Agenda

- Background
  - IRCU 50
  - Uncertainties
  - Robust optimization
- Use Cases
  - Lung Robust 4D Optimization
  - Breast skin flash
  - Craniospinal Independent beam robustness
- Evaluation
- Future of Robustness

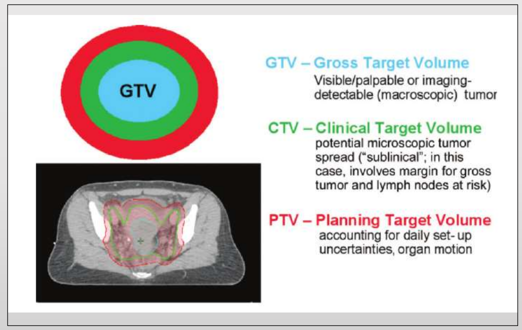
- Disclaimer -

I am a RaySearch employee, images and tool sets presented are from RayStation.

I will attempt to provide a neutral perspective on the current and future status of Robust Optimization.

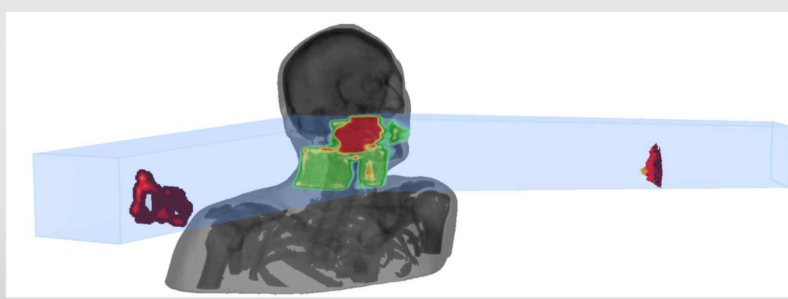
ICRU 50

- Purpose: to promote the use of a common language for specifying and reporting the doses in radiation therapy, as well as the volumes in which they are prescribed
  - GTV & CTV are purely oncological concepts of actual disease or possible extension of disease
  - PTV takes into account the movement of the patient and the inaccuracies due to patient-beam positioning or related to the therapy equipment.

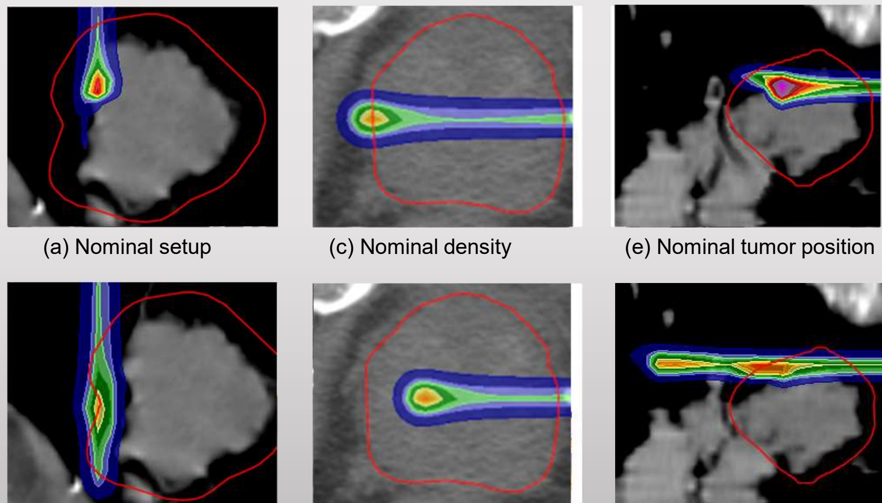


Background

- Primary goal:
  - Dose coverage despite geometric uncertainty
- Conventional solution:
  - Planning margins
- Underlying assumption:
  - Changing the anatomy doesn't change the dose (the static dose cloud approximation)



EXAMPLES OF IMPT DOSES IN DIFFERENT GEOMETRIES



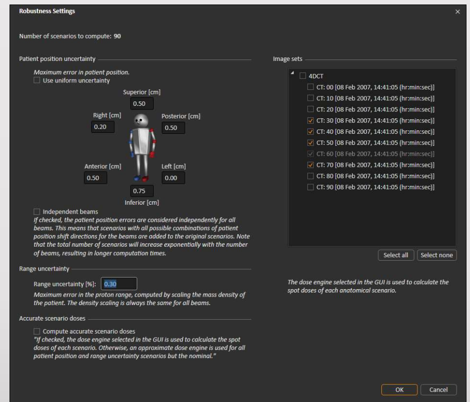
(a) Nominal setup (c) Nominal density (e) Nominal tumor position

(b) Shifted setup (d) Scaled density (f) Shifted tumor position

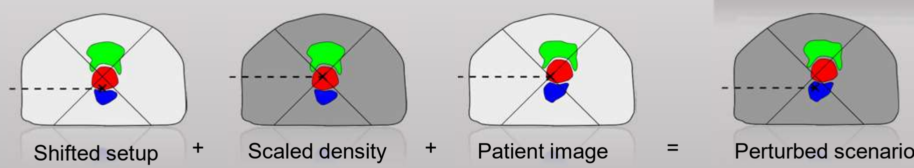
What to do?

- The underlying hypothesis fails, so margins won't work as intended
  - Some heuristics (SFUD and possibly material overrides) may help
- Is Robust Optimization the answer?
  - Robust optimization is a field of optimization theory that deals with optimization problems in which a certain measure of robustness is sought against uncertainty that can be represented as deterministic variability in the value of the parameters of the problem itself and/or its solution.

What is robust optimization



- Explicitly create scenarios
  - Positioning change
  - Density Error
  - Organ and target motion
- Optimize on covering all scenarios
- To do so, uses a new algorithm!



