Calculating and Visualizing 3D Dose Rates for Proton FLASH Radiotherapy

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Introduction

Ultra-high dose rate irradiation (FLASH radiotherapy) recently demonstrated great impact in sparing normal tissues while maintaining good tumor control [1-4]. FLASH effect has been observed in preclinical experiments for various location and particles type including proton [5].

To further these studies we have created a set of tools to explore plan-specific and machine parameters needed to achieve the FLASH conditions in protontherapy: a 3D dose rate calculation tool and a dose rate visualization and analysis tool.

Both tools can be launched from ECLIPSE™ using the Eclipse Scripting API capabilities.

Dose rate calculation

A typical Pencil Beam Scanning (PBS) irradiation is depicted in Fig.1. In such scheme, several pencil beams (or spots) are delivered one by one along a scanning pattern. Each spot is delivered within a certain time and contribute to a fraction of the total dose received by a given voxel.

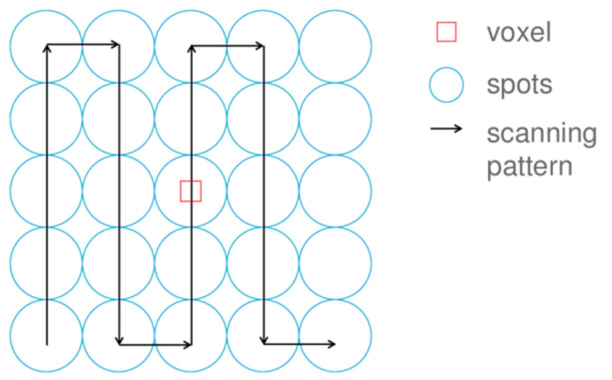

Fig.1. in PBS protontherapy, a given voxel receives dose from different pencil beam (spots), irradiated one by one along a scanning pattern.

Although different metrics have been proposed to capture the instantaneous dose rate in such delivery technique [6,7], we explore here a definition that account for the dead time needed to move from spot-to-spot and therefore reflects the average dose rate.

For each field of a plan, the 3D dose rate is calculated as follows:

1) the dose distribution is calculated for each individual pencil beams of the field (influence matrix) using ECLIPSE™ dose calculation algorithm,
2) the scanning dynamics information (time spent per spot) is evaluated based on the ProBeam® machine capabilities e.g. beam current, magnets speed,
3) For each voxel, the time and influence matrix are combined to compute the dose accumulated as a function of time as shown in Fig.2.
4) the PBS dose rate [8] is then calculated for all voxel as:

$$\dot{D}_{PBS} = \frac{D^*_{voxel}}{t^*_{voxel}}$$

where

- $D^*_{voxel} = D_{total,voxel} - 2 \cdot D_{th,voxel}$ [Gy],
- $D_{total,voxel}$ is the total dose in the voxel [Gy],
- $D_{th,voxel}$ is an arbitrary threshold dose set to 0.01 Gy,
- t^*_{voxel} is time needed for the accumulated dose to rise from $D_{th,voxel}$ to $D_{total,voxel} - D_{th,voxel}$ [s].

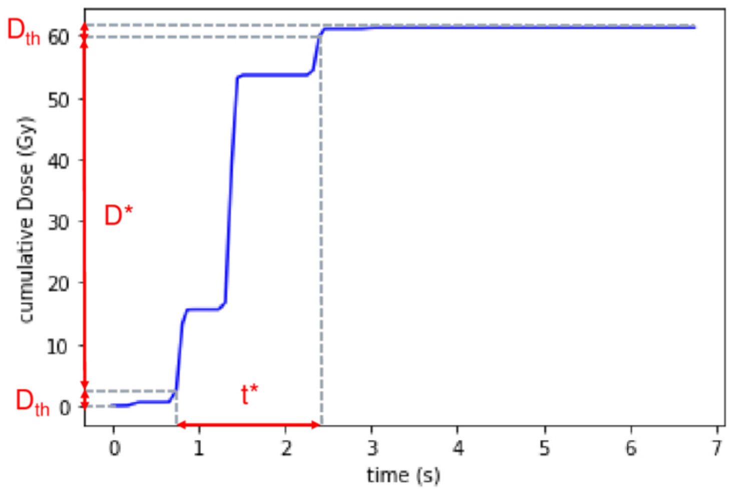

Fig.2. Example of dose accumulated in a single voxel as a function of time (blue curve). The PBS dose rate is calculated as D*/t*.

