Streamlined four-dimensional CT dose calculation using a GPU-based Monte Carlo simulation for pencil beam scanning proton therapy

Jungwook Shin and Harald Paganetti
Massachusetts General Hospital, Harvard Medical School, Boston, MA

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INTRODUCTION

- When dosimetric effects of patient's respiratory motion are studied, it often involves cumbersome and time-consuming steps utilizing external scripts, such as pre-processing to decompose 4D for 3D individual calculations and post-processing to accumulate 3D results [1-2].

- To fast and accurately evaluate the impact of a patient's respiratory motion on dose distributions of scanned proton beams, **we have simplified this workflow by integrating fast Monte Carlo dose calculations into a DICOM-interface.**

METHOD

- A streamlined workflow (**Figure 1**) has been implemented to incorporate a GPU-based Monte Carlo code by extending an open source DICOM-RT Ion (RTI) interface [3].

- The workflow supports various DICOM inputs, such as 4D-CT, DICOM-RT Ion plan, and DICOM-REG for deformation vector fields (DVF). Linear dose-warping algorithm is employed.

- The performance of the workflow was tested for an esophagus plan (**Figure 2**), e.g., 5 seconds breathing cycle with 10 phases in the 4DCT (0.5 seconds time-resolution), 10 DICOM-REG files for the DVF, and 40 and 45 seconds for beam delivery for each beams.

- The RTI interface calculates the **time structure of a beam delivery sequence (Figure 3)** from a DICOM plan and provides primary protons per each breathing phase (0.5 sec) for GPU-based dose calculations. Then, the simulated doses are **accumulated using the DVF.**

- The performance test (**Table 1**) includes the **execution time required in addition to the GPU simulation** time during total beam delivery, e.g., data-transfer time between CPU (i7-8850H 2.6 Ghz) and GPU (nVidia GTX 1050 Ti) and dose-accumulations.

RESULTS

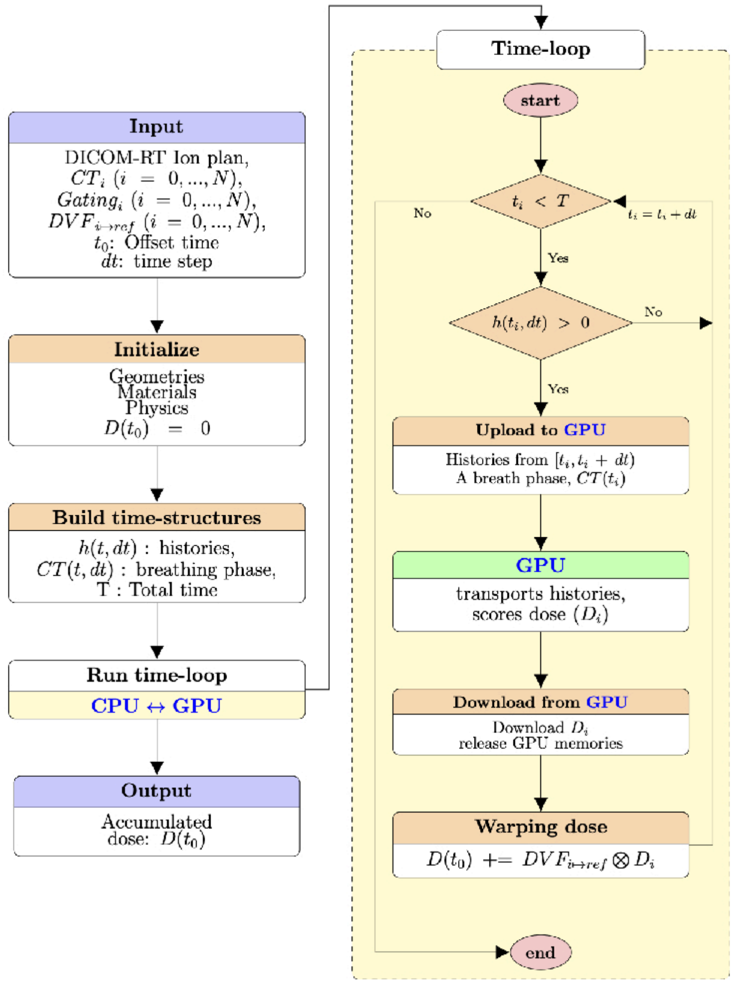

Figure 1: A flowchart for the developed streamlined 4DCT dose calculation. Purple boxes indicate disk I/O related to read in DICOM files, e.g., plan, dose, 4DCT, and deformable image registration (DIR) files. Orange boxes indicate the operations performed on CPU side while the green box stands for GPU operation. No user interactions are required.

