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Technical note

IEC 61331-1: A new setup for testing lead free X-ray protective clothing

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ABSTRACT

Purpose: Lead free protective clothing can create a higher part of secondary radiation (SR) than products that are based on lead. Hence, the attenuation properties may be downgraded. The international measuring standard IEC 61331-1:2014 declares the "inverse broad beam geometry" (IBG) as standard method, which has recently been modified to IBG* by the Physikalisch Technische Bundesanstalt (PTB). Because of the unspecific partial irradiation of the ionization chamber problems in the evaluation of lead equivalence values (LEVs) can occur. An alternative method proposed in this paper overcomes these problems.

Materials and methods: The alternative setup "modified broad beam geometry" (BBG*) was tested and compared to the IBG* method by performing Monte Carlo simulations and radiation measurements including several lead-composite and lead-free protective materials.

Results: Simulations show a reduced collection efficiency of SR under IBG* whereas BBG* features a high degree of SR collection. Material samples with a high amount of SR can feature up to 8% higher LEVs compared to IBG*. For most of the currently salable materials the differences of BBG* vs IBG* amount to < 3% (0.25 mm LEV) and < 1% (0.50 mm LEV). In special cases the currently practiced method can lead to heavier protective clothings.

Conclusions: The proposed BBG* setup meets the specifications of the IEC standard with respect to energy response and SR collection. The method should be implemented in the IEC standard.

1. Introduction

When irradiated with X-rays, lead free protective materials can create more secondary radiation (SR) than lead products. Alternative test methods have to be established to record this additive part of radiation. The new methodologies have to consider the enhanced exposition of the skin and organs close to the skin when protective clothing is worn [1–4]. Hence, in 2014 the new standard IEC 61331-1:2014 (IEC) [5] for the evaluation of attenuation properties was published. The standard is universally applicable to lead, lead free and lead composite protective materials.

The protective properties according to this standard have to be determined as air kerma "attenuation ratio" F and "lead equivalence value" (LEV). Secondary radiation as fluorescence, Rayleigh-, and Compton scatter radiation causes a dose build up that is enhancing the dose directly behind a protective material. For lead-free products elements with atomic numbers Z from 50 (tin) to 83 (Bi) were used mostly as mixtures but also as layers of pure elements. Composite materials typically contain 30–50% lead. Basically all materials used for protective clothings emit SR, even lead. But especially the part of fluorescence radiation rises with descending atomic number Z because the height of the K-absorption edge increases. An enhanced spectral absorption leads to a higher emission of characteristic X-ray photons. The amount of emission depends also on the energy distribution of the primary radiation. Energies at and narrowly above the K-edge are more efficient than far away from that. The dose enhancement factor is called the "build-up factor" B. Detectors used within the IEC measurements should ideally capture the entire SR emitted into the 2π-space at the backside of the tested material.

The general methodology of the LEV-evaluation is to compare F, including SR, measured at definite X-ray energies to that of reference foils consisting of pure lead. The lead thickness with the equal attenuation ratio F compared to the investigated material sample is called the "lead equivalence value". For the detection of SR with energies in the range of 25–35 keV chambers especially designed for phantom measurements on mammographic units are best suited.

IEC 61331-1 defines 3 different setups.

The setup presented in Fig. 1a equals the former method and is

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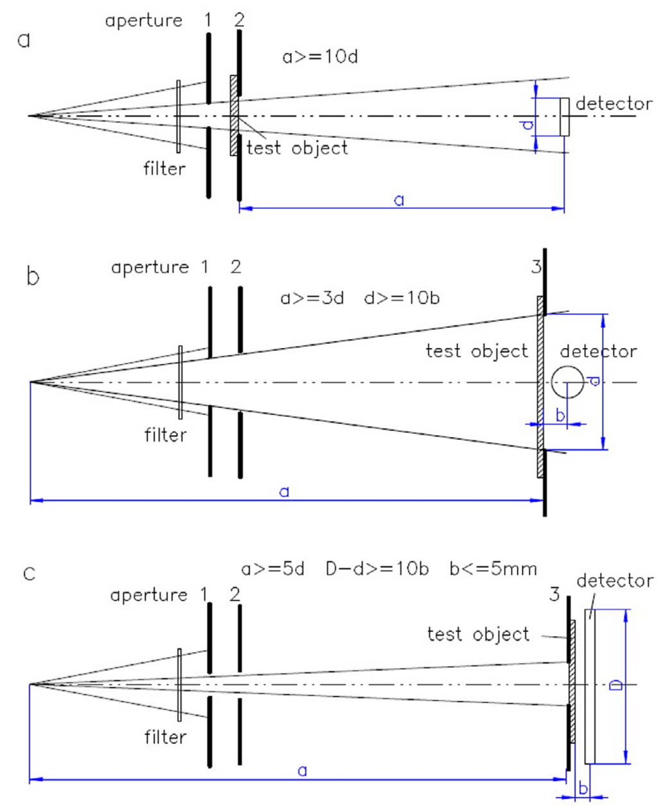

Fig. 1. a) Geometry of the narrow beam configuration (NBG), b) geometry of the broad beam configuration (BBG), c) geometry of the inverse broad beam configuration (IBG).

based on the "*narrow beam geometry*" (NBG). The NBG method is used to measure only transmitted photons and does not consider SR.

