ENABLING FLASH TREATMENT OF LARGE ULTRA-CENTRAL LUNG TUMORS USING A NOVEL OPTIMIZATION METHOD

P. Lansonneur*, A. Magliari, L. Rosa, J. Perez, R. Sharma and M. Folkerts
Varian, a Siemens Healthineers Company

Introduction

Lung cancer is one of the most common cancers, and the leading cause of cancer deaths in men and women in North America and other developed countries. For patients with co-morbidities, the surgical resection of centrally located tumors is not necessarily suitable and these patients are typically considered for radiotherapy.

Previously developed ultra-high dose-rate (FLASH-RT) optimization schemes failed to achieve both suitable dose and dose rate distributions for such cases. To enable the potential benefit from the sparing effect of FLASH-RT for large ultra-central lung tumor treatments, we propose a novel algorithm to simultaneously optimize spots weights and positions using Intensity Modulated Proton Therapy (IMPT).

Spots positions optimization

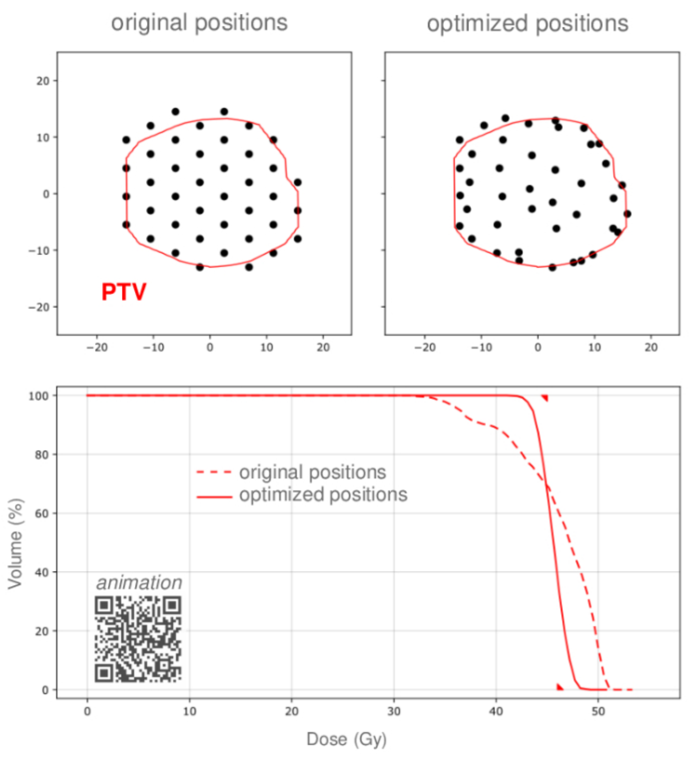

Fig. 1. Example of position optimization starting from a hexagonal grid. The PTV dose objectives are shown on the DVH.

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

Unlike standard IMPT optimization, where only the spots weights W are optimized, the influence matrix IM now explicitly depends on the spot positions x, y:

	Spot weights Optimization	Positions and weights Optimization
Dose D	$\sum_{j=1}^{N} w_j \cdot IM_{ij}$	$\sum_{j=1}^{N} w_j \cdot IM_{ij}(x_j, y_j)$
Gradient ∇D	$\frac{\partial D_i}{\partial w_j} = IM_{ij}$	$\begin{pmatrix} \frac{\partial D_i}{\partial x_j} \\ \frac{\partial D_i}{\partial y_j} \\ \frac{\partial D_i}{\partial w_j} \end{pmatrix} = \begin{pmatrix} w_j \cdot \frac{\partial IM_{ij}}{\partial x_j} \\ w_j \cdot \frac{\partial IM_{ij}}{\partial y_j} \\ IM_{ij} \end{pmatrix}$

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 transmission IMPT plans were created for ultra-central lung cases with large PTV sizes (6 x 8 cm, 150 cc). Guided by SBRT RTOG protocol [1], each plan was prescribed to deliver 50 Gy in five fractions to the PTV. MU and spot positions were optimized while enforcing a minimum spot MU of 600 to ensure high dose-rates [2].

Dose metrics were compared to conventional (spot weight optimization only). PBS dose rate [3] was calculated and evaluated for each field.

