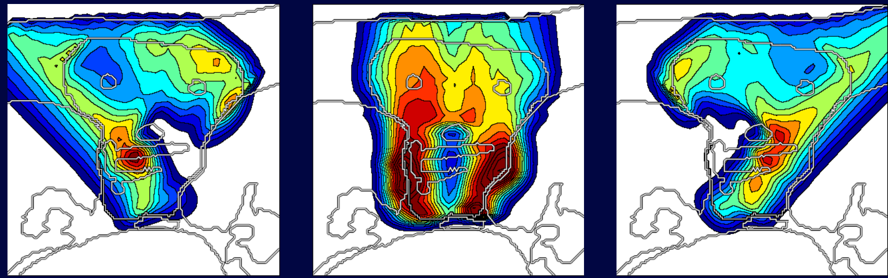


MASSACHUSETTS GENERAL HOSPITAL
CANCER CENTER℠

Why the safety margin concept is insufficient in particle therapy

Techniques for handling range and setup uncertainty in intensity modulated proton therapy

J. Unkelbach, B. Martin, T. Bortfeld

Content:

1. Motivation

- why IMPT plans may be very sensitive to errors

2. Results -- Outline

- Features of more robust plans

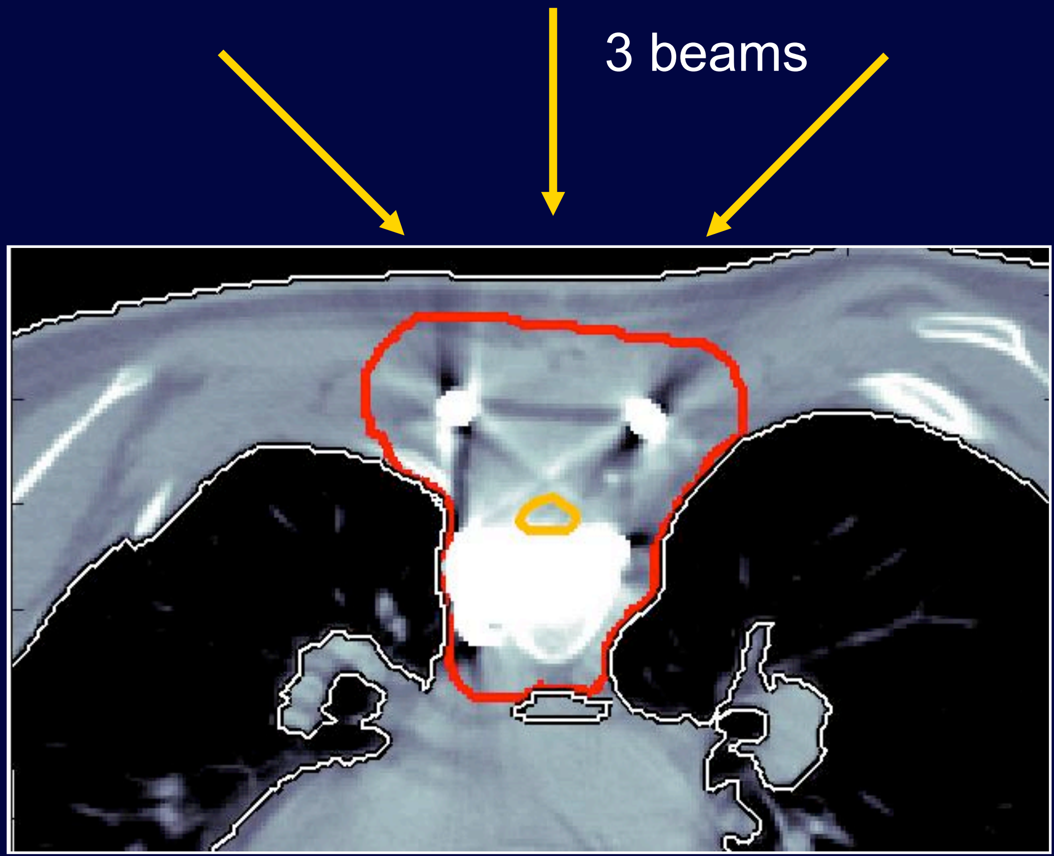
3. Methods

- probabilistic approach to obtain robust plans

Following Talk by D. Pflugfelder:

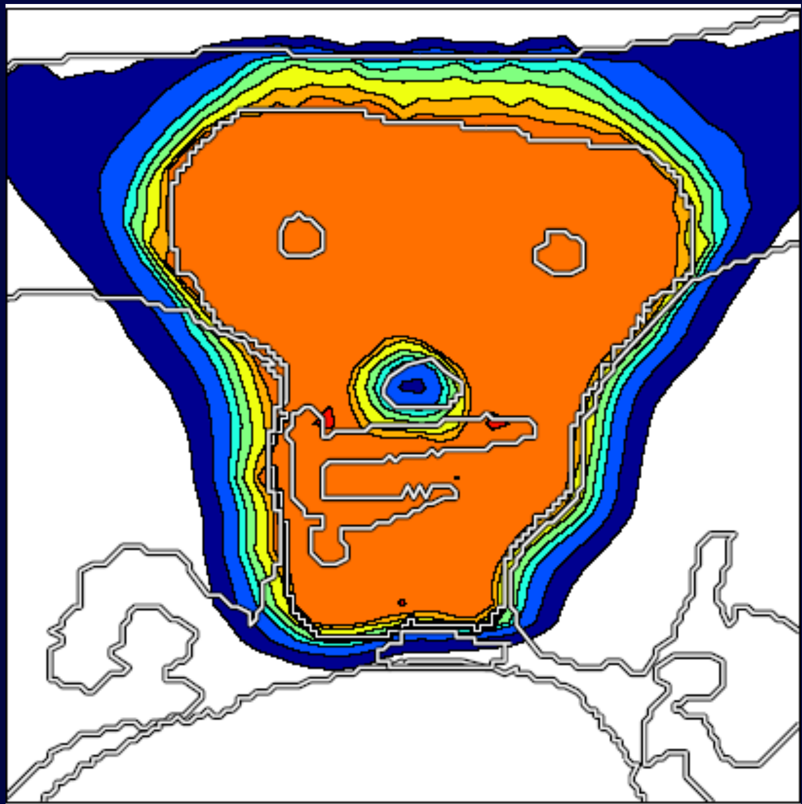
- worst case optimization
- more results

Example: Para-spinal case:



- IMPT technique:
  3D spot scanning
  (5mm σ, 5mm grid)
- range uncertainty
  (e.g. due to metal implants)
- setup error

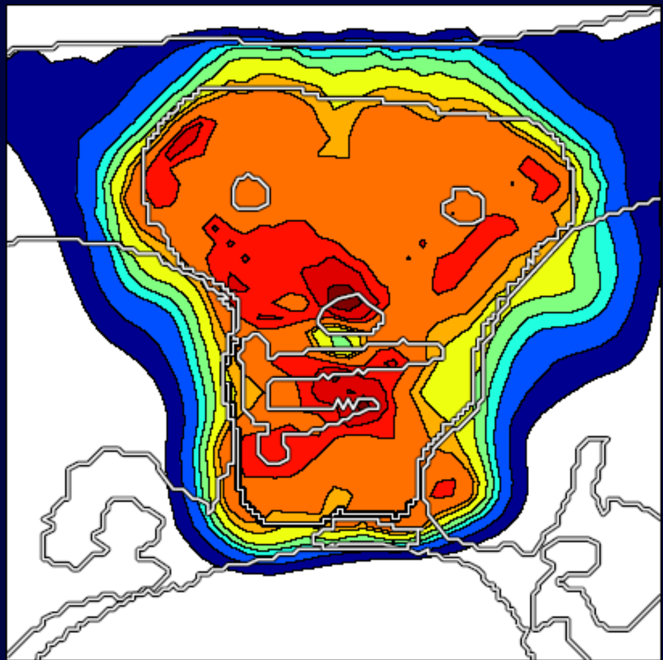
"Conventional" IMPT treatment plan:



- highly conformal and homogeneous dose distribution if
  - the assumed range for each pencil beam is realized
  - no setup error occurs

Sensitivity analysis: range overshoot

→ strongly degraded dose distribution the actual range differs from the assumed range

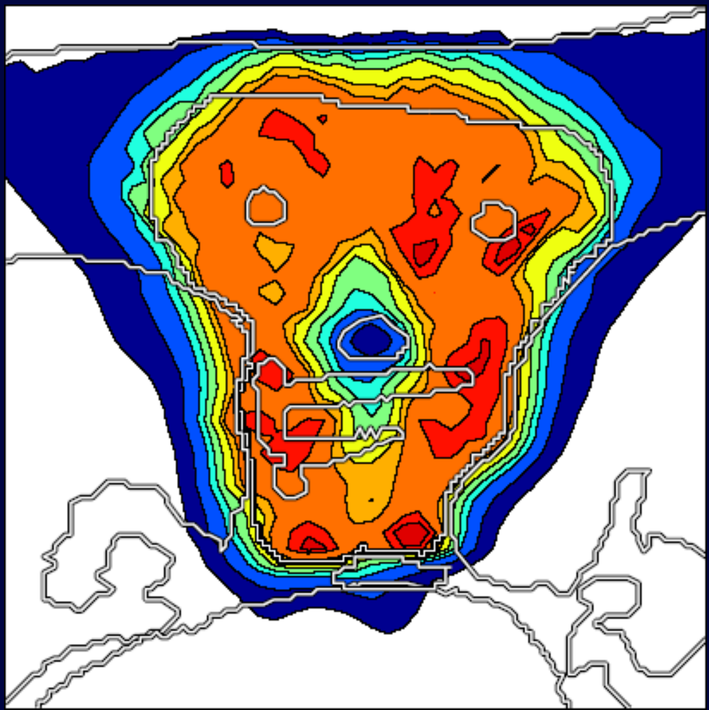


(5 mm range overshoot)

