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Unfolding X-ray spectra using a flat panel detector

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Abstract—**It is difficult to measure the energy spectrum of X-ray tubes due to the pile up effect produced by the high fluence of photons. Using attenuating materials, appropriate detector devices and the Monte Carlo method, primary X-ray spectrum of these devices can be estimated. In this work, a flat panel detector with a PMMA wedge has been used to obtain a dose curve corresponding to certain working conditions of a radiodiagnostic X-ray tube. The relation between the dose curve recorded by the flat panel and the primary X-ray spectrum is defined by a response function. Normally this function can be approximated by a matrix, which can be obtained by means of the Monte Carlo method. Knowing the measured dose curve and the response matrix, the primary X-ray spectrum can be unfolded. However, there are some problems that strongly affect the applicability of this method: i.e. technical features of the flat panel and inherent characteristics of the involved radiation physics (ill-posed problem). Both aspects are analyzed in this work, concluding that the proposed method can be applied with an acceptable accuracy for spectra without characteristic lines, for instance, tungsten anode in the 50-70 kVp range.**

I. INTRODUCTION

Obtaining X-ray spectra from radiodiagnostic X-ray units is a complex task mainly due to the high photon flux and the low energy of particles emitted by the tube. To reduce the high fluence reaching the detector, a dispersive or attenuating material is needed. The X-ray spectrum can be estimated using a flat panel detector and an attenuating material. The basis of flat panels consists in transforming the absorbed X-rays into charge carriers by means of direct or indirect methods. In direct devices, amorphous Selenium (a:Se) is normally used to directly transform photon fluence into current. In indirect devices, a scintillator material absorbs the X-rays and converts them into visible light photons that pass onto a photodiode array. A semiconductor foil is used to convert visible light photons into charge carriers. Normally amorphous Silicon is preferred due to its high rate for Detective Quantum Efficiency (DQE). The most common scintillators used in flat panel imaging in indirect measurements are Gadolinium Oxysulfide (GOS), Thallium doped Cesium Iodide (CsI(Tl)), Cadmium Teluride (CdTe) and Mercury Iodide (HgI).

In this work, a method comprising experimental measurements and the Monte Carlo method is tested. The experimental equipment includes a flat panel with GOS scintillator, a poly-(methylmethacrylate) (PMMA) wedge and the appropriate acquisition software. The PMMA wedge is placed between the X-ray focus and the flat panel. When the flat panel is irradiated, a gray-scaled image is obtained. From this image, a dose curve can be easily obtained. On the other hand, the Monte Carlo N-Particle transport code version 5 (MCNP5) based on the Monte Carlo method [1] has been used to model the actual experimental conditions (X-ray focus - PMMA wedge - flat panel). Simulating several monochromatic beams and calculating the dose curve for each one, the response matrix of the system can be obtained. Knowing the response matrix and the dose curve for certain working conditions of the equipment, the primary X-ray spectrum can be unfolded. Different methods to unfold primary spectra can be found in the literature. Most of them are based on the Singular Value Decomposition (SVD) [2] of a response matrix. For our approach, the Modified Truncated Singular Value Decomposition (MTSVD) method [3] has been used. This method has been tested simulating the dose curve for different X-ray spectra extracted from the IPEM 78 Report [4] and verified with experimental measurements. It has been proved that Bremsstrahlung continuous is unfolded in good agreement with the theoretical distribution, but characteristic X-ray lines are not properly unfolded due to the loss of information of the dose curves. Furthermore, the GOS scintillator presents a K-edge at 50 keV in the mass-energy absorption coefficient [5]. This K-edge produces an abrupt change in the absorbed dose and consequently in the response matrix. It has been also proved with Monte Carlo simulations, that using a flat panel with direct conversion, amorphous selenium for instance, the matrix response is better conditioned, improving results of the unfolding.

