Quality Assurance Procedures for Digital Radiography

Charles E. Willis, Ph.D., DABR
Associate Professor
Department of Imaging Physics
The University of Texas M.D. Anderson Cancer Center
Houston, Texas

Learning Objectives:

- Review components of a QA program and show how they apply to DR.
- Understand how some conventional tests should be modified for a digital radiographic system integrated into an electronic image management system.
- Identify key references and standards that can be useful in QA of DR.

Quality Assurance (QA) is...

- All activities that ensure consistent, maximum performance from physician and imaging facility (NCRP 99: 1988)
- Mandated in radiology by ACR Standards
- Often confused with Quality Control (QC)
- AKA QL, CQI, PI, TQM = constantly seeking improvement
- Vehicle for providing highest quality medical care

Alternate definition of Quality Assurance (QA)

- Are we operating the devices properly?
- Are the devices, themselves, operating properly?
- Are the devices properly supported?
Some traditional components of a QA Program

- QA Committee
- Policies and Procedures
- Reject Analysis
- Radiologist Film Critique
- Operator QC Activities
- Service Events
- Technologist Inservice training
- Medical Physicist QC Activities
- Incident investigation/troubleshooting

Quality Control is...

- Most tangible aspect of QA
- "...a series of distinct technical procedures which ensure the production of a satisfactory product."
- Four major aspects:
  - Acceptance testing of new equipment or post major repair
  - Establishment of baseline performance
  - Diagnosis of changes in performance before radiologically apparent
  - Verification of corrective action

Who is responsible for QC?
("It takes a village ..." Sec. of State H. Clinton, Health Care Expert)

- Physician responsible for clinical service is ultimately responsible
- Medical Physicist oversees the program
- QC Technologist makes day-to-day measurements, verify post-repair integrity
- Service engineer carry out repairs, PM, calibrations

“What’s my motivation?”
(unknown screen actor)

- Regulatory Compliance
  - Title 12, Code of Federal Regulations (CFR) Part 20, Standards for Protection Against Radiation
  - State regulations [link]
- Standards of Care
  - ACR Standard for Diagnostic Medical Physics Performance Monitoring of Radiographic and Fluoroscopic Equipment
  - ACR Radiography and Fluoroscopy Accreditation Program [link]
  - NCRP Report No. 99 “Quality Assurance for Diagnostic Imaging”
  - Nationwide Evaluation of X-ray Exposure Trends (NEXT)
  - Reference Values
- Providing the highest quality medical care
- MANAGING RADIATION DOSE

Many factors affect image quality and patient dose

Wolbarst. Physics of Radiology (1993) Table 19-1

<table>
<thead>
<tr>
<th>Factor</th>
<th>Contrast</th>
<th>Resolution</th>
<th>Noise</th>
<th>Patient Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal spot size</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Off-focus radiation</td>
<td>X</td>
<td>(x)</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Beam filtration</td>
<td>X</td>
<td>(x)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage waveform</td>
<td>(x)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>kVp</td>
<td>X</td>
<td>(x)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mA</td>
<td>(x)</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>SID</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Field size</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scatter rejection</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Where can we find instructions for how to perform QC tests?


Medical Physicist’s Worst Nightmare

- “They’re installing the new DEMI-RAD™ system tomorrow.”
- “We need you to come tell us if it’s okay to use with patients.”
- “BTW, we’re scheduling patients on it for Monday.”

Your first thoughts …

- “What the heck is a DEMI-RAD™?”
- “How bad do I need this job?”
- “Where is that monograph from the AAPM 2004 Summer School?”
Is this a plausible scenario?

- 3 categories of DR plus CR
- 17 DR manufacturers of 37 products plus 5+ CR vendors
- This was 5 years ago

What is “Acceptance”?

- Acceptance is a process whereby a customer determines whether...
  - newly installed imaging equipment is functioning as designed.
  - complies with regulatory standards, and
  - produces high quality images.
- Data gathered during acceptance testing establishes a baseline for later quality control (QC) testing.
- There are legal, financial, and warranty consequences to acceptance.

Acceptance testing is an opportunity...

- To identify and resolve discrepancies prior to clinical use
- To become familiar with the controls and operation of the equipment
- For Continuing Education on new technology and products

Acceptance testing (AT) could be as simple as an inspection and inventory.

- Verification that what was purchased was indeed delivered and installed.
- Purchasing agent, radiological technologist, or biomedical engineer may not recognize missing critical components.


