Survey meter measurements of X-ray tube leakage in the loading state

INTRODUCTION

This white paper discusses how to perform X-ray tube leakage measurements with survey meters, in relation to relevant standards and regulations.

X-ray tube leakage measurements are performed to find potential leakage of ionizing radiation from X-ray tubes. It is part of the radiation safety procedures at hospitals and manufacturers of X-ray machines. During a leakage measurement, the X-ray machine is operated with the radiation on and the collimator closed. The person who performs the measurement uses a survey meter to examine the area around the X-ray tube at a specific distance. The position where the leakage dose is the highest is identified and quantified, as is the number of exposures that could be performed during one hour in the lab. The result is compared to an upper dose limit, provided in standards and regulations, to determine if the X-ray machine passes or fails.

International standards[1] and local regulations[2] provide guidelines on:

- The **upper limit** for dose measured in one hour
- The **area** over which the dose measurement should be averaged
- At what **distance** the limit is valid, either from the X-ray focal spot or from the X-ray tube housing

The numbers provided in standards and regulations often raise practical questions about the measurement procedure, and how the design of the survey meter may affect the measurements. **This white paper** discusses the interpretation of the referred standards and regulations, with focus on:

- the X-ray modality, such as fluoroscopy or radiography
- a homogeneous versus a non-homogeneous X-ray field
- the size of the active sensor area of the survey meter
- the distance to the X-ray source or tube housing

The paper ends with a discussion of how different survey meter properties affect accuracy and practicalities at measurements.

---

[1] The International Electrotechnical Commission: IEC 60601-1-3, *12.4 – Leakage radiation in the loading state* (IEC 60601-1-3)
[2] The Food and Drug Administration: FDA, Code of Federal Regulations Title 21, *Performance standards for ionizing radiation emitting products*, §1020:30 (k) and (l) (CFR 21)

WHAT TO MEASURE – DOSE OR DOSE RATE

Is dose or dose rate a better measure at leakage measurements? The answer depends on what modality you measure on, *e.g*. fluoroscopy or radiography.

The referred standards and regulations provide upper limits for the **dose** from leakage **measured in one hour** (the busiest hour) in the lab. However, how the radiation is distributed over time is different depending on modality, Figure 1.

Continuous or **repetitively pulsed** radiation is used at a low average dose rate to provide visual guidance during interventional procedures, or study other real-time processes. The equipment can conservatively be estimated to be in use 100 % of the time. Therefore, the measured maximum average **dose rate** can be used to estimate the maximum dose in one hour. Note that the measurement must be longer than the stabilization time of the survey meter, which may be up to a minute at low dose rates.

In **radiography**, imaging is performed at much higher dose rates but with an exposure time in the range of milliseconds. The short exposure time makes it hard to quantify the dose rate. A better approach is to use the maximum single-exposure leakage **dose**, produced from the least favorable exposure settings for clinical use, **multiplied with the maximum number of such exposures** that can take place during one hour in the lab.

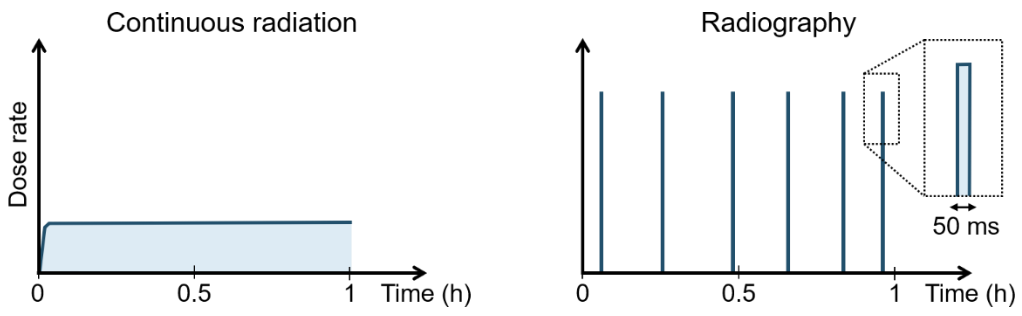

Figure 1: Illustration of dose rate versus time. Left: Continuous radiation. Right: Radiography with 50 millisecond exposures (right). Following the referred standard, the sum of the integrated areas (light blue) should not exceed 1 mGy in one hour at 1 m from the X-ray source.

Conclusions & Discussion: For continuous or repetitively pulsed radiation, the dose in one hour can be estimated from the measured maximum average dose rate. For exposures, the leakage dose from one exposure, and the maximum number of procedures in the lab in one hour, need to be considered to avoid over-estimating the leakage.

HOW TO FIND LEAKAGE

How many measurements are needed to ensure that the worst spot of leakage is detected? The answer greatly depends on assumptions on the properties of the radiation, *e.g.*, if the radiation field is **homogeneous** or **non-homogeneous**.

