Enhanced Sparing of Organs at Risk with the Single-Energy-Modulated Proton Arc Therapy (SEM-PAT); A Proof of Concept in Central Lung and Pelvis

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INTRODUCTION

- Using larger number of beams in proton therapy and modulating proton energy (like in an arc) has shown potential advantages over traditional proton treatment planning in reducing the sensitivity to uncertainties.
- One concern with proton arc therapy is the practical deliverability of the plans. Changing energy as the gantry rotates is a critical technical difficulty.[1]
- Planar arc proton therapy with single-energy-modulation using a tertiary energy modulator was successfully used in a phantom study by Langner et al.[2]

AIM

We investigated single-energy-modulated proton arc therapy (SEM-PAT) planning in real patient cases and

- reported on an end-to-end planning process in the clinically used Eclipse treatment planning system (Varian, Palo Alto) to show translatability.
- demonstrated dosimetric characteristics.
- calculated water equivalent thickness (WET) for the energy modulator.

METHOD

- Under an umbrella IRB approval, two disease sites were retrospectively studied: (gynecology) pelvis and lung.
- Two plans were compared per case: the original clinical plan used for the patient treatment and the proposed SEM-PAT plan.
- Multifield optimization process was performed within Eclipse treatment planning system (TPS) V15.6.
- Arc plans were simulated as 10-degree gantry-spacing static beams that delivered the dose to the isocenter plane.
- The clinical plan and SEM-PAT plan used non-linear universal proton optimizer (NUPO) and proton convolution superposition (PCS) algorithms, respectively. Eclipse TPS does not allow NUPO in planar irradiation.
- For SEM-PAT plans, proximal and distal ends were set to 0cm from isocenter and lateral margins were set to the max (20cm).
- The clinical plan was optimized using dose-volume constraints based on our institution's clinical guidelines. For SEM-PAT, we added an extra constraint for a sharp dose fall-off in a 1cm-thick ring around the tumor.

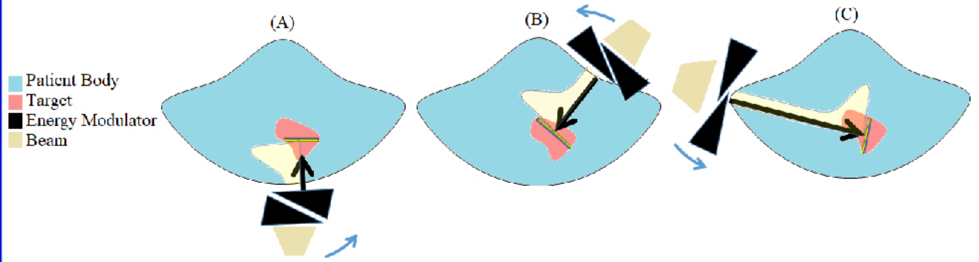

***Fig1.** An illustrative schematic of SEM-PAT in 3 sample gantry angles*

RESULTS

- While the SEM-PAT planning complexity increased for larger tumors, the benefits of it when compared to the clinical plans, seemed disease-site-independent.
- For the pelvis plan, SEM-PAT's main dosimetric advantage was in significant sparing of femoral heads (63%-69% in mean dose) and therefore bone marrow sparing. For the lung plan, it was in significant reduction in volumes of heart and lung that received doses >10Gy (e.g., 63%-70% in V30).
- The SEM-PAT plans were deliverable in a single gantry rotation (1-minute per rotation) with $8cm \leq WET \leq 11cm$.

The Pelvis Case (CTV: 195cc)

Organ at risk	Constraint	Clinical guideline for the constraint	Constraint value achieved by the plan (units follow the previous column)	
			Clinical plan	SEM-PAT plan
Right Femoral Head	V40	< 40%	0	0
	V45	< 25%	0	0
	V50	≤ 0.5cc	0	0
Left Femoral Head	V40	< 40%	0	0
	V45	< 25%	0	0
	V50	≤ 0.5cc	0	0
Rectum	V40	< 80%	49.4	47.6
Bladder	V40	< 40%	39.8	25.9
	V45	< 15%	34.0	19.8
	V50	≤ 0.5cc	15.4	7.0
Small Bowel	V15	≤ 120cc	19.3	12.1
	V20	≤ 50%	9.2	5.3
	V45	≤ 15%	3.6	1.0
	V50	≤ 10%	1.9	0.2
Target	Conformity index	1	1	0.998
	Homogeneity index	1	1	0.98

