Comparison of accuracy and performance of Monte Carlo dose calculations involving magnetic fields: ARCHER VS. TOPAS

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JULY 12–16 2020 VIRTUAL JOINT AAPM | COMP MEETING
EASTERN TIME [GMT-4]

INTRODUCTION

Realtime MRI guided radiation therapy (MRgRT) system is an advanced form of image-guided radiation therapy in which the MR scanner is integrated with a traditional electron accelerator (or other types of charged particle accelerator) for radiation treatment [1]. MRgRT, which provides superior soft tissue imaging, is expected to revolutionize radiotherapy by supporting improved online plan adaptation according to both geometric and anatomical changes during the treatment. Two products, MRIDian Linac and Elekta Unity, have received FDA clearance.
MRgRT introduces additional complexity into dose calculations because the Lorentz force changes the trajectory of charged particles, thus altering the dose distributions - a problem known as the electron return effect [2]. Monte Carlo simulation method is the only reliable dose calculation method for magnetic field, but it can be very slow. There is an urgent need for an independent dose-check software that is fast and accurate. ARCHER [3-8] is a next-generation commercial MC code that takes advantage of computing power of GPUs. This paper reports the recent effort to integrate a magnetic field module into the ARCHER platform for independent dose-check applications.

AIM

To evaluate GPU accelerated Monte Carlo dose simulation code ARCHER with TOPAS in the presence of magnetic fields in MRgRT.

METHOD

In the ARCHER magnetic field module, the electron's trajectory is split into two equal steps in the magnetic field. For a short-travelled path length, particle velocity was changed twice (midpoint and endpoint) per step, namely:

$$\Delta\hat{\mathbf{v}} = \frac{qs/2}{mc\sqrt{\left(\frac{K_0}{mc^2}+1\right)^2 - 1}}\hat{\mathbf{v}}_0 \times \mathbf{B}_0.$$

Description of magnetic field in the ARCHER:

1. The first half of the step is applied to change the particle position.
2. The first order magnetic field approximation using the old energy value is applied to change the particle direction.
3. The second half of the step is used to change the particle position.

Dosimetric differences between ARCHER and TOPAS [9] were calculated and compared in the presence of different magnetic field strengthes from zero up to 1.5 T orthogonally to the beam axis. Two irradiation situations were considered. First, 20-MeV electrons were injected perpendicularly to a tissue phantom. Then, 2-MeV photons were injected perpendicularly to a tissue phantom, a tissue-lung-tissue slab phantom, and a tissue-bone-tissue slab phantom, respectively. ARCHER only transport in the phantom. The dose distributions were scored using 3D grids comprising 0.2×0.2×0.2 cm^3 voxels.

RESULTS

Sufficient histories are simulated to ensure the relative standard deviation of critical regions under 1%. Fig. 1 and 2 show good agreements between TOPAS and ARCHER for 20-MeV electron dose distributions in a 15×15×15 cm^3 water phantom under the influence of a 1.5T and 0T magnetic field, respectively. For electrons in different magnetic fields, dose results show good agreements between TOPAS and ARCHER, with all of the 2%/2mm gamma pass rate being close to 100%.

For photons, a global gamma index test is performed in a tissue phantom in 10% cut off and displayed in Table 1. the maximum difference was found to be with the 1.5 T magnetic field. PDDs at the central axis and lateral dose profiles at different depths from two codes agreed for all points outside high gradient regions within 4.0% and 1.5%, 5% and 2%, 4.8%, and 1.7%, for tissue phantom, tissue-lung-tissue phantom, and tissue-bone-tissue phantom, respectively. The 2%/2mm gamma passing rate was greater than 98.9%, 98.3%, 98.5%, respectively. The greater the magnetic field, the more pronounced the electron return effect due to the large material density difference between tissue and other material components. For the photon transportation, the percent depth dose, the lateral dose profiles at the 10cm depth in the tissue phantom, tissue-lung-tissue phantom and tissue-bone-tissue phantom under the influence of a 1.5T magnetic field, are depicted in the Fig. 3-8, respectively. The dose distributions are in good agreements for two codes in the tissue, lung and bone.

