

A Field Guide to Radiation Safety Terminology

An overview of key radiation dosimetric quantities and terms.

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Radiation safety is an important topic for interventionalists, and one of the most confusing aspects of this field is the variety of terms that are used. The average interventionist may not use this terminology on a regular basis; therefore, definitions and acronyms can become blurred, and terms can be used imprecisely.

Interventionalists use the term “dose” on a daily basis and in a fairly casual fashion. We want to optimize dose and speak of it with regard to patients, staff, and operators, but what is it? “Dose” may mean absorbed dose or effective dose (ED), but it may also refer to peak skin dose (PSD) or even x-ray tube output. For complex procedures, we are concerned about the risk of adverse skin reactions, in which case the dose of interest is the PSD. When patients or their families inquire about the dose from a procedure, they are more likely concerned about the risk of cancer induction, given the attention paid to this issue in the popular press. In this situation, the ED is a more relevant parameter, although we are currently unable to estimate individual risks accurately. Given these common uses, attention should be paid to the context, as this will often reveal the intent.

The purpose of this article is to provide a “field guide” that can be used as a quick review prior to reading the rest of this issue of *Endovascular Today* and also as a quick reference in the future. It is not comprehensive; therefore, the references cited should be considered suggested reading for the motivated reader to learn more. Common terms to clarify and add precision to our communication on matters regarding “dose” are reviewed herein.

FUNDAMENTAL TERMS

Kinetic Energy Released in Matter (kerma)

This is the energy released from an x-ray beam per unit mass of a specified material in a small irradiated volume of matter (eg, air, soft tissue). For x-rays in tissue, this is numerically equivalent to the absorbed dose.¹ The unit of measurement is the gray (Gy). One Gy is equivalent to one joule (J) of energy per kilogram of matter. For x-rays in air, the kerma is somewhat higher than the absorbed dose, as some of the released energy will be carried out of the small test volume as electron kinetic energy and will not contribute to the local dose.

Air Kerma

Air kerma is the kerma in a small irradiated air volume. Most interventional equipment will report air kerma in milligray (mGy) as well as kerma-area product (KAP). Air kerma is used to characterize the intensity of the x-ray beam² and has replaced the roentgen (R), the old unit of beam intensity. Patient entrance exposures are now reported as air kerma values and indicate the value that would be measured in a patient’s absence to eliminate effects due to backscatter in the patient. Values reported by integrated KAP/air kerma meters are air kerma values at a specified point in space, usually referred to as the interventional reference point (IRP). Machine-reported air kerma values do not take into account beam repositioning or attenuation by the table and therefore tend to overestimate the entrance air kerma (EAK) at the patient’s skin.

Absorbed Dose

Absorbed dose is the energy from ionizing radiation absorbed in matter per unit mass of irradiated material at a

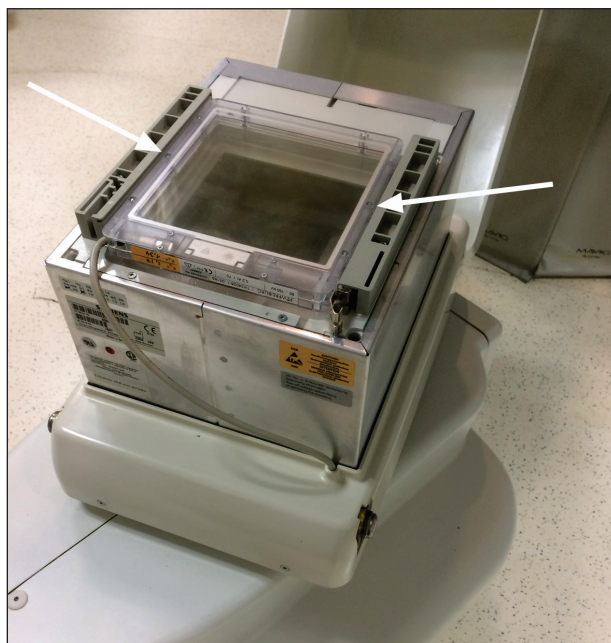


Figure 1. Photograph of a KAP meter, which is visible once the cover is removed from an angiographic unit. The KAP meter is between the arrows, close to the source. The smaller meter, which is used to measure air kerma, is not easily seen because it is transparent.