What about functional tests?
- May test all operator controls to determine if they function.
- May test the manufacturer's claims of performance.
- May test specific performance that was crucial to the selection of this equipment.
  - May or may not be contract provisions
  - Ex: Throughput
- May test compliance/conformance with industry standards of practice.
  - Ex: DICOM, IHE
- May test whether manufacturer's installation instructions were followed.
- May collect "engineering data" for later reference.

Clinical Acceptability is the trump card!
- Any Diagnostic Radiographic Imaging System must produce images of sufficient quality to support clinical diagnosis at reasonable radiation dose to the patient.
  - Physician defines diagnostic quality
  - Regulatory bodies may define reasonable dose, else comparison to standard of care
- Humans must be able to safely operate the equipment

Machines that produce radiation are subject to government regulations
- Irrespective of the detector technology, you must assess the degree to which the x-ray generator allows the precise and reproducible control of the primary imaging technique factors
  - Attenuation (kVp)
  - Tube current (mA)
  - Exposure duration (msec)
- Evaluation of Automatic Exposure Control (AEC) devices differs because "consistent and reproducible Optical Density (OD)" is no longer an appropriate criterion.
- Evaluation of focal spot size, "measure me first!" and "congruence/positive beam limitation may differ.
- Total filtration (HVL) and leakage radiation are measured the same.

Lesson #1: Tests that rely on the receptor to assess generator performance must be modified.

Lesson #2: Tests that involve production of large amounts of radiation require protection of the image receptor.

Non-invasive kVp measurement of a DR system
Sensors in beam
No sensors in beam
It might be nice to have the DEMI-RAD™ service engineer present during testing

- To assist you with operation of the machine
  - Test modes
  - Vendor-supplied tests
- To provide technical references such as the service manual or installation instructions
- To observe your measurements
  - to "share the experience"
  - in case of "questions" from the factory
- To correct deficiencies on-the-spot when possible

Let’s consider the “DEMI-RAD™” system to be a “black box”

- Gain
- Characteristic
- Uniformity
- Contrast
- Sharpness
- Noise
- Artifacts
- Dose

DEMI-RAD™

Input
Output

How can I test the imaging functions of a “black box”?

- A fixed input should produce a specific output (aka Gain).
- Output should bear a specific relationship to input (aka Characteristic function).
- Input that is uniform in two dimensions should produce uniform output (aka Flat-field).
- Projected details will be represented in the output with a particular contrast and sharpness.
- Output will contain noise related to noise in the input and internal sources of noise.
- Output should be free from artifacts.
- Identical black boxes should produce similar output.
- Output should be free from signal from previous output (erasure).
- Output involves a penalty, that is, radiation dose to the patient

What is “output”?

- Could be laser-printed film
  - Measure with densitometer
- Could be luminance from monitor
  - Measure with photometer
- Could be digital values
  - Measure with Region of Interest (ROI) or Pixel tool by viewer software
  - Code values (CV) = Pixel values (PV) = grayscale values (GY)
  - quantization levels (QL)
- Could be derived indicator of exposure
  - Includes "metadata" from the DICOM header

Must address calibration of both output device and measurement device before collecting acceptance data
Important information about DR acquisition and processing is in metadata

- CR vs. DX object
- Mandatory vs. optional vs. private tags
- Automatic vs. manual entry of data
- PACS interpretation of metadata

Lesson #3: Assessment of DR performance likely involves access to DICOM images

Gain

- Set technique factors according to manufacturer specification
- Measure/calculate the radiation exposure to the detector
- Measure the output of the system
- Complications
  - Auto-ranging
  - Bucky factor

Exposure indicators in Computed Radiography - exposure delivered to detector

- Fuji
  - S number, Sensitivity Number
    - \( \frac{1}{200} \) at 80kVp \( \Rightarrow 200 \)
    - \( 200 S = X \)
- CareStream
  - EI, Exposure Index, (mSv): \( \frac{1}{200} \) at 80kVp + 1.5mm Al and 0.5mm Cu \( \Rightarrow 2000 \)
    - \( +300 EI = 2X \) and \( -300 EI = \frac{1}{2}X \)
- Agfa
  - lgM, logarithm of the Median of the histogram, (bels)
    - \( \frac{1}{200} \) at 75kVp + 1.5mm Cu \( \Rightarrow 100 \)
    - \( +0.3 \) lgM = \( 2X \) and \( -0.3 \) lgM = \( \frac{1}{2}X \)

