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DOSIMETRY FOR MEDICAL APPLICATION OF IONIZING RADIATIONS: CALIBRATION REQUIREMENTS AND CLINICAL APPLICATIONS

Abstract: *Diagnostic and interventional procedures involving x-rays are the most significant contributor to total population dose from man made sources of ionizing radiation. They cover a diverse range of examination types, many of which are increasing in frequency and technical complexity. This has resulted in the development of new dosimetric measuring instruments, techniques and terminologies which affect the work in the clinical environment and calibration facilities. Calibration is an essential part of any dose measurement, in particular if these activities are related to human health. The paper gives an overview of current system of dosimetry in diagnostic and interventional radiology that is relevant for metrology and clinical applications. It also reflects recently achieved international harmonization in the field promoted by International Commission for International Units and Measurements (ICRU) and International Atomic Energy Agency (IAEA). Presented requirements for calibration facilities, in particular for the Secondary Standards Dosimetry Laboratories (SSDL) are given in terms of necessary equipment for generation of beam qualities, dosimetry and auxiliary equipment necessary for operation of SSDL. Objectives of clinical dose measurements in diagnostic and interventional radiology are described, as well as requirements for dosimeters and procedures to assess dose to standard dosimetry phantoms and patients in clinical diverse modalities.*

Key words: diagnostic radiology, dosimetry, kerma, dose to patient, calibrations.

INTRODUCTION

Diagnostic and interventional procedures involving x-rays are the most significant contributor to total population dose from man made sources of ionizing radiation [1]. This is particularly evident for examinations using computed tomography equipment and interventional radiological and cardiology procedures [1,2]. However, x-ray imaging generally covers a diverse range of examination types, many of which are increasing in frequency and technical complexity. This has resulted in the development of new dosimetric measuring instruments, techniques and terminologies which affect the work both in the clinical environment and calibration facilities [3-6].

This paper gives an overview of dosimetry in diagnostic and interventional radiology, that is relevant both for metrology and clinical applications.

1. BASIC METROLOGY ELEMENTS

The International Measurements System (IMS) for radiation metrology provides the framework for dosimetry in diagnostic radiology. It ensures consistency in radiation dosimetry by disseminating to users calibrated radiation instruments, which are traceable to primary standards. The IMS consists of Bureau International des Poids et Mesures (BIPM), national Primary Standard Dosimetry Laboratories (PSDL), Secondary Standards Dosimetry Laboratories (SSDL) and various users performing measurements [3]. A PSDL is a national laboratory designated by the government for the purpose of developing, maintaining and improving primary standards in radiation dosimetry. A PSDL participates in the international measurement system by making comparisons through the medium of the BIPM and provides calibration services for secondary standard instruments. An SSDL may be either national or regional. A national SSDL is a laboratory which has been designated by the competent national authorities to undertake the duties of a calibrating laboratory within that country. An SSDL is equipped with secondary standards which are calibrated against the primary standards of laboratories participating in the IMS [5,7-9].

A decade ago, the SSDL were focused only on the calibrations in the field of radiotherapy and radiation protection [8,9], while diagnostic radiology calibration have drown attention in the last decade due to increased demands for establishment of quality assurance programme in diagnostic radiology [5,6].

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DOSIMETRIC QUANTITIES IN DIAGNOSTIC RADIOLOGY

Dosimetric quantities are used in diagnostic and interventional radiology for patient dose assessment, establishment of diagnostic reference levels and assessment of equipment performance.

Set of dosimetric quantities and units used for patient dose assessment in the diagnostic and interventional radiology reflects recently achieved international harmonization in the field promoted by International Commission for International Units and Measurements (ICRU) and International Atomic Energy Agency (IAEA) [3,4]. This concept is now based on the dosimetric quantity air kerma. A number of earlier publications have expressed measurements in terms of the absorbed dose to air. Recent publications point out the experimental difficulty in determining the absorbed dose to air, especially in the vicinity of an interface; in reality, what the dosimetry equipment registers is not the energy absorbed from the radiation by the air, but the energy transferred by the radiation to the charged particles resulting from the ionization. For these reasons, ICRU recommend the use of air kerma rather than absorbed dose to air, that applies to quantities determined in air, such as the entrance surface air kerma (rather than entrance surface air dose) and the kerma-area product (rather than dose–area product) [4]. The PSDL maintains the primary standard of quantity air kerma and therefore, all calibrations at PSDL and SSDL are performed in terms of air kerma. This quantity is also the basis for other application - specific quantities used in diagnostic and interventional radiology.

