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NaI(Tl) scintillator detectors stripping procedure for air kerma measurements of diagnostic X-ray beams

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ABSTRACT

Air kerma is an essential quantity for the calibration of national standards used in diagnostic radiology and the measurement of operating parameters used in radiation protection. Its measurement within the appropriate limits of accuracy, uncertainty and reproducibility is important for the characterization and control of the radiation field for the dosimetry of the patients submitted to diagnostic radiology and, also, for the assessment of the system which produces radiological images. Only the incident beam must be considered for the calculation of the air kerma. Therefore, for energy spectrum, counts apart the total energy deposition in the detector must be subtracted. It is necessary to establish a procedure to sort out the different contributions to the original spectrum and remove the counts representing scattered photons in the detector's materials, partial energy deposition due to the interactions in the detector active volume and, also, the escape peaks contributions. The main goal of this work is to present spectrum stripping procedure, using the MCNP Monte Carlo computer code, for NaI(Tl) scintillation detectors to calculate the air kerma due to an X-ray beam usually used in medical radiology. The comparison between the spectrum before stripping procedure against the reference value showed a discrepancy of more than 63%, while the comparison with the same spectrum after the stripping procedure showed a discrepancy of less than 0.2%.

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1. Introduction

X-ray tubes are widely used for medical and odontological diagnosis because it is a non-invasive procedure to obtain images from internal structures of the human body. However, there are some risks associated with these procedures, even for the reduced exposure level achieved with the advances in equipment and techniques. The increasing use of X-rays and the longevity of the population require a better determination and settings of the radiation field, in accordance with its use, in order to reduce the radiation dose to the patient. For this purpose, it is necessary to implement an easy quality control routine procedure.

The measurement procedure must accurately assess the radiation field and the air kerma measurement provides a helpful manner for characterizing the radiation field because it is related to the photons energy fluency in a given region in space.

The use of a spectrometric system to the measurement of X-rays beam can significantly improve its accuracy. An easy to use and portable detector like NaI(Tl) could represent an important asset.

A spectrum acquired with a NaI(Tl) detector based system provides information on the amount of photons for each and every energy emitted by the X-ray tube, but it also includes partial interactions due to the Compton scattering and scape peaks. Therefore, a stripping procedure [1] should be applied in order to obtain a spectrum representative of the incident X-ray flux.

This paper presents spectra stripping procedure to evaluate the photon beam from X-ray tubes with a NaI(Tl) detector. It is based on a set of single energy spectra obtained by the MCNP5 Monte Carlo computer code and experimental data for the detector's response function determination.

2. Stripping procedure

A spectrum from a NaI(Tl) detector is a combination of total energy deposition (photoelectric effect), partial energy deposition (Compton scattering) and escape peaks. In addition to those, there is the contribution of photon scattering in the detector's structural material. However, in the present case, the total energy

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deposition is not a well-defined photopeak due to the fact that the beam emitted by a X-ray tube is not composed by discrete energies, but a continuous spectrum (Bremsstrahlung effect) ranging from low energies, depending on the filter used, up to higher energies, depending on the high voltage applied to the tube.

Due to its complexity, it is not possible to analyze the X-ray spectrum without taking into account the effects of the different types of interactions in the crystal and structural materials. Therefore, it is necessary the use of a stripping procedure to account for each different photon interaction, subtracting the unwanted ones, in order to calculate air kerma accurately.

This work presents a stripping procedure for collimated NaI(Tl) of 2″ × 2″ detector X-ray spectra. The procedure is composed of the following steps: (1) simulation of the NaI(Tl) detector; (2) determination of the Full Width at Half Maximum – FWHM versus energy curve by point sources measurements; (3) development of single energies spectra database produced by simulations with MCNP5, in energy intervals corresponding to FWHM/2, starting from the highest energy limit to be assayed; (4) calculation of stripping factors to account for the difference between the photopeaks areas in the spectra database and the corresponding areas in the measured spectrum; and (5) withdrawal of the events related to partial energy deposition in the detector's active volume and interactions in the structural material.

2.1. *Detector's simulation*

In order to build the spectra database, it is necessary to simulate precisely the NaI(Tl) detector and its response to the radiation. The internal dimensions were taken by radiography and the response function by experimental measurements and the simulation were performed by the Monte Carlo method.

The response functions determined experimentally consist of: (a) the relationship between resolution and energy, for precise spectrum shape; and (b) the detection efficiency for validation of the detector's simulation.

