Is IMPT still superior to 3D conformal proton therapy (3DCPT) in the presence of setup errors and range uncertainties?

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Sensitivity analysis for two patients

Sites

- Paraspinal case
- Skull-base case

Nominal plans

- Clinical plan (3DCPT): XIO, CMS → Set of RC and apertures
- IMPT plan: KonRad Pro → Set of intensity maps

Sensitivity analysis

- Setup errors: beam isocenter shifted by ±1 mm in x,y,z
- Range uncertainties: nominal range changed by ±2.5 mm
1st Clinical example: the paraspinal case

- Multiply recurrent G2 chondrosarcoma T4
- 4 fields (Boost: 27 CGE with protons)
- 2 patching combinations (4 fields)
1st Clinical example: the paraspinal case
1st Clinical example: the paraspinal case

- 2nd patch beam
- 2nd patch line
- Target uncovered
- 2nd thru beam

Key points:
- ref. pnt X(cm): 1.01
- Y(cm): 0.83
- Z(cm): 0.18
- dose(cGy): 89.6
- global max(cGy): 3428.9
- local max(cGy): 3007.5

(Note: The image depicts a medical scan with highlighted areas indicating the second patch beam, patch line, and target uncovered areas.)
1st Clinical example: the paraspinal case
2nd Clinical example: the skull-base case

- Skull-Base Chondrosarcoma
- 9 fields (69 CGE)
- 2 patching combinations (5 fields)
2nd Clinical example: the skull-base chondrosarcoma case

![Graph showing dose response with GTV and Chiasm percentages]

- GTV: 85%
- Chiasm: 62%

Dose [CGE] vs. Volume [%]
2nd Clinical example: the skull-base chondrosarcoma case

3DCPT
72
69
68
62
58
50
30

IMPT
2nd Clinical example: the skull-base chondrosarcoma case

![Graph showing dose vs. volume for different treatment plans: 3DCPT, IMPT, RT OPT TR, RT NRV. The x-axis represents dose in CGE, and the y-axis represents volume as a percentage. The graph demonstrates the dose distribution for each treatment plan, highlighting differences in coverage and dose intensity.]
2nd Clinical example: the skull-base chondrosarcoma case

- LT Cochlea
- RT Cochlea
- Hypoth.
2nd Clinical example: the mean dose to OAR

- Chiasm: 6.8 CGE
- Brainstem: 12.7 CGE
- RT OPT NRV: 9.2 CGE
- RT Cochlea: 28.4 CGE
- Hypothalamus: 7.4 CGE
- LT Cochlea: 18.0 CGE
- RT OPT TR: 13.3 CGE

3DCPT
IMPT
IMPT and 3DCPT under setup and range errors
Paraspinal case: systematic SETUP error of 1 mm
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![Graph showing dose distribution for GTV and Sp.Cord with 3DCPT and IMPT methods.]
Paraspinal case: systematic RANGE error of 2.5 mm
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Conclusions for boost with Patching vs. IMPT

**Target under setup and range errors**
- Significant changes in target coverage
- Similar changes in target coverage for both modalities
- IMPT remains superior

**OAR under setup and range errors**
- Setup errors are more critical than range errors
- Dose more likely to exceed tolerances when using IMPT
- 3DCPT insensitive to range errors

**Solution**
- Assure patient positioning
- Add margin to OAR (PRV)
Skull-base case: systematic SETUP error of 1 mm
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Skull-base case: the mean dose

- Chiasm
- Brainstem
- RT OPT NRV
- RT COCHLEA
- Hypothalamus
- LT COCHLEA
- RT OPT TR

Legend:
- SETUP errors
- RANGE errors
- 3DCPT
- IMPT
Skull-base case: the mean dose

[Diagram showing mean dose for different structures such as Chiasm, Brainstem, RT Cochlea, Hypothalamus, RT OPT NRV, LT Cochlea, RT OPT TR, with error bars indicating setup and range errors for 3DCPT and IMPT techniques.]
Conclusions for skull-base case

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**OAR under setup and range errors**

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- Dose more likely to exceed tolerances when using IMPT under range overshoots
- 3DCPT insensitive to range errors

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**Target** under setup and range errors
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**OAR** under setup and range errors
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- Dose more likely to exceed tolerances when using IMPT under range overshoots
  - 3DCPT is sensitive to range errors too, but not for all organs (no general trend)

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- **Under setup errors** IMPT remains superior (better spare of OAR)

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- The benefits of IMPT are questionable under range overshoots

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**Target under setup and range errors**
- **Significant** changes in target coverage *only under range errors*
- **Larger** changes in target coverage for IMPT
- IMPT remains **superior**

**OAR under setup and range errors**
- **Range errors** are more critical than setup errors
- Dose more likely to exceed tolerances when using **IMPT under range overshoots**
- **3DCPT is sensitive** to range errors too, but not for all organs (no general trend)
- Under setup errors IMPT remains superior (better spare of OAR)
- The benefits of IMPT in case of range overshoot is questionable

**Solution**
- **Intelligent IMPT** using robust optimization techniques against setup & range errors
- Add margin to OAR (PRV)
If a clear a priori benefit of IMPT is observed in nominal plans, the use of IMPT remains attractive over 3DCPT even when taking into account the effects of setup errors and range uncertainties on the dose distribution. Nevertheless, refined range verification and further mitigation techniques need to be developed.