Simulation of online treatment monitoring in carbon therapy using mixed carbon helium beams

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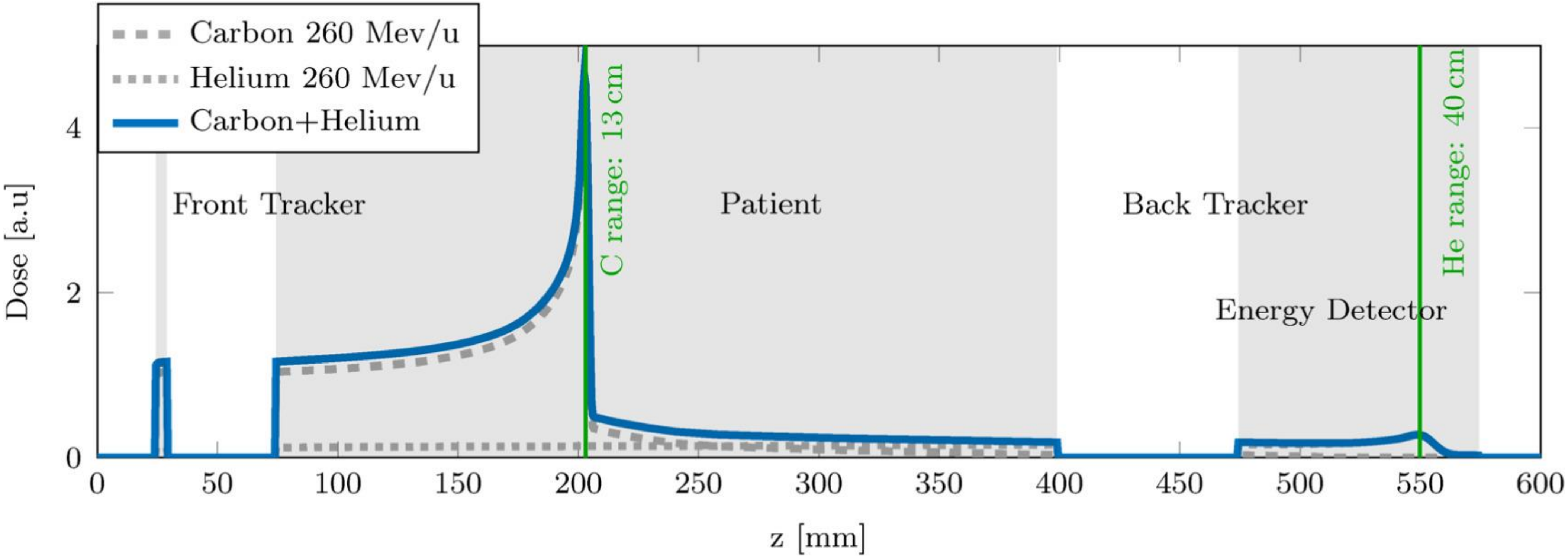
GERMAN CANCER RESEARCH CENTER IN THE HELMHOLTZ ASSOCIATION

Research for a Life without Cancer

Mixed Carbon-Helium Beam

- Radiation therapy with carbon ions – **Problem: Range uncertainties**
- Simultaneous acceleration of carbon and helium possible
- **Online range probe with a mixed Carbon-Helium(10%) beam**



Mixed Carbon-Helium Beam Dose Calculation

❖ **Helium Kernel set for pencil beam dose calculation**

- Based on carbon kernel set – assumption: same emittance, energy spectrum
- Simulation with Monte Carlo (TOAPS)
- Scored deposited energy and LET

❖ **Calculation of combined RBE weighted dose:**

- Combined dose weighted α and β values:

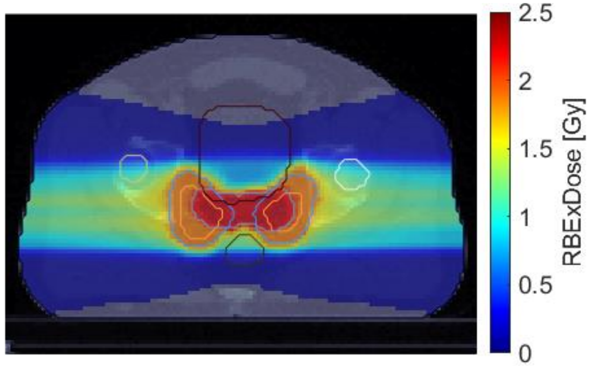
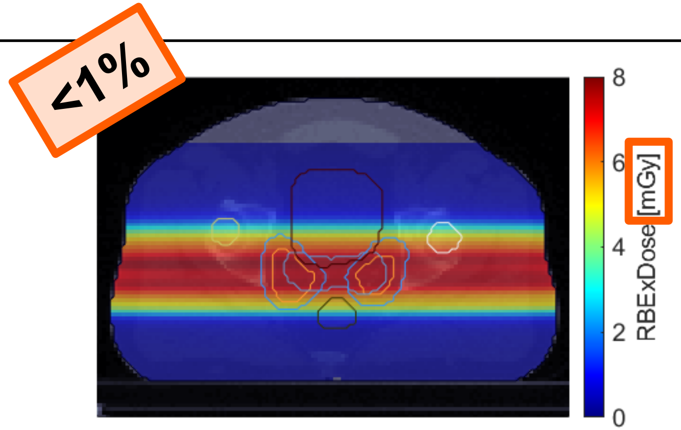
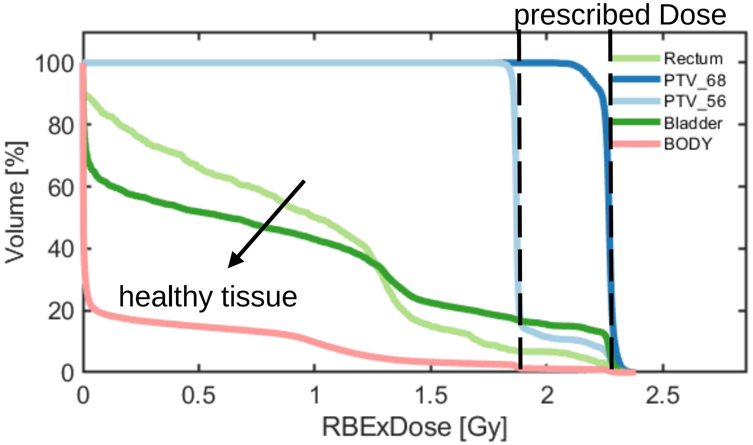
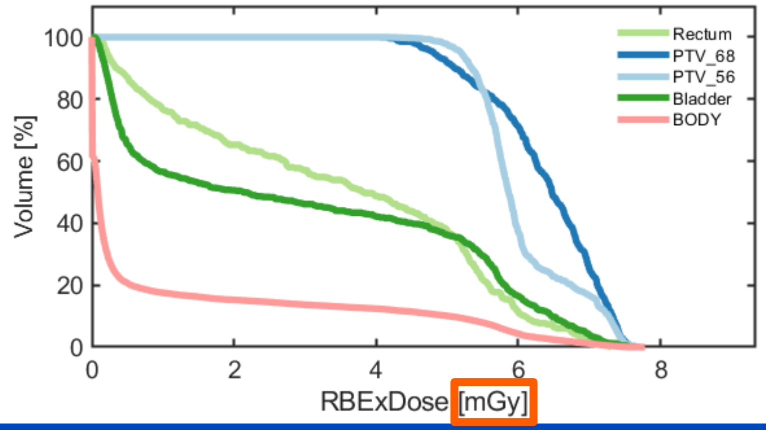
$$A_{ij} = \alpha_{ij}^{C} D_{ij}^{C} + \alpha_{ij}^{He} D_{ij}^{He}, \quad B_{ij} = \sqrt{\beta_{ij}^{C}} D_{ij}^{C} + \sqrt{\beta_{ij}^{He}} D_{ij}^{He}$$

- RBE weighted dose from effect:

$$\epsilon = A \cdot w + (B \cdot w)^2, \quad \mathrm{RBExD} = -\frac{\alpha}{2\beta} + \sqrt{\left(\frac{\alpha}{2\,\beta}\right)^2 + \frac{\epsilon}{\beta}}$$

Mixed Carbon-Helium Beam Dose

❖ Prostate patient, optimized carbon RBExDose

	Carbon-Helium RBExDose	Helium RBExDose
Axial Dose Slice		
Dose Volume Histogram		

Simulation and Reconstruction of Radiographs

Score phase space of **primary Helium** ions at tracker position

From initial/final energy calculate

$$\mathbf{WEPL = R_{Init} - R_{Final}}$$

Reconstruct **particle path** and calculate intersection point with Isocenter plane