The parameter used for experimental validation of the detector's model was the comparison of the experimental efficiency and the calculated one by the MCNP5 simulation. The activity of the point sources was measured with the NaI(Tl) detector to well-defined distance between source-detector, in the axial direction of the detector and, afterward, the same geometry was reproduced with the MCNP5 code. The standard sources are shown in Table 1 and present energies that cover the energy range of interest [2].

Fig. 1 presents the schematic representation of the NaI(Tl) detector considered for the simulation.

2.2. *FWHM versus energy curve determination*

The full width at half maximum (FWHM) versus energy curve was determined by the measurement of point sources in the energy range of 14.413–661.657 keV with the NaI(Tl) detector. The point sources' isotopes, the corresponding energies and the FWHM are presented in Table 1. Although the last two energies, 356.013 keV and 661.657 keV, are beyond the energy range for X-ray diagnosis, they were used for a better curve fitting.

The curve was fitted to the data according to Eq. (1) [2] and the fitting coefficients were used in the GEB (Gaussian Energy Broadening) option in the MCNP5 computer code in order to have a Gaussian distribution in the simulated spectra [2,3].

$$FWHM = a + b\sqrt{E + cE^2} \quad (1)$$

Table 1
Sources data used for the determination of the energy resolution curve.

Isotope	Energy (keV)*	FWHM (keV)	Resolution (%)
^{57}Co	14.413	4.495	31.19
^{210}Pb	46.539	8.556	18.38
^{241}Am	59.541	9.808	16.47
^{133}Ba	80.998	13.213	16.31
^{133}Ba	356.013	35.028	9.84
^{137}Cs	661.657	50.448	7.62

* Nucléide Gamma and Alpha Library at http://laraweb.free.fr

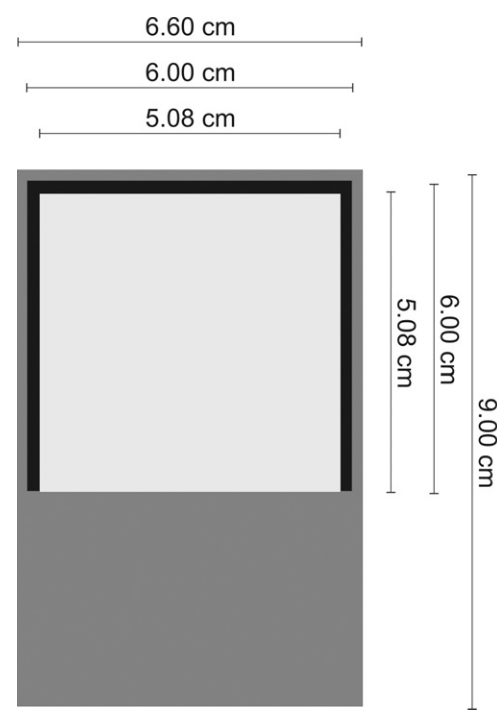

Fig. 1. Schematic representation of the NaI(Tl) detector considered for simulation.

where:

E energy (MeV);
a, b, c fitting coefficients.

2.3. *Spectra database*

The spectra database was built by the simulation of a set of single energies sources using the MCNP5 computer code. The energies values to be simulated were established by considering the detector's resolution. In this work, the energy range of interest was divided in FWHM/2 intervals, starting from the highest energy.

X-ray energies between 0.021 MeV and 0.097 MeV have been used to produce the database spectra. The FWHM/2 varies between 0.003 MeV and 0.007 MeV.

Fig. 2 shows the spectra for the 0.090 MeV and 0.076 MeV photon energies and Fig. 3 shows the spectra for the 0.043 MeV and 0.034 MeV photon energies. It is possible to observe a strong influence of the escape peak in the spectrum shape.

Fig. 4 shows the position of the spectra in the database relative to a typical X-ray spectrum.

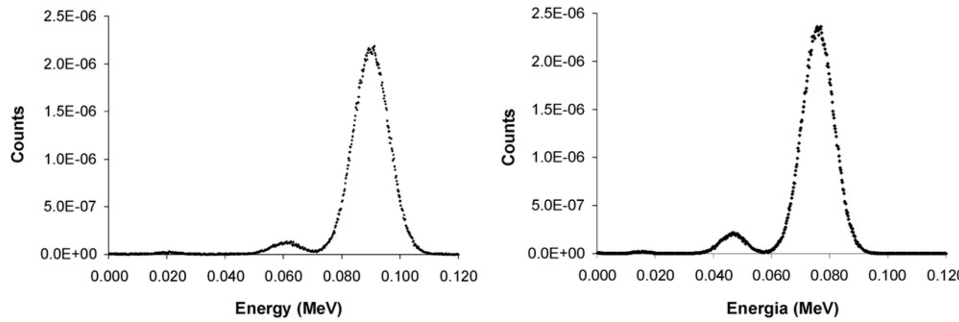

Fig. 2. Spectra related to the energies of 0.09 MeV and 0.076 MeV.

