Quantifying robustness and calculating the probability of meaningful error in proton radiotherapy delivery utilizing a dense D_{ij} matrix

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Robust Optimization

- **Systematic errors** from the range uncertainties of proton radiation therapy can cause significant underdosing of targets or overdosing of healthy tissues
- **Robust Optimization** mitigates these risks by yielding a treatment plan that incorporates uncertainties, often including a distribution of 3-5 possibilities for proton range,

Limitations

- There are currently limited tools available to **evaluate robustness** and convey this information to the physician.
- Incorporating **both range and setup uncertainties**, requires simulation of many scenarios and was formerly considered impractical

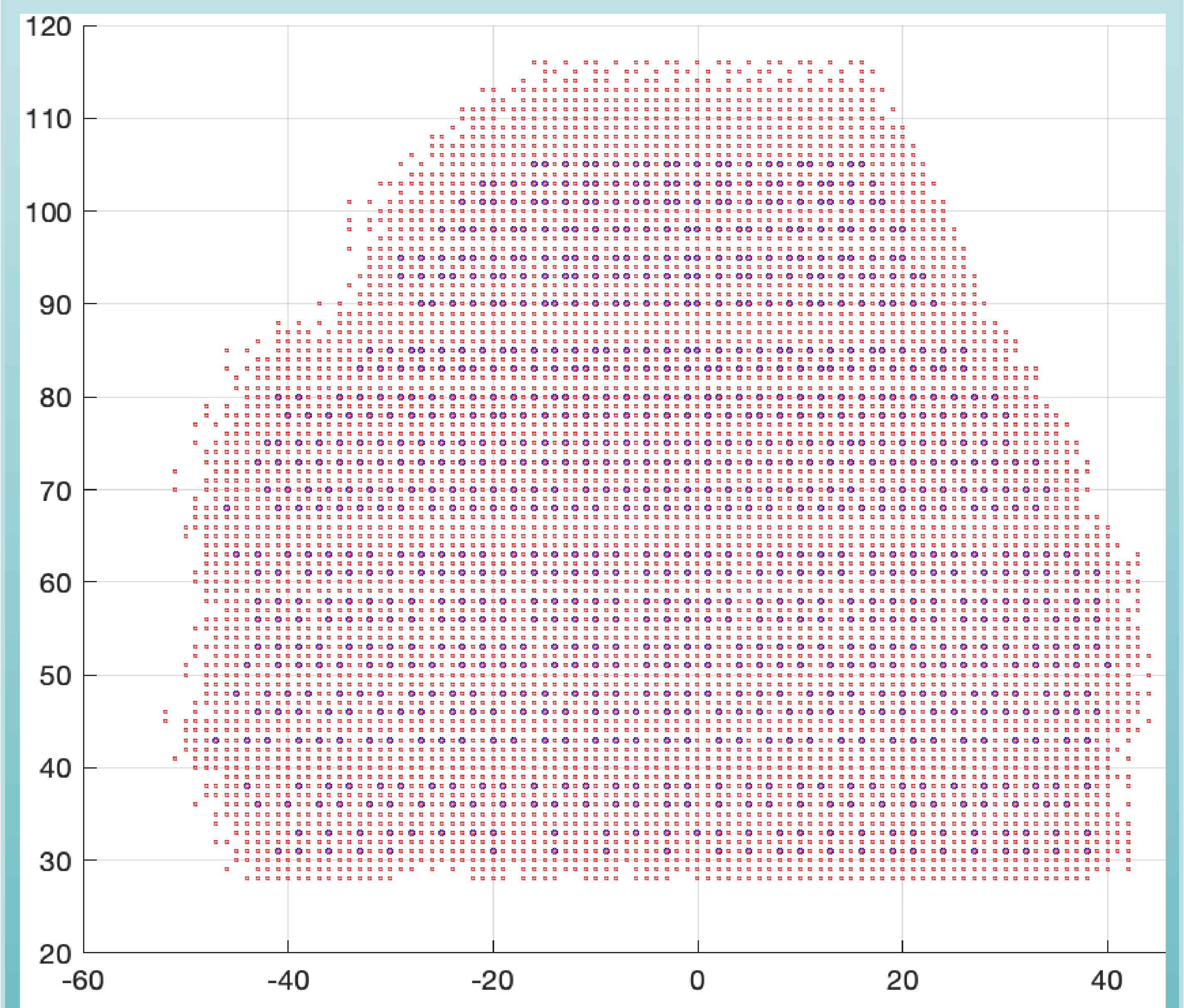
Aim: Design a streamlined platform that allows optimization and evaluation of 100 error scenarios that simultaneously considers both setup and range uncertainties