II. EXPERIMENTAL MEASUREMENTS

The experimental equipment is composed by a commercial X-ray tube (Toshiba mod E7299X), a flat panel (Hamamatsu C9312SK), a PMMA wedge (12.5x12.5x10 cm) and a laptop with the appropriate acquisition software. The C9312SK flat panel uses an indirect converting scintillator made of Gadolinium Oxysulfid (GOS-deposited FOP), which is connected to the image sensor through a fiber optic plate. The pixel size is 50 x 50 μm^2. X-rays hit the 140 µm thick scintillator through the entrance window of 1 mm thick carbon. The 3 mm thick fiber optic is located behind the scintillator. This flat panel is suitable to be used in the energy 20 and 110 keV range. Shielding is provided by a thin copper foil. Distance between the flat panel surface and the X-ray focus was fixed at 85 cm. A picture of the experimental equipment is shown in Figure 1.

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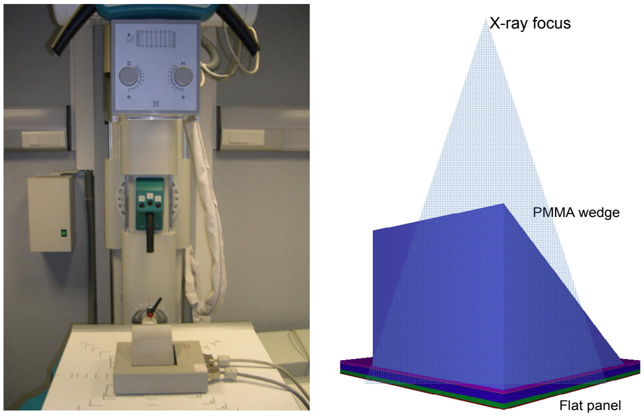

Figure 1. Experimental equipment and geometry layout.

A radiation field of 15x15 cm^2 was used. The PMMA wedge and the flat panel were irradiated at different working conditions varying high voltage from 40 kVp up to 80 kVp and maintain 20 mA current and 0.1 ms exposition time. A gray-scaled matrix (2490x2490) is obtained for each case. Figure 2 shows the gray-scaled matrix for 80 kVp. To minimize penumbra effects a central band should be selected on the matrix. Collapsing this central band a dose curve is obtained.

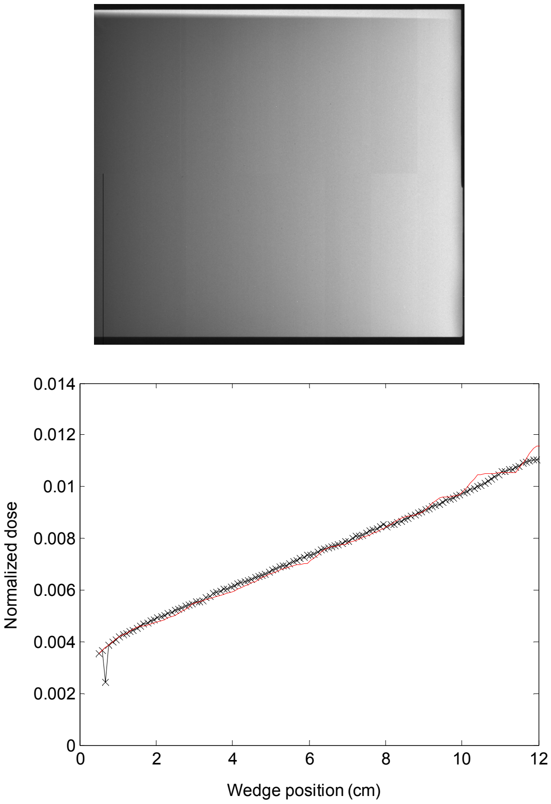

Figure 2. Gray-scaled image acquired with flat panel including the PMMA wedge. Experimental and MCNP dose curves for 80 kVp.

The relation between dose and gray pixel values has been experimentally obtained using the flat panel and a solid-state detector (Piranha Dose Probe). The procedure was to irradiate the flat panel without the PMMA wedge, but with the Piranha detector above it. Several measurements have been done by varying high voltage (increments of 1 kV) and maintaining constant both current and exposition time. By this procedure, the relation between gray level and dose is obtained. This conversion is necessary to transform gray level values obtained by the flat panel in total absorbed dose (micro Gy).

