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Assessment of quality control parameters for an X-ray tube using the Monte Carlo method and unfolding techniques

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Abstract— **Quality Control (QC) parameters for an X-ray tube such as Half Value Layer (HVL), homogeneity factor and mean photon energy, can be obtained from the primary beam spectrum. A direct Monte Carlo (MC) simulation has been used to obtain this spectrum. Indirect spectrometry procedures such as Compton scattering have been also experimentally utilized since direct spectrometry causes a pile-up effect in detectors. As well the Compton spectrometry has been simulated with the MC method. In both cases unfolding techniques shall be applied to obtain the primary spectrum. Two unfolding methods (TSVD and Spectro-X) have been analyzed. Results are compared each other and with reference values taken from IPEM Report 78 catalogue. Direct MC simulation is a good approximation to obtain the primary spectrum and hence the QC parameters. TSVD is a better unfolding method for the scattered spectrum than the Spectro-X code. An improvement of the methodology to obtain QC parameters is important in Biomedical Engineering (BME) applications due to the wide use of X-ray tubes.**

I. Introduction

Half Value Layer (HVL), homogeneity factor and mean energy are important quality control parameters for an X-ray tube. These parameters can be obtained by conventional methods. They can be also obtained from the primary beam spectrum. However, this spectrum is not so easy to obtain. It can be performed a Monte Carlo (MC) simulation of the photon production process. The primary spectrum can be also determined using indirect spectrometry techniques to obtain a scattered spectrum either experimentally or by a MC simulation. In both cases, unfolding techniques shall be applied to obtain the primary spectrum. In the MC model both the photon scattering and their recording in a Germanium detector are considered in order to finally obtain Pulse Height Distribution (PHD). The whole spectrometer and detection system has been included in the model.

Applying the MC method, the solution is sought by calculating random particle histories based on the particle cross-section libraries (event probabilities) and geometrical information.

In this paper the primary beam spectrum has been obtained by direct MC simulation using the MCNP code [1] and by two different unfolding methods applied to both experimental and MC Compton scattering technique. From these primary spectra, the quality control parameters HVL, homogeneity factor and mean energy are estimated. Results are compared each other and with values obtained from IPEM Report 78 catalogue [2].

The aim of the paper is to assess the influence of the unfolding procedure used on the accuracy of the QC parameters obtained for an X-ray tube used for biomedical applications.

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II. Obtaining primary beam spectrum

The primary beam spectrum of an X-ray tube can be obtained by direct simulation using the MC method. It is more difficult to obtain experimentally this spectrum. Indirect spectrometry procedures are normally preferred in order to reduce the pile-up effect in the detector, but they require the use of unfolding techniques.

A. Obtaining spectrum by direct Monte Carlo simulation

A simulation of the photon production phenomena at the X-ray tube can be performed with the MCNP5 code [1].

Incident electrons on the tungsten anode are tracked. Bremstrahlung and characteristic photons produced in the tube are registered. The source is a point source emitting electrons within a solid angle. Electron energy is defined by the voltage applied. MCNP was run in photon and electron mode to enable full electron and photon transport. The MC simulation model has been based on the Philips MCN 322 X-ray tube, whose main features are the following: tungsten anode, 22º anode angle, 2.2 Beryllium and 3.5 Aluminium mm of inherent filtration.

A point detector tally (F5) measuring photon flux at a point was used in the simulation.

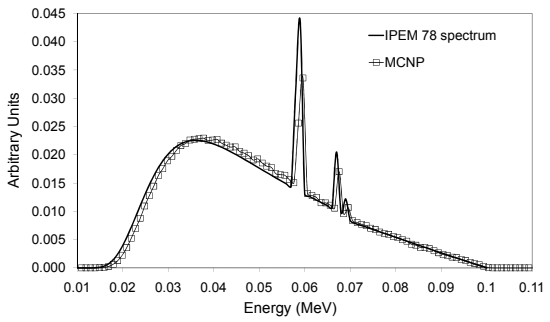

Fig. 1. Primary X-ray spectrum (100 keV). Comparison between IPEM no. 78 report and MCNP5 simulation.