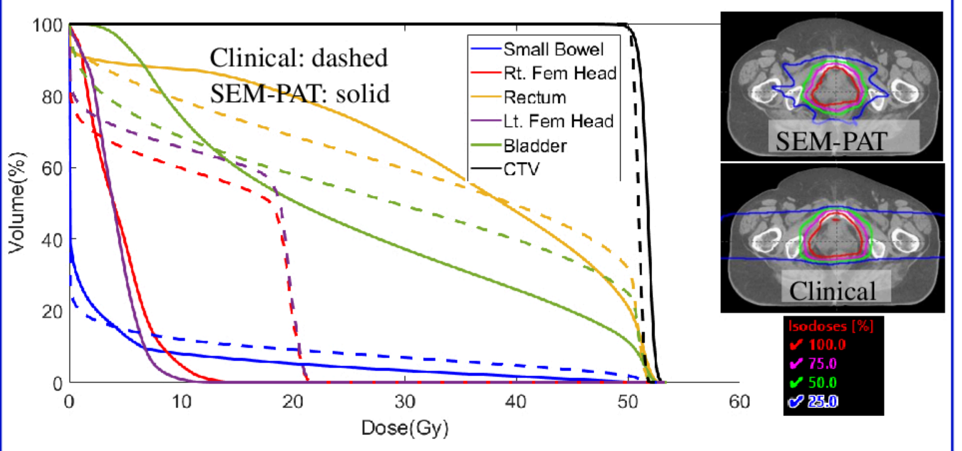

***Fig2a.** Comparing dose-volume histograms and dose distributions on axial isocenter plane for the pelvis case*

The Lung Case (CTV: 62cc)

Organ at risk	Constraint	Clinical guideline for the constraint	Constraint value achieved by the plan (units follow the previous column)	
			Clinical plan	SEM-PAT plan
Spinal cord	V48	< 0.1cc	0	0
Spinal cord+2mm	V50	< 0.5cc	0	0
Heart	V30	< 50%	5.7	1.7
	V45	< 35%	0.9	0.3
	D(0.3cc)	< 66Gy	0	0
Right Brachial Plexus	V66	< 0.1cc	0	0
Left Brachial Plexus	V66	< 0.1cc	0	0
Esophagus	Mean dose	< 34Gy	6.8	5.1
Total lungs	Mean dose	< 18Gy	6.4	5.3
	V5	< 45%	32.6	36.3
	V20	< 25%	11.7	5.4
	V25	< 20%	8.7	3.5
	V35	< 15%	4.5	1.6
	V50	< 10%	0.3	0.2
Target	Conformity index	1	0.9979	0.9979
	Homogeneity index	1	0.9952	1

