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Rethinking Robustness in Head-and-Neck IMPT: Systematic Versus Random Setup Uncertainty

Suresh Rana[1,2], Noufal Manthala Padannayil[1], Ranjith Cholakkara Poyil[1], Stewart Mein[1], Nishan Shrestha[1], Shyam Pokharel[1], Hem Moktan[1], Nebi Demez[1], Lauren Rigsby[1], Ross Taylor[1], Michael Kasper[1], Hina Saeed[1,2]

[1]Radiation Oncology, Lynn Cancer Institute, Boca Raton Regional Hospital, Boca Raton, FL, United States of America
[2]Oncological Sciences, Florida International University, Miami, FL, United States of America

Objective

To compare intensity modulated proton therapy (IMPT) robustness using a conventional systematic setup uncertainty model versus a probabilistic random (interfractional) setup error model in a bilateral head and neck patient.

Methods

- Two IMPT plans (70Gy(RBE) in 35 fractions) for a bilateral HN cancer patient were generated in RayStation (research version) using identical beam parameters, planning objectives, and objective weightings; no plan scaling was performed to force CTV coverage.
- IMPT-R used robust optimization with probabilistic random per-fraction setup uncertainty and ±3.5% range uncertainty. Random setup error was modeled as a 3D Gaussian distribution (σ=1 mm), discretized on a 5×5×5 grid and truncated at 3σ; robust evaluation used a 200-scenario per-fraction with ±3.5% density uncertainty.
- IMPT-S used robust optimization and evaluation with systematic setup uncertainty (±3 mm) and ±3.5% density uncertainty.
- Nominal target coverage was summarized using D95 and D98, while robustness for targets focused on voxelwise-worst D95.
- OAR endpoints included mean dose (D_{mean}) to the oral cavity, contralateral-parotid, and ipsilateral-parotid, reported as nominal and voxelwise-worst values.

Results

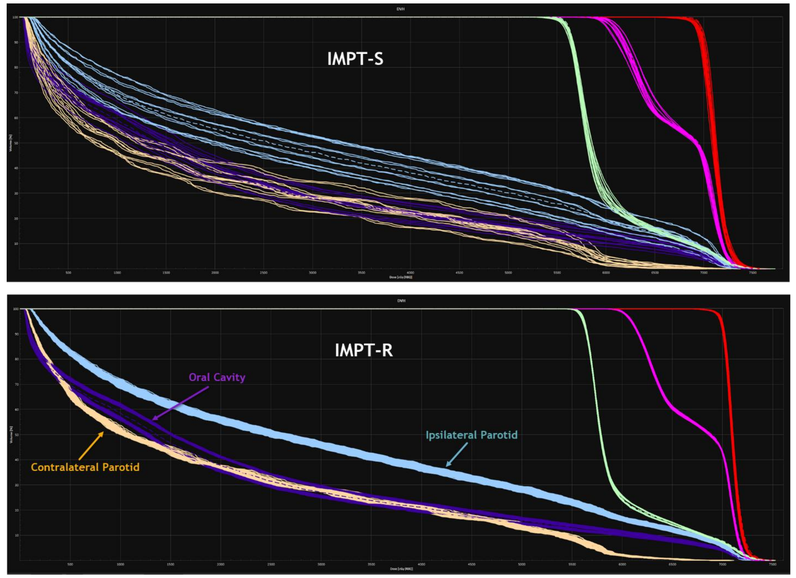

***Figure 1**. Dose–volume histograms (DVHs) for the head-and-neck IMPT plan evaluated under systematic setup uncertainty (IMPT-S, top) and probabilistic random (interfractional) setup uncertainty (IMPT-R, bottom).*

For each case, the nominal DVH (bold curve) and robustness-evaluated DVHs are shown. Target DVHs (CTV_7000 in red, CTV_5950 in magenta, and CTV_5600 in light green) demonstrate comparable nominal coverage, while robustness evaluation reveals greater degradation of the high-dose falloff for IMPT-S compared with IMPT-R.

Organ-at-risk DVHs illustrate larger spread for IMPT-S, whereas IMPT-R shows reduced spread.

Overall, the DVHs visually demonstrate that systematic setup uncertainty leads to greater target coverage loss and increased OAR dose variability compared with probabilistic random setup uncertainty.

Results

- Across all CTV dose levels (CTV_7000, CTV_5950, and CTV_5600), nominal D_{95}/D_{98} values were comparable between IMPT-R and IMPT-S.
- Under robustness evaluation, voxelwise-worst CTV D_{95} reductions from nominal ranged from 0.37–0.52 Gy(RBE) for IMPT-R, compared with larger reductions of 1.37–1.70 Gy(RBE) for IMPT-S.
- Relative increases in OAR D_{mean} from nominal to voxelwise-worst were also larger for systematic than random setup uncertainty, at approximately 21% vs 9% for the oral cavity, 22% vs 5% for the contralateral parotid, and 19% vs 4% for the ipsilateral parotid.

Conclusions

- This novel comparison shows that systematic setup uncertainty causes larger degradations in voxelwise-worst CTV D_{95} and higher robust OAR doses than random setup uncertainty in HN IMPT.
- While systematic robustness remains the clinical standard, these results suggest that random setup error robustness merits further study as a complementary approach with potential to reduce OAR dose without compromising target coverage.

Corresponding Author

Suresh Rana, PhD; AVP and Chief of Medical Physics
- *Email: sureshr@baptisthealth.net or suresh.rana@gmailcom*
- *Phone: 1-405-795-6697*