physicists in Medicine. [DOI: 10.1118/1.1350586]

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I. INTRODUCTION

Computed radiography (CR), scientifically known as photostimulable phosphor radiography, is a digital technology for the acquisition of radiographic images.^{1,2} CR is the most common digital radiography modality in radiology departments today, with an estimated 7000 systems in use worldwide. The technology uses a conventional radiographic acquisition geometry to deposit x-ray energy in a photostimulable phosphor screen with delayed luminescence properties. After irradiation, the screen is stimulated by a scanning laser beam, to release the deposited energy in the form of visible light. The released photostimulated light is captured by a light detector, converted to digital signals, and registered with the location on the screen from which it has been released. The digital data are then postprocessed for appropriate presentation, and are sent to a hard-copy printer or a soft-copy display monitor for medical evaluation.

Upon installation and prior to clinical use, CR devices should be evaluated for satisfactory performance.^{3,4} As of September 2000, there are five manufacturers of CR imaging

devices, Agfa Medical Systems (Ridgefield Park, NJ), Fuji Medical Systems (Stamford, CT), Eastman Kodak Health Imaging (Rochester, NY), Konica Imaging Systems (Wayne, NJ), and Lumisys, Inc (Sunnyvale, CA). There are currently no industry standards for specifying the performance of these

TABLE I. CR systems evaluated in this study.

Manufacturer	CR device	Phosphor screen
Agfa	ADC-70 ADC-Compact ADC-Solo	MD-10
Fuji	FCR-9501 FCR-9501-HQ AC3-CS FCR-5000	ST-VA and ST-VN ST-VN
Kodak	CR-400	GP-25 and HR
Lumisys	ACR-2000	MD-10

TABLE II. Testing devices required to perform the acceptance testing of a CR imaging device.

Testing device
Calibrated x-ray source
Calibrated hard/soft-copy display devices
Densitometer (if a hard-copy display is to be used)
Copper and aluminum filters
Calibrated ion chamber
Stand for the ion chamber
Screen cleaning solution and cloths
Two metric 30 cm steel rulers (for laser-beam function and spatial accuracy tests)
Three sector-type (0.4°) line-pair phantoms of up to 5 lp/mm frequency (≥ 0.05 mm lead thickness)
Low-contrast phantom (e.g., Leeds TO.12)
Screen-contact wire-mesh pattern
Screen-contact fine wire-mesh pattern (e.g., mammography screen-film contact tool)
Small lead block (>3 mm thick)
Antiscatter grid (10:1 or 12:1, 103 ln/in.) (if the x-ray system does not have one)
Anthropomorphic phantoms (foot, hand, pelvis, chest, etc.)
Timer
Measuring tape
Flashlight
Role of masking tape

devices. The lack of uniformity in measurement procedures among different manufacturers has introduced ambiguity in the meaning of the system specifications. For example, different manufacturers calibrate the response of the system to a given exposure value using different beam qualities and re-

port the response using indices which have different dependences on exposure. In a large medical institution in which CR devices of different kinds might be employed, it is important to assure that the patient images are acquired within a certain exposure range to prevent over- and underexposures. However, the lack of calibration uniformity makes the definition of the acceptable exposure ranges from the CR response values cumbersome.

In general, in order to achieve a consistent level of clinical performance, acceptance testing should utilize a uniform cross-platform methodology and uniform criteria so that the results of the tests can be correlated with clinical performance standards. Currently, Task Group No. 10 of the American Association of Physicists in Medicine (AAPM TG10)⁵ is making an effort to provide a comprehensive standardized testing protocol for acceptance testing and quality control of CR systems. In this work, we have used the preliminary guidelines established by the AAPM Task Group to evaluate the performance of CR systems currently in use at different institutions represented by the co-authors. The paper provides a summary of the tests recommended by the AAPM Task Group, delineates the specific technical aspects of the tests, suggests quantitative measures of the performance results, and recommends uniform quantitative criteria for satisfactory performance. The recommendations provided in this paper are a first step toward meeting a need perceived by practicing clinical medical physicists for quantitative guidelines to be used in conjunction with AAPM TG10 recommended testing procedures.

TABLE III. Testing protocol and acceptance criteria for the dark noise test.

	Agfa	Fuji	Kodak	Lumisys
Exposure condition		No exposures. Erase a single screen and read it without exposing it.		
Screen processing	System diagnostics/flat field, speed class=200	Test/sensitivity ($L=1$), fixed EDR ($S=10\ 000$)	Pattern	Standard
Image postprocessing	None musica parameters=0.0 Sensitometry=linear	“Linear” ($GA=1.0$, $GT=A$, $RE=0.0$)	“Raw data” and “no edge enhancement” settings, window=512, level=exposure index	None
Measurements to be made	IgM, average pixel value (PV) and its standard deviation (PVSD), and scan average level (SAL) within 80% of the image	Avg. pixel value (PV) and its standard deviation (PVSD) within 80% of the image area	Exposure index (EI), average pixel value (PV), and its standard deviation (PVSD) within 80% of the image area	Average pixel value (PV) and standard deviation (PVSD) within 80% of the image area
Qualitative criteria for acceptance	Uniform image without any artifacts		Uniform without any artifacts except for collector profile bands in the screen-movement direction	Uniform image without any artifacts
Quantitative criteria for acceptance	IgM<0.28 SAL<130 PV<350 PVSD<5	PV<280 ^a PVSD<4	EI _{GP} <80, EI _{HR} <380 PV _{GP} <80, PV _{HR} <80 PVSD<4	PV>3425 PVSD<4

^aFor those systems in which there is a direct relationship between PV and $\log(E)$. In the case of an inverse relationship, PV should be greater than 744.