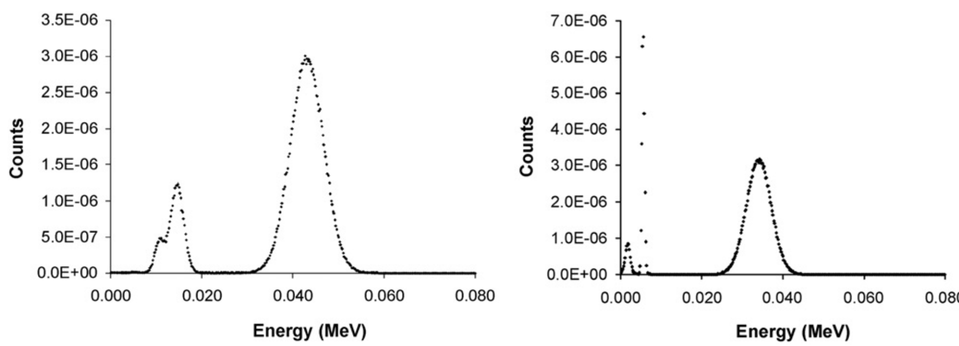

Fig. 3. Spectra related to the energies of 0.043 MeV and 0.034 MeV.

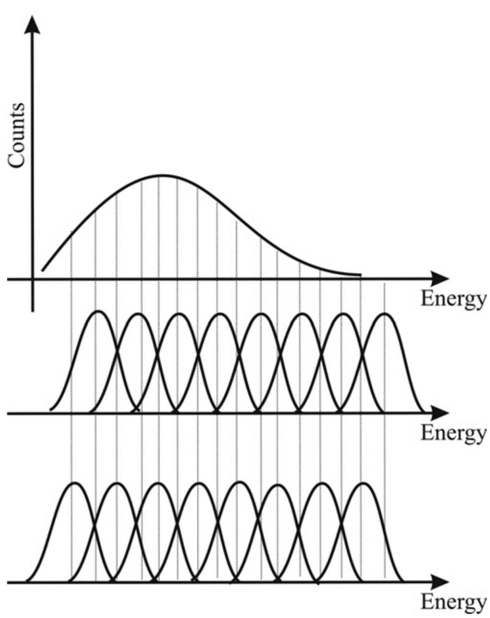

Fig. 4. Position of the spectra in the database relative to a typical X-ray spectrum.

2.4. Stripping factors

The spectra in the database consist of a photopeak area, escape peaks and a continuum due to partial energy deposition in the crystal and scattered photons in the structural material which reaches the detector's crystal. There is a correlation between the counts in the photoelectric area and the Compton continuum and is related to the spectrum in analysis by the stripping factor.

The stripping factor is the ratio between the photopeak areas of the spectra in the database and the X-ray spectrum in order to correctly estimate the contribution of the continuum to the X-ray spectrum [4].

Due to the interference of iodine scape peaks with energies of 0.0286 MeV (Kα) and 0.0332 MeV (Kβ) [5] in the left side of the photopeak, its area was calculated by its right half multiplied by two. The stripping factor is defined as:

$$SF_j = \frac{R_j}{(MC_j)2} \tag{2}$$

where:

- SF_j Stripping factor to photons with energy j (MeV);
- R_j Corresponding area in the X-ray spectrum that is being stripped, in the energy range j (MeV) until the adjacent energy separated by FWHM/2;
- MC_j The half right area of the photopeak of the energies j (MeV) present in the spectra database.

2.5. Stripping procedure

The stripping procedure of the X-ray spectrum consists of the subtraction of the undesired partial energy contributions. For energies below the photopeak area, the stripping factor is applied to the single energy spectra stored in the database by Eq. (3).

$$CP_{i,j} = H_{i,j} SF_j \tag{3}$$

where:

- $CP_{i,j}$ Partial contribution in energy (i) due to energy (j);
- $H_{i,j}$ Counts in energy (i) in the simulated spectrum of energy (j);
- SF_j Stripping factor.

3. Air kerma calculation

After the stripping procedure the resultant X-ray spectrum is composed solely by photoelectric interactions and the detector's efficiency correction can be applied to the whole spectrum. The resultant spectrum is representative of the energy photon flux and the air kerma can be calculated [6].

