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Monte Carlo dose calculations for high-dose–rate brachytherapy using GPU-accelerated processing

Z. Tian[1,*], M. Zhang[2], B. Hrycushko[1], K. Albuquerque[1], S.B. Jiang[1], X. Jia[1,*]

[1]*Department of Radiation Oncology, University of Texas Southwestern Medical Center, Dallas, TX*
[2]*Department of Radiation Oncology, Rutgers Cancer Institute of New Jersey, New Brunswick, NJ*

ABSTRACT

PURPOSE: Current clinical brachytherapy dose calculations are typically based on the Association of American Physicists in Medicine Task Group report 43 (TG-43) guidelines, which approximate patient geometry as an infinitely large water phantom. This ignores patient and applicator geometries and heterogeneities, causing dosimetric errors. Although Monte Carlo (MC) dose calculation is commonly recognized as the most accurate method, its associated long computational time is a major bottleneck for routine clinical applications. This article presents our recent developments of a fast MC dose calculation package for high-dose–rate (HDR) brachytherapy, gBMC, built on a graphics processing unit (GPU) platform.

METHODS AND MATERIALS: gBMC-simulated photon transport in voxelized geometry with physics in ^{192}Ir HDR brachytherapy energy range considered. A phase-space file was used as a source model. GPU-based parallel computation was used to simultaneously transport multiple photons, one on a GPU thread. We validated gBMC by comparing the dose calculation results in water with that computed TG-43. We also studied heterogeneous phantom cases and a patient case and compared gBMC results with Acuros BV results.

RESULTS: Radial dose function in water calculated by gBMC showed <0.6% relative difference from that of the TG-43 data. Difference in anisotropy function was <1%. In two heterogeneous slab phantoms and one shielded cylinder applicator case, average dose discrepancy between gBMC and Acuros BV was <0.87%. For a tandem and ovoid patient case, good agreement between gBMC and Acruos BV results was observed in both isodose lines and dose-volume histograms. In terms of the efficiency, it took ~47.5 seconds for gBMC to reach 0.15% statistical uncertainty within the 5% isodose line for the patient case.

CONCLUSIONS: The accuracy and efficiency of a new GPU-based MC dose calculation package, gBMC, for HDR brachytherapy make it attractive for clinical applications.

Keywords: High-dose–rate brachytherapy; Monte Carlo; Dose calculation; GPU

Introduction

High-dose–rate (HDR) brachytherapy has proved to be a highly successful treatment for cancers in a variety of disease sites (1), such as cervical cancer, breast cancer, prostate cancer, etc. By placing an applicator in the targeted area and having a motor-controlled radioactive source dwell in a series of planned positions with preset time, HDR brachytherapy delivers a highly conformed dose to the target while sparing nearby critical organs. Accurate dose calculation in patients is a critical step in treatment planning for HDR brachytherapy to ensure good target coverage and sharp dose gradients for critical structure sparing. The standard dosimetry protocol currently used in clinical brachytherapy is based on the Association of American Physicists in Medicine Task Group report 43 (TG-43) (2, 3). This method approximates a three-dimensional (3D) dose distribution by superposition of interpolated and precalculated discrete dose matrices in an infinitely large water medium. Although this approach is straightforward and fast, the influence of material

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* Corresponding authors. Department of Radiation Oncology, University of Texas Southwestern Medical Center, Dallas, TX 75390. Tel.: 214-648-5031; fax: 214-645-2885.

E-mail addresses: zhen.tian@utsouthwestern.edu (Z. Tian), xun.jia@utsouthwestern.edu (X. Jia).

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heterogeneity is ignored (4), causing dosimetric errors. For instance, the skin dose has been shown to be overestimated by as large as 15% (5–8). In breast brachytherapy, the TG-43 approach tends to underestimate dose to lung by ~10% (9). In addition, neglecting dosimetric impacts of nontissue heterogeneities, such as applicator material and the shielding material, is another concern. It has been shown that ignoring the shielding of an HDR colorectal applicator leads to an overestimation of the target volume within 100% isodose lines by >5% (10), which implies potential tumor cold spots. Therefore, it is proposed in Task Group report 186 (4) to move toward more accurate model-based dose calculation algorithms for brachytherapy, such as collapsed-cone superposition/convolution methods (11, 12), deterministic solutions to the linear Boltzmann transport equation (13, 14), and Monte Carlo (MC) simulations (15).

