Theoretical evaluation of a Sawtooth PAT planning algorithm across multiple treatment sites

Sam Burford-Eyre

Conflicts of Interest

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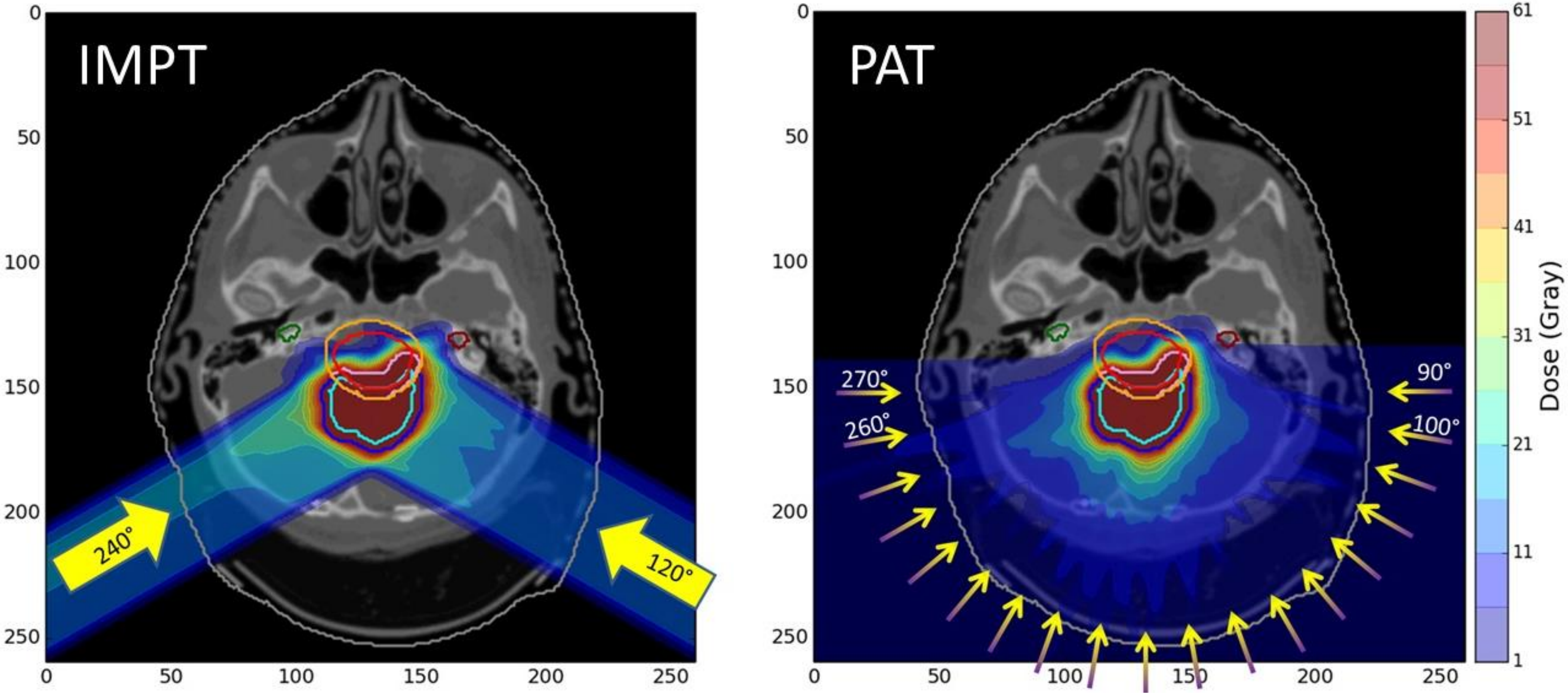
The Precise Group
The Cockcroft Institute of Accelerator Science and Technology

- No disclosures

Proton Arc Therapy (PAT) Introduction



Courtesy: Yunzhou Xia

Tami Freeman. "Proton arc therapy: the next evolution in proton delivery?." *Physics world (Oct 2019)*

Proton Arc Therapy (PAT) Introduction

Outstanding questions:

1. Energy selection algorithm
2. Robustness to setup uncertainties
3. Suitability for different treatment sites
4. Biological effectiveness
5. Delivery time requirements on current PBT systems
6. QA devices
7. Interlock / safety procedures

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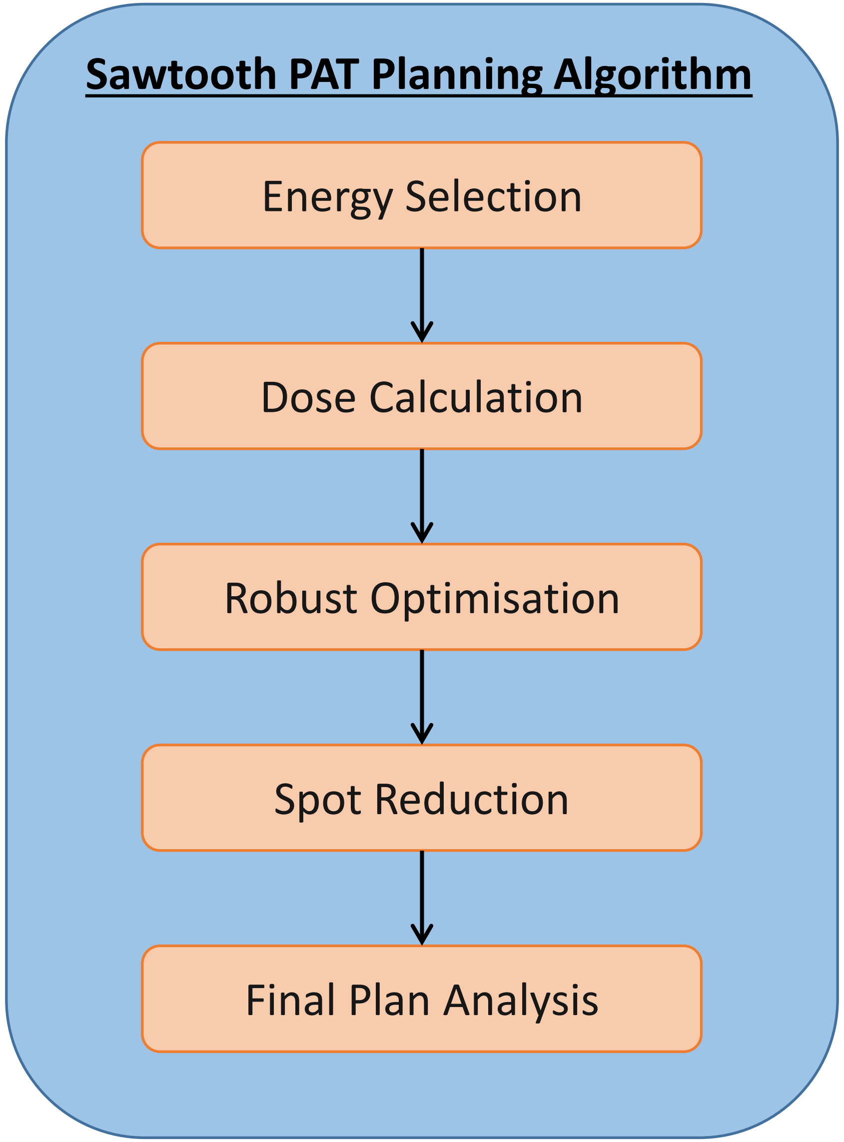
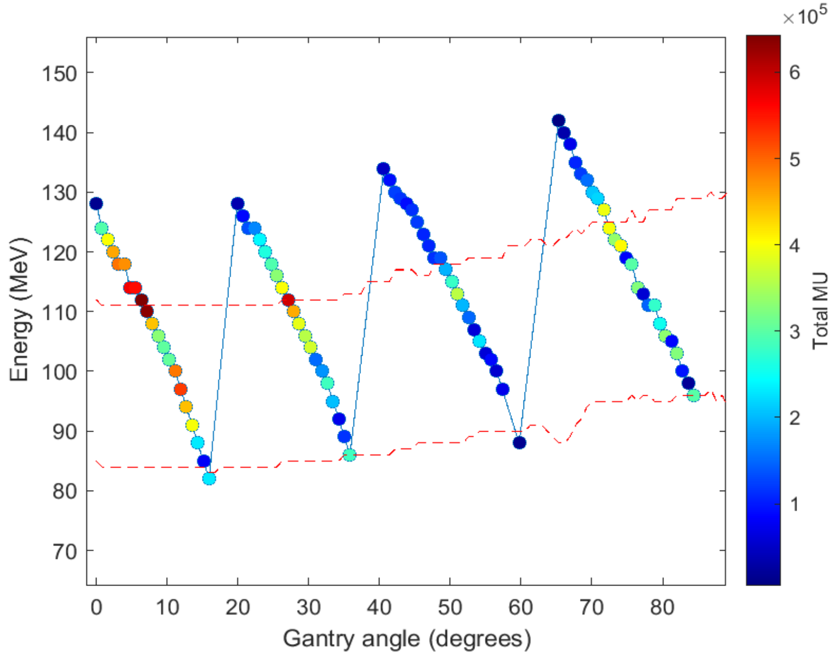


Methods

Sawtooth PAT planning algorithm developed in matRad [1]:

- Beam model from experimental measurements in Christie Proton Research Room
- Step – and – shoot PAT with 1 energy per control point
- Robust optimisation using clinical dose objectives
- Field specific targets
- Single, dual and partial arc delivery regimes
- Linear Energy Transfer (LET) analysis



[1] Wieser, Hans-Peter, et al. "Development of the open-source dose calculation and optimization toolkit matRad." *Medical physics* 44.6 (2017): 2556-2568.

