White paper

Why it is important to perform quality assurance testing for diagnostic X-ray

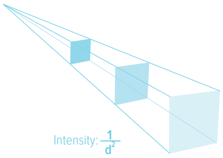
Each year, billions of diagnostic X-ray examinations are carried out globally helping doctors to quickly make correct diagnoses and saving lives.

However, it is known that there is an increased risk of cancer among people who have been exposed to high doses of radiation. When it comes to lower levels, it is not easy to find a direct relationship between added dose and increased risk of cancer, but scientists say they cannot exclude a potential increase even for low exposures. Many cancer types also develop slowly, so it may be difficult to establish the root cause.

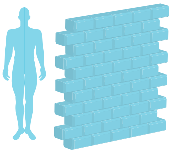
Undoubtedly, X-ray examinations are fantastic diagnostic tools, but one must always strive for as low doses as reasonably achievable (ALARA) since there is no safe level of radiation.

ALARA Principles

Time:
Linear relationship between time and dose. Shorter time, less dose.



Distance:
Inverse square law applies, $1/d^2$. Longer distance, less dose.



Shielding:
Passive devices can reduce radiation exposure dramatically.

Quality assurance testing of X-ray machines

In a diagnostic procedure, X-rays are used to obtain a diagnosis. It is important to ensure optimal performance of the X-ray machine to achieve good image quality, but also to reduce unnecessary radiation to patients and staff.

In order to do this, X-ray machines should be monitored regularly through strict quality control programs. These could be local guidelines, national or international recognized standards, or manufacturer recommendations. Some examples are AAPM (the US), IEC 60601-2-43 to IEC 60601-2-65, 61223-2 (constancy testing), and 61223-3 (acceptance testing).

Quality Assurance (QA) tests are done to check equipment performance under routine clinical conditions, following established protocols for facilities, equipment and procedures.

However, in many countries, a significant number of X-ray systems used in diagnostic radiology departments are not part of a QA program. This could be due to lack of relevant guidance/ regulations, and/or professionals trained in quality assurance testing.

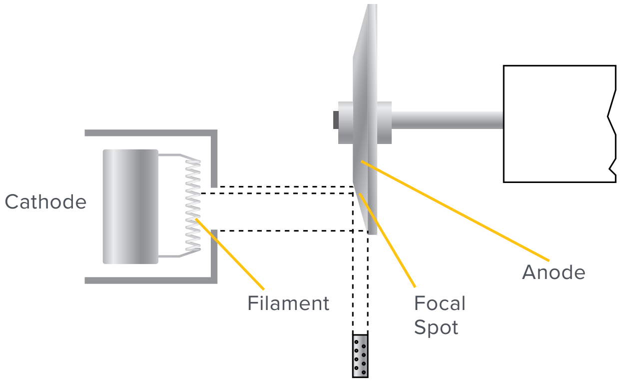
In addition to patient and staff safety, QA-testing is used for:

- Predictive maintenance to avoid machine failure and unplanned service
- Reproducibility between images/exposures
- Avoiding repeated procedures due to malfunctioning equipment
- Extending equipment lifetime when properly maintained

X-ray tube functionality and equipment health

Quality assurance tests are first done to establish measurement references and thereafter serve to uncover possible malfunctions or wear and tear problems in the X-ray machine over time.

There are several problems that can occur in the X-ray machine which regular quality assurance testing can detect at an early stage. Before we go into details, let's describe how the X-ray tube works.



X-ray is produced inside a vacuum container of glass or metal. The reason why it has vacuum inside is that electrons cannot be accelerated in air.

The X-ray tube has two crucial parts, the anode and the cathode. The cathode has one or two metal wires, called filaments, usually made of tungsten to withstand heat. When a filament is heated by electric current, electrons are released as a cloud around it. The difference in electric potential between the anode and the cathode makes these electrons accelerate towards the anode. When electrons hit the anode they transfer their energy to X-ray photons, which are emitted through an opening in the tube.

