The coupled photon/electron Monte Carlo transport code in the RayStation treatment planning system

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Background

A coupled photon/electron Monte Carlo dose algorithm has been written in CUDA directly for GPU in the latest version of RayStation (8B).

Monte Carlo implementation

The Monte Carlo code transports photons, electrons and positrons in voxelized geometries. Photons and electrons are sampled from the fluence distributions generated by the same virtual source algorithm as is used for the RayStation Collapsed Cone dose engine.

Photons are transported in the patient with hybrid Woodcock tracking between events. Compton scattering uses the Klein-Nishina cross section, i.e. binding effects are ignored. Photoelectric absorption is modeled by killing the photon and creating an electron with energy of the photon and the direction sampled from the Sauter distribution. In pair creation events the photon energy is distributed randomly between the electron and the positron. Photon cross sections for the elements are taken from the NIST XCOM database.

Electrons are transported with a class II condensed history method. Møller scattering and bremsstrahlung are treated as discrete events. Cutoff for secondary electrons is 250 keV. The modelling of multiple scattering uses the theory of Goudsmit-Saunderson. Cross sections are computed for any material composition. Positrons are treated as electrons except that they can undergo annihilation, either at rest or in flight. Dose is reported as dose to medium.

The algorithm can support any material that can be defined in RayStation. Stopping power is computed from the material composition, mass density and mean excitation energy following the method described in ICRU 37, with a density correction factor evaluated according to Sternheimer.

GPUs are built to run the same instructions on data that is localized in the same memory area. Monte Carlo algorithms are by their nature stochastic which leads to threads diverging and executing different instructions on scattered data. To obtain good performance the focus has been on reducing thread divergence as well as optimizing memory access patterns. For random numbers the XORWOW pseudo random number generator available in the NVIDIA SDK is used.

Validation vs measurements

The combination of a virtual source algorithm and Monte Carlo has been validated against an extensive series of measurements made at Freeman Hospital in Newcastle. The series includes measurements in heterogeneous phantoms near bone, air and lung inserts with oblique incidence for a Varian TrueBeam (6 MV, 10 MV, 10 MV FFF).

All cases have gamma < 1 for more than 95% of the measured data points using a 3%/3mm gamma criterion. Figure 1-2 show cases with typical agreement to measurement. Worst agreement was seen for oblique incidence beams for FF beam qualities.

The algorithm has also been succesfully validated against parts of the measurements used for the validation of the RayStation Collapsed Cone dose engine. These measurements include validation of IMRT, VMAT, 3DCRT and DMLC plans.

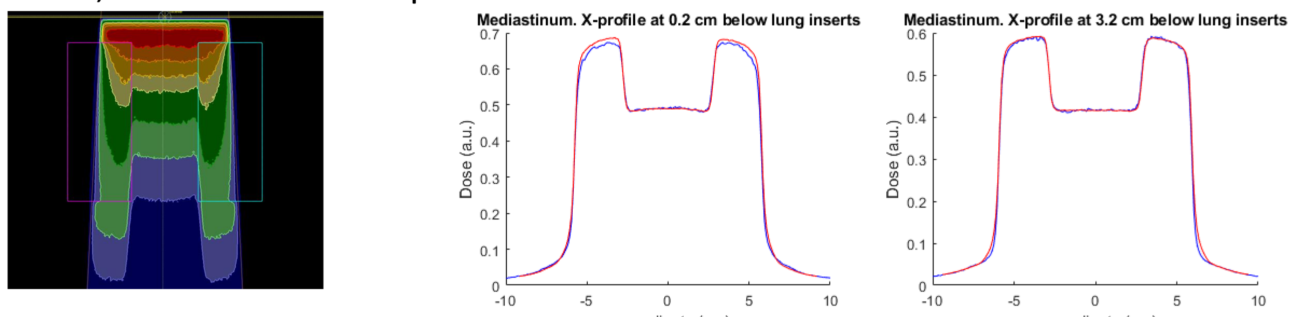

Figure 1: *Measured and computed dose at 0.2 cm and 3.2 cm depth below the lung inserts in a mediastinum phantom (a water phantom with two parallel lung blocks on either side of the central axis, ranging from 2 cm below the surface to 14.4 cm). Beam quality 6 MV, field size 10 cm x 10 cm.*

