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Comparison between transmission and scattering spectrum reconstruction methods based on EPID images

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Abstract— **Numerous improved physics-based methods for Linac photon spectra reconstruction have been published; some of them are based on transmission data analysis and others on scattering data. In this work, the two spectrum unfolding approaches are compared in order to experimentally validate its robustness and to determine which is the optimal methodology for application on a clinical quality assurance routine. Both studied methods are based on EPID images generated when the incident photon beam impinges onto plastic blocks. The distribution of transmitted/scatter radiation produced by this object centered at the beam field size was measured. Measurements were performed using a 6 MeV photon beam produced by the linear accelerator. The same radiation distribution conditions were also simulated with Monte Carlo code for a series of monoenergetic identical geometry photon beams for both cases. Two systems of linear equations were generated to combine the polyenergetic EPID measurements with the monoenergetic simulation results. Regularization techniques were applied to solve the systems for obtaining the incident photon spectrum.**

We present a comparison between the well-known photon Spectral Reconstruction based on Transmission Data (Trans-based) technology and the Spectral Reconstruction based on Scattering Data (Scatt-based), which we both developed using EPID images. It is shown that Trans-based reconstruction results display much better agreement with photon spectrum theoretical predictions.

I. INTRODUCTION

The importance of a characterization methodology of Linac photon energy spectra has been recurrently reported [1]. The goal of these approaches is to provide the means for periodic quality assurance, improved dosimetric accuracy and for Electronic Portal Imager Devices (EPID) optimization. Moreover, current 3D treatment planning systems use robust convolution or Monte Carlo based algorithms which require precise knowledge of the Linac emitted spectrum to adequately carry out complicated dose calculations involving non homogeneous media, lack of electronic equilibrium and multi-leaf field modifying jaws.

Spectral reconstruction by attenuation analysis has recently received considerable attention. The method consists in measuring the transmission of a beam through several thicknesses of a material and go back from the registered data to the beam spectral energy distribution [2], [3]. The measurement of transmission or depth dose curves is reasonably simple to perform in any radiotherapy department and it may offer an available routine check on emitted spectra if a reconstruction methodology is established which reliably describes megavoltage photon spectrum over the full range of beam energies.

On the other hand, alternative spectral reconstruction methods are based on scattering data and require fewer measurements [4], [5]. This method consists in irradiating a plastic phantom and inferring primary beam spectral information based on the measurement of scatter around the phantom at several specific scatter positions: a scatter curve is measured which is characteristic of the primary spectrum at hand.

This work compares the preliminary development of these two alternatives of spectral reconstruction methods and validates the superiority of the transmission data-based method through the experiment. The mathematical method is similar in both cases and it is based on a linear matrix built by Monte Carlo simulations of the transmitted (Trans-based method) / scattered (Scatt-based method) results for a set of consecutive monoenergetic photon beams. EPID measurements along with the simulation matrix constitute the mathematical model that relates the transmitted/scattered radiation to reveal the energy distribution of the primary beam.

The Amorphous silicon electronic portal imaging devices (a-Si EPIDs) studied in this work consist on an amorphous silicon array detector which is specially suited for patient positioning verification. We show in this paper the advantages of using this EPID as an alternative to spectrum verification.

II. METHODS AND MATERIALS

The two methodologies of determining a bremsstrahlung spectrum proposed in this work are based on a combination of monoenergetic simulations, polyenergetic measurements, and mathematical matrix equations system. The monoenergetic simulations and the matrix solution methodology are generated initially, and then the spectrum reconstruction method can be applied for all beams within the simulations energy range just taking new EPID measurements [6].

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A. *Experimental Procedure*

All the measures and images acquisitions were performed with an *Elekta Sli Precise* linear accelerator using a 6 MeV photon beam and with a machine dose rate setting of 100 monitor units (MU).

The *iView GT*-type EPID (*Elekta*) [7] is based on the amorphous silicon detector panel XRD 1640 (*Perkin-Elmer Optoelectronics*, Fremont, CA) with a fixed source detector distance (SDD) of 160 cm and a detection area of 46 cm x 46 cm. This system has a 1024 x 1024 pixel resolution. Portal images were acquired maintaining the gantry angle at 0° in the mentioned irradiation conditions using the commercial *iViewGT* software. All images were generated by integrating the frames acquired during the total radiation dose delivered. The number of frames integrated during beam delivery was estimated to range between 40 and 50, when using 100 monitor units.

