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Fast dose analysis of movement effects during treatments with scanned proton and carbon-ion beams

A Vignati[1], M Varasteh Anvar[1,2], S Giordanengo[1], V Monaco[1,2], A Attili[1], M Donetti[3], F Marchetto[1], F Mas Milian[4], M Ciocca[3], G Russo[1], R Sacchi[1,2] and R Cirio[1,2]

[1]Istituto Nazionale di Fisica Nucleare (INFN), Torino, Italy
[2]Università degli Studi di Torino, Torino, Italy
[3]Centro Nazionale di Adroterapia Oncologica (CNAO), Pavia, Italy
[4]Universidade Estadual de Santa Cruz, CNPq Fellow, Bahia, Brazil

E-mail: anna.vignati@to.infn.it

Abstract. Charged particle therapy delivered using scanned pencil beams shows the potential to produce better dose conformity than conventional radiotherapy, although the dose distributions are more sensitive to anatomical changes and patient motion. Therefore, the introduction of engines to monitor the dose as it is being delivered is highly desirable, in order to enhance the development of adaptive treatment techniques in hadrontherapy. A tool for fast dose distributions analysis is presented, which integrates on GPU a Fast Forward Planning, a Fast Image Deformation algorithm, a fast computation of Gamma-Index and Dose-Volume Histogram. The tool is being interfaced with the Dose Delivery System and the Optical Tracking System of a synchrotron-based facility to investigate the feasibility to quantify, spill by spill, the effects of organ movements on dose distributions during treatment deliveries with protons and carbon-ions. The dose calculation and comparison times for a patient treated with protons on a 61.3 cm^3 planning target volume, a CT matrix of 512x512x125 voxels, and a computation matrix of 170x170x125 voxels are within 1 s per spill. In terms of accuracy, the absolute dose differences compared with benchmarked Treatment Planning System results are negligible ($<10^{-4}$ Gy).

1. Introduction

Although showing a strong expansion in recent years [1], charged particle therapy as a standard treatment is still developing, and auxiliary technologies that are standard in modern photon radiotherapy [2, 3] systems are still lacking [4]. In particular, adaptive radiotherapy methods would need to be introduced, since the advantage of the better dose conformity offered by charged particle therapy comes to the price of greater sensitivity to delivery-time targeting uncertainties [5], such as patient motion. This work presents a tool (named RIDOS, from *Real-Time Ion DOse Planning and Delivery System*) for fast dose distribution analysis, able to monitor the dose as it is being delivered, whilst maintaining similar accuracy to current clinical standard and without prolonging the delivery time. The core of the tool is represented by a benchmarked irradiation-outcome computation algorithm (*Forward Planning*, FP) for scanned ion beams [6], parallelized and adapted to run efficiently on the GPU architecture (*Fast-FP*, F-FP). The tool receives in real-time the measured beam parameters through a direct and transparent connection with the Dose Delivery System (DDS) of a synchrotron-based facility. Online motion monitoring data will be used to correlate tumour and organ motion with the temporal structure of the

beam delivery and 4D computed tomography (CT) image to reconstruct a dose-time distribution, incorporating both interplay effects and range changes. The dose distribution will be repeatedly calculated during the irradiation, i.e. after the delivery of each energy layer (spill). Moreover, thanks to a Fast Image Deformation (F-ID) algorithm, each spill-dose is mapped back to the reference image. This would make possible to monitor the progressive emergence of a motion-corrected dose distribution during treatment, and therefore to promptly identify motion artefacts.

2. Materials and Methods

The scheme of the RIDOS pipeline is shown in Fig. 1, where the reported times are related to a synchrotron-based facility. Some of the tool components are executed before the start of the treatment, while the others are performed in the inter-spill time, which is approximately 3 seconds. The planned and the delivered dose are calculated in around 300 ms, while the fast dose comparison takes 400 ms. The whole pipeline is completed by far within 1 second.

