Development of fast Monte Carlo code for high dose rate brachytherapy

Ankang Hu¹,², Rui Qiu¹,², Zhen Wu¹,³, Chunyan Li¹,³, Hui Zhang¹,² and Junli Li¹,²
¹Department of Engineering Physics, Tsinghua University, Beijing, China
²Key Laboratory of Particle & Radiation Imaging (Tsinghua University), Ministry of Education, Beijing, China
³Nuctech Company Limited, Beijing, China

E-mail: qiurui@mail.tsinghua.edu.cn

Abstract. Brachytherapy plays an important role in the treatment of various cancers. The TG-43 formalism is widely used in dose calculation for brachytherapy, but it is not accurate as it assumes the patient as homogeneously constituted of water. Monte Carlo simulation can obtain accurate result, but computing time using traditional code is too long to be accepted in clinical application. This work developed a fast Monte Carlo code THUBrachy for high dose rate brachytherapy dose calculation. THUBrachy can simulate photon with energy up to 3MeV for heterogeneous materials and obtain dose, fluence and dose distribution. It applies several accelerators such as Graphics Processing Unit (GPU), Intel Xeon Phi to perform dose calculation with good accuracy and high speed. THUBrachy adopts several parallel programming models to transplant the code onto different hardware accelerators. Voxel geometry based on CT images is used to describe the tissues of patient. A linear track-length estimator is used for dose calculation. In the preliminary accuracy test, a cuboid water model and a heterogeneous-material model were selected as the phantoms. Dose and fluence distributions were calculated by both THUBrachy and FLUKA which is a well-benchmarked Monte Carlo code. A total of $5 \times 10^8$ photons were simulated to make the uncertainty in all area less than 5%. The maximum difference of the results in low dose area is less than 3% and in high dose area is less than 1%, indicating a good agreement. In the performance test, a phantom consisted by 24 types of human tissue materials was chosen to estimate the performance in practical application. Dose distributions with an uncertainty of 2% or less for the target volume were obtained in less than 1 min by simulating $5 \times 10^7$ photons with a GTX 1080Ti, while FLUKA taking several hours to simulate the same number of particles. There is great potential for clinical application in brachytherapy dose planning using this fast Monte Carlo code.

1. Introduction

Brachytherapy plays an important role in the treatment of various cancers by placing radiation sources inside or next to the area requiring treatment. The radiation field of brachytherapy is extremely nonuniform [1]. Dose rate in some area is very high, especially for high dose rate brachytherapy which is up to 300cGy/min. To ensure curative effect and reduce the damage on healthy tissue as possible, medical physicist should formulate therapy plans carefully based on accurate dose distributions. Brachytherapy dose calculation is a key process of therapy planning. Nowadays, the TG-43 formalism is widely used in dose calculation for brachytherapy. This formalism depends on a set of predefined...
parameters for each radiation source seed model. These parameters are obtained from Monte Carlo simulations and experimental measurements in water phantom [2]. For complex human tissue especially for bone, TG-43 formalism would cause large deviation. More accurate dose calculation methods are required for brachytherapy.

Monte Carlo methods could describe the medium and interaction of particles accurately to obtain accurate dose distribution. It is often regarded as the gold standard for dose distribution calculations in radiation therapy [3]. But it takes long computation time to track a large number of particles to obtain a result with low uncertainty. The computation time using traditional Monte Carlo code in brachytherapy dose calculation is not acceptable in clinical application.

Hardware accelerators such as Graphics Processing Unit (GPU) and Intel Xeon Phi have been developed greatly in recent years. These hardware accelerators provide high calculation speed and reduce the power consumption by simplifying the complex function of processors and strengthening the function of calculation. Hardware accelerators have been adopted to accelerate Monte Carlo simulation. Jia et al developed a GPU-based fast Monte Carlo code for brachytherapy [4]. Parallel computing with hardware accelerators is considered as an effective method to accelerate Monte Carlo simulation [5].

This paper describes the development of a fast Monte Carlo code THUBrachy which can be accelerated by various hardware accelerators. This code is designed for dose calculation and image simulation for low energy photon. Preliminary accuracy test and performance test were performed to verify that this code could complete dose calculation and get accurate result for high dose rate brachytherapy in clinically reasonable time.

2. Material and methods

2.1. Physics models

THUBrachy takes transportation and interaction of low energy photon into account. Photoelectric effect, Compton scattering, Rayleigh scattering and pair production were modeled in this code. Because the continuous slowing down approximation (CSDA) range of secondary electrons inside the human body at the considered energy range is generally much smaller than voxel size. The electron are not simulated in this code.

The cross-section values used in THUBrachy come from the NIST XCOM database [6]. A pre-calculated lookup table is used to speed up the calculation of photon transportation. Accurate cross section value is obtained by interpolating from the value of lookup table based on the energy of photon. For dose calculation, a linear track-length estimator is used to reduce the number of simulated photons while keeping a low statistical uncertainty. This method calculates the track-length in each voxel to obtain fluence and covert fluence to dose by multiplying the mass attenuation coefficient.

\[ D = \int \phi(x, E) \frac{\mu_{en}(E)}{\rho} EdE \]  

\( \phi \)-photon fluence; \( D \)-dose, \( \mu_{en}/\rho \)-mass attenuation coefficient; \( E \)-photon energy.