1) *Transmission based methodology measurements*

The experimental set-up presented in Figure 1 involves the acquisition of images using an square open field size of 20 cm x 20 cm at the isocentre, and followed by several images of different solid water blocks (from 2 cm thickness to 20 cm stepped in 2 cm increments), maintaining a source to isocenter distance (SID) of 100 cm. We have selected these water equivalent blocks thickness in order to obtain a wide grey level intensities range.

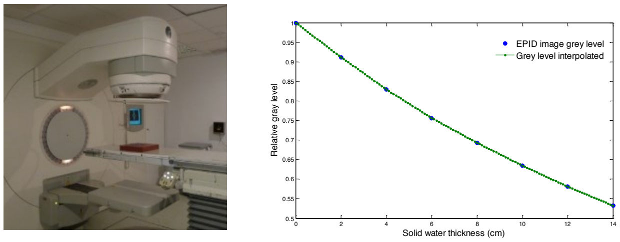

Figure 1. Experimental procedure for transmission images adquisition and attenuation curve obtained with EPID images using solid water slabs.

Figure 1 also displays the relative attenuation curve obtained after all images (from 2 cm to 14 cm thickness) were analyzed. For each phantom thickness the EPID response was measured as the mean pixel value in a 1 cm x 1 cm region of interest in the centre of the image. The data for each detector were normalized with the white image.

2) *Scattering based methodology measurements*

In this approach an experiment was designed to determine the photon energy spectrum based on the scattered radiation measured at different positions generated by a scattering block.

The experimental set-up involves the acquisition of images using a square open field size of 10 cm x 6.3 cm at the isocentre. The obtained EPID images show the primary beam scattered radiation around the 10 cm x 10 cm x 20 cm plastic parallelepiped located at the EPID top surface and put at a 157 cm SSD along the central axis. PMMA (Polymethyl methacrylate) is the material of choice for the scattering medium because of its low Z material is required to enforce the assumption that Compton scattering is the dominant type of interaction at the energy range of interest.

Figure 2 shows the analyzed column pixel values in order to study the produced scattering. Measurements were repeated twice, with and without the scatterer to estimate head leakage effect on the measurements. Red curve correspond to previous images subtraction values. The figure also shows the gray pixel values for these columns, representing the scattered radiation at 8.5 cm from the block centre.

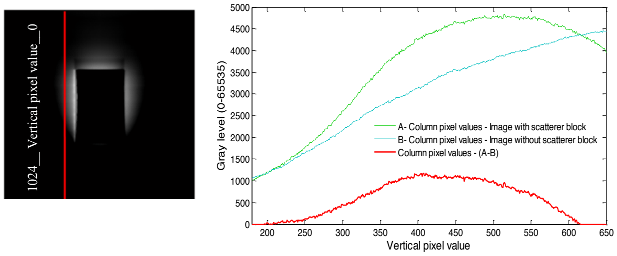

Figure 2. EPID images obtained with and without block using a 6MeV photon beam and a 10 cm x 6.3 cm field size. Scattering gray level pixel values delivered for *Elekta*

Red curve was then normalized to maximum value. The signal inherent in scatter measurements is very small and can suffer from inaccuracy due to leakage current in the flat panel EPID. Errors are inherent in these empirical measurements so that the resulting spectra will include the effects the errors.

B. *Monte Carlo simulation*

The Monte Carlo method is widely used for simulating particle transport through different materials, and recording tallies (results) of the particles interactions. The code used in this work is Monte Carlo N-Particle (MCNP version 5) [8], which is a general purpose Monte Carlo transport code developed at Los Alamos National Laboratory. MCNP5 was used to simulate radiation transport from a monoenergetic, monodirectional collimated source, ensuring the same conditions and using identical collimator field size as used in experimental measures.

The detailed geometry of the radiotherapy treatment head unit *Elekta Precise* (operating with a 6 MeV photon beam), the solid water/PMMA slabs and the EPID amorphous silicon flat-panel have been accurately implemented in the Monte Carlo model according to the manufacturer data. The validation of MLC Linac MC model was previously validated using depth dose curves in a water phantom [9], [10].

The relationship between dose and EPID response is further complicated due to the spreading of optical photons generated in the scintillating screen before reaching the photodiode array. EPID images for a set of solid water phantoms of varying thicknesses were simulated and the data converted to dose values via a calibration matrix developed in previous works [11]. The response of the imager in the sensitive layer of the detector was simulated in the same irradiation conditions as the experimental procedure was done. The energy response of the EPID detector used in this work is flat over the energy region of interest.

