UNIVERSITY OF MORATUWA, SRI LANKA

Faculty of Engineering

Department of Electronic and Telecommunication Engineering

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BM3122 - Medical Imaging

X-ray Imaging Quality Assurance

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Table of Contents

1. Introduction

Diagnostic X-ray imaging systems play an important role in modern medicine, offering non-invasive insights into the human body's internal structures and functions. These imaging systems utilize X-rays, a form of ionizing radiation, to capture detailed images of bones, organs, and tissues. With their ability to aid in the detection, diagnosis, and monitoring of various medical conditions, diagnostic X-ray imaging systems have become essential tools for healthcare professionals, enabling them to provide accurate and timely medical care to patients.

2. Why Quality Assurance in Diagnostic X-ray imaging systems?

The goal of quality assurance in diagnostic X-ray imaging systems is to consistently produce high-quality medical images while reducing radiation exposure to patients and medical personnel. The performance of X-ray equipment, image quality, and safety standards are monitored and maintained by a variety of protocols and procedures. Quality assurance is essential because it directly impacts the accuracy of diagnoses and patient care. It helps identify and rectify issues with equipment, preventing diagnostic errors and unnecessary radiation exposure. By adhering to quality assurance practices, healthcare facilities can improve the reliability of their diagnostic imaging, reduce healthcare costs, and, most importantly, enhance patient outcomes and safety.

3. Image quality measures of X-ray imaging systems

Image quality in medical imaging refers to the attribute of an image that affects a clinician's confidence in accurately perceiving diagnostic features visually. Key measures of radiographic image quality include contrast, dynamic range, spatial resolution, noise, and artifacts.

Radiographic contrast is the difference in signal or brightness between the structure of interest and its surroundings, primarily influenced by the differential attenuation of X-rays by various tissues. Digital radiography allows for the adjustment of contrast through post-processing techniques to meet specific clinical requirements.

Dynamic range represents the spectrum of X-ray intensities that the detector can capture. A wide dynamic range is crucial for achieving high-quality digital radiographs, as it ensures visibility of both low and high exposure values in an image.

Spatial resolution pertains to the imaging system's ability to distinguish adjacent structures from each other. It can be measured subjectively in units of line pairs per millimeter or objectively through metrics like the modulation transfer function (MTF). Factors affecting spatial resolution include magnification, X-ray focal spot size, detector resolution, patient motion, and image processing. A minimum spatial resolution of 2.5 mm is typically required for digital radiographs.

Noise refers to random or structured variations within an image that are unrelated to X-ray attenuation differences. Quantum noise is a primary contributor to image noise, and controlling exposure factors is the most effective means of reducing it.

Signal-to-noise ratio (SNR) is a critical metric that combines the effects of contrast, resolution, and noise. Higher SNR indicates better image quality and the ability to recognize smaller, low-contrast structures. Detective quantum efficiency (DQE) is a measure of SNR transfer efficiency in the imaging system and plays a vital role in reducing radiation exposure while maintaining diagnostic quality.

Artifacts can negatively impact image quality due to factors other than resolution, noise, and SNR. These may include issues with magnification, non-uniform images caused by detector problems, aliasing, and improper grid use.

4. Factors affecting Image quality

The quality of diagnostic X-ray images depends on various factors:

1. **Beam Energy (kVp):** The energy of the X-ray beam affects image contrast and dose. Higher energies result in lower contrast but lower radiation doses, while lower energies yield higher contrast but require more radiation.

2. **Tube Current (mAs):** The product of tube current (in milliamperes) and exposure time (in seconds) influences both image quality and patient dose. Choosing the right mAs setting is crucial to balance noise and dose.

3. **Acquisition Geometry:** Factors such as source-to-image receptor distance, magnification, and focal spot size impact image quality and resolution.

4. **Magnification:** Increasing the distance between the patient and the image receptor can improve contrast and reduce scatter radiation, but it also increases radiation exposure and may introduce blurriness.

5. **Focal Spot Size:** Smaller focal spots enhance spatial resolution but may require longer exposure times and risk patient motion.

6. **Detector Performance:** Detector resolution, element size, and signal-to-noise ratio (SNR) are essential for image quality. Smaller detector elements and better SNR improve resolution.

7. **Collimation:** Precise collimation limits scattered radiation, improving image contrast, noise, and SNR while minimizing radiation exposure.

8. **Anti-Scatter Grid:** Anti-scatter grids reduce scattered radiation but may attenuate the primary X-ray beam.

9. **Image Processing:** Post-processing techniques, such as histogram equalization and noise reduction, adjust contrast to meet clinical needs.