TABLE IV. Testing protocol and acceptance criteria for uniformity (CR screen test).

	Agfa	Fuji	Kodak	Lumisys
Exposure condition	This test is applied to all the screens. Visually inspect the screens for physical defects. Verify that the cassette label matches the type of screen inside. Expose the screen to 10 mR (2.58×10^{-6} C/kg) ^a entrance exposure using 80 kVp, 0.5 mm Cu and 1 mm Al filtration, and 180 cm source-to-image distance (SID). If significant heel effect is present, test can be performed with two sequential half-exposures between which the orientation of the cassette is reversed.			
Screen processing	System diagnosis/flat field, speed class=200	Test/sensitivity ($L=1$), Semi EDR	Pattern	Standard
Image postprocessing	None, Musica parameters=0.0 Sensitometry=linear	“Linear” (GA=1.0, GT=A, RE=0.0)	“Raw data” and “no edge enhancement” settings, window=512, level=exposure index	None
Measurements to be made	Average pixel value (PV) and its standard deviation (PVSD) within 80% of the image area <i>Screen-to-screen variations:</i> Standard deviation of IgM (LMSDs), and mean and standard deviation of PV among screens (PVs and PVSDs)	Average pixel value (PV) and its standard deviation (PVSD) within 80% of the image area <i>Screen-to-screen variations:</i> Standard deviation/mean sensitivity (SD/Ss) and standard deviation of average PV among screens (PVSDs)	Average pixel value (PV) and its standard deviation (PVSD) within 80% of the image area <i>Screen-to-screen variations:</i> Standard deviation of exposure index among screens (EISDs)	Average pixel value (PV) and its standard deviation (PVSD) within 80% of the image area <i>Screen-to-screen variations:</i> Standard deviation of average PV among screens (PVSDs)
Qualitative criteria for acceptance	Uniform image without any artifacts			
Quantitative criteria for acceptance	PVSD<25 (single screen) LMSDs<0.02 PVSDs<25	PVSD<20 (single screen) SD/Ss<5% PVSDs<20	PVSD<20 (single screen) EISDs<20	PVSD<20 (single screen) PVSDs<20

^aThroughout these tables, for convenience, all exposures are expressed in units of mR ($1 \text{ mR} = 2.58 \times 10^{-7} \text{ C/kg}$).

II. METHODS AND RECOMMENDATIONS

As listed in Table I, CR devices in use at five different institutions from four major CR manufacturers were evaluated. The inventory of equipment used for testing is listed in Table II. Each system was evaluated for dark noise, screen uniformity, exposure indicator calibration, linearity and autoranging response, laser beam function, limiting resolution, noise and low-contrast resolution, spatial accuracy, erasure thoroughness, aliasing and grid response, and throughput.⁶ Special attention was paid to applying a uniform testing protocol for different CR systems, following the recommendations of the AAPM TG10 as closely as practicable. The data from different institutions were collected and processed in a single database. Prior to or shortly after the evaluations, each system’s performance was judged clinically acceptable by attending radiologists based on image quality of clinical images acquired with the system. Tables III–XIII tabulate the testing protocol and the acceptance criteria derived from the results. For a full description of the tests and the rationale for performing each test, the reader is advised to consult the AAPM TG10 report.

The quantitative acceptance criteria were established based on the results of the tests performed on the clinical systems and a uniform level of tolerance in system response across different systems. Table XIV tabulates the response tolerance levels based upon which the acceptance criteria were established. These levels were translated to system-

specific parameters, as reported in Tables III–XIII, using the response relationships of the systems tabulated in Table XV. None of the clinically acceptable systems tested in this collaborative effort generated results beyond the established criteria. In most instances, the acceptance criteria were at least 20% beyond the extremes of the evaluation results, a reasonable margin considering that the evaluated systems were not operating at the borderline of clinical acceptability.

Several experimental precautions were observed in the evaluation of the systems. All the phosphor screens were cleaned and erased prior to executing the testing procedures. Consistent delay times between 1 to 15 min were observed between exposing and reading the screens. Care was taken to reduce backscattered radiation by utilizing cross-table exposures and significant interspace behind the screens. A large source-to-image distance (SID~180 cm) was used to minimize the heel effect. The “raw” signal values which were proportional to the log of the incident exposure without any postprocessing were used in the evaluations.

All exposures were measured in a consistent fashion: The collimators were set to expose the whole cassette with additional 7 cm margins on each side in the direction perpendicular to the anode–cathode axis. The ion chamber was then placed at the center of the beam at 2/3 of the SID. The exposure was measured in five consecutive exposures and the values averaged, E_1 . Keeping the ion chamber at 2/3 SID, the chamber was shifted on the central axis perpendicu-

TABLE V. Testing protocol and acceptance criteria for exposure indicator calibration.