Robust Optimization

•Calculate the the number of combinations

- Number of combinations = (+,-,0 range shift) x (setup)x(number of images)
  a) +5mm range with (3mm… -3mm… 0mm…)
  b) -5mm range …

• Minimize the worst case scenario (maximum)

- Fluence - x
- Scenarios - k
- Dose - d

$$\underset{x}{\text{minimize}} \quad \max_{k} \left[f(\boldsymbol{d}^k) \right]$$

Range and Setup Uncertainty

Setup uncertainty

- The patient may not be placed in the correct position each day
- There are mechanical tolerances that determine some physical limits

Range uncertainty

- The CT scan contains uncertainty as a model of the patient
  - Weight loss or weight gain
  - Conversion of Hounsfield units to stopping power
  - Imaging artifacts

MINIMAX OPTIMIZATION

- minimax optimization to achieve robustness

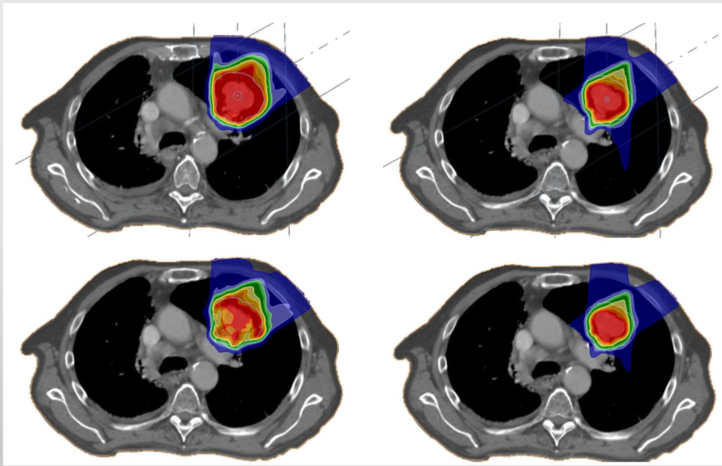
$$\begin{aligned} \underset{x \in \mathcal{X}}{\text{minimize}} \quad & f_0(d(x; s_0)) + \max_{s \in \mathcal{S}} f(d(x; s)) \\ \text{subject to} \quad & g_0(d(x; s_0)) \leq 0, \\ & g(d(x; s)) \leq 0, \qquad s \in \mathcal{S} \end{aligned}$$

f_0 — nominal objectives
f — robust objectives
g_0 — nominal constraints
g — robust constraints
s_0 — nominal scenario
$\mathcal{S}$ — set of scenarios
$d(x; s)$ — dose as function of variables x under scenario s

RESULTS: Lung case

Nominal setup

Shifted setup

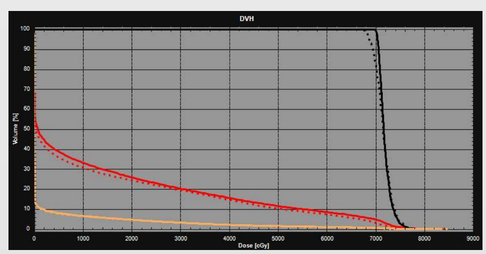


IMPT with margins only

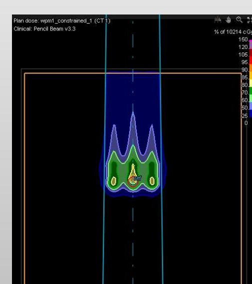
Robust IMPT

SCENARIO selection

- How to select the sc $\max_{s \in S} f(d(x;s))$
- For small setup errors, use scenarios along main axes
- For larger errors, include additional directions
- Include intermediate setup and density scenarios



DVHs for plan using robust constraint and axis scenarios only.
Solid: nominal scenario Dashed: (0, 0.7, 0.7) cm setup shift



Small target, large uncertainty, no intermediate scenarios

SCENARIO selection

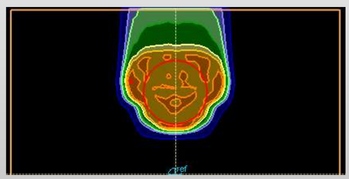
- Setup errors, density errors, and organ motion are generally independent

n_s setup scenarios
n_d density scenarios
n_i 4D CT

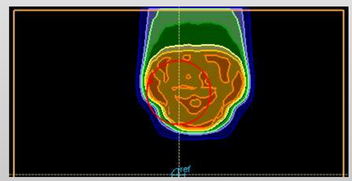
→ $n_s n_d n_i$ scenarios

Example not using independent setup and density errors:

Setup error



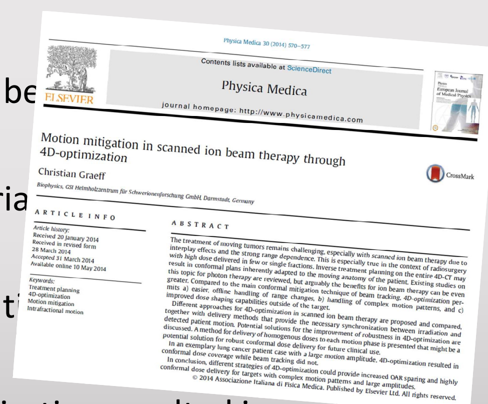
Density error



Setup and density error

Lung: Robust 4D-CT optimization

- For lung cases, respiratory motion must be
- Conventionally: ITVs, average CTs, materia
- Robust optimization with respect to mult
- Independent study from GSI: "4D-optimization resulted in conformal dose coverage while beam tracking did not."