To register the contribution of photons and electrons, the *FMESH fluence deposition tally has been used and was placed at the GOS layer of the EPID representing the active part of the detector. 10^9 particles were simulated for each energy bin. Each Monte Carlo simulation was run until the uncertainty in all evaluated points was less than 0.3%, passing all internal MCNP statistical tests.

1) Transmission method

Figure 3 represents the response matrix (dim. 134x134) with energy range between 0-6.7 MeV (50 keV). Results are normalized to the maximum value. Each attenuation curve (stepped in 134 bins from 0 to 14 cm) was then calculated by simulation for each monoenergetic beam.

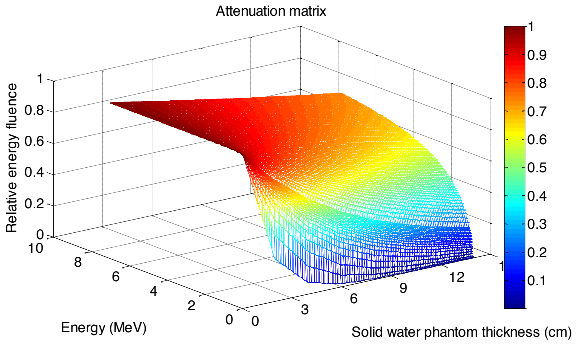

Figure 3. Transmission matrix results obtained by simulation

2) Scattering method

Monoenergetic beams were simulated one at a time and the scattered to primary photons were generated at each scoring pixel. The simulation scattering results for each monoenergetic beam is displayed in figure 4. Every scatter value was generated by subtracting the tally output of a specific voxel at a specific scattering position by the tally value without block. The set of data was normalized to the maximum value.

The pixel resolution of the Monte Carlo EPID model was set to 0.5 cm x 0.5 cm to allow good statistical accuracy in the dose calculation.

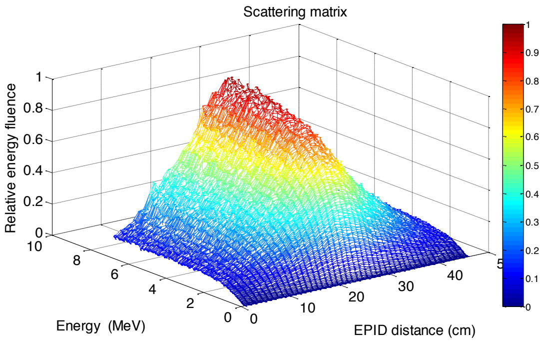

Figure 4. Scattering matrix results obtained by simulation

B. Inverse Problem Regularization and Matrix inversion

A Fredholm equation of the first kind was proposed to characterize the transmission/scatter as shown in Equation 1. This equation is similar in principle and application to Trans-based method and Scatt-based, with the exception that the attenuation matrix is replaced with the scattering matrix, and attenuation curve obtained with the EPID is replaced with the scattering curve (described previously).

$$E(x) = \int_0^{E_{max}} A_E(x) S(E) dE \qquad (1)$$

S(E) is the photon energy spectrum, unknown in this case. For the Trans-based method, the matrix $A_E(x)$ is a function that represents the relative energy fluence component transmitted with a solid plastic block of thickness x and was derived from the Monte Carlo simulations and *E(x)* is the EPID attenuation curve at different block thicknesses *x*. For the Scatt-based method, the matrix $A_E(x)$ is a function that represents the relative energy fluence component scattered in the position x and was also derived from the Monte Carlo simulations and *E(x)* is the EPID scatter signal measured at position *x*.

The problem is transformed into a discrete matrix system:

$$\begin{array}{c} a_{11} \cdot S_1 + a_{21} \cdot S_2 + \cdots + a_{M1} \cdot S_M = E_1 \\ a_{12} \cdot S_1 + a_{22} \cdot S_2 + \ldots + a_{M2} \cdot S_M = E_2 \\ \vdots \qquad \vdots \qquad \vdots \qquad \vdots \\ a_{1N} \cdot S_1 + a_{2N} \cdot S_2 + \ldots + a_{MN} \cdot S_M = E_N \end{array} \qquad (2)$$

Where, E_1, E_2, …E_N are the EPID readings, *S* is the energy fluence at different energy bins and a_{ij} are elements of the simulated matrix *A*.

