Robust Treatment Planning

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Disclaimer

• HollandPTC has reasearch agreements with Varian, RaySearch, Siemens, and Philips
Radiotherapy Workflow

1. Localization
   a. Contouring of tumor and organs at risk
   b. Multimodality: image registration

2. Dose prescription
   a. Prescription dose and iso-dose line
   b. Fractionation and treatment duration
   c. Conversion to biologically equivalent dose

3. Treatment plan optimization
   a. Dose commissioning
   b. Dose calculation
   c. Treatment planning

4. Treatment delivery
   a. Patient setup
   b. Tumor setup (by imaging, frame, or surrogate)
   c. Immobilization and intra-fraction motion

5. Treatment device
   a. Mechanical accuracy of the system
   b. Alignment of treatment beam and imaging or localization system
Safety Margin
Why do we use margins?

- To **a-priori** compensate for (unknown) **deviations** between the intended target position and the real target position during dose delivery.

- Deviations are estimated from **population-based measurements** of geometrical errors (can be patient specific, e.g. respiratory motion).
How Large Should The Margin Be?

• What is the incentive?
  • 90% of patients in the population receives a minimum cumulative CTV dose of at least 95% of the prescribed dose - van Herk et al.

\[ M = 2.5\Sigma + 0.7\sigma \]

Not all patients will be treated to 100% of the prescription dose in all fractions

Distribution of systematic errors  Distribution of random errors
Important Assumptions

• Margin recipes are based on a dose distribution that is invariant under errors

• Margin recipes typically does not account for errors in dose calculation
Treatment Uncertainties

• Proton therapy is relatively sensitive for uncertainties in proton range:
  1. Patient setup error
  2. Error in range (uncertainty in stopping power prediction)
  3. Patient anatomy changes
Dose Invariant Under Setup Errors

A Kraan et al. IJROBP 2013; dx.doi.org/10.1016/j.ijrobp.2013.09.014
Non-Robust and Robust Treatment Plans

Minimax robust optimization

• Include multiple ‘error scenarios’ in inverse optimization:
  • Construct dose matrices for each scenario
  • Minimize worst-case objective (function) value:

\[
\min_{x \geq 0} \sum_{i=1}^{n} w_i \max_{s \in S} f_i(d(x; s))
\]
Minimax: Minimizing the Worst Case

### Cost Function

\[
\text{Cost Function} = \frac{1}{N} \sum_{i=1}^{N} (D_i - D_0)^2
\]

**Nominal Setup Error**

\[
\begin{bmatrix}
2 & 5 & 6 \\
1 & 5 & 4 \\
2 & 4 & 6 \\
\end{bmatrix}
\]

**Setup Error - \( \Delta x \)**

\[
\begin{bmatrix}
2 & 5 & 6 \\
3 & 4 & 4 \\
3 & 5 & 6 \\
\end{bmatrix}
\]

**Setup Error + \( \Delta y \)**

\[
\begin{bmatrix}
2 & 3 & 6 \\
3 & 3 & 3 \\
3 & 2 & 1 \\
\end{bmatrix}
\]

**Range Error - \( \Delta r \)**

\[
\begin{bmatrix}
2 & 5 & 5 \\
3 & 2 & 2 \\
3 & 1 & 3 \\
\end{bmatrix}
\]
Minimax: Minimizing the Worst Case

\[
\begin{bmatrix}
1 & 5 & 3 \\
1 & 2 & 4 \\
2 & 4 & 3 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
2 & 2 & 2 \\
3 & 2 & 2 \\
3 & 2 & 4 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
2 & 3 & 6 \\
3 & 3 & 3 \\
3 & 2 & 4 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
2 & 1 & 3 \\
3 & 2 & 2 \\
3 & 1 & 3 \\
\end{bmatrix}
\]

Cost Function:

\[
\frac{1}{N} \sum_{i=1}^{N} (D_i - D_0)^2
\]
Minimax Robust Optimization

• Implemented in most commercial treatment planning systems

• User has to select:
  • Number of error scenarios, typically:
    • 9 scenarios  (1 nominal + 6 setup + 2 range)
    • 21 scenarios  ([nominal + 6 setup] * [nominal + 2 range])

• Magnitude/size of error scenarios:
  • Setup errors  \( \rightarrow \)  ? mm
  • Range errors  \( \rightarrow \)  ? %
Robust Evaluation
Robust Optimization Evaluated

Robust against 1 mm setup error

Robust against 7 mm setup error

Robust against 9% range error

Range Error (%)

CTVlow V95% (%)

CTVhigh V107% (%)

Setup Error (mm)

Range Error (%)
Increasingly More Robust

Minimax Robust Optimization
How robust should a treatment plan be to give an adequate treatment under given setup and range error distributions?
Robustness Recipes

PTV margin

Margin recipe: \( M = 2.5\Sigma + 0.7\sigma \)

Robust planning

- Patient shift
- Proton undershoot
- Patient shift
- Nominal scenario
- Proton overshoot

S. van de Water
Adequate CTV Coverage

• Adequate treatment defined as
  • $V_{95\%} > 98\%$ for a fractionated treatment
  • $>98\%$ of the treatments/population

• Determined for various robustness settings in range and setup for which systematic range and setup error and random setup errors an adequate CTV coverage was obtained
Polynomial Chaos Expansion

• Multi-dimensional polynomial function:

\[ D_{PCE}^i(\xi) = \sum_{k=0}^{N} r_k^i \Psi_k(\xi) \]

PCE dose in voxel i  PCE coefficients (PCCs)

\[ \xi = (x, y, z, r) \]

setup error  range error

• Expected dose for entire fractionated treatment course analytically derived and calculated in a split second:
  • Systematic setup (\(\mu\)) and range error (\(r\))
  • Assumes infinite number of fractions

Adequate CTV coverage: V95%>98% for at least 98% of the patients
Anatomical Robust
Dose Degradation in IMPT

- Intended dose: seconds
- Degraded dose: days
- Breathing
- Gas in bowel
- Tumor shrinkage in lung

M Hoogeman
Anatomical Robust Optimization

Anatomical Robust Optimization

MultiCT Robust Optimization

CT1

CT2

CT3

D. Reijtenbagh
MultiCT Robust Plans

MultiCT Robust

MultiCT Robust with interplay

D. Reijtenbagh
Impact of Fractionation

D. Reijtenbagh
Conclusions

• Each Proton Therapy treatment plan needs to be evaluated on robustness even if robust optimization has been used
• A limited analysis of error-scenarios can be linked to the probability of an adequate treatment in terms of CTV coverage
• Voxel-wise minimum dose distribution is a useful tool to evaluate dose distributions on CTV coverage
• CTs and pseudo CTs can be simply included in scenario-based optimization to account for “predictable” anatomical changes
Questions?

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- Steven Habraken
- Carlijn ter Haar
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- Steven van de Water