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Application of a semi-empirical model for the evaluation of transmission properties of barite mortar

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HIGHLIGHTS

- Barite mortar attenuation curves using X-ray spectra were calculated.
- Optimized thickness of protective barrier was estimated.
- An optimized model considers the energy spectra for protective barrier calculation.

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ABSTRACT

The aim of this study was to estimate barite mortar attenuation curves using X-ray spectra weighted by a workload distribution. A semi-empirical model was used for the evaluation of transmission properties of this material. Since ambient dose equivalent, $H^*(10)$, is the radiation quantity adopted by IAEA for dose assessment, the variation of the $H^*(10)$ as a function of barite mortar thickness was calculated using primary experimental spectra. A CdTe detector was used for the measurement of these spectra. The resulting spectra were adopted for estimating the optimized thickness of protective barrier needed for shielding an area in an X-ray imaging facility.

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1. Introduction

Shielding calculations for medical X-ray imaging facilities are currently based on methods recommended by National Council on Radiation Protection and Measurements (NCRP report 147) (NCRP, 2004). This publication presents physical and operational parameters to be considered in the selection of shielding materials and it establishes modern fundamentals for calculating thicknesses of barriers to be adopted for protecting diagnostic X-ray imaging facilities. This publication uses Archer's model for calculation of transmission curves of shielding materials (Archer et al., 1994) and the workload distributions obtained in US X-ray imaging facilities (Simpkin, 1996). However, NCRPs recommendations are based on data obtained from air kerma measurements, which do not take into account the direct spectral distribution of the X-ray beam transmitted by the protective material. The NCRP data considers different beam qualities, since different applied voltages in use in diagnostic X-ray beams were used, but these data are limited on the representation of the transmitted X-ray spectra. Furthermore, the original model for the evaluation of the transmission curves of the shielding material is presented using the quantity air kerma (Archer et al., 1994), which does not comply to modern requirements which adopt the quantity ambient dose equivalent ($H^*(10)$) to represent the shielding design goals and environmental monitoring (IAEA, 2014). Ambient dose equivalent, $H^*(d)$, at a point of radiation field, is the dose equivalent that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth, d, on the radius opposing the direction of aligned field (ICRU, 1998). For penetrating radiation with $d = 10$ mm, this is $H^*(10)$.

The transmission curves of different shielding materials presented in NCRP report 147 cover a large sort of materials commonly used for shielding propose, such as lead, concrete, gypsum wallboard, steel and others. However, the report does not present transmission data for barite mortar, which is a material widely used for shielding proposes in many countries (Akkurt et al., 2006; Esen and Yilmazer, 2010; Okkalides, 1991). Some authors studied barite mortar transmission properties for diagnostic X-rays energy range. These data were obtained by computational methods (Hoff

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and Firmino, 2007; Hoff et al., 2009) or experimentally by measurements of transmitted air kerma by an ionizing chamber (Costa and Yoshimura, 2011; Ling et al., 2013). Li et al. (2012) also applied a similar method for X-ray spectra typically used in mammography imaging facilities using Monte Carlo simulations. McCaffrey et al. (2009) also used Monte Carlo methods for studying shielding optimization applying non-lead bilayers.

Some of these works present evaluations of the transmission properties of conventional barite mortar or mortars composed of different barite aggregates, but do not present the results in terms of a radiometric quantity, nor do they take into account the effect of these materials on transmitted X-ray spectra. Moreover, these authors do not present correlations between the transmission properties and the workload commonly found in real X-ray imaging facilities (Santos and Costa, 2014). They also used simulated X-ray beams, not measured radiation spectra with radiation qualities commonly found in diagnostic devices (Kharrati and Zarrad, 2004).

The radiation spectra are a more complete representation of the X-ray beam, since they provide information about the intensity and energy of the photons (Johns and Cunningham, 1983). Thereby, since the dose depends on the photon energy, the knowledge of the spectral distribution of the beam transmitted by the protective material should be more appropriate for dose assessments of workers and members of the public present in controlled and uncontrolled areas, respectively. In other words, the availability of the energy spectra transmitted by shielding materials allows an better estimation of the absorbed dose (Johns and Cunningham, 1983) for the individuals present in the protected area than the estimations done considering only the air kerma data obtained, for example, from radiation surveys.

A model for shielding calculation which takes into account the influence of the X-ray diagnostic spectra was proposed in 2002 (Costa and Caldas, 2002). This model estimates the attenuation curves of the shielding material in terms of the ambient dose equivalent (mSv) as a function of the thickness of the protective material. These authors applied this model for primary X-ray spectra produced by a semi-empirical model (Costa et al., 2007). Lead was considered as the protective material. The workload distributions observed in some Brazilian X-ray imaging facilities (Mello and Costa, 2007) were adopted, and the energy distribution of the conversion coefficients relating air kerma to ambient dose equivalent (ICRU, 1998) was considered in the calculations.