Methods

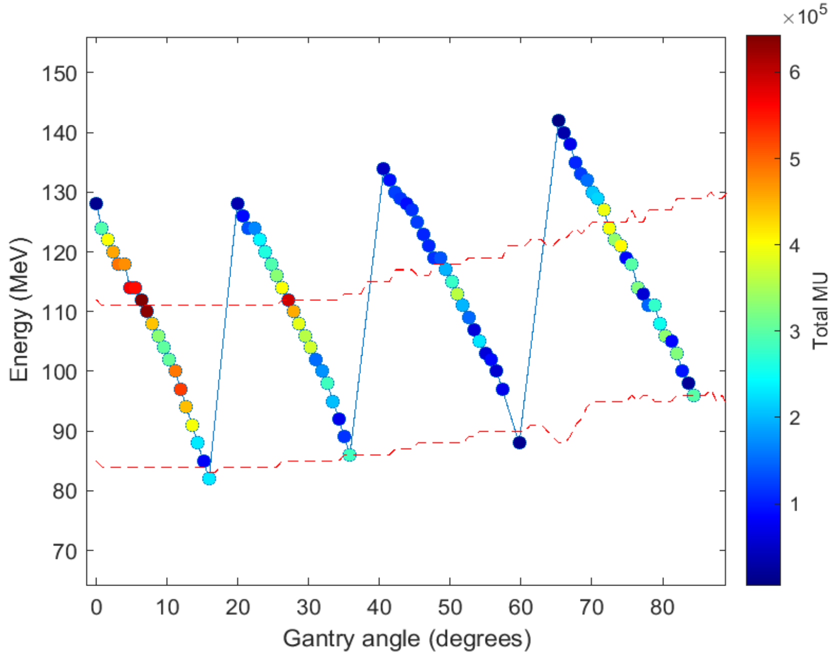
Applied Sawtooth PAT planning algorithm to multiple treatment sites under single and dual arc delivery regimes:

- Abdominal CT phantom [2]
- 2 Brain (Ependymoma)
- 2 H&N (Oropharyngeal)
- 2 BoS (Chondrosarcoma)

IMPT plan generated for each case

Fields / 'teeth' in PAT plan incrementally increased until either clinical standard achieved or no further improvement to plan quality

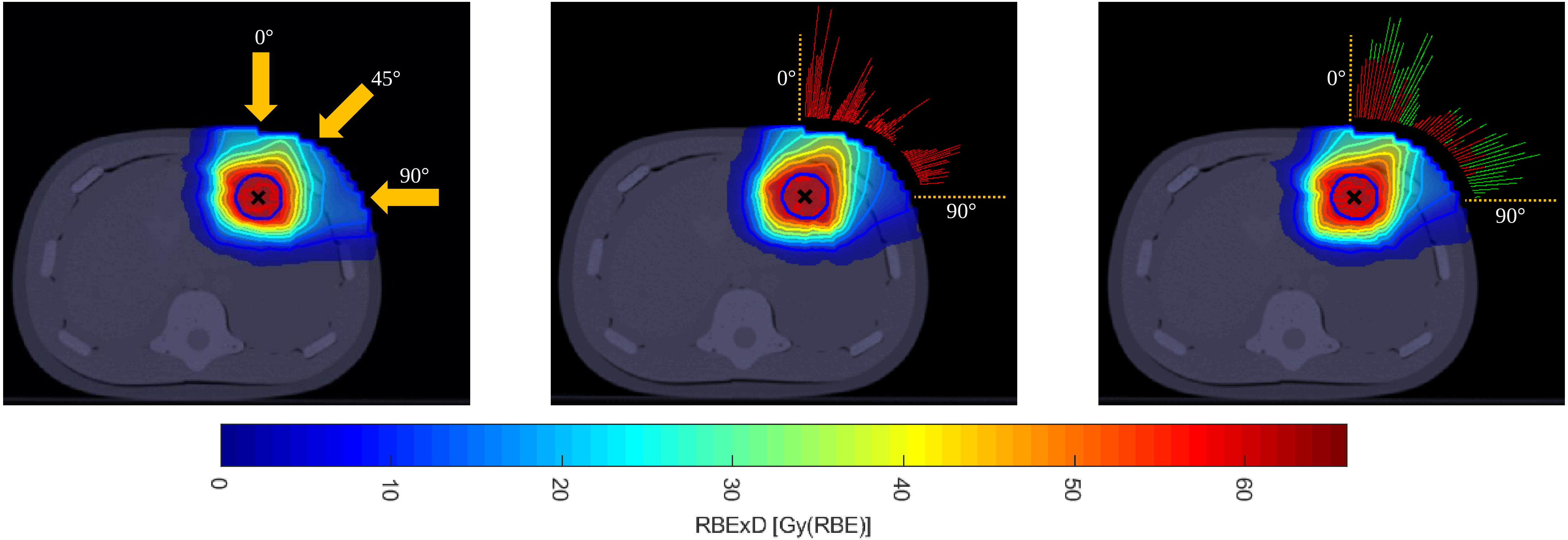
Dose and LET distribution comparison (IMPT vs PAT)



[2] Kalendralis, Petros, et al. "Multicenter CT phantoms public dataset for radiomics reproducibility tests." *Medical physics* 46.3 (2019): 1512-1518.

Results: Abdominal Phantom Dose

Conventional IMPT | **Single arc PAT** | **Dual arc PAT**



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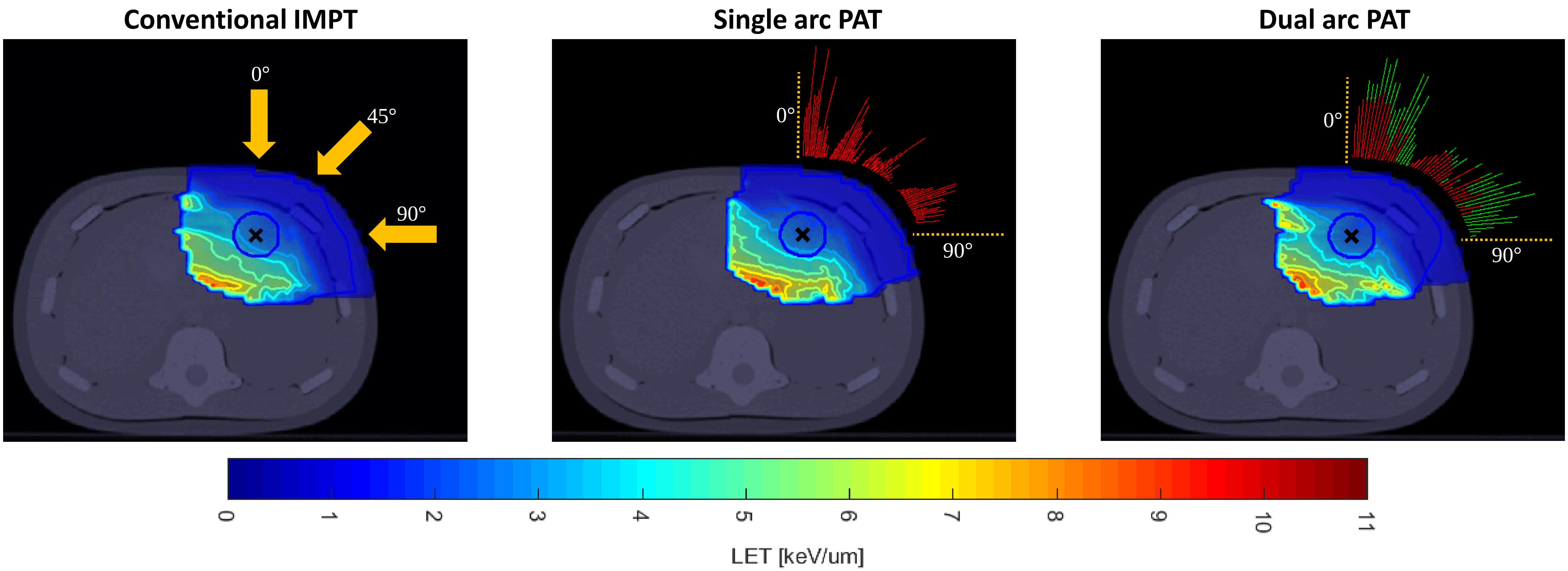
Results: Abdominal Phantom LET



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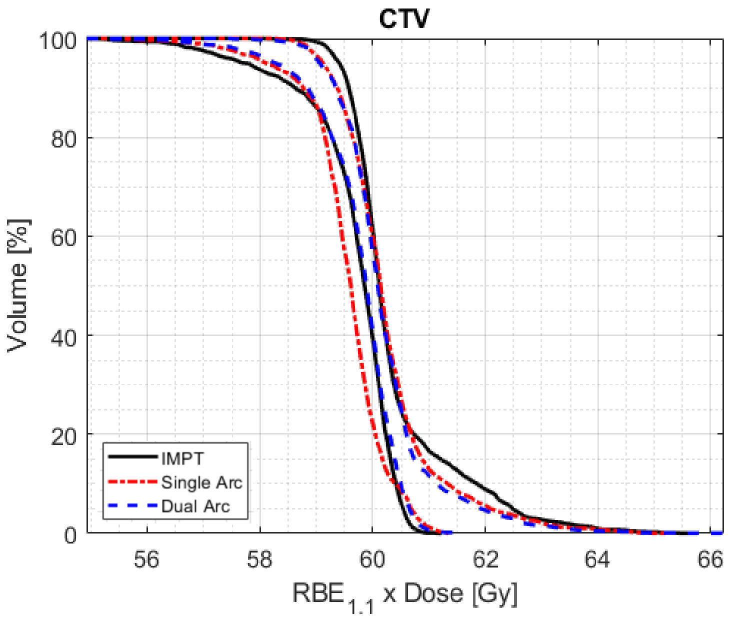
Results: Abdominal Phantom



