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ASSESSMENT OF X-RAY SPECTRA AND QUALITY CONTROL PARAMETERS USING THE MONTE CARLO METHOD.

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ABSTRACT

The Quality Control of X-ray tubes for medical radiodiagnostic services is very important for such devices. The development of new procedures to characterize the X-ray primary beam is highly interesting in order to obtain an accurate assessment of the actual photon spectrum. The Compton scattering technique is very useful to determine X-ray spectra (in the 50 – 150 kVp range), avoiding a pile-up effect in the detector. Using a spectrometry Compton technique a scattered spectrum can be obtained from which the primary spectrum can be estimated using unfolding techniques. From this spectrum other parameters (HVL and mean photon energy) very useful to characterize working conditions of the tube can be calculated. In this paper, a simulation model has been developed using the MCNP code based on the Monte Carlo method to simulate the spectrometry process and to obtain a response matrix. The MTSVD method has been applied to obtain the primary spectrum, which has been also obtained using the SpectroX code. Results from both methods have been compared between them and also with a theoretical spectrum. HVL and mean photon energy obtained from those spectra have been also compared. For both parameters, the agreement with theoretical values is better for the MCNP model using MTSVD method for unfolding than for the SpectroX code. Therefore, the technique presented in this paper is a powerful tool very helpful in Quality Control of X-ray tubes.

Key Words: X-ray spectrometry, Half Value Layer, Mean Photon Energy.

1 INTRODUCTION

The quality control of X-ray tubes for medical radiodiagnostic services is very important for such devices. The best way to develop quality control is to obtain the primary X-ray spectrum. This is a complex task that is not usually performed, but some parameters are measured instead. The most common of these parameters are HVL and mean photon energy. They are used to give a rough assessment of the tube properly working. Therefore, other techniques should be used to obtain an accurate assessment of the primary X-ray spectrum. From this spectrum, the desired parameters can be easily calculated.

In advanced quality control the primary beam spectrum can be characterized with spectrometry techniques. However, spectrometry measurements of X-ray tubes are difficult due to high photon fluence and low photon energy (10-150 keV). The high fluence effect (pile-up) can be avoided using the Compton spectrometer developed by Matscheko and Ribberfors [1].

In a previous work [2] authors developed a Monte Carlo model using the MCNP code [3] in order to simulate the spectrometry process obtaining the pulse height distribution (PHD) for different tube working conditions. Results from this simulation were compared with experimental measurements performed at Centro Nacional de Dosimetría (CND) in Valencia (Spain) in order to validate the Monte Carlo model developed.

The scattered spectrum obtained with the spectrometry (Compton) technique is not the primary spectrum. It is still necessary to take into account some effects such as photon interactions, efficiency variations, perturbations from electronic devices, etc. This is done by means of a response matrix, which can also be obtained with the Monte Carlo method. This matrix requires some special mathematical treatment as it is ill conditioned. A Modificated Truncated Singular Value Decomposition (MTSVD) method [4, 5] has been used to obtain a best-estimate primary spectrum [6, 7, 8].

In this paper, the primary spectrum obtained by the unfolding method above mentioned is compared with that one calculated with the unfolding code SpectroX [9] developed by Matscheko and Ribberfors. Both spectra have been also compared with a theoretical primary spectrum corresponding to X-ray tube working conditions.

Two different versions of the MCNP code, 4C and 5, have been used. HVL and mean photon energy have been calculated using each of the spectra obtained. Afterwards, results have been compared.

2 OBTAINING OF THE PRIMARY X-RAY SPECTRUM

Using the Monte Carlo model mentioned in the previous section a PHD has been obtained for every tube working conditions. This model can also be used to obtain the response matrix necessary to assess the primary X-ray spectrum, as expressed by the following equation:

$$\mathbf{R}\vec{s} = \vec{m} \tag{1}$$

where $\vec{s} = (s_1,...,s_N)^T$ is the unknown spectrum, that is, the primary beam spectrum, and

$\vec{m} = (m_1,...,m_M)^T$ is the PHD registered in the detector system.