Calculate **mean WEPL** in each image pixel

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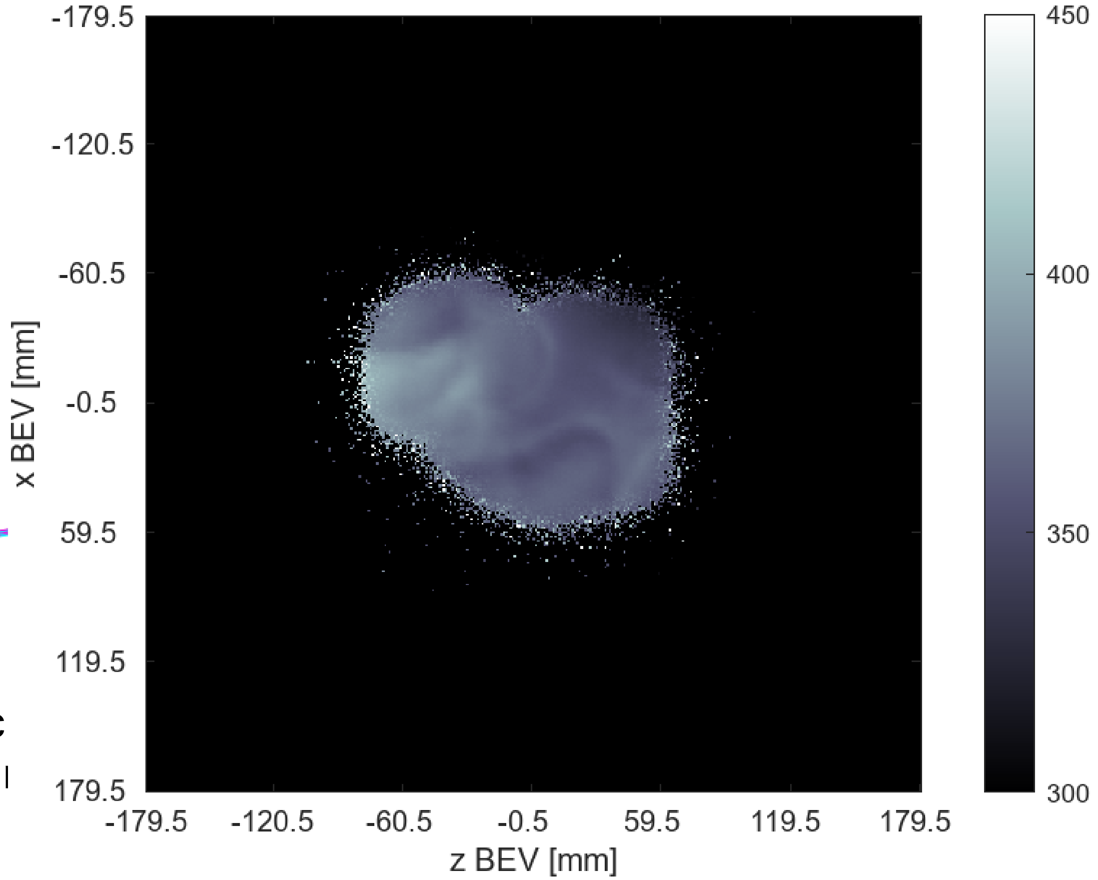

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Reconstructed radiograph of prostate case

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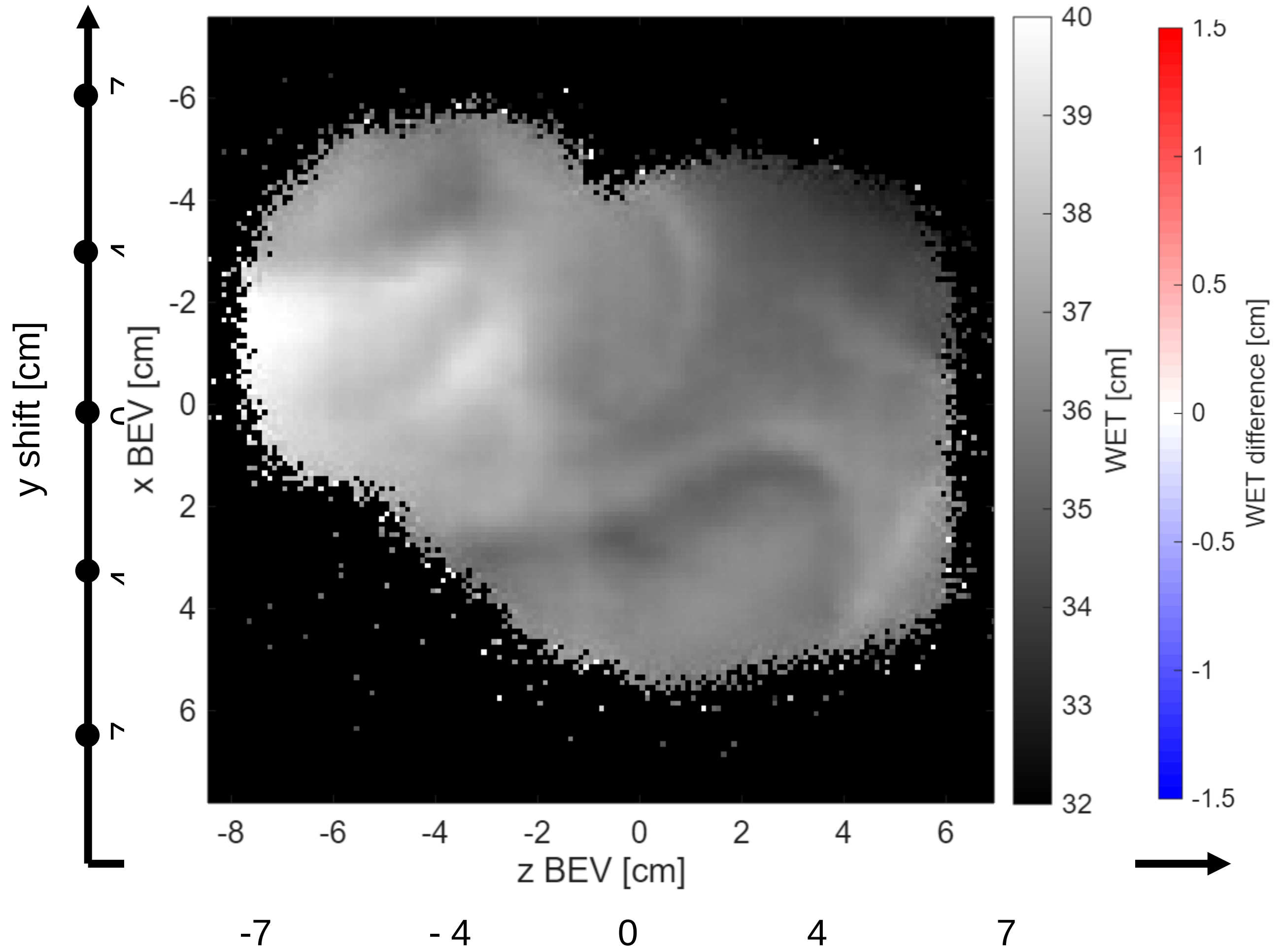
Reconstruction of Patient Position