The second method presented in IEC is based on the "*broad beam geometry*" (BBG), shown in Fig. 1b: The specimen is located in front of a radiation detector (e.g. ionization chamber) being irradiated with a beam much wider than the diameter of the detector. According to the standard, the detector should be a spherical ionization chamber. Using the BBG arrangement, primary and secondary photons are detected at once. According to the IEC specifications, the field diameter must be at minimum the 10-fold of the distance from the test sample to the reference plane of the detector. This condition is a matter of concern since it demands large simple sizes and a large aperture angle, far from an ideal parallel beam condition.

The adverse properties of method 2 lead to a third method in IEC, that is called the "*inverse broad beam geometry*" (IBG) as presented in Fig. 1c.

The test sample is located next to a flat ionization chamber with the beam limited by an aperture that is much smaller than the sensitive diameter of the ionization chamber (ideally close to zero). Primary and secondary photons are detected with this method, specified in IEC 61331-1 as "standard test method" for LEV measurements.

1.1. The modified IBG method

A technical drawback of the IBG method is that the available shadow free flat ionization chambers SFD 34060 and 34069 (PTW, Freiburg) show a severely altered response under the nonspecific sectional irradiation (see discussion). Because of the non-feasibility of the IBG method as described in IEC a two-step measurement guideline was proposed from the PTB (Physikalisch Technische Bundesanstalt, Braunschweig, Germany) [6]. The modified IBG method (IBG*) uses 2 steps for the determination of the attenuation ratio *F*: The first step is to determine the attenuation ratio F_N using the 6 cm^3 chamber 34069 under NBG conditions. In this case the sample is located far from the detector. In a second step the build-up factor *B* is determined using the IBG setup with the 75 cm^3 flat chamber 34060 by the following procedure: In the first measurement the test sample is located far away from the detector ($\dot{K}_{AP}$) and hence, detects only the primary photons. In the second measurement the test sample located close to the detector ($\dot{K}_{AT}$) and thus additionally detects SR. The ratio of $\dot{K}_{AT}/\dot{K}_{AP}$ yields the build-up factor *B*. The total attenuation ratio *F* including SR then is given by:

$$F = F_N/B.$$

Within this procedure the chamber with an active diameter of 91.4 mm is irradiated by a centered beam of typically 20 mm diameter. However, this condition is beyond the chamber's design specifications and creates an altered energy response. According to the PTB assumption the ratio $\dot{K}_{AT}/\dot{K}_{AP}$ should overcome the adverse response behavior of the chamber under the unspecific use since the spectra of both measurements are filtered through the tested material. Spectra computations were performed from the PTB with 0.25 mm Pb and 0.5 mm Sn samples. The maximum relative uncertainty in LEV evaluation was estimated to be approximately 3% for the 0.5 mm tin sample [6] (see also discussion).

1.2. General conditions for measurements

The measurements according to IEC 61331-1 currently are practiced by accredited laboratories under application of the PTB guidance [6]. The following conditions have to be fulfilled:

- standard Al-radiation qualities defined in terms of tube voltage, total filtration and 1st Al-HVL
- the air-kerma ratio *F* (attenuation ratio) shall be known with a standard uncertainty not > 2%.
- the LEVs shall be determined by the inverse broad beam geometry (IBG) for the specified range of radiation qualities (50 kV, 70 kV, 90 kV, 110 kV and 150 kV).

1.3. Scope

In our experience, the methods BBG and IBG, defined in the IEC standard, as well as IBG* show some drawbacks in the practicability and accuracy, respectively. A more elementary and reliable method is sought. In the following the IBG* method will be compared to a modified BBG method (BBG*) that is free from the problems of a partial chamber irradiation and geometrical uncertainties in the current IEC standard.

2. Materials and methods

2.1. Quality assurance (QA)

The new test procedure has to ensure essential conditions, as

- collection of the entire SR on the backside of the material sample
- a flat energy response of the detector beginning from the low energies of the SR (> 15 keV) up to the high energies of the transmitted (primary) part of the radiation.
- limited beam angle to ensure approximately parallel beam conditions

The measurements were conducted on a X-ray facility ISOVOLT US3, used for official calibration procedures. The unit features a high QA status with respect to the requirements of the IEC standard, concerning dose reproducibility, high voltage accuracy, 1st Al-HVL conditions, and calibration with lead foils of 99.9% purity. Radiation qualities according to the IEC standard were realized by applying a total