Towards CT-based proton range uncertainties specifically for pediatric cancer patients

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INTRODUCTION

Proton range uncertainty defines treatment margins in proton therapy. Current uncertainty estimates are derived from adult patients and applied directly to pediatric patients despite differences in body size and tissue composition that affect CT-based stopping-power estimation. Dual-energy CT (DECT) may further reduce uncertainty by mitigating beam hardening.

Aim:
To quantify a **pediatric-specific** proton range uncertainty accounting for anatomical and compositional variations from the adult population.

METHODS AND MATERIALS

- A modular cylindrical phantom (10-40 cm) with tissue-equivalent inserts was scanned using SECT and DECT. Inserts were scanned at both central and peripheral positions to quantify beam hardening effects (Figure 1).

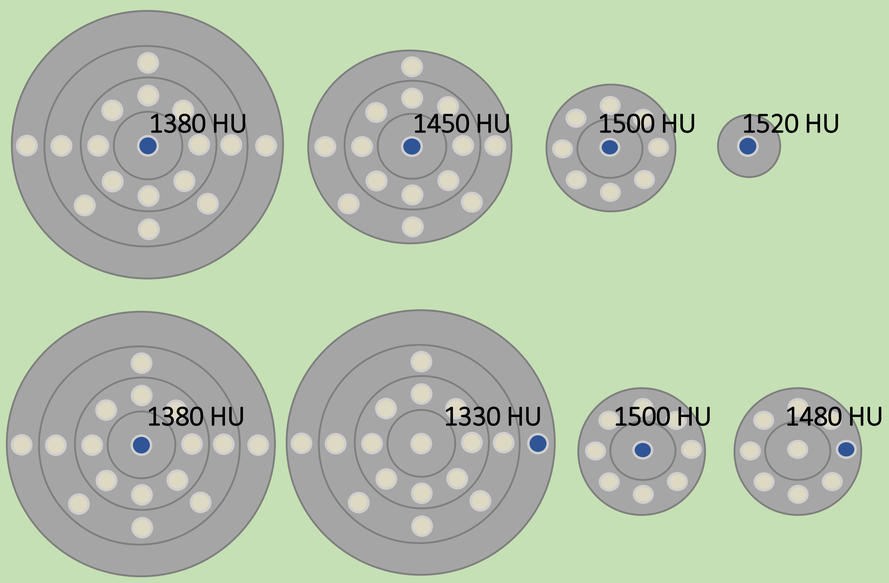
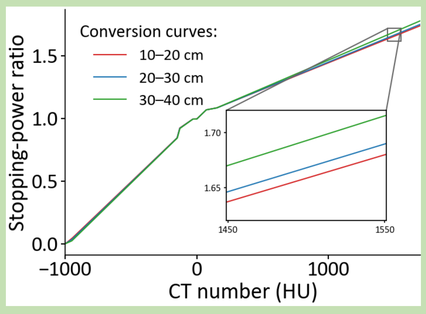


Figure 1: CT number variations of the same tissue insert with phantom size (top) and insert position (bottom).



Pediatric size-specific CT-to-SPR conversion curves were generated for 10-20, 20-30, and 30-40 cm patient sizes. Conventional adult head (20 cm) and body (40 cm) conversion curves served as the reference (Figure 2).

Figure 2: Pediatric CT-to-SPR size-specific conversion curves.

Proton range uncertainty framework:

SPR estimation uncertainty sources:
- **CT image uncertainty (beam hardening)**
- CT spectrum modelling uncertainty
- Population tissue composition variability
- Mean excitation energy uncertainty
- SPR energy dependence uncertainty
- **Pediatric-adult tissue composition differences**

→ Composite SPR uncertainty
↓
Tissue-weighted based on the beam path
↓
Proton range uncertainty

RESULTS

Proton range uncertainty:

- Adult-based estimates **overestimated** pediatric proton range uncertainty.
- The largest reductions were observed in smaller patients.
- Reduced beam hardening was the dominant contributor.
- Pediatric tissue differences had a small impact.
- DECT provided additional uncertainty reduction with the greatest benefit observed in larger patients.