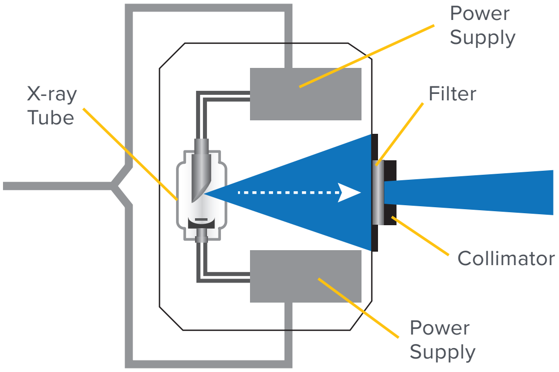
In radiography, the anode is often also made of tungsten material to withstand high temperatures, caused by the electrons hitting it.

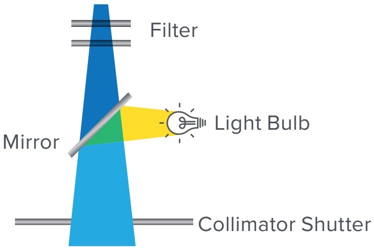
The anode angle differs between different X-ray machines. This angle affects the:

- Energy spectrum since photons will travel different distances throughout the anode material. The energy spectrum affects the quality of produced X-rays (beam quality)
- Focal spot size, and thereby the resolution. A smaller focal spot increases resolution, whereas a bigger focal spot leads to better heat dissipation.

An X-ray machine needs to have a beam restricting device to minimize the X-ray dose and improve image quality. The beam restricting device does that by limiting the X-ray field to the right size for the diagnostic procedure and by reducing scattered radiation.

The most commonly used device is called a collimator. The primary collimator is located at the opening of the X-ray tube. The secondary collimator is placed inside a collimator house and has two sets of lead shutters that can be adjusted to make the X-ray field smaller or bigger. There is also a light bulb that illuminates the X-ray field to show its size and center. The light bulb must be mounted so that the X-ray field and the light field match each other. The light field from the collimator housing represents the area to be irradiated by the X-ray beam.





Cathode filament thinning

Every time X-ray is produced, the filament gets heated due to the current flowing inside of it. This heat may lead to evaporation, meaning atoms disappear from the filament. The amount is extremely small, but with time it will influence filament thickness. If thickness changes over time, the current flowing inside changes since the resistance has changed. Modern machines will auto-adjust for this by changing the voltage over the cathode, but with time, the filament will eventually break.

Tube blackening

Another phenomenon that might occur over time is tube blackening. As atoms get vaporized in the filament, so are anode atoms. These atoms will be deposited on the inside of the X-ray tube, causing the glass to blacken. This will affect the X-ray beam quality since radiation gets shielded.

Anode wear and tear

The anode will also suffer from wear and tear not only caused by vaporization. The image below shows a well-used anode. Repeated heating and cooling have roughened its surface. This anode has also been exposed when not rotating, which has resulted in a melted tungsten spot. The intense heating of this small area has caused a small crack. If the anode starts to rotate again, this crack may propagate into a complete disk fracture. As a result of the roughened surface, there will be a change in the radiation output spectrum.

Light and X-ray field misalignment

Another thing to consider is the collimator light and X-ray field alignment. A reason for misalignment may be if the machine has been handled roughly causing the lamp inside to move.

If misaligned, the operator may take a picture not fully containing the whole area of interest, meaning another picture must be taken which takes time and increases patient dose. There is also a chance that the operator takes a too large picture, which also leads to an unnecessarily high dose.

Distorted focal spot size and shape

As the filament shape changes with time, together with anode wear and tear, the focal spot will also be affected. In general, a small focal spot is used when spatial resolution is important. A large focal spot will induce more photons per time meaning a shorter exposure time is possible. A larger focal spot is also less sensitive to heat since it is spread over a larger area. Focal spot size measurements can be made to see if it matches the size given by the manufacturer.