Results

Unlike previously developed optimization schemes (only optimizing spot MUs with minimum constraint), the plans optimized with this novel algorithm passed the RTOG protocol inspired metrics (table 1). The fraction of irradiated volume (dose above 2 Gy) receiving at least 40 Gy/s reached 92 % for lungs and 95 % for the heart. Overall, this new optimization method resulted in a significant plan quality improvement with similar plan optimization time.

RTOG metric	Goal	Fixed positions	Optimized positions
PTV, $V_{50\,Gy}$ (%)	> 90	90.4	95.6
PTV, D_{max} (Gy)	< 62.5	62.2	60.2
PTV, $D_{99\%}$ (Gy)	> 44.9	48.1	48.2
Heart, D_{mean} (Gy)	< 15	16.8	14.7
NS_Ring100, $V_{44\,Gy}$ (%)	< 5	3.0	0.3
NS_Ring80, D_{max} (Gy)	< 45.5	36.9	34.8
GreatVessels, D_{mean} (Gy)	< 15	8.0	7.7
GreatVessels, D_{10cc} (Gy)	< 47	49.8	42.1
BrachialPlexus, D_{3cc} (Gy)	< 27	0.0	0.0
BrachialPlexus, D_{max} (Gy)	< 30.5	0.3	0.3
Tracheobronc, D_{mean} (Gy)	< 25	14.5	12.6
Tracheobronc, D_{4cc} (Gy)	< 16.5	11.5	8.0
SpinalCord, $D_{0.35cc}$ (Gy)	< 23	20.1	12.6
SpinalCord, $D_{1.2cc}$ (Gy)	< 14.5	19.1	10.9
SpinalCord, D_{max} (Gy)	< 30	21.2	14.4
Ribs, D_{1cc} (Gy)	< 35	23.7	23.3
Ribs, D_{max} (Gy)	< 43	26.1	24.9
Ribs, D_{mean} (Gy)	< 15	4.4	4.1
Esophagus, D_{5cc} (Gy)	< 19.5	19.2	14.6
Esophagus, D_{mean} (Gy)	< 20	4.5	3.9
Esophagus, D_{max} (Gy)	< 35	21.0	20.6
Stomach, D_{mean} (Gy)	< 15	0.0	0.0
Stomach, D_{10cc} (Gy)	< 18	0.2	0.2
Stomach, D_{max} (Gy)	< 32	0.4	0.4
Skin, D_{10cc} (Gy)	< 36.5	13.2	13.6
Skin, D_{max} (Gy)	< 39.5	20.6	17.4
Lungs-GTV, D_{mean} (Gy)	< 15	8.5	7.9
Lungs-GTV, $V_{20\,Gy}$ (%)	< 15	15.4	13.8
Lungs-GTV, D_{1000cc} (Gy)	< 13.5	9.8	9.0
Lungs-GTV, D_{1500cc} (Gy)	< 12.5	1.1	1.3
External, $V_{25\,Gy}$ (cc)	< 504	555.0	458.9

Table 1. Several dose metrics and associated RTOG passing criteria for plans created with fixed and optimized positions. Colors indicate failing, acceptable variations, or passing metrics.

The dose distribution delivered above 40 Gy/s is displayed in figure 3. For all fields, most of the dose is delivered at a dose rate above 40 Gy/s.

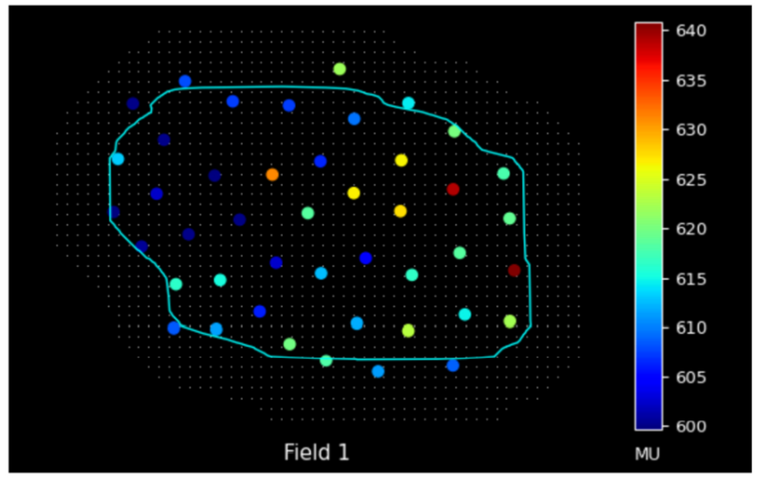

Fig. 2. Optimized spot positions and Monitor Units (field 1).