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Motion mitigation in scanned ion beam therapy through 4D-optimization

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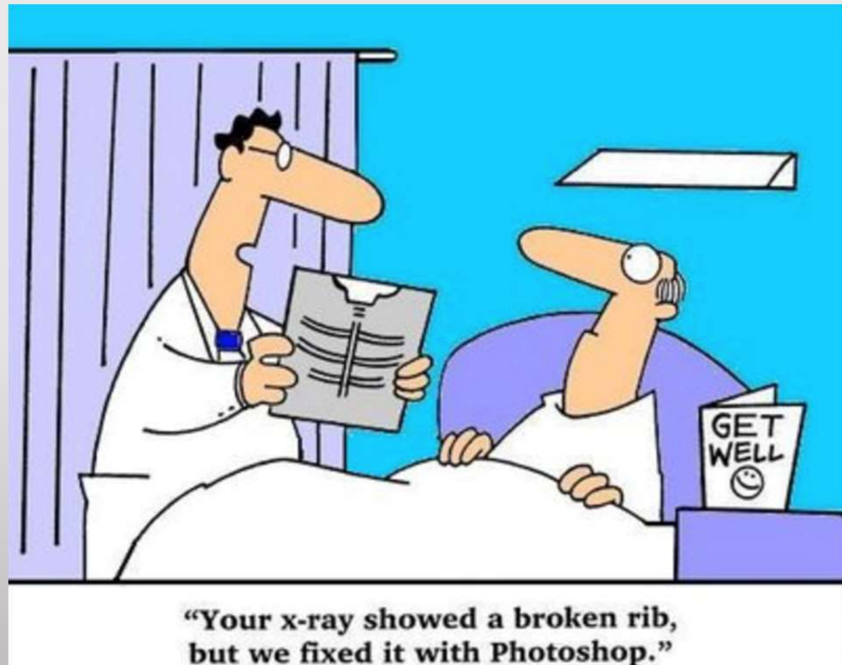
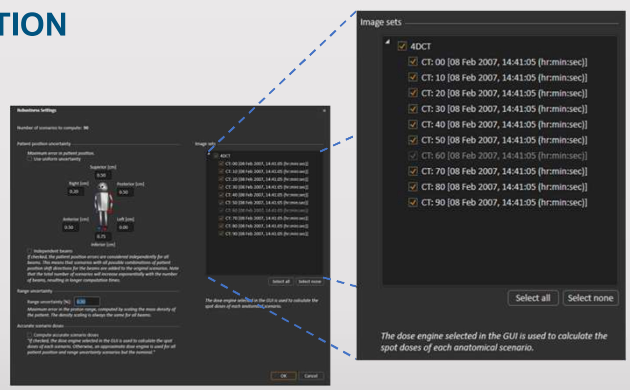
ABSTRACT
The treatment of moving tumors remains challenging, especially with scanned ion beam therapy due to interplay effects and the strong range dependence. This is especially true in the context of radiosurgery with high dose delivered in few or single fractions. Inverse treatment planning on the entire 4D-CT may result in conformal plans inherently adapted to the moving anatomy of the patient. Existing studies on this topic for photon therapy are reviewed, but arguably the benefits for ion beam therapy can be even greater. Compared to the main conformal mitigation technique of beam tracking, 4D-optimization permits a) easier, offline handling of range changes, b) handling of complex motion patterns, and c) improved dose shaping capabilities outside of the target.
Different approaches for 4D-optimization in scanned ion beam therapy are proposed and compared, together with delivery methods that provide the necessary synchronization between irradiation and detected patient motion. Potential solutions for the improvement of robustness in 4D-optimization are discussed. A method for delivery of homogenous doses to each motion phase is presented that might be a potential solution for robust conformal dose delivery for future clinical use.
In an exemplary lung cancer patient case with a large motion amplitude, 4D-optimization resulted in conformal dose coverage while beam tracking did not.
In conclusion, different strategies of 4D-optimization could provide increased OAR sparing and highly conformal dose delivery for targets with complex motion patterns and large amplitudes.

Case Discussion

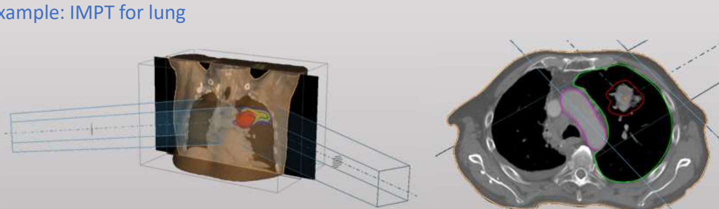


LUNG: ROBUST 4D-CT OPTIMIZATION

- Select phases over which to optimize
- Combinable with setup and range robustness: allows for CTV planning
- Requires contours on all selected image sets

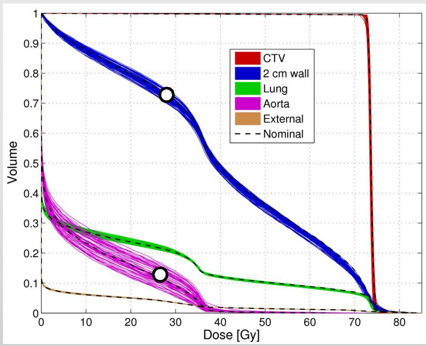


Example: IMPT for lung



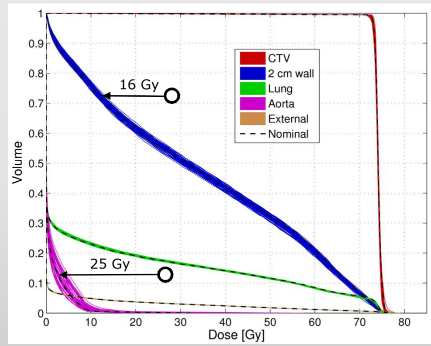
LUNG: ROBUST 4D-CT OPTIMIZATION

Evaluation over 50 scenarios:



Conventional planning

- Single field uniform dose
- Material override
- Margins for setup errors
- ITV for respiratory motion