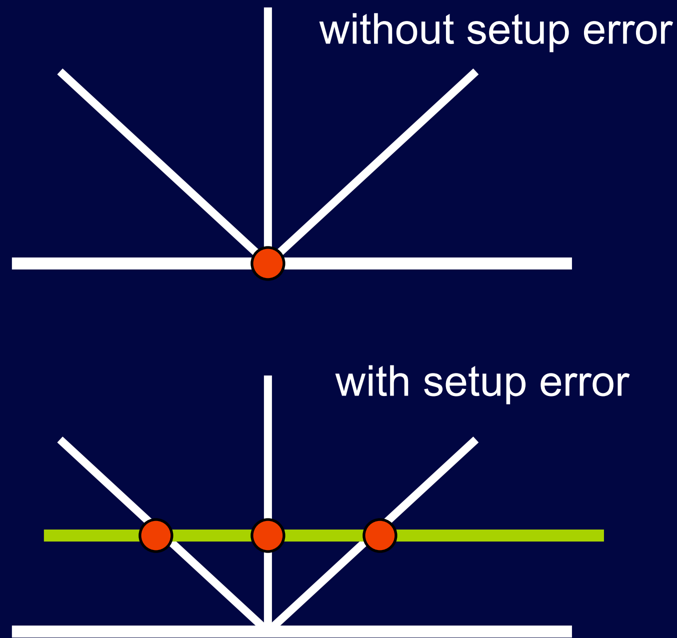
- very high dose is delivered to the spinal cord
- cold spots in the CTV

Sensitivity analysis: setup errors

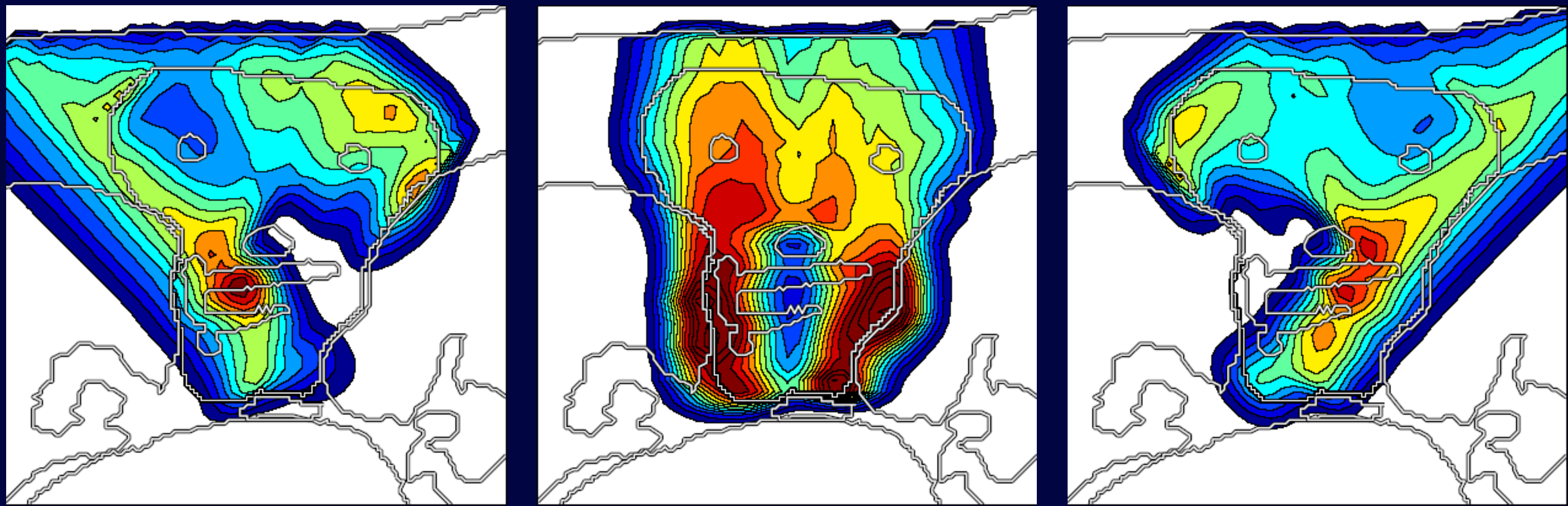
→ effect of relative shift of beams



(3.5 mm setup error posterior (up))



Why?