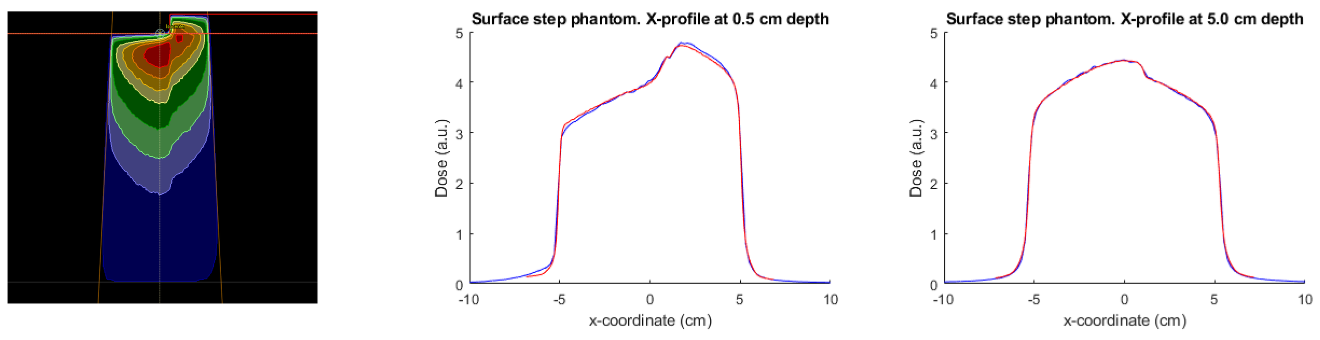

Figure 2: *Measured and computed dose at 0.5 cm and 5.0 cm depth in a water phantom where a solid water slab has been positioned above the surface to create a surface step. Beam quality 10 MV FFF, field size 10 cm x 10 cm.*

Validation vs simulations

By comparing computed dose to dose distributions computed in DOSXYZnrc[1] it is possible to in detail study the dose calculation without uncertainties related to material description, beam model or measurements. The algorithm has been validated against simulations in different phantoms for different energies (500 keV to 20 MeV), field sizes (0.4 x 0.4 cm^2 to 40 x 40 cm^2). All cases have gamma < 1 for more than 95% of the measured data points using a global 2%/2 mm gamma criterion.

DOSXYZnrc doses were computed with the default transport parameters except that ECUT was set to 521 keV and photon cross sections were taken from XCOM.

	0.5MeV	2 MeV	12 MeV	20 MeV
Water phantom	99.14%	99.0%	99.56%	99.63%
ICCR phantom	99.22%	99.49%	99.95%	99.49%
Off-axis bone insert	96.12%	96.1%	99.61%	99.75%
Off-axis lung insert	99.59%	99.49%	98.63%	99.35%

Table 1:. Average fraction of voxels with gamma < 1 when comparing doses from RayStation and DOSXYZnrc using a global 2%/2 mm gamma criterion for different energies and phantoms.

ICCR phantom

As part of the validation, dose has been computed in a phantom created to simulate dose through a chest wall, similar to the phantom described in [2]. It consists of slabs of

- 2 cm water
- 1 cm aluminum, 2.7 g/cm^3
- 3 cm lung, inflated (ICRP), 0.26 g/cm^3
- 34 cm water