III. MONTE CARLO SIMULATIONS

The Monte Carlo code MCNP5 [1] has been used to model the X-ray source, the PMMA wedge and the flat panel detector. Figure 1 shows the geometry layout of the MCNP model developed. The theoretical spectrum has been extracted from the IPEM78 Report Catalogue [4] considering a Tungsten anode with 12º angle, 4 mm Aluminum inherent filter and different voltages. This spectrum has been used to characterize the X-ray focus of the MCNP model. When the flat panel is irradiated, the photon fluence can be calculated in the scintillator layer at different positions using a F4MESH tally [1]. This photon fluence can be converted into dose using the mass energy-absorption coefficient (μ_en/ρ) provided by the National Institute of Standards and Technology (NIST) [5]. With this method a dose curve in μGy per emitted photon is obtained for a given X-ray spectrum. It has been simulated 100 million particles to obtain relative errors lower than 3.0 %. MODE P, E has been activated to follow tracks of photons and electrons. A cutoff of 5 keV for electrons has been used to reduce computation time. Experimental and simulated dose curves have been obtained for voltages between 40 and 80 kVp. It has been stated that decreasing the voltage, dose curves present more discrepancies between experimental and simulated ones. It affects the experimental unfolded spectra, as it has been discussed in Section IV of this paper. Experimental and simulated dose curves for 80 kVp are shown in Figure 2. To compare gradients, both curves have been normalized.

The same MCNP model can be used to determine the response matrix of the system. With this aim, several monochromatic beams have been simulated, calculating the dose curve for each of them. Figure 3 shows the response matrix obtained simulating 168 monoenergetic beams covering the range between 15 and 100 keV, i.e. using 0.5 keV energy bin. In this matrix it can be clearly seen the effect of the GOS K-edge on the response system at 50 keV. It can also be seen that the relation between dose and beam energy is not linear. In fact, for energies below the GOS K-edge, the maximum dose per emitted photon is found at 40 keV. Both features (K-edge and dose variation) produce an important effect on the reconstruction of the primary spectrum. To minimize these effects, a normalization of the response matrix should be done. Response functions with and without PMMA wedge have been simulated for each monoenergetic beam. The normalized response matrix is obtained by calculating the dose ratio with and without wedge for every monochromatic beam. The normalized response matrix obtained using this method is shown in Figure 4.

This normalized response matrix is used to unfold the primary X-ray spectrum.

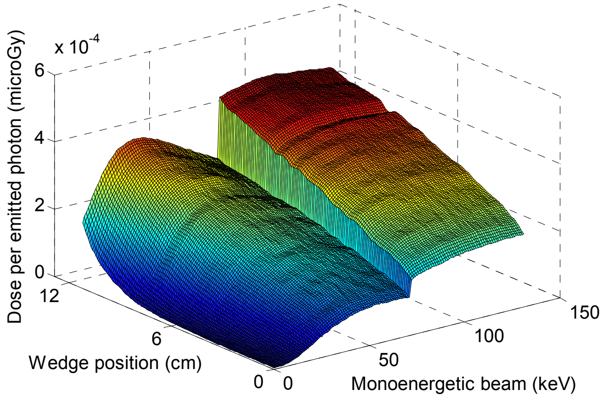

Figure 3. MCNP5 response matrix for GOS.

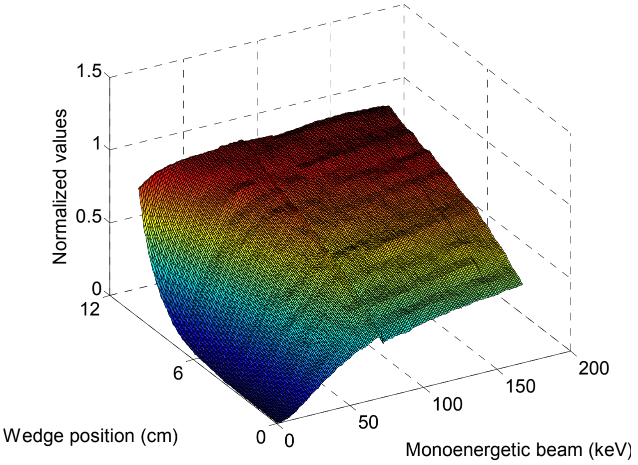

Figure 4. MCNP5 normalized response matrix for GOS.