	Agfa	Fuji	Kodak	Lumisys ^b
Recommended exposure condition ^a	Use multiple screens (at least three) of a given size/type. Expose the screens to approximately 1 mR (2.58×10^{-7} C/kg) enhance exposure using 80 kVp and 0.5 mm Cu/1 mm Al filtration. Screens should be read with a precise 10 min delay.			
Exposure condition (manufacturer specified ^a)	Expose a screen to approximately 1 mR (2.58×10^{-7} C/kg) entrance exposure using 75 kVp and 1.5 mm Cu filtration. Screen should be read promptly.	Expose a screen to approximately 1 mR (2.58×10^{-7} C/kg) entrance exposure using 80 kVp without filtration. Screen should be read with a precise 10 min delay.	Expose a screen to approximately 1 mR (2.58×10^{-7} C/kg) entrance exposure using 80 kVp and 0.5 mm Cu/1 mm Al filtration. Screen should be read with a precise 15 min delay.	Expose a screen to approximately 8 mR (2.064×10^{-6} C/kg) entrance exposure using 80 kVp with 1 mm Cu filtration. Screen should be read promptly.
Screen processing	System diagnosis/flat field, speed class=200	Test/sensitivity ($L=1$), semi-EDR	Pattern	Standard
Image postprocessing	None, musica parameters=0.0		Irrelevant	None
Measurements to be made	IgM and IgM normalized to exactly 1 mR exposure to the screen ($IgM_{1\text{ mR}}$) using $IgM_{1\text{ mR}} = IgM - \log(\text{exposure})$, SAL and SAL normalized to exactly 1 mR exposure to the screen ($SAL_{1\text{ mR}}$) using $SAL_{1\text{ mR}} = SAL / (\text{exposure})^{0.5}$	Sensitivity and sensitivity normalized to exactly 1 mR exposure to the screen ($S_{1\text{ mR}}$) using $S_{1\text{ mR}} = S$ exposure	Exposure index (EI) and exposure index normalized to exactly 1 mR exposure to the screen ($EI_{1\text{ mR}}$) using $EI_{1\text{ mR}} = EI - 1000 \times \log(\text{exposure})$	Mean pixel value (PV) within 80% of the image area normalized to exactly 1 mR ($PV_{1\text{ mR}}$) or 8 mR ($PV_{8\text{ mR}}$) exposure to the screen using $PV_{1\text{ mR}} = PV + 1000 \log(\text{exposure})$ $PV_{8\text{ mR}} = PV + 1000 \log(\text{exposure}/8)$
Qualitative criteria for acceptance			None	
Quantitative criteria for acceptance	$IgM_{1\text{ mR}} - 2.2 < \pm 0.045$ single screen $IgM_{1\text{ mR}} - 2.2 < \pm 0.023$ for all screens averaged $SAL_{1\text{ mR}} - 1192 < \pm 60$ single screen $SAL_{1\text{ mR}} - 1192 < \pm 30$ for all screens averaged	$S_{1\text{ mR}} - 200 < \pm 20$ single screen $S_{1\text{ mR}} - 200 < \pm 10$ for all screens averaged	$EI_{1\text{ mR}} - 2000 < \pm 45$ single screen $EI_{1\text{ mR}} - 2000 < \pm 23$ for all screens averaged	$PV_{8\text{ mR}} - 600 < \pm 45$ single screen $PV_{1\text{ mR}} - 1505 < \pm 45$ single screen $PV_{1\text{ mR}} - 1505 < \pm 23$ for all screens averaged

^aThere is currently a strong consensus that CR systems should be calibrated with a standard filtered beam. Until such time as manufacturers change their recommendations, the calibration procedure can be performed both with the manufacturer-defined technique, to verify conformance with the manufacturer's specifications, and with 0.5 mm Cu/1 mm Al filtration and 10 min delay time, for benchmarking and constancy checks.

^bThe Lumisys ACR-2000 software did not make use of an exposure index at the time of testing. The system is calibrated to produce a pixel value of 600 in response to an 8 mR (2.064×10^{-6} C/kg) exposure to the screen.

lar to the anode-cathode axis toward the edge of the field just outside the useful beam area (the shadow of the ion chamber was still fully within the beam without projecting over the cassette area). The exposure was measured in five consecutive exposures again and the values were averaged, E_2 . The chamber was kept at the second location during the tests for verification of the exposure values. The average exposure to the cassette in each single exposure was calculated as $(E_1/E_2)(2/3)^2$ (measured exposure).

III. DISCUSSION

To achieve a consistent level of clinical performance from CR systems, acceptance testing procedures should be performed according to a uniform cross-platform methodology. As in any medical physics survey, the performance evaluation of a CR system is also more definitive and objective

when the evaluation is quantitative and the results are compared against specific quantitative acceptance criteria. In this work, an attempt was made to outline a cross-platform uniform methodology based on the guidelines being developed by the American Association of Physicists in Medicine Task Group 10. Furthermore, a first attempt was made to recommend quantitative acceptance criteria for satisfactory performance of a CR system based on the current state of practice. The criteria were established using uniform tolerance levels and test results acquired from CR systems in clinical use at five different institutions. The *user* specificity (as opposed to the conventional *manufacturer* specificity) of the acceptance criteria suggested in this paper was necessitated by the desired uniformity of the testing procedures. The criteria, however, do not guarantee optimal clinical performance, which may not be ascertained without comprehensive clinical trials.