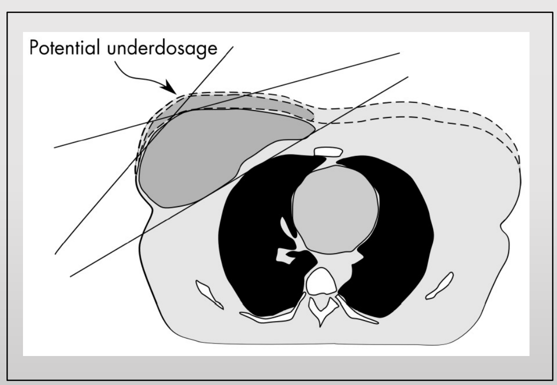
Robust optimization

- 4D-CT and setup scenarios

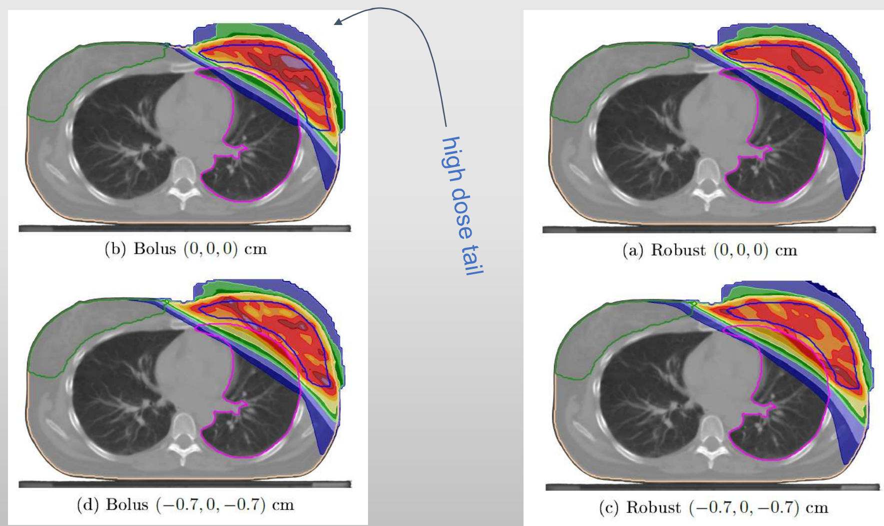
Albin Fredriksson and Björn Hårdemark, Robust optimization accounting for organ motion, range errors, and setup errors in IMPT, 11th Biennial On Physics & Radiation Technology For Clinical Radiotherapy, 2011

Breast: skin flash

- In the skin flash region, the static dose cloud approximation doesn't even hold for photons
- Heuristic solutions
  - Expanding fields (3D-CRT)
  - Virtual Bolus
- Robust optimization solves this directly

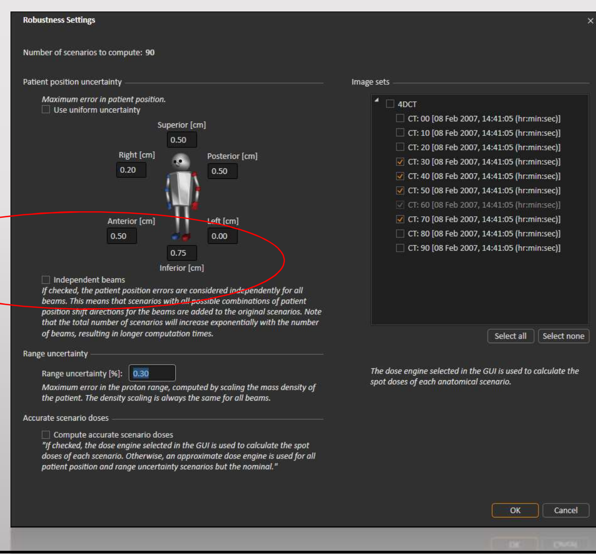


BREAST: Skin flash



Optimization of independent beams

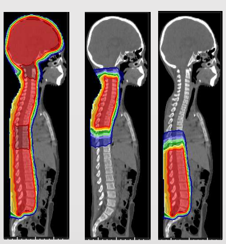
- Individual beam dose



Craniospinal: INDEPENDENT BEAMS

- What if beams shift relative to each other?
- Use beam dose ramps at field junctions
- Achieved by robust optimization with independent beams
- Ramp size can be controlled by a single structure for each junction
- Exponential growth of scenarios, but polynomially many beam doses