The incident air kerma, K_i, is the kerma to air from an incident x-ray beam measured in the central beam axis at the position of the patient or phantom surface. Backscattered radiation is not included in this quantity and unit is gray (Gy). Entrance surface air kerma, K_e, is the kerma to air in the central beam axis at the position of the patient or phantom surface that includes backscattered radiation. The entrance surface air kerma is related to the incident air kerma by the backscatter factor, B: $K_e = K_i \cdot B$. The air kerma-area product, P_{AK} or *KAP*, is the integral of the air kerma over the area of the x-ray beam in a plane perpendicular to the beam axis: $P_{KA} = \int_A K(x,y)dxdy$, while unit of this quantity is Gy·cm^2. This quantity is used for dose assessment in radiography and fluoroscopy. The air kerma-length product, P_{KL}, is the integral of the air kerma over the line: $P_{KL} = \int_L K_{air}(z)dz$. The unit of this quantity is Gy·m. P_{KL} is applied for computed tomography and dental panoramic dosimetry [3,4]. Apart from above listed dosimetric quantities a quantity called practical peak voltage is measured to provide consistent information of the x-ray tube and generator voltage as a part of quality assurance process [3, 10,11].

CALIBRATION OF DOSIMETERS IN DIAGNOSTIC RADIOLOGY

Calibration is an essential part of any dose measurement, in particular if these activities are related to human health. Thus, all instruments used in conventional diagnostic radiology, interventional radiology, mammography and CT must be calibrated, having a valid calibration certificate from an accredited calibration laboratory, typically SSDL.

Requirements for calibration facilities, in particular for the SSDL are given in terms of necessary equipment for generation of beam qualities, dosimetry and auxiliary equipment necessary for operation of SSDL. All equipment used for calibration at an SSDL shall be of a reference class and be available in duplicate at the SSDL. This includes: ionization chambers, electrometers, thermometers, barometers and a device to measure the relative humidity of air [12]. As already mentioned, reference standard for diagnostic radiology calibrations is an ionization chamber, and it should comply with International Electrotechnical Commission (IEC) 61674 standard in order to perform measurements with sufficient accuracy and reliability [13]. Radiation beam quality is the indication of photon fluence spectrum. In practice, it is determined by the tube voltage, first and second half-vale layer (HVL) and total filtration [5]. Required radiation qualities shall be established in accordance with recommendations given in the standards of International Electrotechnical Commission (IEC) [14]. The qualities used for the calibration of dosimeters for different applications are shown in the Table 1.

Table 1. *Radiation qualities used for calibrations in diagnostic radiology. Adopted from [3]*

Radiation quality	Radiation origin	Phantom material	Application
RQR	Unfiltered beam emerging from x-ray assembly	No phantom	General radiography, fluoroscopy, dental radiology
RQA	Radiation beam from an added filter	Aluminium	Measurements behind the patient (on the image intensifier)
RQT	Radiation beam from an added filter	Copper	CT applications (free in air)
RQR-M	Unfiltered beam emerging from x-ray assembly	No phantom	Mammography (free in air)
RQA-M	Radiation beam from an added filter	Aluminium	Measurements behind the patient (on the image intensifier)

For conventional radiography, fluoroscopy, CT and dental applications a tungsten anode tube and x-ray unit operating at the x-ray tube voltage ranging from 50 kV to 150 kV are used. For the calibration of mammography dosimeters, a molybdenum anode tube with molybdenum filtration is recommended.

The detailed description of methods for establishment of beam qualities used for calibrations in diagnostic radiology is given in the International Code of Practice [3].

The general principles for the calibration of dosimeters used in diagnostic and interventional radiology are similar to principles valid for instruments used in radiotherapy and radiation protection [8,9]. The SSDL shall provide a calibration coefficient in terms of air kerma or air kerma-length product, where appropriate. Air kerma-area product meters require great care in their calibration, as their performance depends on the actual set-up in the hospital. They may be calibrated *in situ*.

The calibration of dosimeters is usually performed using substitution method when quantity under question is measured in the same reference point by reference standard and instrument to be calibrated (user's instrument) [9]. The reading of the reference dosimeter is converted to air kerma or air kerma rate by means of the calibration coefficient that should be supplied by PSDL. To ensure the accuracy of measurements, the calibration and the energy dependence of response must be known to the SSDL. The calibration coefficient should have a form appropriate to the nature of the reference dosimeter.

