Specificity of dosimetry in diagnostic radiology

Dosimetry methods intended for pulsed and multipulse X-rays used in diagnostic radiology are discussed. For the determination the X-ray machines' radiation output the use of integral quantities is proposed: dose and the electric charge per exposure, and for dosimetric measurements the use of dose per exposure.

Key words: X-radiation; dose per exposure; electric charge per exposure; ICRP Publication 74.

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In modern medical X-ray diagnostics in order to minimize image distortion associated with patient movement during examination, X-ray exposures of short duration are used. To prevent anode overheating the radiation used in fluoroscopy also consists of short pulses. Below we are considering distinctions between dosimetry in X-ray diagnostics and dosimetry in stationary radiation fields resulting from pulsed nature of X-rays in the first case.

The purposes of dosimetry in X-ray diagnostics are:
- determination of the radiation characteristics of X-ray machines;
- dosimetry of patients;
- dosimetry of staff.

Radiation output.
The quantity “radiation output” is adopted as the parameter that determines radiation characteristic of X-ray machine; it is defined in SanPiN 2.6.1.1192-03 [1] as follows: “the ratio of the absorbed dose rate (air kerma) in the primary beam of X-ray radiation at a fixed distance from the tube focus, multiplied by that distance squared, and the anode current”. The squared distance in this definition is present to bring the measured value of the dose rate at 1 m distance, as the dose rate changes inversely with the square of the distance from the source.

The values of the radiation output are used for estimation of the expected personnel exposures, for shielding design of X-ray rooms and for calculation of patients’ doses. Determination of the radiation output is performed when the X-ray machine is manufactured; afterwards the constancy of its value is checked in the context of periodic monitoring of operating parameters. Change in the radiation output is the evidence of apparatus aging (due to the anode aging and other causes).

The fact that radiation output quantity is used for dosimetry of patients and staff suggests measurement of dose, not the dose rate for its determination, because pulsed nature of the X-rays used in diagnostic radiology does not allow correct measurement of the dose rate. For example, Figure 1 shows the profile of X-ray pulse obtained with dosimeter Unfors.

Dosimeter Unfors, as can be seen from Figure 1, correctly measures the dose and calculates the dose rate by dividing the dose by the duration of exposure. The uncertainty of the dose-rate calculation due to the difference between dose measurement interval and measured duration of exposure is low due to the fact that the instrument determines pulse profile in details by recording signal from detector (every 100μs). In addition, the measurement results are stored in memory, and it is possible to introduce corrections in the results.

Figures 2 and 3 show the radiation pulses in multipulse fluoroscopy and radiography using a half-wave single-phase generator. In examples shown in Figures 2 and 3, the dosimeter will measure the total dose from the individual X-ray pulses and calculate the average dose rate by dividing the value of the dose by the duration of exposure. However, it would be incorrect to calculate the value of the radiation output obtained by dividing the average dose rate by the anode current value set on the X-ray machine, as required by the definition of the radiation output quoted above, because during considerable part of the exposure the current was actually absent. In addition, in this case we do not have a unified approach to determining the values of the radiation output of X-ray machines with a continuous radiation and machines with different pulse filling factor (the filling factor is the ratio of the pulse repetition period and their duration). In the Figure 3 the filling factor is approximately equal to four, i.e. the same dose of radiation exposure will be created by continuous radiation with at least 4 times less anode current and, consequently, the radiation output in accordance with the above definition will be 4 times higher.
Figure 1. Pulse profile of X-ray radiation when performing measurements using dosimeter Unfors

In fact, the term “radiation output” has the following physical meaning: it is the amount of radiation, generated by the X-ray tube per quantity of electricity unit (quantity of electricity passed through the tube), i.e. actual efficiency factor (EF) of the tube. The amount of radiation is best characterized by the absorbed dose in air (air kerma).

In the ICRU Report 74 [2] the following definition of the radiation output is given: “The x-ray tube output, $Y(d)$, is defined as the quotient of the air kerma, $K_a(d)$, at a specified distance, $d$, from the x-ray tube focal spot (usually 1 m) by the tube-current exposure–time product, $Pit$. Thus $Y(d)=K(d)/Pit$. Unit: $J/(kg/C)$, or $Gy/mA·s$. (Here $Y(d)$ is the radiation output, $K(d)$ is the air kerma).