specific point. This is the quantity that is relevant when considering biological effects. The unit of absorbed dose is the Gy.^{3,4} Note that the absorbed dose does not take into account the type of ionizing radiation or the radiosensitivity of the tissue exposed. It is important to note that absorbed dose is a point measurement. A good analogy is temperature, which reflects the local energy per unit mass of a material. It is typical to have varying absorbed dose values over the region of tissue irradiated during a procedure. This is due to beam repositioning, varying distance from the x-ray focal spot, varying patient thickness that causes changes in x-ray tube voltage and current, as well as other effects.

Equivalent Dose

Different types of radiation, such as x-rays, protons, neutrons, and alpha particles, cause varying degrees of biological damage per unit absorbed dose. In order to take this into account, a weighting factor can be used based on the type of radiation.⁵ By definition, the weighting factor for x-rays is 1. Because x-rays cause biological damage by releasing energetic electrons in tissue, electrons also have a radiation weighting factor of 1.⁵ The unit of measurement is the sievert (Sv), which is the same unit that is used for effective dose.

Effective Dose (ED)

Different tissues have varying degrees of radiosensitivity. For example, breast, bone marrow, and colon are much more radiosensitive than bone surface, brain, and skin.⁵ To account for this, tissue weighing factors have been developed. Mathematically, ED is the sum over irradiated tissues of the product of the equivalent dose and the tissue weighting factor for those tissues. The unit is the Sv.^{4,5} For x-rays, if we could produce a uniform whole-body absorbed dose of 1 Gy, by definition, this results in an ED of 1 Sv.

One can think of ED as a currency measured in Sv, which allows us to compare the relative stochastic detriment of various types of studies that utilize ionizing radiation. It is important to note that tissue weighting factors are based on population age- and sex-specific averages, which contribute significantly to differences in individual risk. There are also other individual risk factors that are not completely understood. Therefore, ED should not be used to retrospectively determine individual risk.⁶

Entrance Skin Dose (ESD)

ESD is the absorbed dose to the skin. This value generally cannot be accurately reported but may be estimated if the EAK is known. To be as accurate as possible, the EAK would be multiplied by a factor to account for the slight differences in energy absorbed by air versus soft tissue due to composition differences. This is a factor of about 1.07 for the beam energies used by interventional machines.⁷ A more important issue is that a significant amount of backscatter is generated in the patient, which increases the skin dose. This increase can be a factor of 1.3 to 1.4.⁷ The backscatter factor is not included in the reference values reported by interventional units and is generally ignored in the author's experience.

Peak Skin Dose (PSD)

PSD is the maximum ESD to the most heavily irradiated localized region of the skin. This would generally be the area of the skin that lies within the primary beam for the longest amount of time during a procedure.⁴ PSD is difficult to measure, as using film or thermoluminescent detectors placed directly on the patient is impractical,⁸ and angiographic units that can estimate it are not widely available.

METRICS USED TO HELP ESTIMATE DOSE

Fluoroscopic Time

This is the length of time that fluoroscopy is used during a procedure. It is the least useful metric to use for estimating dose or risk because it does not take into account the fluoroscopic frame rate, collimation, geometry, or beam intensity, and it does not include any fluorographic imaging ("spot" images and digital subtraction angiography).

