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Application of the Monte Carlo method to analyze materials used in flat panel detectors to obtain X-ray spectra

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ABSTRACT

An accurate knowledge of the photon spectra emitted by X-ray tubes in radiodiagnostic is essential to better estimate the imparted dose to patients and to improve the quality image obtained with these devices. In this work, it is proposed the use of a flat panel detector together with a PMMA wedge to estimate the actual X-ray spectrum using the Monte Carlo method and unfolding techniques. The MCNP5 code has been used to model different flat panels (based on indirect and direct methods to produce charge carriers from absorbed X-rays) and to obtain the dose curves and system response functions. Most of the actual flat panel devices use scintillator materials that present K-edge discontinuities in the mass energy-absorption coefficient, which strongly affect the response matrix. In this paper, the applicability of different flat panels for reconstructing X-ray spectra is studied. The effect of the mass energy-absorption coefficient of the scintillator material has been studied on the response matrix and consequently, in the reconstructed spectra. Different unfolding methods are tested to reconstruct the actual X-ray spectrum knowing the dose curve and the response function. It has been concluded that the regularization method Modified Truncated Singular Value Decomposition (MTSVD) is appropriate to unfold X-ray spectra in all the scintillators studied.

1. Introduction

Obtaining X-ray spectra in radiodiagnostic 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.

Flat panels are based on 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 as a semiconductor foil to convert visible light photons into charge carriers due to its high rate for Detective Quantum Efficiency (DQE). Although silicon has outstanding electronic properties, it is not a particularly good absorber of X-ray photons. For this reason, X-rays first impinge upon scintillators usually made from either Gadolinium OxySulfide (GOS) or Cesium Iodide. Stopping power, speed and luminosity are the main characteristics to take into account to have a good scintillator material. Stopping power is maximized by maximizing density and atomic number. High density and stopping power are important for reducing the amount of the scintillator material needed Derenzo et al., 2003). Alternative materials like Cadmium Telluride and Mercury Iodide are being studied as they have better stopping power (Hubbell and Seltzer, 2011). Taking into account these considerations, flat panels with different scintillator materials have been analysed.

A PMMA (polymethylmethacrylate) wedge has been used as attenuating material. This 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, an absorbed dose curve can be easily obtained. The absorbed dose curve obtained using different scintillator materials can be transformed into tissue equivalent dose multiplying the dose in the first material by the ratio of mass energy absorption coefficients for the second and first material taking into account the photons of interest (always under conditions of secondary charged particle equilibrium).

In this frame, the Monte Carlo code MCNP5 (X-5 Monte Carlo Team, 2003) has been used to simulate the energy absorption in the flat panel and to obtain the dose curve corresponding to certain

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working conditions of a X-ray tube. The developed MCNP5 model can be used to analyse the behaviour of different scintillators and to determine their response function depending on the X-ray energy. The response function of different materials used in direct and indirect measurements have been determined.

Simulating several monochromatic X-ray 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, the primary X-ray spectrum can be unfolded. However, it has been proved that response matrices characterizing the described problem are ill-posed.

In order to unfold the primary X-ray spectrum, regularization methods can be applied.

Unfolding methods are widely used in different fields of gamma and X-ray spectrometry, environmental radiation, imaging and nuclear data. For instance, the Maximum Entropy Method (MEM) has been successfully used for gamma ray unfolding (Los Arcos, 1996) and for neutron unfolding with the code MAXED (Reginatto et al., 2002). Regarding to nuclear data, the general problem of estimating parameters in nuclear spectroscopy can be undertaken using stochastic numerical Bayesian technique and the reversible-jump Markov-chain Monte-Carlo method (Gulam Razul et al., 2003). Bayesian and Maximum Entropy Methods have been used in diagnostic measurements with compact neutron spectrometers (Reginatto and Zimbal, 2008). All these methods, partially using the Monte Carlo method, represent some of the new perspectives of spectra and imaging unfolding.

In this work, unfolding methods based on the Singular Value Decomposition (SVD) (Golub and Van Loan, 1996) of a response matrix have been used. Specifically, the Truncated Singular Value Decomposition (TSVD), the Modified Truncated Singular Value Decomposition (MTSVD) (Hansen et al., 1992), the Dump Singular Value Decomposition (DSVD) (Hansen et al., 1992), and the Tikhonov method (Hansen, 1999) have been used. These methods have been tested simulating the dose curve for different X-ray spectra extracted from the IPEM 78 Report (Cranley et al., 1997) and verified with experimental measurements.

2. Methodology

2.1. The Monte Carlo model

The Monte Carlo code MCNP5 (X-5 Monte Carlo Team, 2003) has been used to model an X-ray source, a PMMA wedge and different flat panel detectors including a:Se, CdTe CsI(Tl), GOS and HgI2.