F5 tally requires an uncertainty lower than 5% in order to produce a generally reliable confidence level [1].

Spectra obtained by simulation were compared with the corresponding spectra of IPEM Report 78 catalogue [2] in order to validate the model. This comparison is represented in Figure 1 for 100 kV tube voltage, but simulations have been done for several tube voltages in the radiodiagnostic range (70, 80, 90, 100, and 120 kV). The direct MC simulation reproduces successfully the Bremstrahlung continuous, but characteristic lines are slightly underestimated.

B. Obtaining spectrum by unfolding

Obtaining primary beam spectrum experimentally in actual X-ray tubes implies some important difficulties. The use of direct spectrometry for determining primary X-ray spectrum is practically forbidden as detectors cease to work properly at high count rates. To avoid the pile-up effect in the detector produced by a high fluence rate, a Compton spectrometry technique [3, 4] is proposed. In a previous work [5], authors described a MC model using the MCNP code to simulate the spectrometry process by obtaining the PHD for different tube working conditions.

MCNP5 is suitable for modelling the detector response, since it contains a tally, F8, which is specifically designed for detector pulse height determination. Detector resolution has been taken into account in the simulation by choosing an adequate number of energy bins. In addition, a Gaussian Energy Broadening GEB function of MCNP has been used in order to reproduce the real detector FWHM (full width at half maximum). Coherent scattering (Rayleigh and Thomson) has not been taken into account in order to improve result statistics. Really, this type of scattering usually masks the scattered spectrum increasing computer time. Furthermore, Rayleigh and Thomson scattering only becomes important at low energy level, less than 20 keV.

The experimental equipment included a commercial Compton spectrometer (with PMMA scatterer), a multi channel analyzer (MCA), an X-ray tube (Philips MCN 322 whose main features have been described above) and an ultra-low high purity germanium detector. Experimental PHD's were obtained for different working conditions (70, 80, 90, 100 and 120 kV).

The spectrum obtained with the spectrometry technique needs to be unfolded since some effects such as photon interactions, efficiency variations, or perturbations from electronic devices, produce a distortion in the actual spectrum. The response function of the process is approximated by a response matrix containing all the required information to unfold the PHD measured experimentally, but also that one simulated by MCNP code. It is however an ill conditioned matrix and requires some special mathematical treatment. A Truncated Singular Value Decomposition (TSVD) method [6, 7] was used to obtain a best-estimate primary spectrum. In a previous work [8] authors described this unfolding method and its application to the Compton scattering in detail.

The Spectro-X code [9] uses another unfolding algorithm, based on the Klein-Nishina formula including coherent and incoherent scattering processes.

Both methods, TSVD and Spectro-X, have been applied to both PHD's, experimental and simulated with MCNP, obtaining reconstructed spectra that are compared each other and also with a theoretical primary spectrum corresponding to X-ray tube working conditions (IPEM Report 78). Comparison results are represented for 100 kV in Figures 2 and 3 respectively for experimental and simulated PHD.

It can be seen that both reconstructions (TSVD and Spectro-X) give a good estimation of characteristic X-ray lines, but Bremstrahlung is better reproduced by the TSVD method.

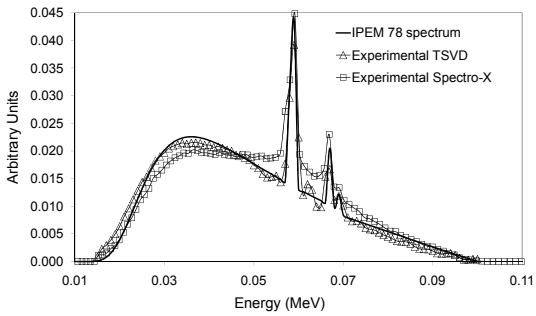

Fig. 2. Primary X-ray spectrum (100 keV). Comparison between IPEM no. 78 report, TSVD unfolding applied to an experimental PHD and Spectro-X unfolding applied to an experimental PHD.