- **Quality Assurance: Does the irradiated position of the patient conform to the planned position ?**
  - Recalculate and simulate radiographs for different patient setup error scenarios
  - Evaluate MSE to 225 reference images (planning CT) → find minimum
- **Accuracy < 1mm**



Helium Radiograph, Prostate

Difference to reference images

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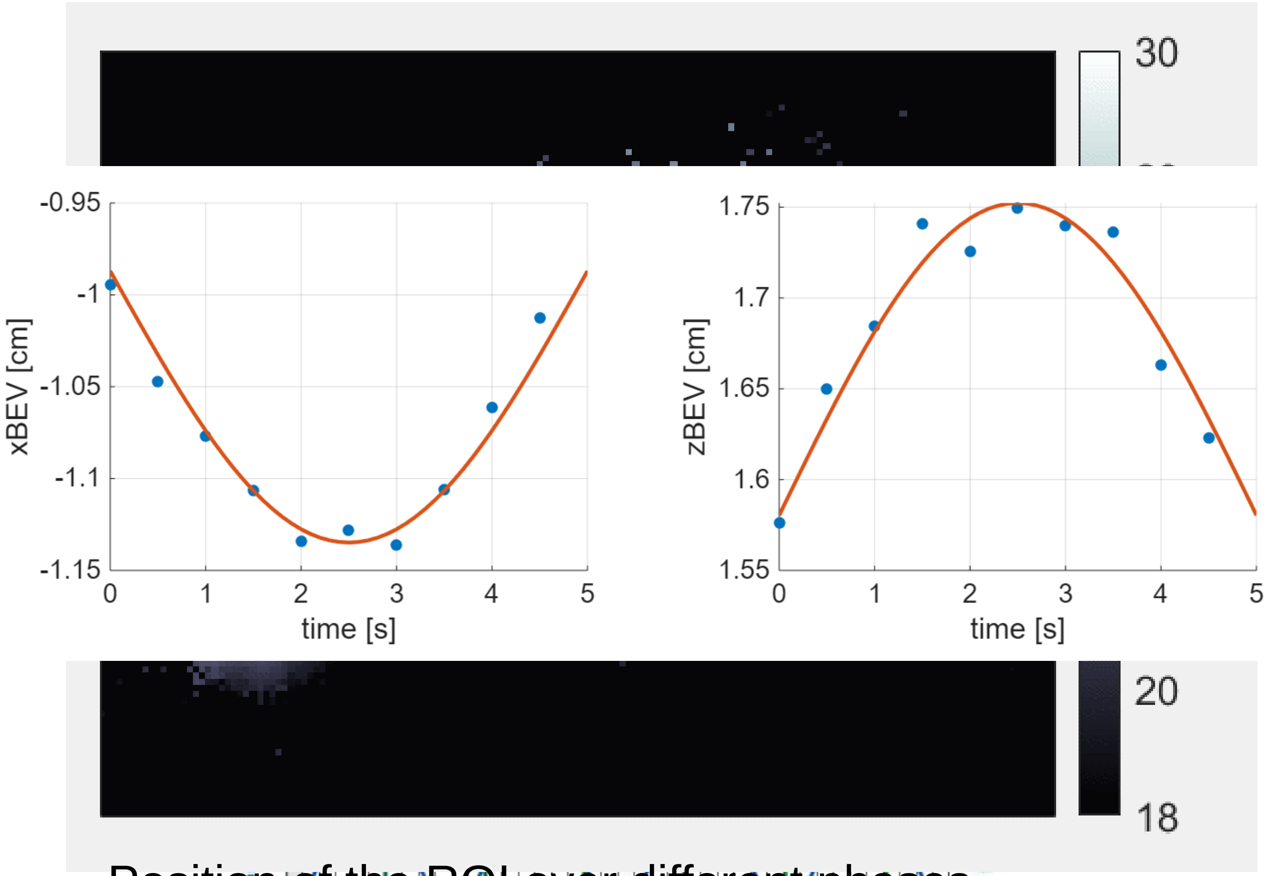
Investigation of strategies for intrafractional motion

- Relative motion between the tumor and the scanning beam causes deviations of the delivered dose distribution

- **Good to know motion/ breathing Phase during irradiation**

- minimum MSE
- Motion function: Segment spine and extract movement of COM of spine over time