2.2. Random generators

Accurate dose calculation requires the simulation of a large number of primary particles. And for codes executes on accelerators have many threads. To obtain high quality random, Tiny Mersenne Twister (TinyMT) random generated were used to provide a random series with period up to \( 2^{127} \). A jump function making the internal state of TinyMT \( N^{th} \) forward state was used for each parallel thread to avoid repetition.
2.3. Parallel programming

This set of fast are consisted of 5 versions. Every version of code is programmed using a parallel programming model used in the selected accelerators. This table shows the programming model and accelerators used in each version of THUBrachy.

| Version | Programming model | Accelerator                      |
|---------|-------------------|----------------------------------|
| 1       | OpenMP            | Multicore CPU                    |
| 2       | OpenMP            | Intel Xeon Phi                   |
| 3       | OpenACC           | GPU                              |
| 4       | CUDA              | NVIDIA GPU                       |
| 5       | OpenACC           | SW26010(used in Sunway Taihu Light) |

2.4. Preliminary accuracy and performance test

This set of fast are consisted of 5 versions. Every version of code is programmed using a parallel programming model used in the selected accelerators. This table shows the programming model and accelerators used in each version of THUBrachy. To validate the code, a water model was selected as the test phantom. The size of water model is 20×20×20cm³. And the model was divided to 40×40×40 voxels. A 2×2×2cm³ isotopic 350keV photon source is placed in the center of the model.

Figure 1. Diagram of source and model.

Both dose and fluence in each voxel were calculated when performing simulation. A general purpose Monte Carlo code FLUKA was selected as the benchmark. 5×10⁸ primary photons were simulated to make the uncertainty of dose in fringe less than 5%. Results obtained by the fast Monte Carlo code were compared with the benchmark.

For performance test, a heterogeneous-material model containing main human tissue were selected as the phantom. The phantom is consisted by 24 materials differing in composition and density. The size of model is 512×512×200mm³, which is divided to 512×512×200 voxels. To compare the acceleration effect of different version of codes, a server equipped with 2 Intel Xeon E5-2630 v4 CPUs, 64GB RAM and a Nvidia GTX 1080Ti was chosen as the test platform. Intel Parallel Studio XE 18.0 was used to compile code executing on CPU. The GPU code was compiled with g++ 5.0 and CUDA toolkit 8.0. A total of 5×10⁷ primary photons were simulated using each tested version of codes. The model and number of simulated particles are both similar to clinical application. So, the performance of code in this test could represent the true performance in clinical application.
3. Results

3.1. Preliminary accuracy test
To compare the result obtained from THUBrachy in this work and benchmark intuitively, dose distributions in cross section are shown below. The difference between the two results can hardly be observed.

![Figure 2. Dose distribution in cross section obtained by THUBrachy (left) and FLUKA (right).](image)

For quantitative comparison, dose distributions on x-axis were shown in Figure 3.

![Figure 3. Dose distribution in x-axis obtained by THUBrachy and FLUKA.](image)

Two curve is almost coincident with each other. For low dose area, the maximum difference between two codes is less than 3%. And in high dose area, the maximum difference is below 1%. This result verifies the accuracy of the fast Monte Carlo code preliminarily. Further accuracy test is ongoing.

3.2. Preliminary accuracy test
THUBrachy executed on different accelerators to test the performance. Limited by the test platform, GPU code and multicore CPU code were tested. The results were shown below.

![Table 2. Performance comparison between different accelerators.](image)

| Code     | Number of threads | Compiling option | Executing speed |
|----------|-------------------|------------------|-----------------|
| Single core | 1                 | -O3 -ipo         | 946s/10^7 photons |
| Multicore | 32                | -O3 -ipo -qopenmp | 55s/10^7 photons |
| GPU      | -                 | default          | 15s/10^7 photons  |
| FLUKA    | 1                 | -                | 4h/10^7 photons   |

The result shows that multicore CPU and GPU could speed up the code effectively. It takes 4 hours to simulate 10^7 particles using FLUKA on a single core. THUBrachy is much faster than general purpose Monte Carlo codes. And the computational speed of GPU code reaches the demand of clinical application.
4. Conclusion
This work develops a fast Monte Carlo code THUBrachy for high dose rate dose calculation. The code
takes main physics interactions of photon in considered energy into account. Preliminary accuracy test
validated the code by comparing the result generated by this code and general-purpose Monte Carlo
code. Performance test indicated that accelerators could accelerate the dose calculation effectively. The
speed of this code is significantly faster than general purpose code. And there is great potential for
clinical application in brachytherapy dose planning using this fast Monte Carlo code.

For future work, the code will be used in clinical case to perform stricter test. This code is expected
to execute on other accelerators such as Intel Xeon Phi, SW2601 and future accelerators.

5. References
[1] Hurley C et al 2006 *Nucl. Instrum. Meth. A* 565 801-11
[2] Nath R et al 1999 *Med. Phys.* 26 2514
[3] Taylor R E et al 2007 *Med. Phys.* 34 445-57
[4] Tian Z et al 2016 *Brachytherapy* 15 387-98
[5] Xu X et al 2015 *Annals of Nuclear Energy* 82 2-9
[6] Hubbell J H and Seltzer S M B 2005 *XCOM: Photon Cross Sections Database*