Craniospinal: INDEPENDENT BEAMS

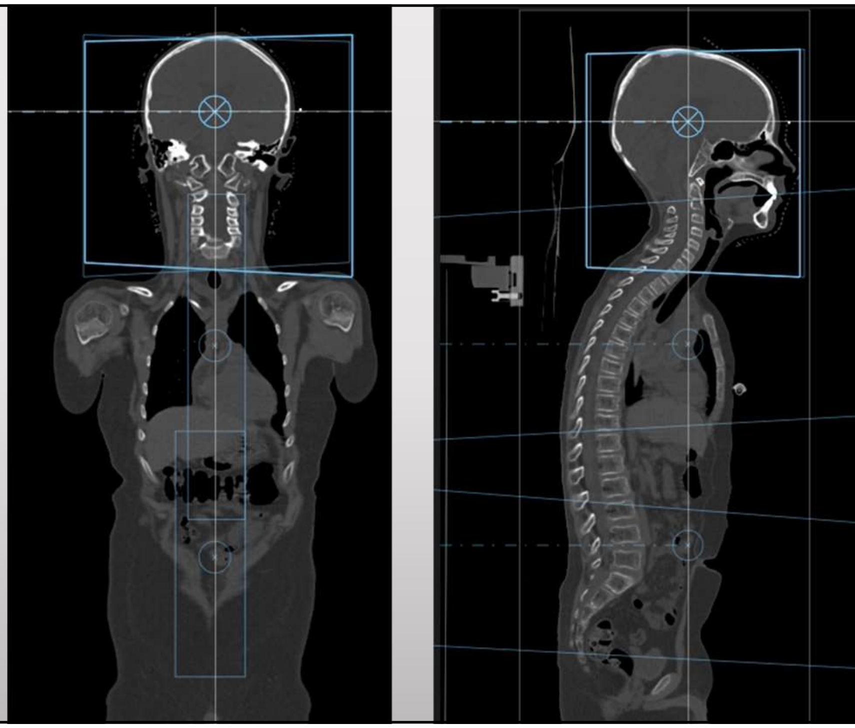


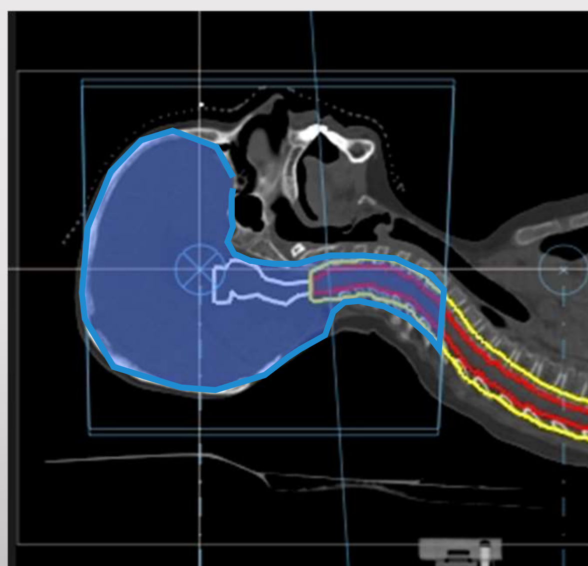
- Example: IMPT with independent beams for craniospinal
- Robust PTV constraint: min 20 Gy
- If nominal uniform dose is prioritized: robust PTV objective