The first unit, $J/(kg/K)$ corresponds to the physical meaning of the term “radiation output”, but the definition itself where the “product of current and the exposure time” is used allows an incorrect interpretation in case of multipulse exposure. The dose rate ($Gy/s$/mA in the definition of “radiation output” given in SanPiN 2.6.1.1192-03 [1] was introduced because time in seconds in the product mA·s is treated incorrectly by authors of this document as the interval of kerma measurement, whereas actually it is the time during which the radiation was generated: the pulse duration for single-pulse exposure and total duration of pulses for multipulse exposure.

For the correctness of formulations presented above and below, we need to introduce the definition of “exposure” as the “process of single exposure of image receiver (or patient) that is performed for production of one X-ray image or during one fluoroscopic procedure”.

In this way we can then offer a definition of “radiation output”, which is fully in line with its physical meaning: the radiation output $Y(d)$ is the ratio of the absorbed dose in air $K(d)$ at a distance $d$ from the focus of the tube, multiplied by the square of the distance, to the quantity of electricity during the exposure interval ($P$): $Y(d) = K(d)·d^2/P$. The measurement unit is $Gy·m^2/(mA·s)$. 
Dosimetry of patients.

The dosimetry of patients was discussed in detail in [3], but we would like to add that dosimetry of patients is not subject to regulation, and hence no dose limits are set in section 5.4.1 of the Radiation Safety Norms NRB-99/2009 [4], so there is no need to determine effective doses of patients for comparison with dose limits.

At the same time aspects of dosimetry of persons who are examined in connection with their professional activities or for medical-legal purposes or in the course of medical or scientific studies requires separate discussion, because in accordance with section 5.4.4 of NRB-99/2009 the their annual effective dose should not exceed 1 mSv.

Determination of patients’ effective doses is a complex process, as evidenced from the Figure 4 quoted from the ICRP Publication 74 [5].

As can be seen from Figure 4, the ratio of effective dose to air kerma (of absorbed dose in air) in the energy range of interest of up to 100 keV, strongly depends on both the photon energy and the exposure projection; besides, it depends on the age of the exposed person (Fig. 5).

In regard to the foregoing, it is diagnostic reference levels (DRLs) introduced in OSPORB-99/2010 [6] in measurable terms that should be used as a tool for radiation protection of patients, not effective doses. The practicability of establishing values of DRLs in terms of the dose area product (DAP) for general procedures was discussed in detail elsewhere [3]. Procedures for establishing and monitoring DRLs in medical institutions require it would be reasonable in these areas to look at the experience of European countries.

In Sweden, for example, in accordance with the Swedish Radiation Safety Authority recommendations [7] diagnostic reference levels for several general purpose procedures are set in terms of DAP, for mammography “average glandular dose” (AGD) in Joules is used and for CT it is “Computed Tomography Dose Index” (CTDIvol) and “dose length product”, (DLP).

Dependence of the ratio of effective dose to air kerma on the energy of photon radiation for AP projection and different ages of exposed persons.

The value of DAP is directly measured by a dosimeter of DRK-1 type, and for the determination of AGD in J it is necessary to measure the dose at the surface of the breast $D_{\text{SURF}}$ by dosimeter DRK-1 [8] or Unfors. The transition from $D_{\text{SURF}}$ to Joules is carried out using the coefficient, which depends on the “half-value layer” of radiation and the compressed breast thickness. To determine the CTDI and DLP doses measurements shall be performed in special of phantoms, according to correspondent procedures. Thus, determination of DRLs is in general not feasible for the staff of health facilities with the exception of general purpose X-ray procedures, which is feasible provided DRK-1 is available. Due to this it would be appropriate to assign this task to testing laboratories, which carry out monitoring of performance characteristics of X-ray machines.

Dosimetry of staff.

Personal dosimetry of medical staff is carried out in two ways:
- radiation monitoring at workplaces;
- personal monitoring (for group “A” personnel according to Russian regulations, i.e. radiation workers).

Radiation monitoring at workplaces. Workplace monitoring is conducted to determine annual doses for group “B” personnel (non-radiation workers, whose workplace is close to the source) and to forecast doses of group “A” personnel. Determination of annual doses of the group “A” personnel is carried out based on the results of individual monitoring.

In the dosimetry of staff regulation and dose limits are in place, so operational quantities should be applied in this case, determined in the guidelines MU 2.6.1.2118-06 [9] as “the quantity that is definitely determined through physical characteristics of the radiation field at a given point, and as close as possible, under standard conditions, to
the quantity, which is subject to regulation in order to limit the exposure, and is designed for a conservative estimate of this quantity in the context of radiation monitoring”.