The relationship between dose curve and primary spectrum can be expressed by the matrix relation:

$$R \cdot \vec{s} = \vec{m}, \quad (1)$$

where $\vec{s}$ is the unknown spectrum, and $\vec{m}$ is the dose curve for given conditions.

R can be considered as rank deficient matrix, it means that there are a large number of solutions for the Least Squares problem $\left\|R\vec{s} - \vec{m}\right\|_2$ [2, 3]. An optimum solution can be obtained generating a new response matrix, R_k, removing those parts of the solution corresponding to the smallest singular values [3, 6]. The obtained vector is the solution of the minimization problem:

$$\min\{\|\vec{s}\|_2\} \text{ subject to } \min\{\|R_k\vec{s} - \vec{m}\|_2\} \quad (2)$$

In the Modified Truncated Singular Value Decomposition (MTSVD) [3], the 2-norm, $\|\vec{s}\|_2$, is replaced by the seminorm $\|L_P\vec{s}\|_2$, where L_P is a discrete approximation to the p-th derivative operator.

IV. RESULTS AND DISCUSSION

When the response matrix and dose curves are known, the primary spectrum can be unfolded using the MTSVD method. The quality of results strongly depends on the regularization parameter, k. When the number of singular values considered is too low, the unfolded spectrum has a poor resolution. However, for higher k values, strong fluctuations and noise start to appear in the spectrum. The optimal k corresponds with the corner of the L-curve. In the Figure 5 it is shown the representation of the solution norm and the residual norm for different singular values (L-curve).

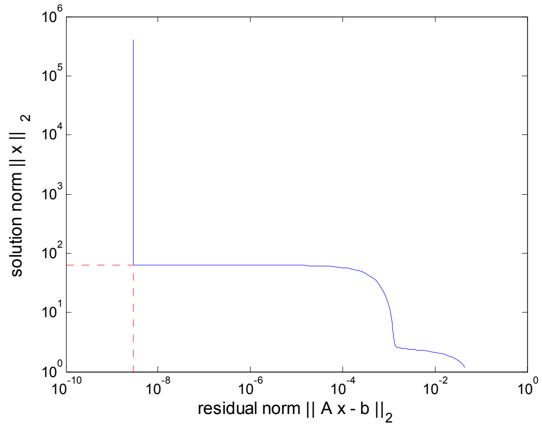

Figure 5. L-curve (corner marks the optimal k value).

The value of k corresponding to the L-curve corner minimizes both the solution and residual norms. Using the response matrix, the dose curve and fixing k=3, the primary spectrum can be estimated. Figures 6-10 show a comparison between theoretical and unfolded spectra for different voltages (40, 50, 60, 70 and 80 kVp).

In general, it is observed that simulated spectra are slightly shifted to higher energies in comparison to theoretical ones when the voltage is increased. In the 80 kVp spectrum (Figure 10), the higher intensity of the Bremsstrahlung continuous is shifted about 5 keV. These discrepancies appear for voltages higher than 50 kVp, which can be attributed to the discontinuity in the response matrix due to the GOS K-edge at 50 keV.

Regarding to experimental unfolded spectra, it is observed some discrepancies respect to simulated spectra. Maximum intensity of Bremsstrahlung is underestimated in all cases obtaining a broader energy distribution. The discrepancies between experimental and simulated unfolded spectrum can be attributed to differences in absorbed dose curves. This effect is more accused when voltage is decreased (Figure 6). It is necessary to study in more detail the behavior of the actual GOS at low energies (less than 50 keV).

Furthermore, this method is not able to unfold the characteristic X-rays, which are confused with the Bremsstrahlung continuous as it can be seen in Figure 10 (for both experimental and simulated spectra). In fact, this is the main disadvantage of this method.

For a quantitative comparison between unfolded and theoretical spectra, the Root Mean Squared (RMS) has been calculated to know whether discrepancies are acceptable. For MCNP unfolded spectra, RMS is lower than 2% for low voltages (40 and 50 kVp), but reaches 8% for higher voltages due to the GOS K-edge at 50 keV. Respect to experimental unfolded spectra, RMS increases for lower voltages, reaching maximum RMS values of about 20% due to discrepancies found between experimental and simulated dose curves.