Tube leakage

The tube must be completely closed, except for the beam opening, to avoid leakage. Design flaws or rough handling could be reasons why the tube is not completely closed.

Measurements for patient safety

mA measurements

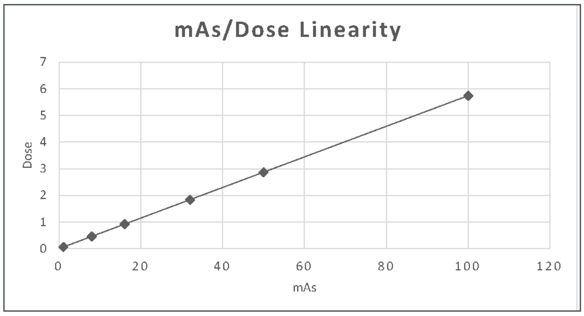
Milliampere (mA) is the electrical current flowing from the cathode to the anode. Since mA controls the number of electrons hitting the anode per second, it is directly proportional to the quantity of X-rays produced. Milliampere seconds (mAs) is the mA multiplied by the exposure time in seconds. The mAs value determines the total number of photons delivered during an X-ray exposure.

There are mainly two ways of measuring mAs. One can measure it invasively by hooking a sensor to the internal circuit in the X-ray machine. By doing this, one will measure a current corresponding to the same current that goes through the filament.

The second way is non-invasively by measuring the electric field around the high voltage cables feeding the generator.

There is also a third way to get an indication of a changed mAs, and that is to measure dose from the X-machine output. Although more parameters are in play, dose is directly related with mAs.

If mAs is changing over time, the quality of the X-ray image taken will also change. Most likely there is something wrong with the internal circuits in the X-ray machine. Thinning of filament will change mAs, but this is usually controlled by the X-ray machine itself. Another issue may be a flaw in the power grid.

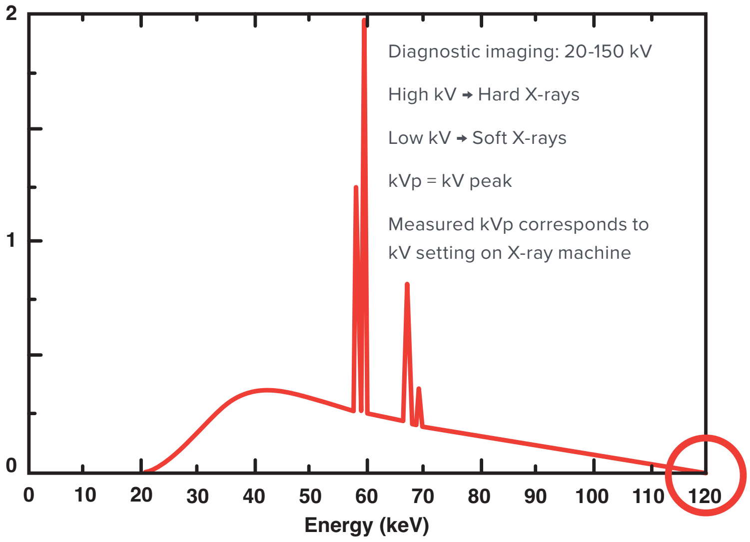


kVp measurements

Kilovoltage (kV) is a parameter affecting image quality. It is the tube potential and the energy of electrons accelerated towards the anode target. In medical imaging, the kV value usually ranges between 20 – 150 kV depending on X-ray modality and diagnostic procedure type.

A high kV setting on the X-ray machine means radiation with high frequency/short wavelength, high energy, and strong penetration is generated. Radiation with these qualities is referred to as hard X-rays. A low kV setting will on the contrary generate radiation with low frequency/long wavelength, low energy, and less penetration. Radiation with these qualities is referred to as soft X-rays.