During the workplace monitoring is necessary to measure the operational quantity, which is the ambient dose equivalent $H^*(10)$ and, by comparing its value with the dose limit (effective dose per year) given in the Radiation Safety Norms (NRB-99/2009), determine whether or not the dose limits could be exceeded.

In practice, during the workplace monitoring the dose rates $H^*(10)$ (in $\mu$Sv/h) are measured and are multiplied by the annual working hours, and the resulting value is compared with the dose limits, which is reasonable for stationary exposure conditions. But this practice is unreasonably transferred to monitoring of workplaces with pulsed X-ray sources.

The most commonly used dosimeters for workplace monitoring in the diagnostic radiology are dosimeters equipped with scintillation detectors with a low limit of measured photon energy range of 15-20 keV. Dosimeters measure the dose by recording the number of pulses during the measurement interval and calculate the dose rate dividing the measured dose value by the time of measurement. At that, the time is measured with a specific increment. For example, in the operational manual for dosimeter DKS-AT1123 [10] it is specified as follows: “The dosimeter determines the exposure time as the time starting from the moment when the dose exceeds 3-5 $\mu$Sv/h. The time is determined in increments of 10 ms”. In the same manual a figure is presented showing the pulse profile described by the instrument (Fig. 6).

![Figure 6. Pulse profile described by dosimeter DKS-AT1123.](image)

It is clear from the operation manual and Figure 6 that the dosimeter automatically starts the dose rate measuring mode when the dose rate exceeds 3-5 $\mu$Sv/h after a pulse occurs and then calculates current dose rate value every 10 ms. Consequently, for a 4 ms pulse duration, for example, the dose will be calculated by dividing the dose by 10 ms, thus the dose rate will be understated by 2.5 times.

In the case of pulsed radiation, as in Figures 2 and 3 the maximum and effective values of dose rates indicated by the dosimeter will also provide inaccurate characteristics of the dose received by personnel during exposure.

As in the case of determination of the radiation output there is the only way out of this situation, namely to measure the dose during the exposure but not dose rate when monitoring workplaces.

The procedure is simple. It is necessary to start measurement, for example, as described for dosimeter DKS-96G [11]: “Select the DOSE mode from the menu by pressing MODE and SELECT buttons. Press and release the START button. From this point on, the dosimeter -radiometer begins to accumulate dose. Its value is displayed on the display in $\mu$Sv or mSv depending on the sub-range”, and turn on the X-ray machine in a controlled mode.

Based on measured dose values $H^*(10)$ for the exposure and the workload of the X-ray machine (Table 4.1 in SanPiN 2.6.1.1192-03 [1]) the annual dose $H^*(10)$ at the workplace is calculated in accordance with guidelines MU 2.6.1.2118-06 [9] as follows: $H^*(10)_{\text{YEAR}} = H^*(10) \times W \times 52 / P$, where: $H^*(10)$ is the measured dose during exposure, $\mu$Sv; $W$ is the X-ray machine workload (mA-min)/week; $P$ is the amount of electricity per exposition, mA\hspace{0.1cm}s; 60 is “seconds per minute” and 52 is “weeks per year”.

The change in the formula above, compared with formula in MU 2.6.1.2118-06 is that in definition of the amount of electricity during exposure the product of the current and exposure time (I*t) is excluded in order to avoid incorrect interpretations in case of multipulse exposure.

Comparison of workplace monitoring results with dose limits. In accordance with the above definition of the operational quantity the annual dose $H^*(10)$ is a conservative estimate of the quantity for which the limit is set – the effective dose, and it should be compared with dose limits: 20 mSv per year for the group “A” personnel and 5 mSv per year for group “B” personnel.

Conservatism of the effective dose (E) assessment using the operating values of $H^*(10)$ lies in the fact that the values of $H^*(10)$ for all photon energies are above E values (Fig. 7 [5]).
As can be seen from Figure 7, the overestimation of the effective dose using the dose $H^*(10)$ for photons of high energy ($60$ keV $– 10$ MeV) is in the range 10 to 25%, but for the region of interest of X-ray radiation it is even bigger: for example, for $40$ keV $–$ from 40% to 2-fold for different exposure projections.

**Individual monitoring (personal dosimetry).** With the purpose of individual monitoring (IR) of staff the operating quantity is measured, which is the personal dose equivalent $H_p(10)$, by a dosimeter worn on the chest, and the effective dose is considered numerically equal to the reading of a dosimeter $H_p(10)$. In some cases personal dose equivalent $H_p(0.07)$ - the dose to the skin and $H(3)$ - the dose to the lens of eye are also measured.