- dose gradients in beam direction
  - → sensitive to range variations
  - → risk of overdosing the OAR
- dose gradients horizontally
  - → sensitive to setup errors

How can IMPT plans become less sensitive?

- <u>By redistributing the dose among the beam directions</u>

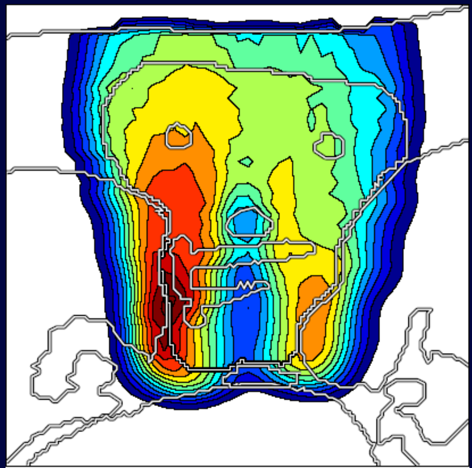
How?

- safety margins do not help
- can only be achieved by incorporating uncertainty directly into the optimization
- so that the optimization can take advantage of the physical characteristics of the pencil beam and features of a specific uncertainty

Results
(outline)

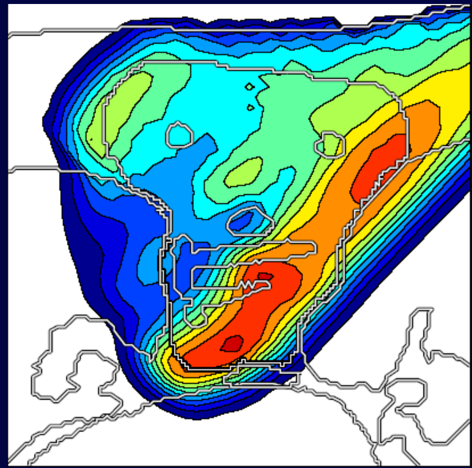
Including a Gaussian range uncertainty (σ=5mm)

beam at 0 degrees

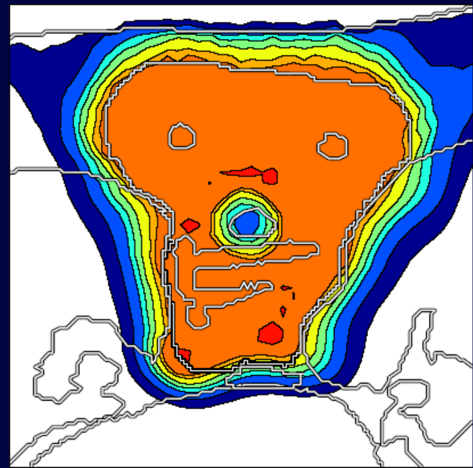


(including range variation)