The response matrix, **R**, can be obtained by calculating the PHD produced by different monoenergetic primary beams. Rewriting eq. (1), the next expression can be obtained:

$$\begin{bmatrix} m_1 \\ \vdots \\ m_i \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} a_{11} & \cdots & a_{1i} & a_{1M} \\ & & a_{2i} & \\ & & \vdots & \\ & & \vdots & \\ a_{N1} & \cdots & a_{Ni} & a_{NM} \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ 1 \\ \vdots \\ 0 \end{bmatrix} \tag{2}$$

From eq. (2) the i[th] column can be identified as:

$$\begin{bmatrix} a_{1i} \\ \vdots \\ a_{ii} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} m_1 \\ \vdots \\ m_i \\ 0 \\ 0 \end{bmatrix} \tag{3}$$

Applying eq. (3) to every monochromatic primary beam considered a response matrix is obtained.

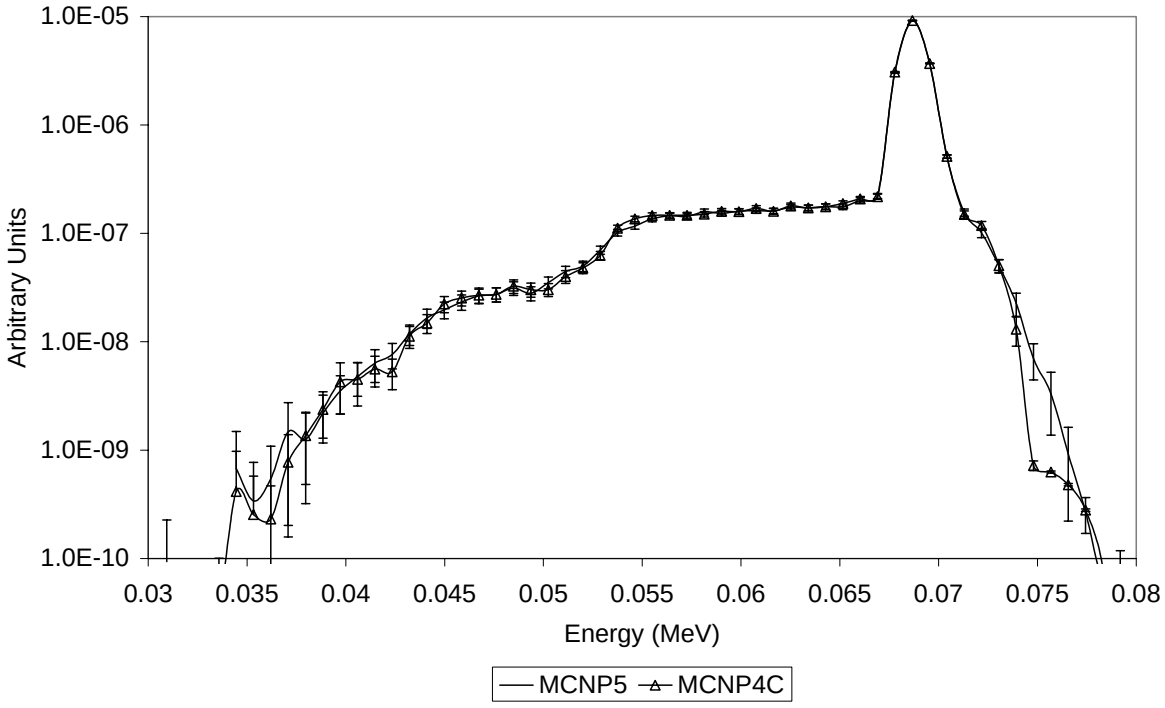

Figure 1. PHD corresponding to 90 keV monochromatic primary beam spectrum.

This matrix has been calculated using two versions of MCNP: 4C and 5. MCNP5 uses a photoatomic data library named MCPLIB04, which is a new set of data taken from ENDF/B-VI release 8, including cross sections, form factor, scattering functions and fluorescence data. On the other hand, MCNP4C makes use of the data library called MCPLIB02. For a specific monochromatic primary beam spectrum, some slight differences have been found between PHD obtained with MCNP4C and MCNP5. Figure 1 shows the PHD obtained for both versions of MCNP corresponding to a monochromatic primary beam spectrum of 90 keV. Both PHD have been simulated with 50 million particles, and with identical variance reduction techniques. It can be seen in this figure that PHD are practically identical (including the 2-sigma error bar) for all energies except at some energy bins around 73 keV, where PHD are slightly different.