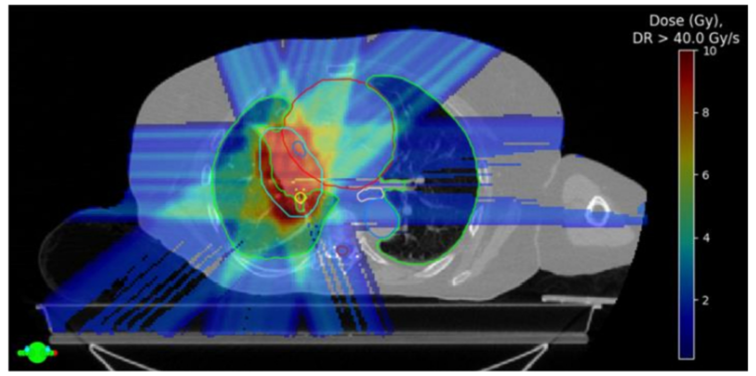

Fig. 3. Optimized dose delivered above 40 Gy/s.

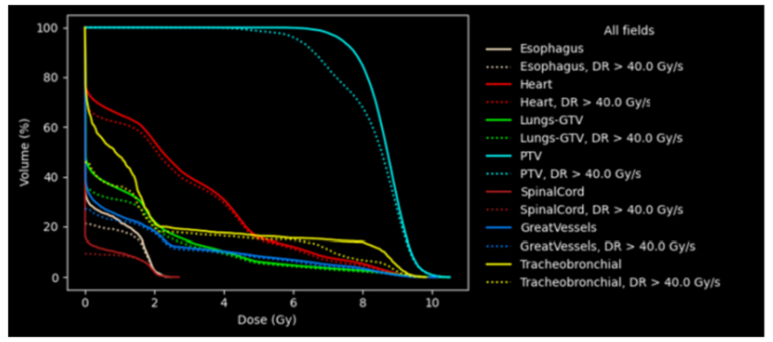

Fig. 4. Dose-volume histograms of the full dose distribution (solid lines) and of the dose with voxels irradiated above 40 Gy/s (dashed line).

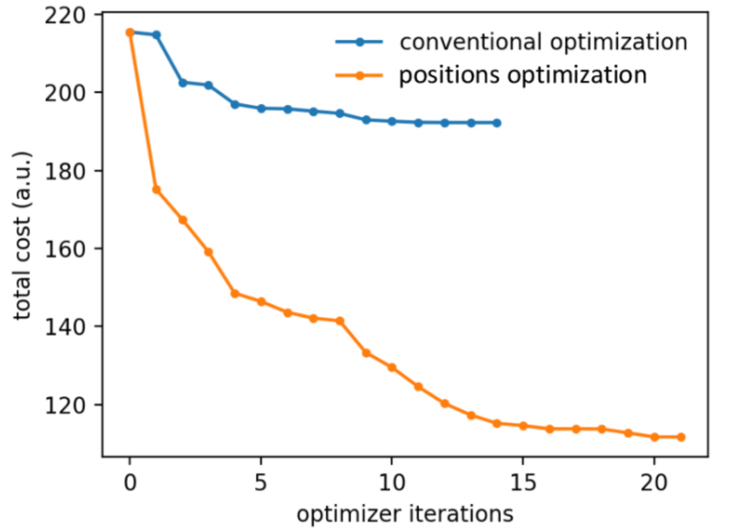

Fig. 5. Objective function evolution for conventional optimization and spot position optimization.

Structure	Fraction of irradiated volume above 40 Gy/s
PTV	100 %
Heart	95 %
Lungs-PTV	92 %
Spinal Cord	97 %
Great vessels	95 %
Tracheobronchial	90 %

Table 2. Fraction of irradiated volume (dose > 2 Gy) above 40 Gy/s for the PTV and 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 optimizing only the weights. This work will support the creation of fractionated IMPT plans for FLASH-RT. The spot position optimization algorithm is covered by a pending patent application.

References

[1] https://www.nrgoncology.org/Clinical-Trials/Protocol/rtog-0813 **[2]** P. Lansonneur et al. *PTCOG 60 poster* (2022). **[3]** M. Folkerts et al. *Medical Physics* (2020).

FLASH therapy is under development and not available for commercial sale.

* pierre.lansonneur@varian.com