A way to measure this kV is to measure photon energy. The photon spectrum contains energies between 0 – set kV. If the machine is set to 120 kV, a number of photons should have this energy. By looking at the highest energy photons in the spectrum, the kV called kVp (kV peak) can be achieved.

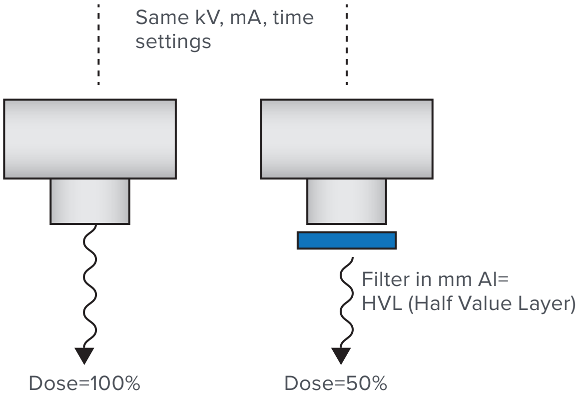


HVL measurements

Half Value Layer (HVL), is a more abstract parameter defining the machine output.

One way to control the photon spectrum is by using filters. By adding filters, one will change the relationship between high and low energy photons. The optimal relationship depends on modality and which part of the patient is being imaged.

HVL is defined by how much Aluminum is needed to decrease dose to 50%.



More shielding will affect the HVL. A low HVL means bigger share of low energy photons compared to a high HVL. And a change in HVL means a change in beam quality, which affects the X-ray image quality.

There are mainly two ways of measuring HVL. The manual way is to first measure dose, then add filters until the measured dose is 50% of the original dose. This is hard to do, and uncertainty is high. After the entrance of solid-state sensors instead of ion chambers, it is possible to get enough information from the X-ray beam to calculate HVL from a single exposure.

All previously discussed hardware defects will affect HVL. Filament and anode vaporization will add to the filtration. Roughening of the anode surface may also change HVL.

Dose measurements

Dose is a combination of kV and mA together with HVL, and it contains information to the image receiver. If you have a high mA and therefore a lot of photons, you will get a high dose. If you have a high kV, you will also get a high dose.

If the information to the image receiver is perfect, a high-quality image can be produced while the patient has received minimum dose.

If information is bad, it will lead to poor image quality, a need for more/new images to be taken, or even faulty diagnoses.

Since dose is the product of all the other parameters, any X-ray machine hardware defects will most likely affect the dose. By combining changes in dose, kV, mAs and HVL, one can make certain conclusions of the machine's status.

Other measurements

There are many types of QA measurements that can be done. Exactly which tests are required differs from country to country. Even if countries have the same tests, there may be different procedures and acceptance criteria. It is therefore of utmost importance to be aware of local regulations. Here are some additional examples of tests:

Linearity/reproducibility, consistency/constancy

Reproducibility means that the output must be the same over several exposures with the same settings. The same kV setting should be tested at different mA settings to ensure consistency.

Luminance and Illuminance

Luminance tests are not involving the X-ray machine. Such tests are carried out on screens or monitors showing the X-ray image. If the screen is too dark in certain areas, there is a risk of a wrong interpretation of the image. It is also preferable if an image looks the same on different screens.
In diagnostic radiology it is important to measure the luminance of computer screens and light boxes to ensure they are bright enough with good contrast so all X-ray image details can be displayed. Illuminance tests can also be done on the collimator light bulb.

Total filtration (TF)

X-ray service technicians are interested in knowing the TF for the X-ray machine, because filtering low energy photons is important in order to minimize dose.

Focal spot size

Initial verification of the size can be made using a slit camera or pinholes.

