DIRECT MACHINE PARAMETER OPTIMIZATION FOR INTENSITY MODULATED PROTON THERAPY

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Introduction

In conventional Intensity Modulated Proton Therapy (IMPT), the weights of individual pencil-beams, or spots, are optimized to fulfill dosimetric constraints. These spots are usually placed on a regular lattice and their positions are unchanged during optimization. To achieve ultra-high dose rate (FLASH-RT) delivery, the range of spot weights may be constrained to high values, leading to sub-optimal plan quality. To further improve the quality of FLASH plans, we propose a Direct Machine Parameter Optimization (DMPO) algorithm which simultaneously optimizes spot weights and positions.

DMPO Algorithm

We present an example of a FLASH transmission plan created with DMPO, having a minimum and maximum dose objective on the PTV (figure 1). The spots are initially placed on a regular hexagonal grid.

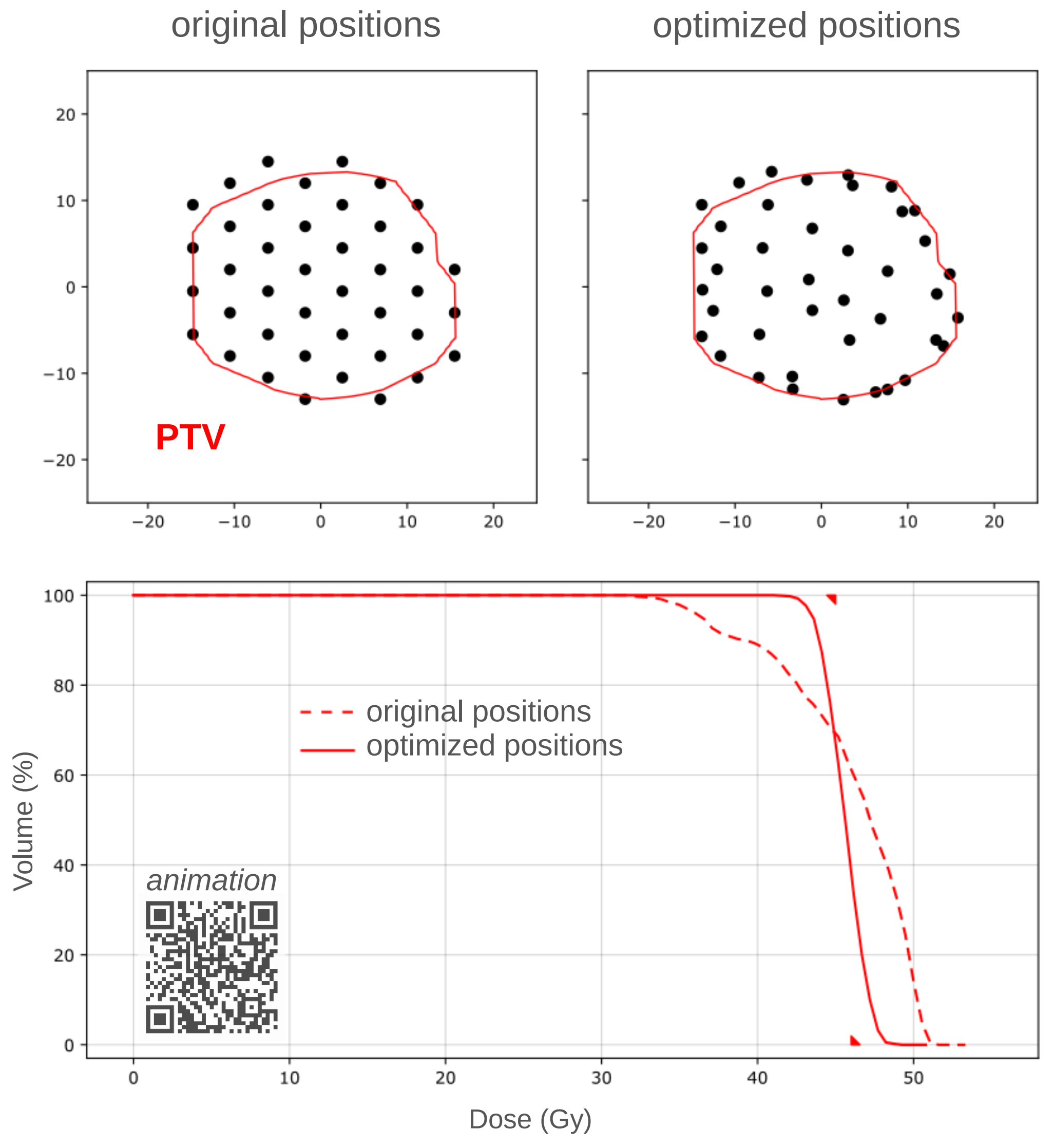

Fig. 1. Example of DMPO starting from a hexagonal grid. The PTV dose objectives are shown on the DVH.

Compared to conventional IMPT optimization, where only the spots weights W are optimized, the influence matrix IM now explicitly depends on the spot positions X, Y.

	Conventional optimization	DMPO
Dose D	$IM \cdot \boldsymbol{W}$	$IM(\boldsymbol{X},\boldsymbol{Y}) \cdot \boldsymbol{W}$

The following steps are repeated until the optimization has converged:

1. objective function and gradient evaluation,
2. the spots are moved to their new positions,
3. the spots weights are adjusted.

Methods

Single-energy-layer FLASH transmission plans were created for peripheral lung cases with varying PTV sizes. Guided by SBRT RTOG protocol [1], each plan was prescribed to deliver 15 Gy in 3 fractions to the PTV. Optimization of both MU and spot positions was performed while enforcing a minimum spot MU [2] of 400 or 600. Scorecards [3] were used to optimize and evaluate the resulting plan quality.

Several dose metrics were characterized, and performance was compared between DMPO and conventional spot weight optimization with minimum MU enforcement. The PBS dose rate [4] was then calculated and evaluated for the DMPO plans.

	PTV dimensions	MU_{min}	N_{spots}
case 1	2.5 x 2.8 cm	400	115
case 2	3.0 x 3.7 cm	400	177
case 3	3.2 x 5.2 cm	600	180
case 4	5.1 x 4.0 cm	600	184