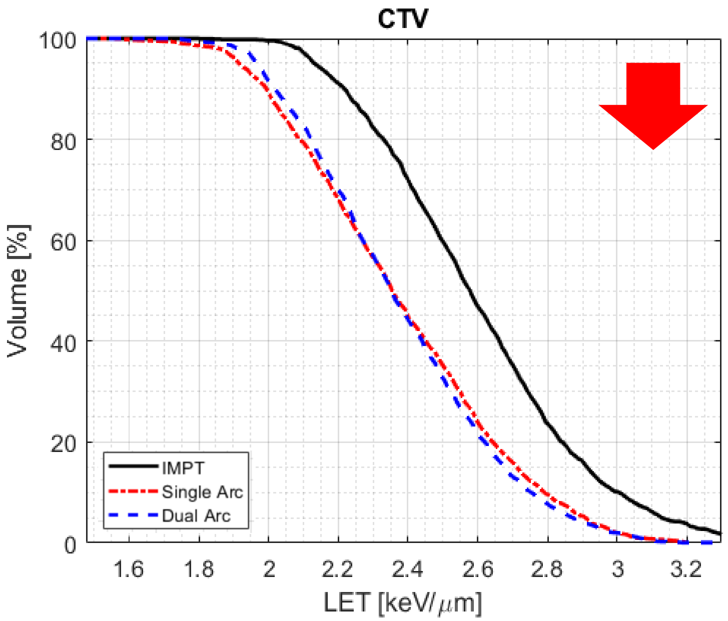
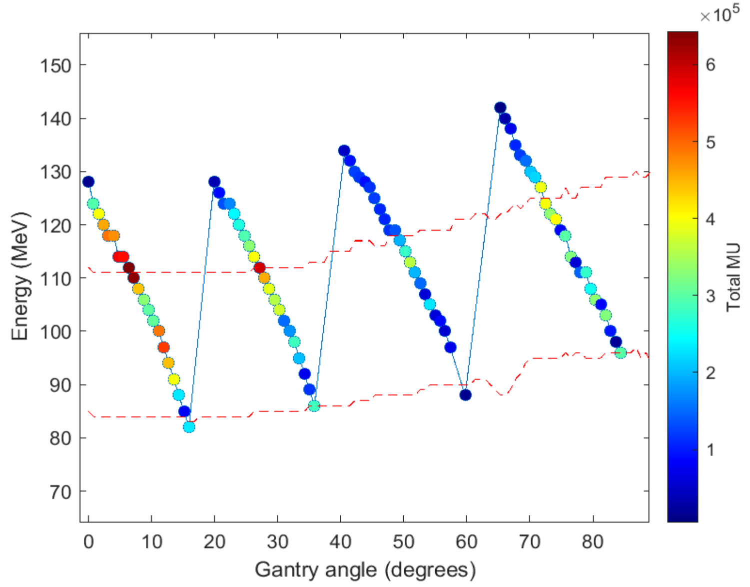


Table 2. Dose metrics under each delivery technique for the abdominal phantom. Bracketed number shows the number of fields/teeth within each final plan. Abbreviations: ID = Integral dose.

ROI	Metric	IMPT (3)	Single Arc (4)	Dual Arc (4)
CTV	$V_{95\%}$ / $\%V_{CTV}$	97.57	98.89 ↑	98.82 ↑
	$V_{105\%}$ / $\%V_{CTV}$	2.71	2.15 ↓	1.53 ↓
	ΔD / Gy	3.06	3.01 ↓	2.83 ↓
Patient	ID / J	0.461	0.451 –	0.436 ↓



- ➢ 4 teeth required to meet clinical objectives
- ➢ PAT improved target dose homogeneity relative to IMPT
- ➢ PAT reduces target LET and integral dose to patient

[2] Kalendralis, Petros, et al. "Multicenter CT phantoms public dataset for radiomics reproducibility tests." *Medical physics* 46.3 (2019): 1512-1518.

Results: Brain 1

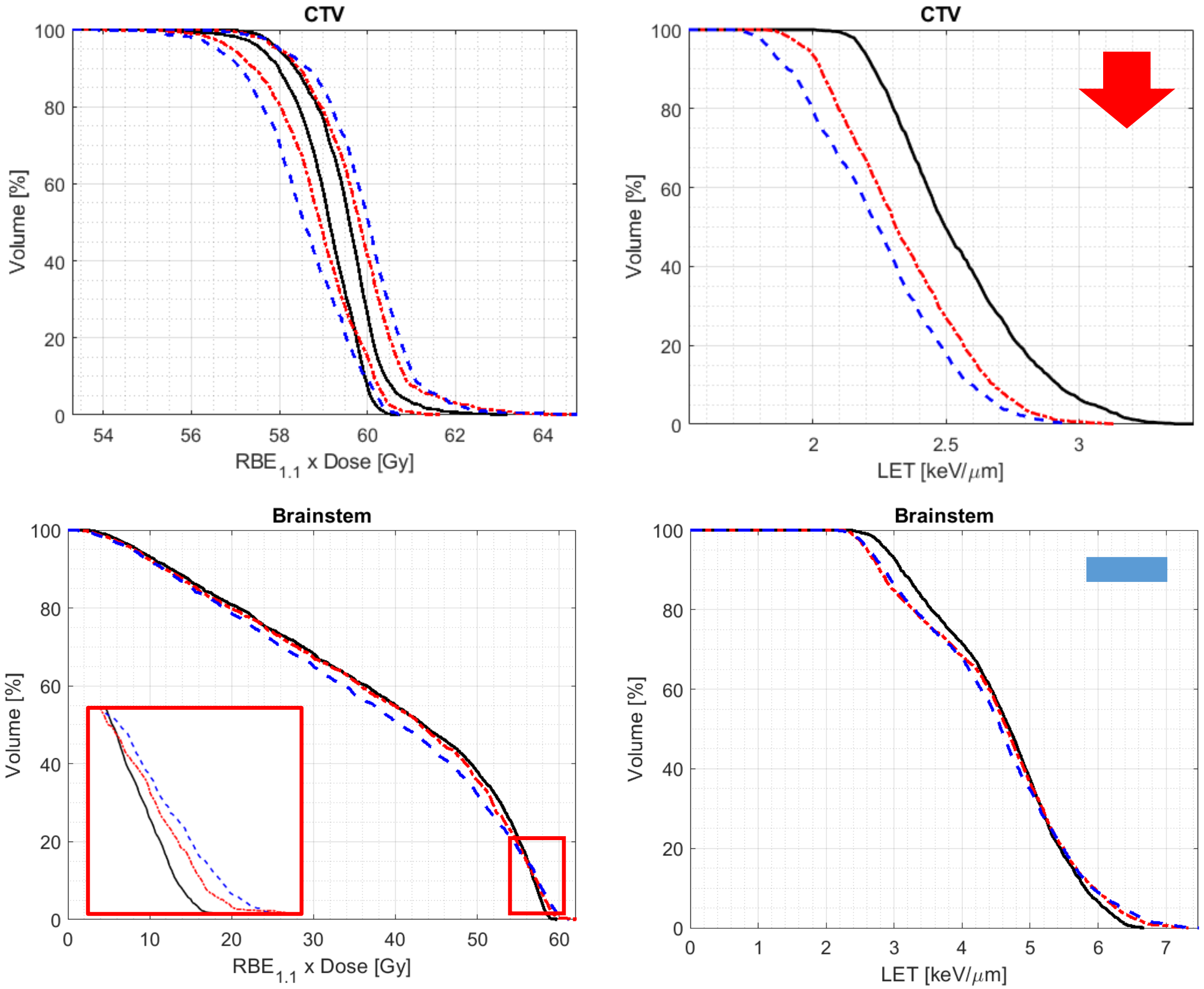


Table 3. Relevant worst-case clinical dose tolerances and custom metrics under each delivery technique for the ependymoma E1 case. Violated tolerances are shown in bold. Bracketed number shows the number of fields/teeth within each final plan. Abbreviations: ID = Integral dose.

