# Mid-Range Arc Therapy for Efficient and RBE-Robust Proton Treatment

Stanford MEDICINE Radiation Oncology

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## INTRODUCTION

Proton arc therapy (PAT) has the potential to mitigate range uncertainties, improve target coverage, and minimize dose to normal tissues by optimizing treatment plans with a large number of beam angles. We demonstrate the performance and feasibility of a monoenergetic-per-beam-angle PAT planning strategy that enables potential continuous dynamic arc delivery while ensuring safe delivery of both $LET_d$ and RBE within the central portion of the target tumor.

### Challenges

- Delivery inefficiency due to the large number of energy layer.
- Proton beam range uncertainties associated with relative biological effectiveness.

### Aims

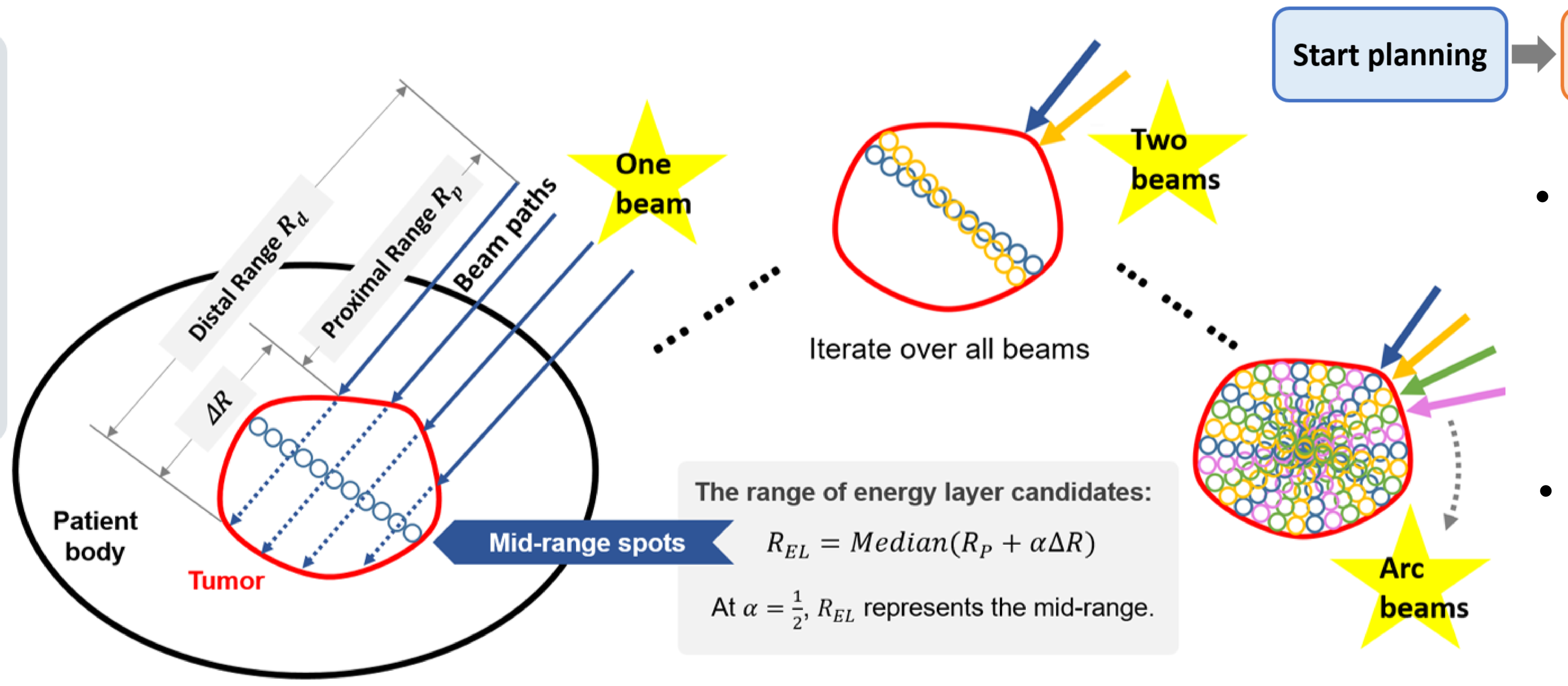
- Design a PAT planning approach, mid-range proton arc (MRPAT), that synchronizes energy layer switching with gantry rotation.
- Demonstrate that MRPAT achieves dosimetric plan quality comparable to a multi-energetic plan.
- Demonstrate MRPAT's benefit by boosting the relative biological effect inside the target volume.

## METHODS: Mid-Range Proton Arc Planning

Start planning → Mid-range energy layer selection → Spot intensity optimization → MRPAT treatment plan created

**Step1: Defining the potential energy deposition region.**

The potential energy deposition region along each beam path is confined between the corresponding $R_p$ to $R_d$, spanning a range of $\Delta R = R_d - R_p$.