Dose rate visualization

The patient structures and CT images are automatically loaded from the ECLIPSE™ External Beam Planning workspace. The dose rate is then imported for every field composing the plan.

Among others, the tool allows the user to display per field:

- dose rate distributions, displayed as color wash,
- dose rate volume histograms (DRVH) per structure,
- dose rate profiles along a given line,
- dose distributions.

The dose rate distribution is displayed for the axial, coronal and sagittal views and the user can select which field to display. The tool allows moreover to display the dose distribution per field or for the entire plan (each field dose is then summed).

An example of PBS dose rate distribution calculated for a thoracic case is displayed in Fig.3. It deals with a single-fraction plan (16 Gy prescribed to the PTV) composed of 5 transmission fields [6,7,9]. The plan was optimized in ECLIPSE™ to ensure a high dose rate in the organs-at-risk while maintaining a good dose homogeneity in the target volume (conformity index of 0.8).

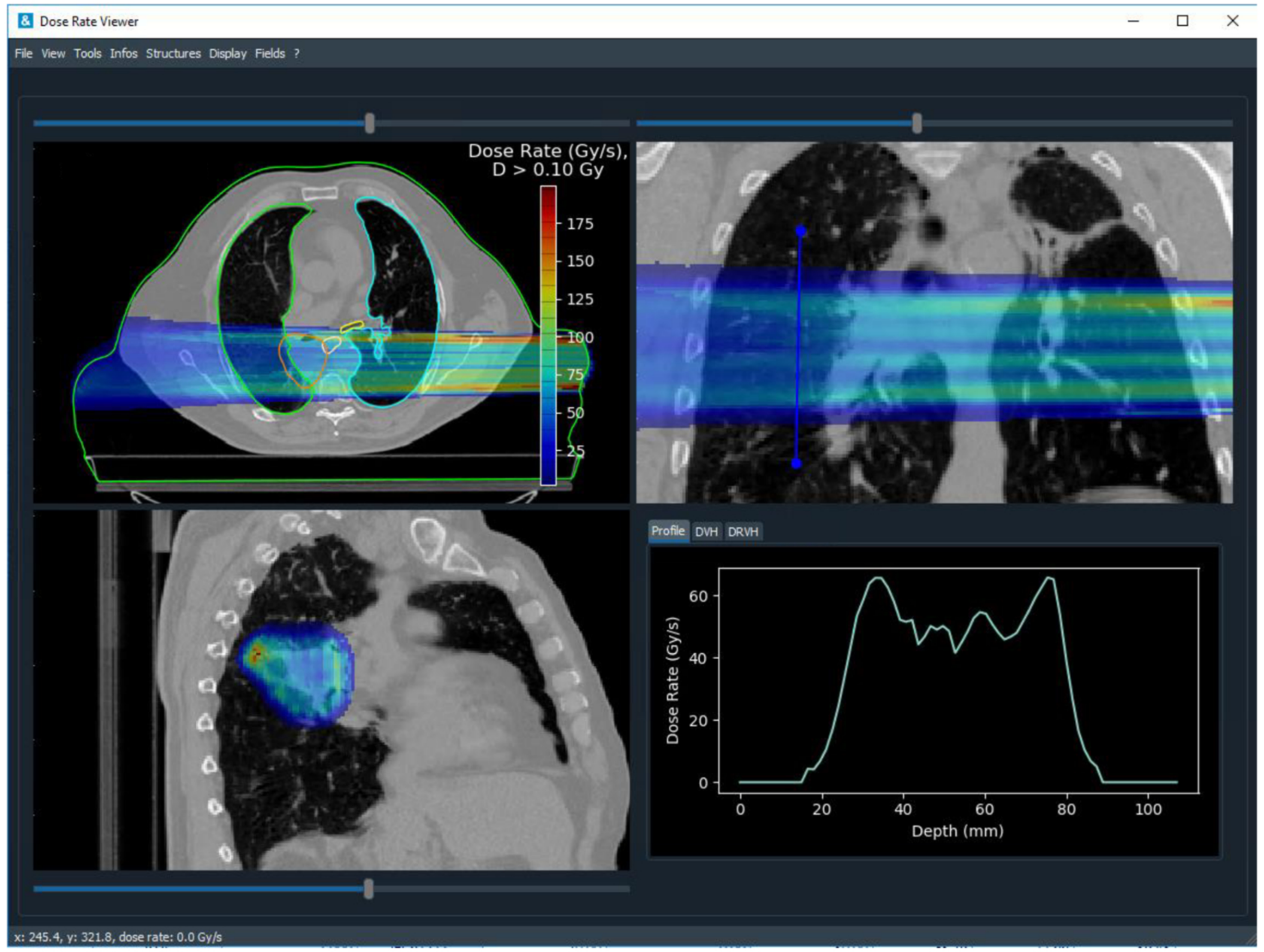

Fig.3. Screenshot of the dose rate visualization tool. The PBS dose rate distribution, calculated for one beam angle, is displayed on top of CT image and structures. A profile of the dose rate in the lung (blue line, top right corner) is displayed in the bottom right pane.

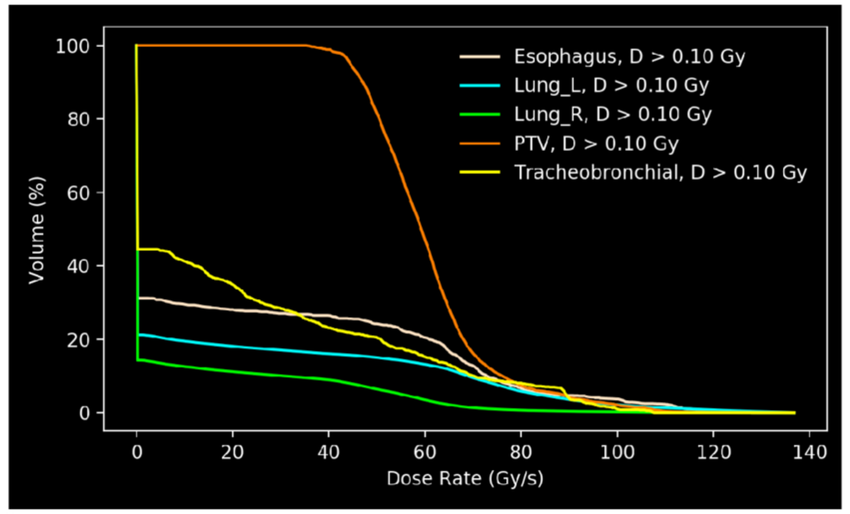

