Scanning Beams
(Clinical Physics)

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PENN RADIATION ONCOLOGY
Penn Medicine

Outline

- **Scanning Beams and Intensity Modulated Proton Therapy**

  -Treatment Planning Techniques (SFUD, IMPT, DET)
  - Robust Optimization and Evaluation
  - 4D Treatment Planning and Interplay

- Site Specific Implementation; Technical Protocols.

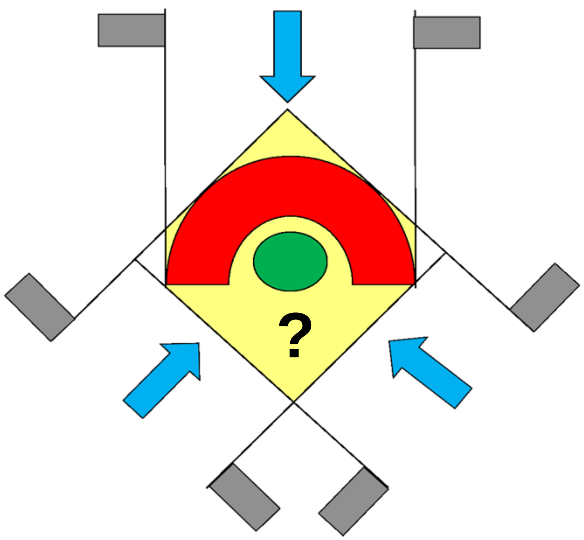
- Summary.

Scanning Beams and IMPT

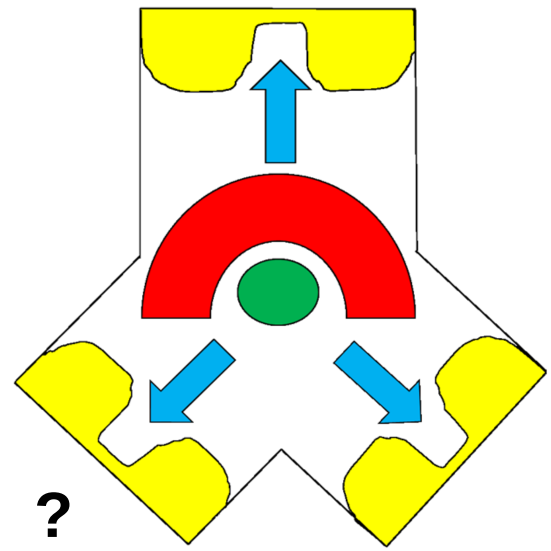
- IMPT exploits physical potential of PT => fare comparison with IMRT
- Lowest Integral dose(2 to 3 times vs. XRT).
- 3D HIGH DOSE CONFORMALITY in addition to reduced low and medium dose.
- Requires limited number of fields:(1- 4Fs)~ IMXT (4-9Fs).
- Can treat large fields, comparable with XRT.
- Penetrates at larger depths if no beam modifiers present.
- Produces less neutrons contamination outside of the patient as no beam modifiers are required(less nuclear interactions).

IMPT Treatment Plan Optimization

- **IMPT plans are optimized using inverse planning techniques ~ IMRT**



3D Forward planning



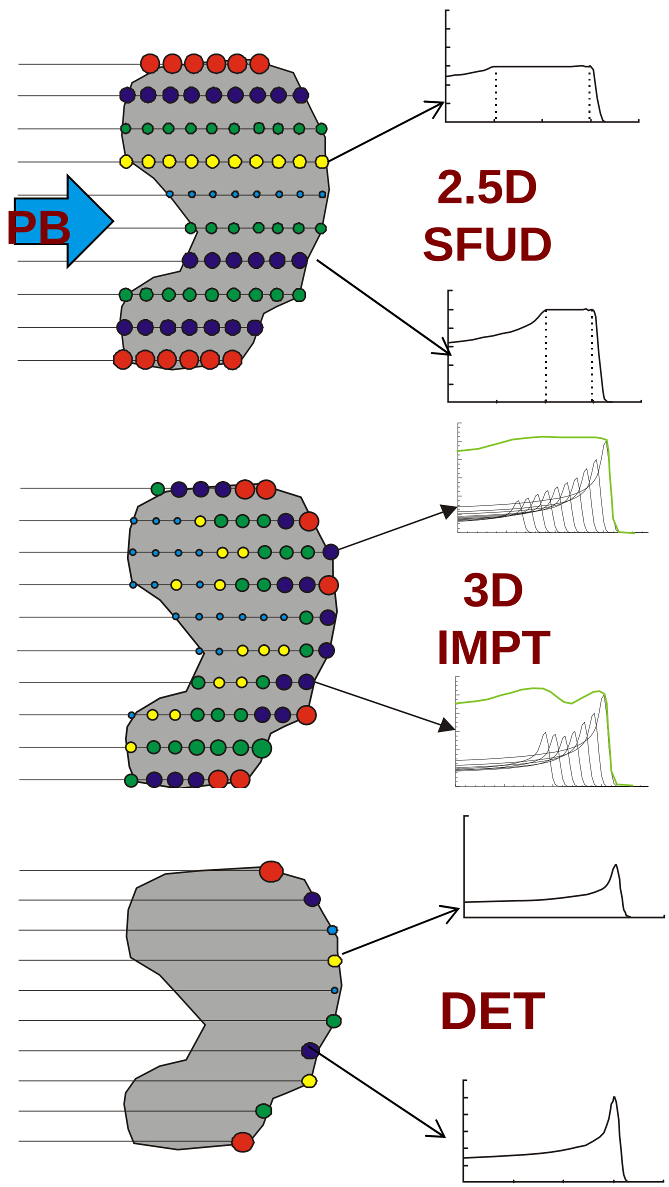
Inverse planning

IMPT≠ IMRT, as it varies the *Energy* of each pencil beam besides its Intensity =>increased degree of freedoms vs IMXT=> better dose shaping

The increased computational and delivery complexity of IMPT can be simplified if certain IMPT techniques are preselected.

(*Paganetti & Bortfeld, PBR*)

IMPT Planning Techniques



- **2.5D uses poli-energetic SOBP pencil beams(different weights by different colors) individually adapted distally and proximally to TV=> dose is constant along the depth of TV.**

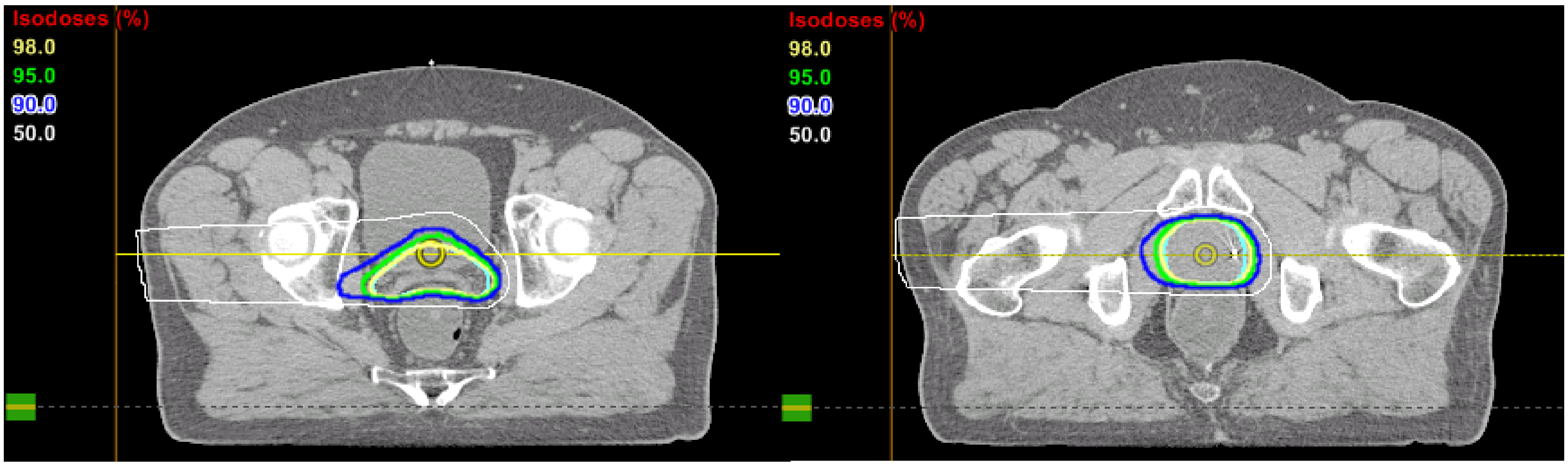
- **3D uses poli-energetic pencil beams, non-uniformly distributed and adapted distally and proximally to TV => non-uniform dose per field.**

- **DET-Distal Edge Tracking** *(Deasy 97)* **uses pencil beams distributed individually only on the distal TV edge => high non uniform dose per field.**