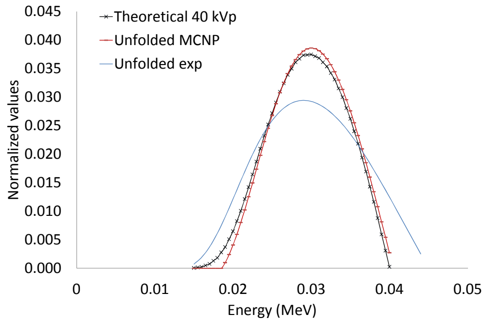

Figure 6. Comparison of theoretical and unfolded spectra for 40 kVp.

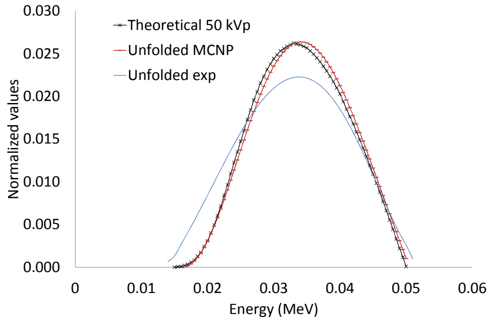

Figure 7. Comparison of theoretical and unfolded spectra for 50 kVp.

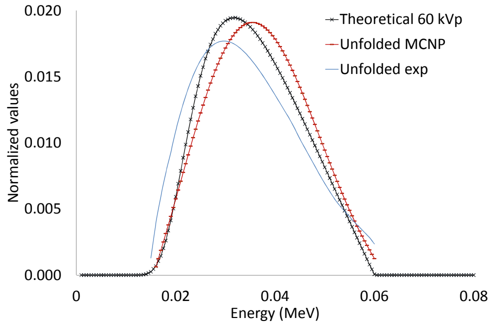

Figure 8. Comparison of theoretical and unfolded spectra for 60 kVp.

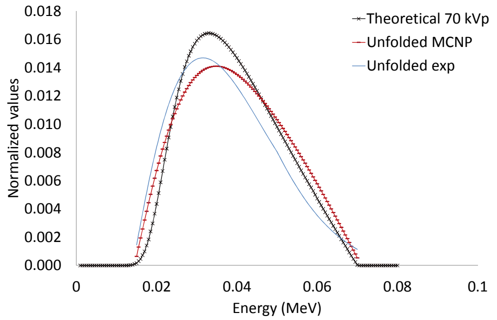

Figure 9. Comparison of theoretical and unfolded spectra for 70 kVp.

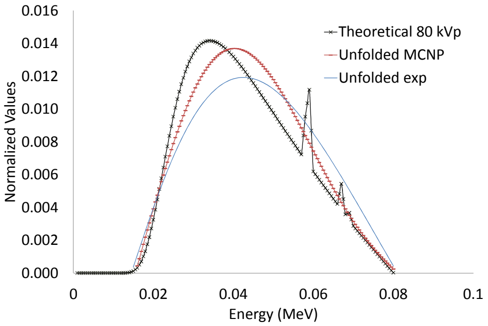

Figure 10. Comparison of theoretical and unfolded spectra for 80 kVp.

V. CONCLUSION

A mixed experimental – Monte Carlo technique using a flat panel and a PMMA wedge has been used to estimate primary X-ray spectra in the diagnostic energy range. The MTSVD method has been used to unfold spectra obtained experimentally and by simulation.

Unfolded simulated spectra show a good agreement with theoretical ones for voltages lower than 60 kVp showing slight discrepancies for higher voltages. Nevertheless, unfolded experimental spectra show greater discrepancies respect to theoretical spectra. Furthermore, characteristic lines are not reproduced.

Moreover, any variation in the geometry model, such as flat panel or distance between X-ray tube and detector, involves obtaining a new response matrix. In addition, uncertainties should be as minimal as possible, which implies a high computational time. For these reasons, this technique is considered as complementary tool and not easy to apply in a commercial quality control of X-ray tubes mainly for spectra without characteristic lines. This could be the case of Tungsten anode with peak voltages between 50 and 70 kVp.

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