Exposure indicators in Direct Radiography - exposure delivered to patient

- GE
  - DAP, Dose Area Product, dGy-cm²
  - "ESE", Entrance Skin Exposure, mGy, at 25 cm (default)
  - DEI (new)
- Philips/Seimens/Thompson (Trexel)
  - DAP
  - EI, Exposure Index or Indicator, similar to S (Philips - exception)
  - EXI (Seimens - exception)
- Canon (exception)
  - REX, Reached Exposure Value, f(Brightness, Contrast)
  - EI (new)
- Hologics (semi-exception)
  - Exam Factor, Center of Mass of log E Histogram, old
  - DAP and "Accumulated Dose" for exam, new
- SwissRay
  - mA, sec, field size, kVp, no exposure indicator, old
  - New, similar to Agfa lgM
**DR has wide dynamic range (latitude)**

- **Exposure (mR)**
- **Density (OD)**
- **Intensity (rel)**
- **Film/screen**
- **PSL**
- **High KV, L=2.2, S=750**
- **Over-exposed**

**Auto-ranging**

![Auto-ranging Diagram]

** Fuji Auto-ranging Specification**

<table>
<thead>
<tr>
<th>Exposure (mR)</th>
<th>Sensitivity (S)</th>
<th>Gamma (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>100</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>1000</td>
<td>1.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

**Auto-ranging**

- **High K V**
- **Low K V**
- **Under-exposed**
- **Over-exposed**

**There is a documented tendency to overexpose in CR and DR**

- Oversight of exposure factor selection is impossible without an exposure indicator


**How much exposure was used?**

- QA based on exposure indicator reduces doses
- 33% dose reduction if exposure indicator target followed
- AAPM Task Group #116 is effort to standardize indicators


- AAPM Task Group #116 is effort to standardize indicators

- ** Actually EXI**

- **Table 7**

<table>
<thead>
<tr>
<th>Exposure</th>
<th>S=200, G=1.2</th>
<th>S=190, G=1.2</th>
<th>S=220, G=0.9</th>
<th>S=190, G=0.9</th>
<th>S=220, G=1.1</th>
<th>S=190, G=1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 mR</td>
<td>66%</td>
<td>66%</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
</tr>
<tr>
<td>1 mR</td>
<td>66%</td>
<td>66%</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
</tr>
<tr>
<td>10 mR</td>
<td>66%</td>
<td>66%</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
</tr>
<tr>
<td>100 mR</td>
<td>66%</td>
<td>66%</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
</tr>
<tr>
<td>1000 mR</td>
<td>66%</td>
<td>66%</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
</tr>
</tbody>
</table>

- **High KV**
- **Low KV**
- **Under-exposed**
- **Over-exposed**
Exposure Indicator
from image of calibrated stepwedge, REX adjusted until each step disappears

Characteristic function

- Vary the input
  - Change mAs
  - Stepwedge
- Measure output
- Complications
  - Digital Look-up Tables (LUT)
  - Auto-ranging
  - Energy dependence of code values: Beam hardening

Spectral dependence of characteristic function

A very fancy calibrated stepwedge

AGFA Test Object 75 kVp +1.5 mm Cu, 47 µGy exit
Lesson #4: Assessment of Detector requires access to "for processing" image data as well as processed image data.

Using large Source-to-image Distance (SID), produce a uniform input.

Inspect and measure the uniformity of the output.

Complications:
- Heel effect: if possible, rotate detector 180°
- Backscatter: Pb backing or tabletop
- Fixed SID

Uncorrected DR image is inherently non-uniform

Non-uniformities are corrected by “flat-fielding”

Lesson #5: Assessing the receptor may require access to uncorrected image.

Artifacts related to gain and offset correction

GE DR
Canon DR

Lesson #6. A grayscale histogram is also helpful in assessing the receptor.

Contrast: what kind?