As the output of the x-ray unit may vary with time it is recommended to use monitor chamber to check stability of the output during calibration. The indications of reference instrument and user's instrument M_{ref} and M_{user} shall be related to monitor chamber readings. For the reference radiation qualities the calibration coefficient is given by equation:

$$N^{user}_{K,Qo} = N^{ref}_{K,Qo} \cdot \frac{M^{ref} k^{ref}_{TP}}{M^{user} k^{user}_{TP}} \cdot \frac{(mk_{TP})^{user}}{(mk_{TP})^{ref}} \qquad (1)$$

where m is reading from the monitor chamber and k_{TP} correction for temperature and pressure. For other beam qualities further correction is applied [3]. The general procedure described above applies to calibrations in terms or air kerma, however, whereas calibrations in terms of kerma-area product and kerma-length product are considered as special cases. Computed tomography dosimeters are designed for non-uniform exposure from a single scan. Primary beam is not more than 10 % of the full length of the chamber [15]. The calibration of this type of dosimeter is performed in air in a uniform x-ray field with known air kerma rate by irradiation of a well defined fraction of the useful volume of the chamber. The calibrated quantity is the air kerma-length.

The actual measurement using KAP meter is the integral of the exposure over the area of the x-ray beam. The calibration of such a device needs to include the ionization response and the correct beam area. The reading is the product of air kerma and the area of the x-ray field. The units are usually in Gy·cm^2. Various methods for KAP meter calibration are described in the literature, performed in situ and at a SSDL [3,6]. *Larsson et al.* suggested laboratory calibration by mapping X-ray field to account for field heterogeneity [16]. Such calibration may be time consuming and inappropriate for field application. Field calibration is performed in the geometry and beam quality used clinically. The air kerma-product, P_{KA}, should be determined for the x-ray beam transmitted through the chamber and incident on the patient.

The uncertainty of calibration procedure is related to the complexity and quality of the established reference radiation for a particular calibration. The contributing factors to the uncertainty budget include properties of high-quality specialized equipment, physical and radiological environment, and presence of skilled and experienced personnel. The level of uncertainty should be appropriate to the use of the measurement, and it should be derived by the each calibration laboratory. Typically, uncertainty of calibration in the field of diagnostic radiology is of order of magnitude of few percents, expressed as relative, combined and expanded uncertainty.

DOSIMETERS IN DIAGNOSTIC RADIOLOGY

Ionization chambers are the main devices used for dosimetry in diagnostic radiology [3]. In the energy region considered, the free air chamber is the primary standard for realizing the unit of air kerma [3,5]. The advantage of ionizing chamber as a dosimetric device is precision, easy use and few other complicating factors [3]. Parallel-plate ionization chambers are mainly used, but cylindrical chambers are used, as well. Air kerma area-product meters are special types of parallel plate ionization chambers used to measure the integral of air kerma over the beam area. Parallel plate ionizing chambers are calibrated with plates perpendicularly oriented to the beam axis. They are also used in the same orientation for patient dose measurement. The response of the cylindrical chamber is symmetrical with respect to the chamber axis. A version of cylindrical ionizing chamber, designed for non-uniform response, is used for computed tomography dosimetry.

Other devices with special properties like thermoluminescent or semiconductor detectors are also used in diagnostic radiology. Real-time measurements can be accomplished with semiconductor dosimeters, while small size thermoluminescent dosimeters are used for measurements on patients. The main disadvantage of these dosimeters is their energy dependence of response that differs from ionizing chambers. In addition, those dosimeters must always be calibrated against ionizing chamber. The required accuracy and precision of a given measurement will depend on the purpose for the measurement and the type of equipment being monitored. It is recommended that the combined uncertainties of in-beam dose measurements not exceed ±10% [3].

CLINICAL DOSIMETRY IN DIAGNOSTIC RADIOLOGY

Due to increasing importance of radiation burden for medical x-ray examination, clinical dosimetry is becoming an active research and practical area. Objectives of clinical dose measurements in diagnostic and interventional radiology are multiple, as assessment of equipment performance, optimization of practice trough establishment of diagnostic reference levels (DRL) or assessment of risk emerging from use of ionizing radiation [2]. Various dosimetric quantities are needed to assess radiation exposures to humans in a quantitative way, in order to assess dose–response relationships for health effects of ionising radiation which provide the basis for setting protection standards as well as for quantification of exposure levels. However, risk-related dosimetric quantities as absorbed dose or equivalent dose to the tissue or organ have been established. Either for measurements on patients or on phantoms, different application-specific dosimetric quantities were established. Therefore, from the clinical point of view, procedures to assess dose to standard dosimetry phantoms and patients in clinical diverse modalities, as radiography, fluoroscopy, mammography and computed tomography include measurements of a) incident air kerma, entrance surface air kerma and kerma-area product (radiography); b) kerma-area product and entrance surface air kerma rate (fluoroscopy); c) incident and entrance surface air kerma (mammography); and d) kerma-length product (computed tomography). Measurements on phantoms cannot provide an estimate of the average dose for patient population. Therefore, these must be supplemented by measurements on patients. As an example, results of patient dose assessment in Serbia for diverse x-ray examinations are presented in Table 2.

