TRANSMISSION PROPERTIES OF BARITE MORTAR USING X-RAY SPECTRA MEASURED WITH CdTe DETECTOR

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Abstract

Current methods for calculating X-ray shielding barriers do not take into account spectral distribution of the beam transmitted by the protective material. This consideration is important in dose estimations for radiation workers and general public in diagnostic radiology facilities. The aim of the present study was to estimate barite mortar attenuation curves using X-ray spectra weighted by a workload distribution. These curves were described in units of ambient dose equivalent (H*(10)), since it is the radiation quantity adopted by IAEA for dose assessment in medical environment. Attenuation curves were determined using the optimized model for shielding evaluation presented by Costa and Caldas (2002). Workload distribution presented by Simpkin (1996), measured primary spectra and mass attenuation coefficients of barite mortar were used as input data in this model. X-ray beams in diagnostic energy range were generated by an industrial X-ray tube with 3 mm of aluminum additional filtration. Primary experimental spectra were measured by a CdTe detector and corrected by the response function of detector by means of a stripping procedure. Air kerma measurements were performed using an ionization chamber for normalization purpose of the spectra. The corrected spectra presented good agreement with spectra generated by a semi-empirical model. The variation of the ambient dose equivalent as
a function of barite mortar thickness was calculated. Using these data, it was estimated
the optimized thickness of protective barrier needed for shielding a particular area in
an X-ray imaging facility. The results obtained for primary protective barriers exhibit
qualitative agreement with those presented in literature.

**Keywords:** Shielding barriers, X-ray Spectrometry, Solid state detector.

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 establish the fundamentals for
the calculation of barrier thicknesses to be adopted for protecting diagnostic X-ray imaging
facilities. This publication uses the 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, the NCRP’s recommendations do not take
into account spectral distribution of the beam transmitted by the protective material, such as
walls and screens. Furthermore, the model for transmission curves of the shielding material
are presented using the quantity air kerma, which is not totally adequate for the countries
which adopt the quantity ambient dose equivalent (H*(10)) to represent the shielding
design goals (Brasil, 1998).

The radiation spectra is the more complete representation of the X-ray beam, since it
provides 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 in workers and members of the public, which must
be present in controlled and uncontrolled areas, respectively.
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. The authors applied this model for primary X-ray spectra produced by the semi empirical model (Costa et al., 2007). Lead was considered 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 function of thickness of the shielding material.

Therefore, the purpose this work was to determine the transmission properties of barite mortar using X-ray spectra measured with CdTe detector. This properties are related to barite mortar transmission curves, calculated by means of X-ray spectra weighted by an specific workload distribution, and represented in ambient dose equivalent units. This analysis represents a new method for shielding calculation, which takes into account the transmitted spectra by the shielding barrier, providing an adequate conversion between air kerma and H*(10).
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 equation (1), represents the primary radiation levels as a function of the kind of shielding material, $m$, and its thickness, $x_p$.

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

In equation (1), $\left( \frac{H^a(10)}{K_{air}} \right)(E)$ 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. $N^V_{p,m}(E)$ represents the primary spectra measured in 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 the Archer’s equation (Archer et al., 1983), as follow in equation 2:

$$B(x) = \frac{H^m(10,x_p)}{H^m(10,x_p = 0)} = \left[ \left( 1 + \frac{\beta}{\alpha} \right) e^{\alpha y x_p} - \frac{\beta}{\alpha} \right]^{\frac{1}{y}}$$  \hspace{1cm} (2)
In equation (2), $\alpha, \beta, \gamma$ are fitting parameters obtained by using a non-linear least-square method, and $x_0$ is the thickness of the attenuating material.

2.1.-X-Ray spectra measurements

Diagnostic X-ray beams (60-150 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 80kV). 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 to a PTB traceable standard. Figure 1 presents a scheme of the experimental setup:

![Experimental configuration: instrumentation positions.](image)

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 by (Tomal et al., 2014) using PENELOPE code (Salvat, 2003), while the Compton scattering fraction was estimated (Terini et al., 1999) using the cross sections from XCOM database (NIST).

Measurements of air kerma were performed simultaneously to be the X-ray spectra in order to be used as normalization factor. It was taken into consideration that the area of the
corrected spectra is numerically equal to air kerma value obtained with the ion chamber measurements (mGy).

2.2-Calculation input

Transmission curves were calculated using the equation (1). The workload distribution obtained by Simpkin (1986) for chest examinations was considered in the calculations. This distribution is part of workloads distributions determined at 14 US medical institutions and is adopted in model of the NCRP 147 (NCRP, 2004) for shielding calculations in X-ray images facilities.