Repeating this comparison for each monochromatic energy spectrum, a matrix of differences between both response matrices can be mapped as can be seen in figure 2. This matrix represents for every bin of each PHD, the difference between results obtained with both codes, MCNP4C and MCNP5.

Once more, it can be seen in this figure that the most important discrepancies are observed around 73 keV. This fact can be attributed to differences in cross sections libraries used (MCPLIB02 and MCPLIB04).

The slight differences in response matrices obtained with MCNP4C and MCNP5 are masked during the unfolding process, so no differences are found between the unfolded primary beam spectra. This can be attributed to the fact that the error produced in the truncation process is more important than the differences induced by using different cross sections libraries.

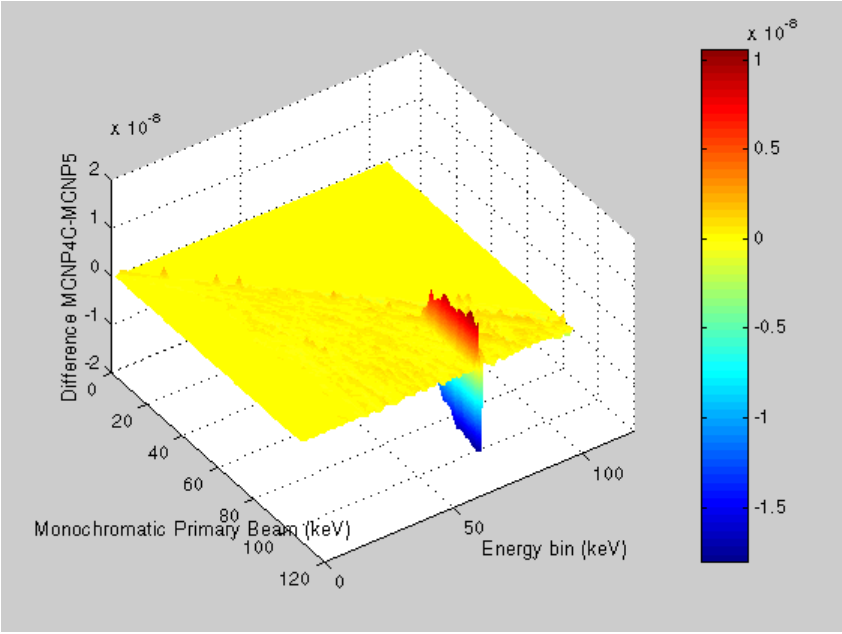

Figure 2. Differences between response matrices (MCNP4C and MCNP5).

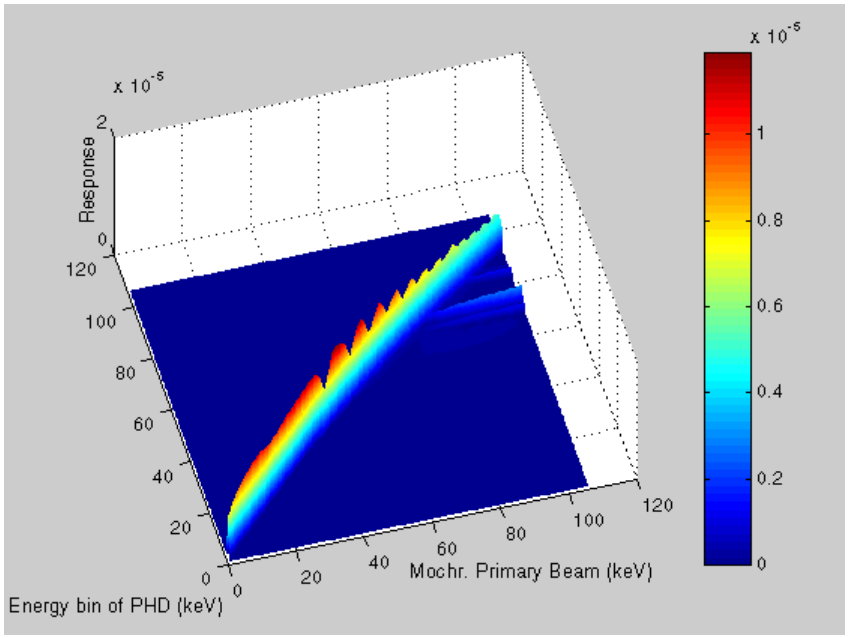

Figure 3. Response matrix obtained with MCNP4C.