Lomax, 1999 PMB

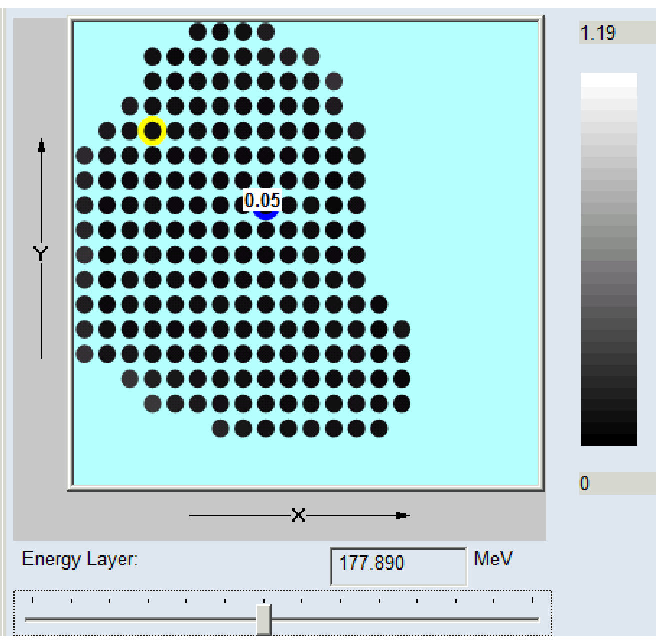
IMPT Planning Techniques

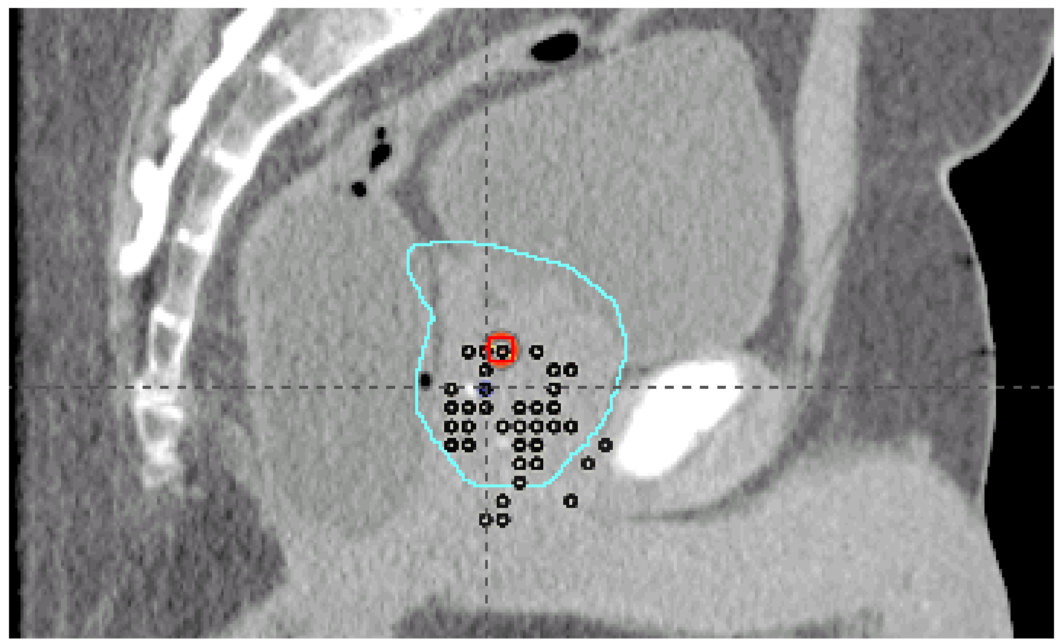
- **The width of the SOBP for scanning beams is determined by the width of the target in depth along each line of spots.**



IMPT Planning Techniques

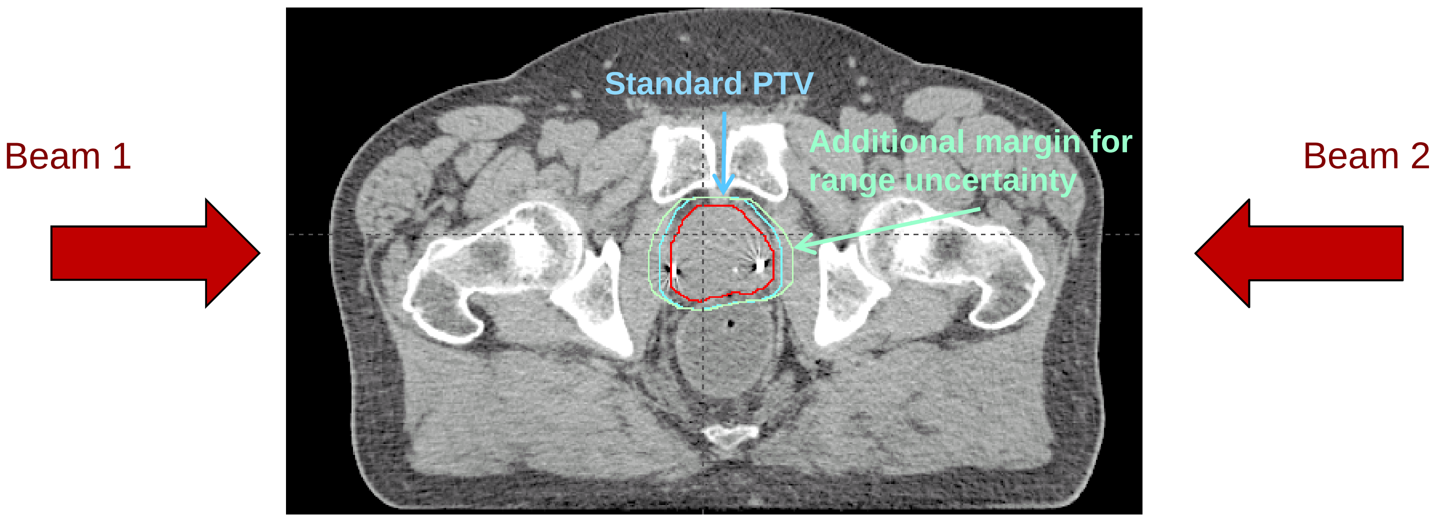
- **The lateral dose distribution is determined by the placement and weights of the spots on each energy layer.**
- **Spot weights are optimized for each beam direction using inverse planning techniques => beam weight maps for different energy layers.**





Treatment Planning

- **It is common for Inverse planning to require that any margins for set-up or range be incorporated into a structure which can be used to optimize the dose distribution.**



Treatment Planning

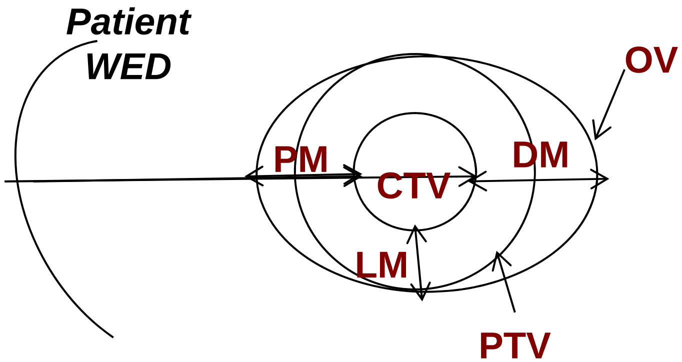
- **Uncertainty in setup and range along the path of the beam must be accounted for:**
  - **Through margins in the optimization structure**.
  - Through robust evaluation.
  - By including beam robustness as an explicit parameter in the optimization algorithm.

Treatment Planning Optimization

- To create margins to account for range uncertainty, **each beam orientation** would need a different PTV**, beam specific PTV(bsPTV).**

- Generally, in practice, the dose distribution is determined based on an Optimization Volume(**OV**) derived from **CTV** adding lateral and range margins which may vary among institutions. At UPenn:

  - **DM = (0.035 x CTVdist) + 1 mm**
  - **PM = (0.035 x CTVprox) + 1mm**
  - **LM** based on setup, motion, penumbra.



3.5%- uncertainty in the HU and their conversion to proton stopping power

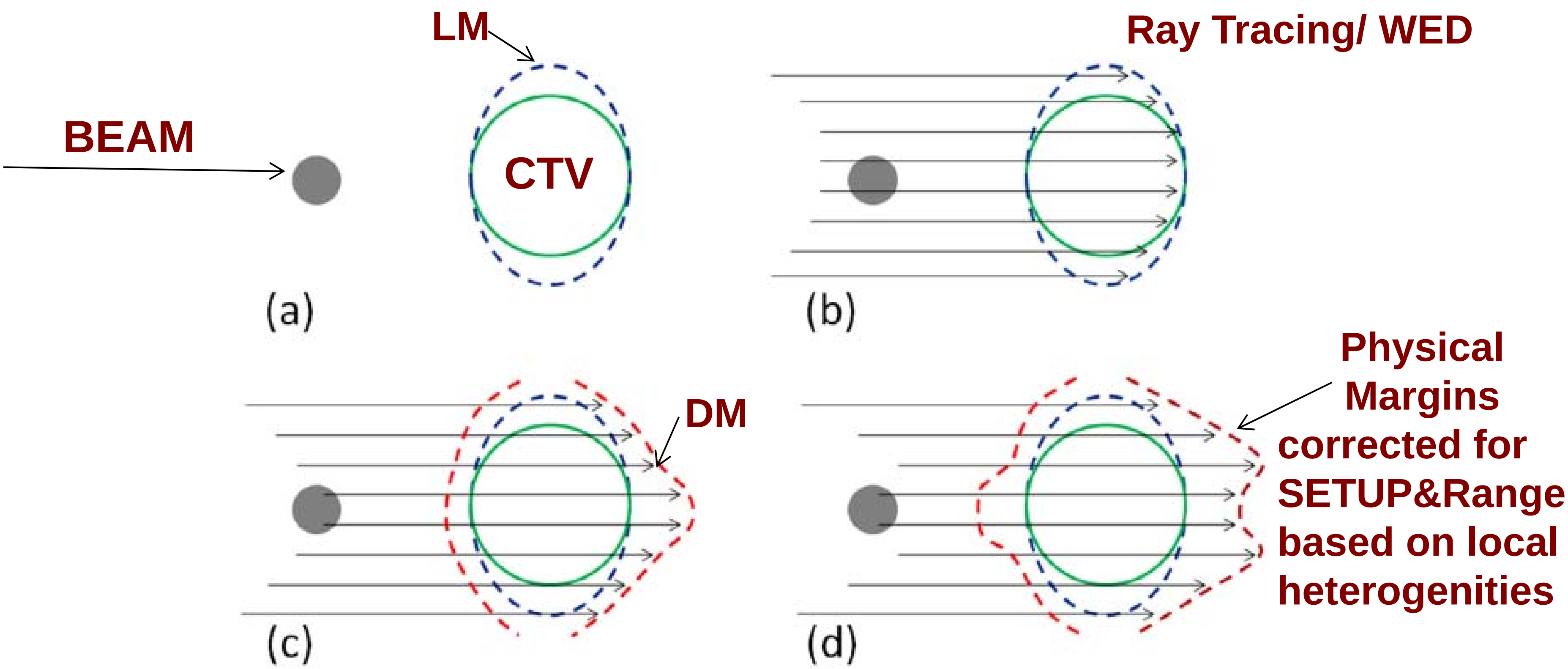
1 mm - added to correct for range uncertainty in beam delivery

Beam Specific PTV(bsPTV)

•Avoids geometrical miss of the CTV through lateral expansion.