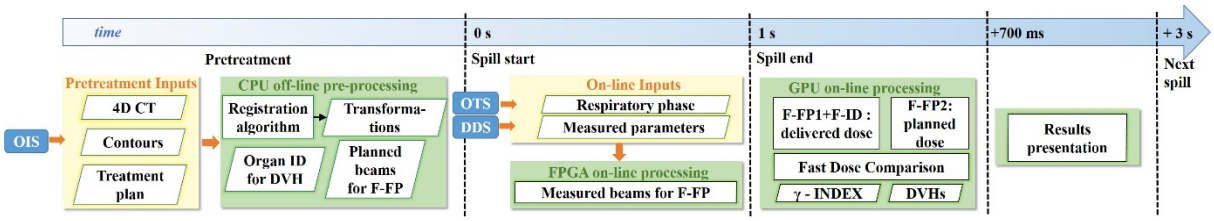

Figure 1. General scheme of the presented tool. OIS = Oncological Information System; OTS = Optical Tracking System; DDS = Dose Delivery System; F-FP = Fast Forward Planning; F-ID = Fast Image Deformation.

2.1 CPU off-line pre-processing

2.1.1 Registration. A 4D-CT scan is an image covering the entire breathing cycle, composed by a set of 3D-CT volumes, each corresponding to a particular breathing phase. Due to the respiration, voxels may migrate and distort among breathing phases, making the comparison of the different 3D-CT volumes on a voxel-by-voxel basis problematic. Image registration is a method of aligning two images into the same coordinate system, so that the aligned images can be directly compared, combined and analyzed [7]. A deformable image registration method was performed on CPU, before the treatment, between each breathing phase CT (moving image) and the CT used to plan the treatment (reference image), in order to obtain the corresponding transformation. A parametric non-rigid registration method was adopted, using Bspline transformation and Mattes Mutual Information [8] as similarity measure. Those transformations are then used by the F-ID algorithm (see paragraph 2.3.1).

2.1.2 Pretreatment inputs. The following data are loaded and processed before the treatment start: a) the patient CT (or 4D-CT), needed by the off-line registration step, by the F-FP, and the F-ID; b) the target and the region-of-interest contours, to compute the Dose Volume Histogram (DVH); c) the treatment plan with the list of planned beam parameters to compute the reference dose distributions, spill by spill.

2.2 FPGA on-line processing

A National Instruments (NI - Austin, USA) digital I/O module, equipped with a Xilinx Virtex II FPGA (San Jose, California, US) and hosted on a NI-PXI chassis, interfaces the DDS with the Workstation (WS). The FPGA firmware receives in real-time the measured beam parameters (i.e. fluence and positions) as soon as they are available in the DDS FPGA. These data are transferred spot by spot to the PXIe-CPU via DMA-FIFO to be promptly sent to the WS. A second NI-FPGA module, in the same NI-PXIe system, will receive on-line the three-dimensional patient position corrections and the respiration phase from the optical tracking system (OTS).

2.3 GPU on-line processing

2.3.1 Fast Forward Planning and Fast Image Deformation. The F-FP algorithm has been obtained by implementing on GPU the computing kernel of a benchmarked Treatment Planning System (TPS) called PlanKIT [6]. The dose calculation program, implemented in the CUDA (Nvidia Corporation, Santa Clara, CA, USA) C/C++ programming language, consists of the following steps:

- ray-tracing operations are performed in the voxelized CT volume to identify the segments of the beam axis belonging to different traversed materials;
- the path length of a beam in a heterogeneous material is converted into its water equivalent path length (WEPL), using the information of the stopping power assigned to each CT voxel by a CT-scanner-specific curve that relates Hounsfield numbers to stopping power ratios;
- a downsampled matrix of the CT matrix (*computing grid*) is hereinafter considered, and for each beam the voxels of the computing grid are selected within a chosen radial distance (*radial cut-off*) from the beam axis. The radial cut-off is the distance at which the interaction is considered.
- for each voxel position $r_m=(x_m,y_m,z_m)$ in the beam coordinate system, the projection on the beam axis z_m is rescaled to z_w according to the WEPL and a water-equivalent position $r_w=(x_m,y_m,z_w)$ is obtained;
- the dose for every selected voxel is obtained through the interpolation from the look-up tables (LUTs) of PlanKIT. The LUTs are 3D sampling of the beams effectiveness in water, in terms of dose per single particle, obtained simulating the used beamline with the Monte Carlo method (Fluka).

Spill by spill, the F-FP calculates the dose on the specific CT phase and on the reference CT. The cumulative planned dose is repeatedly updated by summing the dose calculated on the reference CT. The F-ID receives in input the transformation parameters of each CT phase created by the registration algorithm in the pretreatment step, and warps the dose distribution of the specific CT phase according to the reference CT, and the cumulative delivered dose is updated.

2.3.2 Fast dose comparison. The delivered dose is compared online to the planned dose distribution using a fast 3D gamma evaluation algorithm. The method was implemented in CUDA according to Persoon et al [9]. Moreover, the DVHs are calculated.

