The effects of proton range uncertainties on organ at risk doses

S. Tattenberg [1,2], T. Madden [2], B. L. Gorissen [2], and J. Verburg [2]
1 Ludwig Maximilian University of Munich, Munich, Germany
2 Massachusetts General Hospital and Harvard Medical School, Department of Radiation Oncology, Boston, USA

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INTRODUCTION

One of proton therapy's biggest advantages is the conformality of the dose distribution and the steep fall-off at the distal beam edge.[1] However, a variety of range uncertainties cause the exact location at which the protons stop *in vivo* to be unknown.[2] Robust treatment planning techniques and the lateral beam edge are often used to address these issues.[3,4] However, such solutions come at the cost of sub-optimal doses to the nearby organs at risk (OARs). The effect of range uncertainties on OAR doses is depicted in Figure 1.

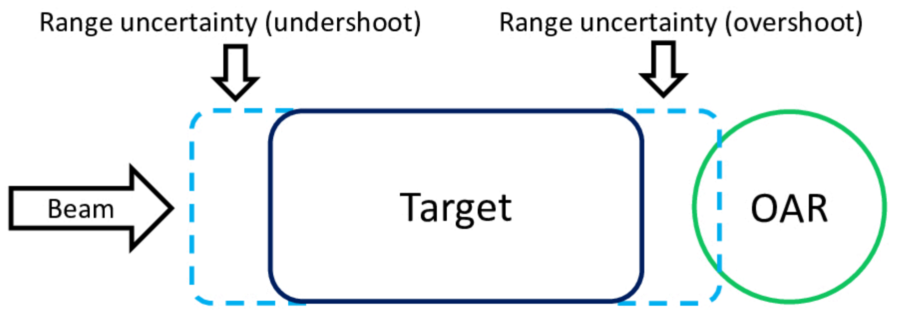

Figure 1: The effect of proton range uncertainties on the doses to nearby organs at risk. Range uncertainties can cause additional dose to be "pushed" into OARs.

AIM

Range verification approaches that aim to reduce the range uncertainties in proton therapy include:

- **Dual-energy computed tomography (DECT)** and **proton computed tomography (pCT)**, which address uncertainties stemming from the single-energy CT images on which the treatment plan is based[5,6]
- **Positron emission tomography (PET)** and **prompt Gamma-ray imaging**, which verify the *in vivo* proton range by detecting particles emitted during or after treatment[7,8]

This project quantifies the potential clinical benefit of such range uncertainty reduction approaches.

METHOD

The study included 15 patients who received pencil beam scanning (PBS) proton therapy at Massachusetts General Hospital:

- 10 head & neck (H&N) patients with clival tumors
- 5 spine patients

Six robust treatment plans corresponding to range uncertainties of 0-5% were created per patient. The optimization approach used was composite worst case optimization over three scenarios (nominal, overshoot, and undershoot). [3]

The evaluated metrics were:

- **Maximum OAR doses**
- **OAR volume** receiving at least **70% of the prescription dose**
- **Healthy tissue volume** receiving at least **30 Gy**

The potential benefit of range uncertainty reductions was quantified by the OAR dose reductions caused by a decrease of the range uncertainty from the current clinical uncertainty (approximated as 4%) to 1%.[4,9]

RESULTS

The organs at risk that were relevant most frequently in the studied patients were the **brainstem**, the **spinal cord**, the **optic chiasm**, and the **optic nerves**.