•DM, PM margins calculated from the target in beam direction for each Ray

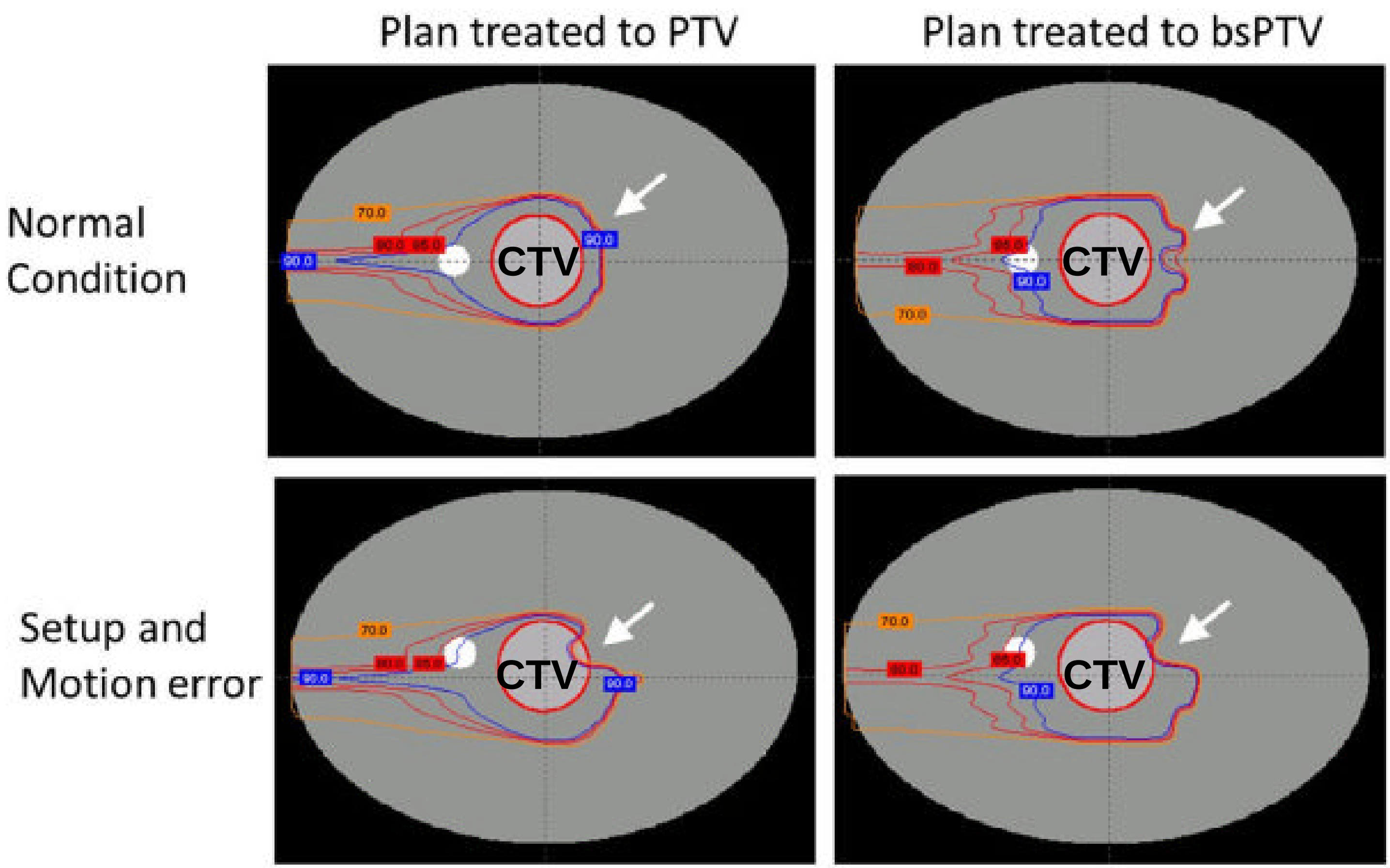
•Extra margins based on local heterogeneities, using a density correction kernel



P.Park, L.Dong et al, IJROBP 2012

PTV vs bsPTV Optimization

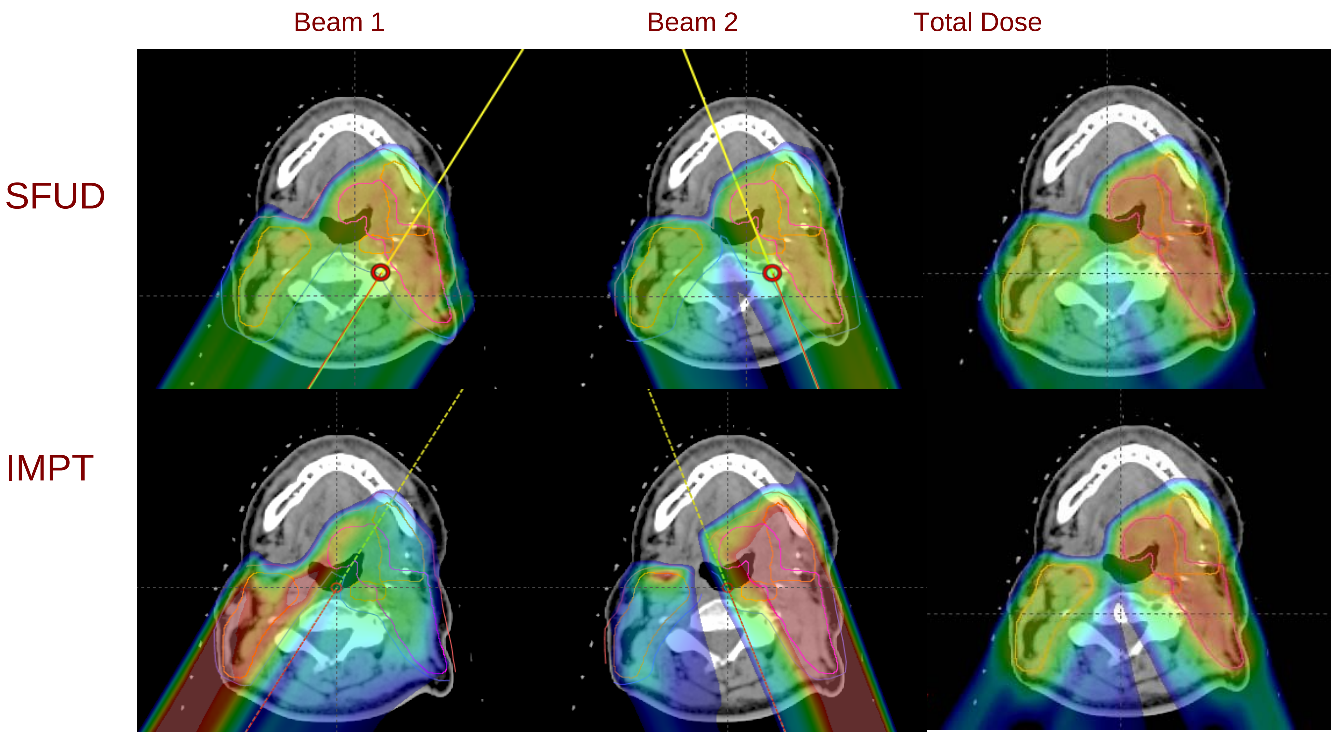
Dose distributions conforming dose to **CTV** using **PTV**(>30%)& **bsPTV**(<5%).



P.Park, L.Dong,et al IJROBP 2012

Treatment Planning

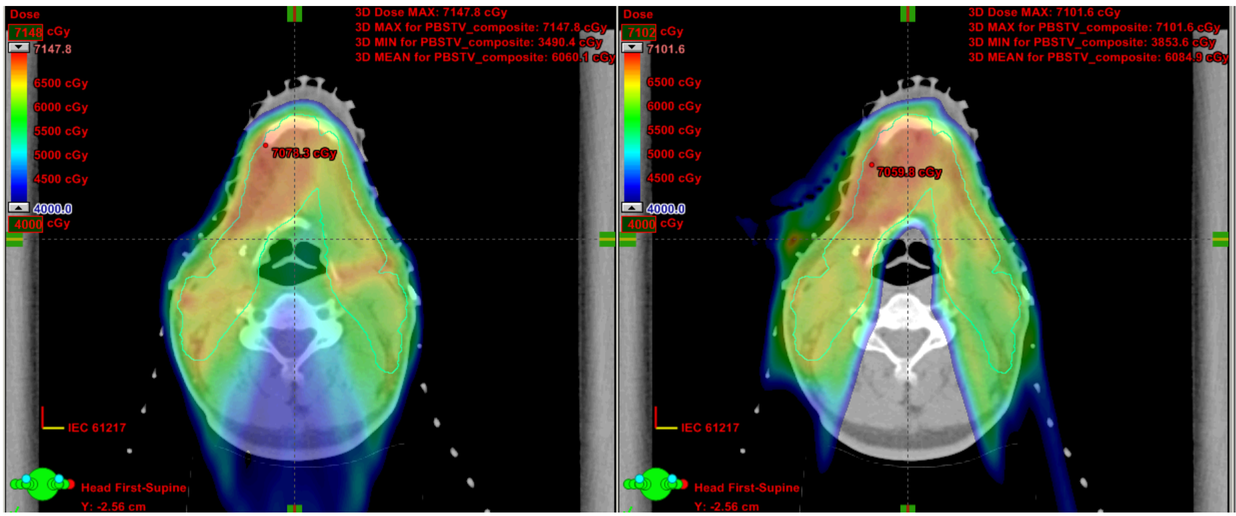
- **Treatment** plans can be optimized such that each of the beams covers the target uniformly with dose (single field uniform dose, **SFUD**) or such that the sum of all beams covers the target uniformly with dose (intensity modulated proton therapy, **IMPT**)



Treatment Planning

- IMPT provides more degrees of freedom to optimize a treatment plan and can provide better normal tissue sparing, especially for OARs which are on the proximal side of the target