**Step 2: Determining the range of MREL.**

The potential range of EL is given by $R_p + \alpha\Delta R$, where $\alpha \in (0, 1]$. The mid-range for a given beam direction is defined as $R_{MREL} = median\left(R_p + \frac{1}{2}\Delta R\right)$.

**Step 3: Generating the MREL sequence for arc beams.**

Repeat Steps 1 and 2 for each beam direction, generating a MERL sequence for arc beams.

- MRPAT is designed to use a single energy layer per beam direction, positioning the Bragg peak near the central region of the target throughout the entire arc delivery.
- The spot intensity optimization and dose calculation were performed using our in-house planning toolkits [1-2], which enables very large scale optimization without the need for pre-calculated beamlets.
- We used the McNamara RBE model [3] to compute the RBE-weighted dose, with $(\alpha/\beta)_x = 3$ Gyfor normal tissues and $10\ Gy$ for the target, and $LET_d$ calculation was commissioned and benchmarked using TOPAS.

## REFERENCES

[1] Lu, W. (2010). Physics in Medicine & Biology.

[2] Chen M., Gu X., and Lu W. (2022) Medical Physics.

[3] McNamara AL, Schuemann J, Paganetti H. (2015). Physics in Medicine & Biology.

## ACKNOWLEDGMENTS

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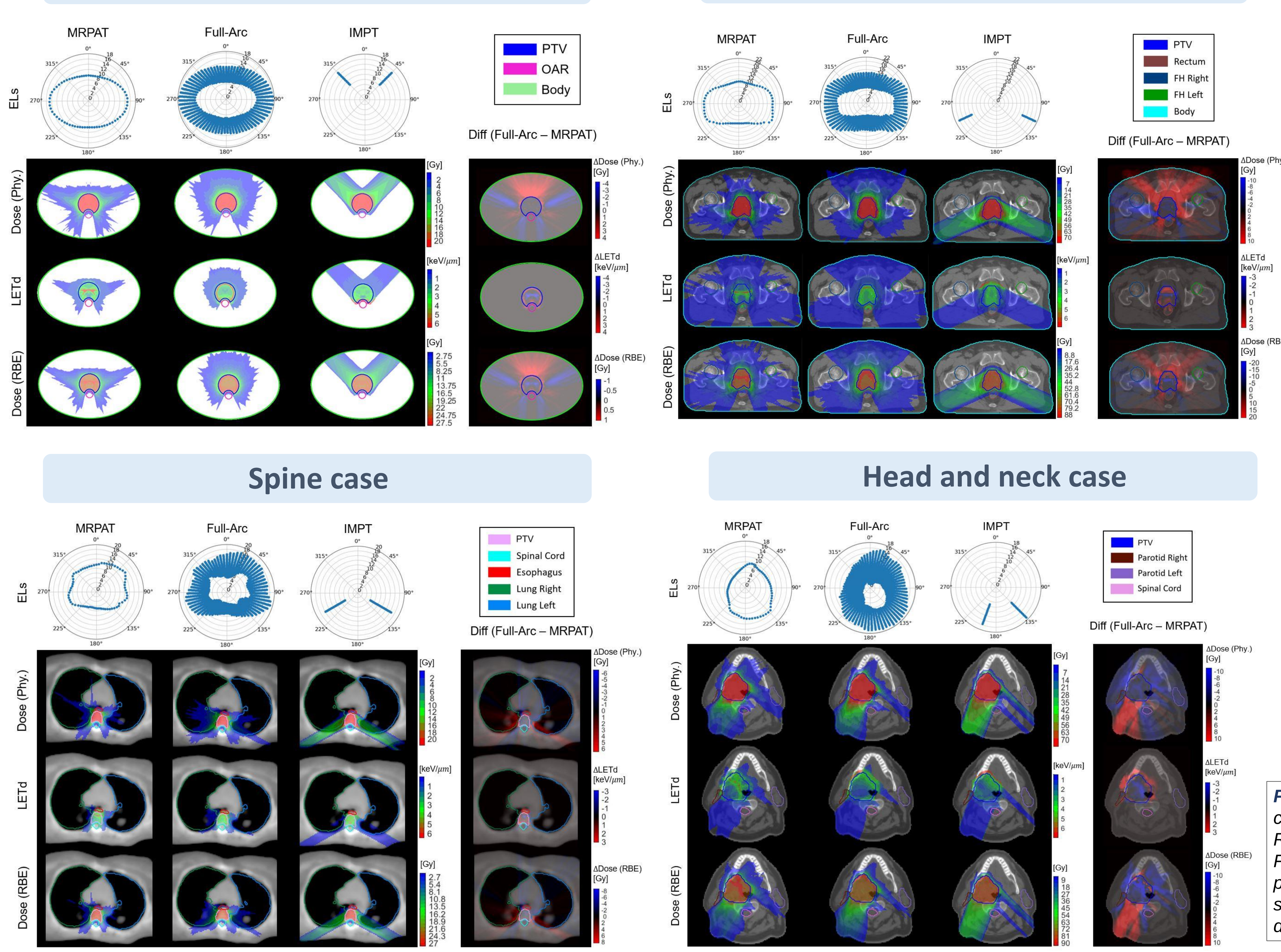
## RESULTS: MRPAT Plan Delivery Efficiency