Planned dose

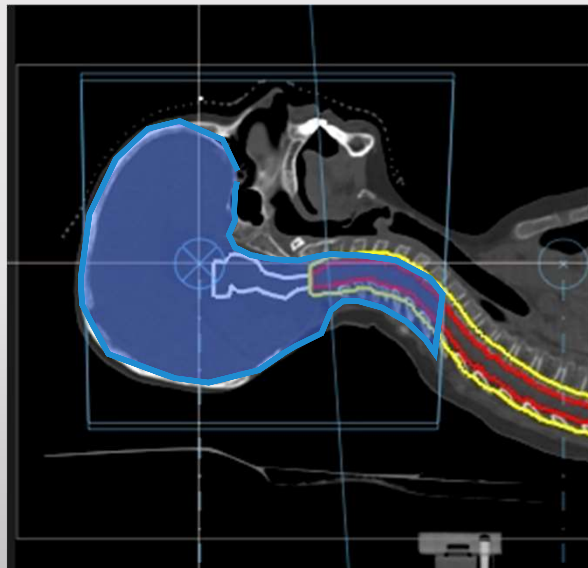
Beams moving apart

Beams moving together

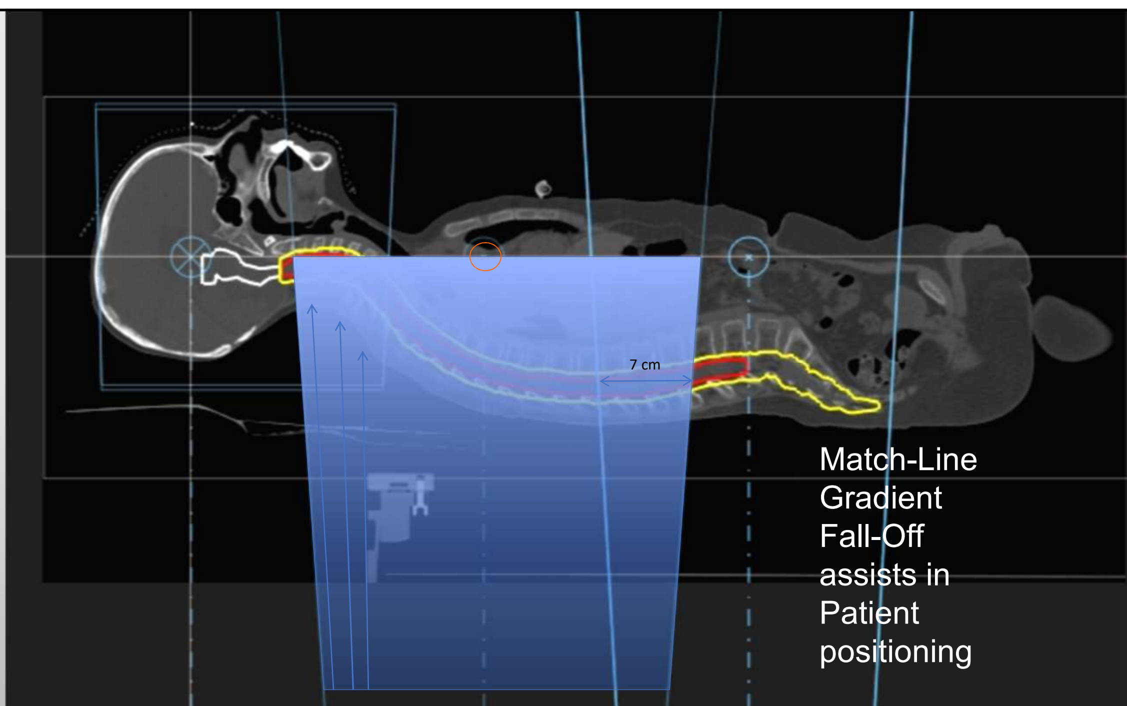




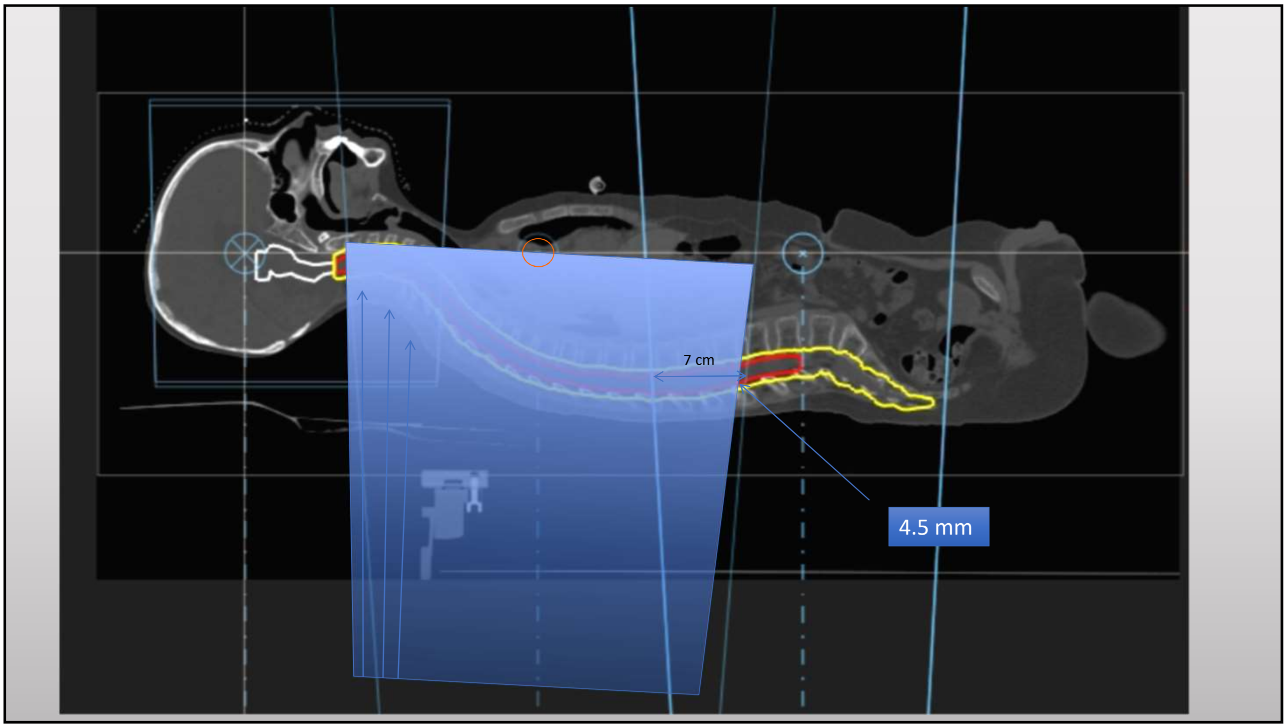
Brain
C-spine
Fields

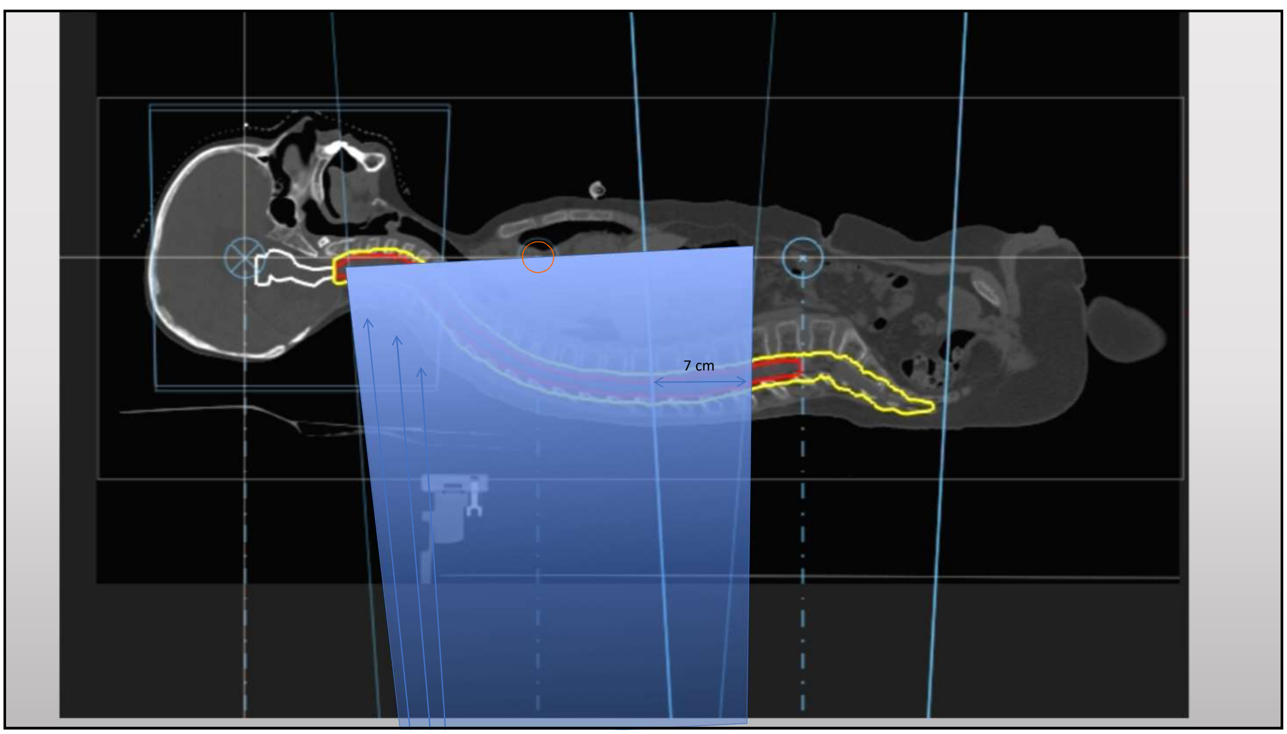


Planning to a Robust Pitch Set-up



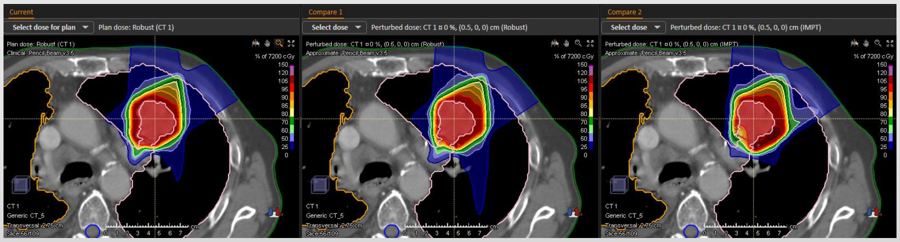
Match-Line Gradient Fall-Off assists in Patient positioning

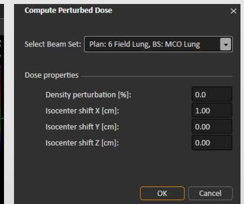