- Contrast
  - slope of detector characteristic
- Contrast resolution
  - Detector ability to distinguish features of similar signal level
  - Grayscale bit depth
- Contrast detectability
  - Observer ability to distinguish features of similar signal levels
Same exposure conditions

Identical machine, same exposure conditions

Calibrated step wedge: ROI indicates loss of latitude

LucAl Chest phantom w/QC object
Sharpness

- Spatial resolution
  - \( f(\text{digital matrix size}) \), i.e. pixel dimensions
  - Nyquist frequency = \( \frac{1}{2} \) sampling rate
    (need two pixels to represent a line pair)
- Bar patterns oriented orthogonal to matrix, else 1.414 factor high

Leeds Test Object TODR[CR]

Practical resolution is less than the Nyquist frequency

- Factors besides sampling compromise sharpness
  - X-ray focal spot dimensions
  - Blur in Indirect DR and CR
  - Optical and mechanical imprecision in IDR and CR
  - Afterglow in fast-scan dimension in CR
- Limit of resolution is where Modulation Transfer Function (MTF) has decreased to 10%

Swissray DR

AGFA CR Test Object
Primary, unavoidable source of noise in radiographic imaging is quantum noise.

Absolute magnitude of quantum noise increases with $\sqrt{D}$.

Standard deviation of ROI is an indication of noise.

Complication
- Non-linear Characteristic function

Combination of quantum noise and anatomic noise limits low contrast detection.

When pixel value is proportional to $\log D$, SD of ROI should be proportional to $D^{-1/2}$.

![Graph showing noise indicators (simulation)](image)

$\text{SD}_{\text{pixel}}, \text{SD}_{\text{mR/Ave mR}}, \text{Power (SD pixel)}, \text{Power (SD mR/Ave mR)}$

**SNR should improve with exposure**

**Variation in Exposure-dependent SNR is improved by gain and offset calibration**

Eleven GE DR systems, LucAl Chest phantom at 125 kVp
SNR from central ROI of “for processing” image

**New artifacts from the discrete nature of DR**
- Interference pattern between fixed grid lines and down-sampling rate for display
- Disappeared on zoom
- Bad choices
  - Display default magnification factor
  - Line rate of grid

**Configuration management**

Lesson #7: Performance data on large numbers of DR systems under simulated clinical conditions are needed to establish action limits
**Entrance Exposure**

- Position representative material between tube and detector.
  - CDRH phantoms
  - ANSI/AAPM phantoms
  - ACR Phantoms
  - Acrylic/lucite blocks
  - Cu or Al filter on collimator => scatter-free
- Use appropriate clinical technique settings.
- Use AEC if appropriate.
- Measure entrance exposure and record output.
- Compare to regulations, national trends, or reference levels.


**Erasure**

- Re-usable image media (RIM)
- Consequences of poor erasure
  - "Ghost" structures
  - Noise
- Immediately subsequent to normal exposure, produce image with no input and high gain setting. Inspect output.

**Anthropomorphic phantoms**

- Approximate clinical subject
- Complication: non-human histogram

Before calibration  Post calibration

**When is an anthropomorphic phantom not anthropomorphic?**

"Lawyer" Phantom

Inadequate subject contrast
Phantoms may not adequately represent radiographic projections of human anatomy


Pass/fail criteria: How do you know?

- Government regulations
- Specifications and service manuals
- Scientific literature
- Comparison with other devices or customer experience

Summary of four additional tests

- Flat-field => Gain and uniformity
  - Manufacturer’s conditions
  - Measure exposure
- Calibrated Stepwedge => detector characteristic, display processing, contrast, noise
- Bar patterns => spatial resolution
- Erasure => “base plus fog”
- Entrance exposure => patient dose
  - Not an extra test!

A postscript on Quality Control...

- Still necessary with digital radiography
- Repeat acceptance tests periodically and incidental to service events
- Routine QC must be performed by operators/supervisors of system
Institute processes to detect, correct, report, and document errors.

- Check images before release and archive.
- Exercise vigilance over rejected images.
  - Analyze reasons for repeated exams
  - Take action based on the analysis

Perform and document cleaning and maintenance on a regular basis.

Automated evaluations of the image receptor

What do you do with the QC data?

- Because systems are relatively new, manufacturers are uncertain about longitudinal data
- Lower limit for test is MTF @ 2.5 lp/mm = 17%
- CsI(Tl) is hygroscopic - columnar structure is degraded
- Both systems depicted required detector replacement
Involve all local resources in a team approach to the QC effort.

- Radiologist
  - Ultimate responsibility for quality of images
  - Department can provide only the lowest quality that is acceptable to radiologist
- Radiology Administrator
  - Responsible for efficiency of imaging operations
- Radiology Lead Technologist
  - First-line supervision of quality control operations
- Clinical Engineer
  - Responsible for equipment life cycle management
- Medical Physicist
  - No other person has image quality as first priority

References:
Comprehensive QC Plan for CR