Monte Carlo simulations framework for scatter correction of kV and MV CBCT images of the Varian TrueBeam STx Linac

Laboratorio de Imágenes Biomédicas

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INTRODUCTION

Image-guided radiation therapy (IGRT) consists on the use of medical images to improve the precision and accuracy of radiation therapy treatments. Images are used and necessary in all stages of treatment, such as treatment planning or patient positioning verification. Currently, the widespread use of IGRT (and other non-conventional radiation therapy modalities) has led to the development of imaging systems incorporated into the Linacs. The Varian TrueBeam STx Linac incorporates both an electronic portal imaging device (EPID), which uses a flattening filter-free 2.5 MV beam, and an on-board imaging system (OBI) which consists of a kilovoltage cone-beam CT. The optimization of imaging parameters and their effects on dosimetry and image quality of these systems is very important because there is always a compromise between image quality and patient dose.

AIM

To develop and validate a Monte Carlo simulation framework based on EGSnrc code for the imaging systems of the Varian TrueBeam STx Linac, and study the scattered radiation in CBCT for the implementation and assessment a scatter correction method.

METHODS

MONTE CARLO SIMULATIONS

BEAMnrc simulation [1]

1. 2.5 MeV gaussian electron source: 10^9 histories.
2. 2 mm thick copper (Cu) target.
3. 1 mm thick brass (ZnCu) filter.
4. Tungsten (W) primary collimator.
5. X and Y-jaws made of W.
6. Open multileaf collimator (MLC) made of W

- Phase-space, 100 cm from electron source.
- VRT methods: DBS and range rejection.
- Field sizes: 10×10 cm² and 40×40 cm².

DOSXYZnrc simulation [2, 3]

- 10^9 histories using previous phase-space.
- ECUT=0.700 MeV, PCUT=0.010 MeV
- Water voxel-phantom of 30×30×30 cm³ and isotropic voxels of 5×5×5 mm³.
- VRT methods: HOWFARLESS, range rejection and photon splitting.

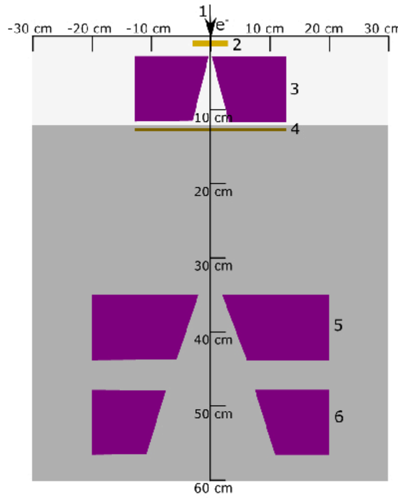


Figure 1. MC model of the TrueBeam STx head

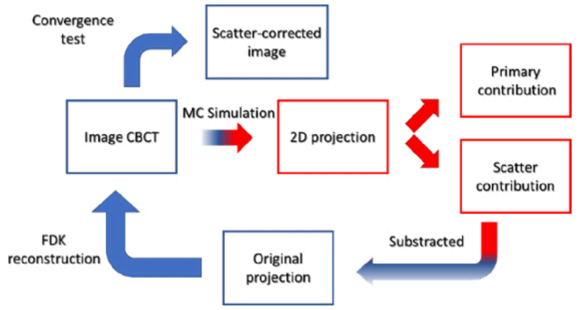
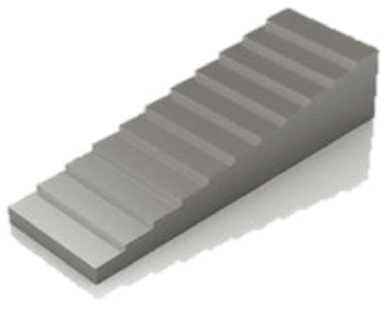


Figure 2. Workflow of the scatter correction method

VALIDATION OF MC SIMULATIONS

- Acquisition of Al and Cu wedge-phantom images.
- Calculation of transmission values:



$$T(x_m) = \exp\left(-\frac{\bar{v}_m - \bar{v}_0}{k}\right)$$

where $\bar{v}_m$ is the mean value on a ROI located at m-th step, $\bar{v}_0$ mean background value and k is a normalization factor.