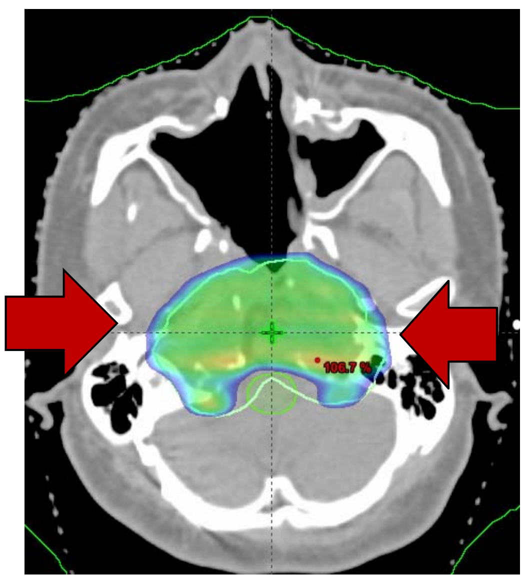
SFUD IMPT



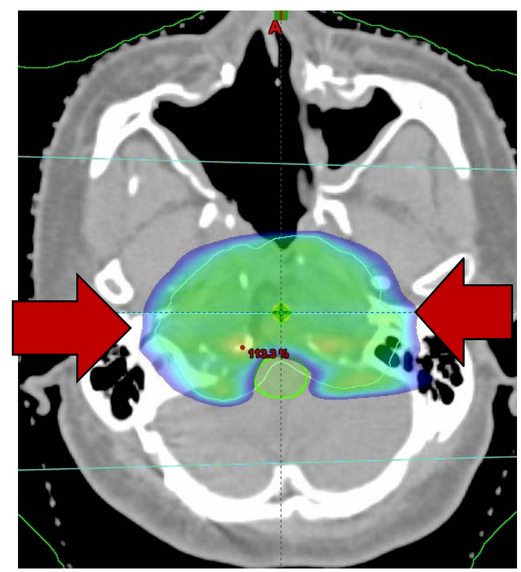
- The higher degree of modulation in the spot maps causes IMPT plans to be less robust to uncertainties.

Degeneracy of solution in inverse planning

In general, based on the input the optimization problem may posses many equivalent solutions. It is difficult to decide whether a result produced by a planning algorithm can be further improved (e.g. adding more beams, reducing #of spots, etc.)



SFUD



IMPT

Treatment Planning

Uncertainty in setup and range along the path of the beam must be accounted for:

- Through margins in the optimization structure.
- **Through robust evaluation.**
- **By including beam robustness as an explicit parameter in the optimization algorithm.**

Plan Robustness

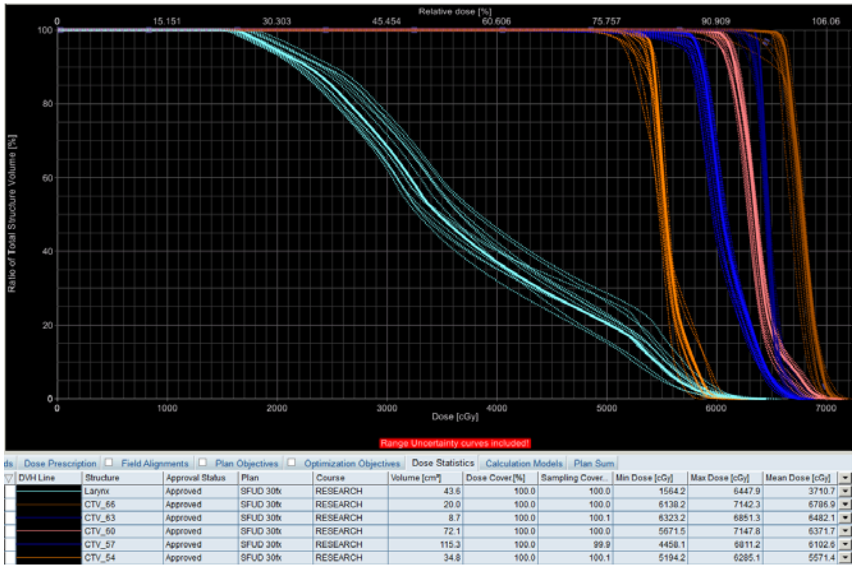
- **Plan robustness** measures the differences in quality between planned and delivered dose in the presence of uncertainties(e.g. setup and range uncertanties)
  - **Robust Plan Optimization**
    - ✓ Account for uncertainties(patient, physics, machine, biology) in the optimization function
  - **Robust Plan Evaluation**
    - ✓ “Worst case scenario”: Standard robustness test
    - ✓ For example: *systematically simulate setup error by shifting isocenter in 6 directions, introduce HU # variation*

M. Engelsman, M, Schwartz, L.Dong, SRO 2013

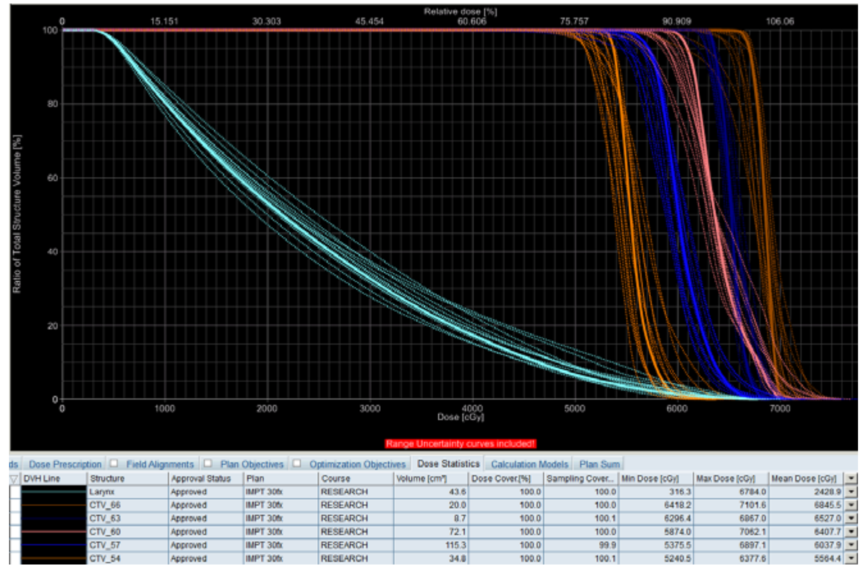
Robust Plan Evaluation

Relative to Target and OARs

SFUD



IMPT



Conformality		Robustness	
Best	Worst	Best	Worst
IMPT	SFUD	SFUD	IMPT

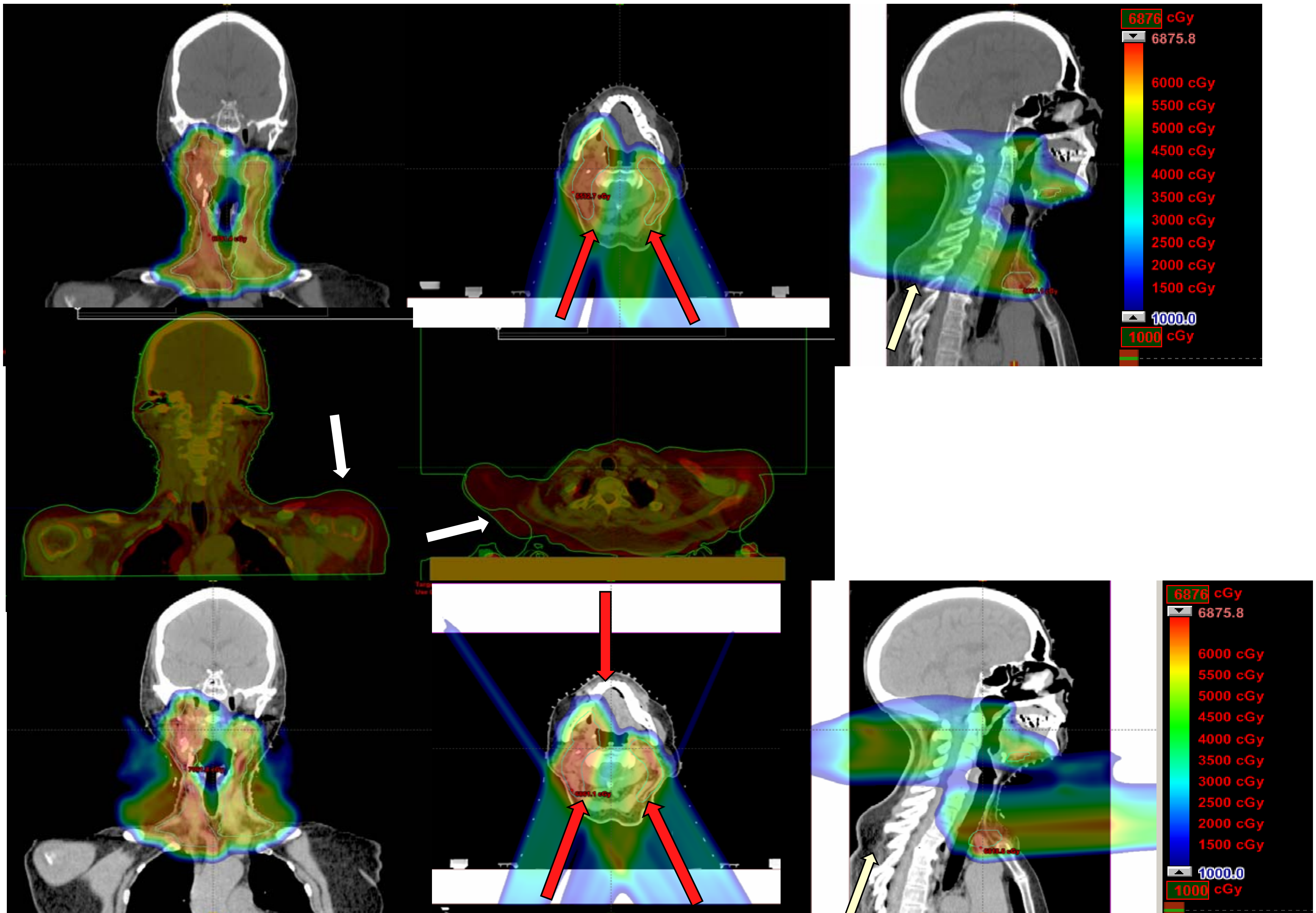
Plan Robustness & Beam Orientation

- Choosing the right beam orientation
- *Shortest and most homogeneous path to target*