Fig.4. Dose rate volume histograms calculated for PTV and several organs-at-risk. The structure colors match the one in Fig.3.

The associated DRVH calculated for relevant structures is shown in Fig.4. As a regular dose volume histogram, the fraction of volume covered is here plotted as a function of the dose rate. For instance, in this field, approximately 20% of the left lung receives a dose rate higher than 40 Gy/s.

Conclusion & acknowledgements

We have developed a toolkit in order to calculate and visualize the 3D dose rate in protontherapy. The tool integrates the scanning information from ProBeam® delivery systems and ECLIPSE™. The toolkit is versatile in handling different dose rate definitions. These tools will support FLASH clinical planning.

This work was designed to address a need expressed by the FlashForward™ Consortium.

References

[1] V. Favaudon et al. *Sci Transl Med* 6, 245ra93 (2014).
[2] M.C. Vozenin et al. *Clin Cancer Res.* 25(1):35-42 (2019).
[3] P. Montay-Gruel et al. *Radiother Oncol.*124(3):365-369 (2017).
[4] E. Schüler et al. *Int J Radiat Oncol Biol Phys.* 97(1):195-203 (2017).
[5] M. Buonanno et al. *Radiother. Oncol. (*2019).
[6] S. van de Water et al. *Acta Oncologica*, 1-7 (2019).
[7] P. van Marlen et al. *IRJOBP* (2019).
[8] M. Folkerts et al. submitted article.
[9] J. Perez et al., PTCOG 58 e-poster (2019).

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