TABLE VI. Testing protocol and acceptance criteria for linearity and autoranging response.^a

	Agfa	Fuji	Kodak	Lumisys
Exposure condition	Use a single screen (multiple screens may also be used if the screen-to-screen variations in the previous test were found minimal). Expose the screen to approximately 0.1, 1, and 10 mR (2.58×10^{-8} , 2.58×10^{-7} , 2.58×10^{-6} C/kg) entrance exposures in a sequence of three exposure-reading cycles using 80 kVp, 0.5 mm Cu and 1 mm Al filtration, and 180 cm SID. Each time read the screen with a consistent delay time.			
Screen processing	System diagnosis/flat field, speed class=200	Test/ave 4.0 Semi-EDR and fixed EDR=200 repeat also with Test/contrast semi-EDR and fixed EDR=200	Pattern	Standard
Image postprocessing	None, musica parameters=0.0	“Linear” (GA=1.0, GT=A, RE=0.0)	“Raw data” and “no edge enhancement” settings	None
Measurements to be made	IgM, average pixel value (PV), and scan average level (SAL) within 80% of the image area. Slopes and correlation coefficients (CCs) of linear fits to log(SAL) vs log(E), PV vs log(E), and IgM vs log(E)	<i>For Semi EDR</i> , correlation coefficient (CC) of a linear fit to log(S) vs log(E) plot. <i>For fixed EDR</i> , avg. pixel value (PV) within 80% of the image area, slope and correlation coefficient (CC) of a linear fit to PV vs log(E)	Exposure index (EI) and avg. pixel value (PV) within 80% of the image area. Slope and correlation coefficient (CC) of a linear fit to EI vs log(E) and PV vs log(E) plots	Mean pixel value (PV) within 80% of the image area. Slope, intercept, and correlation coefficient (CC) of a linear fit to P vs log(E)
Qualitative criteria for acceptance	SAL vs exposure on a linear-log plot should result in a straight line	<i>For semi-EDR</i> , slope and correlation, sensitivity vs exposure on a log-log plot should result in a straight line. <i>For fixed EDR</i> , to PV vs exposure on a linear-log plot should result in a straight line	The plot of EI and PV vs exposure on a linear-log scale should result in straight lines	The plot of PV vs exposure on a linear-log scale should result in a straight line
Quantitative criteria for acceptance	$\text{Slope}_{\text{IgM}} - 1 < \pm 0.1$ $\text{Slope}_{\text{SAL}/0.5} - 0.1 < \pm 0.1$ $\text{Slope}_{\text{PV}/1250} - 0.1 < \pm 0.1$ CCs > 0.95	$\text{Slope}_s + 1 < \pm 0.1$ $\text{Slope}_{\text{PV}/256} - 1 < \pm 0.1$ (Ave 4) ^b $\text{Slope}_{\text{PV}/511} - 1 < \pm 0.1$ (Con.) ^b CCs > 0.95	$\text{Slope}_{\text{EI}}/1000 - 1 < \pm 0.1$ $\text{Slope}_{\text{PV}}/1000 - 0.1 < \pm 0.1$ CCs > 0.95	$\text{Slopes}/1000 + 1 < \pm 0.1$ CCs > -0.95

^aIf this test is performed with hard copy prints, the relationship between the pixel value (PV) and optical density (OD) should be established beforehand using an electronic test pattern. The relationship between OD and PV should then be incorporated as a transformation in the quantitative analysis of the results.

^bNote that in some Fuji systems, there is an inverse relationship between PV and log(E). For those systems, the polarity of the slope in these equations should be reversed.

TABLE VII. Testing protocol and acceptance criteria for the laser beam function.

	Agfa	Fuji	Kodak	Lumisys
Exposure condition	Place a steel ruler roughly perpendicular to the laser-scan direction on a screen. Expose the screen to about 5 mR (1.29×10^{-6} C/kg) entrance exposure using a 60 kVp beam without any filtration (SID=180 cm). Examine the edges of the ruler on the image for laser beam jitters using 10–20× magnification.			
Screen processing	System diagnosis/flat field, speed class=200	Test/sensitivity Semi-EDR	Pattern	Standard
Image postprocessing	None, musica parameters=0.0 sensitometry=linear	“Linear” (GA=1.0, GT=A, RE=0.0)	“Raw data” and “no edge enhancement” settings, window=512, level=exposure index	None
Measurements to be made	If any jitter is present, jitter dimension using workstation’s “measurement” or ROI tool.			
Qualitative criteria for acceptance	Ruler edges should be straight and continuous without any under- or overshoot of the scan lines in light to dark transitions.			
Quantitative criteria for acceptance	There should not be more than occasional ± 1 jitters.			

TABLE VIII. Testing protocol and acceptance criteria for the limiting resolution and resolution uniformity.^a

	Agfa	Fuji	Kodak	Lumisys
Exposure condition	This test should be done for each type and size of the screens. Use a 60 kVp, unfiltered x-ray beam (SID=180 cm). Place three line-pair pattern devices on the cassette, two in orthogonal directions and one at 45°. Expose the screen with an exposure of about 5 mR (1.20×10^{-6} C/kg). Also acquire an image of a fine wire mesh (e.g., mammography screen–film contact test tool) in contact with the cassette to examine the consistency of the resolution response across the image.			
Screen processing	System diagnosis/flat field, speed class=200	Test/sensitivity semi-EDR	Pattern	Standard
Image postprocessing	None, musica parameters=0.0 sensitometry=linear	“Linear” (GA=1.0, GT=A, RE=0.0)	“Raw data” and “no edge enhancement” settings, window=512, level=exposure index	None
Measurements to be made	Maximum discernible spatial frequencies in the three directions (R_{hor} , R_{ver} , R_{45}) using a magnified ($>10\times$), narrowly windowed presentation of the images			
Qualitative criteria for acceptance	The image of the wire mesh should be uniform without any blurring across the image			
Quantitative criteria for acceptance	$R_{hor}/f_{Nyquist} > 0.9$ $R_{ver}/f_{Nyquist} > 0.9$ $R_{45}/1.41 f_{Nyquist} > 0.9$			

^aNote that the spatial resolution response of a CR system can be more comprehensively evaluated by measuring the modulation transfer function (MTF) of the system (Refs. 7–9, 11–14).