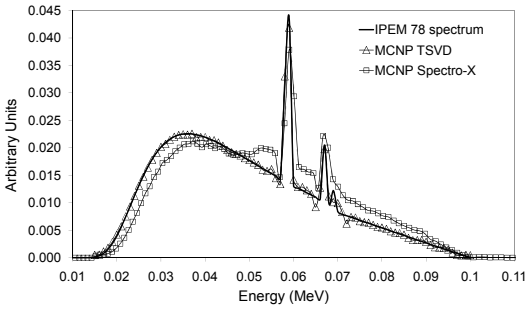

Fig. 3. Primary X-ray spectrum (100 keV). Comparison between IPEM no. 78 report, TSVD unfolding applied to a simulated PHD and Spectro-X unfolding applied to a simulated PHD.

It can be also seen that the spectrum obtained with Spectro-X is shifted to higher energies. This is a conservative estimation of the actual primary spectrum. Obviously, a subsequent treatment of this spectrum will provide higher values for air kerma values, half value layer and mean photon energy.

III. Obtaining HVL, Homogeneity Factor and Mean Energy

The HVL is defined for different quantities: photon fluence, energy fluence, air kerma or absorbed dose.

Normally, the HVL is experimentally obtained by overlapping aluminum or copper foils of certain thickness and certified purity between the X-ray focus and an ionization chamber. A commonly used method to certify the X-ray beam quality is to obtain HVL values for working conditions experimentally and then to compare them with the certified values registered in the quality procedures. However, HVL can also be determined by calculation if the primary X-ray spectrum is known. HVL for air kerma is calculated for X-ray according to the following expression:

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

where:

$(\mu_{en}/\rho)_{air}$ is the linear attenuation coefficient in air [10].

d is the distance between the X-ray focus and the detector, in practice an ionization chamber.

$h\nu_i$ is the photon energy of the i^{th} interval.

N_i is the number of photons in the i^{th} energy interval.

μ_{Al} is the linear attenuation coefficient in aluminum [10].

Eq (1) takes into account the correction for attenuation in air of X-ray spectra. When measuring multiple half value layers, the second HVL is found to be greater than the first one. This is due to the fact that the mean energy of the X-ray spectrum is increased after the first HVL, which results in X-rays becoming more penetrating.

Homogeneity factor is defined for each voltage as the ratio between the first and the second HVL.

The mean photon energy is calculated from the expression:

$$\overline{h\nu} = \frac{\sum_i N_i h\nu_i}{\sum_i N_i} \quad (2)$$

where $h\nu_i$ is the photon energy of the i^{th} interval and N_i is the number of photons in the i^{th} energy interval. For a given photon spectrum the mean photon energy is an important parameter because it represents the chromatic quality of the spectrum.

IV. Results

Values obtained for first and second HVL are listed in Table I and II, respectively. These values have been calculated considering 120 cm of air thickness. IPEM values have been always taken as reference for comparisons. Calculated second HVLs are greater than first HVLs as predicted above.

TABLE I
First Half Value Layer (mm of Aluminum)

Tube Volt. (kV)	IPEM 78[a]	Direct MC[b]	MC[c] TSVD	Exp[d] TSVD	MC[e] SpecX	Exp[f]. SpecX
70	*2.36*	*2.35*	*2.35*	*2.25*	*2.59*	*2.48*
		(-0.4)	*(-0.4)*	*(-4.7)*	*(9.7)*	*(5.1)*
80	*2.68*	*2.66*	*2.69*	*2.60*	*2.95*	*3.00*
		(-0.7)	*(0.4)*	*(-3.0)*	*(10.1)*	*(11.9)*
90	*3.02*	*3.01*	*3.00*	*2.90*	*3.29*	*3.30*
		(-0.3)	*(-0.7)*	*(-4.0)*	*(8.9)*	*(9.3)*
100	*3.37*	*3.35*	*3.34*	*3.31*	*3.70*	*3.75*
		(-0.6)	*(-0.9)*	*(-1.8)*	*(9.8)*	*(11.3)*
120	*4.10*	*4.08*	*4.25*	*4.10*	*4.50*	*4.45*
		(-0.5)	*(3.7)*	*(0.0)*	*(9.8)*	*(8.5)*

[a]First HVL obtained from IPEM Report 78 spectrum.