ROI	Clinical goal	IMPT (3)	Single Arc (6)	Dual Arc (6)
CTV	$V_{95\%} > 98\%\ V_{CTV}$	99.22	**97.84** ↓	**96.03** ↓
	$V_{110\%} < 10\%\ V_{CTV}$	0.00	0.09 ▬	0.09 ▬
	ΔD / Gy	2.96	4.50 ↑	4.71 ↑
Brainstem	$D_{1\%} < 59.4$Gy	58.67	**59.58** ↑	**60.15** ↑
	$D_{10\%} < 58$Gy	56.98	57.28 ▬	57.43 ▬
	$D_{50\%} < 56$Gy	43.30	43.06 ▬	40.64 ↓
Spinalcord	$D_{2\%} \leq 54$Gy	45.06	42.54 ↓	44.86 ▬
Cochlea	$D_{mean} < 30$Gy	16.70	16.37 ▬	16.03 ▬
		4.79	4.13 ▬	4.30 ▬
Patient	ID / J	0.182	0.178 ▬	0.178 ▬

- 6 teeth required to meet clinical objectives
- Target dose homogeneity and LET reduced by PAT
- PAT fails clinical high dose Brainstem tolerances

Results: BoS 1 Dose

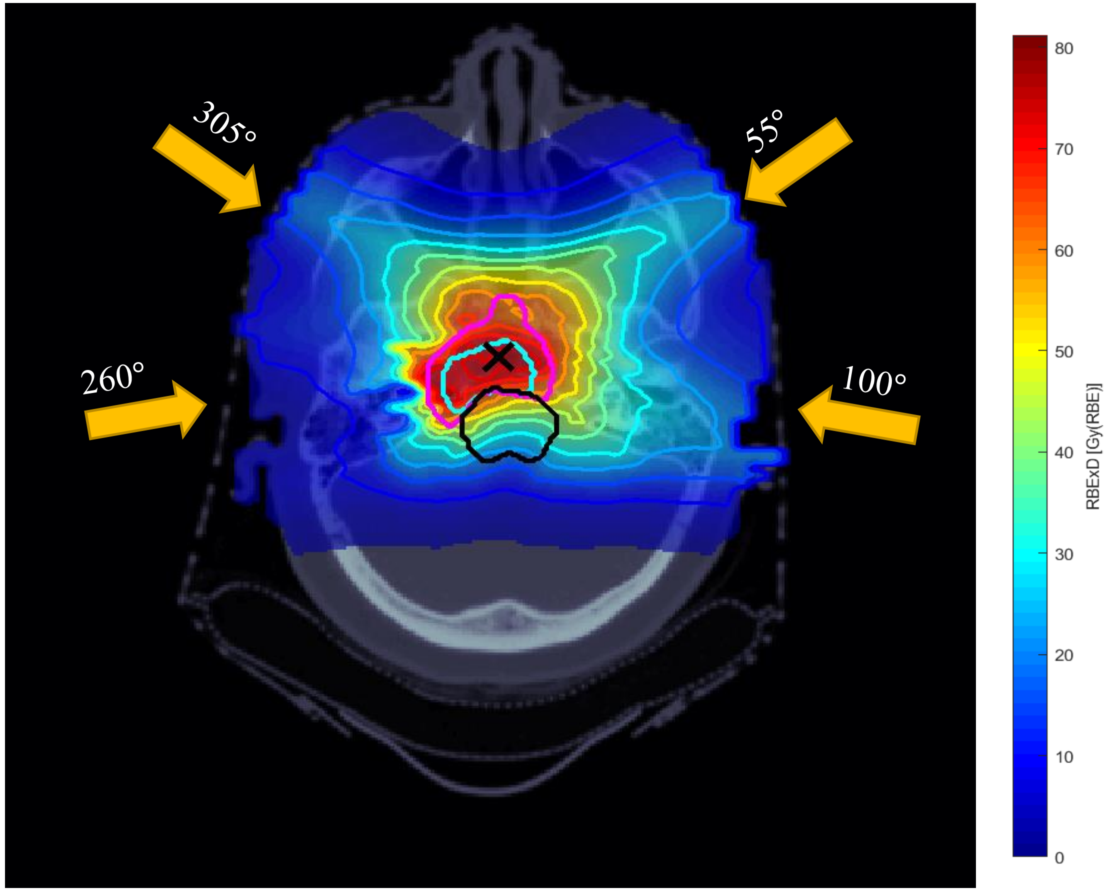


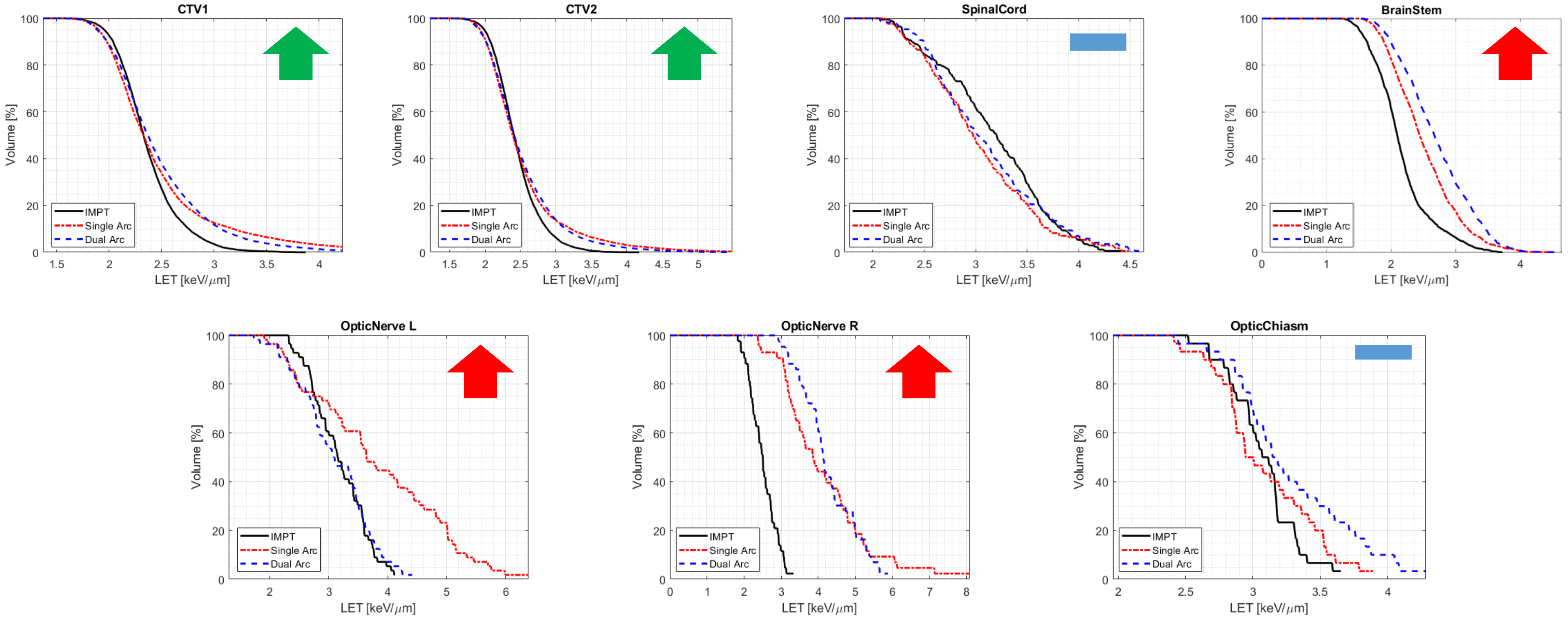
Table 4. Relevant worst-case clinical dose tolerances and custom metrics under each delivery technique for the chondrosarcoma B1 case. Violated tolerances are shown in bold. Bracketed number shows the number of fields/teeth within each final plan. Abbreviations: ON = Optic Nerve, OC = Optic Chiasm, D_{pres} = prescribed dose, ID = Integral dose, L = Left, R = Right.

ROI	Clinical goal	IMPT (4)	Single Arc (7)	Dual Arc (10)
CTV1	$D_{98\%} > 90\%\ D_{pres}$	**79.41**	**79.11** –	**79.74** –
	$D_{95\%} > 95\%\ D_{pres}$	**84.46**	**83.67** –	**83.88** –
	$D_{2\%} < 110\%\ D_{pres}$	109.48	**111.40** ↑	**110.99** ↑
	ΔD / Gy	15.24	17.50 ↑	16.49 ↑
CTV2	$D_{98\%} > 90\%\ D_{pres}$	**86.66**	92.09 ↑	91.90 ↑
	$D_{95\%} > 95\%\ D_{pres}$	**95.66**	97.44 ↑	97.94 ↑
	ΔD / Gy	19.28	20.05 ↑	17.99 ↓
OC[a]	$D_{2\%} < 60Gy$	58.25	59.11 ↑	58.49 –
	$D_{mean} < 54Gy$	48.94	51.11 ↑	50.63 ↑
ON L[a]	$D_{2\%} < 60Gy$	59.56	56.11 ↓	56.61 ↓
	$D_{mean} < 54Gy$	32.93	28.33 ↓	27.01 ↓
ON R[a]	$D_{2\%} < 60Gy$	56.17	55.29 ↓	54.81 ↓
	$D_{mean} < 54Gy$	31.36	27.15 ↓	26.02 ↓
Brainstem	$D_{2\%} < 63Gy$	60.77	61.57 ↑	61.00 –
Spinalcord	$D_{max} < 67Gy$	40.43	40.49 –	37.04 ↓
Cochlea L[b]	$D_{mean} < 45Gy$	35.31	31.82 ↓	32.22 ↓
Cochlea R[b]	$D_{mean} < 45Gy$	28.42	23.66 ↓	25.40 ↓
Patient	ID / J	1.83	1.67 ↓	1.48 ↓

[a] If unilateral blindness accepted, failure of one ON permitted if dose to other ON and OC significantly lower than threshold.
[b] Failure of one Cochlea permitted.