Position of the ROI over different phases

Helium Radiograph (45, 223.56 MeV u),
for all 10 phases

4D CT of a Lung Patient, 10 phases, Motion Period = 5 s

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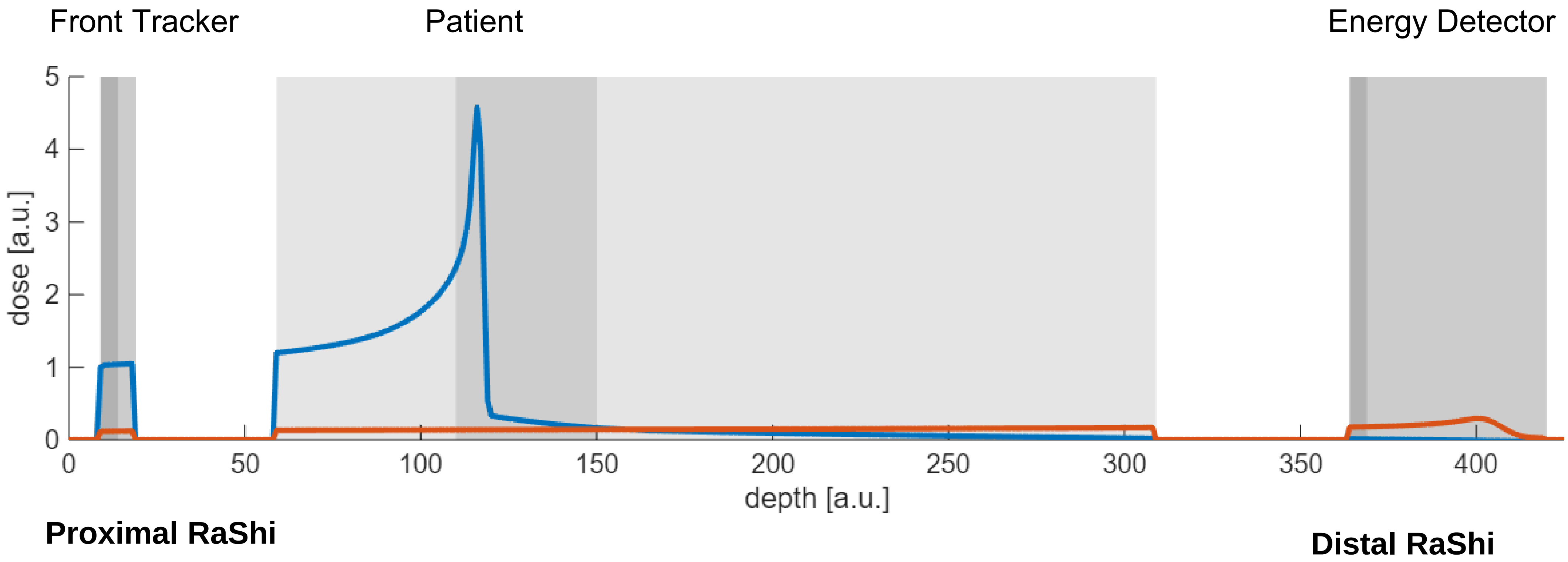
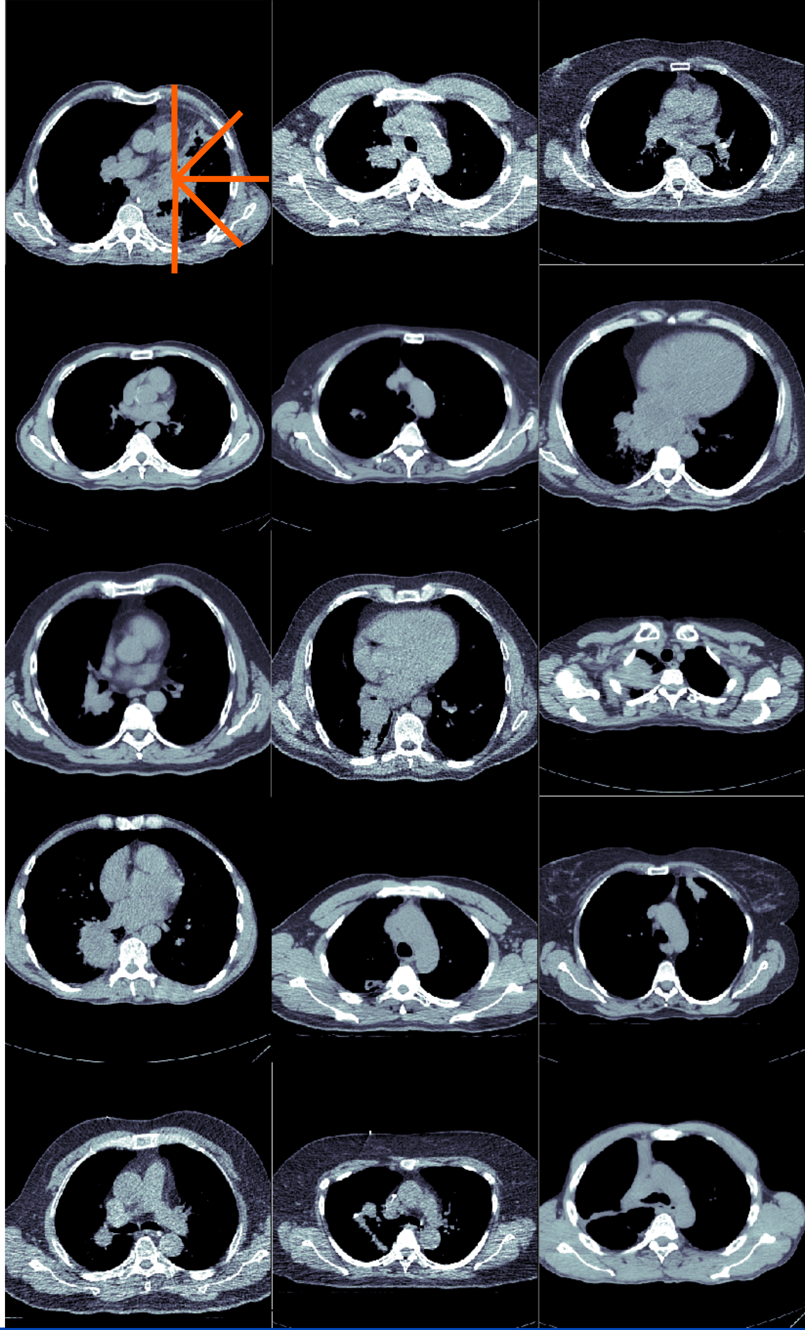
Mixed Carbon-Helium Beam Range Problem