- Theoretical detector signal:

$$S(x_m) = \int_0^{E_{max}} \Phi(E) \cdot E \cdot e^{-\mu_m x_m} \cdot \rho_q(E) \cdot \left(\frac{\mu_{en}}{\rho}\right) dE$$

where $\Phi(E) \cdot E$ is energy fluence spectrum, $\rho_q(E)$ is quantum efficiency of the energy integrating detector of thickness D.

VRT OPTIMIZATION FOR SCATTER ESTIMATION

- Variance reduction techniques (VRTs) used were forced detection, delta transport, and photon splitting [4].
- We used different combinations of photon splitting parameters N_p and N_s, to estimate the scatter radiation in one CBCT projection of a solid-water cylindrical phantom (Ø=180 mm and h=50 mm).
- In each simulation we evaluated the *efficiency factor* $\epsilon = 1/(T \times MSE)$ where T is the simulation time and $MSE = (1/N)\sum_i^N (\Delta x_i / x_i)^2$ where x_i is the scatter signal and Δx_i is the uncertainty of scatter signal in each pixel of the projection.

SCATTER CORRECTION METHOD

- We performed MC simulations of a cylindrical phantom (Ø=180 mm and h=100 mm) with 4 cylindrical (Ø=30 mm) tissue-equivalent inserts (cortical bone, trabecular bone, adipose and exhaled lung).
- We used an iterative scatter correction method based on FDK reconstruction and fast MC simulations of low-resolution voxel models with sparse angular sampling [5].

RESULTS

2.5 MV FFF SPECTRA AND PDD CURVES

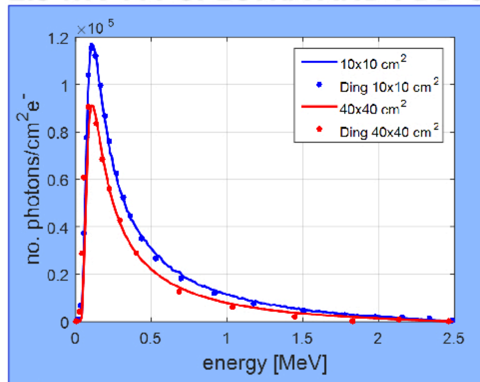


Figure 3. 2.5 MV spectra calculated with MC. This work (lines) and previously results by Ding, et al. 2017 (points)

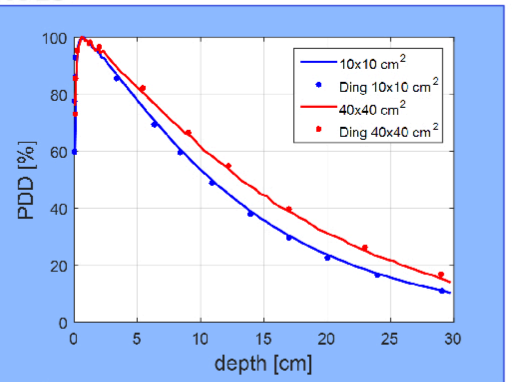


Figure 4. PDDs of 2.5 MV beam. Calculated with MC (lines) and measured by Ding, et al. 2017 (points)

TRANSMISSION CURVES

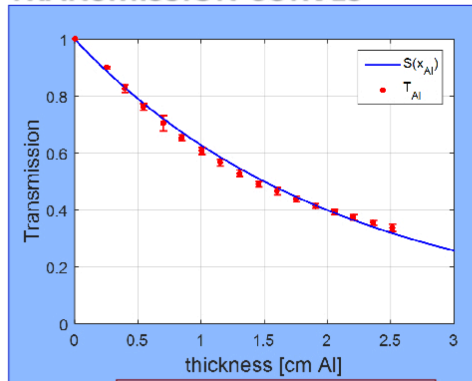


Figure 5. Transmission curve for Al. Measured (red) and calculated (blue)

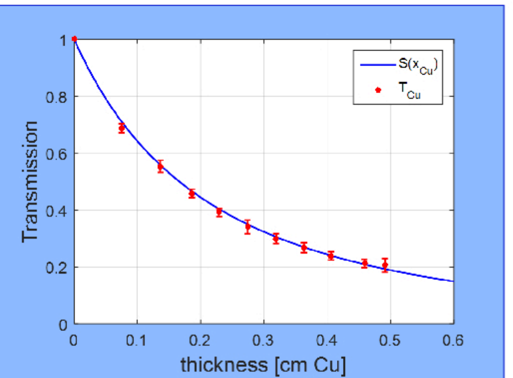


Figure 6. Transmission curve for Cu. Measured (red) and calculated (blue)