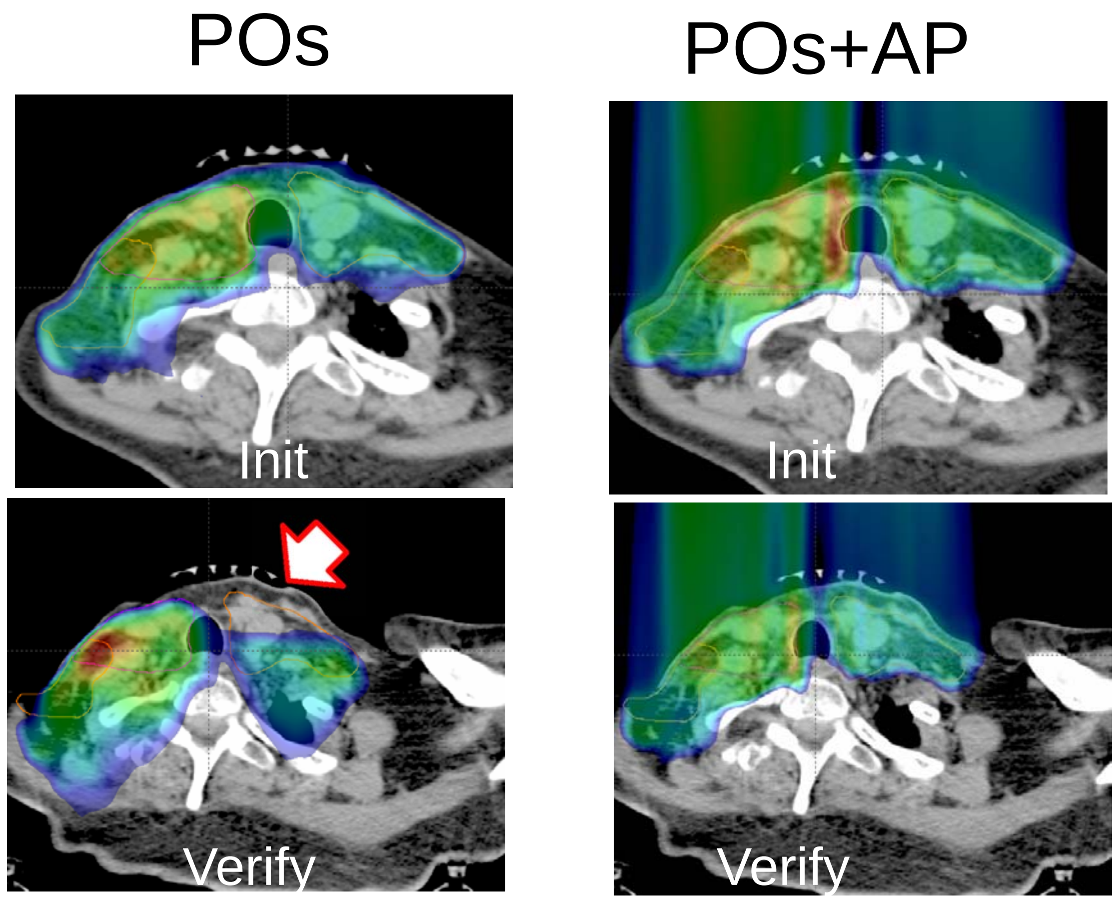
Ex: Pelvis (3 to 9 o'clock , CW)

- Choosing the best geometry of irradiation
- *Limited numbers of beams, avoid heterogeneities, serial OARs, etc..*
- *Coplanar vs. non-coplanar beams.*

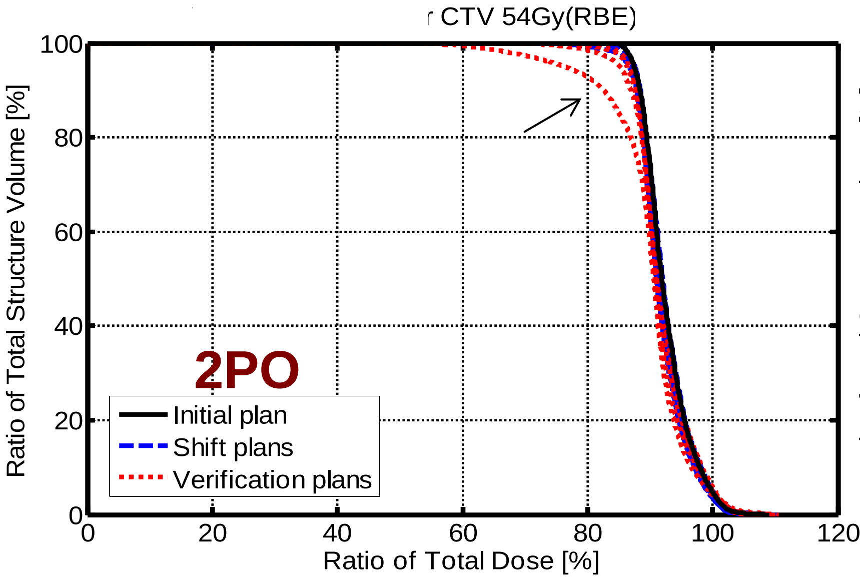
Robust Evaluation: HN SFUD(2POs vs. 2POs+AP)

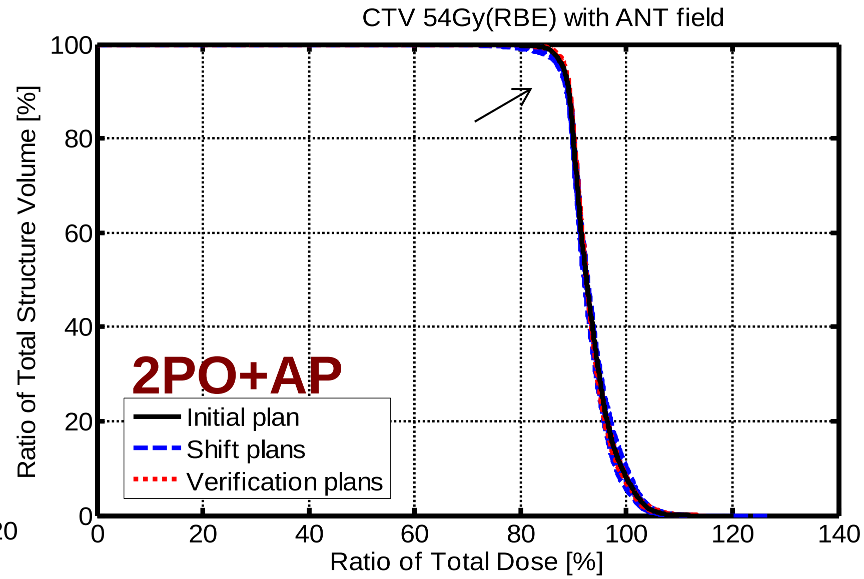


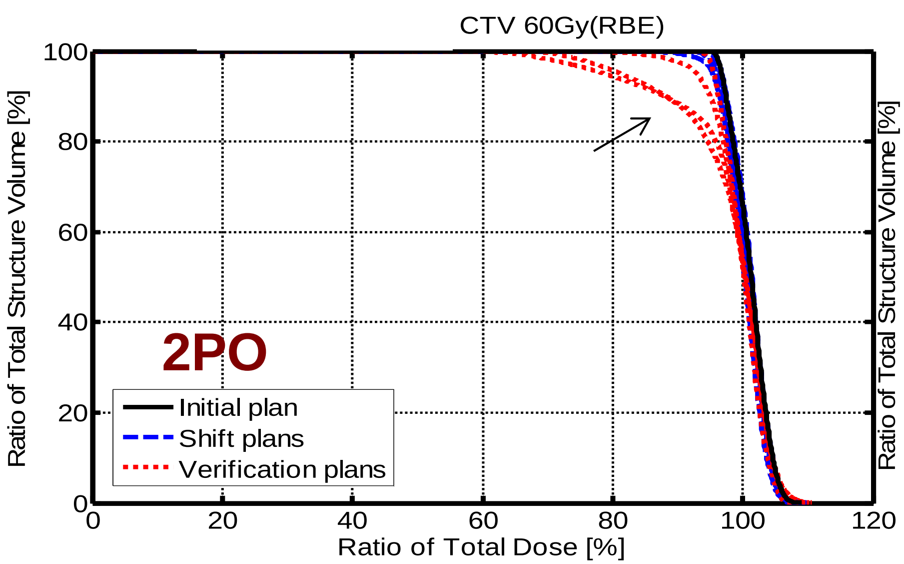
Robust Evaluation: HN SFUD(2POs vs. 2POs+AP)