The adequacy of the protective barrier (radiation protection survey) is usually assessed by estimating the transmission factor ($B(x)$), which is defined as the ratio of the air kerma beyond the barrier to the non-attenuated air kerma at the same distance (NCRP, 2004). When the shielding design goals are represented in units of ambient dose equivalent (mSv), the conversion between these quantities must take into account the complete radiation energy spectra (ICRU, 1998). The inadequate assessment of the shielding adequacy can be avoided by using a model that allows calculating ambient dose equivalent from air kerma by means of the X-ray spectra and conversion coefficients, as a function of thickness of the shielding material.

Therefore, the aim of the present study was to obtain transmission curves by using measured X-ray spectra in terms of ambient dose equivalent and associate these transmitted spectra to workload characteristic of four typical imaging procedures. This work uses a methodology proposed by Costa and Caldas (2002) which was applied for lead. McCaffrey et al. (2007) took a similar approach using transmitted spectra, but for studying shielding garments. Therefore, the application of this methodology for barite mortar and its association of workload distributions is the main innovative purpose of the present work.

2. Materials and methods

The method used in this work for transmission curve calculation was proposed by Costa and Caldas (2002). This method takes into account the influence of the X-ray spectra represented in ambient dose equivalent units (mSv) and also incorporates the workload distribution of the X-ray facility into the calculations. The function, $H^m(10, x_p)$, showed in Eq. (1), represents the primary radiation levels as a function of the kind of shielding material, m, and its thickness, x_p.

$$H^m(10, x_p) = \sum_{V=0}^{V_{max}} \int_0^{E_{max}} \left(\frac{H*(10)}{K_{air}}\right)(E) N^V_{p,n}(E) W(V) e^{-\mu_m(E) x_p}\, dE \tag{1}$$

In Eq. (1), $(H*(10)/K_{ar})(E)$ are the coefficients which convert the air kerma (mGy) to ambient dose equivalent (mSv) as a function of the photon energies. These conversion coefficients are provided for monoenergetic photons by ICRU (ICRU, 1998) and they have a strong energy dependence in the diagnostic energy range. $N^V_{p,n}(E)$ represents the primary broad beam spectra measured at a tube potential, V, as a function of the photon energy, E, and normalized by the current–time product (mAs). $W(V)$ represents the workload distribution, $\mu_m(E)$ are the linear attenuation coefficients of the shielding material and V_{max} is the maximum voltage applied for measurements of spectra in the workload distributions.

The transmission factor can be represented by Archer's equation (Archer et al., 1983), as follows:

$$B(x) = \frac{H^m(10, x_p)}{H^m(10, x_p = 0)} = \left[\left(1 + \frac{\beta}{\alpha}\right) e^{\alpha\gamma x_p} - \frac{\beta}{\alpha}\right]^{-1/\gamma} \tag{2}$$

In Eq. (2), α, β and γ are fitting parameters obtained by using a non-linear least-square method, and x_p is the thickness of the attenuating material.

2.1. X-ray spectra measurements

Diagnostic X-ray beams (40–150 kV) were generated by a tungsten target X-ray tube (Philips, model MGC 450) with 3 mm Al additional filtration (HVL=3.51 mm Al in 80 kV). The X-ray spectra were measured using a CdTe spectrometer with a 9 mm^2 sensitive area (Amptek, model XR-100T). This detector includes a tungsten collimator with 1 mm diameter. Air kerma measurements for each tube potential were performed with a 30 cm^3 cylinder ionization chamber (PTW, model TW23361) calibrated against a PTB traceable standard. Fig. 1 presents a scheme of the experimental setup.

The measured spectra were corrected by the response function of the detector using the stripping procedure (Di Castro et al., 1984) implemented using a Matlab program. This procedure takes into account the K-escape, Compton scattering and detector efficiency corrections. The efficiency curve and K-escape fractions were simulated (Tomal et al., 2014) using PENELOPE code (Salvat et al., 2003), while the Compton scattering fraction was estimated (Terini et al., 1999) using the cross sections from XCOM database

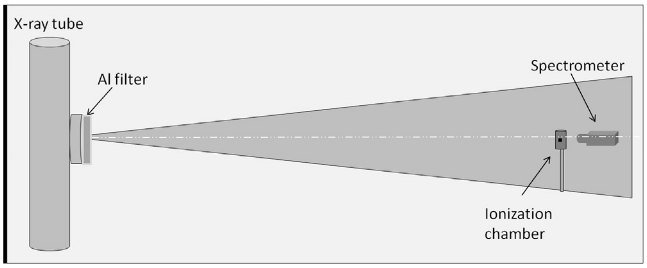

Fig. 1. Experimental setup: positions of devices for air kerma and X-ray spectra measurements. This picture is not in scale.

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