- 7 and 10 teeth required for single and dual arc PAT
- PAT provides increases OAR sparing at expense of further target dose reduction

Results: BoS 1 LET



➢ PAT slightly increases LET to most OARs and targets

Results: H&N 1 Dose

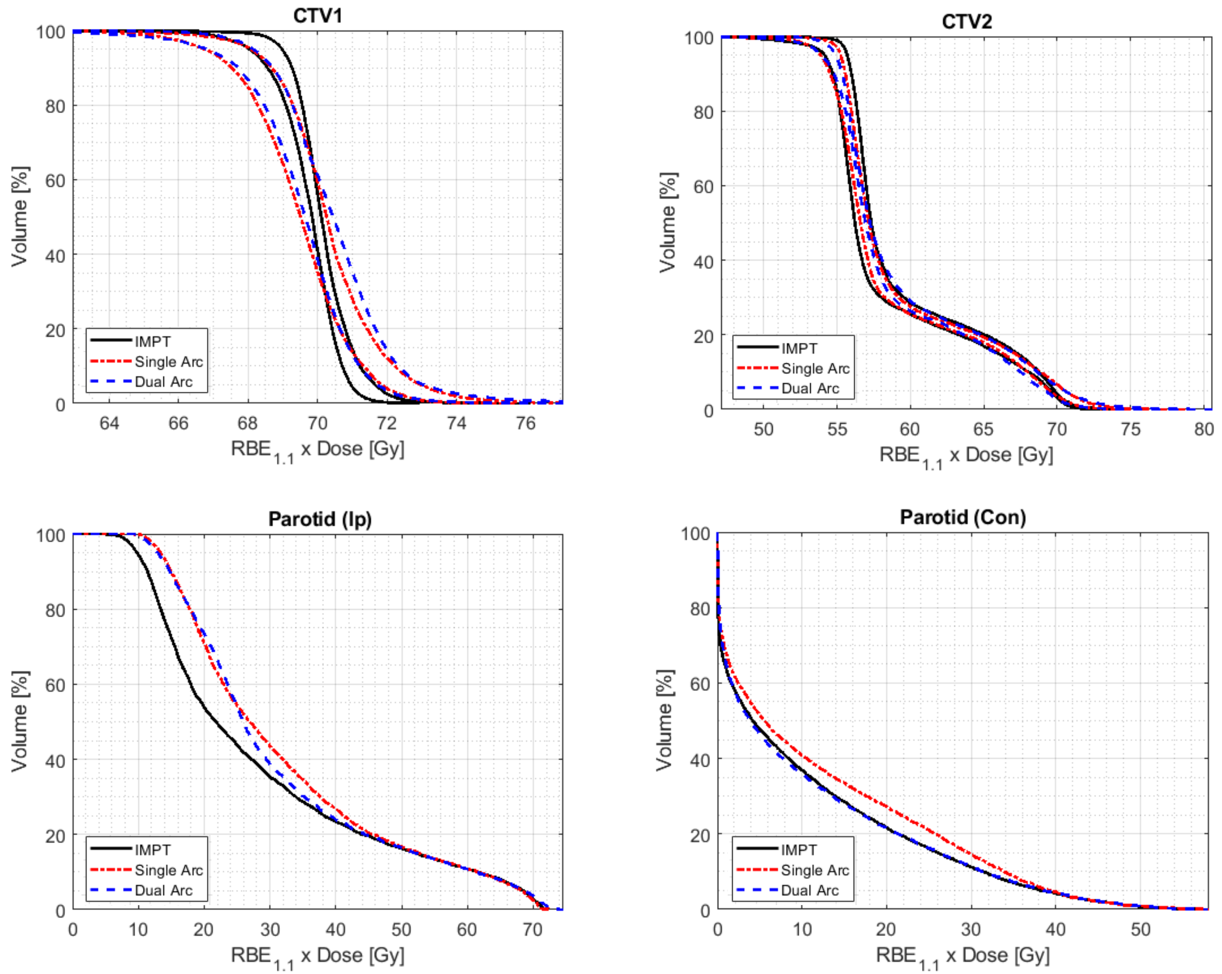
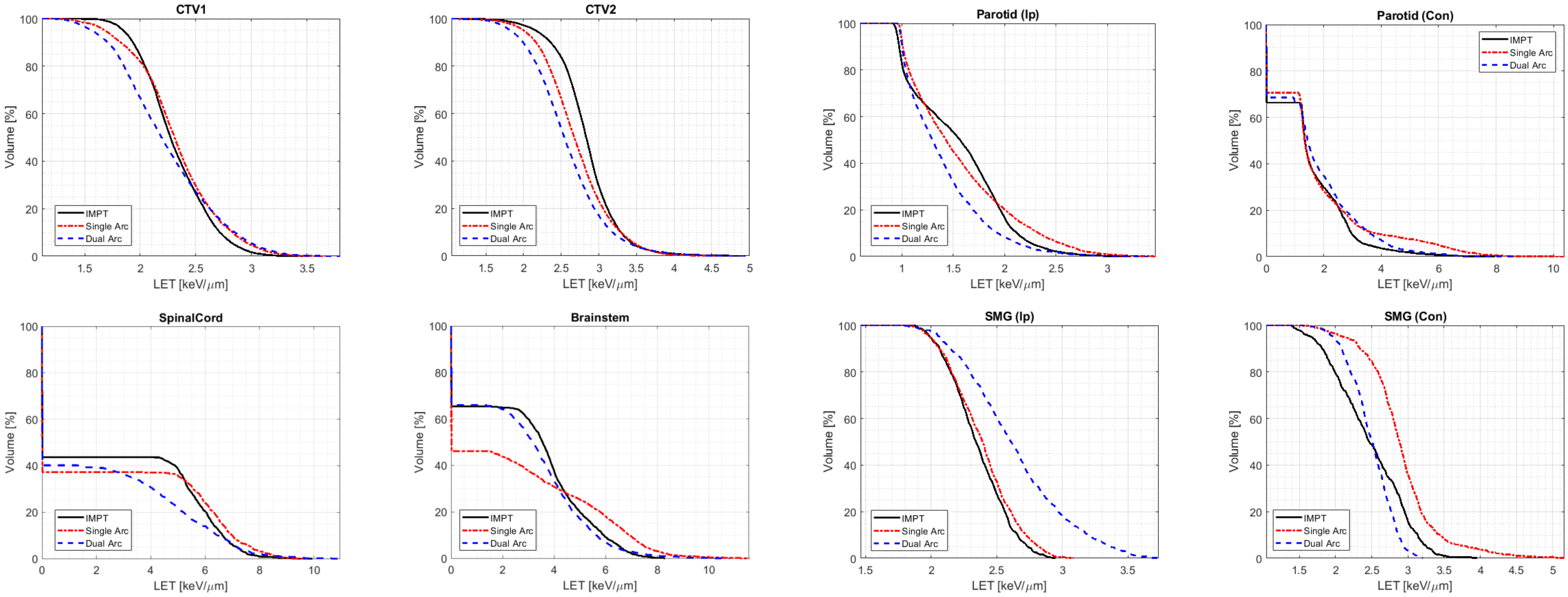


Table 5. Relevant worst-case clinical dose tolerances and custom metrics under each delivery technique for the oropharyngeal O1 case. Bracketed number shows the number of fields/teeth within each final plan. Abbreviations: SMG = Submandibular Gland, Ip = Ipsilateral, Con = Contralateral, ID = Integral dose, ALAP = As low as possible, D_{pres} = prescribed dose.

ROI	Clinical goal	IMPT (5)	Single Arc (8)	Dual Arc (6)
CTV1	$D_{99\%} > 90\%\ D_{pres}$	95.40	92.64 ↓	91.55 ↓
	$D_{95\%} > 95\%\ D_{pres}$	97.18	95.36 ↓	95.42 ↓
	$D_{5\%} \leq 105\%\ D_{pres}$	102.31	104.21 ↑	104.40 ↑
	$D_{2\%} \leq 107\%\ D_{pres}$	103.09	105.63 ↑	106.40 ↑
	ΔD / Gy	3.50	5.79 ↑	5.54 ↑
CTV2	$D_{99\%} > 90\%\ D_{pres}$	92.64	91.04 ↓	91.68 ↓
	$D_{95\%} > 95\%\ D_{pres}$	96.18	95.88 –	96.36 –
	$D_{5\%}$ ALAP / Gy	69.82	70.55 ↑	70.48 ↑
	$D_{2\%}$ ALAP / Gy	70.76	71.96 ↑	72.38 ↑
Brainstem	$D_{1cc} < 54Gy$	6.97	2.73 ↓	7.57 ↑
	$D_{0.1cc} < 55Gy$	23.56	25.72 ↑	30.81 ↑
Spinalcord	$D_{1cc} < 48Gy$	3.75	2.00 ↓	2.36 ↓
	$D_{0.1cc} < 46Gy$	29.30	28.37 ↓	30.81 ↓
Parotid (Ip)	D_{mean} / Gy ALAP	28.61	32.09 ↑	31.53 ↑
Parotid (Con)	$D_{mean} < 20Gy$	10.42	11.94 ↑	10.36 –
SMG (Ip)	D_{mean} / Gy ALAP	68.16	69.03 ↑	68.64 –
SMG (Con)	$D_{mean} < 20Gy$	32.05	30.12 ↓	32.67 –
Patient	ID / J	23.13	22.84 –	23.34 –