TABLE IX. Testing protocol and acceptance criteria for noise and low-contrast resolution.^a

	Agfa	Fuji	Kodak	Lumisys
Exposure condition	This test should be done for each type and size of the screens. A low-contrast resolution pattern is used (e.g., Leeds TO.12, 75 kVp beam with 1 mm of Cu filtration). For each screen type/size, acquire three images of the low-contrast phantom using 0.1, 1, and 10 mR (2.58×10^{-8} , 2.58×10^{-7} , 2.58×10^{-6} C/kg) exposures to the screens. Use a constant delay time of 10 min in reading each of the screens.			
Screen processing	System diagnosis/flat field, speed class=200	Test/contrast Semi-EDR	Pattern	Standard
Image postprocessing	None, musica parameters=0.0 Sensitometry=linear	“Linear” (GA=1.0, GT=A, RE=0.0)	“Raw data” and “no edge enhancement” settings, window=512, level=4096–EI (for GP screens) or level=3796–EI (for HR screens)	None
Measurements to be made	Minimum discernible contrast for each object size (contrast detail threshold), Standard deviation of pixel value (PVSD) within a fixed (size and location) small region of the images, correlation coefficient (CC) of the linear fit to $\log(\text{PVSD})$ vs $\log(E)$. ^b			
Qualitative criteria for acceptance	Contrast-detail threshold should be proportionately lower at higher exposures.		Contrast-detail threshold should be proportionately lower at higher exposures, with higher contrast thresholds for standard-resolution screens.	Contrast-detail threshold should be proportionately lower at higher exposures.
Quantitative criteria for acceptance	CC > 0.95 ^b			

^aNote that the noise response of a CR system can be more comprehensively evaluated by measuring the noise power spectrum (NPS) and the detective quantum efficiency (DQE) of the system at different exposure levels (Refs. 8 and 9, 11–14).

^bThe quantitative evaluation is more valid with uniform images acquired for the linearity test (Table VI) because of the absence of scattering material in the beam. The expected quantitative response is based on the assumption of a logarithmic relationship between pixel value and exposure (Table XV).

TABLE X. Testing protocol and acceptance criteria for spatial accuracy.

	Agfa	Fuji	Kodak	Lumisys
Exposure condition	Place a regular wire-mesh screen–film contact test tool over cassette. Expose the cassette to about 5 mR (1.29×10^{-6} C/kg) entrance exposure using a 60 kVp beam without any filtration (SID=180 cm). Repeat the acquisition with two steel rulers in the vertical and the horizontal directions.			
Screen processing	System diagnosis/flat field, speed class=200	Test/contrast Semi-EDR	Pattern	Standard
Image postprocessing	None musica parameters=0.0	“Linear” (GA=1.0, GT=A, RE=0.0)	“Raw data” and “no edge enhancement” settings, window=512, level=EI	None
Measurements to be made	Distances in the orthogonal directions (15 cm minimum length) measured using the measurement tool of the workstation. ^a			
Qualitative criteria for acceptance	Grid pattern spacing should be uniform without any distortion across the image.			
Quantitative criteria acceptance	Measured distance should be within 2% of the actual values.			

^aAlternatively, length measurements can be made on a hard-copy film printed in “true-size.”

TABLE XI. Testing protocol and acceptance criteria for erasure thoroughness.

	Agfa	Fuji	Kodak	Lumisys
Exposure condition	Place a thick lead block at the center of a 14×17 cassette and expose the screen to about 50 mR (1.29×10^{-5} C/kg) using a 60 kVp x-ray beam without any filtration (SID=180 cm). Read the screen, and expose it a second time to 1 mR (2.58×10^{-7} C/kg) entrance exposure without the lead object using the same beam quality collimated in by about 5 cm on each side of the screen. For a quantitative test <i>re-read</i> the screen after the second exposure <i>without exposing it</i> .			
Screen processing	System diagnosis/flat field, speed class=200	Test/sensitivity semi-EDR	Pattern	Standard
Image postprocessing	None, musica parameters=0.0 Sensitometry=linear Window setting default or equivalent to 1 log(exposure) unit	“Linear” (GA=1.0, GT=A, RE=0.0) Window setting default or equivalent to 1 log(exposure) unit	“Raw data” and “No edge enhancement” settings, level=EI, window setting default or equivalent to 1 log(exposure) unit	Window setting default or equivalent to 1 log(exposure) unit
Measurements to be made	IgM, average pixel value (PV) and its standard deviation (PVSD), and scan average level (SAL) within 80% of the reread/unexposed image	Avg. pixel value (PV) and its standard deviation (PVSD) within 80% of the reread/unexposed image	Exposure index (EI), average pixel Value (PV), and its standard deviation (PVSD) within 80% of the reread/unexposed image	Average pixel value (PV) and standard deviation (PVSD) within 80% of the reread/unexposed image
Qualitative criteria for acceptance	Absence of a ghost image of the lead block from the first exposure in the reexposed image. ^{a,b}			
Quantitative criteria for acceptance	IgM=0.28 SAL<130 PV<630 PVSD<5	PV<280 ^c PVSD<4	EI _{GP} <80, EI _{HR} <380 PV _{GP} <80, PV _{HR} <80 PVSD<4	PV>3425 PVSD<4

^aIn our tests on the ACR-2000 system, the length of the standard erasure cycle was sufficient for exposures up to 32 mR (8.256×10^{-6} C/kg). Higher exposures to the screen required an additional erasure cycle for complete screen erasure.