beam at 45 degrees

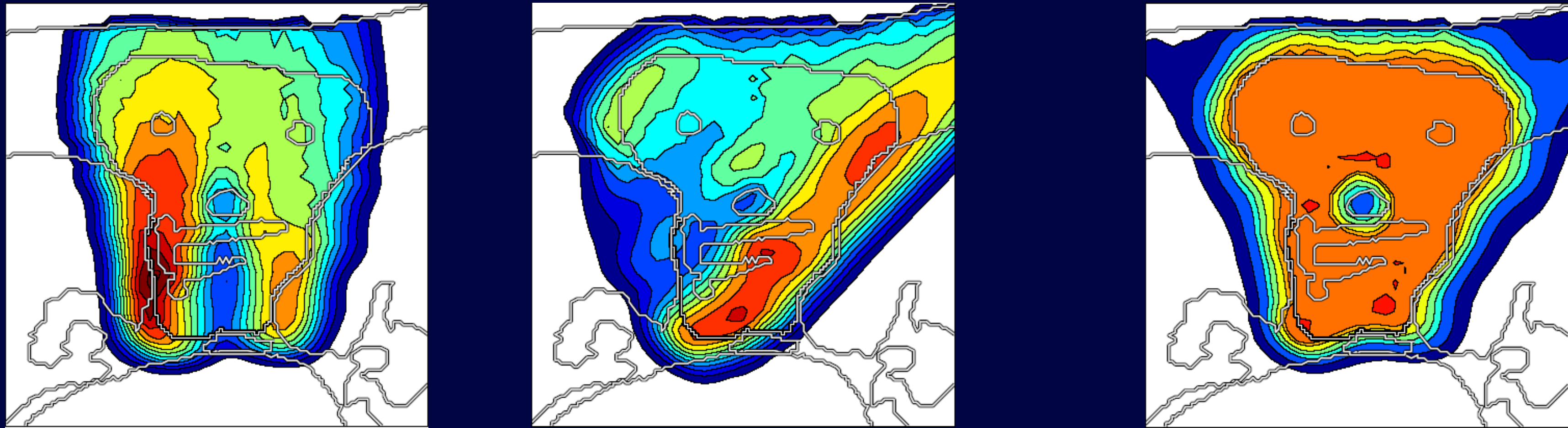


cumulative dose

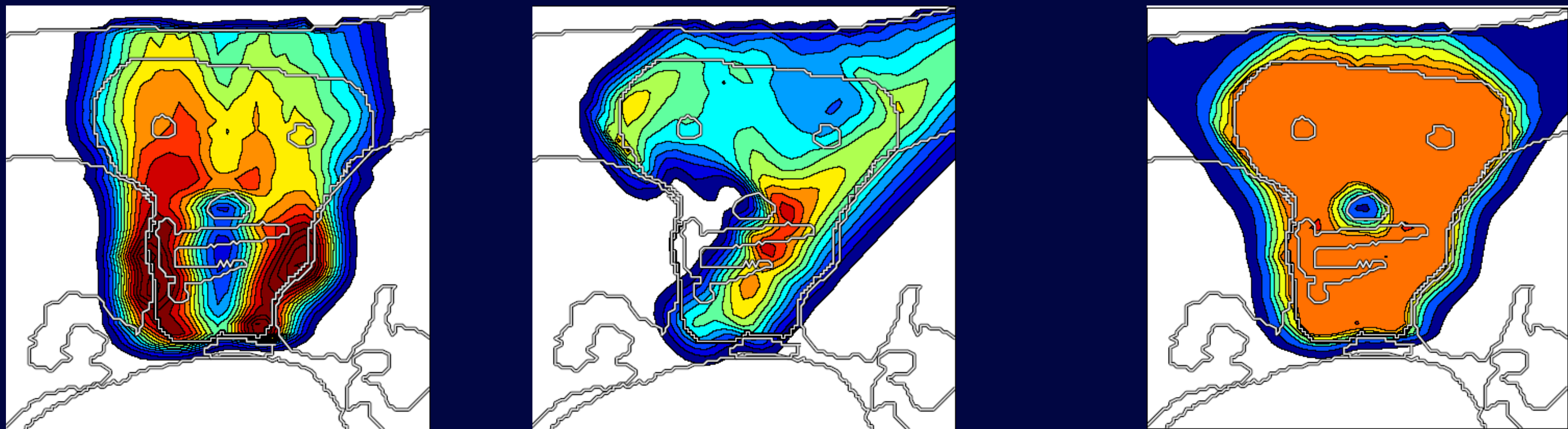


Including a Gaussian range uncertainty (σ=5mm)

beam at 0 degrees | beam at 45 degrees | cumulative dose



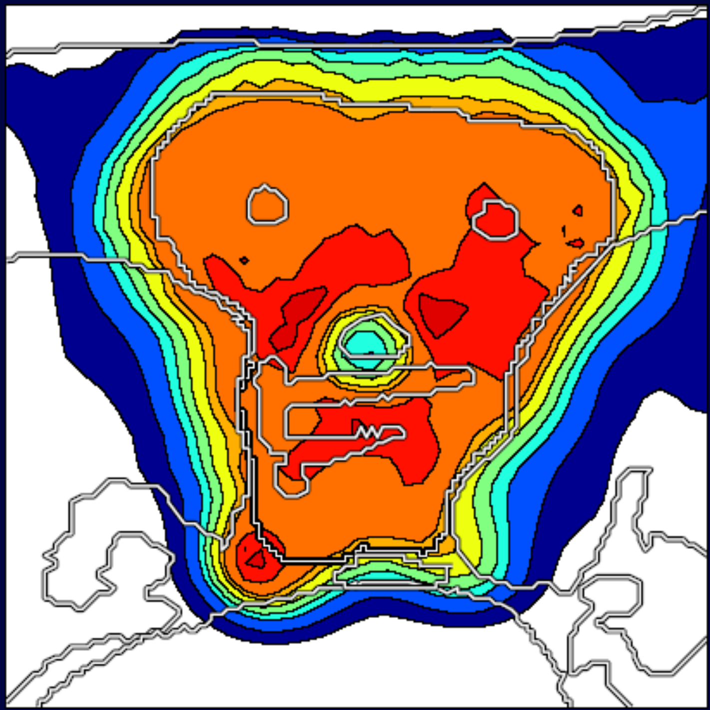
(including range variation)