- 8 and 6 teeth required for single and dual arc PAT
- PAT decreases target dose homogeneity and OAR sparing but remains of clinical standard

Results: H&N 1 LET

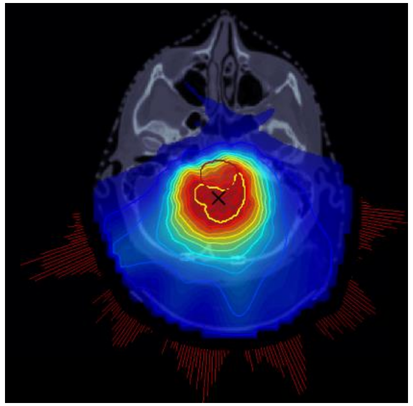


- ➢ LET differences between PAT and IMPT are OAR dependent

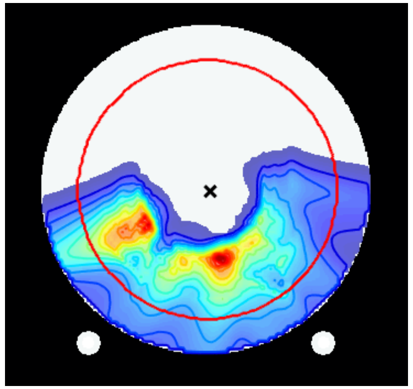
Future Work

Simulate and deliver PAT plan in Christie PBT Research Room

Patient



ArcCheck



Summary

- Developed a 'Sawtooth'- based PAT treatment planning algorithm → capable of robust optimisation
- Applied to treatment sites: Abdominal phantom, Brain (x2), H&N (x2) and BoS (x2)
- All PAT plans met clinical dose objectives in the nominal scenario
- Robustness of PAT relative to IMPT highly dependent on treatment site, favouring simple symmetrical targets
- PAT consistently requires more teeth (fields) than IMPT
- Future work: Simulate and deliver PAT plan in Christie PBT Research Room.

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Sam Ingram
John William – Warmenhoven
Nick Henthorn
Yunzhou Xia

Other PRECISE members:
Josephine Jones
Charlie Heaven
Hannah Wanstall
Abigail Hemming
Jack Aylward
Joseph Hallett
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Chris Smith
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Thank You