^bNote that erasure time in some systems (e.g., Agfa) is configurable on an exam-by-exam basis.

^cFor those systems in which there is an direct relationship between PV and log(*E*). In the case of inverse relationship, PV should be greater than 744.

TABLE XII. Testing protocol and acceptance criteria for the aliasing/grid response.

	Agfa	Fuji	Kodak	Lumisys
Exposure condition	This test should be performed for each type and size of screens that will be commonly used. Place the screen in a bucky that contains an antiscatter grid so that the grid lines are parallel to the laser-scan direction. Alternatively, a grid may be placed directly on the screen. Make sure the grid movement is disabled. Expose the screen to 1 mR (2.58×10^{-7} C/kg) using an 80 kVp beam filtered with 0.5 mm Cu/1 mm Al filter and a SID according to the specification of the grid. Repeat, placing the screen perpendicular to the laser-scan direction. Repeat the exposures with a moving grid.			
Screen processing	System diagnosis/flat field, Speed class=200	Test/contrast semi-EDR	Pattern	Standard
Image postprocessing	None, musica parameters=0.0 sensitometry=linear A narrow window setting	“Linear” (GA=1.0, GT=A, RE=0.0) A narrow window setting	“Raw data” and “no edge enhancement” settings, level=EI, a narrow window setting	None
Measurements to be made	None			
Qualitative criteria for acceptance	Moiré pattern should not be present when the grid lines are perpendicular to the laser-scan direction. For moving grids, no moiré pattern should be apparent when the screen is placed in either direction. ^a			
Quantitative criteria for acceptance	None			

^aMoiré patterns caused by display sampling (not addressed in this protocol) can be distinguished by their changing behavior with changing the magnification of the image on the soft-copy display device.

In light of this limitation, the recommended quantitative criteria should only be considered as helpful suggestions that require further clinical validation in the future.

Another limitation of the current work is the fact that many of the evaluation procedures were not fully quantitative or can be influenced by the subjectivity of the examiner. The evaluations of limiting resolution and noise performance (Tables VIII and IX) are two important examples. The resolution tests used do not evaluate the system transfer characteristics but only establish that some modulation can be detected at the limiting frequency. The noise tests subjectively evaluate the contrast-detail characteristics of the system, and

the proposed quantitative test does not evaluate the spatial characteristics of image noise. Ideally, the resolution and noise characteristics of a CR system should be more objectively evaluated by measuring the frequency-dependent modulation transfer function, the noise power spectrum, and the detective quantum efficiency of these systems. A number of investigators have been able to successfully and reproducibly characterize the resolution and noise performance of CR systems using these indices,¹¹⁻¹³ and more recently reproducible measurements have been made in the field.^{7,14} However, a routine implementation of these measurements awaits further standardization of measurement methods, and the de-

TABLE XIII. Testing protocol and acceptance criteria for the throughput.

	Agfa	Fuji	Kodak	Lumisys
Exposure condition	Expose 4 screens to 80 kVp, 2 mR (5.18×10^{-7} C/kg). Process the screens sequentially without delay. ^a			
Screen processing	System diagnosis/flat field, speed class=200	Test/contrast semi-EDR	Pattern	Standard
Image postprocessing	musica parameters typical of those in clinical usage		Irrelevant	None
Measurements to be made	Time interval (t , in minutes) between putting the first screen in and the last image appearing on the CR viewing station ^b Throughput (screens/h)= $60 \times 4/t$			
Qualitative criteria for acceptance	None			
Quantitative criteria for acceptance	Throughput should be within 10% of the system's specifications.			

^aThe test can be performed multiple times with different size cassettes.

^bContribution of the network configuration is not considered.

TABLE XIV. The CR response tolerance levels based upon which the uniform quantitative acceptance criteria were derived (using the equations tabulated in Table XV). All signal levels and standard deviations are expressed in terms of corresponding exposure (E) values deduced from those quantities.

Characteristics	Quantity of interest	Acceptable tolerance
Dark noise	Average signal and its standard deviation within 80% of the image area	$E < 0.012$ mR ($E < 3.1 \times 10^{-9}$ C/kg) $\sigma_E/E < 1\%$
Uniformity	Signal standard deviation within 80% of the image area, and the standard deviation of the average screen signal among screens	$\sigma_E < 5\%$
Exposure calibration	The exposure indicator response (expressed in terms of exposure) to 1 mR (2.58×10^{-7} C/kg) entrance exposure	$E_{\text{measured}} - 1 < \pm 10\%$
Linearity and autoranging	The slope of the system response (expressed in terms of logarithm of exposure) vs logarithm of actual exposure	Slope $-1 < \pm 10\%$ Correlation coefficient > 0.95
Laser beam function	Jitter dimension in pixels	Occasional jitters $< \pm 1$ pixel
Limiting resolution	Maximum discernible spatial frequencies of a high-contrast line-pair pattern in two orthogonal and 45° angle directions	$R_{\text{hor}}/f_{\text{Nyquist}} > 0.9$ $R_{\text{ver}}/f_{\text{Nyquist}} > 0.9$ $R_{45}/1.41f_{\text{Nyquist}} > 0.9$
Noise and low-contrast resolution	A linear fit of system noise (expressed in terms of logarithm of corresponding σ_E/E) to logarithm of actual exposure	Correlation coefficient > 0.95
Spatial accuracy	The difference between the measured (d_m) and actual distances (d_0) in the orthogonal directions	$(d_m - d_0)/d_0 < 2\%$
Erasure thoroughness	Average signal and its standard deviation within 80% of the reread/unexposed image	$E < 0.012$ mR ($E < 3.1 \times 10^{-9}$ C/kg) $\sigma_E/E < 1\%$
Aliasing/grid response	No quantitative tolerance levels	
Throughput	Measured throughput in screens per hours (T_m) and the specified throughput (T_0)	$(T_0 - T_m)/T_0 < 10\%$

velopment of automated commercial QC products.

