PhD Thesis Title: Development of an Efficient Algorithmic Framework for Deterministic Patient Dose Calculation in MRI-guided Radiotherapy

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Graduation Date: March 2020
Available Online: https://doi.org/10.7939/r3-34st-gq39

ABSTRACT:

Accurate and efficient patient dose calculation for Magnetic Resonance Imaging (MRI)-guided Radiotherapy is pursued based on a deterministic solution to the Linear Boltzmann Transport Equation (LBTE) with magnetic fields. This technique does not suffer from statistical uncertainty and presents an emerging alternative to Monte Carlo simulations. In this framework, magnetic fields are modeled by an angular advection operator which introduces unique challenges and a new frontier to devise accurate and efficient solution techniques. Key innovations in this work include: (1) the development of conventions to discretize 6-dimensional phase-space permitting harmonious interplay between space and angle, while retaining an acyclic space-angle discontinuous finite element solution sweep graph for all magnetic field orientations, (2) the development of a novel angular advection upwind stabilization framework for curvilinear finite elements on the unit-sphere with flexibility energy adaptive forward-peaked angular meshing for parallel and perpendicular magnetic fields, and (3) a novel runtime approach which ray-traces primary fluence using underlying continuous densities, while secondary scatter is reasonably approximated using a limited set of bulk material densities parameterized by k-means clustering. This enables an efficient transport sweep architecture leveraging batched multiplication by pre-inverted matrices and hierarchical batched assembly of the iterative scatter source. Through the development of these novel mathematical frameworks and algorithms, overall computational complexity is greatly reduced. Then, we have the flexibility to compute multi-beam treatment plans on patient anatomies in the presence of strong magnetic fields parallel or perpendicular to the radiation beam. At anatomical sites including lung, liver, and brain, over 99% (94%) of points pass a stringent 2%/2 mm (1%/1 mm) gamma criterion validated against GEANT4 reference Monte Carlo calculations in the presence of clinical magnetic field configurations. Runtimes of approximately 10 minutes per beam were achieved on a non-parallelized workstation implementation. The algorithmic building blocks and prototype code developed in this work demonstrate feasibility for highly accurate patient dose calculations in clinical magnetic field configurations, and serves as a robust launching point for further investigation towards real-time adaptive magnetic resonance image-guided radiotherapy (MRIgRT).

References to author publications that relate specifically to the dissertation:

[1] R. Yang, O. Zelyak, B.G. Fallone, and J. St-Aubin, "A novel upwind stabilized discontinuous finite element angular framework for deterministic dose calculations in magnetic fields," *Phys. Med. Biol.* **63**(3), 035018 (2018). DOI: https://doi.org/10.1088/1361-6560/aaa2b1

[2] R. Yang, D.M. Santos, B.G. Fallone, and J. St-Aubin, "Feasibility of energy adaptive angular meshing for perpendicular and parallel magnetic fields in a grid based Boltzmann solver," *Biomed. Phys. Eng. Express* **6**(2), 025006 (2020). DOI: https://doi.org/10.1088/2057-1976/ab6e15

[3] R. Yang, D.M. Santos, B.G. Fallone, and J. St-Aubin, "A Novel Transport Sweep Architecture for Efficient Deterministic Patient Dose Calculations in MRI-guided Radiotherapy," *Phys. Med. Biol.* **64**(18), 185012 (2019). DOI: https://doi.org/10.1088/1361-6560/ab35bc