These factors collectively determine the quality of diagnostic X-ray images and require careful consideration to optimize contrast, resolution, and patient dose.

5. Quality Assurance Tests in X-ray Imaging systems

To ensure the primary objective of achieving high-quality X-ray images in an energy-efficient manner while minimizing radiation exposure to patients, technicians, and the general population, a series of Quality Assurance (QA) tests are conducted in accordance with the guidelines provided by regulatory bodies like the Atomic Energy Regulatory Board (AERB). These tests are crucial in maintaining the accuracy and safety of X-ray imaging equipment.

Congruence of Radiation and Optical Fields

The congruence of radiation and optical fields is a critical aspect of quality assurance in radiography. It refers to the precise alignment of the X-ray field with the light field used for positioning and framing the image. In a radiographic procedure, the X-ray field must accurately coincide with the light field visible to the operator. When these fields are not congruent, there is a risk of misalignment, potentially leading to the imaging of unintended areas or missing the region of clinical interest.

If the X-ray field is not aligned with the light field, the operator may inaccurately position the patient or the imaging receptor. This misalignment can result in suboptimal radiographs, retaking the scan and, most importantly, exposing the patient to unnecessary radiation. Therefore, ensuring the congruence of these fields is vital for achieving precise and diagnostically valuable X-ray images while minimizing radiation exposure and avoiding the need for repeat exposures.

Tolerance: $|a_1| + |a_2| \leq 0.02$ of S

Here S represents the focal spot to image receptor distance and a_1 and a_2 are the discrepancies in one dimension of imaging field.

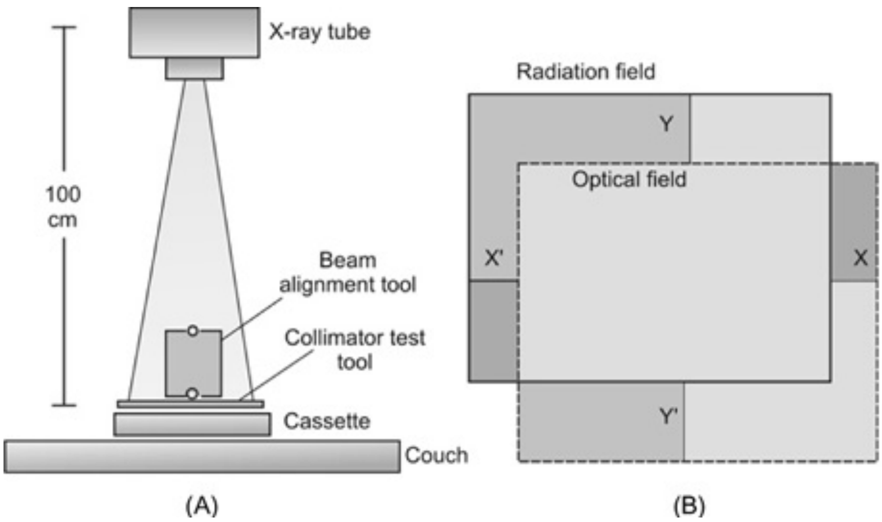

Fig 1 - (A) Setting of the Beam alignment and Collimator test tool,
(B) Congruence of radiation and optical fields

Central Beam Alignment

Central beam alignment is a critical aspect of radiography quality assurance. It involves aligning the X-ray beam precisely with the center of the imaging receptor or detector. Proper alignment is essential to prevent image distortion, maintain image quality, and ensure patient safety. Misalignment can lead to distorted images, grid-related issues, uneven radiation exposure to patients, and potential harm. Regular checks and maintenance of central beam alignment are crucial components of quality assurance programs in radiology, ensuring accurate and undistorted X-ray images for diagnostic purposes. Beam alignment test can be done simultaneously with the test for congruence of optical and radiation field.

