A novel IMPT optimization method enforcing a minimum spot MU per energy layer for FLASH

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Introduction

In Intensity-Modulated Proton Therapy (IMPT), the monitor units (MU) of each spot are optimized to fulfill dosimetric constraints. In ProBeam™ system, the cyclotron beam current is moreover determined by the minimum MU of a spot in the energy layer [1]. Therefore, a high minimum MU/spot supports ultra-high dose-rate delivery (FLASH-RT) but may reduce significantly the number of spots, thus degrading the plan quality. Here, we propose a method to optimize spot MUs above a user-defined value while preserving dosimetric constraints.

Minimum MU soft constraint

To enforce a minimum spot MU per energy layer, an extra term is added to the optimizer objective function:

$$f_{total} = f_D + \alpha \cdot f_{MU},$$

where:

- f_D accounts for the dosimetric objectives,
- f_{MU} is the minimum MU soft constraint (see fig. 1),
- α is the relative strength of the min. MU constraint.

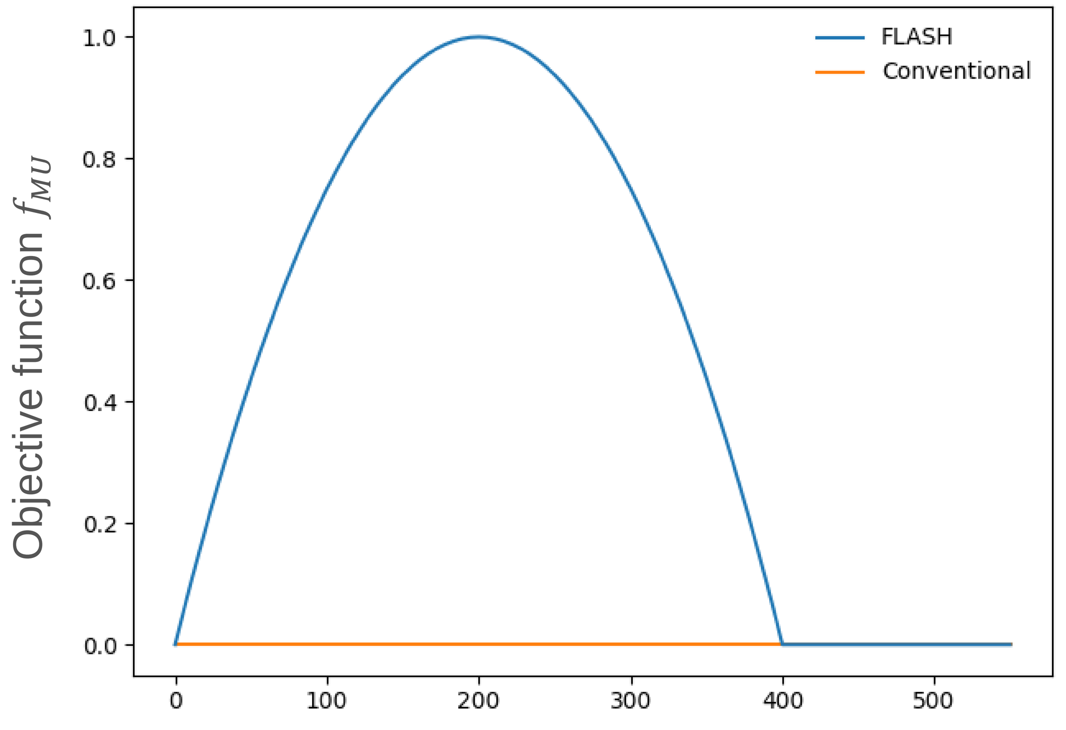

Fig. 1. Example of a minimum MU objective function, for a minimum MU $MU_{min} = 400$. Spots MUs above 200 tend to get increased to 400 while spots MUs below 200 tend to get reduced to zero and removed.

Methods

An optimization algorithm using the minimum MU soft constraint was implemented in ECLIPSE™. Single-energy-layer transmission proton IMPT plans were optimized for four lungs cases with varying PTV sizes (cf. table 1). Following SBRT protocol [2], each plan was optimized to deliver 34 Gy in one fraction to the PTV while maintaining a minimum spot MU of 400 or 600. The spot spacing was set to 5 mm (hexagonal grid).