Figure 3 shows a representation of the response matrix obtained with MCNP4C. As the response matrix is ill-conditioned, its inverse matrix can not be calculated by usual methods without large errors and the MTSVD method has been applied.

Unfolded spectra obtained with both SpectroX and MTSVD method are compared with theoretical spectrum in figures 4 and 5 for 80 and 90 keV, respectively.

In figure 4 it can be seen that MTSVD unfolding fits better the theoretical primary beam spectrum corresponding to 80 kVp tube voltage. However, it can be observed that characteristic X-ray lines are smaller than those from theoretical spectrum. SpectroX unfolding spectrum does not reproduce bremmstrahlung continuos as well as MTSVD unfolding does, but it simulates better characteristic X-ray lines.

As voltage is increased, discrepancies between SpectroX results and theoretical spectrum become larger.

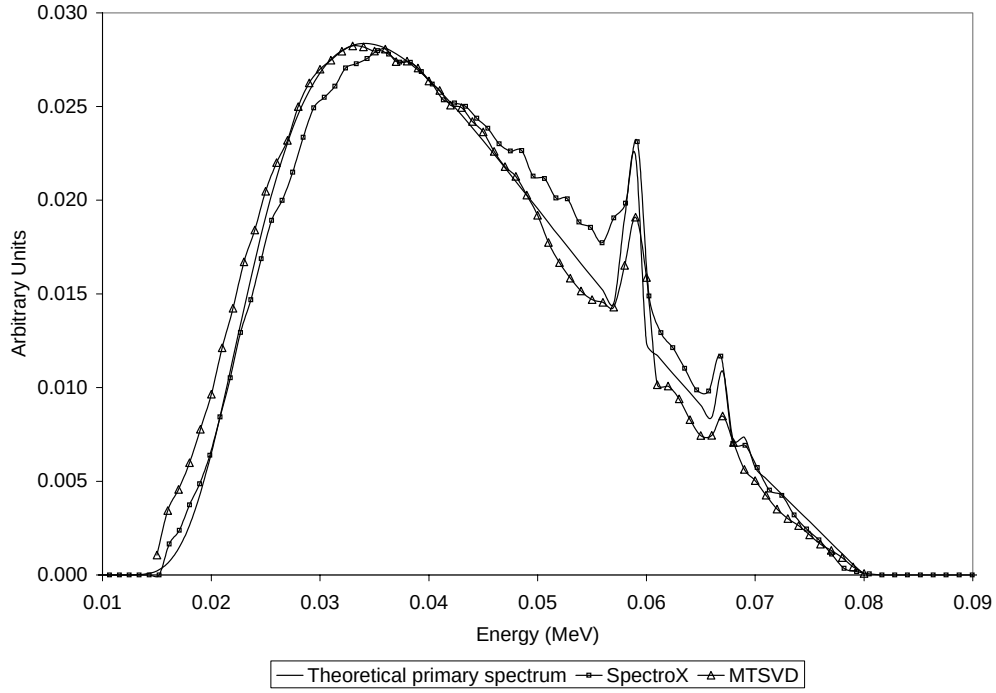

Figure 4. Primary beam spectra. 80 kVp.