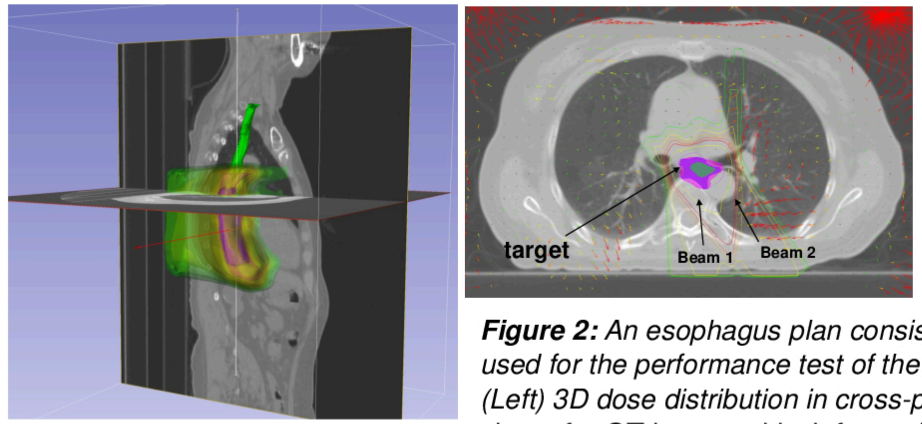

Figure 2: *An esophagus plan consisting of 2 PA beams was used for the performance test of the developed workflow: (Left) 3D dose distribution in cross-plane view. (Right)* Axial view of a CT image with deformation vector fields from MIM DICOM software. The 10 DVFs were input for the workflow.

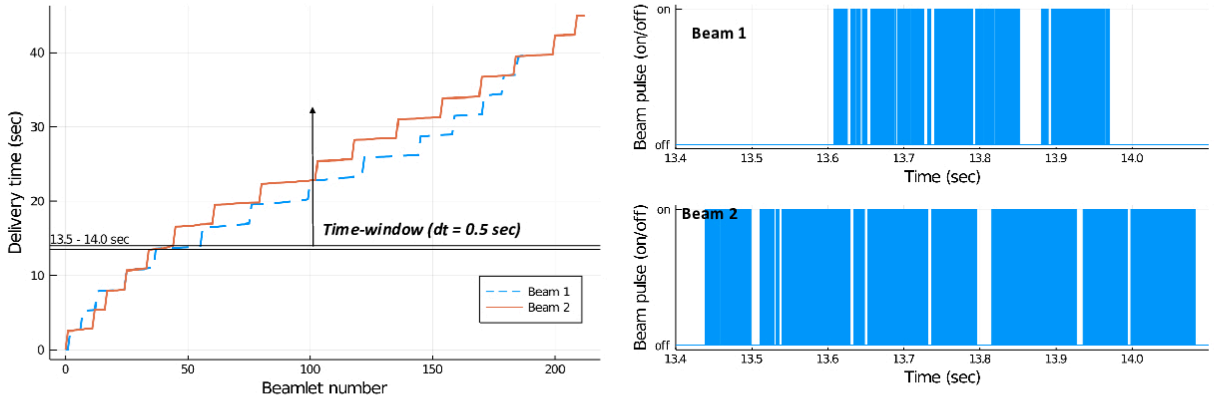

Figure 3: Calculated time structures of the beams based on beam current (2 nA) and times of energy-changing (2.5 sec), beam on-off switching (< 1 ms), and magnet setting (30 m/s and 3 m/s). (Left) Beam delivery times as a function of beamlet number. The time window, indicated within two horizontal lines, moves from 0 to reach a final delivery time. (Right) Beam pulses within a window of 13.5 to 14 sec. As a 4D-CT time resolution is 0.5 sec, all histories between the time interval (0.5 sec) are simulated. Histories are splitted when a CT-phase changes during a pulse.

Table 1: *Compution times for dose-warping, changing patient's CT on the GPU, and transfering histories from CPU to GPU in developed workflow. Beam 1 perform a total of 23 times of dose-warping and changing CT sets while Beam 2 performs 26 times for those operations.*

	Dose warping	Data transfer (changing CT on GPU)	Data transfer (upload histories to GPU)		
			1 M	10 M	100 M
Beam 1	13.9 s ± 0.3 s	1.7 s ± 0.02 s	0.17 s ± <0.01 s	1.6 s ± 0.04 s	15.9 s ± 0.6 s
Beam 2	15.1 s ± 0.7 s	1.85 s ± 0.05 s	0.18 s ± <0.01 s	1.73 s ± 0.02 s	17 s ± 0.3 s

CONCLUSIONS

- For a given plan, a total of 15 sec to 30 sec are required additionally to dose computations on GPU when the impact of patient's respiratory motions on the dose distribution is studied.
- Time to compute dose-accumulations using DVF and changing patient geometries on GPU are independent of number of histories to be simulated. They will increase with a total beam delivery time.
- All operations to access dosimetric impact of continuously changing patient geometries, characterized by 4D-CT can be performed on-the-fly.
- By integrating a GPU-based MC system into a DICOM interface software, thus 4D-CT dose calculations became easy to use and efficient.

ACKNOWLEDGEMENTS

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CONTACT INFORMATION

jshin13@mgh.harvard.edu
hpaganetti@mgh.harvard.edu