[b]First HVL obtained from the spectrum calculated by direct Monte Carlo simulation.

[c]First HVL obtained applying the TSVD unfolding method to the simulated (MCNP5) Pulse Height Distribution.

[d]First HVL obtained applying the TSVD unfolding method to the experimental Pulse Height Distribution.

[e]First HVL obtained applying the Spectro-X unfolding method to the simulated (MCNP5) Pulse Height Distribution.

[f]First HVL obtained applying the Spectro-X unfolding method to the experimental Pulse Height Distribution.

Relative error (% into brackets) is calculated taking as a reference the first HVL obtained from IPEM Report 78.

HVLs calculated from direct MC simulation are in full agreement with reference IPEM values. Therefore, the model developed is a good tool to obtain the primary spectrum of an X-ray tube, at least for the QC parameters analyzed.

TABLE II
Second Half Value Layer (mm of Aluminum)

Tube Volt. (kV)	IPEM 78[a]	Direct MC[b]	MC[c] TSVD	Exp[d] TSVD	MC[e] SpecX	Exp[f]. SpecX
70	*3.32*	*3.31*	*3.29*	*3.25*	*3.71*	*3.55*
		(-0.3)	*(-0.9)*	*(-2.1)*	*(11.7)*	*(6.9)*
80	*3.91*	*3.89*	*3.88*	*3.92*	*4.26*	*4.35*
		(-0.5)	*(-0.8)*	*(0.3)*	*(9.0)*	*(11.3)*
90	*4.53*	*4.51*	*4.53*	*4.52*	*4.87*	*4.98*
		(-0.4)	*(0.0)*	*(-0.2)*	*(7.5)*	*(9.9)*
100	*5.18*	*5.15*	*5.21*	*5.19*	*5.72*	*5.77*
		(-0.6)	*(0.6)*	*(0.2)*	*(10.4)*	*(11.4)*
120	*6.62*	*6.61*	*6.75*	*6.8*	*7.18*	*7.22*
		(-0.2)	*(2.0)*	*(2.7)*	*(8.5)*	*(9.1)*

[a]Second HVL obtained from IPEM Report 78 spectrum.

[b]Second HVL obtained from the spectrum calculated by direct Monte Carlo simulation.

[c]Second HVL obtained applying the TSVD unfolding method to the simulated (MCNP5) Pulse Height Distribution.

[d]Second HVL obtained applying the TSVD unfolding method to the experimental Pulse Height Distribution.

[e]Second HVL obtained applying the Spectro-X unfolding method to the simulated (MCNP5) Pulse Height Distribution.

[f]Second HVL obtained applying the Spectro-X unfolding method to the experimental Pulse Height Distribution.

Relative error (% into brackets) is calculated taking as a reference the second HVL obtained from IPEM Report 78.

Discrepancies are higher for unfolding methods, in particular for Spectro-X with greater deviations with respect to reference values. On the other hand, values calculated with MCNP are better than experimental measurements,

probably due to detector efficiency variations.

TABLE III
HOMOGENEITY FACTOR (MM OF ALUMINUM)

Tube Volt. (kV)	IPEM 78[a]	Direct MC[b]	MC[c] TSVD	Exp[d] TSVD	MC[e] SpecX	Exp[f]. SpecX
70	*0.71*	*0.708*	*0.718*	*0.692*	*0.682*	*0.699*
		(0.5)	*(1.0)*	*(5.1)*	*(13.7)*	*(8.6)*
80	*0.69*	*0.687*	*0.690*	*0.679*	*0.692*	*0.689*
		(0.8)	*(0.9)*	*(3.0)*	*(13.5)*	*(16.3)*
90	*0.67*	*0.671*	*0.667*	*0.644*	*0.676*	*0.662*
		(0.5)	*(0.7)*	*(4.0)*	*(11.6)*	*(13.6)*
100	*0.65*	*0.649*	*0.644*	*0.638*	*0.647*	*0.650*
		(0.8)	*(1.0)*	*(1.8)*	*(14.3)*	*(16.1)*
120	*0.62*	*0.617*	*0.629*	*0.613*	*0.627*	*0.616*
		(0.5)	*(4.2)*	*(2.7)*	*(12.9)*	*(12.4)*