Contact: samuel.burford-eyre@manchester.ac.uk

Methods: Planning Parameters

Table 1. Details of the anatomical location, target volume, prescribed dose in a given number of fractions (#), irradiation angles and range shifter thickness used for each dataset. Partial arcs used for PAT delivery to both BoS datasets. Bracketed tag used as dataset reference. Abbreviations: RS = Range Shifter, D_{pres} = prescribed dose.

Treatment site	Target Volume (cm^3)	Prescribed Dose (Gy)	#	IMPT (°)	PAT (°)	RS (cm)
Abdominal[a] (A1)	22.52	60.00	30	0,45,90	0 → 90	3
Brain (E1)	18.15	59.40	33	120,180,240	90 → 270	None
Brain (E2)	67.30	59.40	33	15,90,330	330 → 90	5
BoS (B1)	9.23 (CTV1) 32.03 (CTV2)	73.80 (CTV1) 59.45 (CTV2)	41	55,100,260,305	225 → 315 45 → 135	None
BoS (B2)	99.49 (CTV1) 144.99 (CTV2)	73.80 (CTV1) 59.45 (CTV2)	41	80,130,230,275	225 → 315 45 → 135	2
H&N (O1)	121.34 (CTV1) 191.27 (CTV2)	70.00 (CTV1) 56.00 (CTV2)	33	0,60,90,270,315	270 → 90	5
H&N (O2)	98.73 (CTV1) 177.49 (CTV2)	70.00 (CTV1) 56.00 (CTV2)	33	0,45,125,270,325	270 → 90	3

[a] CT phantom.

PAT Energy Layer distribution: Abdominal Phantom

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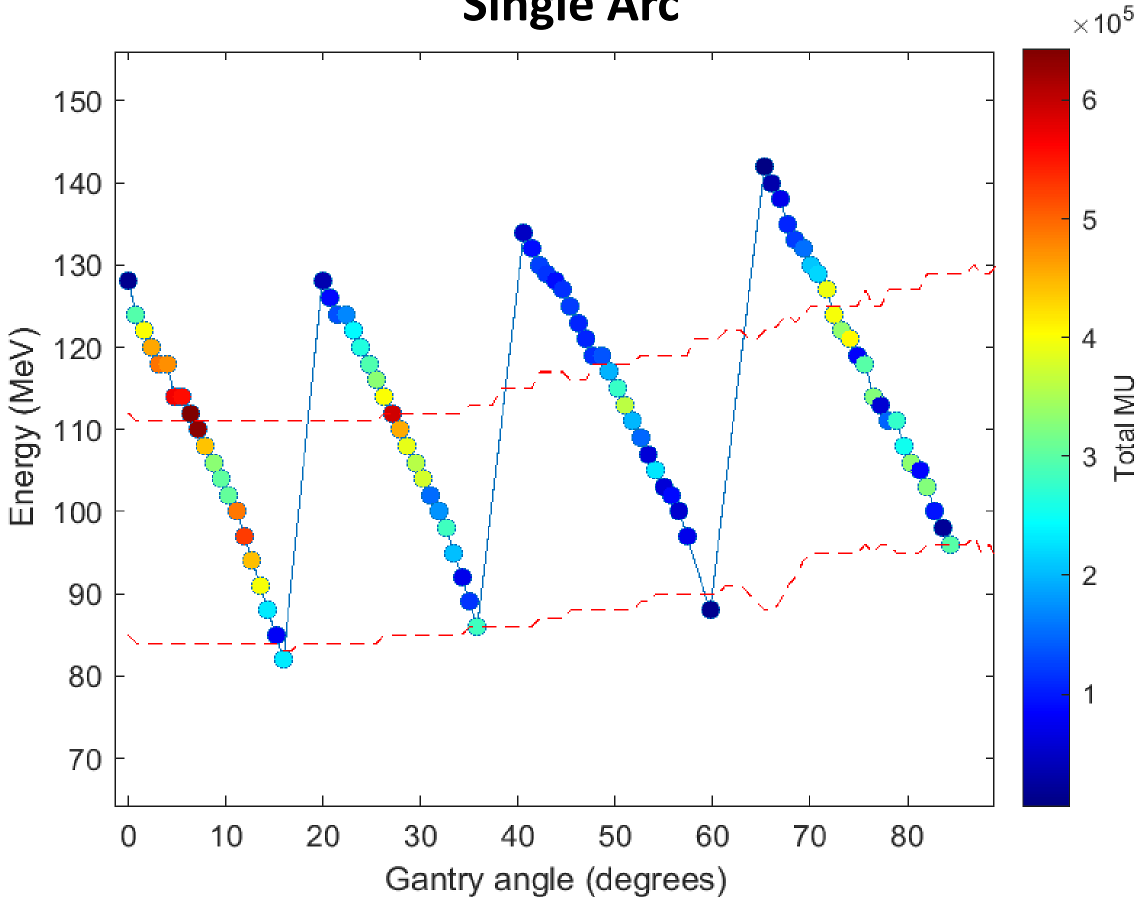
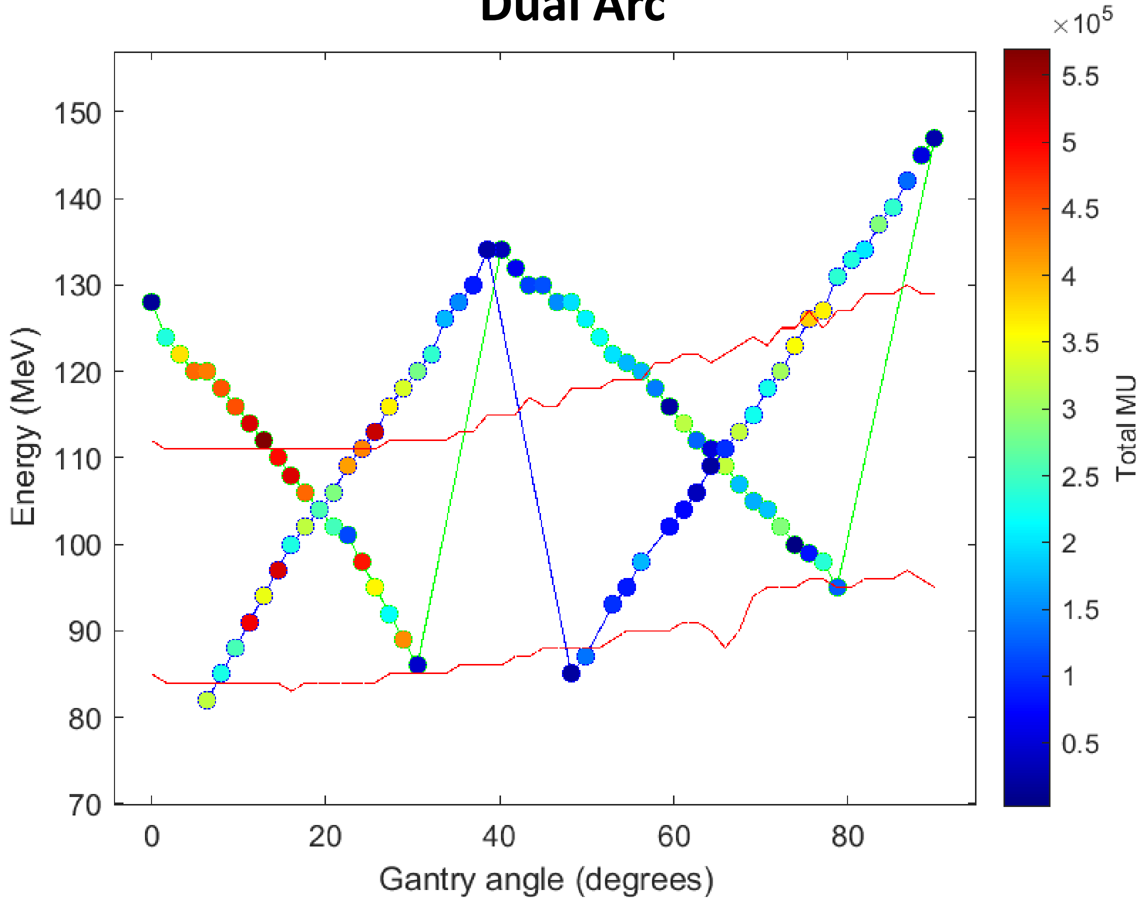
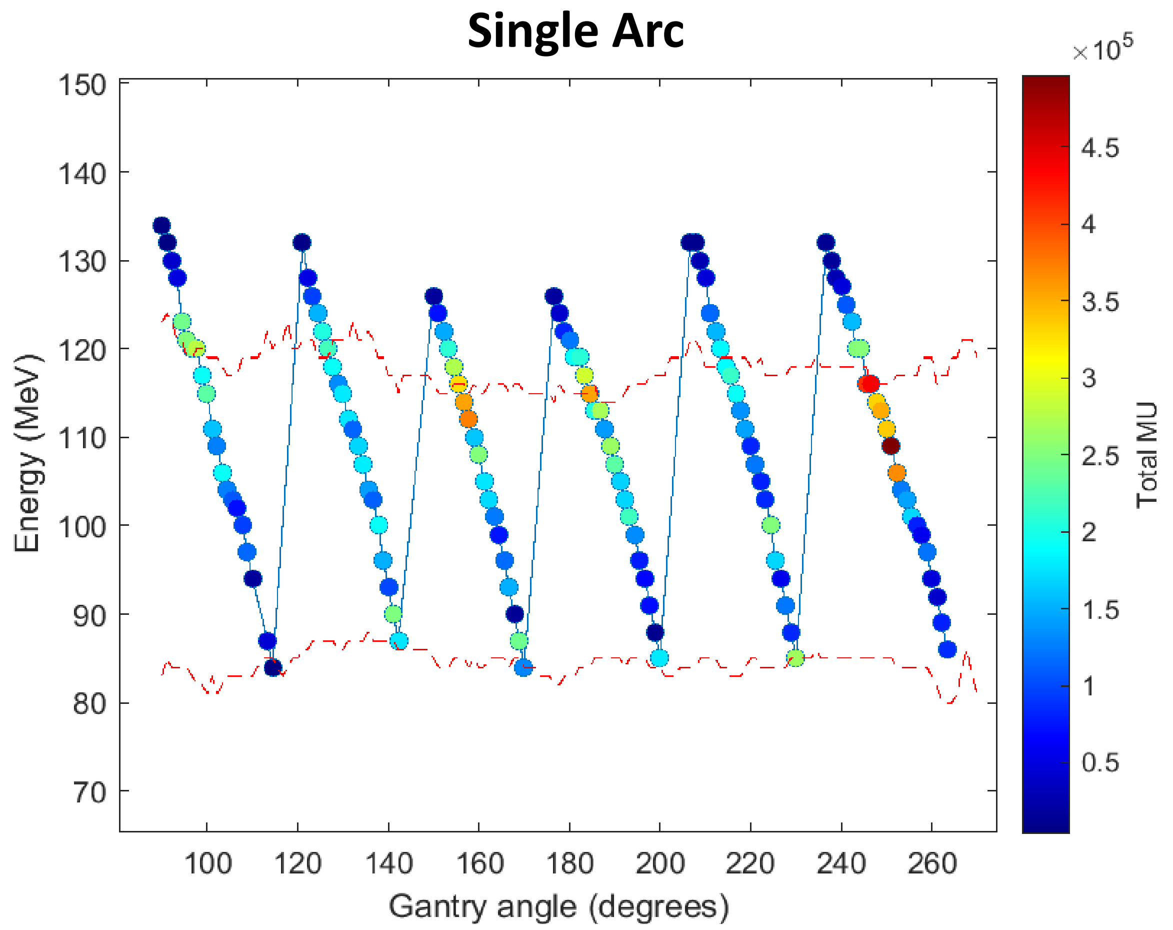
Single Arc