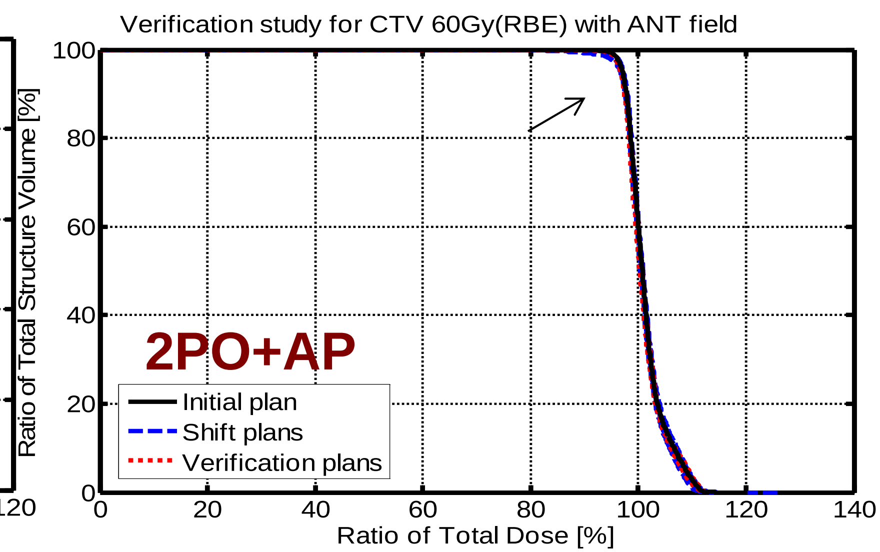


HN Target Robustness: $CTV_{54Gy(RBE)}$/$CTV_{60Gy(RBE)}$

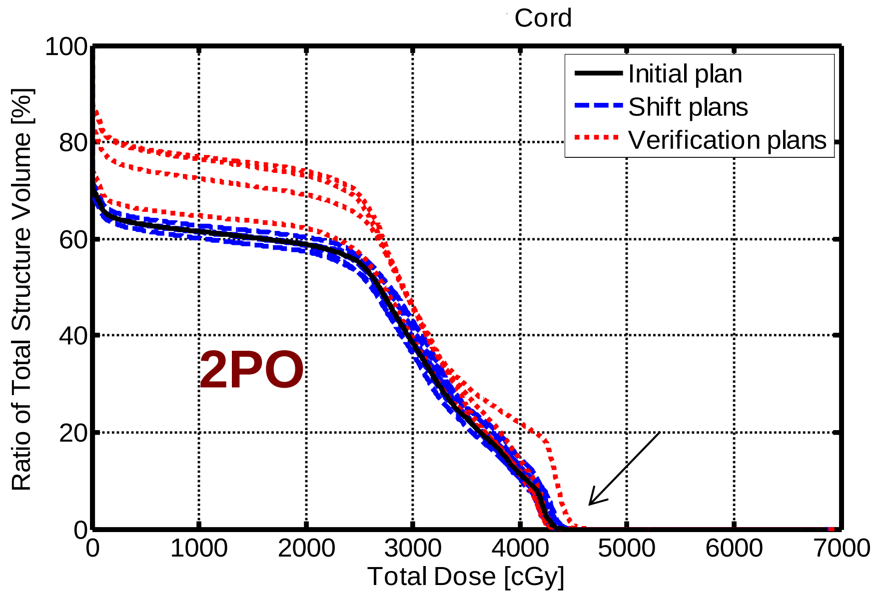


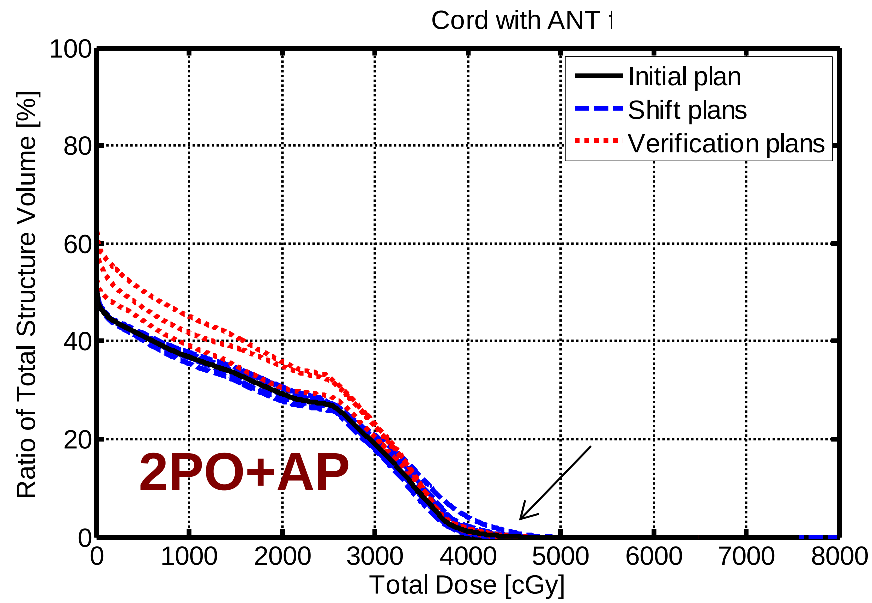






HN OAR Robustness: Cord

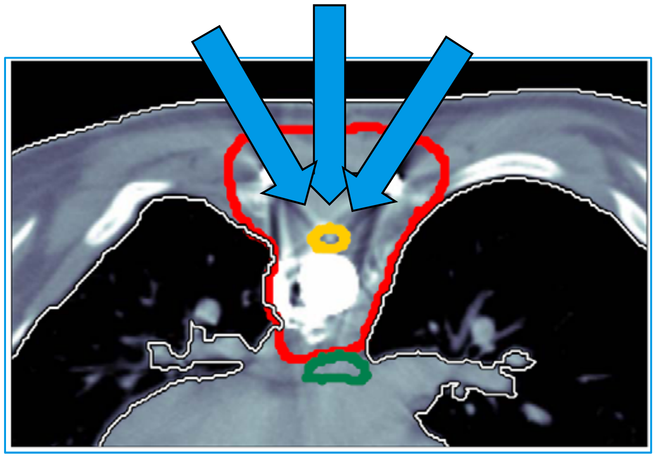




- **The shift plans may not always revel potential problems and therefore verification volumetric imaging should be used.**

- **We can learn from robust evaluation how to come up with the clinically relevant cost functions for robust optimization.**

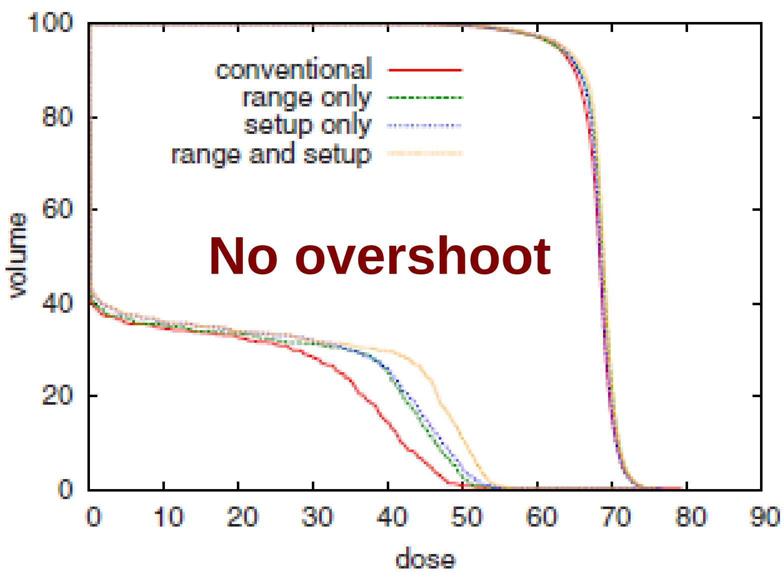
Robust Optimization

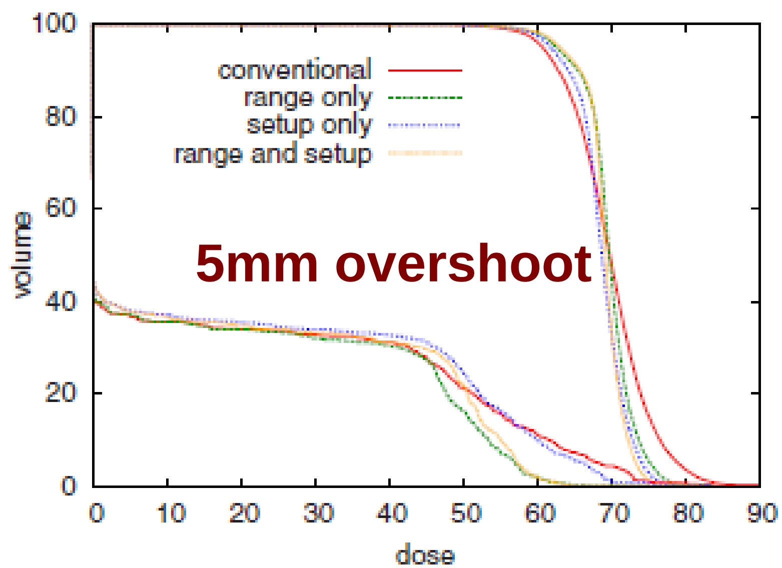


Unkelbach et al, Med Phys 2009

- Probabilistic Optimization:

  The range of each pencil beam is a random variable, the quantity to be optimized is the residual cost over the possible setup errors and range uncertainties weighted based on their probability.





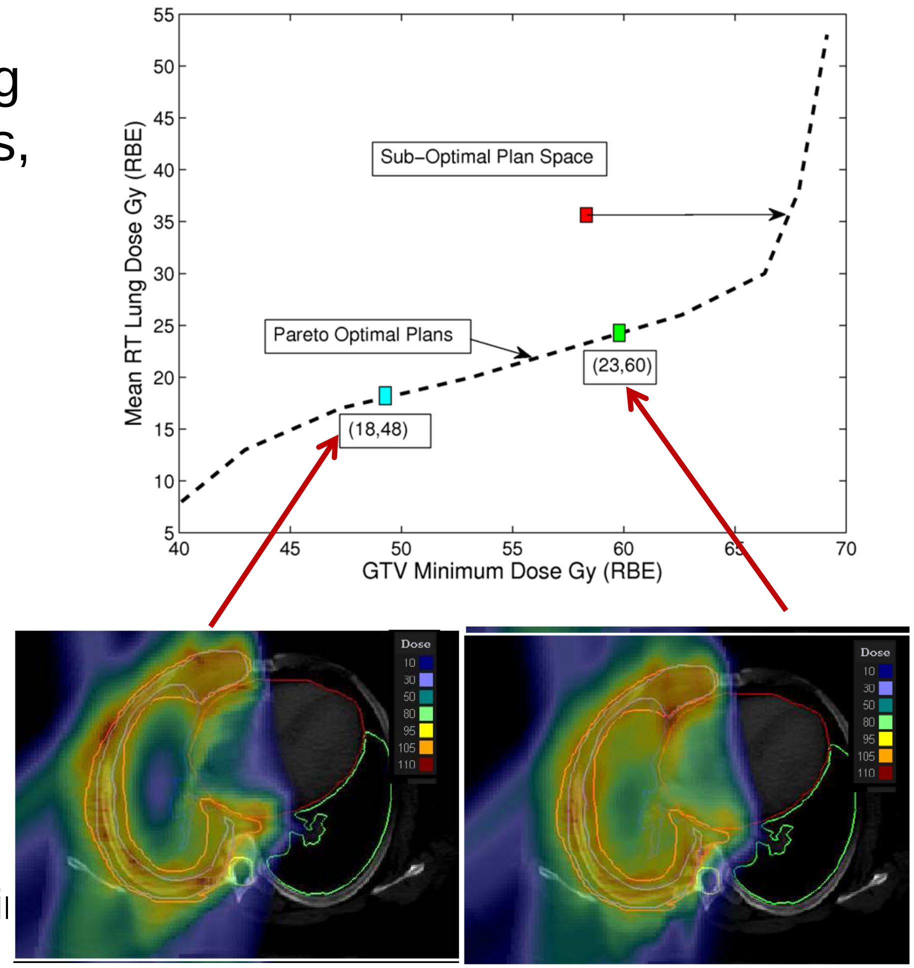
Multi-Criteria Optimization (MCO)

- In MCO:

- a database of plans each emphasizing different treatment planning objectives, is pre-computed to approximate the Pareto surface.