For photons, for the same model mentioned above, ARCHER can complete the dose calculations within 5 seconds running on the Nvidia GTX 1060 6G, while TOPAS would take about 100 minutes running on the Intel(R) Xeon(R) CPU E5-4607 using 32 threads.

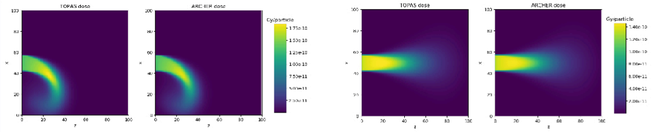

Fig. 1. Dose distribution in the 1.5T magnetic field

Fig. 2. Dose distribution without magnetic field

Table 1: Gamma pass rate between the ARCHER and TOPAS codes for photons

	0T	0.35T	0.6T	1.0T	1.5T
3mm/3%	100	100	99.91	99.56	99.38
2mm/2%	100	100	99.74	99.02	98.90
1mm/1%	99.70	99.65	98.71	97.96	97.80

Table 2: The time performance of ARCHER and TOPAS

Code	Processor	Time
TOPAS	Intel(R) Xeon(R) E5-4607 CPU	100 minutes
ARCHER	Nvidia GTX 1060 GPU	5 seconds

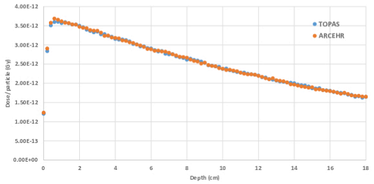

Fig. 3. Percent depth dose in the tissue phantom

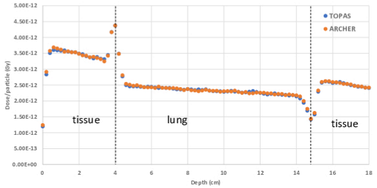

Fig. 5. Percent depth dose in the tissue lung tissue phantom

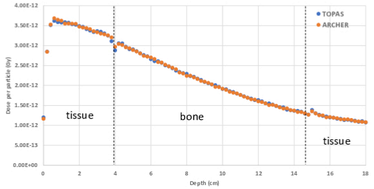

Figure 7: percent depth dose in the tissue bone tissue phantom

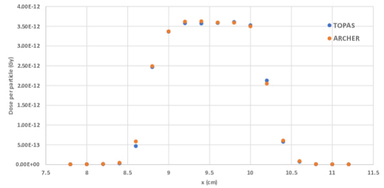

Fig. 4. Lateral dose profiles in the tissue phantom

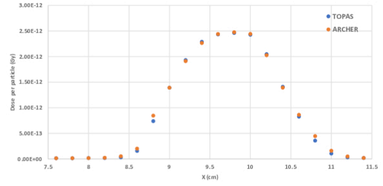

Fig. 6. Lateral dose profiles in the tissue lung tissue phantom

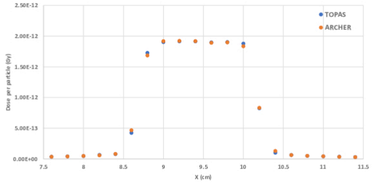

Figure 8: lateral dose profiles in the tissue bone tissue phantom

CONCLUSIONS

It is clear that for the online adaptive MRI guided radiotherapy, the rapid Monte Carlo dose engine is critical and the only method to take into account the dosimetric changes due to the magnetic field.

In this study, a module for dose calculation in the uniform magnetic field was added to ARCHER, making ARCHER an accurate and more efficient Monte Carlo method for X-ray dose calculation with magnetic fields compared with the reference TOPAS code.

The virtual source model of the MRgRT system is under development, which uses the commissioning data of the MRgRT machine to optimize the parameters of the virtual source. This virtual sources model combine with the fast and accurate ARCHER would help bring the secondary dose check software realistic.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the funding from National Natural Science Foundation of China with Grant No.11575180 and 2017YFC0107500.

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