Uncertainty Models

Model	Description
Standard	No Uncertainty
"Shift0mm"	σ_{range}=3.5%; No Setup Uncertainty; n=100 scenarios
"Shift1mm"	σ_{range}=3.5%; σ_{ISO}=1mm; n = 100 scenarios
"Shift2mm"	σ_{range}=3.5%; σ_{ISO}=2mm; n = 100 scenarios
"FiveScen"	σ_{range}=3.5%; No Setup Uncertainty; n=5 scenarios

Creating Dense D_{ij} Matrix

- Considering assumed uncertainty conditions (e.g. σ_{range}=3.5%; σ_{ISO}=1mm), apply 100 random normal shifts to the isocenter and range of each beam spot in the nominal plan
- Quantize shifted beam spots of each uncertainty scenario to a dense grid with 1mm beam spot spacing
- Utilize Monte Carlo to calculate Dense D_{ij} matrix comprised of every quantized beam spot encountered in 100 scenarios.
- Employ the Dense D_{ij} matrix to efficiently calculate individual D_{ij} matrices for each of the 100 scenarios.
- Utilize the scenario D_{ij} to evaluate uncertainty and/or facilitate robust optimization
- Dense D_{ij} matrix ~35 x size of standard Dij matrix (i.e. 35% the size of simulating 100 scenarios)



Dense D_{ij} Matrix in X-Z plane. Red dots are beam spot locations in Dense D_{ij} Matrix. Blue dots are beam spot locations for an individual scenario D_{ij}, which correspond to beam spots already calculated in the Dense D_{ij} Matrix

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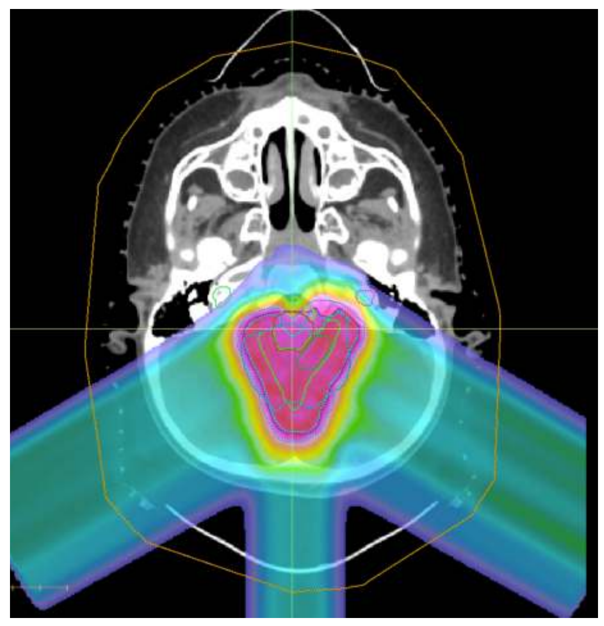
Results



4 yo with ependymoma

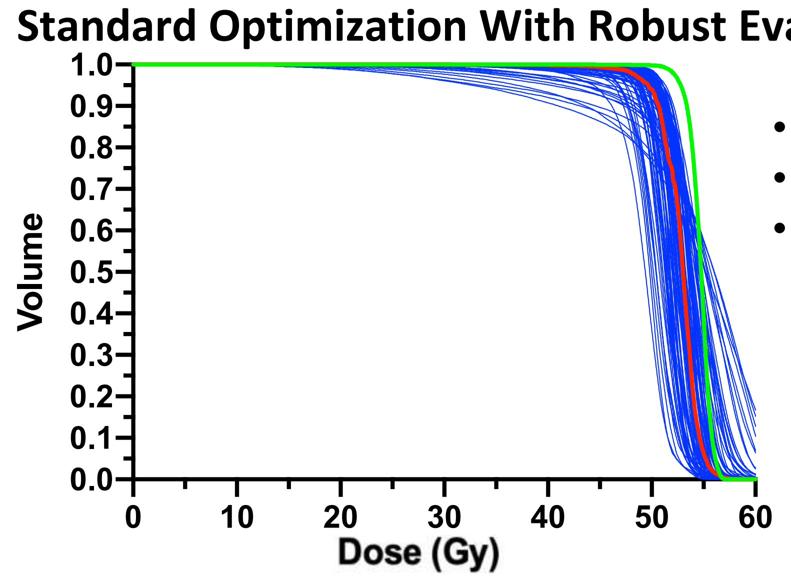
Objectives

Optimization Mean Square Error

- GTV > 54Gy**, GTV < 55.8 Gy**
- Brainstem < 56 Gy**
- Cord < 50 Gy**
- Cochlea < 45 Gy