Clinical impact:

- Clinical 3-beam proton plan for an 8-year-old brain cancer patient re-optimized using the pediatric-specific range uncertainty.
- Range uncertainty reduced from 3.5% to 1.1%.
- Optimization objectives and objective weightings were kept identical for the re-optimized plan.
- **Target coverage maintained** (Figure 5)
- **Reduced dose to adjacent organs-at-risk:**
  - Brainstem D0.03cc: -1.0 Gy
  - Optic nerves D0.03cc: -1.6 Gy

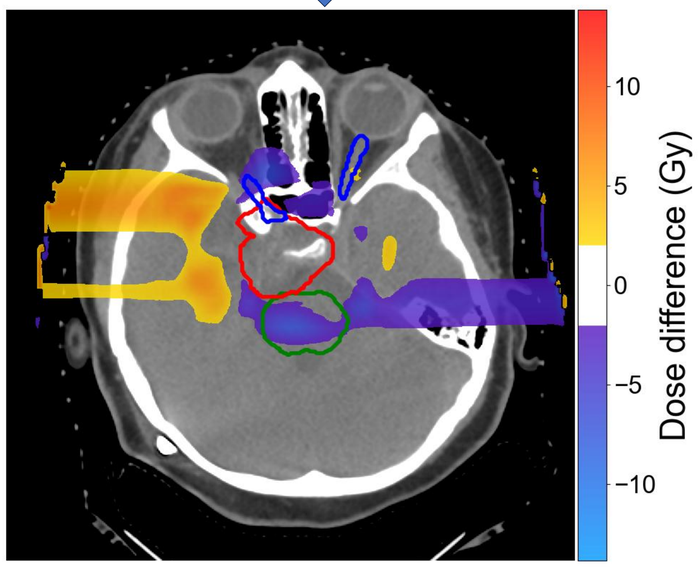


Figure 4: Dose difference map between treatment plans optimized using conventional (3.5%) and pediatric-specific (1.1%) range uncertainties. The contours indicate the CTV (red), brainstem (green), and optic nerves (blue).

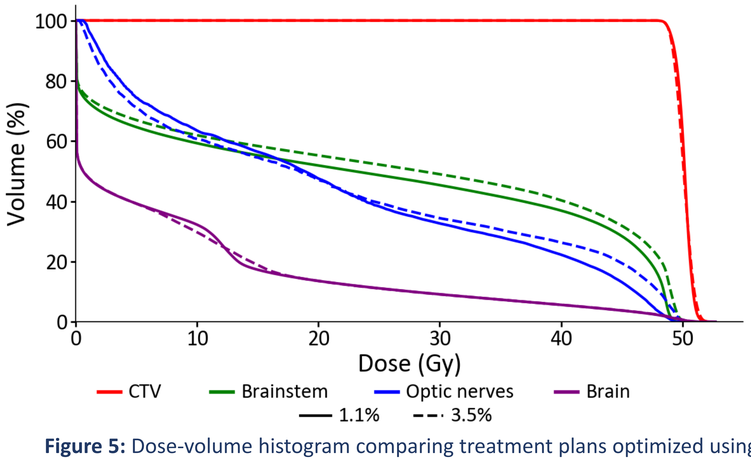


Figure 5: Dose-volume histogram comparing treatment plans optimized using 3.5% and 1.1% proton range uncertainties.

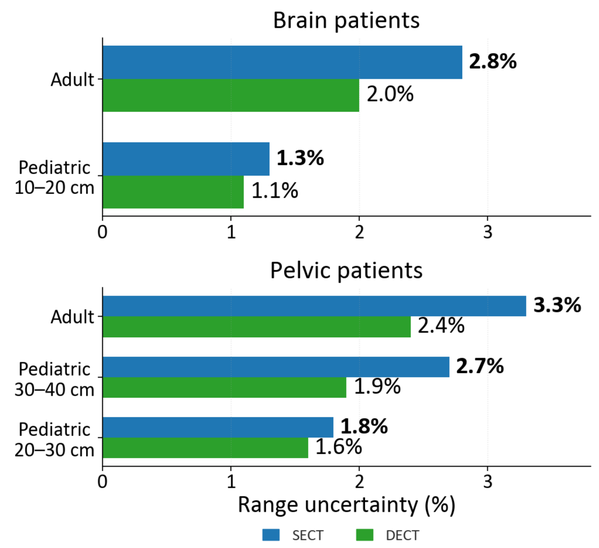


Figure 3: Proton range uncertainties for adult and pediatric patient size groups using SECT (blue) and DECT-derived VMIs (green).

DISCUSSION

- Adult-based uncertainty estimates do not accurately represent pediatric patients.
- Beam hardening, driven by patient size, was the dominant contributor to proton range uncertainty.
- The benefit of size-specific uncertainty estimation persisted after accounting for pediatric-adult tissue composition differences.
- The pediatric tissue uncertainty remains constrained by the limited availability of pediatric tissue data and the absence of reported measurement uncertainties.
- The clinical benefit of DECT was patient-size dependent, with the greatest benefit observed for larger patients.
- Reduced range uncertainty expanded the robust optimization solution space, enabling lower organ-at-risk doses while maintaining target coverage.

TAKE-HOME MESSAGE

- Pediatric-specific approach **reduced proton range uncertainty.**
- Smaller patients → reduced beam hardening → lower range uncertainty.
- Reduced margins enable lower OAR dose, while maintaining target coverage.
- Move beyond one population-based uncertainty and towards patient size-specific uncertainty estimates.

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