- **Helium range not always sufficient !**
- Possible Solutions: different angle, deletion of spots, **use of range shifters**

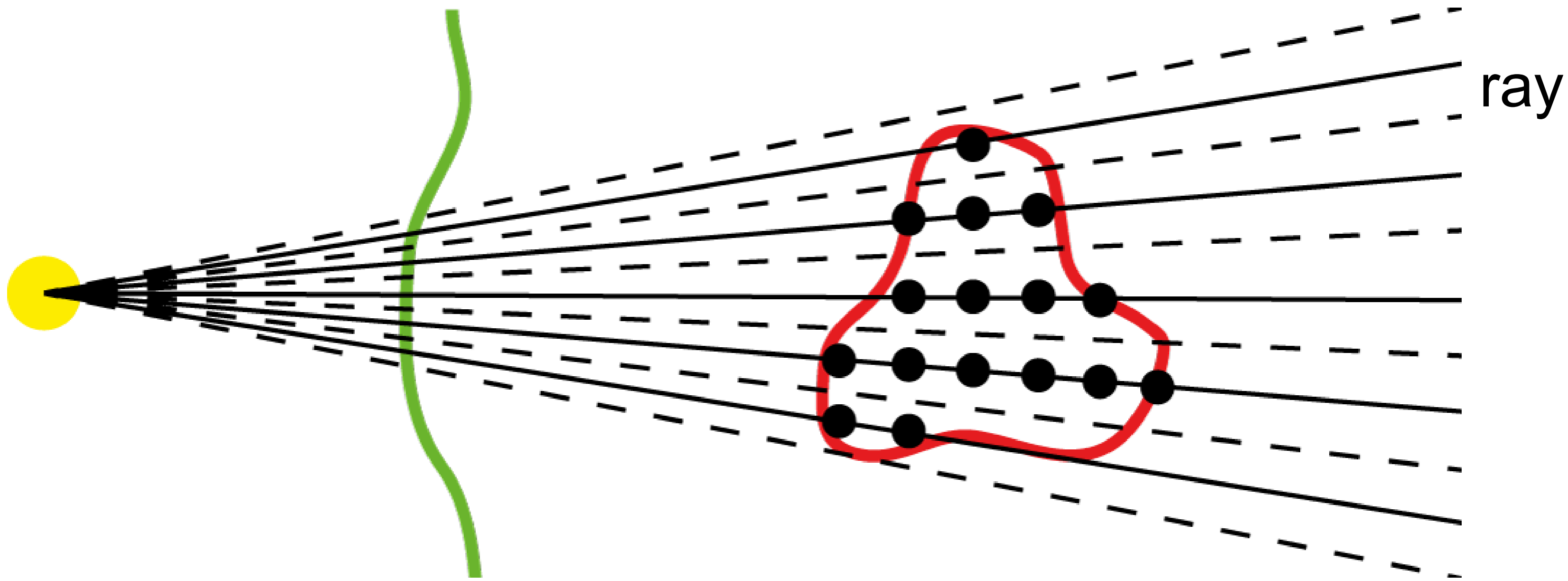


Residual range analysis Lung

- 15 patients
- 5 gantry angles (0°, 45°/315°, 90°/270°, 135°/225°, 180°)
- Gantry angle 0°: 8/15 patients have helium stopping in patient
- All angles: 47/75 patients have helium stopping in patient



Selection of Range Shifters



Schematic visualization of the ray and bixel concept

Selection of Range Shifters

Possible energy proximal RaShi combinations

$$\text{isAvaliable}(x^P, E) = (WEPL^{TargetIn} \leq R_C(E) - x^P \leq WEPL^{TargetOut}) \;\&\; ((R_{He}(E) - WEPL^{PatientOut} - x^P) > 0)$$