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

Results

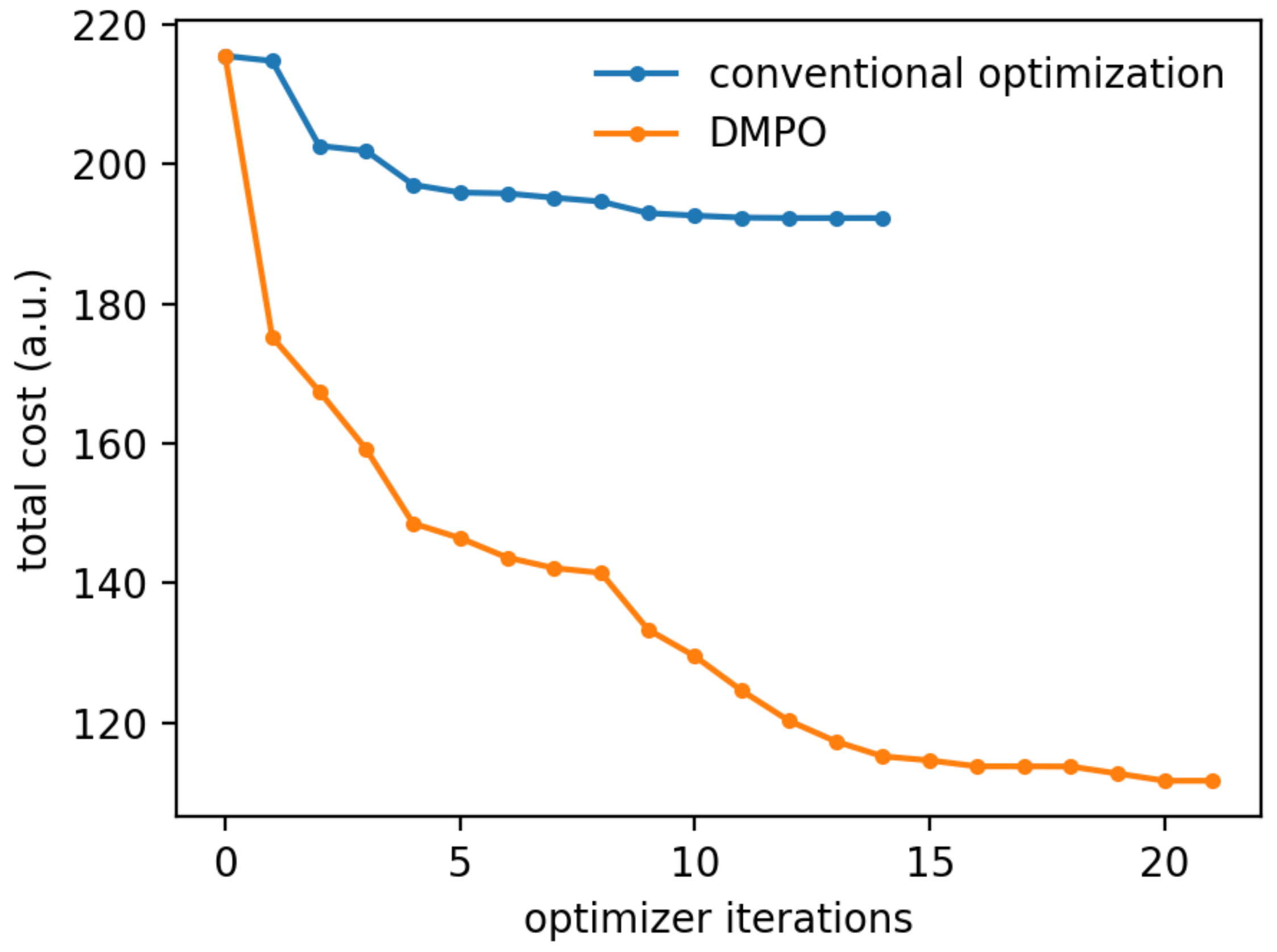

Fig. 2. Objective function evolution for conventional optimization and DMPO (case 1).

The evolution of the objective function during optimization is displayed in fig 2. The final cost reached with DMPO was two times lower than conventional optimization, with similar number of iterations. Unlike the conventional optimization scheme, all plans optimized with the DMPO algorithm passed the RTOG protocol inspired metrics (see table 2).

Metric	Goal	Conventional	DMPO
PTV, $V_{45\,Gy}$ (%)	> 90	99.0	99.0
PTV, D_{max} (Gy)	56.2	54.2	53.9
Ring80, D_{max} (Gy)	< 26.2	28.5	25.8
Ribs, D_{max} (Gy)	< 36.9	33.9	32.0
Ribs, D_{1cc} (Gy)	< 28.8	28.9	26.3
Spinal Cord, D_{max}	< 18	8.0	7.6
Esophagus, D_{max} (Gy)	< 25.2	15.4	13.7
Lungs, D_{mean} (Gy)	< 13.5	3.9	3.9

Table. 2. Several dose metrics and associated passing criteria evaluated for conventional optimization and DMPO. Failing metrics are indicated in red, marginal in orange and passing in green.

The dose distributions delivered above 40 Gy/s are displayed for each case in figure 3. For all fields, most of the dose is delivered at a dose rate above 40 Gy/s. Example field dose distributions are shown in figure 4.