	PTV dimensions	MU_{min}	N spots
case 1	2.5 x 2.8 cm	400	223
case 2	3.0 x 3.7 cm	400	339
case 3	3.2 x 5.2 cm	600	358
case 4	5.1 x 4.0 cm	600	362

Table. 1. PTV dimensions and number of spots for each case.

The PTV dose homogeneity and several dose metrics were characterized and compared to the one reached for conventional IMPT plans. The PBS dose rate [3] distribution was then calculated and evaluated using the 40 Gy/s volume coverage.

Results

As shown in fig. 1, no spots below the minimum MU remains after optimization. All plans achieved clinically acceptable target uniformities (see table 2: homogeneity indices from 1.04 to 1.13) and the maximum dose in the PTV increased at most by 8 % for case 3. The Dose Volume Histograms (DVH) are shown in fig. 3.

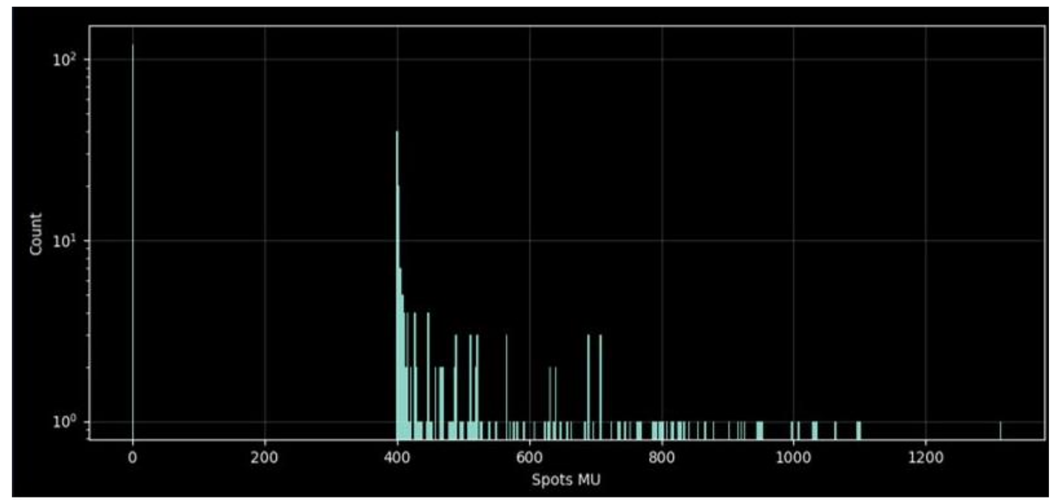

Fig. 2. Histogram of the optimized spots MU (case 1).