Is the residual helium range in detectable range of detector:

$$\text{isDetectable}(x^P, x^D, E) = R^{min} \leq (R_{He}(E) - WEPL^{DetectIn} - x^P - x^D) \leq R^{max}$$

Const RaShi

$$[x^{P*}, x^{D*}] = \underset{x^P,\, x^D}{\operatorname{argmax}} \left(w_1 \left(\sum_s \text{isDetectable}(x^P, x^D, E_s) \right) - \frac{w_2}{2}(x^P + x^D) \right)$$

spots that can be detected

WEPL of RaShi

EW RaShi

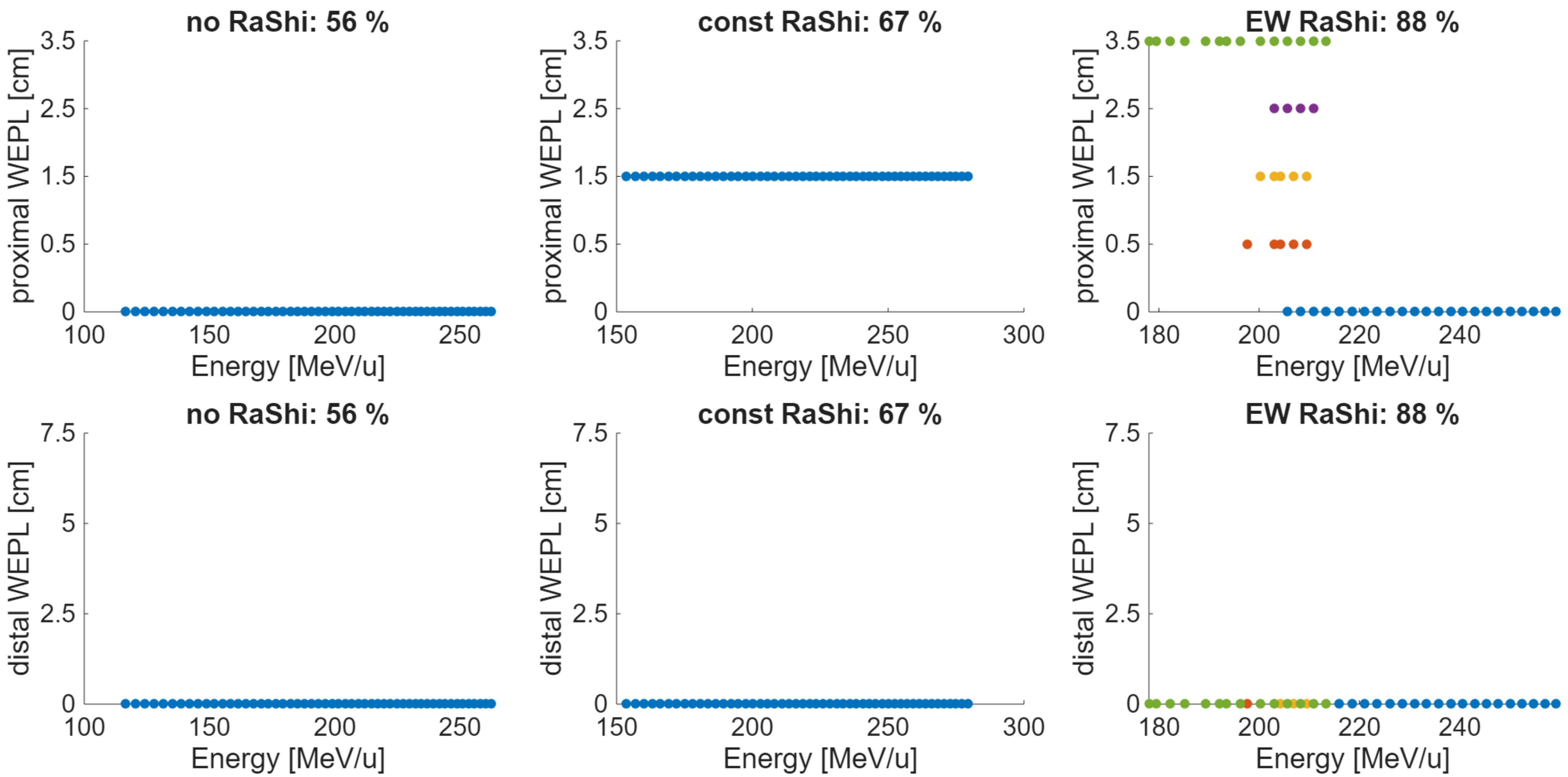
For all distal RaShi (j)

For all carbon range Intervals (i)

$$[x_{ij}^{P*}, E_{ij}^*] = \underset{x^P}{\operatorname{argmax}} \left(\sum_s \text{isDetectable}(x_s^P, x^D, E_s) \right)$$

$$x^{D*} = \underset{x^D}{\operatorname{argmax}} \left(w_1 \left(\sum_i \text{isDetectable}(x_{ij}^{P*}, x^D, E_{ij}^*) \right) - \frac{w_2}{2} \left(\sum_i (x_{ij}^{P*} + x^D) \right) \right)$$