MC has been considered as one of the most accurate dose calculation method for determining radiation dose deposition in heterogeneous materials. Particle transport and interactions with the medium are simulated based on fundamental physics principles (4,15–17). However, MC simulations have been associated with extremely long calculation time, impeding applications in clinical practice. An accelerated CPU-based MC dose calculator (HDRMC) was recently developed (18) which used a fast ray–tracing technique to transport photons through a 3D mesh of voxels representing the patient anatomy. It took ~5 min to calculate a typical HDR brachytherapy treatment plan consisting of 20–30 dwell positions. A track length estimator was used to improve the efficiency of the MC simulation (19). This track length estimator requires calculation of mass energy absorption coefficient before the simulation run, and the absorption energies used in the simulation must be identical to that used to determine the mass energy absorption (20). Recently, there have been tremendous research efforts in accelerating MC simulations using graphics processing unit (GPU) platforms (21–30). For HDR brachytherapy dose calculations, bGPUMCD (31) was developed by extending the photon transport part of the GPUMCD system (23) into the brachytherapy energy range. By using GPU's rapid parallel processing power, GPU-friendly parallelization schemes, and a track length estimator, the dose calculation can be completed in seconds. This MC package was also extended to low-dose–rate brachytherapy calculations (32,33).

Grid-based Boltzmann equation solvers are another category of model-based dose calculation methods for brachytherapy. By directly solving the linear Boltzmann transport equation, the dose distribution is derived from fundamental physics principles and, hence, achieves guaranteed accuracy (14). This algorithm has been introduced for brachytherapy dose calculations in a clinic setting as Acuros BV (Varian Medical Systems, Palo Alto, CA). However, the calculation time for a treatment plan typically ranges in several minutes on a multicore CPU platform. This speed may be acceptable for plan dose calculation but becomes burdensome when repeated calculations are needed, such as in inverse plan optimization.

In this report, we will present our recent developments of a GPU-based MC dose engine for HDR brachytherapy, named gBMC (GPU-based brachytherapy Monte Carlo). We will show high computational efficiency without using variance reduction techniques except the Woodcock tracking method, a method that has been widely used in GPU-based photon transport simulation tools (34). To validate our gBMC package, we have benchmarked against the TG-43 results in a water phantom and against Acuros BV results in a heterogeneous slab phantom and shielded cylinder applicators. The feasibility of applying our gBMC package for clinical practice will also be shown in a typical HDR brachytherapy patient case.

Methods and materials

Source modeling and physics

The gBMC package was developed on top of our established GPU-based MC packages, gDPM for dose calculation for external radiotherapy (22, 24) and gCTD for imaging dose calculation of CT and cone-beam CT (35), both of which have been validated against the conventional CPU-based MC codes.

The gBMC package currently focuses on ^{192}Ir, the most commonly used radionuclide for HDR brachytherapy. The source model in gBMC was a phase-space file generated from the MC simulation of radioactive source decay and particle transport for a VariSource VS2000 ^{192}Ir HDR source (Varian Medical Systems) using GEANT4 (36). The source was modeled as a radioactive core inside a connecting cable with geometry and material composition following published data (37,38). For the 2×10^7 decay events sampled uniformly throughout the radioactive core, about 4.2×10^7 photons exited the surface of the cable, which were stored in the phase-space file. The energy spectrum of these recorded photons is shown in Fig. 1.

In our gBMC package, we adopted the tissue compositions from the International Commission on Radiation Protection Publication 23 (39), which were used in Acuros BV. The cross-section data in our package for particle transport simulation are from NIST XCOM database (40). We would like to mention that our package supports a certain number of material types but allows continuous density variations for each voxel. The mass attenuation coefficients for these materials were stored. During the simulation, the actual density of a voxel is multiplied with the mass attenuation coefficient to yield the actual attenuation coefficient.

Because the particle transport physics in the relevant energy range for HDR brachytherapy, indicated by Fig. 1, is well known, we only present it here briefly. In this low-energy range, three main photon interactions, Compton scattering, Rayleigh scattering, and photoelectric absorption, were considered. Compton scattering was modeled using a