PhD Thesis Title: "Application of efficient Monte Carlo photon beam simulations to dose calculations in voxellized human phantoms"

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ABSTRACT:

Monte Carlo (MC) simulations provide the most accurate estimate of radiotherapy dose, promising agreement with measurement to within 1%, even at tissue/bone interfaces. EGSnrc is one of the most widely-used general purpose MC codes in radiotherapy research. Crucial to the ongoing utility of EGSnrc are the many computation time saving and variance reduction techniques available to the user for increasing simulation efficiency. The published research in this thesis covers the development and implementation in EGSnrc of several key algorithms for improving the efficiency of photon beam simulations and MC beam commissioning along with two applications of efficient photon beam simulations to answer critical questions regarding dose to sensitive skeletal tissue during radiotherapy.

Chapter 1, the Introduction, establishes the desirability of using MC in clinical treatment planning as ongoing motivation for improving the efficiency of simulation codes. Variance reduction techniques (VRTs) increase the efficiency of MC simulations by increasing the sampling of certain events while preserving the overall physics in the system, resulting in a decrease in the uncertainty of scored quantities (*e.g.*, dose) that more than offsets any increase in CPU time. Interaction splitting, in which many low-weight ("split") particles are generated per event, is introduced as a VRT commonly employed in MC simulations. In particular, splitting bremsstrahlung events, the primary source of photons in treatment beams, can increase photon beam simulation efficiency.

Any estimate of accuracy or efficiency requires a robust method of estimating uncertainty. **Chapter 2** in the thesis covers the implementation in EGSnrc of the history-by-history method for uncertainty estimates. History-by-history statistics account for correlations between scored quantities by grouping them according to primary, statistically independent event. This method is shown to be stable and accurate and, moreover, can be propagated through simulations using secondary sources (*i.e.*, phase space sources).

Chapter 3 describes the development and implementation of a method for reducing the CPU time required for MC commissioning calculations in a homogeneous phantom by eliminating the

restriction of voxel boundaries during simulated charged particle transport. The technique, called ``HOWFARLESS,'' has been implemented in DOSXYZnrc, an EGSnrc application for dose calculations in rectilinear phantoms, where it increases the efficiency of photon beam dose calculations by factors of 1.5-5, depending on the boundary crossing algorithm used.

Chapter 4 in this thesis describes the development and implementation of the directional bremsstrahlung splitting (DBS) algorithm in BEAMnrc, an EGSnrc application for simulating treatment heads. DBS differs from the previous uniform bremsstrahlung splitting (UBS) algorithm primarily in that it simulates only those split photons directed into a user-defined treatment field. With judicious setting of splitting parameters, DBS can increase the efficiency of photon beam dose calculations by a factor of 160 compared to no splitting and a factor of 20 compared to UBS. DBS is now considered a necessary option for efficient MV and kV photon beam simulations.

An analogous splitting algorithm for increasing the efficiency of cobalt-60 treatment head simulations, called directional source biasing (DSB), is described in **Chapter 5**. DSB increases the efficiency of cobalt-60 treatment head simulations by a factor of up to 400. It, too, has been implemented in BEAMnrc and is expected to make routine MC commissioning of these treatment heads feasible.

MC simulations are also capable of providing realistic dose estimates in tissue microstructures. **Chapter 6** presents a study in which EGSnrc is used to simulate cone beam CT (CBCT) imaging beams incident on voxellized human phantoms in which bone spongiosa is resolved into trabecular bone and the radiosensitive components, red bone marrow and bone surface cells. The results of these simulations show significant dose to bone surface cells, thus motivating guidelines for the routine use of CBCT during image-guided radiotherapy (IGRT).

Another advantage of MC simulations is their ability to calculate both dose to medium (D_m) and dose to water-in-medium (D_w) at the same time. The latter is the historical basis for prescribed dose and is provided by treatment planning systems, while the former may provide a more realistic representation of radiobiological effect. In **Chapter 7**, simulations of MV treatments in voxellized human phantoms show that D_w is an overall better representation of dose to red bone marrow and bone surface cells, although the difference between D_m and D_w is only clinically significant (5%) at sites with a high fraction of trabecular bone.

Chapter 8, the thesis Discussion, considers the ongoing D_m vs D_w debate in the context of photon beam treatments in the kV range (*e.g.*, brachytherapy, preclinical small animal irradiators) where the conversion from D_m to D_w is highly dependent on the size of the effective dose volume (cavity) considered. The chapter presents simulations of small animal irradiations, using DOSXYZnrc, showing that the D_w for bone evaluated assuming nm- scale cavities, where Bragg-Gray conditions exist, is 80% higher than that assuming mm-scale cavities, where charged particle equilibrium prevails.

References to author publications that relate specifically to the dissertation:

1. **B.R.B. Walters**, I. Kawrakow, D.W.O. Rogers, “History by history statistical estimators in the BEAM code system”, Medical Physics 29(12), 2745-2752 (2002).

2. Kawrakow, D.W.O. Rogers, **B.R.B. Walters**, “Large efficiency improvements in BEAMnrc using directional bremsstrahlung splitting”, Medical Physics, 31(10), 2883-2898 (2004).

3. **B.R.B. Walters**, I. Kawrakow, “A ``HOWFARLESS’’ option to increase efficiency of homogeneous phantom calculations with DOSXYZnrc”, Medical Physics, 34(10), 3794-3807 (2007).

4. **B.R.B. Walters**, G.X. Ding, R. Kramer, I. Kawrakow, “Skeletal dosimetry in cone beam computed tomography”, Medical Physics, 36(7), 2915-2922 (2009).

5. **B.R.B. Walters**, R. Kramer, I. Kawrakow, “Dose to medium versus dose to water as an estimator of dose to sensitive skeletal tissue”, Phys. Med. Biol., 55(16), 4535-4546 (2010).

6. **B.R.B. Walters**, “Increasing efficiency of BEAMnrc-simulated Co-60 beams using directional source biasing”, Medical Physics, 42(10), 5817-5827 (2015).