Example Selection of Range Shifter Lung Patient



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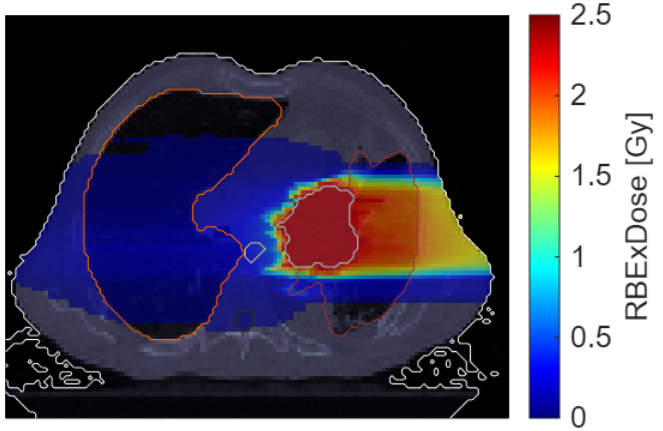
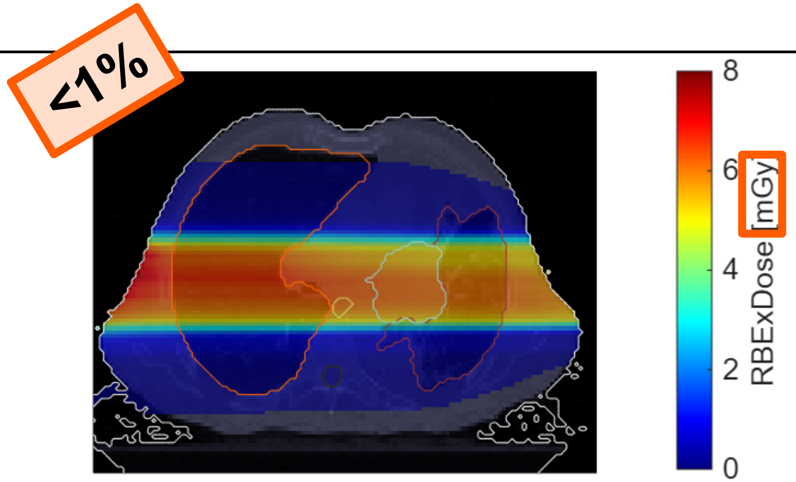
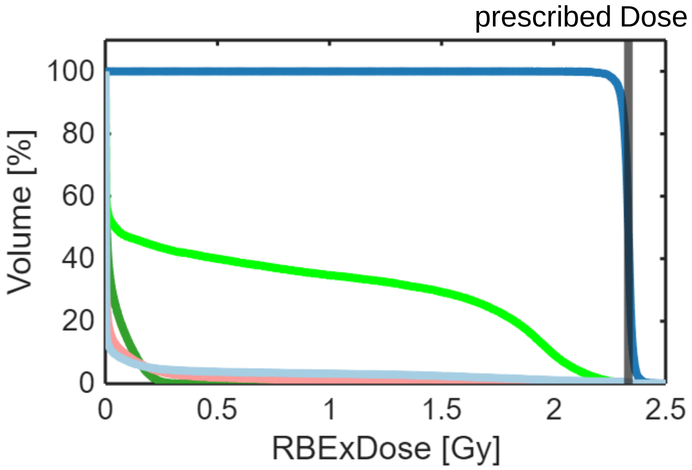
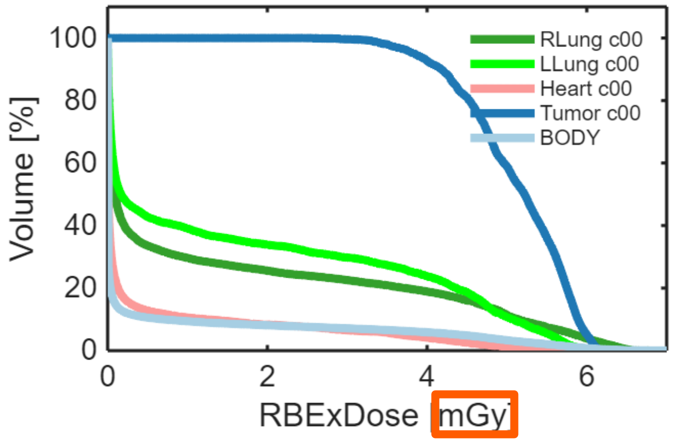
Lung Patient EW RaShi - Dose

	Carbon-Helium RBExDose	Helium RBExDose
Axial Dose Slice		
Dose Volume Histogram		

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Take Home Messages

- Developed a framework in matRad to calculate and simulate mixed beam treatment plans and corresponding radiographs
- The mixed Carbon-Helium beam method has a high sensitivity to WEPL changes inside the patient
- Motioning of anatomical changes
- **Outlook:**
  - Dose calculation and Simulation with range shifters
  - Adaption of proton radiograph detector for helium imaging

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