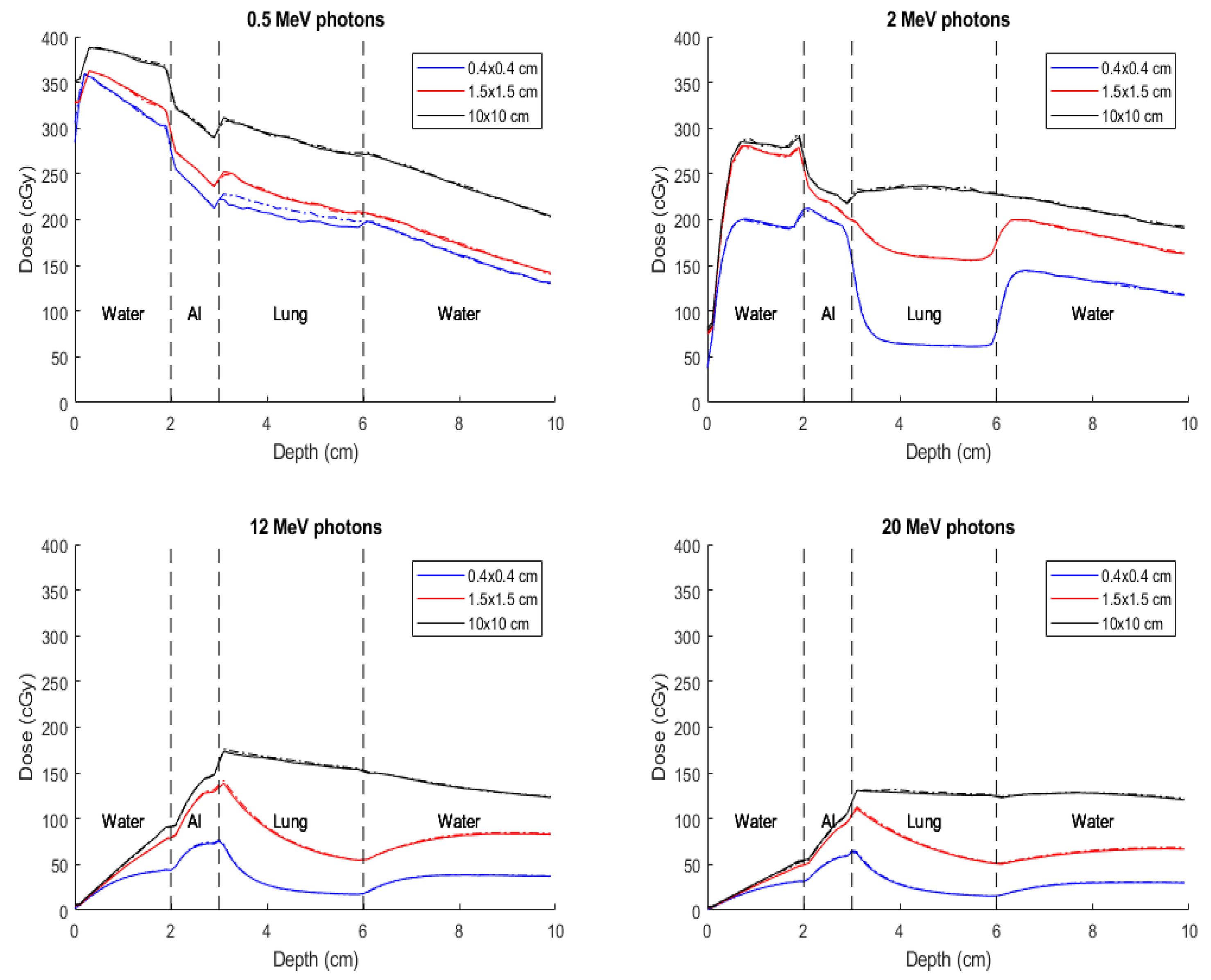

Figure 3: *Depth dose curves computed with DOSXYZnrc (dashed lines) and RayStation (solid lines) for monoenergetic photon beams for different energies and field sizes in the ICCR-phantom.*

Performance evaluation

	1% uncertainty	0.5% uncertainty
7 beam IMRT lung case 2.2M voxels 89 cm^3 target volume	7.5 s	20 s
Dual arc prostate case 1.5M voxels 125 cm^3 target volume	10.5 s	21 s