Tolerance: Central beam alignment < 1.5°

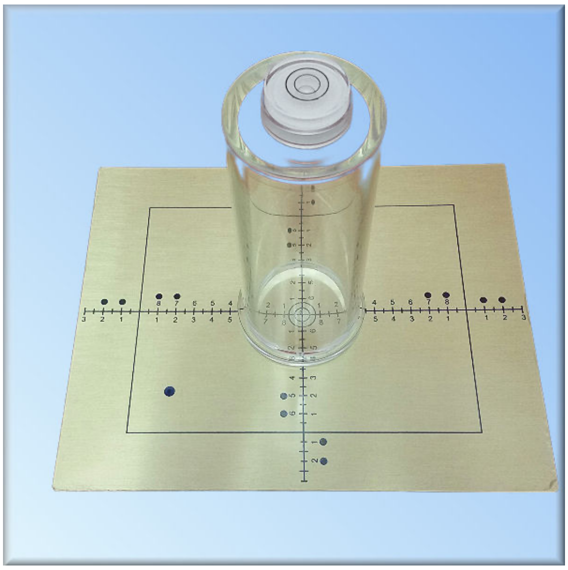

Fig 2 - Beam Alignment Test Tool

Effective Focal Spot Size Measurement

Effective focal spot size measurement is a crucial quality assurance procedure in radiography. It involves assessing and confirming the actual focal spot size in X-ray equipment to ensure it matches the intended size. The focal spot size directly affects image quality, with smaller focal spots providing sharper images. Regular measurements are essential to maintain image quality and prevent excessive heat generation in the X-ray tube.

Tools used for effective focal spot size measurements:
Pinhole camera
Slit camera
Star pattern
Resolution bar pattern

Tolerance:

for $f < 0.8$ mm	$+0.5\ f$
for $0.8 \leq f \leq 1.5$ mm	$+0.4\ f$
for $f > 1.5$ mm	$+0.3f$

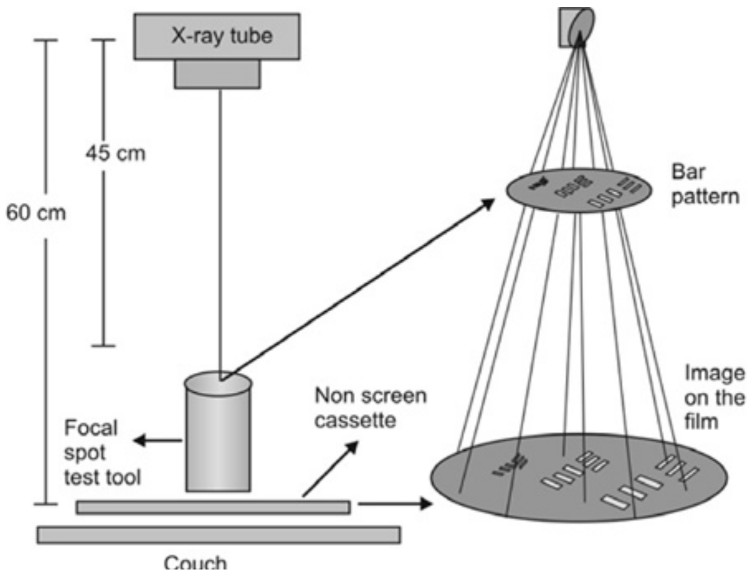

Fig 3 - Effective focal spot size measurement

Bar pattern images demonstrate the effective resolution parallel and perpendicular to the A-C axis for a given magnification geometry.

Timer Accuracy

Timer accuracy is essential to control exposure time accurately. Inaccurate timers can lead to underexposed or overexposed radiographs, impacting image quality. To assess this accuracy, a method known as the absolute timer method is employed, which involves measuring and comparing the set exposure time with the measured time using digital timers.

Tolerance: Accuracy of exposure timer % Error ± 10 %

Accuracy of Accelerating Tube Potential (kVp)

The peak potential of the X-ray generator significantly affects the quality of the X-ray beam and the patient's exposure. In modern equipment, solid-state detectors that employ non-invasive methods are commonly used for this measurement, ensuring that the delivered kVp closely matches the set value is crucial for maintaining image quality.