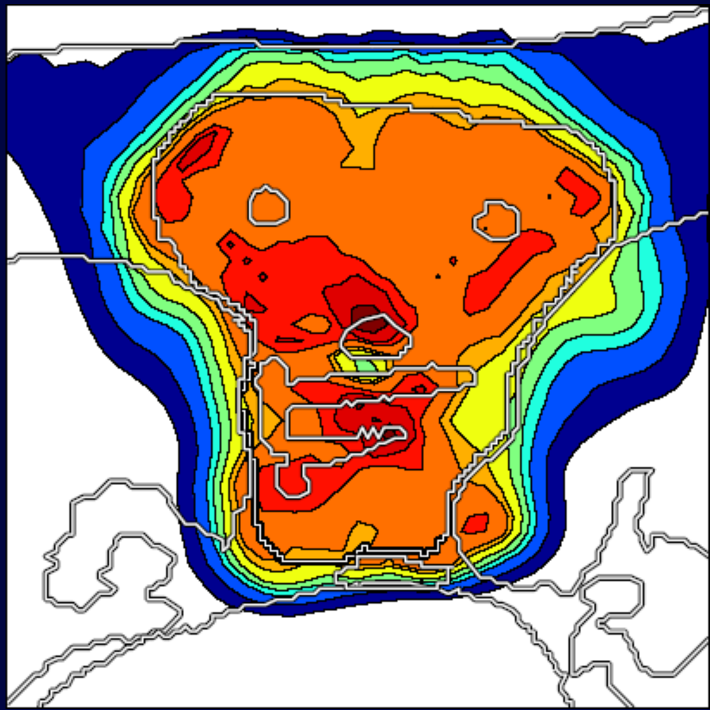
(conventional)

Including a Gaussian range uncertainty (σ=5mm)

plan comparison for 5 mm range overshoot



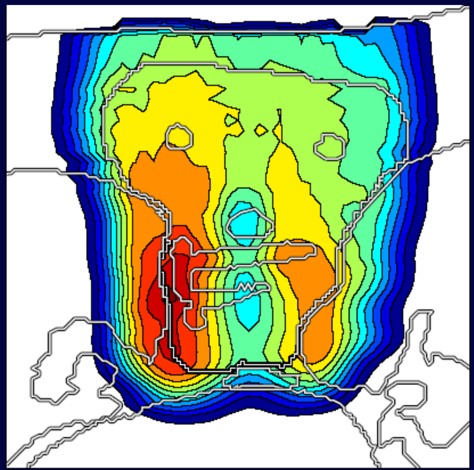
(including range error)



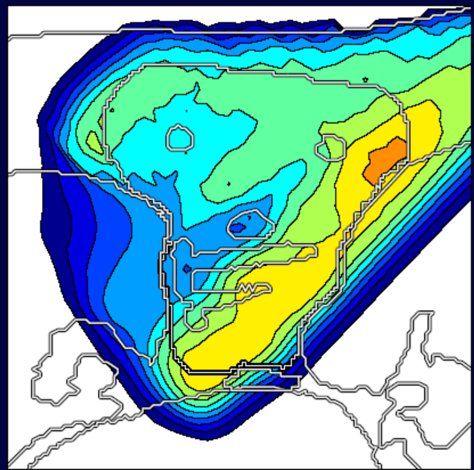
(conventional)

Including both, setup (2.5mm) and range uncertainty (5mm)