- robustness can be integrated by adding robustified objectives and constraints to the MCO problem.

Chen et al, PMB 2012



- Minimal set of absolute constraints
  - D(GTV) > 50 Gy(RBE)
- Specify competing objectives –
  - "minimize max OAR" vs "maximize mi GTV dose"

H. Kooy, MGH

Scanned Beams have a time structure => Sensitive to motion

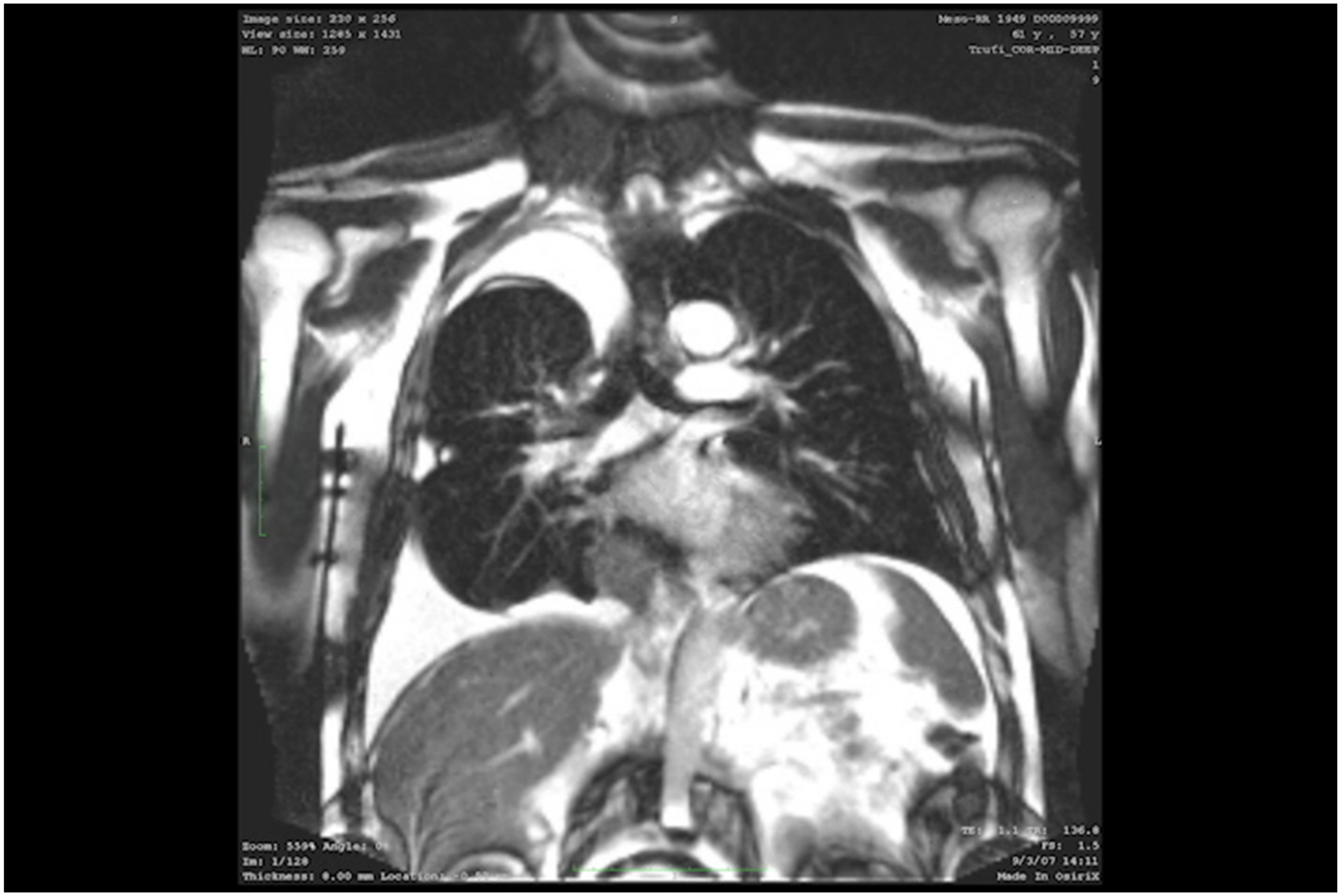
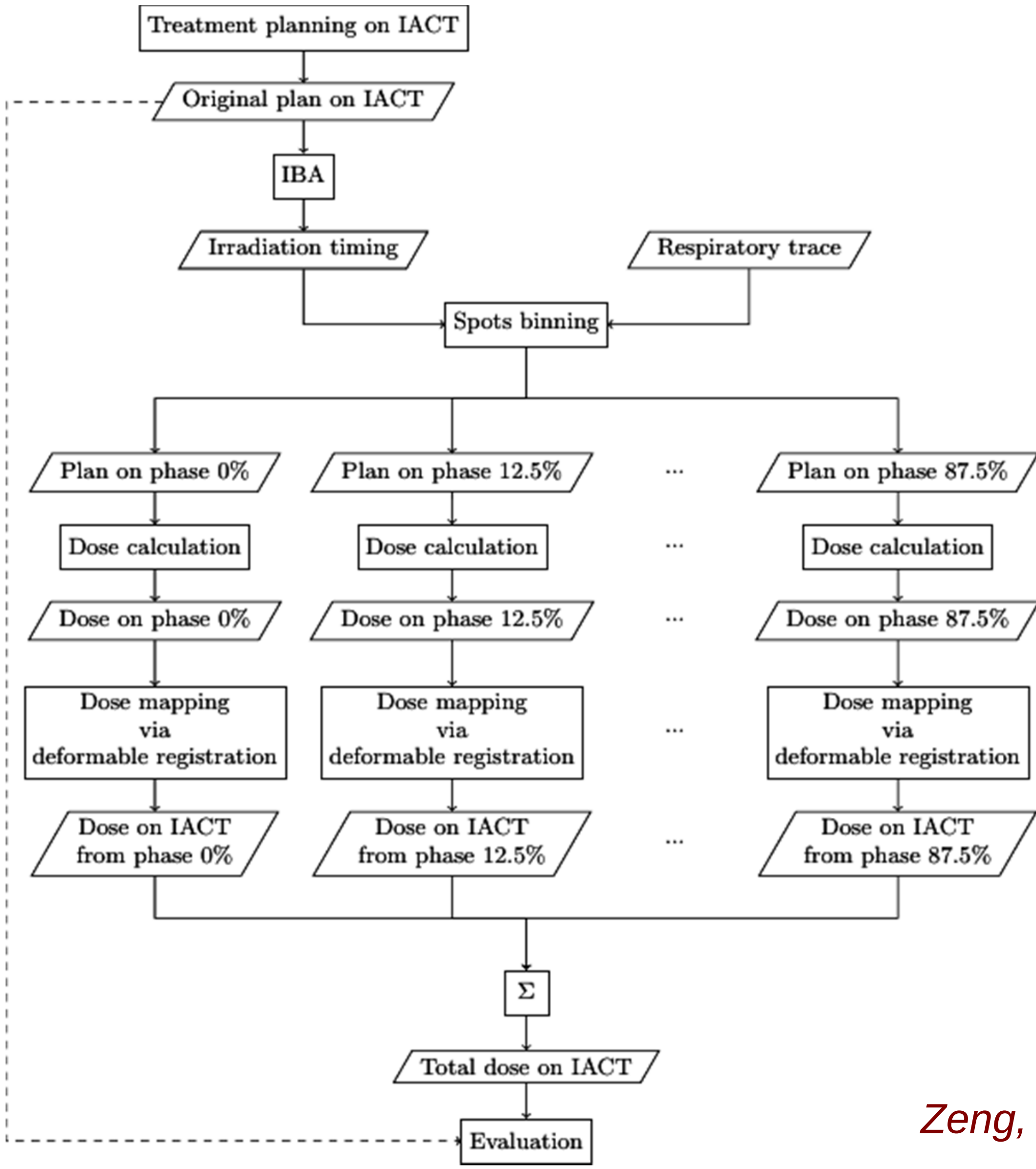


