

# Application of efficient Monte Carlo photon beam simulations to dose calculations in voxelized human phantoms

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## Summary

Since the mid-80's, it has been acknowledged that Monte Carlo (MC) transport algorithms provide the most general and most accurate method of estimating dose due to ionizing radiation. This is because MC algorithms model individual interactions between subatomic particles and matter, allowing accurate dose calculations at interfaces between media having a large difference in atomic number (*e.g.*, tissue-bone interfaces) and in irregular geometries, both instances where the analytical algorithms commonly used in treatment planning are known to be inaccurate. In addition, MC simulations can provide information unavailable with current analytical methods, such as particle energy and angular distribution at any location within a treatment volume. Historically, the long calculation times required to obtain sufficient precision have made the routine use of MC methods in radiotherapy treatment planning (RTP) clinically impractical. Recent improvements in efficiency of MC techniques, including the development of dedicated clinical MC algorithms, together with the ongoing exponential increase in computing power, however, have rendered clinical MC calculations feasible. The research presented in this thesis covers several key efficiency improvements in EGSnrc, a well-benchmarked general purpose MC transport simulation code commonly used in Medical Physics research, and two practical applications of EGSnrc answering questions about dose to sensitive red bone marrow and bone surface cells in the skeletal system. The first paper describes the implementation of an improved technique for estimating uncertainty on calculated dose, and other scored quantities, in EGSnrc applications. The technique considers each incident primary particle, or history, a statistically independent event, resulting in a small variance in the uncertainty estimate. This has many implications, among them an ability to accurately calculate simulation efficiency that has helped pave the way for the efficiency improvement techniques described in the next three chapters. The first of these techniques is a time-saving algorithm, called "HOWFARLESS," implemented in DOSXYZnrc, an EGSnrc application for calculating dose in geometries composed of rectilinear voxels. The research shows that use of "HOWFARLESS" can result in efficiency improvements by factors ranging from 70% to  $17\times$  in routine commissioning calculations, essentially making it the default for

such calculations in a homogeneous volume. A common technique to reduce the variance, and increase the efficiency, of an MC calculation is to split certain particle interactions. This results in improved sampling of these events and, provided the resultant split products of the interaction do not deposit dose in the same volume, improved statistics. The third paper describes the technique of directional bremsstrahlung splitting (DBS) implemented in BEAMnrc, an EGSnrc application for simulating linear accelerators. In DBS, bremsstrahlung events, which are the primary sources of photons in a photon treatment beam, are split to selectively generate a large number of photons directed towards the radiotherapy treatment field. The paper shows that DBS can increase dose calculation efficiency by a factor of 160×. Improvements are even greater for X-ray tube simulations, and DBS is now considered necessary for efficient simulation of photon beams, in general. The next paper details the implementation in BEAMnrc of directional source biasing (DSB), a splitting technique designed to improve the efficiency of treatment beams making use of an isotropically radiating source. The most common example of this is a cobalt-60 treatment head, and, while cobalt-60 is one of the oldest radiotherapy modalities, there has been a resurgence in its use due to its cost-effectiveness and the relative ease with which it can be adapted for use with magnetic resonance imaging for image-guided radiotherapy (IGRT). Similar to directional bremsstrahlung splitting, DSB splits photons and selectively generates those directed towards the treatment field. In the case of DSB, however, these photons are the primary particles, generated at the source, and have an isotropic angular distribution. The paper shows that DSB can increase the efficiency of a cobalt-60 dose calculation by 400×, making routine MC commissioning of these units feasible. The last two papers in this thesis illustrate how efficient MC photon beam simulations, combined with MC calculations of dose in human phantoms, can be used to obtain clinically-relevant information about dose to radiosensitive tissue in the human skeleton. The human phantoms are constructed from CT image data and have the useful feature that computed dose to skeletal spongiosa, the portion of bone within which blood cells originate, can be resolved into dose to its radiosensitive components: red bone marrow and bone surface cells. In the first of these papers, simulation of routine cone-beam CT imaging during IGRT demonstrates that the additional dose to bone surface cells from the imaging procedure may be a significant fraction of the overall dose received by radiosensitive bone tissue, thus motivating imaging guidelines. Research in the final paper shows that dose expressed as dose to water-in-medium, the output from commercially available treatment planning systems, is, in general, a more accurate estimate of dose to red bone marrow and bone surface cells than dose expressed as dose to medium, the standard output from MC dose calculation algorithms. Thus, in the case of the latter dose computation, conversion to dose to water-in-medium would seem to be justified.

However, there is ongoing debate over which method of dose specification is a more accurate reflection of radiobiological effects. Moreover, conversion to dose to water-in-medium is not straightforward, particular at lower photon energies, and depends upon the effective volume considered. New research in the Discussion section of this thesis provides a quantitative and qualitative illustration of the effect of the particular cavity theory used to perform this dose conversion.