Timer accuracy and reproducibility

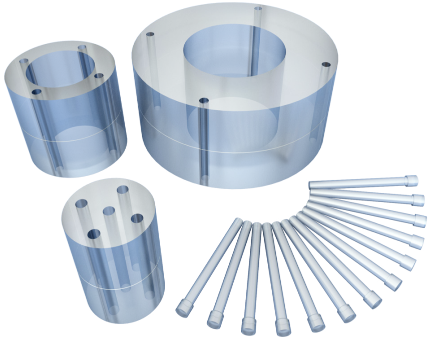
This is tested by comparing the set time value on the machine with the measured length of the exposure. A certain deviation is allowed but a well-functioning timer is important because it directly affects the dose.

Image resolution

The X-ray image resolution can be tested by using test patterns.

CTDI – CT Dose Index

CTDI (Computed Tomography Dose Index) is a measure of dose from a single rotation of the gantry. The CTDI is used for estimating the total dose to a patient during a CT scan procedure. Measurements are done with a pencil shaped ionization chamber together with a phantom simulating a patient.



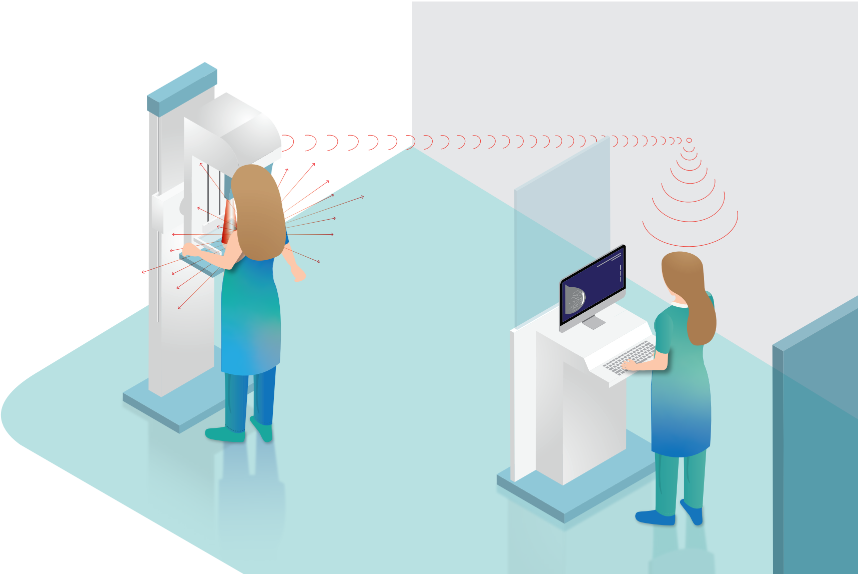
AGD – Average Glandular Dose

AGD is an estimate of the average absorbed dose to the glandular breast tissues during mammography.

Staff safety in conventional X-ray

In most applications, medical staff is not close to the source when an image is taken. They usually leave the room, or go behind shielding.

The patient always gets the highest dose during a procedure, but staff on the other hand are exposed to small amounts of radiation every day, and the accumulated dose over years can be quite high. It is therefore important to control the environment also from a staff perspective.

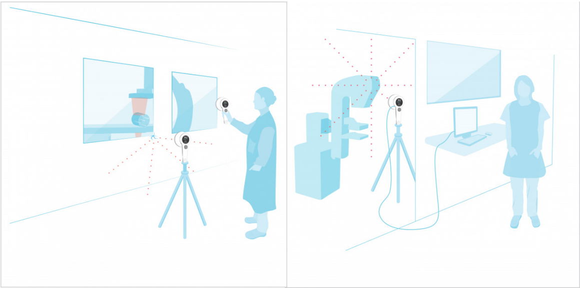


When an exposure happens, there will be scattered radiation all over the room. If the operator is behind a shield, it is still important to measure the efficiency of the shield. Also, the geometry of the room can give a local hotspot of scattered radiation. If there is a tube leakage, a high-energy unfiltered beam is propagating in the room creating even more scatter, maybe also behind the shield. In some countries leakage levels are regulated by law to not exceed a certain amount of Gray (Gy) or Sievert (Sv) [Roentgen (R) or rem] per hour.