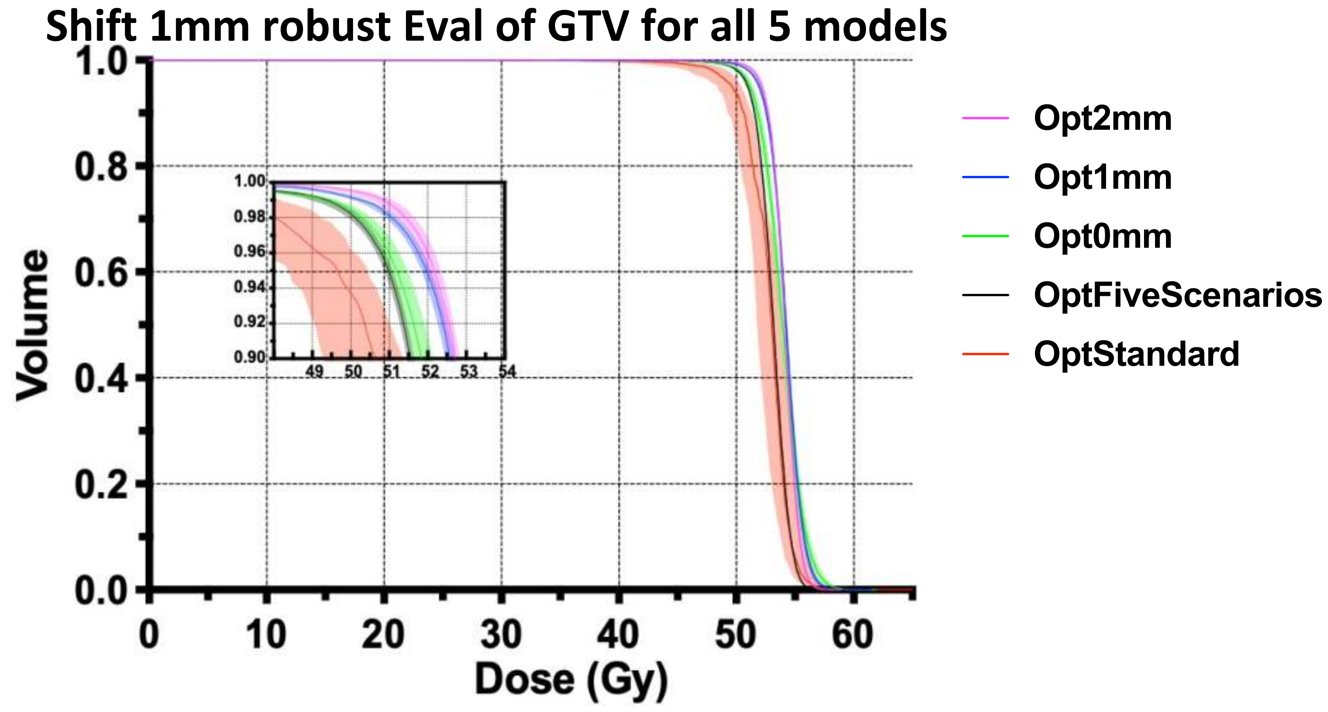
** Robust optimization for expected dose

Standard Optimization With Robust Evaluation with "Shift1mm"



- Green line = nominal scenario
- Blue lines = 100 scenarios
- Red line = median scenario

Shift 1mm robust Eval of GTV for all 5 models



(Bright lines = median DVH; Shaded regions = IQR)

GTV Statistics-Robust Evaluation with "Shift 1mm" model

	Median Min	Median D95	P(D95>50Gy)	P(D95>52Gy)
Standard	36.7 Gy	49.6 Gy	40%	0%
Shift 0mm	46.7 Gy	51.9 Gy	98%	45%
Shift 1mm	47.2 Gy	52.2 Gy	100%	61%
Shift 2mm	48.9 Gy	52.5 Gy	100%	78%
FiveScen	46.5 Gy	51.2 Gy	98%	0%

Conclusion:

- Efficient robust evaluation/optimization for both setup and range uncertainties is feasible utilizing dense D_{ij} Matrix.
- Failure to evaluate robustness may lead to a plan with substandard metrics (e.g. Standard or FiveScen)