In this study, the exposures for quantitative measurements were made with 0.5 mm copper and 1 mm additive aluminum filtration in the beam. The use of filtration was based on prior studies^{10,15,16} indicating that the use of 0.5 mm Cu filter minimizes the dependency of the results on the kVp inaccuracy and on the variations in the x-ray generator type, as the filter attenuates the ‘‘soft’’ portion of the spectrum, predominantly responsible for tube-to-tube variations (Fig. 1). The use of this filtration also makes the spectrum a more accurate representative of primary x rays incident on the detector in clinical situations (Fig. 2). The additional post-Cu, 1-mm-thick Al filter is used to attenuate any potential secondary low-energy x rays generated in the Cu filter. The use of 0.5 mm Cu/1 mm Al filtration, therefore, is advised for checking the consistency of the response in the acceptance testing and annual compliance inspections of CR systems.

This paper outlines the steps for only the *physical* evaluation of CR systems. In a newly installed system, after completion of the physical acceptance testing and prior to a full clinical utilization, the system should also be evaluated for its *clinical* performance. The appearance of CR images

may vary as a function of radiographic technique factors, the specific recipe of image processing parameters applied to the images, and the type and calibration of the display media. The default image processing parameters of the system for various anatomical sites and views (e.g., chest PA, chest lateral, chest portable, knee, etc.) should be tested and customized by the application specialists of the manufacturer with assistance of the diagnostic medical physicist and under the direction of the radiologist who is ultimately responsible for the clinical acceptability of the images. Using radiographic techniques provided by the manufacturer, images of various anthropomorphic phantoms should be acquired with various combinations of collimation and positioning, utilizing the appropriate prescribed anatomical menus of the system. In each case, the proper processing of the image and the absence of unexpected positioning and collimation errors should be verified. Attending radiologists should be consulted for acceptability of the image processing parameters for each anatomical menu. Since standard anthropomorphic phantoms have a limited ability to represent human anatomy and patient-to-patient variations, the clinical evaluation and cus-

TABLE XV. The relationship between exposure and pixel value/exposure indicator responses of various CR systems. The relationships which were provided by the manufacturers or derived from their literature, were verified against experimental measurements at 80 kVp with 0.5 mm Cu/1 mm Al filtration. In these relationships, PV is the pixel value, E is the exposure in mR, B is the speed class, and L is the latitude of the system.

	Agfa	Fuji	Kodak	Lumisys
Exposure indicator quantities	IgM and scan average level (SAL)	Sensitivity (S)	Exposure index (EI)	None
Exposure indicator relationship	$SAL = 90\sqrt{0.877cBE}$ $IgM = 2\log(SAL) - 3.9478$ $= \log(cBE) - 0.0963$ $c = 1.0$ for MD10 screens	$S = 200/E$	$EI = 1000 \log(E) + 2000$	None
Pixel value relationships	$PV = 2499 \log(SAL) - 4933$ $= 1250 \log(cBE) - 121^a$ $c = 1.0$ for MD10 screens	$PV = (1024/L) \times (\log E + \log(S/200)) + 511^b$	$PV = 1000 \log(E) + c_0$ $c_0 = 2000$ for GP screens $c_0 = 1700$ for HR screens	$PV = 1000 \log(32/E)$
Exposure/reading condition	75 kVp and 1.5 mm Cu filtration, no reading delay	80 kVp without filtration, 10 min reading delay	80 kVp and 0.5 mm Cu/1 mm Al filtration, 15 min reading delay	80 kVp with 1 mm Cu filtration, no reading delay

^aUsing a 12 bit, linear $\log(E)$ data transfer from Agfa QC workstation.

^bAssuming a direct relationship between exposure and pixel value.

tomization of the image processing parameters should include actual clinical images.

Care should be taken that in the validation of the system settings, all examinations performed at the facility are represented. The final customized image processing parameters and system settings for different anatomical menus should be loaded into all units from the same manufacturer in place at the institution or associated medical facilities, where the same exam may be performed on different machines, to assure consistency of image presentations. They should also be documented in a list for future reference.

Patient dose is one of the important implementation considerations in the use of CR in a traditional film-based radiology department.¹⁷ In screen-film radiography, film density is a direct indicator of patient dose. In CR, however, because of the dissociation of the detection and the display functions of the imaging system, optical density can no longer be used as an indicator of the patient dose. In reading a CR screen, almost all CR systems provide an index that reflects the average exposure received by the screen during the image acquisition (Table XV). This exposure indicator can be used to define and monitor patient exposures. Based on the manufacturer's recommendations regarding the intrinsic speed of the system and on the applicable standards of practice, the user should establish, monitor, and enforce the acceptable range of exposure indicator values for the clinical operation in the facility. Note, however, that if a filtration other than that suggested by the manufacturer is used for the exposure calibration of the CR system, as suggested previously, the accepted range of exposure indicator values should be derived based on the comparative results of the two filtration conditions.