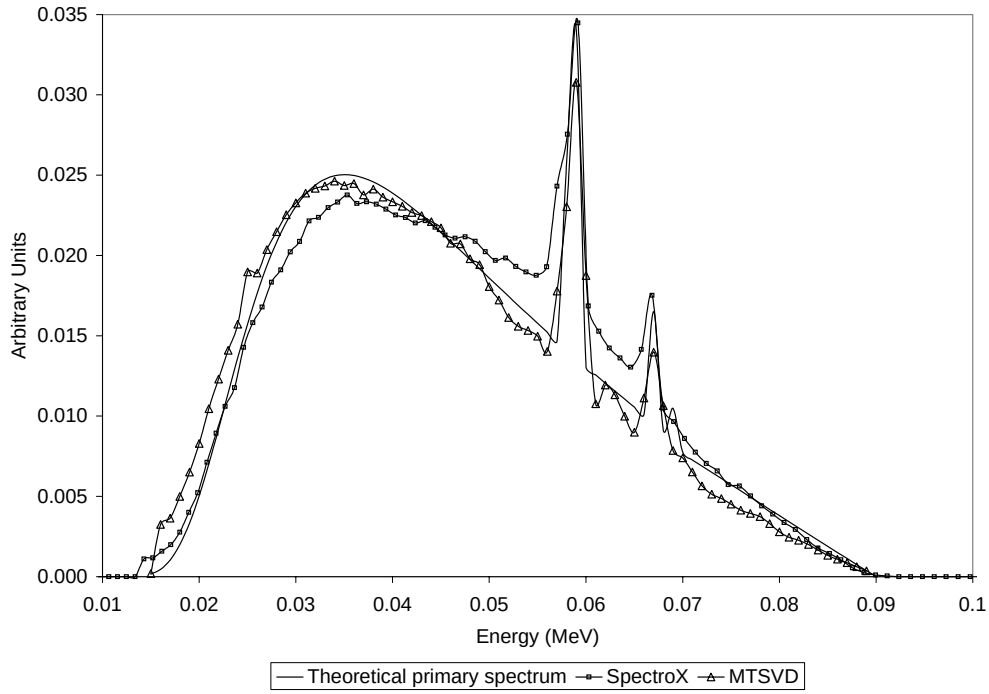

Figure 5. Primary beam spectra. 90 kVp.

3 OBTAINING OF HVL AND MEAN PHOTON ENERGY

The HVL and mean photon energy are common parameters traditionally used in quality control to verify the X-ray tube properly working. The HVL is the amount of material required to reduce the intensity of an X-ray beam to half. For X-ray beams, this is normally expressed in terms of aluminum or copper thickness. Strictly, the half value layer is defined for different quantities: photon fluence (number of photons/cm^2), energy fluence (number of photons multiplied by photon energy/cm^2), air kerma or absorbed dose. The HVL is an important parameter since it allows determining the inherent tube filtration. A method to certify the X-ray beam quality is to obtain experimentally HVL value for all working conditions. HVL can also be determined by calculations if the input X-ray spectrum is known. Transmitted X-ray spectrum after the aluminum layer can be calculated according to

$$N_j = (N_0)_j \exp(-\mu_{Al} x) \tag{4}$$

where N_j is the number of photons in the jth photon energy interval after passing through x mm of aluminum, $(N_0)_j$ is the number of photons in the jth interval entering in the aluminum layer and μ_{Al} is the total linear attenuation coefficient of aluminum taken from Berger and Hubbell [10].

The HVL in air kerma is calculated for the X-ray according to the following expression:

$$\frac{1}{2} = \frac{\sum_i \left(\frac{\mu_{en}}{\rho}\right)_{air} N_i h\nu_i \exp(-\mu_{Al} HVL)\exp(-\mu_{Air} d)}{\sum_i \left(\frac{\mu_{en}}{\rho}\right)_{air} N_i h\nu_i \exp(-\mu_{Air} d)} \tag{5}$$

where

$\left(\frac{\mu_{en}}{\rho}\right)_{air}$ is the mass energy absorption coefficient for air,

μ_{Air} is the linear attenuation coefficient of air, and

d is the distance between the X-ray focus and the ionization chamber.

These values have been taken from Hubbell and Seltzer [11].

The mean photon energy is defined by the equation:

$$\overline{h\nu} = \frac{\sum_i N_i h\nu_i}{\sum_i N_i} \tag{6}$$

where

$h\nu_i$ is the photon energy of the ith interval, and

Ni is the number of photons in the ith energy interval.