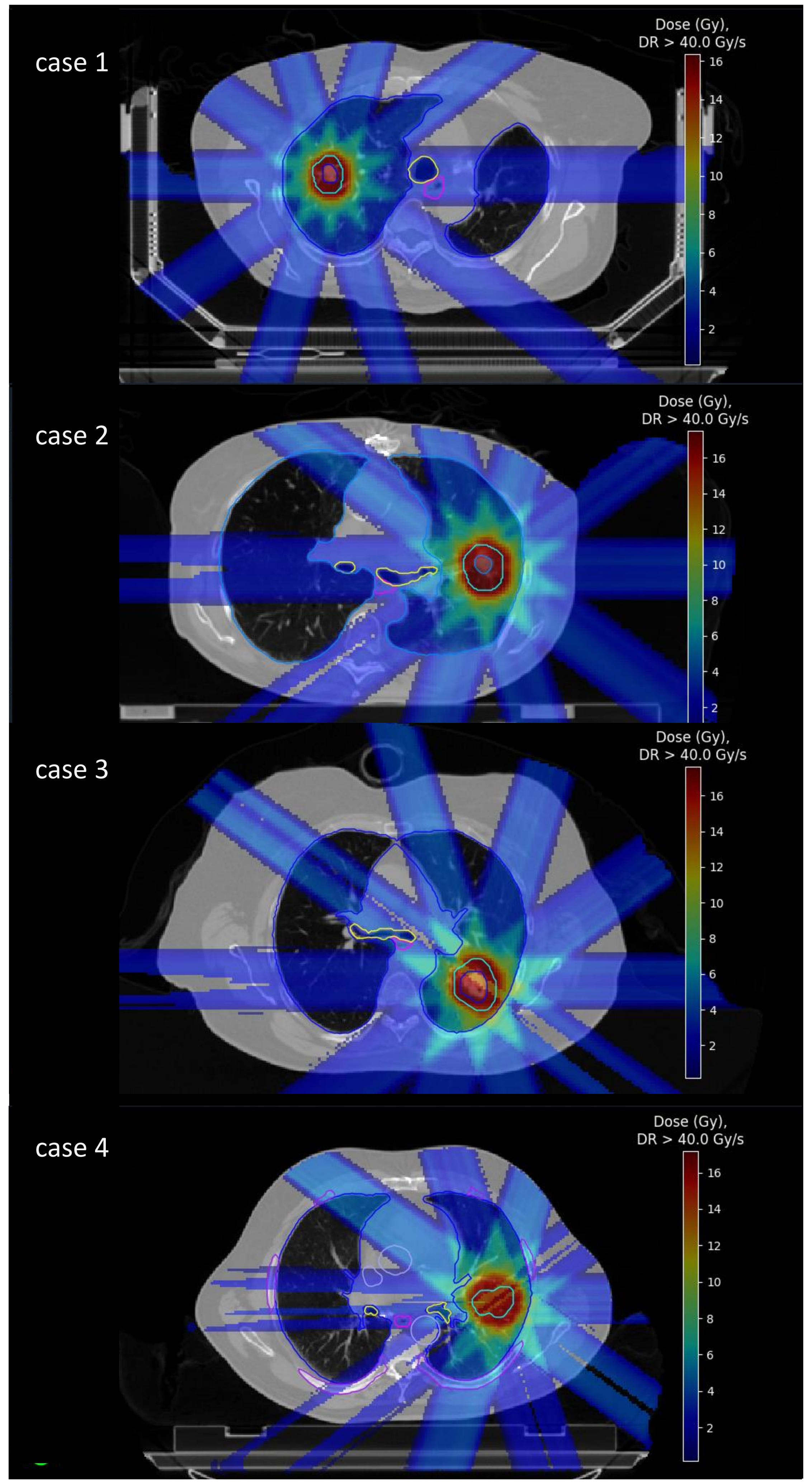

Fig. 3. Dose delivered at dose rate above 40 Gy/s.