Tolerance : ± 5 kV

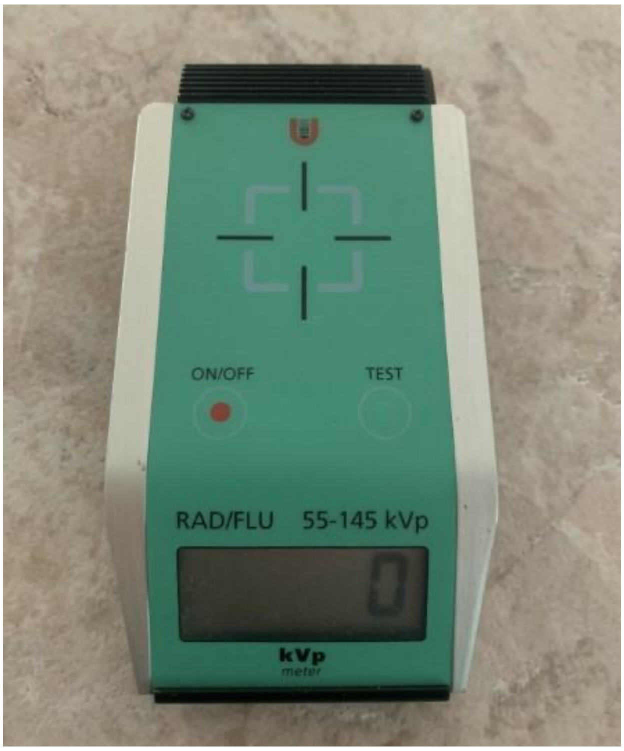

Fig 4 - KVP meter

Linearity of Radiation Output

Checking the linearity of radiation output concerning changes in tube current (mA) is vital. It aims to assess the linearity of radiation output by keeping exposure time and kVp constant while measuring radiation output at various mA loading stations. To ensure accuracy, multiple measurements are taken at each station to reduce statistical errors. The average radiation output readings are then used to calculate the coefficient of linearity (CoL) in units like mR/mAs or mGy/mAs.

Coefficient of linearity = $(X_{max} - X_{min}) / (X_{max} + X_{min})$
Tolerance: Coefficient of Linearity < 0.1

Reproducibility of Radiation Output

This test assesses the consistency of radiation output at different available kV settings while keeping tube current and exposure time constant. It helps ensure that the X-ray unit maintains consistent performance.

$$C = \frac{S}{\overline{X}} = \frac{1}{\overline{X}}\left[\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}\right]^{1/2}$$

where X_i = ith exposure measurement

$\overline{X}$ = mean value of exposure measurements

n = number of exposure measurements

Tolerance : Coefficient of Variation < 0.05

Total Filtration

Filtration is essential to remove low-energy X-ray components that do not contribute to diagnostic image quality but increase patient exposure. The total filtration, including inherent and added filtration, should meet recommended standards to optimize image quality and patient safety.

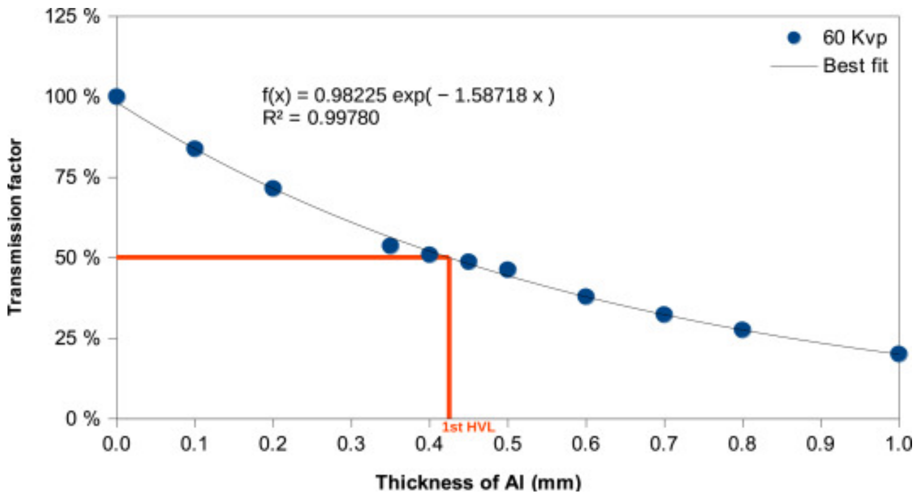

Fig 5 - Evaluation of HVL and Total Filtration

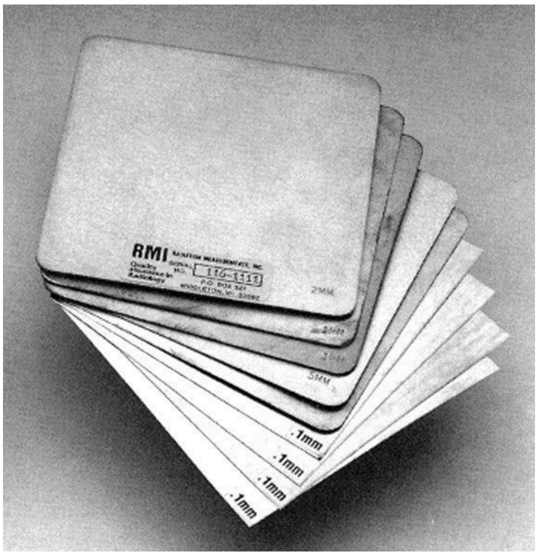

Fig 6 – Aluminium filters

For ensuring radiation quality of the x-ray beam,

Material Used : Aluminum filters of purity 99.99% or higher and density 2.70 g cm-3

Tolerance : 1.5 mm Al for kV $\leq$ 70

2.0 mm Al for 70 $\leq$ kV $\leq$ 100

2.5 mm Al for kV $\leq$ 100

Aluminum Equivalence of table top (Couch) $\leq$ 1.2 mm Al

Radiation Leakage Through Tube Housing

Measuring and eliminating unintended radiation leakage is crucial for the safety of individuals in the vicinity of X-ray equipment. Procedure of the test and the tolerance values is as follows.