If the staff, or other people, are in adjacent rooms or hallways, it is important to have shielded walls. Otherwise, they may receive unnecessary dose. A common way to shield a wall is to have lead plates inside. If the lead shielding is damaged, or if plates have been poorly assembled within the wall, radiation might pass through.

One should therefore always do wall leakage measurements before commissioning and start-up of the X-ray room.

Survey Meters can be used to measure scattered radiation and to detect leakage.



Staff safety in fluoroscopy

Fluoroscopy is a special type of X-ray modality where staff is exposed to high doses.

Fluoroscopy is mainly used during surgeries. The surgeon may insert instruments into a major blood vessel, guiding it for instance to the heart. To be able to do this, the surgeon must know where the instrument is.

By having a pulsed exposure with a high frequency, one can follow what is happening inside the body in real time.

Since the exposure lasts for a long time during the surgery, photon energies must be much lower compared to regular radiography.

If the machine gives too much dose compared to what is required, the increased accumulated dose to staff over years may be significant. If something is wrong with the machine, it could of course also be a danger to the patient. Not does it only increase the risk of long term illness e.g. cancer, but it can also give short term damages such as burns and dead tissue.

Tube and wall leakage in these types of rooms are also important. Especially since the exposure time is long compared to other modalities.

Summary

QA testing is mainly driven by regulations to ensure patient and staff safety. Consistent X-ray machine output is important to secure good image quality enabling correct diagnoses at minimum radiation doses. The output must match machine settings.

Maximized Uptime

Financial Savings

Greater Control

Lasting Equipment

Periodical QA testing is critical for uncovering possible malfunctions in the X-ray machine. It helps you to:

- Increase efficiency by avoiding unplanned service, downtime, and repeated X-ray procedures
- Save money due to increased lifetime, and improved maintenance planning – no costly fast delivery of spare parts

Malfunctioning can also lead to increased doses to both patients and staff. Avoiding unnecessary dose should always be top priority when working in accordance with ALARA.

Different types of QA measurements can be done to secure patient safety e.g. kVp, mAs, HVL and Dose.

Unnecessary patient dose is given if:

- There is too much low energy photons present that gets absorbed in the body
- The image taken is not including the whole interesting area and more exposures are needed
- The image taken is including more than the interesting area
- If image quality is poor and more images must be taken

Staff can be protected by minimizing tube/wall leakage, and scattered radiation via proper shielding. In addition, when using fluoroscopy, it is important to control time and photon energies to avoid excessive short-and long term high accumulated doses.

RaySafe focuses on solutions for the X-ray room that help to protect patients from unnecessary radiation, help staff reduce their radiation exposure and simplify measurement
on X-ray equipment. Visit www.raysafe.com for more information.

References

Government of Canada:

- https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/radiation/diagnostic-imaging-quality-assurance-overview.html. Article “Diagnostic X-Ray Imaging Quality Assurance: An Overview” also appearing in “The Canadian Journal of Medical Radiation Technology”, October 1996, 27(4), pgs. 171-177.

IAEA:

- Handbook of basic quality control tests for diagnostic radiology, February 2023

Pan American Health Organization:

- Quality Assurance in Radiology Facility: https://www3.paho.org/hq/index.php?option=com_content&view=article&id=3364:-programas-de-garantuna-de-calidad-&catid=1162:radiologicalhealth-saludradiologica&Itemid=2164&lang=en
- Organization, Development, Quality Assurance and Radiation Protection in Radiology Services: Imaging and Radiation Therapy, December 1997

IEC Standards:

- IEC 60601-2-43 to IEC 60601-2-65
- 61223-2 (constancy testing)
- 61223-3 (acceptance testing)

RaySafe
We empower our everyday heroes to focus only on protecting lives.

Unfors RaySafe AB
Uggledalsvägen 29
427 40 Billdal, Sweden

For more information, contact us at:

+46 31 719 97 00
customerservice.se@raysafe.com
raysafe.com

10/2024 22450b-en