On-line forward planning integrated in a dose delivery system for scanned ion beams

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Background: In order to verify the quality of a dose delivered with scanned ion beams, a forward planning (FP) computation is commonly used. The beam directions and fluences monitored on-line with dedicated chambers and the patient position deviations are the basic input data to a forward computation which provides useful feedback on the quality of the delivery.

Purpose: The purpose of the system under development is to integrate very fast FP into a dose delivery system (DDS) in order to be able to compare the delivered and planned dose distributions on-line (spill by spill or every 5 seconds) as well as promptly at the end of the irradiation.

Methods: A fast forward dose computation has been developed parallelizing the following algorithms on a Graphic Processing Unit (GPU) using the CUDA architecture: ray-tracing in the patient CT, sorting of the beam intercepts, computation of water equivalent path lengths for selected voxels within a cut-off around the beam direction and the interpolation of 3D pre-loaded look-up-tables to compute the dose contribution in each voxel of the computing grid.
The fast FP will run on Nvidia TESLA-K40 GPU and will receive the measured spot fluences and positions spill by spill from the DDS through a National Instruments (NI) crate that hosts a NI-FPGA-7813R. Additionally the FP will also receive the patient respiratory phase on-line and will use it to select proper CTs for dose computation (when 4DCT is available).
In the final system both the planned and actual dose distributions will be computed at the same time when the DDS sends the end-of-spill trigger and their difference will be quantified via a GPU-based 3D gamma-index, spill by spill.

Results: The fast FP has been benchmarked against similar and validated algorithms developed for a Treatment Planning System implemented for execution on CPUs. The gain in time for the ray-tracing depends on the number of intercepts and rays while the time for the dose computation mainly depends on the number of selected voxels. As an example, the ray-tracing algorithms for 5000 rays on a 512x512x127 CT grid (for 6x10^6 intercepts) takes 400 ms when running on the CPU (XeonE5-1620v2-3.7-4C-16GB) and 27 ms on GPU (Nvidia TESLA-K20c). Moreover, the whole dose computation for 1500 spots over 40 energies takes 2500 s on the existing CPU-based TPS (without time optimizations) and 3.5 s with optimized codes running on GPU. The dose comparison shows negligible absolute differences (<10^-4Gy) mainly due to the limited numeric precision of the interpolations performed using GPU textures. The accuracy of the pencil beam algorithm was assessed by comparing with MC computations.

Conclusions: A new system, able to check on-line the uncertainties in the delivered dose distributions due to measured patient and beam deviations from the planned conditions, is in progress. A fast FP for ion beams has been developed and its interface with a dose delivery system has been designed.