In Table I, the first HVL calculated from MCNP is compared with that one obtained using the theoretical primary beam provided by the X-ray tube manufacturer. Results have been also compared with values coming from an unfolded spectrum calculated using the SpectroX code.

For each value in Table I and following, a relative error (%) indicated in brackets is defined as follows:

$$\text{Relative error} = \frac{\text{unfolded} - \text{theoretical}}{\text{theoretical}} \text{x}100 \tag{7}$$

Table I. First Half Value Layer (mm Al).

Voltage (kVp)	Theoretical spectrum	MTSVD MCNP	SpectroX
70	2.360	2.250 (-4.6%)	2.480 (5.1%)
80	2.680	2.650 (-1.1%)	3.000 (11.9%)
90	3.020	2.900 (-3.9%)	3.300 (9.3%)
100	3.370	3.310 (-1.8%)	3.750 (11.3%)
120	4.100	4.170 (1.7%)	4.450 (8.5%)

Table I shows a good agreement between results obtained with the MTSVD unfolding method and theoretical spectra for the first HVL. The maximum relative error is less than 5% in any case, while SpectroX unfolding spectra present a higher relative error, around 10%. This relative error is due to the conservative estimation of primary beam spectrum carried out by SpectroX code, as can be seen in figure 4 and figure 5.

Table II. Second Half Value Layer (mm Al).

Voltage (kVp)	Theoretical spectrum	MTSVD MCNP	SpectroX
70	3.320	3.250 (-2.1%)	3.550 (6.9%)
80	3.910	3.900 (-0.3%)	4.350 (11.2%)
90	4.530	4.500 (-0.7%)	4.980 (9.9%)
100	5.180	5.190 (0.2%)	5.770 (11.4%)
120	6.620	6.800 (2.7%)	7.220 (9.1%)

Table II shows results from MCNP and SpectroX for the second half value layer (thickness of aluminum to reduce air kerma from 50% to 25%). In this case, relative errors produced by MTSVD unfolding are less than 1% except for 70 and 120 kVp. The second HVL obtained by SpectroX presents a higher relative error (around 10%) in any case.

Finally, the analysis of mean photon energy is shown in table III. It is found again a good agreement between results from MCNP model and theoretical primary beam spectrum. On the other hand, due to the fact that SpectroX gives a conservative estimation of the primary spectrum (continuous bremsstrahlung placed at higher energies), it produces higher mean photon energies for each voltage. It can also be observed that mean photon energy calculation produces smaller errors in comparison to HVL calculation. This is due to some implicit uncertainties in both linear attenuation data and energy-absorption data.

Table III. Mean Photon Energy (keV)

Voltage (kVp)	Theoretical spectrum	MTSVD MCNP	SpectroX
70	39.17	38.75 (0.8%)	39.94 (1.9%)
80	42.74	42.52 (-0.2%)	43.99 (2.9%)
90	46.05	45.63 (0.8%)	47.22 (2.5%)
100	49.03	49.02 (-0.1%)	50.78 (3.5%)
120	54.29	54.05 (-0.5%)	56.40 (3.8%)

Mean photon energy relative error using MTSVD unfolding is smaller than 1% in any case. Relative errors produced in SpectroX unfolding are around 4%. From this data, it can be said that MTSVD unfolding reproduces accurately primary beam spectrum.

4 CONCLUSIONS

Good and accurate information about the primary beam spectrum is very important for Quality Control in X-ray tubes. Upon learning this spectrum other very useful parameters to characterize working conditions of the tube can be calculated. Using a spectrometry Compton technique a scattered spectrum can be obtained from which the primary spectrum can be estimated using unfolding techniques.

In this paper, it has been developed a simulation model using the MCNP code based on the Monte Carlo method to simulate the spectrometry process and to obtain a response matrix. Then, the MTSVD method has been applied to obtain the primary spectrum, which has been also obtained using the SpectroX code.

Results from both methods have been compared each other and also with a theoretical spectrum. Comparison has been completed by calculating two important parameters of Quality Control, HVL and mean photon energy. For both parameters, the agreement with theoretical values is better for the MCNP model plus MTSVD method than for SpectroX code.

Therefore, the technique presented in this paper is a powerful tool very helpful in Quality Control of X-ray tubes.

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