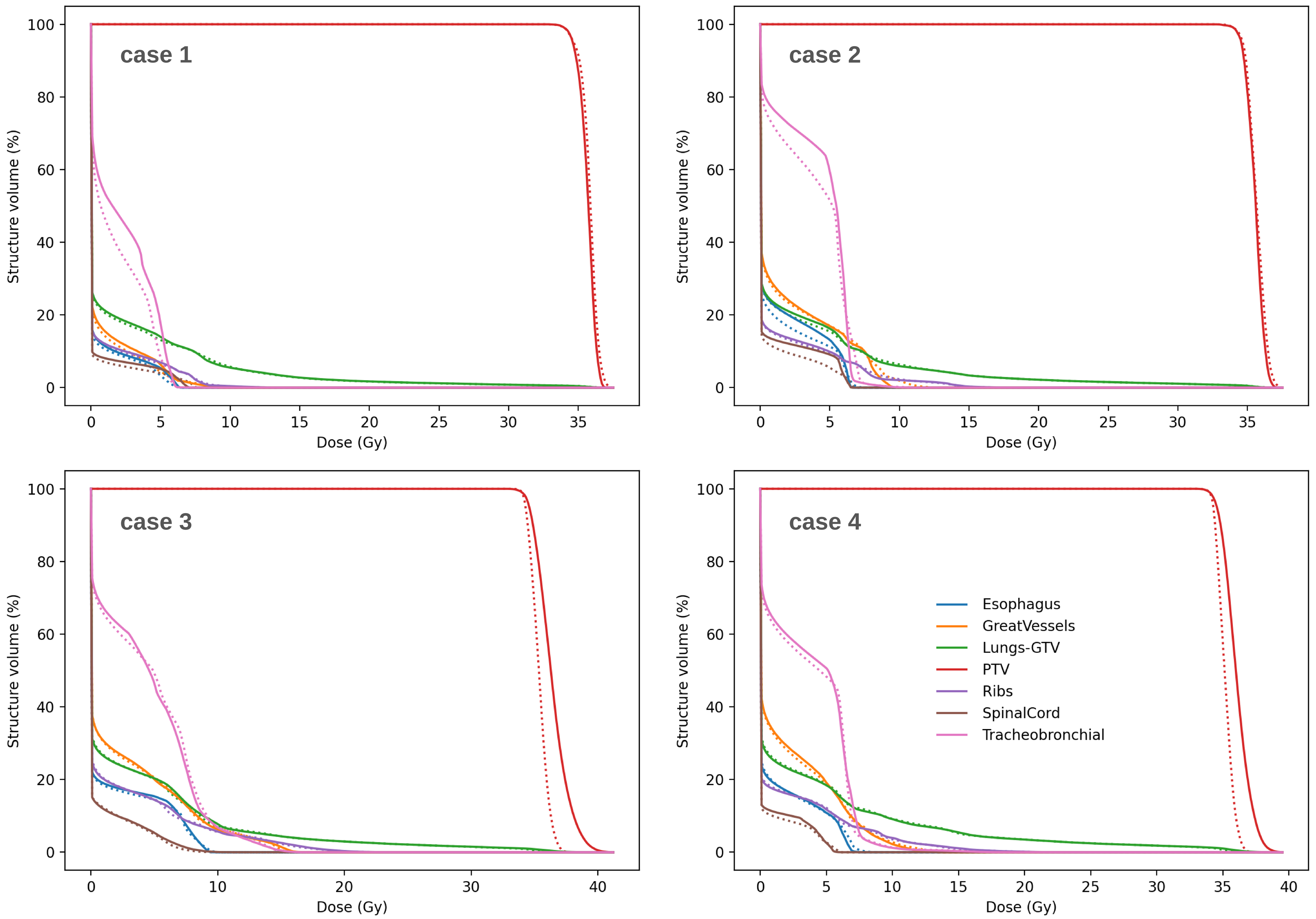

Fig. 3. DVH of plans optimized with the minimum MU soft constraint (solid line) and without (dashed line).

	$MU > 0$				$MU > MU_{min}$			
	D_{mean} (Gy)	D_{max} (Gy)	HI	CI	D_{mean} (Gy)	D_{max} (Gy)	HI	CI
case 1	35.8	37.6	1.05	1.25	35.6	37.1	1.04	1.24
case 2	35.6	37.6	1.05	1.19	35.5	37.2	1.05	1.18
case 3	35.3	37.9	1.07	1.1	36.4	41.2	1.13	1.19
case 4	35.1	37.6	1.07	1.09	36.0	39.5	1.10	1.15

Table. 2. Mean PTV dose, maximum PTV dose, homogeneity index ($HI = D_{max}/D_{mean}$) and conformality index (CI) for each case.

	$MU > 0$		$MU > MU_{min}$	
	D_{max} (Gy)	V_{DR}/V_D	D_{max} (Gy)	V_{DR}/V_D
case 1	6.5	0 %	6.4	96 %
case 2	7.4	0 %	6.7	88 %
case 3	10.4	0 %	9.6	86 %
case 4	9.0	0 %	8.0	94 %

Table. 3. Maximal dose and fraction of irradiated volume above 40 Gy/s for esophagus.

The fraction of irradiated volume (dose > 2 Gy) receiving at least 40 Gy/s ranged from 88 to 96 % for esophagus for plans optimized with the minimum MU constraint (table 3). The total number of iterations was increased at most by 30% with the soft constraint (see table 4), resulting in a total execution time of the algorithm only two to three times longer than for conventional optimization

	$MU > 0$	$MU > MU_{min}$
case 1	158	223
case 2	145	200
case 3	104	180
case 4	187	256

Table. 4. Number of optimizer iterations.

Conclusion

We have proposed a new IMPT optimization method enforcing a minimum spot MU per energy layer. No reduction of the plan quality was observed on the plans optimized with this method. This work was designed to address a need expressed by the FlashForward™ Consortium. The authors submitted a patent application for the minimum MU soft constraint.

References

[1] M. Kang et al, *Cancers*, *13*(14), 3549, 2021. **[2]** https://www.nrgoncology.org/Clinical-Trials/Protocol/rtog-0915?filter=rtog-0915 **[3]** M. M. Folkerts et al, *Medical Physics*, *47*(12), 6396-6404, 2020.

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