3. Results

A WS HP Z420 (2xIntel XeE5-2670v2) equipped with a NVIDIA Tesla K20c was used to test the algorithms. Since, at present, the connection with the DDS and the OTS is not complete, to evaluate the results of the F-FP, F-ID and Fast Dose Comparison an artificial rotation of 2 degrees (around the perpendicular to the axial plane) was applied to a static CT case, and the rotated CT image was used as CT phase. The static CT case was referred to a 61.3 cm^3 planning target volume (PTV) brain case, treated with protons (one beam entrance direction, 39 energy layers, and 1248 spots). The dimension of the CT matrix was 512x512x125 voxels (320x320x250 mm^3), while the computing grid was 170x170x125 voxels. Table 1 presents the time gain of the RIDOS F-FP in respect to the PlanKIT FP to calculate the dose distribution of the entire treatment, although it is worth to underline that no particular effort has been made to optimise the computing times of PlanKIT.

The gamma index calculation times were inversely dependent on the dose interpolation resolution. Using an interpolation of 0.1 mm and the already defined computing grid, gamma values were obtained in about 400 ms. Fig. 2 presents the results of the dose comparison step. The absolute differences between the dose distribution computed by the RIDOS F-FP and the PlanKIT FP are negligible ($<10^{-4}$ Gy). As already mentioned, for individual spills, the F-FP dose calculation and the F-ID times are about 300 ms, while fast gamma index and the DVHs computation times are estimated to

be around 400 ms. Therefore, the dose computation and comparison of one spill are expected to be within 1 s. Similar results are obtained considering a carbon-ion treatment.

Table 1. Computing times of the RIDOS F-FP and the PlanKIT FP, and related gain, by varying the radial distance from each beam axis at which the interaction is considered (*radial cut-off*). The dose is calculated for the number of voxels selected, which increase by augmenting the radial cut-off.

Radial cut-off (mm)	Number of voxels	RIDOS F-FP time (s)	PlanKIT FP time (s)	Gain
20	44678	1.35	157	116
40	178702	2.33	636	273
50	279243	2.76	997	361
80	714861	4.68	2534	541

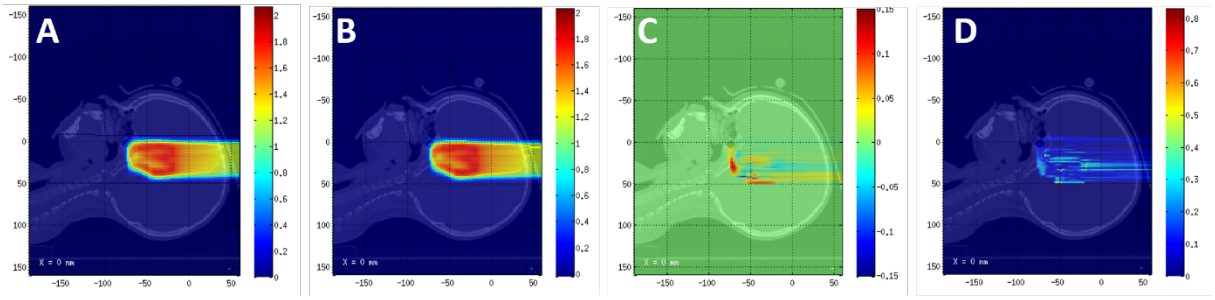

Figure 2. Comparison of the planned dose calculated on the reference CT in Gy (A), the delivered dose calculated on the rotated CT in Gy (and that warped according to the reference CT by the F-ID algorithm) (B), the absolute dose difference between A and B in Gy (C), and the gamma index (C) for a distance to agreement = 3 mm, and dose difference = 3%.

4. Discussion

The precise dose localization enabled by ions makes them favourable for highly conformal radiotherapy treatments but also sensitive to uncertainties due to range variations, patient intra-fractional motion and interplay effects between target and beam movement during delivery. This work represents an important step towards adaptive hadron therapy providing the pre-clinical validation of a new GPU-based system, able to monitor the dose as it is being delivered. These preliminary results suggest the readiness of the tool for the possible test in a clinical environment, to verify its potential contribution to the developments of on-line dose measurements and verification modalities. Additionally, the system could find application in the real-time interactive treatment planning [10], or to monitor the dose delivery in hypofractionated treatments.

5. Acknowledgments

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6. References

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