7 cm
4.5 mm

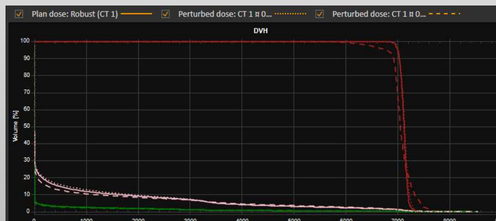

7 cm

Evaluation of robust plans

- Computation of perturbed dose

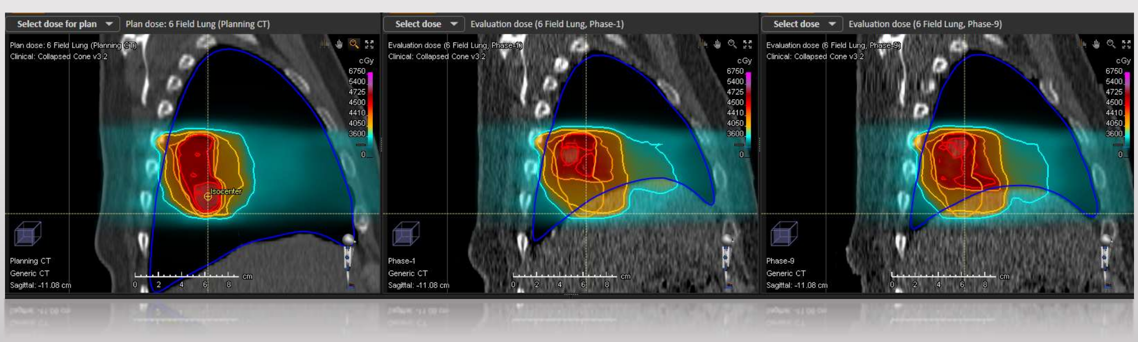






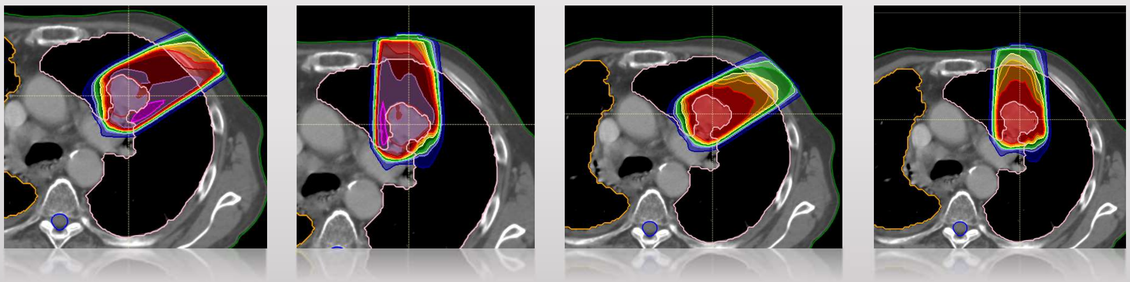
Evaluation of robust plans

- Review dose on phases

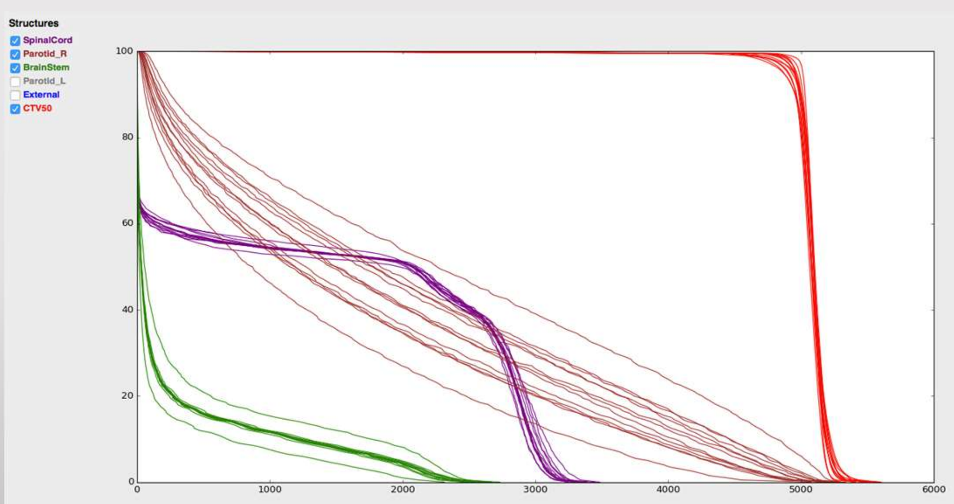


Evaluation of robust plans

- Individual beam dose



Pass Robust Evaluation



What did we achieve?