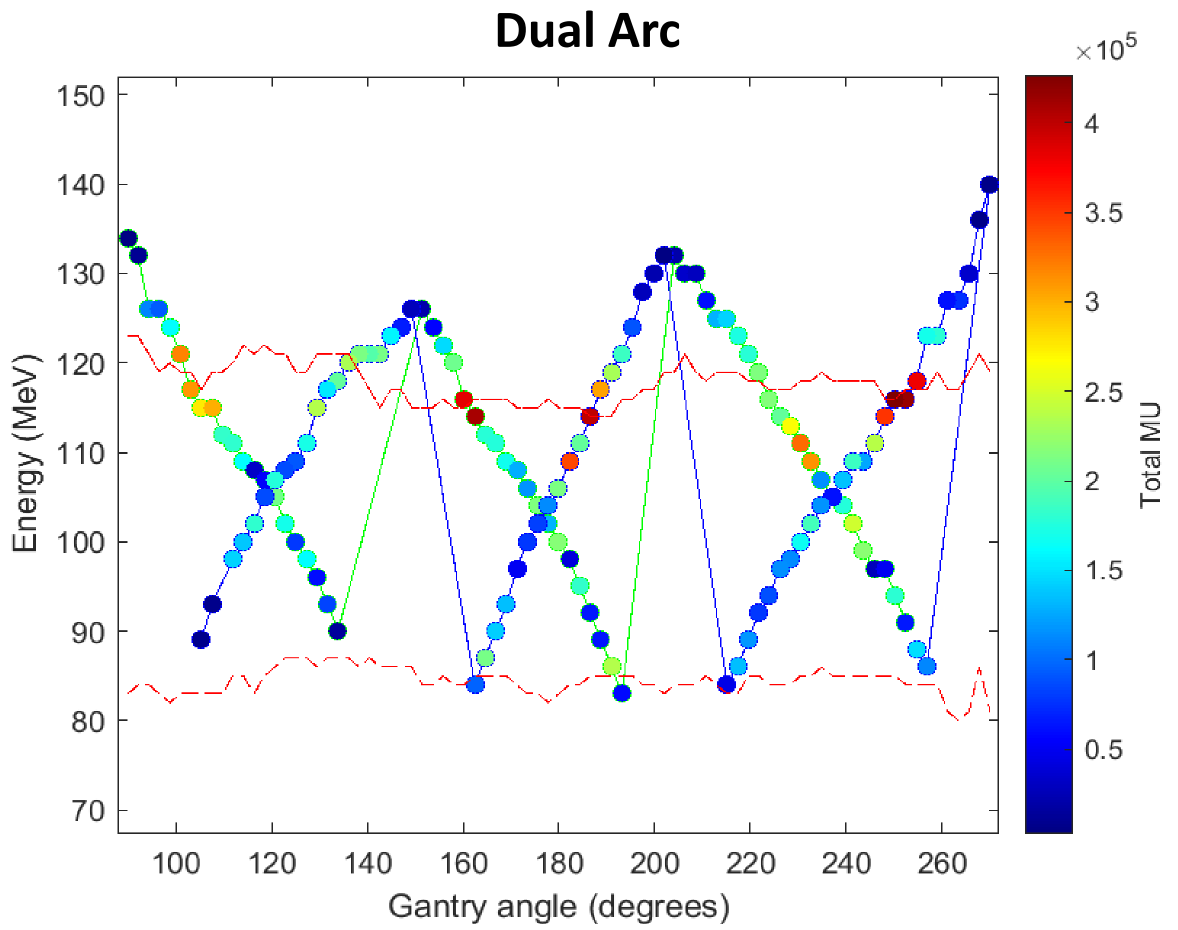


Dual Arc



PAT Energy Layer distribution: Brain 1





PAT Energy Layer distribution: H&N 1

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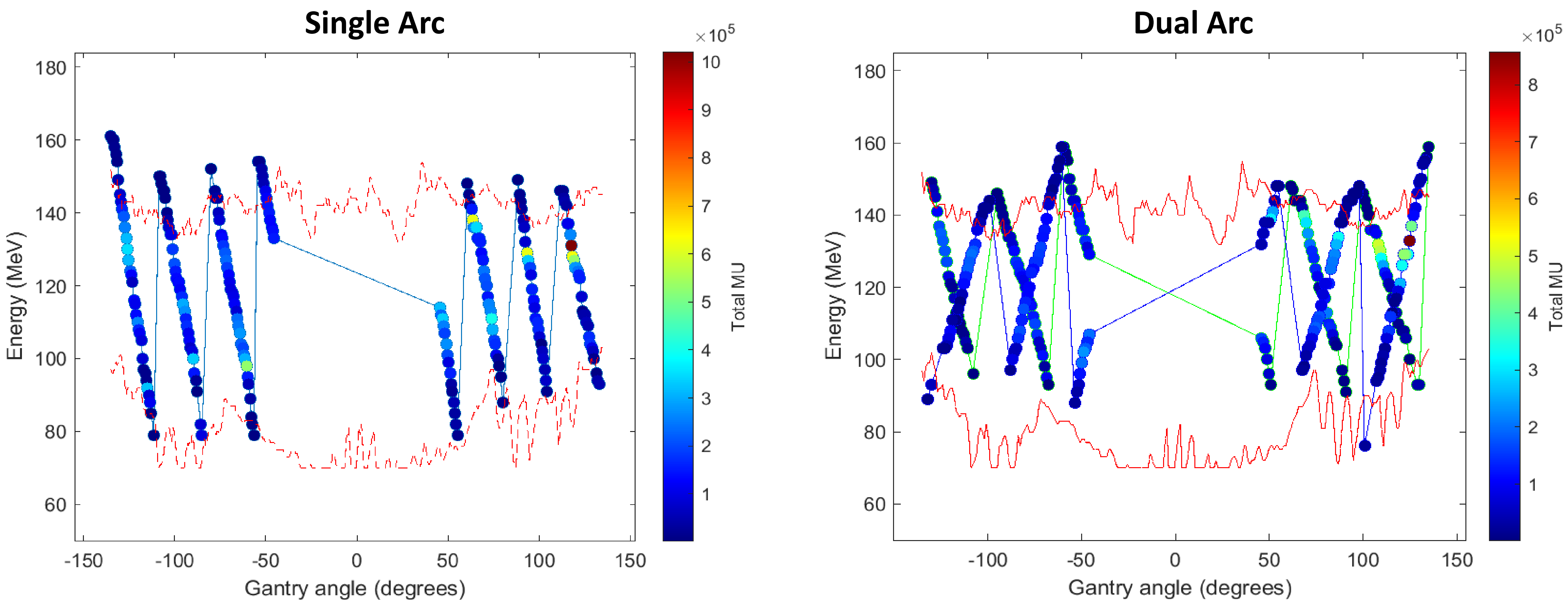
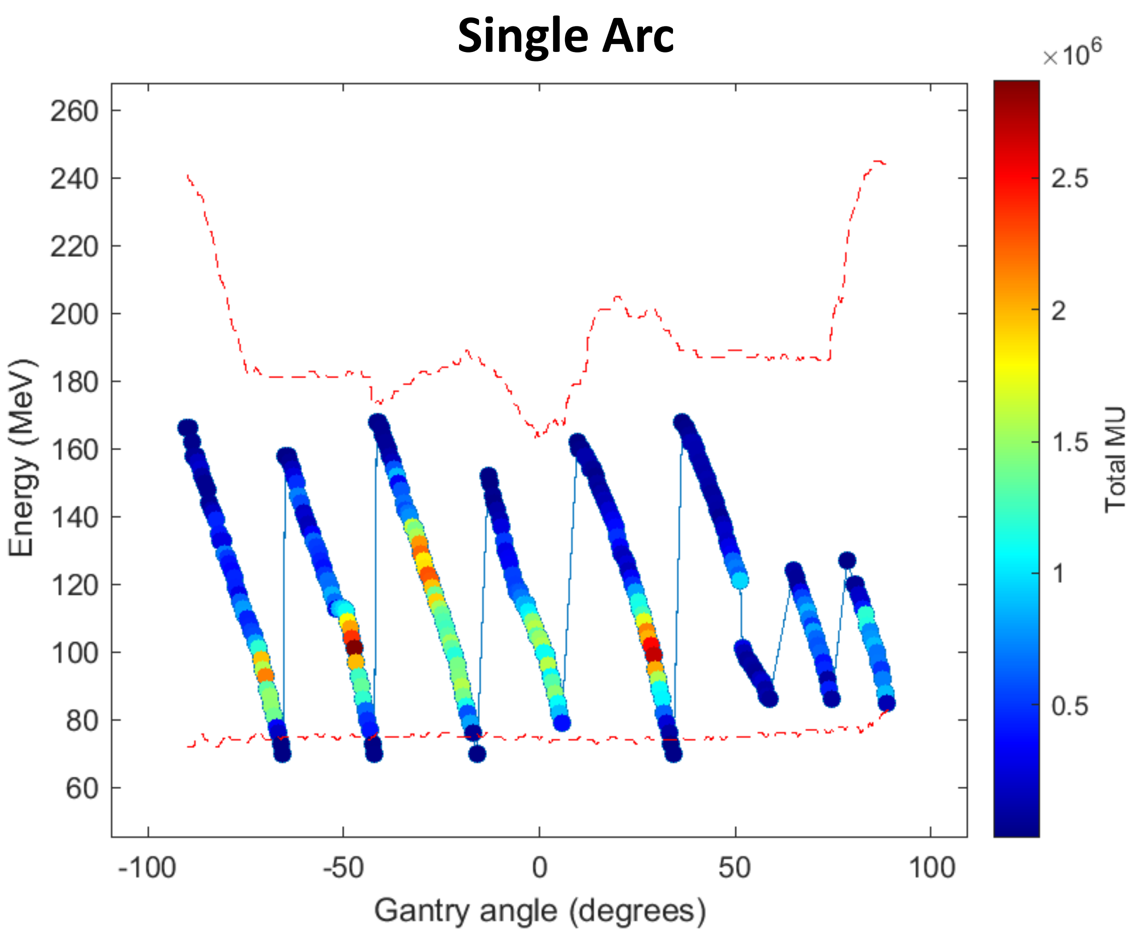
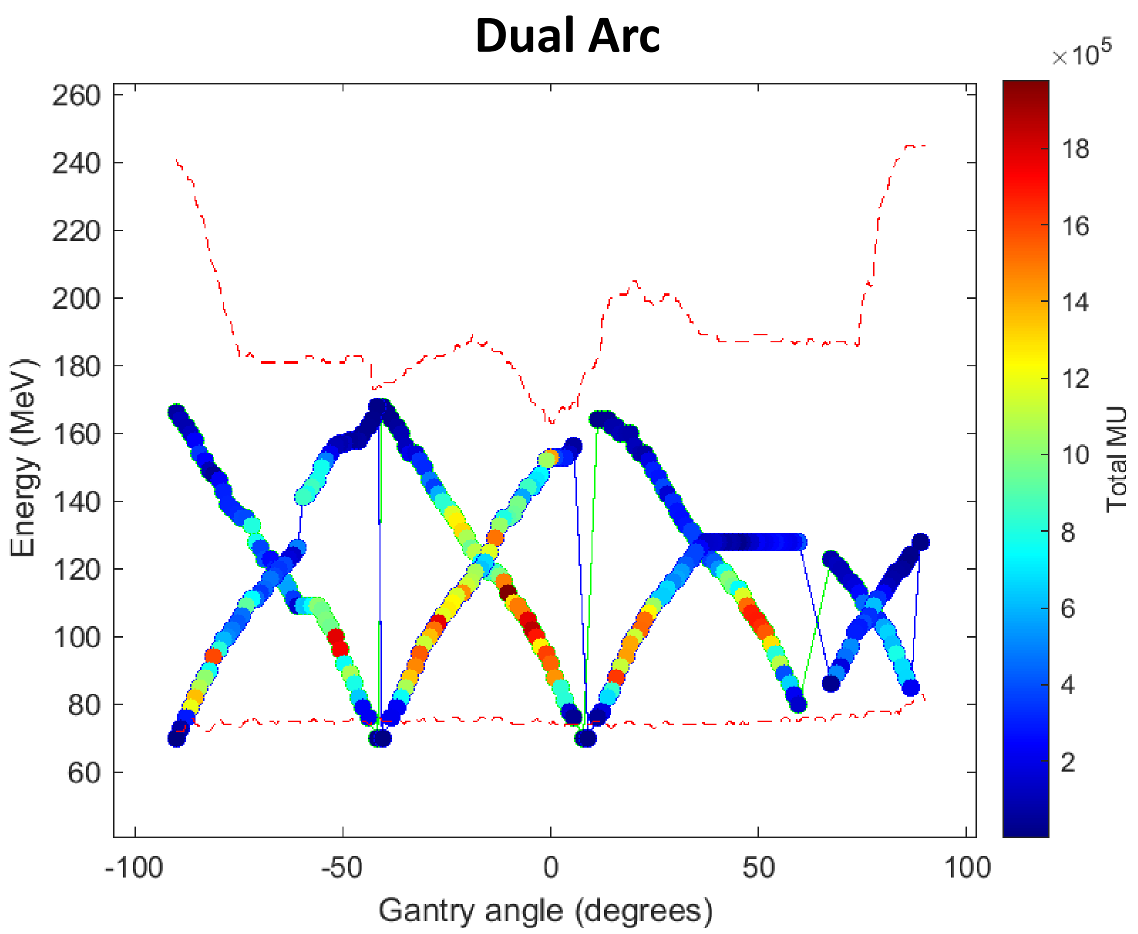


PAT Energy Layer distribution: BoS 1





Limitations

- Algorithm constrains upward energy switches as Christie upward ELST = 30s
- Including a ‘coverage’ based metric during EL selection may improve PAT plan quality
- Method of spot removal may cause low dose streaks within entrance region
- PAT plans optimised under same (highly specific) objectives as IMPT