Automatic exposure control (AEC) is the primary means for controlling patient exposure in general radiography practice. For screen-film systems, the AEC is calibrated for consistency in optical density resultant from varying exposure techniques. Because of the dissimilarity between x-ray ab-

sorption characteristics and radiographic speed of CR and conventional screen-film radiography systems, an AEC calibrated for screen-film radiography is unlikely to be suitable for CR usage.¹⁸ For CR usage, the AEC can be calibrated using an approach similar to that for screen-film imaging using the exposure indicator value of the system as the target variable to be controlled. The AEC should be adjusted to result an exposure indicator value within a narrow acceptable range (10%–15%) when the kVp or phantom thickness is varied within clinical operational limits. It may also be set to provide a constant change in the exposure indicator value

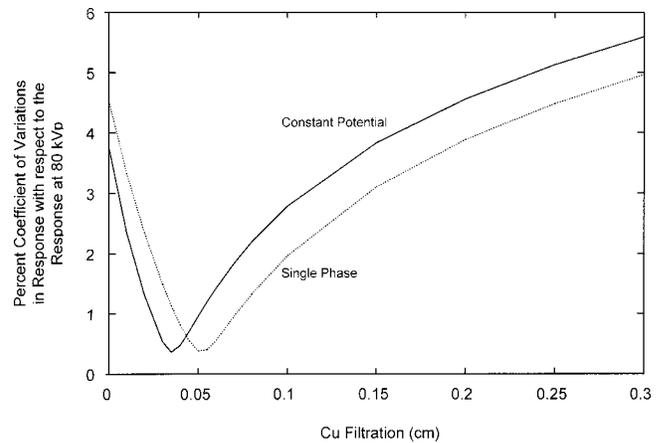


FIG. 1. The relative variation in the response of a CR system (signal per unit exposure), where the energy of the beam is varied within 80 kVp±10% range, as a function of Cu filtration in the beam for both single phase and high-frequency/constant-potential generator x-ray systems (12° anode angle, 2.6 mm intrinsic Al filtration). The data were generated by a computational model for simulation of the x-ray spectra, filter attenuation, and absorption characteristics of BaFBr_{0.85}I_{0.15}:Eu phosphor screens (98 mg/cm² phosphor coating weight). The model accuracy has been previously verified against experimental measurements (Refs. 8, 10, 14). Note that Agfa CR systems use a slightly different phosphor material (Ba_{0.86}Sr_{0.14}F_{1.1}Br_{0.84}I_{0.06}) than the one modeled here.

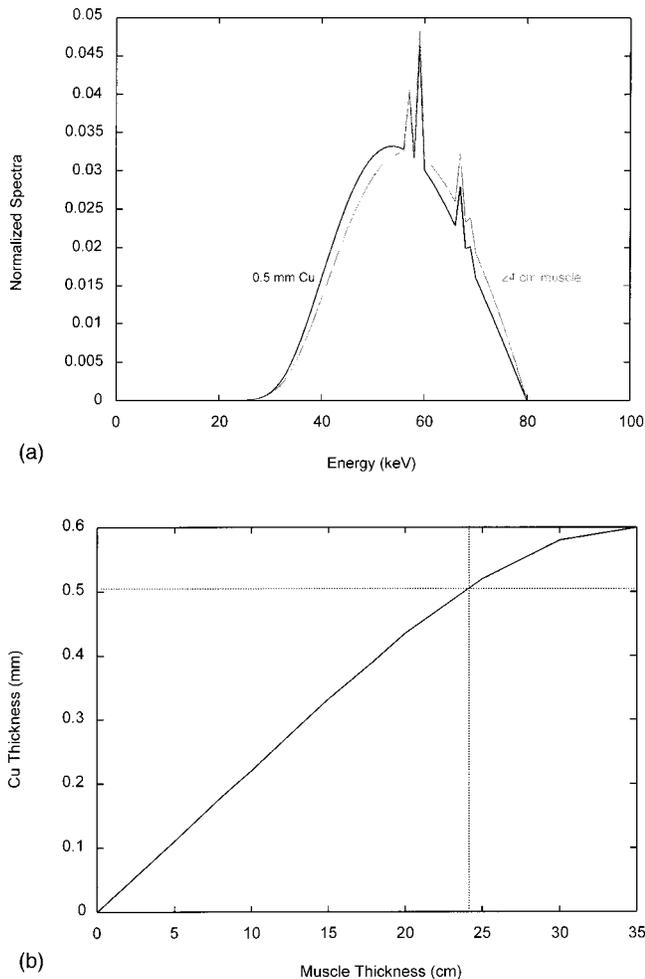


FIG. 2. (a) The model-calculated primary x-ray spectra emerging from a 0.5 mm Cu filter and 24 cm tissue-equivalent material. The spectra were normalized to have the same total area. b) The model-calculated equivalency of the CR signal per unit exposure for various Cu and tissue-equivalent material (see Fig. 1 caption).

when plus or minus density steps are applied. Because the CR exposure indicator is a quantity derived from analysis of the image histogram, care must be exercised in the selection of phantoms and processing menus. The phantoms should produce image histograms representative of clinical images, not a very trivial requirement. Otherwise, inaccurate exposure indicator values may result, leading to faulty AEC calibration. Further work on AEC calibration methodology for CR is warranted.

IV. CONCLUSIONS

The methods and acceptance criteria for the performance evaluation of CR systems were presented in a comprehensive tabular form for imaging systems from four major CR manu-

facturers. The materials can be used as a handbook for acceptance testing and quality control inspection of CR systems to assure the consistency and reliability of their clinical operation.

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