Table 2: *Dose computation time in seconds for two treatment plans. The voxel size was 3 mm in both plans. Uncertainty is defined as in [3]. Doses has been calculated on a computer with a NVIDIA GTX 1080Ti GPU.*

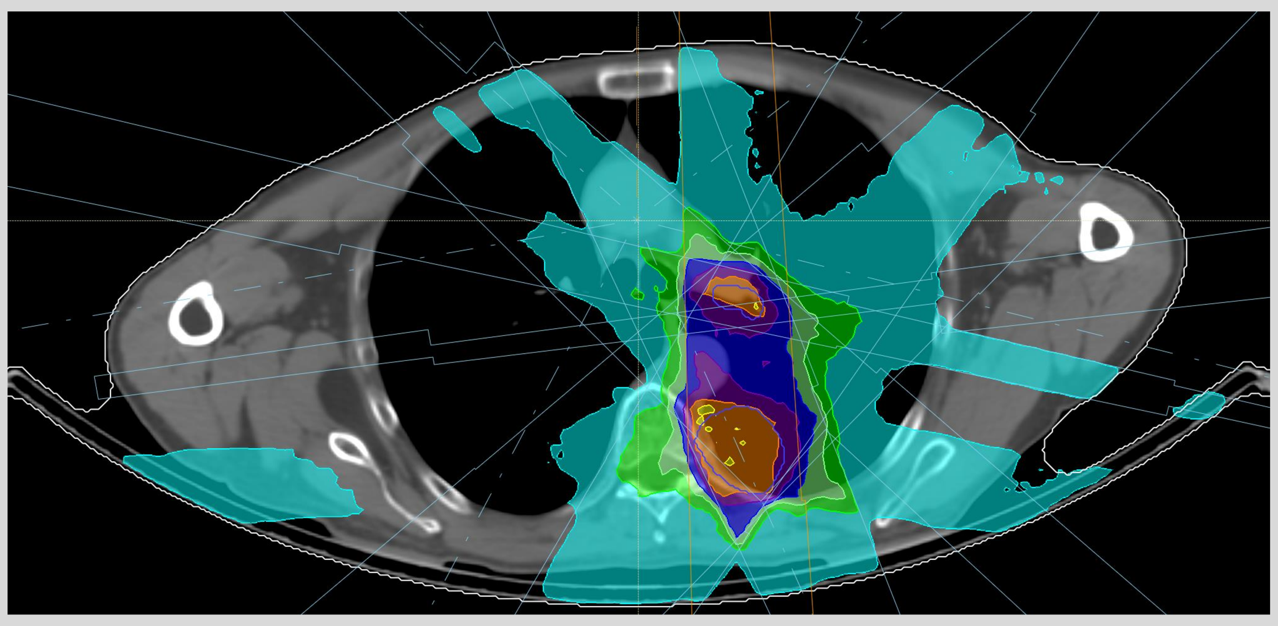

Figure 4: *Transversal view of the 7 beam IMRT lung case used in the performance evaluation.*

Conclusions

- It is possible to compute final dose to 1 % fraction dose uncertainty within 10 seconds
- The photon Monte Carlo dose engine in RayStation 8B has been validated successfully against both DOSXYZnrc and measurements.
- Dose computation has been validated for IMRT, VMAT, 3DCRT and DMLC plans.

[1] Rogers D.W.O, Kawrakow I, Seuntjens J.P., Walters B.R:B., Mainegra-Hing E., NRC User Codes for EGSnrc, Technical Report PIRS-702(revB), National Research Council of Canada, Ottawa, Canada, 2010.

[2] D. W. O. Rogers and R. Mohan, "Questions for comparisons of clinical Monte Carlo codes," in *Proceedings of the 13th ICCR*

[3] Iwan Kawrakow and Matthias Fippel 2000 Phys. Med. Biol. **45** 2163