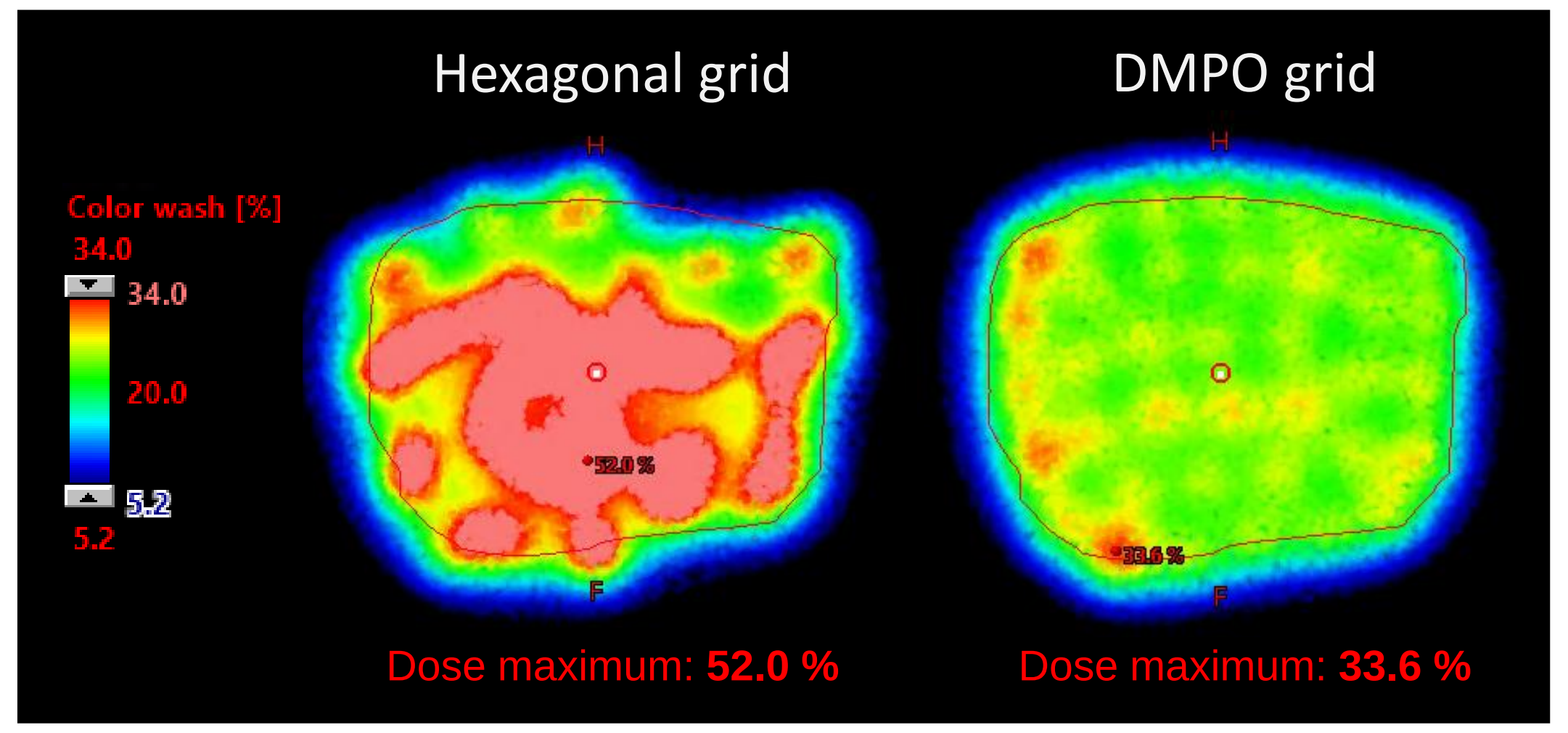

Fig. 4. Field dose distributions as seen from the BEV for a beam optimized from a hexagonal grid and with DMPO.

Compared to conventional optimization on a regular grid, DMPO resulted in smaller “hot” regions of lower magnitude in the final dose distributions. The fraction of irradiated volume receiving at least 40 Gy/s was above 91 % for lungs (excluding PTV) and above 92 % for esophagus (see table 3). Overall, DMPO resulted in significant plan quality improvement for all patients.

% FLASH	Esophagus	Lungs-PTV	Tracheobronchial
case 1	100 %	97 %	98 %
case 2	95 %	94 %	93 %
case 3	98 %	95 %	95 %
case 4	95 %	91 %	92 %

Table. 3. Fraction of irradiated volume (dose > 2 Gy) above 40 Gy/s several organs at risk.

Conclusion

We have proposed a new algorithm to optimize FLASH plans. Optimizing both the spot weights and positions leads to better plan quality than conventional (hex grid) optimization. This work will support the creation of fractionated IMPT plans for FLASH-RT. The authors tank M. Ropo and P. Niemela for their help. The DMPO algorithm is covered by a pending patent application.

References

[1] G. Videtic et al. *RTOG-0915* (2012).
[2] P. Lansonneur et al. *PTCOG 60 poster* (2022).
[3] B. Nelms, *Practical Radiation Oncology* 2, 296–305 (2012).
[4] M. Folkerts et al. *Medical Physics* (2020).

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