The theoretical spectra for certain working conditions of the X-ray tube, has been established using the IPEM78 Report Catalogue (Cranley et al., 1997). This actual version uses the XCOM photon cross section library (Berger and Hubbell, 1987) to calculate linear attenuation coefficients of various materials. The unattenuated photon spectra are given for tungsten targets, tube potential from 30 kV to 150 kV, and target angles from 6° to 22°. The ripple value can be changed from 0% to 30%. In this study a Tungsten anode tube has been considered.

The PMMA wedge is placed between the X-ray focus and the flat panel, as it can be seen in Fig. 1. A scheme of a generic flat panel model it is shown in Fig. 2 with all the materials that conforms a typical flat panel detector. The carbon filter is used to prevent the X-ray penetration the scintillator layer being interfered and absorbed visible light. The scintillator material absorbs the X-rays and converts them into visible light photons that pass onto a photodiode array (fibre optic). The semiconductor foil is used to convert visible light photons into charge carriers.

When the flat panel is irradiated, it registers an absorbed dose gradient due to the attenuation of X-rays produced in the wedge.

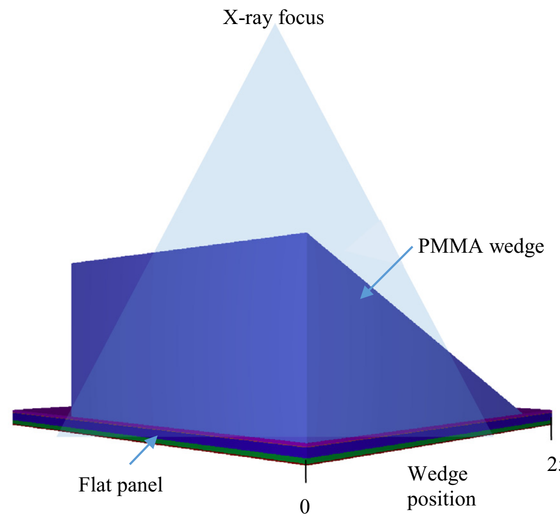

Fig. 1. Geometry layout of the system.

For certain working conditions (high voltage, filter thickness and current) of the X-ray tube, an absorbed dose curve is obtained.

The absorbed dose curve is directly related to the primary spectrum by means of a Response function. In most applications, the Response function can be approximated by a matrix, which can be obtained using the Monte Carlo method. The photon fluence has been measured in the scintillator layer at 25 different positions along the *X* axis using a F4MESH tally (X-5 Monte Carlo Team, 2003). Photon fluence can be converted into dose using the mass energy-absorption coefficient ($\frac{\mu_{en}}{\rho}$) provided by the National Institute of Standards and Technology (NIST) (Hubbell and Seltzer, 2011). The mass energy-absorption coefficients for each material considered in the MCNP5 models are shown in Fig. 3.

Common scintillators used in commercial flat panels present a K-edge in the energy range of interest, as it can be seen in Fig. 3: GOS (at 50 keV), HgI2 (at 33.17 and 83.1 keV), CdTe (at 26.7 and 31.8 keV) and CsI (at 33.17 and 35.98 keV), all of them used in indirect methods. On the other hand, a:Se (direct method) does not present any K-edge in the energy range studied (5–120 keV). Using this model as a reference, different configurations have been evaluated changing the flat panel configuration. The thickness of scintillator is different in each detector (GOS 0.14 mm (Hamamatsu comercial catalogue, 2007), HgI_2 0.25 mm (Iwanczyk et al., 2001), CdTe 0.2 mm (Izumi et al., 2001) and CsI 0.6 mm (Chabbal et al., 2002)). In the direct flat panel the thickness of a:Se is 1 mm (Izumi et al., 2001).

Each model has been run simulating 50 million particles in order to ensure a relative error in F4MESH lower than 1%. MODE P, E has been activated to follow tracks of photons and electrons. A default cutoff of 1 keV for electrons has been considered.

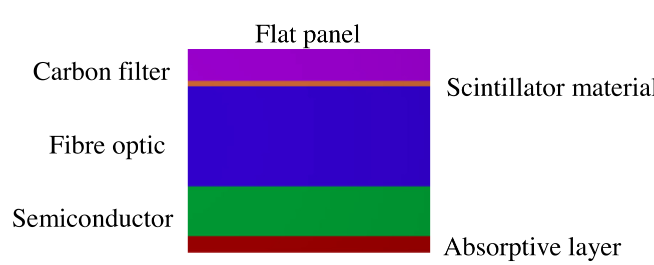

Fig. 2. Flat panel materials.