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Efficient proton arc therapy with column-generation planning

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Introduction Proton arc therapy (PAT) has been demonstrated for its potential benefit of improved dose homogeneity and normal tissue sparing. However, the determination of spot parameters (energy, position and intensities) for proton arc beams can become a very large optimization problem and thus difficult to solve and inefficient to deliver. In this work, we proposed a novel energy layer optimization algorithm to achieve quality plans and efficient delivery for PAT.

Method We formulated the efficient PAT plan optimization problem as to find a minimal set of energies to approach the dose objectives and solved the optimization using column generation (CG) that progressively improves the plan quality. We used a Head & Neck case to study the proposed PAT-CG scheme and compared the results with those of using IMPT and conventional PAT (PAT-full).

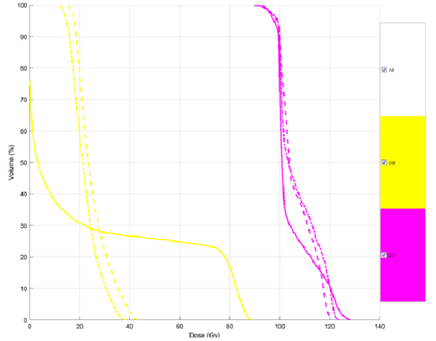
Data & Metrics All plans were optimized with the PTV objective of 100Gy and underdose penalty being 10x overdose penalty. PTV dose-range (PTV-DR) and maximum OAR dose (OAR-D2) were used as plan quality metrics, and the inverse ratio of delivery time to that of IMPT was used to measure the delivery efficiency.

Results CG-based PAT plans achieved comparable plan qualities to those of PAT-full within 4 energy layers (PAT-CG4) and were much better than the IMPT plans. The PTV-DRs were 28.75Gy, 26.42Gy, 24.03Gy, and the OAR-D2s were 86.50Gy, 33.56Gy and 32.59Gy, for IMPT, PAT-CG4 and PAT-full, respectively. The delivery efficiency of PAT-CG4 and PAT-full were 84% and 19%, respectively. PAT-CG4 improved efficiency by four times without sacrificing plan quality compared to PAT-full (Table 1 & Fig. 1).

Table 1 Comparison of the planning parameters and qualities for the static field IMPT (1, 3, 7 angles) and PAT (63 angles) with different numbers of energy layers.

NumAngle	NumEnergy	NumSpot	TotalIntensity	PTV_D2	PTV_D98	PTV-DR	OAR_D2	Delivery Time	Delivery-Efficiency
1	22	298	640.40	124.46	95.70	28.75	86.50	118.17	1.00
3	22	723	634.12	119.68	95.43	24.24	41.02	219.99	0.54
7	22	1326	643.99	120.30	95.38	24.93	42.68	417.48	0.28
63	1	1260	626.20	124.72	95.04	29.68	44.11	107.46	1.10
63	2	1317	615.59	121.77	96.11	25.65	35.15	110.34	1.07
63	4	2129	601.04	122.76	96.34	26.42	33.56	140.49	0.84
63	22	14711	655.65	119.39	95.35	24.03	32.59	609.74	0.19

Fig. 1 DVH comparison for three different proton plans. Solid: Static field with full energy layers. Dash-dot: PAT-CG with 2 energy layers. Dash: PAT with full energy layers.



Conclusion Proton arc therapy is a type of rotational radiotherapy, known for improved plan quality because of cross-firing radiation. With the novel energy layer optimization algorithm, we demonstrated the feasibility of proton arc plans with tractable solutions that can be delivered in a minimal number of energy layers to achieve efficient quality plans. The proposed method may pave the road to clinical implementation of PAT.