The air kerma for each energy range of the X-ray spectrum was calculated by Eq. (4)

$$\dot{K} = 1.602\text{E}{-}10 \sum_{i}^{L} \dot{\Phi}_{i,j} E_i \frac{(\mu_{tr})_{E_i,ar}}{\rho_{ar}} \quad (4)$$

where:

$\dot{K}$ Air kerma rate (Gy/s);
E_i Energy value (i) in each range of the X-ray simulated spectrum (MeV);
$\dot{\Phi}_{i,j}$ Photon fluency rate per energy range (i) (photons/cm^2 s);
$(\mu_{tr})_{E_i,ar}/\rho_{ar}$ Mass energy transfer coefficient for photons with energy E_i in air.

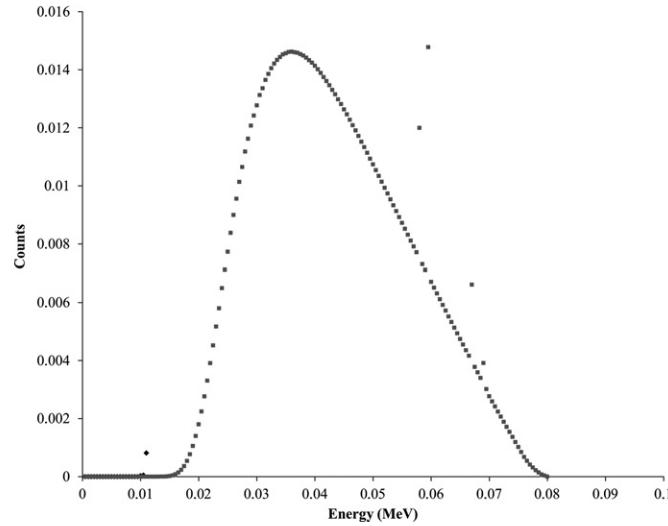

Fig. 5. Photons distribution produced by the IPEM computer code.

4. Stripping procedure evaluation

The Institute of Physics and Engineering in Medicine-IPEM has developed a computer code to simulate X-rays spectra considering several factors related to the quality and quantity of photons of an X-ray beam. It is possible to adjust the following parameters: target material, high voltage of the X-ray tube, anode angle, percentage of the ripple in the applied voltage and kind of material and half value layer (HVL) thickness. With these settings, the computer code simulates the energy spectrum [7].

In order to evaluate the stripping procedure, an X-ray energy distribution calculated with the IPEM (*Report 78 Spectrum Processor*) computer code was used as the input source for the simulation of the NaI(Tl) response with the MCNP5 computer code. The spectrum obtained has undergone the stripping procedure and the air kerma was compared to the air kerma calculated from the original X-ray energy distribution obtained by the IPEM code.

The X-ray tube set up for the IPEM (*Report 78 Spectrum Processor*) computer code was: Tungsten as the target material (anode), 80 kVp for the tube high voltage, 18° of the anode angle, the ripple of high voltage of 5%, 3.5 mm of aluminum as the half value layer. Fig. 5 shows the photons distribution produced by the IPEM computer code.

Table 2
Stripping factors(SF) used for the stripping procedure.

Energy (MeV)	Photopeakarea (MC_j)	X-ray spectrum area (R_j)	Stripping factor (SF)
0.090	1.63E−4 ± 4.03E−7	6.50E−9 ± 1.80E−9	3.99E−5 ± 1.11E−5
0.083	1.64E−4 ± 4.05E−7	1.47E−7 ± 8.56E−9	8.94E−4 ± 5.23E−5
0.076	1.60E−4 ± 4.00E−7	1.24E−6 ± 2.49E−8	7.74E−3 ± 1.57E−4
0.069	1.60E−4 ± 4.00E−7	4.78E−6 ± 4.89E−8	2.99E−2 ± 3.14E−4
0.064	1.55E−4 ± 3.93E−7	6.42E−6 ± 5.67E−8	4.15E−2 ± 3.81E−4
0.058	1.54E−4 ± 3.92E−7	1.22E−5 ± 7.82E−8	7.94E−2 ± 5.47E−4
0.053	1.47E−4 ± 3.83E−7	1.24E−5 ± 7.86E−8	8.41E−2 ± 5.78E−4
0.047	1.44E−4 ± 3.80E−7	1.82E−5 ± 9.56E−8	1.26E−1 ± 7.42E−4
0.043	1.36E−4 ± 3.69E−7	1.31E−5 ± 8.12E−8	9.64E−2 ± 6.53E−4
0.038	1.31E−4 ± 3.62E−7	1.81E−5 ± 9.61E−8	1.38E−1 ± 8.26E−4
0.034	1.27E−4 ± 3.56E−7	1.50E−5 ± 8.79E−8	1.18E−1 ± 7.68E−4
0.030	1.49E−4 ± 3.86E−7	1.42E−5 ± 8.65E−8	9.58E−2 ± 6.32E−4
0.027	1.42E−4 ± 3.77E−7	9.68E−6 ± 7.25E−8	6.80E−2 ± 5.40E−4