**Comparison of individual monitoring results with dose limits.** Estimation of the effective dose with the help of personal dose equivalent $H_p(10)$ in the X-ray energy range is also highly conservative for all exposure projections except for posterior-anterior (Fig. 8 [5]).

The designations $H_p$,slab $(10, \alpha)$ in the Figure 8 mean that the equivalent dose was determined for the dosimeter located on a flat phantom, at a depth of 10 mm, with an angle $\alpha$ between incident radiation and perpendicular to the surface.

It is difficult to estimate the ratio of effective dose and dose $H_p(10)$ for lateral (LAT) and isotropic (ISO) exposures due to definition of personal dose equivalent $H_p(d)$: the dose equivalent in soft biological tissue, determined at the depth $d$ (mm) under considered point on the body (see Fig. 8).

According to this definition the human body is modeled by a flat phantom, and comparison of calculated effective dose with $H_p(10)$ for the LAT and ISO exposure projections is impossible because of strong differences in the geometry of the phantom and the human body. Therefore, in Figure 7 for the LAT and ISO projections ratios are shown of the effective dose and the directional dose equivalent $H'(10,\alpha)$, for which the human body is modeled by the ICRU sphere (Fig. 9).
According to this definition, measurement of dose $H^*(10,\alpha)$ is performed at depth of 10 mm along the radius of tissue equivalent sphere with incidence of radiation at an angle $\alpha$ to the radius.

At Figure 8 sufficient underestimation can be seen of the effective dose using the dose $Hp(10)$ measured by a dosimeter worn on the chest, when the X-ray exposure is from behind (PA projection) due to a significant absorption of low-energy radiation in the human body. In practice, except in rare cases to be discussed below, the exact location of staff in relation to the radiation source is not known, so it is assumed that the underestimation of the effective dose for one location will be offset by the overestimation for the other. However, we believe that the introduction of reduction factors to $Hp(10)$ when evaluating the effective dose as it was done in [9] is incorrect.

One of the cases where we know the locations of staff and radiation source are interventional fluoroscopic procedures during which staff wear two dosimeters: under the apron at the chest and over the apron. The following formula was introduced by the US National Council on Radiation Protection and Measurements for estimation of the effective dose [12]: the effective dose (estimate) is equal to $0.5 \cdot H_w + 0.025 \cdot H_N$, where $H_w$ and $H_N$ are measured $Hp(10)$ under and over the apron. This formula overestimates the effective dose in the range from 6 % to 2.03-fold.

**Conclusion.**

Dosimetry of pulsed and multipulse X-ray radiation in diagnostic radiology should be based on the measurement of integral quantities: the amount of electricity per exposure, i.e. the amount of electricity passed through the X-ray tube during the exposure and dose per exposure, i.e. single exposure of patient to X-ray radiation during radiography or fluoroscopy. The dose per exposure is directly proportional to the amount of electricity per exposure at a given value of anode voltage, and their ratio is independent of the operating modes of the X-ray machine.

In determining the radiation characteristics of X-ray machines and in patient dosimetry, where there dose limits are not set absorbed dose in air is to be measured; in individual monitoring (personnel dosimetry), where dose limits are set, it is necessary to measure operational quantities: the ambient dose equivalent $H^*(10)$ and the personal dose equivalent $Hp(10)$. With respect to persons who are examined in connection with their professional activities or for medical-legal purposes or in the course of medical or scientific studies requires, where there dose limits exist, methods of the effective dose determination shall be in place.

For certain X-ray procedures, where significant radiation doses are possible to the skin of face or hands and to lens of eye may be necessary to measure personal dose equivalents $Hp(0.07)$ and $Hp(3)$.

Conservatism of the effective dose estimates of staff when using operational quantities in the case of X-ray radiation is high enough, and professionals who perform radiation monitoring should be aware of the extent of this conservatism, and be able to use it, if necessary.

**References**


Specialities of dosimetry in X-ray diagnost

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Abstract. Methods of pulsed and multi-pulsed X-ray dosimetry being employed in X-ray diagnostics are discussed. Application of integral quantities: dose and quantity of electricity per unit exposure when determining the radiation output of X-ray machines; dose per unit exposure for dosimetric measurements, is proposed.

Key words: x-rays; dose per unit exposure; quantity of electricity per unit exposure; tCRP Publication 74.

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