[a]Homogeneity factor obtained from IPEM Report 78 spectrum.
[b]Homogeneity factor obtained from the spectrum calculated by direct Monte Carlo simulation.
[c]Homogeneity factor obtained applying the TSVD unfolding method to the simulated (MCNP5) Pulse Height Distribution.
[d]Homogeneity factor obtained applying the TSVD unfolding method to the experimental Pulse Height Distribution.
[e]Homogeneity factor obtained applying the Spectro-X unfolding method to the simulated (MCNP5) Pulse Height Distribution.
[f]Homogeneity factor obtained applying the Spectro-X unfolding method to the experimental Pulse Height Distribution.

Results for homogeneity factor are listed in Table III, where it can be seen that Spectro-X errors are always greater than 10% while errors produced by TSVD unfolding are less than 5% in all cases.

TABLE IV
MEAN ENERGY (KEV)

Tube Volt. (kV)	IPEM 78[a]	Direct MC[b]	MC[c] TSVD	Exp[d] TSVD	MC[e] SpecX	Exp[f]. SpecX
70	*39.17*	*39.16*	*39.18*	*38.75*	*40.29*	*39.94*
		(0.0)	*(0.0)*	*(-1.1)*	*(2.9)*	*(2.0)*
80	*42.74*	*42.70*	*42.82*	*42.52*	*45.06*	*43.99*
		(-0.1)	*(0.2)*	*(-0.5)*	*(5.4)*	*(2.9)*
90	*46.05*	*45.90*	*46.10*	*45.63*	*47.53*	*47.22*
		(-0.3)	*(0.1)*	*(-0.9)*	*(3.2)*	*(2.5)*
100	*49.03*	*49.00*	*49.03*	*49.02*	*50.55*	*50.78*
		(-0.1)	*(0.0)*	*(0.0)*	*(3.1)*	*(3.6)*
120	*54.29*	*54.29*	*54.31*	*54.05*	*55.30*	*56.40*
		(0.0)	*(0.1)*	*(-0.4)*	*(1.9)*	*(3.9)*

[a]Mean energy obtained from IPEM Report 78 spectrum.
[b]Mean energy obtained from the spectrum calculated by direct Monte Carlo simulation.
[c]Mean energy obtained applying the TSVD unfolding method to the simulated (MCNP5) Pulse Height Distribution.
[d]Mean energy obtained applying the TSVD unfolding method to the experimental Pulse Height Distribution.
[e]Mean energy obtained applying the Spectro-X unfolding method to the simulated (MCNP5) Pulse Height Distribution.
[f]Mean energy obtained applying the Spectro-X unfolding method to the experimental Pulse Height Distribution.
Relative error (% into brackets) is calculated taking as a reference the mean energy obtained from IPEM Report 78.

Mean energy values obtained for the different cases are listed in Table IV, where it can be seen that mean photon energies obtained applying the TSVD unfolding method, are very similar to those obtained by means of IPEM Report 78 spectrum. Anyway, values obtained with the Spectro-X method do not show high discrepancies. Therefore, it can be said that there is a weak influence of the unfolding method on the mean energy values.

V. CONCLUSION

Direct MC simulation gives a good approximation to the X-ray production process.

Quality Control parameters for an X-ray tube calculated by a direct MC simulation are in good agreement with values from IPEM Report 78 catalogue.

For indirect methods, QC calculated parameters also show a good agreement with IPEM when a MCNP simulation is done, mainly if the TSVD unfolding is applied. For cases analyzed the TSVD is a better unfolding method than Spectro-X code; and simulations give better results than measurements.

Furthermore, the conservative behaviour of solutions obtained with Spectro-X causes higher air kerma values and consequently higher values of HVL and mean photon energy.

The wide use of X-ray tubes in Biomedical Engineering (BME) applications requires a good Quality Control for the the tube. Therefore, it is very important an improvement of the methodology used to obtain the necessary QC parameters.

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