This problem is considered ill posed since the inverse initially has no meaningful solution. Ill posed problems are common in physics and engineering applications. Such problems are highly affected by measurement errors, where slight changes in the measured data can produce drastic effects on the calculated inverse solution.

However, it can be shown that the spectrum can be recovered with acceptable accuracy after rectification using regularization techniques. In this work Tikhonov regularization described by Hansen [12] has been used.

III. RESULTS

Figure 5 and 6 shows the reconstructed spectrum obtained using the Trans-based unfolding methodology and Scatt-based unfolding methodology respectively along with its corresponding Upper Tolerance Limit (UTL) and Lower Tolerance Limit (LTL) for Uniform Uncertainty in Mean and FWHM, using two-sided tolerance limits of 0.95% and a 100 cases sample size [13].

The resulting spectra were qualitatively similar to the one established by limits and consistent with expected behavior. This suggests that, given the empirical measurements, the Monte Carlo simulations, the assumptions inherent in the model, and the mathematical techniques produce physically consistent results.

Nevertheless it can be seen that both spectra rely between the two limits for higher energies (beyond 2 MeV), although Scatt-based method displays a softer peak compared to those established by UTL and LTL. At lower energies (0-2 MeV) maximum difference between the Scatt-based reconstructed spectrum and Tolerance Limits is 10%. Since maximum difference between the Trans-based reconstructed spectrum and Tolerance Limits is below 5% in all evaluated points we can establish that Transmission methodology is the optimal choice for unfolding spectrum.

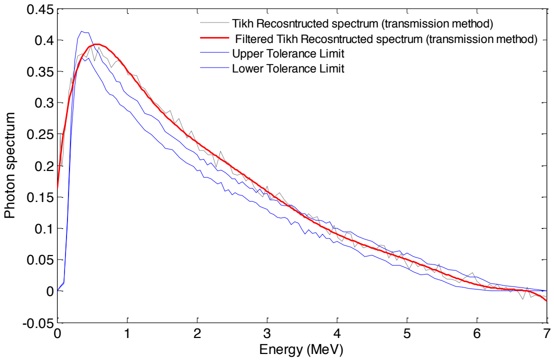

Figure 5. Trans-based method reconstructed spectrum with Upper and Lower Tolerance Limit

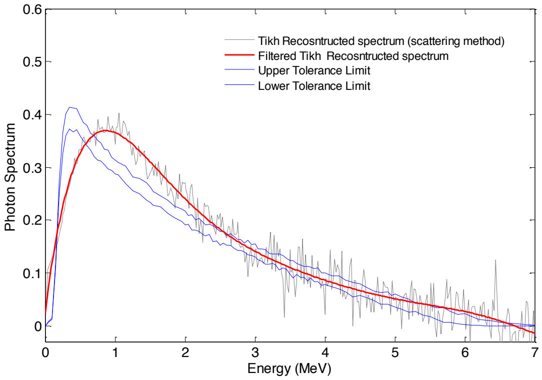

Figure 6. Scatt-based method reconstructed spectrum with Upper and Lower Tolerance Limit

The objective of this work was to demonstrate a first approximation of the viability of reconstructing a spectrum using a mixed Monte Carlo-experimental technology based on EPID images associated to the Linac. Moreover it has been determined that Transmission methodology describes more reliably megavoltage photon spectrum over the full range of beam energies than Scattering methodology.

Future works will be addressed towards the improvement of the accuracy of the obtained results. To that, several aspects will be taken into account, such as the limitation by the fact that the signal is detected at the EPID scintillation material (GOS), and MCNP5 cannot take into account and register the light photons created in this layer. As more light photons are created, the variation in the Monte Carlo results varies slowly from gray level registered at the EPID. Nevertheless the technique has used relative data assuming that the quantity of light photons generated is proportional to radiation arriving. Future works will use the adjoint methodology to solve this problem.

IV. CONCLUSION

To characterize the primary photon spectrum emitted by a Linac, the response function of the process was obtained. This function is approximated by a response matrix that contains all the required information to unfold the attenuation curve taken experimentally with an EPID system using simulated Monte Carlo curves.

An important problem in the unfolding process is to obtain the inverse of the response matrix. A pseudo-inverse matrix based on the TSVD method was used to obtain a good approximation of the inverse matrix. This pseudo-inverse matrix can be obtained easily and it permits an accurate and fast reconstruction of the primary spectrum.

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