Table 2. *Typical patient dose levels from x-ray examinations in Serbia*

X-ray examination type	
Radiography	**Entrance surface air kerma [mGy]**
Chest PA	0.3
Cervical spine	4.1
Thoracic spine	9.9
Lumbar spine	13
Abdomen	3.3
Pelvis	3.0
Mammography	1.8
Fluoroscopy	**Air kerma-area product [Gy·cm^2]**
Barium meal	11
Barium enema	33
PCI*	99
Comp. tomography	**Air kerma-length product [mGy·cm]**
CT head	1060
CT neck	325
CT chest	350
CT spine	320
CT abdomen	500
CT pelvis	500

*Percutaneous Coronary Intervention

In diagnostic and interventional radiology it is common practice to measure a radiation dose quantity that is then converted into organ doses and effective dose by means of conversion coefficients [3-5]. These coefficients are defined as the ratio of the dose to a specified tissue or effective dose divided by the normalization quantity. Incident air kerma, entrance surface air kerma, air kerma-length and kerma-area product can be used as normalization quantities.

CONCLUSION

With respect to the trend in metrology in the field of diagnostic radiology to calibrate dosimeters in the conditions that are similar to the clinical environment, routines for calibration in terms of air kerma, kerma-area product and kerma-length product for dosimeters used in conventional radiography, fluoroscopy, mammography and computed tomography are described, with emphasis on specific radiation qualities, calibration set up and uncertainty assessment. Objectives of clinical dose measurements in diagnostic and interventional radiology are multiple, as assessment of equipment performance, optimization of practice trough establishment of diagnostic reference levels or assessment of risk emerging from use of ionizing radiation. Therefore, from the clinical point of view, the requirements for dosimeters and procedures to assess dose to standard dosimetry phantoms and patients in clinical diverse modalities, as radiography, fluoroscopy, computed tomography and mammography have been presented here.

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BIOGRAPHY

Olivera Ciraj-Bjelac was born in Inđija, Serbia, in 1972. She received the diploma in physics and the M.Sc. and PhD degree in medical physics from the University of Novi Sad. Her main areas of research include general radiation protection, dosimetry of ionizing radiation, external and internal dose assessment, metrology of ionizing radiation, shielding design, and radiation protection in medicine, in particular dosimetry for high-dose diagnostic and interventional procedures and mammography. She is currently working as senior research associate at the Vinča Institute of Nuclear Sciences, University of Belgrade.

DOZIMETRIJA JONIZUJUĆEG ZRAČENJA U MEDICINSKOJ PRIMENI: METROLOŠKI ASPEKTI I KLINIČKA PRIMENA

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Rezime: *Dijagnostičke i interventne procedure zasnovane na primeni x-zračenja predstavljaju najznačajniji činilac u ukupnoj dozi za populaciju koja potiče od veštačkih izvora zračenja. U ove procedure ubraja se širok spektar metoda, od kojih se mnoge odlikuju tehničkom složenošću i rastućom upotrebom. Posledica ovog trenda je razvoj novih dozimetrijskih metoda, tehnika i merila koje imaju reperkusije na kliničku praksu i metrologiju doze u ovoj oblasti. Etaloniranja predstavljaju sastavni deo svakog merenja doze, posebno ako su ove aktivnosti u vezi zdravlja ljudi. U radu je dat pregled važećeg sistema dozimetrije u dijagnostičkoj i interventnoj radiologiji sa aspekta metrologije i kliničke primene, a u skladu sa preporukama Međunarodne komisije za radijacione jedinice i mere (ICRU) i Međunarodne agencije za atomsku energiju (IAEA). Prikazani su zahtevi za etaloniranje, posebno za Sekundarne standardne dozimetrijske laboratorije (SSDL) i to u pogledu dozimetrijske i druge opreme i potrebnih kvaliteta snopova. U radu su prikazani ciljevi kliničke dozimetrije u dijagnostičkoj i interventnoj radiologiji i metode za određivanje doze za pacijente i standardne fantome.*

Ključne reči: dijagnostička radiologija, dozimetrija, kerma, doza za apcijenta, etaloniranje.