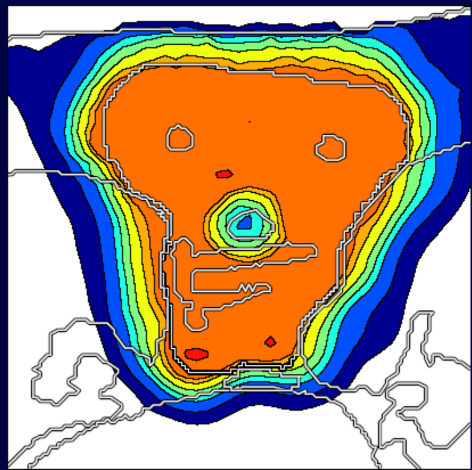
beam at 0 degrees



beam at 45 degrees



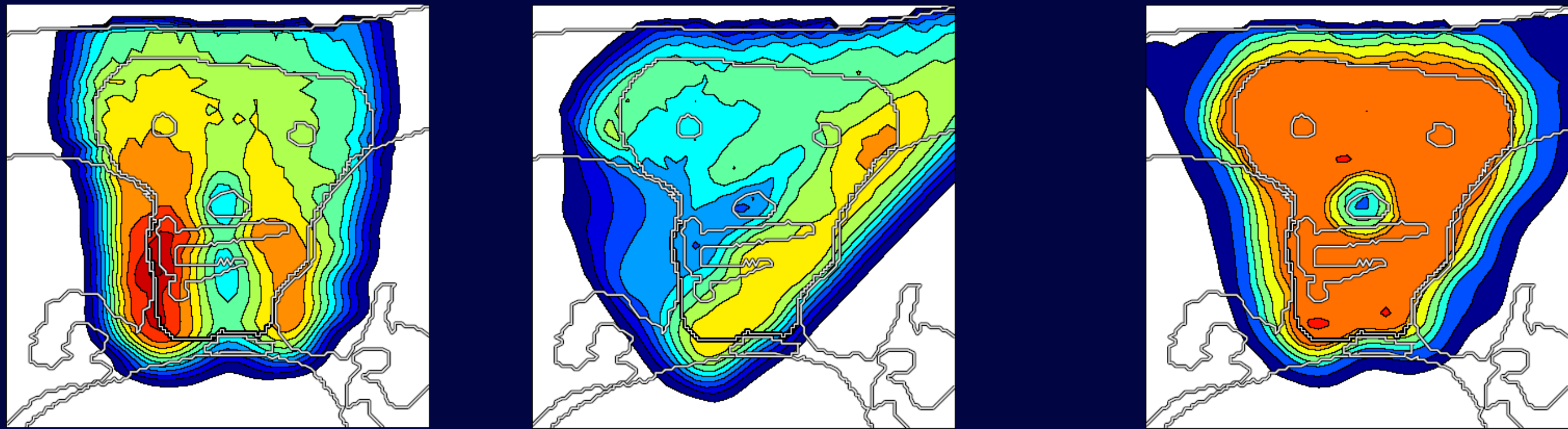
cumulative dose



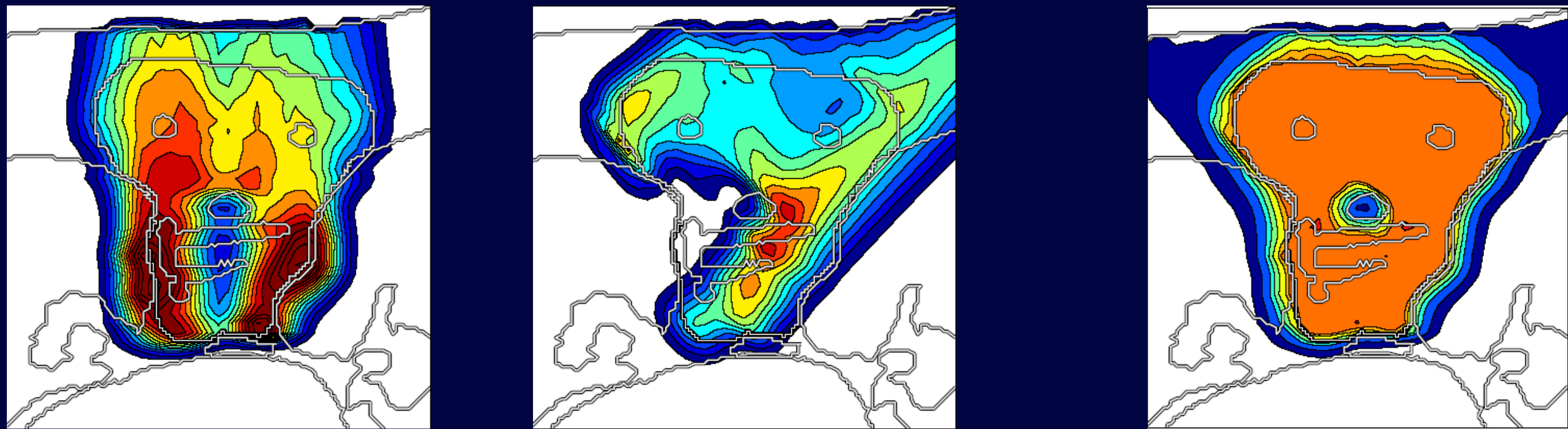
(including range and setup variation)

Including both, setup (2.5mm) and range uncertainty (5mm)

beam at 0 degrees | beam at 45 degrees | cumulative dose



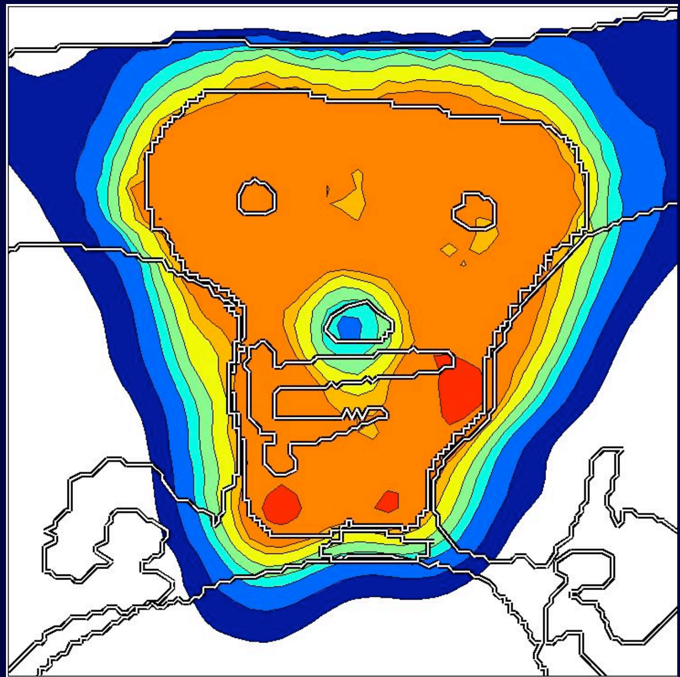
(including range and setup variation)