Radiation leakage through the X-ray tube housing is assessed using an ionization chamber or semiconductor-based radiation survey meter. The measurement is conducted with the collimator of the tube housing fully closed, and the X-ray tube is energized at its maximum rated tube potential and tube current for that kVp setting. The exposure rate is measured at a distance of one meter from the focal spot, with readings taken at various locations around the tube housing and collimator (including anode side, cathode side, front, back, and top). The maximum leakage rate (measured in mR/h) from both the tube housing and collimator is determined, and the leakage radiation in one hour is calculated based on the workload of the X-ray unit.

The workload varies depending on the type of equipment:

- For Radiography, Radiography & Fluoroscopy, C-Arm, Interventional Radiology, dental OPG, and dental CBCT equipment, the workload is 180 mA-min in one hour.
- For dental (Intra-oral) equipment, the workload is 20 mA-min in one hour.
- For mammography units, the workload is 40 mA-min in one hour.

The tolerance limits for radiation leakage are as follows:

- Radiation Leakage at 1 m distance from the focus for various equipment types should be less than 1 mGy in one hour.
- Radiation Leakage limit at 5 cm from the external surface of a mammography unit should be less than 0.02 mGy in one hour.
- Radiation Leakage limit at 1 m distance from the focus of a dental (intra-oral) unit should be less than 0.25 mGy in one hour.

Fig 7 - Ion Chamber Survey Meter with Beta Slide

Exposure Rate at Tabletop

The distance between the X-ray tube's target and the fluoroscopic table affects various aspects of fluoroscopy, including dose rate, image quality, and exposure time. Monitoring and maintaining appropriate exposure rates at tabletop are essential for effective fluoroscopy.

6. Phantoms used in X-ray quality assurance

There are two main types of phantoms used in medical imaging, anthropomorphic and calibration.

Anthropomorphic Phantoms are designed to mimic the characteristics of the human body, using materials that simulate tissue properties. They are versatile tools used for tasks like optimizing radiation protocols, training staff, and testing imaging techniques. Recent advances in 3D printing enhance their realism.

Fig 8 – Head and torso phantom

Fig 9 – Phantom neck X-ray

Fig 10 – Phantom neck X-ray

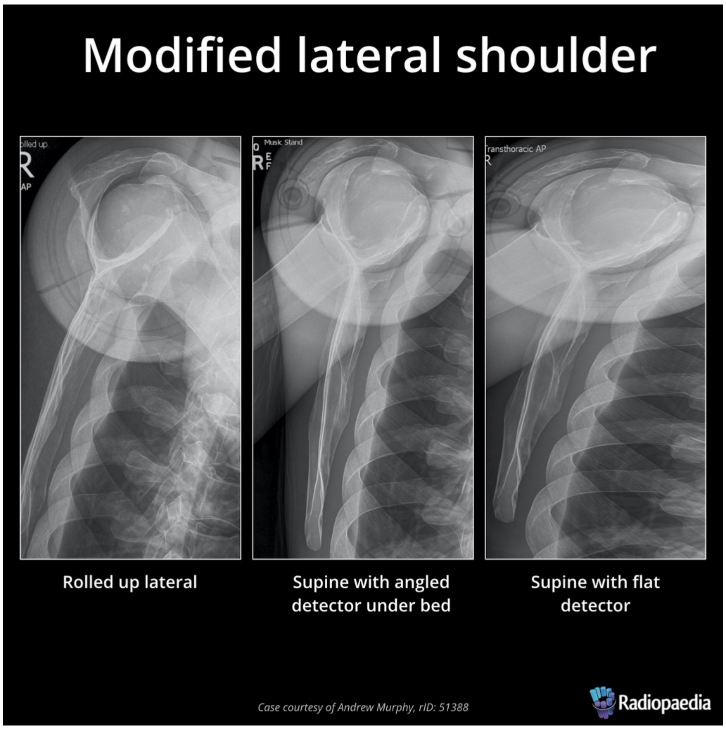

Fig 11 - Anthropomorphic phantom X-ray

Calibration Phantoms typically have known density values and are used for quality control. They ensure that imaging equipment produces accurate results by verifying that the phantom's density matches the expected values. Deviations can signal the need for equipment maintenance or adjustments, ensuring the reliability of medical imaging systems.

Reference

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