Comprehensive sensitivity analysis for FLASH-IMPT plans in a patient geometry using 3DRMs

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Introduction

Exploiting the Bragg Peak in **proton FLASH** is facilitated by using patient-specific hardware like a **3D range modulator** (3DRM). The **accurate positioning** of such devices introduces a new potential error source in the plan delivery and thus the impact of device misalignment on the delivered dose as a function of different hardware parameters requires further investigation.

FLASH-IMPT

IMPT-like plans can be created using a **single-energy** beam delivery and **patient-specific hardware** (Fig. 1). Thanks to the lack of energy layer switching and high beam transmission at 250 MeV, FLASH dose rates are achievable.

In this study, we investigated the impact of hardware misalignments on the resulting dose distribution in a patient geometry.

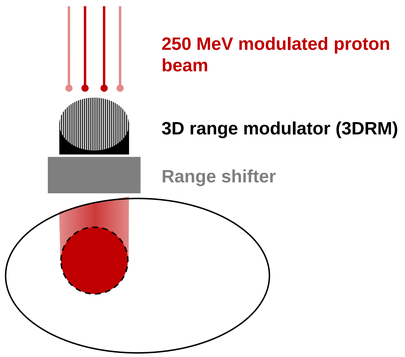

Figure 1: Components used for FLASH-IMPT.

Scenarios

For two clinical cases (**liver and brain**), we optimized a 2-field multi-field optimized plan and created corresponding field-specific 3DRMs using a research-only version of **Eclipse** (16.1 plus ESAPI).

The pin spacing of the 3DRMs varied from 3 to 10 mm, and the pin shape interpolation between spots was either dose-weighted (based on the relative dose contribution of all spots) or nearest neighbor. This resulted in a set of 24 different 3DRMs.

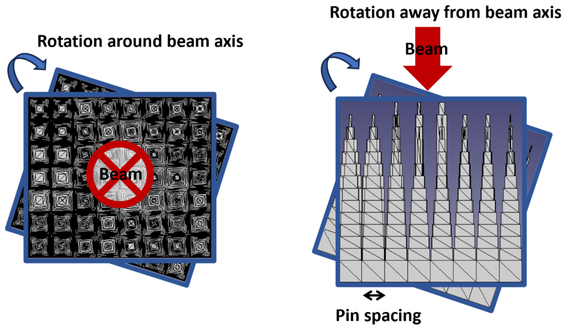

Figure 2: Illustration of the investigated misalignment scenarios.

FLUKA simulations

For one field per scenario, i.e., for 12 different 3DRMs, FLUKA was used to simulate the resulting dose for the **nominal** hardware alignment as well as **rotational** and **tilting** misalignment of 3° (Figure 2). The misaligned dose distributions were compared to the nominal case through **3D Gamma analysis** using various criteria (3%/3mm, 2%/2mm, 1%/1mm) and a 10% global dose threshold.

Results

For one example 3DRM scenario, the resulting FLUKA dose distribution is shown in Figure 4, comparing the two misalignment scenarios with the corresponding nominal distribution. Rotating the 3DRM around the beam axis introduced a smaller dose deviation than rotating it away from the beam axis.

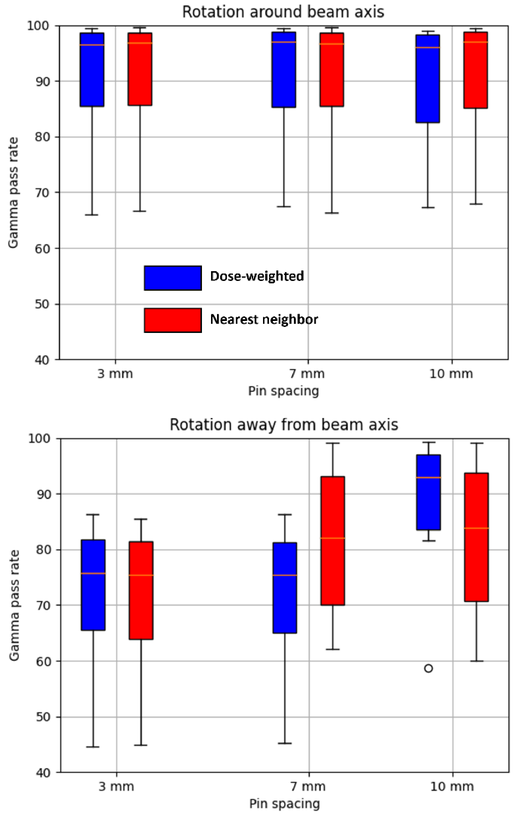

Figure 3: 3D Gamma pass rates for all scenarios. Top: rotation around beam axis. Bottom: tilt away from beam axis. The box plots contain the results for both patients and for all gamma criteria.

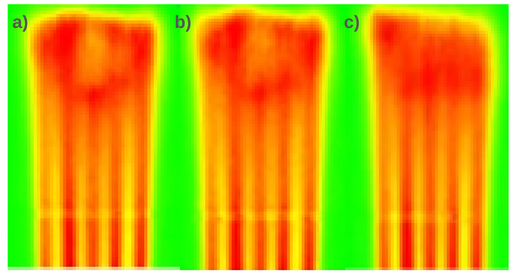

Figure 4: Example FLUKA dose for one 3DRM. **a)** Nominal 3DRM position, **b)** 3° rotation around beam axis, **c)** 3° tilt away from beam axis.

Figure 3 shows that rotating the 3DRM away from the beam axis (tilting) had a larger impact on the resulting dose than rotations around the beam axis for all applied Gamma criteria. Wider pins showed a reduced sensitivity to rotations away from the beam axis than narrower pins, with the dose-weighted pins and 10 mm pin spacing having the least dose degradation due to misalignment. For rotations around the beam axis, neither the interpolation method nor the pin spacing showed any substantial impact on the resulting dose.

Conclusion

Misalignment of patient-specific hardware has the potential to alter the dose distribution substantially. Avoiding small features or high aspect ratios may reduce the sensitivity to misalignments.

For more details about the FLUKA model and 3DRM robustness, please refer to reference [1].

References

[1] Y. Simeonov et al: A Fast 3D Range-Modulator Delivery Approach: Validation of the FLUKA Model on a Varian ProBeam System Including a Robustness Analysis *Cancers* (2024)

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