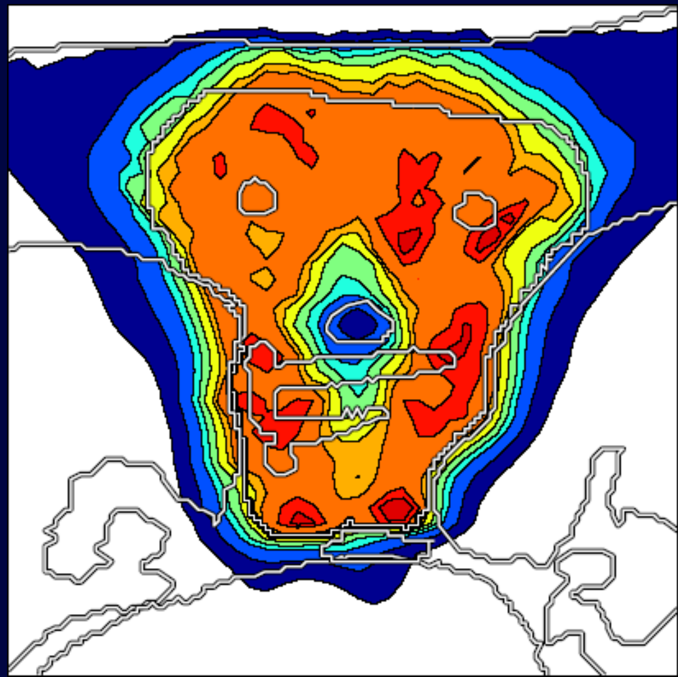
(conventional)

Including both, setup (2.5mm) and range uncertainty (5mm)

plan comparison for 3.5 mm shift posterior



(including uncertainty)



(conventional)

Methods

Including uncertainty into the optimization

dose depends on uncertain parameters

λ (range, setup error)

stochastic programming

robust optimization

Including uncertainty into the optimization

dose depends on uncertain parameters

$\boldsymbol{\lambda}$ (range, setup error)

stochastic programming

robust optimization

probability distribution

$$P(\boldsymbol{\lambda})$$

minimize expected value of objective

$$E_\lambda[C] = \int C(\boldsymbol{D}(\boldsymbol{x}, \boldsymbol{\lambda}))\, P(\boldsymbol{\lambda})\, d\boldsymbol{\lambda}$$

Including uncertainty into the optimization

dose depends on uncertain parameters

$\boldsymbol{\lambda}$ (range, setup error)

stochastic programming

probability distribution

$$P(\boldsymbol{\lambda})$$

minimize expected value of objective

$$E_\lambda[C] = \int C(\boldsymbol{D}(\boldsymbol{x},\boldsymbol{\lambda}))\, P(\boldsymbol{\lambda})\, d\boldsymbol{\lambda}$$

robust optimization

uncertainty set

$$\lambda_j \in [\lambda_j^{min}, \lambda_j^{max}]$$

minimize worst case objective

$$\underset{\boldsymbol{x}}{\text{minimize}} \quad \max_{\boldsymbol{\lambda}} \left[C(\boldsymbol{D}(\boldsymbol{x},\boldsymbol{\lambda}))\right]$$

Multi-criteria interpretation of the objective:

$$E_\lambda[C] = \int C(\boldsymbol{D}(\boldsymbol{x}, \boldsymbol{\lambda}))\, P(\boldsymbol{\lambda})\, d\boldsymbol{\lambda}$$

- objective is weighted sum, where each term reflects plan quality for a given range and setup error
- importance weight reflects the probability of occurance

Techniques to solve the optimization problem

Challenges:

- computationally demanding
  - integral over all possible errors has to be solved in every iteration

→ stochastic gradient methods are used to solve the optimization problem

→ estimate the gradient by taking a subset of voxels and scenarios

Conclusion

- IMPT plans may be sensitive to both range uncertainties and setup errors
- Safety margins do not work for IMPT
- Robustness is achieved by redistributing the dose contributions from individual beams
- Can be realized by incorporating uncertainty into the optimization problem