- Compared to Full-Arc plans, the MRPAT plan utilized less than 5% of the energy layers and required only about 3% of the total beam delivery time.
- The total beam delivery time for MRPAT was comparable to that of IMPT in both phantom and clinical cases.

*Table 1. Comparison of delivery efficiency per fraction for MRPAT, Full-Arc, and IMPT plans.*

| | Ellipse phantom | | | Spine case | | | Prostate case | | | HN case | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MRPAT | Full-arc | IMPT | MRPAT | Full-arc | IMPT | MRPAT | Full-arc | IMPT | MRPAT | Full-arc | IMPT |
| Total MU | 162.93 | 203.76 | 181.06 | 3311.10 | 4031.80 | 3728.70 | 7258.80 | 9690.80 | 8602.50 | 21 201 | 23 021 | 22 347 |
| Energy layer number | 71 | 1531 | 46 | 71 | 1841 | 68 | 71 | 1807 | 47 | 71 | 2280 | 58 |
| Spot number | 1462 | 16 673 | 742 | 12 580 | 109 662 | 7297 | 9481 | 153 143 | 3945 | 25 320 | 222 880 | 16 077 |
| SST (sec) | 4.05 | 5.09 | 4.53 | 16.55 | 20.16 | 18.64 | 36.20 | 48.45 | 43.01 | 106.05 | 115.10 | 111.73 |
| SSWT (sec) | 2.92 | 33.34 | 1.48 | 25.16 | 219.32 | 14.59 | 18.96 | 306.28 | 7.89 | 50.64 | 445.76 | 32.15 |
| ELST (sec) | 0.00 | 876.00 | 26.40 | 0.00 | 1062 | 39.60 | 0.00 | 1041.60 | 27.00 | 0.00 | 1325.40 | 33.60 |
| GRT (sec) | 283.76 | 390.50 | 11.00 | 289.69 | 390.50 | 11.00 | 289.69 | 390.50 | 11.00 | 277.83 | 390.50 | 11.00 |
| TBD (sec) | 290.73 | 1304.90 | 43.41 | 331.40 | 1692.00 | 83.84 | 344.85 | 1786.80 | 88.90 | 434.52 | 2276.80 | 188.49 |

## RESULTS: MRPAT Plan Quality and Robustness Evaluation




Physical dosimetric plan quality: Although the MRPAT plan only utilized one energy layer per angle, it can achieve similar dose objectives as the Full-Arc plan, indicating that spot utilization is highly redundant in arc beams with full energy.

Relative biological effectiveness: MRPAT plans enhances $LET_d$ within the central portion of the target, resulting in a boosted RBE-weighted dose at the tumor core. In contrast, Full-Arc plans produces potentially hazardous $LET_d$ hotspots near the target boundary, as observed in both phantom and clinical cases, while IMPT plans exhibits $LET_d$ hotspots within adjacent OARs.

*Figure 1. Comparison of energy layers (unit: cm), physical dose distribution, LETd and RBE-weighted dose distribution of MRPAT, Full-Arc, and IMPT plans for an ellipse phantom with a C-shaped target, prostate, spine, and HN cases, with corresponding difference maps (Full-Arc – MRPAT).*