Barite mortar was considered as shielding material for primary barrier. The chemical composition of the barite mortar was determined by Dispersive X-ray Fluorescence (WDXRF) and fundamental parameter methods (SCAPIN, 2005). X-ray mass absorption coefficients were obtained from values provided by database XCOM (NIST).

3.- RESULTS

Table 1 shows the technical parameters used during the experimental measurements of the primary spectra and the respective air kerma value corrected by air density factor.

Table 1: Nominal values of tube voltage and current-time product used for to generate the X-ray beams and air kerma measured with uncertainty of 1.5%.

<table>
<thead>
<tr>
<th>TUBE VOLTAGE (kV)</th>
<th>CURRENT-TIME PRODUCT (mAs)</th>
<th>AIR KERMA (mGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>280</td>
<td>3.007</td>
</tr>
<tr>
<td>50</td>
<td>280</td>
<td>6.037</td>
</tr>
<tr>
<td>60</td>
<td>180</td>
<td>6.437</td>
</tr>
<tr>
<td>70</td>
<td>120</td>
<td>6.077</td>
</tr>
<tr>
<td>Energy (keV)</td>
<td>N(E) (mGy/mAs.keV@1m)</td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>------------------------</td>
<td></td>
</tr>
<tr>
<td>40 kV</td>
<td>1x10^-3</td>
<td></td>
</tr>
<tr>
<td>50 kV</td>
<td>2x10^-3</td>
<td></td>
</tr>
<tr>
<td>60 kV</td>
<td>3x10^-3</td>
<td></td>
</tr>
<tr>
<td>70 kV</td>
<td>4x10^-3</td>
<td></td>
</tr>
<tr>
<td>80 kV</td>
<td>5x10^-3</td>
<td></td>
</tr>
<tr>
<td>90 kV</td>
<td>6x10^-3</td>
<td></td>
</tr>
<tr>
<td>100 kV</td>
<td>7x10^-3</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2 shows some primary spectra measured using the CdTe detector, using the technical parameters presented in Table 1 and a 3 mm Al additional filtration.

The results of attenuation curve obtained considering the spectral influence, in ambient dose equivalent units, are presented in Figure 3. The results represented by black dots were calculated using Equation (1) taking into account the workload distribution for chest
examination, for a set of spectra with applied voltages from 40 kV to 150 kV. The red solid line represents the fitting of Equation (2) on the calculated data.

![Graph showing X-ray beam attenuation in function of barite mortar thickness in units of ambient dose equivalent](image)

**Figure 3:** X-ray beam attenuation in function of barite mortar thickness in units of ambient dose equivalent $H^*(10,x_p)$.

Table 2 presents the fitting parameters of Archer’s model, the non-attenuated ambient dose equivalent, $H^*(10, 0)$, and the HVL corresponding to the curve achieved from the non-linear least square fitting of Equation (2) applied on the data points calculated from Equation (1). This curve is presented as a red solid line in Figure 3.

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ ( cm$^{-1}$)</td>
<td>1.36 (13)</td>
</tr>
<tr>
<td>$\beta$ ( cm$^{-1}$)</td>
<td>9.13 (10)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.438 (13)</td>
</tr>
<tr>
<td>$H^*(10,0)$ [mSv/mA.min@1m]</td>
<td>2.0239 (11)</td>
</tr>
<tr>
<td>HVL (cm of barite mortar)</td>
<td>0.075 (2)</td>
</tr>
</tbody>
</table>

Table 2: Fitting parameter of Archer model for values of $H^*(10)$ in function of barite mortar thickness and HVL this distribution.
4.- DISCUSSION

The utilization of an optimized model for protective barrier calculation allows the inclusion of the energy spectra for determination of adequate thickness of shielding material. The result presented in Figure 3 shows the influence of thickness of barite mortar on the beam attenuation caused. From this curve, the adequate shielding material thickness for a primary barrier can be determinate according to shielding design goals established in units of ambient dose equivalent. The result obtained for barite mortar in primary barrier shows qualitative agreement with results found by Costa and Caldas (2002) using lead as protection material and simulated X-ray spectra. The model can be applied for generating other transmission curves representing different shielding materials or workload distributions. Therefore, an user can calculate new transmission curves just replacing the functions $W(V)$ and $\mu(E)$ in equation (1).

5. - CONCLUSIONS

The objective of the study was to validate a previously developed semi-empirical model for calculation of transmission curves of a generic shielding material in units of the quantity ambient dose equivalent. The validation was performed using barite mortar linear attenuation coefficient and the workload distribution. The weighted X-ray spectra were also estimated. The resulting attenuation curves were described in units of ambient dose equivalent ($H^{*}(10)$). The experimental methodology applied for X-ray measurements with CdTe detector was considered adequate. It is believed the consideration of the X-ray spectra in this calculation can let more realistic and optimized values for shielding of x-ray imaging facilities.
Acknowledgments

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