Figure 2 illustrates these two extremes. P1, P2 and P3 represent three different positions where dose measurements are performed, all at a 1 m distance from the X-ray source. Dose is assumed to be averaged over an area of 100 cm^2 with no linear dimensions exceeding 20 cm (as stated in the referred standards and regulations). The active sensor area of the survey meter is facing the X-ray source directly.

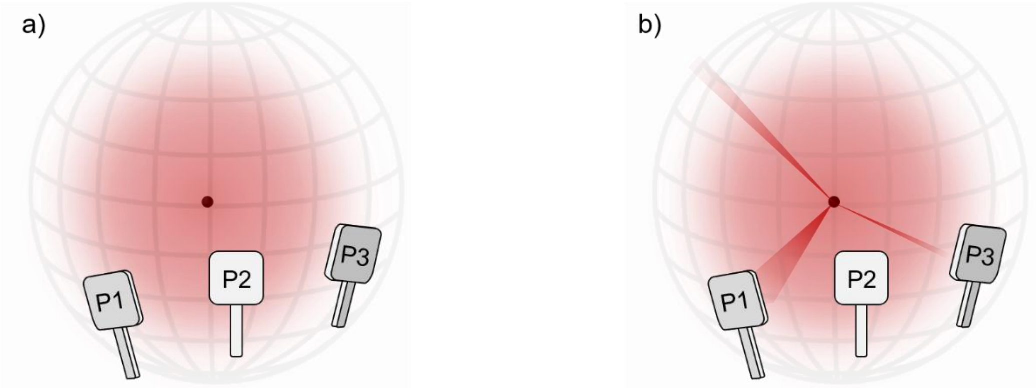

Figure 2: Illustration of a) a homogeneous X-ray field and b) a non-homogeneous X-ray field, with ionizing radiation shown in red. The black dot symbolizes the X-ray source. P1, P2 and P3 mark three measurement positions for a radiation survey meter and are all at a 1 m distance from the X-ray source.

In a **homogeneous** field (Figure 2a), the measured dose value at a 1 m distance from the X-ray source will be the same in position P1, P2 and P3. This value also represents the peak dose. In a homogeneous field, it is therefore enough to measure dose in **one** (any) position at a 1 m distance from the source to find the peak dose value.

In the **non-homogeneous** field (Figure 2b), the dose readings in position P1, P2 and P3 will be different. You may have found the peak value for dose in position P1, but to be sure you would, in theory, need to perform enough leakage measurements to cover the entire sphere at a 1 m distance from the X-ray source. To cover a sphere with a radius of 1 m with a sensor area of 100 cm^2 requires at least **1257** measurements**.**

Conclusions & Discussion: Theoretically, leakage measurements in a homogeneous field require one measurement only, while a non-homogeneous field requires more than a thousand. In real life, the X-ray field is likely to be at least somewhat non-homogeneous, while it is unlikely that there is time to perform thousands of measurements for each X-ray machine. A pragmatic way would be to pay special attention to areas that may be occupied by people, and areas where the X-ray equipment is known to have the most leakage, from previous experience. In the end, while standards and regulations provide guidelines, it is the person performing the measurements on site who needs to take responsibility for the radiation environment for staff and patients, given the local measurement conditions and environmental factors.

SENSOR SIZE

In the previous example, the measured dose was assumed to be averaged over an area of 100 cm^2, as stated in the referred standards. But what happens if the physical sensor is of a different size?

As discussed in the previous chapter, if the radiation field is **homogeneous**, the measured dose is the same in all points on the surface of a sphere with a radius of 1 m from the X-ray source. In this case, the sensor size also does not matter, since the dose averaged over *any* area will be the same. It only takes one measurement in any point, with a sensor of any size, to find the peak dose value (assuming that the sensor design gives negligible distance deviations from the spherical surface).

If the radiation field is **non-homogeneous**, the sensor size will have an impact. Figure 3 illustrates three sensor areas of different sizes, named Sensor 100 (100 cm^2), Sensor 50 (50 cm^2) and Sensor 150 (150 cm^2). All three are hit by leakage radiation of the same intensity and size, at a 1 m distance from the X-ray source.

Sensor 50 will show a higher dose value than Sensor 100 since the radiation field covers a higher percentage of the sensor area of Sensor 50. On the other hand, a smaller sensor area requires more measurements in order to ensure that the leakage is detected. Importantly, Sensor 150 may underestimate the dose, since the leakage is averaged over a larger area than stated in the referred standard.