VRTS OPTIMIZATION AND SCATTER ESTIMATION

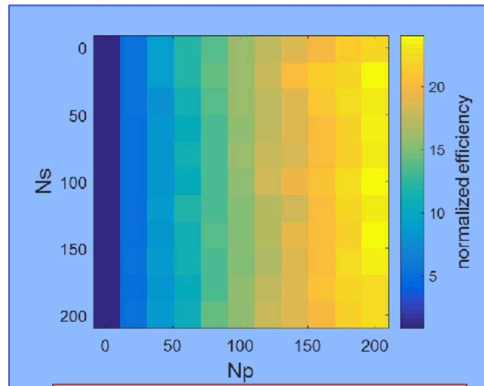


Figure 7. Normalized efficiency (to the efficiency without VRTs). We can see the optimized use of N_p =180-200 and N_s=20-80 increase the efficiency in the scatter estimation about 20 times.

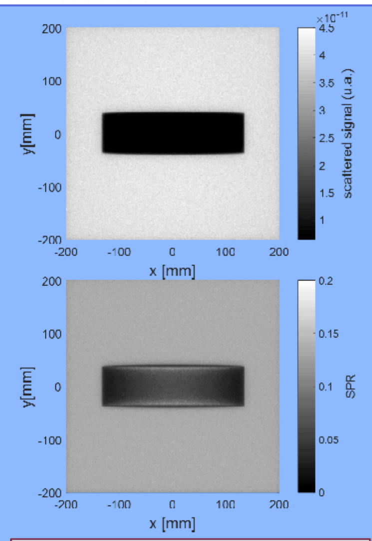


Figure 8. Scatter signal in 2.5 MV-CBCT projection (top) and SPR map (bottom).

SCATTER CORRECTION

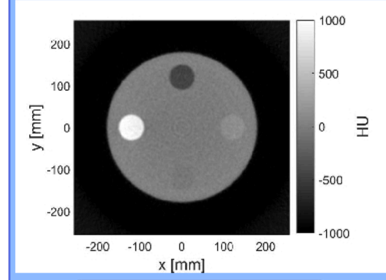


Figure 9. Uncorrected image

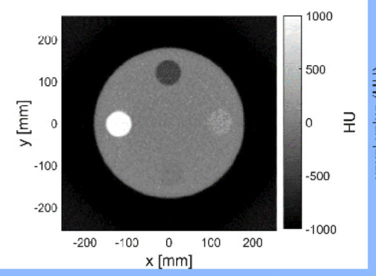


Figure 10. Corrected image

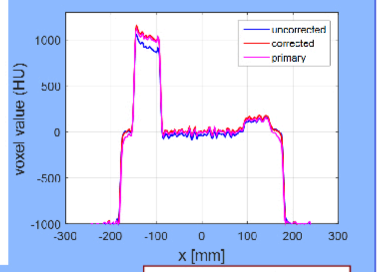


Figure 11. Profiles along x-axis for uncorrected, corrected and primary images

Tissue	Theoretical (HU)	Primary Image (HU)	Uncorrected (HU)	Corrected (HU)
Solid-water	0	0 ± 31.2	-22.9 ± 32.3	-7 ± 33.7
Cortical bone	983.6	1026 ± 35.9	923 ± 42.5	1028 ± 41.2
Trabecular bone	117.5	137 ± 27.6	135 ± 28.7	137 ± 31.0
Adipose	-51.2	-46 ± 30.5	-39 ± 31.4	-45 ± 31.5
Exhaled lung	-500.8	-467 ± 29.1	-435 ± 28.1	-467 ± 30.2

Table 1. Hounsfield Units for different tissues. Comparison between theoretical HU and HU in primary, uncorrected and corrected images.

CONCLUSIONS

- ✓ The spectra and PDD calculated by means of MC simulations show very good agreement with experimental data previously reported in the literature [2,3].
- ✓ Measurement of transmission curves constitutes an excellent method for the validation of spectra calculated by MC simulations.
- ✓ The optimized use of VRTs (fixed detection, delta transport and, photon splitting) increased about 20 times the efficiency in the scatter estimation in CBCT projections.
- ✓ The iterative scatter correction method shows very good results, obtaining a better estimation of the Hounsfield Units for the tissues included in this study.

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