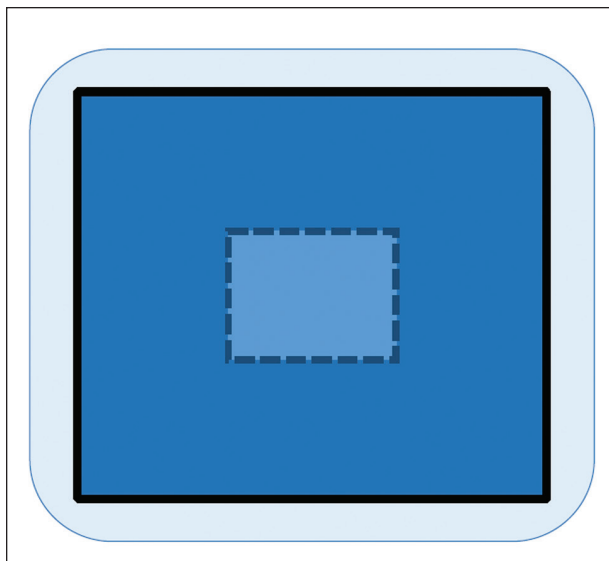


Figure 2. Illustration of the relationship between the beam, KAP meter, and air kerma meter. Outermost shaded area represents the KAP meter, which must intercept the entire beam (solid black line) to accurately calculate KAP. A meter represented by the dashed lines in the center represents the meter that captures air kerma at this point. The $K_{a,r}$ is then calculated for the IRP using the inverse square law.

Kerma-Area Product (KAP)

KAP may also be called the dose area product (DAP). The KAP or DAP is the product of the intensity of the radiation beam (air kerma) multiplied by the area of the beam and is the appropriate way to measure the total amount of radiation delivered to the patient.² It is the most relevant metric when considering stochastic risks but does not indicate the likelihood of skin reactions. More recent publications may abbreviate KAP as P_{KA} .

KAP is measured very close to the source of radiation using a KAP meter (Figure 1). The meter is slightly larger than the beam in order to capture the entire beam (Figure 2). KAP is measured in gray-centimeters squared ($Gy \cdot cm^2$), but may be reported as some variation of this unit, such as $\mu Gy \cdot m^2$. Conversion tables for units reported by commonly used equipment are available.³ Operators should check their equipment to see how KAP is reported and become familiar with how to quickly convert it to $Gy \cdot cm^2$, as this unit is typically used in the literature.

Of note, the KAP does not change along the path of the x-ray beam, as the air kerma decreases by the inverse square law, and the area of the beam increases in the same fashion as distance from the source increases. In other words, KAP as the beam leaves the source is the same as KAP just before the beam enters the patient.

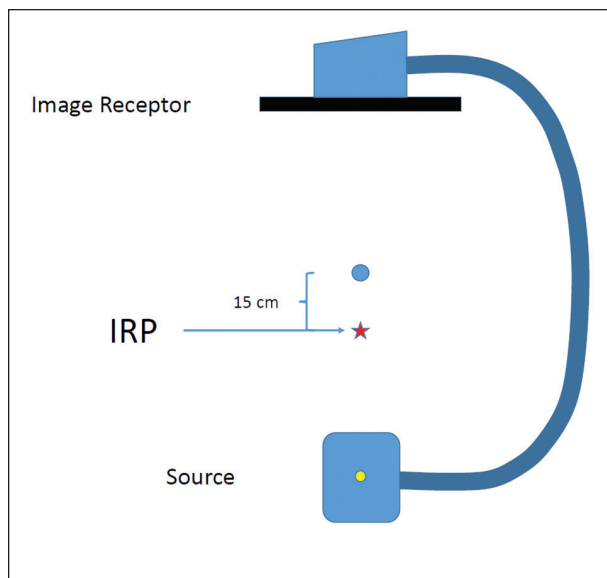


Figure 3. Diagram illustrating the relationship between the source (yellow dot), the image receptor, the isocenter (blue dot), and the IRP. The IRP is fixed and may not precisely correspond to the patient's skin level.