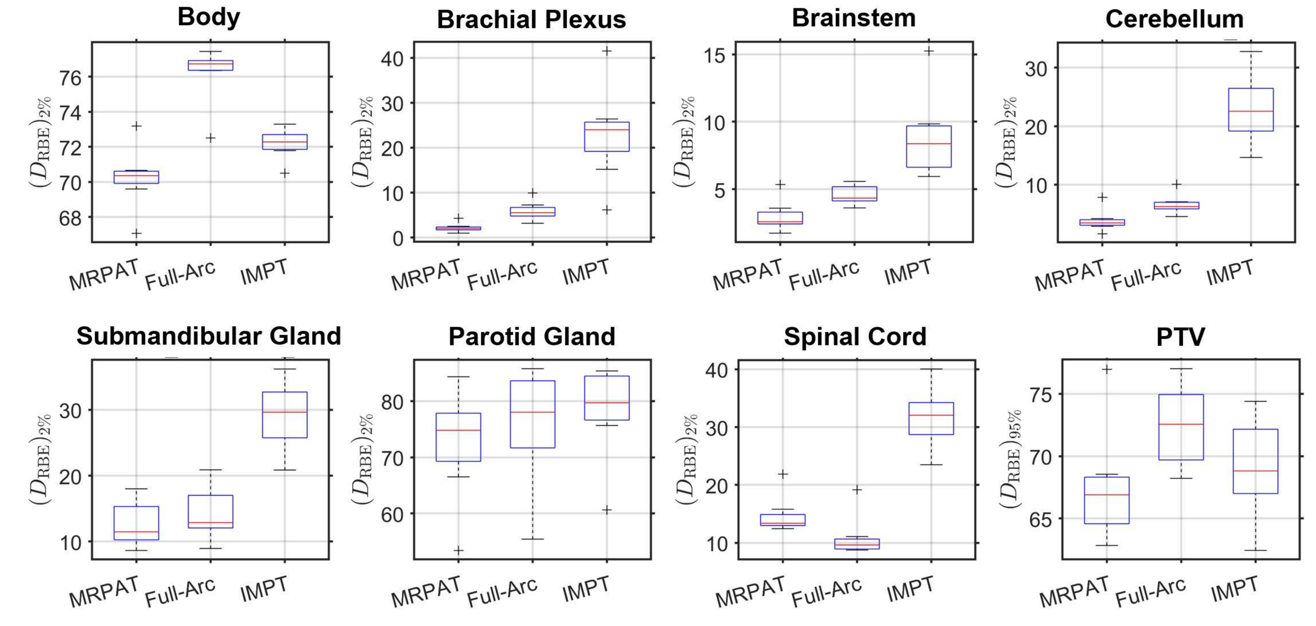



*Figure 2. Robustness analysis comparison of target coverage $(D_{RBE})_{95\%}$ and $(D_{RBE})_{2\%}$ for seven OARs for the HN case. The robustness analysis was performed with a scenario-based approach over 8 scenarios. The middle line in the box plot represents the median of the distribution, the upper and lower lines represent the 5th and 95th percentile.*

*Robustness evaluation: Similar DVH bandwidths for both arc plans, whereas IMPT exhibited broader DVH bandwidths for the parotid gland and spinal cord For most OARs, MRPAT consistently exhibits lower worst-case and median $(D_{RBE})_{2\%}$ values compared with Full-Arc and IMPT plans. In addition, the spread of $(D_{RBE})_{2\%}$ across uncertainty scenarios is generally smaller for MRPAT, indicating reduced sensitivity to setup and range uncertainties.*

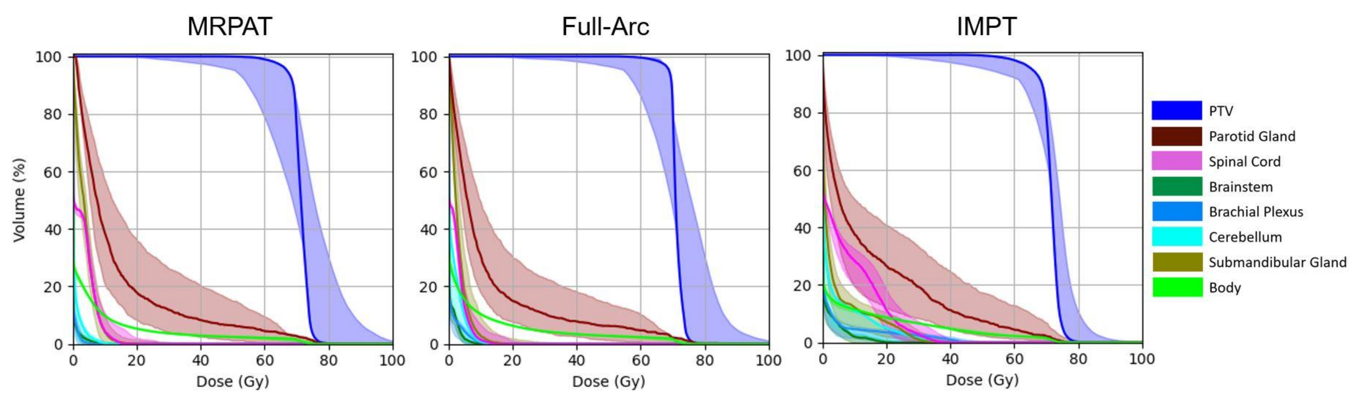



*Figure 3. Scenario-based robustness analysis of physical dose DVHs for MRPAT, Full-Arc, and IMPT plans for the HN case. The nominal solution is shown as a solid line, and the shaded band represents the worst-case dose distributions across all range uncertainty and setup error scenarios.*