H&N patients:

Effects of a range uncertainty reduction from 4% to 1%:

- Reduction of the maximum OAR dose by up to:
  - Brainstem: 6.85 Gy
  - Spinal cord: 5.59 Gy
  - Optic chiasm: 9.63 Gy
  - Optic nerve: 17.42 Gy
- Reduction in the OAR volume receiving at least 70% of the prescription dose by up to (relative to the total OAR volume) :
  - Brainstem: 9.63%
  - Spinal cord: 11.29%
  - Optic chiasm: 19.60%
  - Optic nerve: 5.12%
- Average reduction of the volume of healthy tissue receiving at least 30 Gy by 15.13 cc (σ = 11.51 cc, range: 6.52 cc to 43.17 cc)

Spine patients:

Effects of a range uncertainty reduction from 4% to 1%:

- Reduction of the maximum OAR dose by up to:
  - Spinal cord: 10.02 Gy
- Reduction in the OAR volume receiving at least 70% of the prescription dose by up to (relative to the total OAR volume) :
  - Spinal cord: 15.59%
- Average reduction of the volume of healthy tissue receiving at least 30 Gy by 17.86 cc (σ = 12.49 cc, range: 1.63 cc to 29.17 cc)

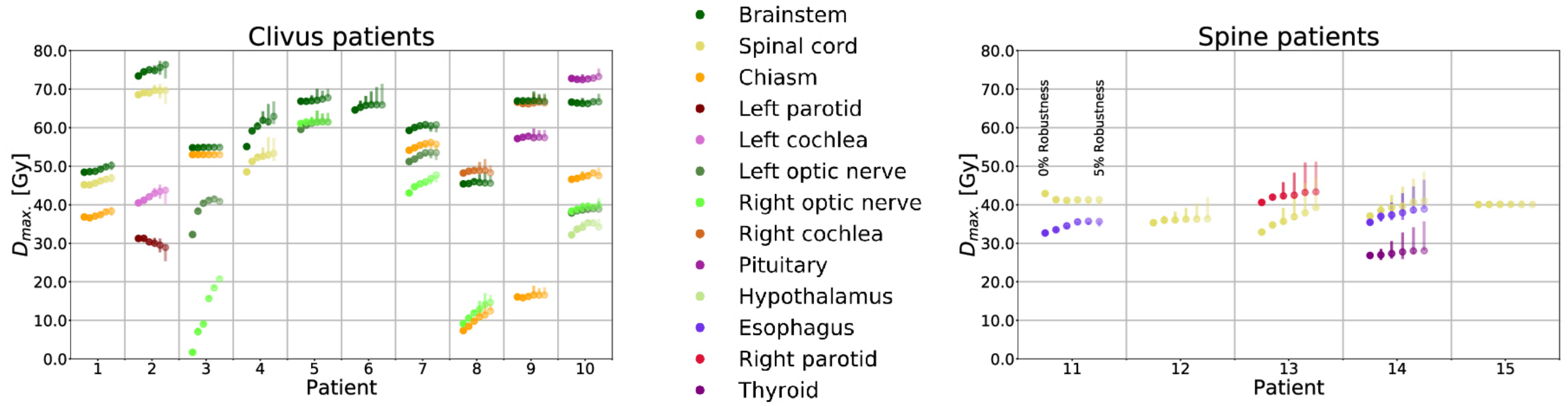

Figure 2: The maximum doses to all relevant organs at risk for all robustness levels, scenarios, and patients. Error bars indicate under-/overshoot scenarios.

CONCLUSIONS

Realistic range uncertainty reductions lead to considerable reductions in OAR and healthy tissue doses. Based on the magnitude of the observed changes and the OAR toxicity data gathered by the Quantitative Analyses of Normal Tissue Effects in the Clinic (QUANTEC) study, the dose reductions caused by range uncertainty reduction techniques may be clinically relevant.

OUTLOOK

- **Limitations:** this project focussed on current clinical treatment planning strategies
- **Future direction:** expanding the study to novel treatment planning strategies making greater use of the distal beam edge
- **Motivation:** heavy reliance on the distal beam edge is currently avoided to reduce the effects of beam over-/undershoots; however, range uncertainty reductions may lead to novel planning strategies using different beam angles
- **Expected outcome:** greater reliance on the distal beam edge should result in preferable non-robust plans but increased OAR doses at higher levels of robustness and therefore greater effects of range uncertainty reductions

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CONTACT INFORMATION

stattenberg@mgh.harvard.edu