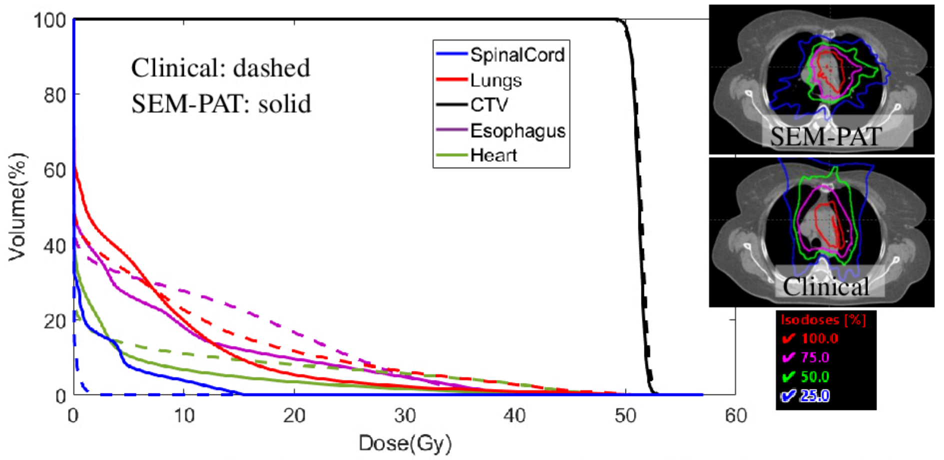

***Fig2b.** Comparing dose-volume histograms and dose distributions on axial isocenter plane for the lung case*

RESULTS

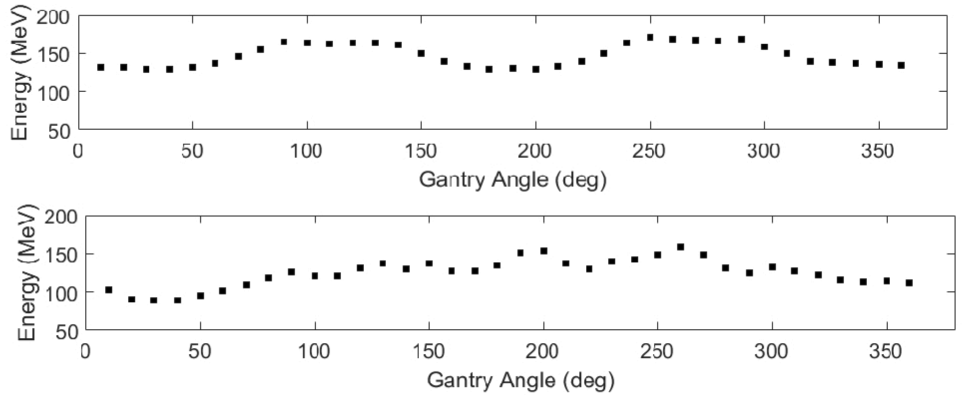

***Fig3.** Energies per beam for the SEM-PAT plans in the pelvis case (top): 129.3MeV ≤energy ≤171.9MeV, and the lung case (bottom): 88.8MeV ≤ energy ≤ 158.1MeV*

We used commissioning data to fit energy (E) versus R80 (the position of 80% dose in the distal fall-off) curve: $E = 31.447 \times R80^{0.5685}$

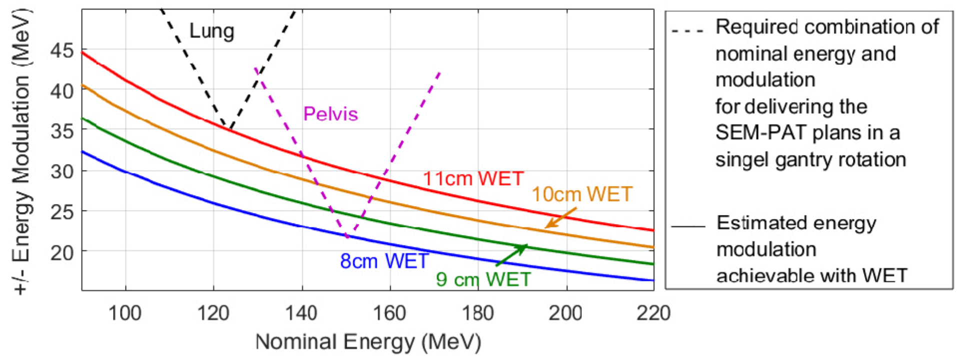

***Fig 4.** The combinations of energy provided by cyclotron and modulation required to deliver the SEM-PAT plans using an 8cm-11cm WET*

CONCLUSION

We investigated SEM-PAT's ability to achieve (a) a safe and yet fast delivery while keeping proton beam Bragg peak well within the target and (b) use of large number of beams in an arc as a degree of freedom for improving dosimetric quality.

REFERENCES

[1] Ding, X., X. Li, et al., *Spot-Scanning Proton Arc (SPArc) Therapy…* Int J Radiat Oncol Biol Phys, 2016.

[2] Langner, U.W., J.G. Eley, et al. *A method to deliver energy modulated planar proton arc therapy (EMPPAT)*. Jour Proton Ther, 2017.

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