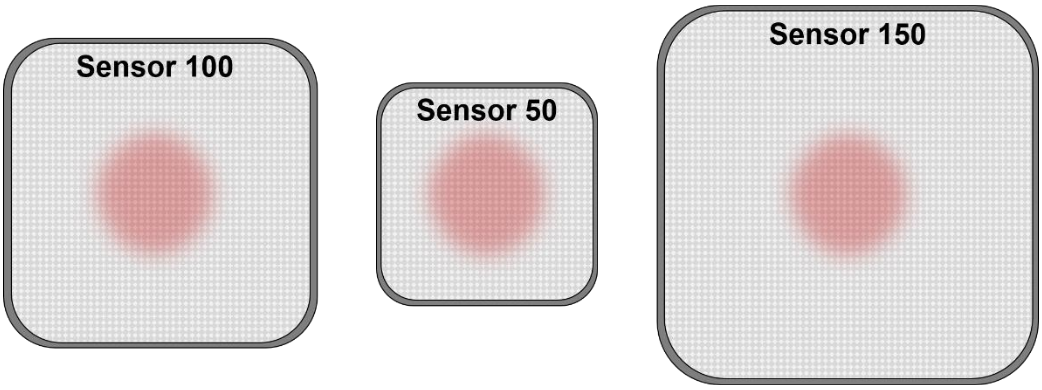

Figure 3: Illustration of three active sensor areas with sizes of 100, 50 and 150 cm^2, respectively. All sensor areas are placed at a 1 m distance from the X-ray source and hit by the same amount of radiation, shown in red.

Conclusions & Discussion: A sensor of a size smaller than 100 cm^2 will never underestimate the dose, which could happen in a non-homogenous field with a sensor larger than 100 cm^2. Therefore, it is safe to use the smaller sensor, provided that enough measurements are made to cover the same area.

REFERENCE DISTANCE

In the examples above, the distance between the sensor area and the X-ray source is one meter. What happens if this distance is shorter, or longer?

The referred standard gives an upper limit for the dose measured at one meter from the **focal spot** (not the tube housing) of the X-ray machine. While there is no explicit requirement to perform measurements at a one-meter distance, it is highly important that the dose limit is given at a specific distance, since ionizing radiation follows the inverse square law: Halving the distance to the X-ray source means quadrupling the dose. In other words, if the measurement distance changes, so does the upper dose limit, and quite dramatically.

The inverse square law is commonly used to calculate how dose varies with the distance to the X-ray source. However, for leakage measurements there are additional factors to consider:

- The relationship between primary and scattered radiation changes with the distance to the X-ray source.
- Close to the X-ray source, the inverse square law may not be applicable.
- Variations in size and shape of the X-ray tube housing, as well as the survey meter, affects how the measurement can be performed, practically.

Therefore, measurements at other distances than one meter – and especially close to the X-ray source – may not be in line with the referred standard, even if the dose limit is recalculated.

Conclusions & Discussion: It is practical to measure leakage dose at a one-meter distance from the X-ray source, since it enables direct comparisons with the upper dose limit given in the referred standard. Changes in distance affects the dose limit and the relationship between primary and leakage radiation. Avoid measurements close to the X-ray source with a recalculated dose limit, since the inverse square law may not be applicable at short distances.

WHAT SURVEY METER TO CHOOSE

From the discussions above, what is a suitable survey meter for leakage measurements?

If the X-ray modality, X-ray field homogeneity, sensor size and reference distance is considered and adjusted for at measurements, any survey meter can be used to measure in accordance with the referred standards and regulations. However, the properties of the meter may offer considerable time savings and improvements in accuracy. Some of the key properties of a survey meter are:

- **Dose rate range and sensitivity** – Does the range of the meter cover your measurement needs or do you need to switch between different meters or sensitivity settings?
- **Energy response** – Is the meter equally sensitive to all energies and shows the "true" dose rate? Or, does it have an under- or over-response at certain energies that require manual corrections? How does the energy response of the meter match with the energies that you need to measure?
- **Response time for dose rate** – For how long do you need to measure to get a stable reading?
- **Stabilization time at start-up** – How long does it take from power on until the meter is ready to use?
- **Data collection and analysis** – Does the meter save measurements automatically? Do the data analysis options suit your needs?

There is a wide selection of survey meters on the market. Some have a broad application range and others are more specialized. Consider what your key measurement needs are and where you would save time in your work.

SUMMARY

To perform leakage measurements in accordance with the referred standards and regulations, it is necessary to consider:

- if the radiation is continuous or in short exposures
- if the radiation is assumed to be homogeneous or non-homogeneous
- the area, over which the dose is averaged
- the distance to the focal spot of the X-ray machine
- the properties of the survey meter

Finally, standards and regulations may provide guidelines, but it is still the person conducting the leakage measurement that is responsible for the accuracy and reliability of the results. While the immediate goal of a leakage measurement is to establish performance of the X-ray machine within a limit, in the end, this limit is stated by regulatory bodies in order to reduce unnecessary radiation to patients and hospital staff.

CONTACT

Please visit www.raysafe.com for more information.

RaySafe™