5. Results and discussion

The stripping procedure described was applied to a spectrum generated by Monte Carlo simulation of a 2″ × 2″ NaI(Tl) detector. The input data for the radiation source was obtained by the IPEM code in order to precisely calculate the air kerma.

The stripping factors(SF) used for the stripping procedure of the spectrum are shown in Table 2. The energy range between 0.047 MeV and 0.034 MeV has great influence on the stripping factors and on the stripping procedure of the spectrum. Fig. 6 shows the spectrum before and after the stripping procedure.

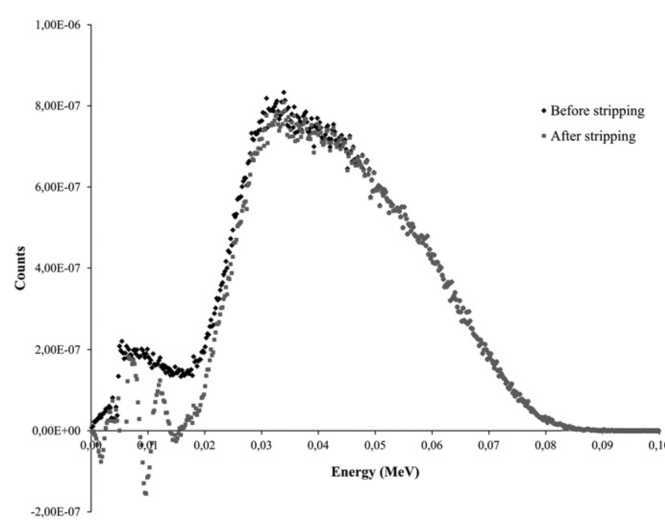

Fig. 6. Spectrum before and after the stripping procedure.

The negative counts for the lowest energies are due to the X-ray tube filter, which deforms the spectrum in comparison to the unfiltered spectra database. The air kerma calculation must stop at the energy which counts intercepts the energy axis.

The air kerma was calculated for: (a) the input source data; (b) the spectrum from the simulated NaI(Tl) detector; and (c) the spectrum from the simulated NaI(Tl) detector after the stripping

Table 3
Comparison of the air kerma calculated for the input source data as the reference value, the original spectrum from the simulated NaI(Tl) detector and the spectrum after the stripping procedure.

	Air kerma (Gy/s)	Discrepancy (%)
Input source data	1.099E−6	
Original spectrum	1.797E−6 ± 0.004E−6	63.51
Spectrum after stripping	1.101E−6 ± 0.004E−6	0.18

procedure. The intrinsic efficiency correction was considered for items "b" and "c". Table 3 presents a comparison of the air kerma calculated for the cases considered.

The results presented in Table 3 show that the stripping procedure described in this work proves to be effective for air kerma determination for complex spectra, such as the resultant from an X-ray tube, which is composed of both continuous and discrete energies.

It is important to emphasize that the values accepted nowadays in Brazil are less than 10% for reproducibility of air kerma rate and less lower than 20% for linearity of air kerma rate in measurements using ionization chamber detectors [8].

6. Conclusion

This work presents a stripping procedure based on a spectra database to calculate partial energy deposition in the detector's active volume for NaI(Tl) detectors.

The procedure was developed and tested by simulations with the MCNP5 Monte Carlo computer code in order to verify its effectiveness and the expected accuracy. The input source data was calculated with a computer code developed by the Institute of Physics and Engineering in Medicine – IPEM that simulates an X-rays tube.

The air kerma calculation must stop at the energy at which the counts intercepts the energy axis due to filtering in the X-ray tube.

The stripping procedure was applied to an spectrum obtained from the simulation of a NaI(Tl) detector with the MCNP5 computer code. The comparison between the original spectrum against the reference value showed a discrepancy of more than 63%, while the comparison with the same spectrum after the stripping procedure showed a discrepancy of less than 0.2%.

The results indicate that scintillation detectors together with the stripping procedure presented in this work can be used to evaluate air kerma rate for X-ray equipment.

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