MCNP4C-based Monte Carlo simulator for fan- and cone-beam x-ray CT: development and experimental validation

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Abstract

An x-ray computed tomography (CT) simulator based on the Monte Carlo N-particle radiation transport computer code (MCNP4C) was developed for simulation of both fan- and cone-beam CT scanners. A user friendly interface running under Matlab 6.5.1 creates the scanner geometry at different views as MCNP4C input file. The full simulation of x-ray tube, phantom and detectors with single-slice, multi-slice and flat detector configurations was considered. The simulator was validated through comparison with experimental measurements of different non-uniform phantoms with varying size on both clinical and small-animal CT scanners. There is good agreement between the simulated and measured projections and reconstructed images. Thereafter, the effects of bow-tie filter, phantom size and septa length on scatter distribution in fan-beam CT were studied in detail.

1 Introduction

X-ray Computed Tomography (CT) images have inherently the tendency to produce physics-related artefacts compared to conventional planar radiology owing to the fact that the images are reconstructed from a large number of independent detector elements. There are several sources of error and artefacts that affect clinical image quality in x-ray CT. It is therefore necessary to understand their importance and influence on image quality in order to reduce their impact either by optimizing the scanner design or by devising appropriate image correction and reconstruction algorithms.

To evaluate the effect of physical, geometrical and other design parameters on scanner performance and resulting image quality, an x-ray CT simulator based on MCNP4C general purpose Monte Carlo code was developed and validated through comparison with experimental measurements. The accelerated Monte Carlo simulator (AMCS) developed by Colijn *et al* [1] was also used as benchmark for validation of parameters difficult or impossible to measured experimentally.

2 Material and Methods

The x-ray CT simulator was built on the top of the MCNP4C Monte Carlo code, which serves as core layer giving the opportunity to the developer to construct application-specific modules in hierarchical layer architecture. The user interface program creates the scanner geometry as input file for MCNP4C according to the parameters selected by user. After simulation of all views, the sinogram is created from detector outputs after blank scan correction by the user interface program. The filtered backprojection reconstruction algorithm was used for image reconstruction of simulated data. The simulation process starts from the x-ray tube where the user interface offers two options for simulation of x-ray spectra. In the full simulation case, all electrons emitted from the filament are fully tracked into the target [2]. Since tracking a large number of electrons into the target is time consuming, a quick spectra option offering the possibility of using spectra generated by different computational models was implemented [3].

The validity of simulator was verified by comparing the simulated and measured distributions from various uniform and non-uniform phantoms on both clinical fan-beam GE HiSpeed X/iF (GE Healthcare Technologies, Waukesha, WI) and small-animal cone-beam SkyScan 1076 (SkyScan, Aarstelaar, Belgium) CT scanners.

3 Results

Figure 1 shows the comparison of simulated and measured profiles of cylindrical water-filled phantom and polyethylene cylinder containing air and steel from the GE HiSpeed X/iF scanner, after blank scan correction. The log-linear scale was used to magnify the differences between simulated and measured profiles in the central area of phantoms where attenuation lengths are maximum. The small discrepancy between measured and simulated projections of the water phantom is due to differences in the central area of the corresponding measured and simulated blank scans. The discrepancy between simulated and measured profiles of the polyethylene phantom arise from two crucial factors: firstly the density and chemical composition of the simulated and commercially available steel were not similar; and secondly the high attenuation of steel in the considered energy of x-ray spectra decreases the probability of photons transmission, thus increasing the statistical error in this area.

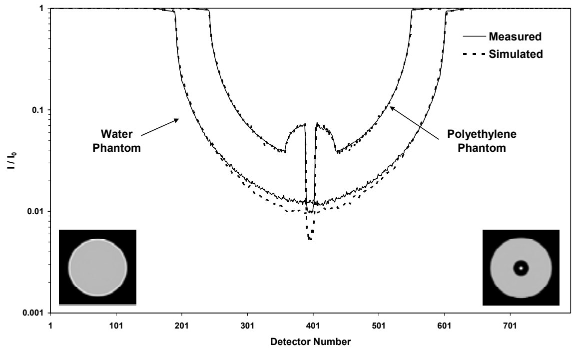

Fig. 1 Comparison between simulations and experimental measurements for GE HiSpeed X/iF scanner.

Comparison of MCNP4C simulated and measured profiles from the SkyScan 1076 cone-beam small-animal CT as well as the simulated profiles using AMCS micro-CT simulator [1] are shown in Figure 2.

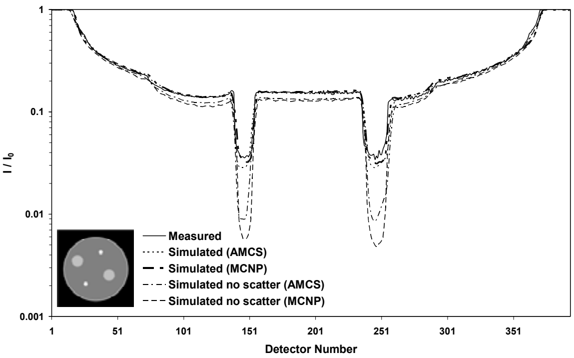

Fig. 2 Comparison between MCNP and AMCS simulated profiles and experimental measurements of the water phantom containing steel and Teflon inserts using SkyScan 1076 scanner at tube voltage 100 kV.

In fan-beam scanners, the collimator (septa) in the detector housing directed toward the focal spot is generally used to decrease the contribution of scattered radiation. The contamination of x-ray projection data with scattered radiation decreases by increasing septa length. Figure 3 shows the effect of septa length on the scattered profile obtained by simulating a cylindrical water phantom (ϕ266 mm) in presence of bowtie filter together with the relative number of detected total, primary and scattered photons. The relative difference between detected total, primary and scattered photons for septa length varying between 0 and 95 mm is 11.2%, 1.9% and 84.1% respectively, whereas the scatter to primary ratio (SPR) decreases by 83.3%.

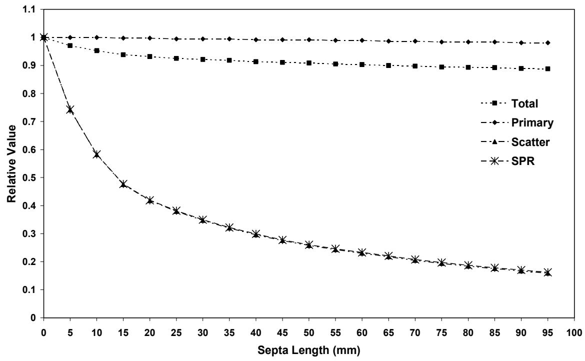

Fig 3 Calculation of relative SPR, total, primary and scattered photons in the GE HiSpeed X/iF CT scanner.

4 Conclusion

The developed x-ray CT simulator is a powerful tool for evaluating the effect of physical, geometrical and other design parameters on the performance of the new generation CT scanner and image quality in addition to offering a versatile tool for optimizing the absorbed dose to the patients and investigating potential artifacts and optimal correction schemes when using CT-based attenuation correction on dual-modality PET/CT units in connection with ongoing research in our lab related to PET quantification using a dedicated Monte Carlo PET simulator [4].

Acknowledgements

This work was supported by the Swiss National Science Foundation under grant SNSF 3152A0-102143. The authors would like to thank W. Zbijewski for providing the measured and simulated results for SkyScan 1076 micro-CT scanner.

5 Literature

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