- Robust Parameters
- Setup and range uncertainties
- Robust Optimization – min/max
- Planning to Pass Robustness Scenarios

Mitigating Setup and Range Uncertainty

- Steep dose gradients cause hot and cold spots during perturbations
- Beam by beam uniform dose – Single Field Uniform Dose (SFUD)
  - Can still lead to hot and cold spots when perturbed because the patient is heterogeneous and the beams use intensity modulated fluence maps (even with SFUD)

Robust observations

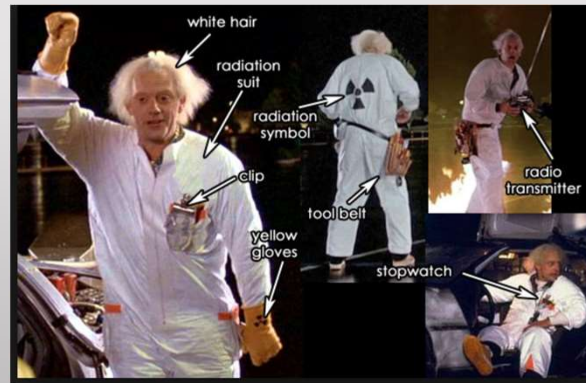
- Robust planning- with many scenarios can increase computation time.
- Plans look different
  - Cover multiple scenarios and data sets as opposed to just the one snapshot in time
- Proton planners understand the need for Robustness, using it in most cases!
- Photon planners are cautious as to how it will change or improve their planning process
  - Perhaps better understand the results?

Future of planning with robust optimization

- **Can we eliminate ICRU 50 definitions one day?**
  - Perhaps only the PTV, CTV must stay
- **Automation**
  - Scripting and protocols exist today but will robustness be inherent in all future plans?
- **Many more variables being accounted for in the optimization?**
  - More organ motion or prediction
  - May reduce the need for adaptive therapy?

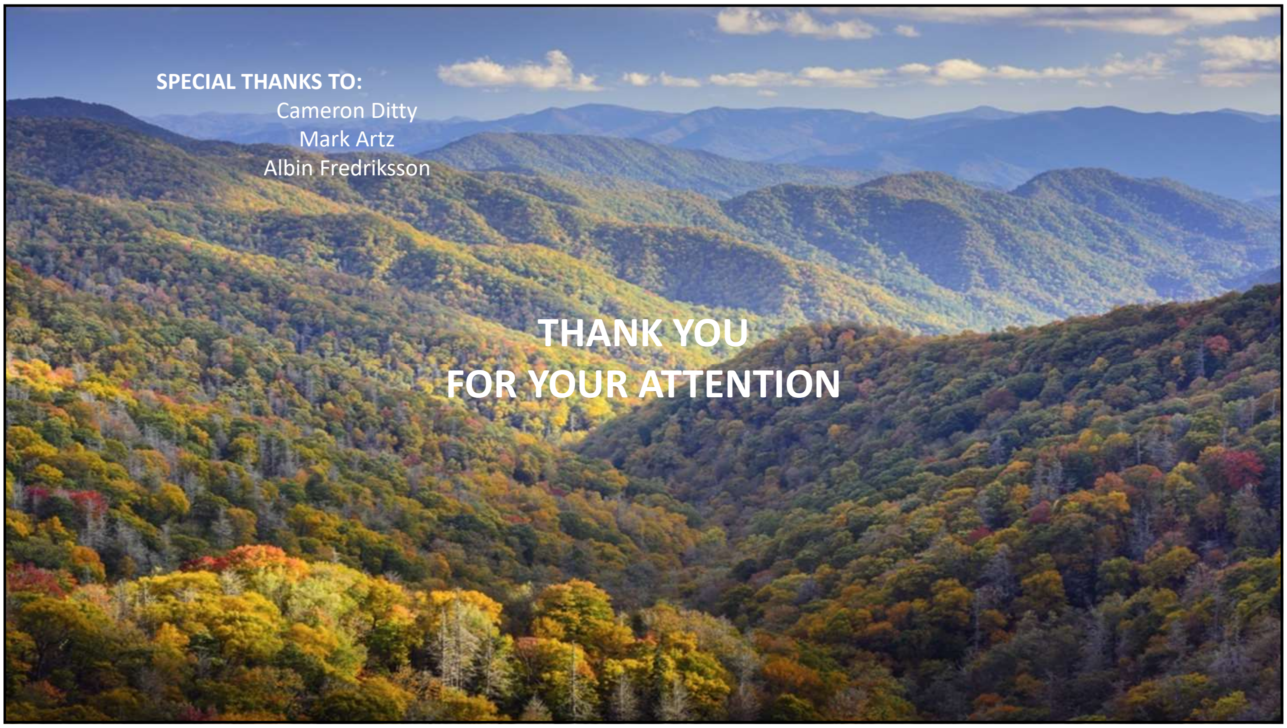
Future of planning with robust optimization

- **Future evaluation**
  - Simulated treatments
  - Generation of probability in fulfilling clinical goals
- **Knowledge building for future cases**
  - How many scenarios are needed?
  - Weight loss prediction?



Conclusions

- Using planning margins is a heuristic solution that doesn't always work
- Explicitly incorporating the actual goal into the optimization is necessary for protons
- Robustness also solves other problems, such as field matching and flash in photon planning
- Many more scenarios can be included going forward, making Robustness applicable in other planning cases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FOR YOUR ATTENTION