Reference Air Kerma ($K_{a,r}$)

Air kerma measured at a fixed point in space is known as the interventional reference point (IRP).³ $K_{a,r}$ is only a rough approximation of skin dose; however, as discussed previously, it is not equivalent to the skin dose. The IRP may correspond to the skin level, a point within the patient, or a point outside of the patient. In addition, $K_{a,r}$ does not include beam repositioning, backscatter, or the attenuation of the table.^{1,3} $K_{a,r}$ has also been referred to as cumulative dose¹ and air kerma at the reference point.⁴

Interventional Reference Point (IRP)

For isocentric fluoroscopic systems, IRP is a point in space along the central x-ray beam, 15 cm back from the isocenter toward the x-ray tube (Figure 3). This is the point where the $K_{a,r}$ is reported.³ Because of variability in patient size, operator height, and angle of the C-arm, the IRP does not precisely correspond to the skin surface. It is worth noting that no meter is positioned at the IRP. Rather, air kerma is measured close to the source (Figure 2) in the center of the beam. Then, using the inverse square law, the value is calculated for the IRP and displayed.

RISKS

Deterministic Effect

Deterministic effect is the detrimental impact caused by radiation, in which the effect is not seen unless it reaches a certain threshold. However, once the threshold is exceeded, the severity of injury increases with increasing dose. Sunburn

TERMS AND THEIR DEFINITIONS

Term	Definition
Kerma	Kinetic energy released in matter
Air kerma	Kerma in a small irradiated air volume
Absorbed dose	The energy from ionizing radiation absorbed in matter per unit mass of irradiated material at a specific point
Entrance skin dose	The absorbed dose to the skin
Peak skin dose	The maximum entrance skin dose
Kerma area product	The product of the air kerma and the area of the beam; the appropriate way to measure the total amount of radiation delivered to the patient
Reference air kerma	Air kerma measured at the interventional reference point

is a reasonable analogy to keep in mind, and skin injury and hair loss are typical examples of deterministic effects. The higher the dose, the worse the skin injury can be.^{3,8}

Stochastic Effect

The probability of a stochastic effect occurring increases with increasing dose; however, the severity of the effect does not increase. Cancer and hereditary effects are stochastic in nature. In other words, the chance of a cancer occurring increases with increasing dose, but the severity of the cancer does not. The assumption here is that even a very low dose carries some risk.^{5,8} The model typically referred to is the “linear no-threshold model”—this topic is controversial, as other models that challenge this assumption do exist.⁵

OTHER IMPORTANT TERMS

Source-to-Skin Distance (SSD)

SSD is the distance from the radiation source to the patient’s skin. This is in part determined by the operator’s height, which may influence table height. Because of the inverse square law, small changes in this distance can significantly impact patient dose.⁹ A small increase in the table height may result in a significant decrease in the patient dose.

Source-to-Image Distance (SID)

SID is the distance from the radiation source to the image receptor/flat panel detector. In general, by bringing the image receptor close to the patient (thereby reducing what is referred to as the “air gap” as well as the SID), the patient’s dose will be decreased.⁹

Scatter

Scatter radiation generated in the patient’s body is the primary source of radiation exposure to personnel.

A simple rule of thumb is that the scatter exposure 1 m from the beam entrance point will be about 1/1,000 of the exposure at the entrance point, or 0.1%.

Lead-Equivalent Thickness

Radiation protective shielding and garments are designed to attenuate the majority of the incident radiation upon them. This relates to lead’s ability to attenuate x-rays and is known as the lead-equivalent thickness. Material with a lead equivalent of 0.5 mm will attenuate x-rays to the same degree as 0.5 mm of lead.⁴ The standard is considered 0.5-mm lead equivalence, although lighter materials are available with little reduction in the attenuating abilities.⁴

Threshold Dose

Threshold dose is the minimum dose at which a specific deterministic injury can occur.¹ This threshold varies among individuals because of biological variation and also varies across tissue types.^{1,5} Numbers worth remembering are a PSD of 2 Gy (2,000 mGy), as this is the approximate threshold for transient skin erythema, and 5 Gy (5,000 mGy), which is the $K_{a,r}$ at which patient follow-up is recommended.³ ■

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