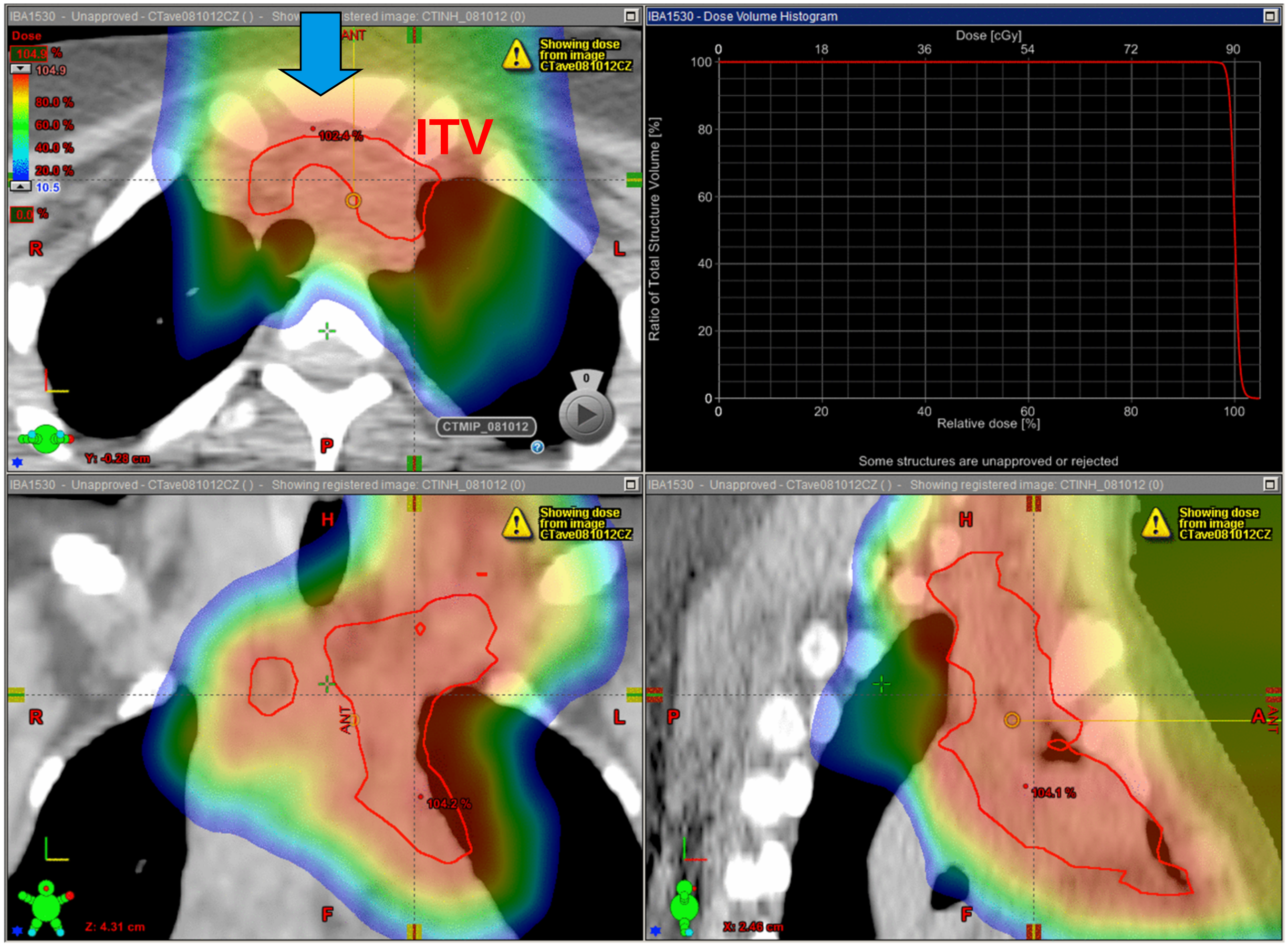
Image by B.White, UPENN

4D Planning/ Simulation of Interplay



Zeng, Both, PMB 2015

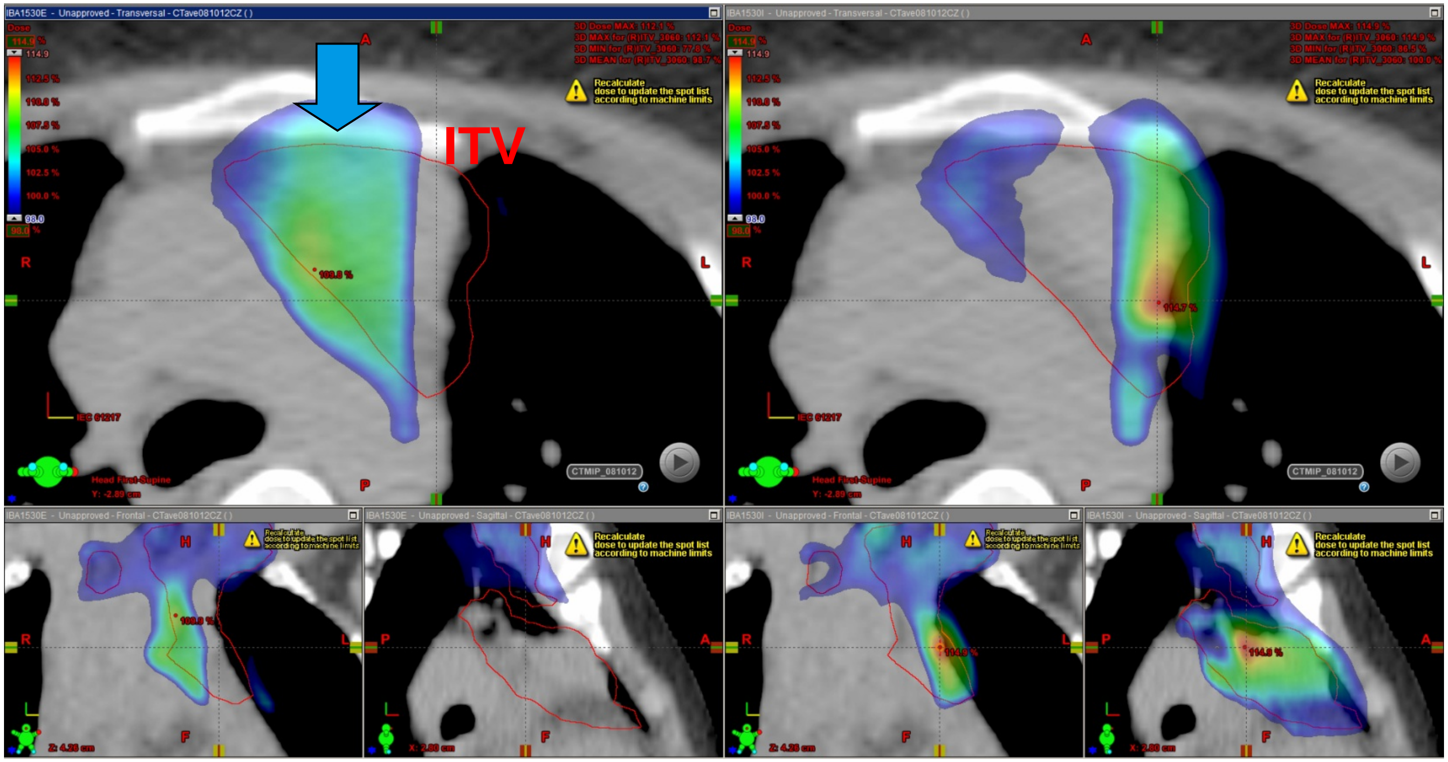
Intrafractional Motion for “Unfavorable” Pt.



- Red contour: ITV
- Color wash: nominal dose distribution

Intrafractional Motion “Unfavorable” Pt.

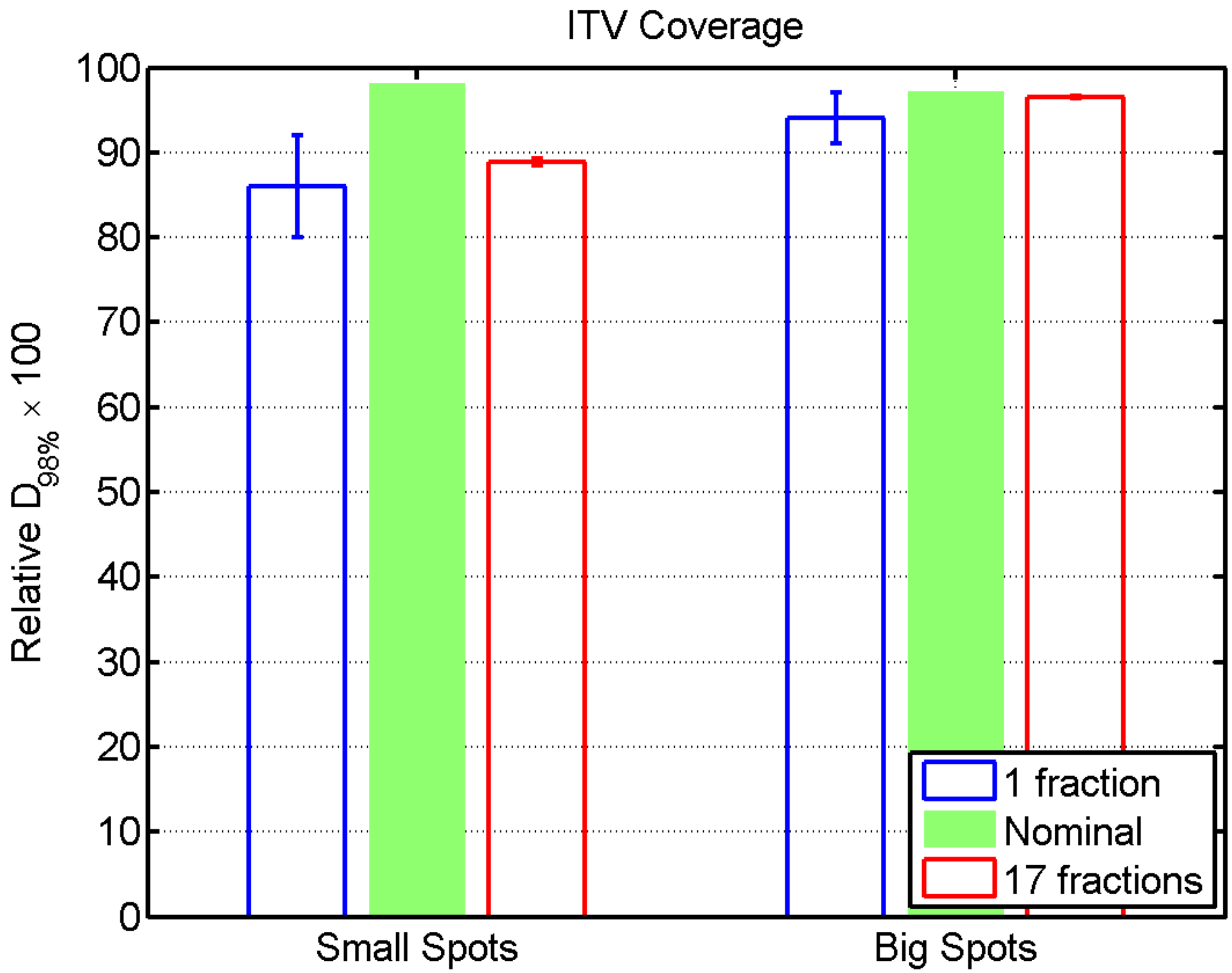
- **Accumulated dose distribution of one painting starting with end of exhalation (left) and end of inhalation (right), truncated at 98% of prescription on the IACT.**



Note: ***Margins do not correct for the interplay effect.***

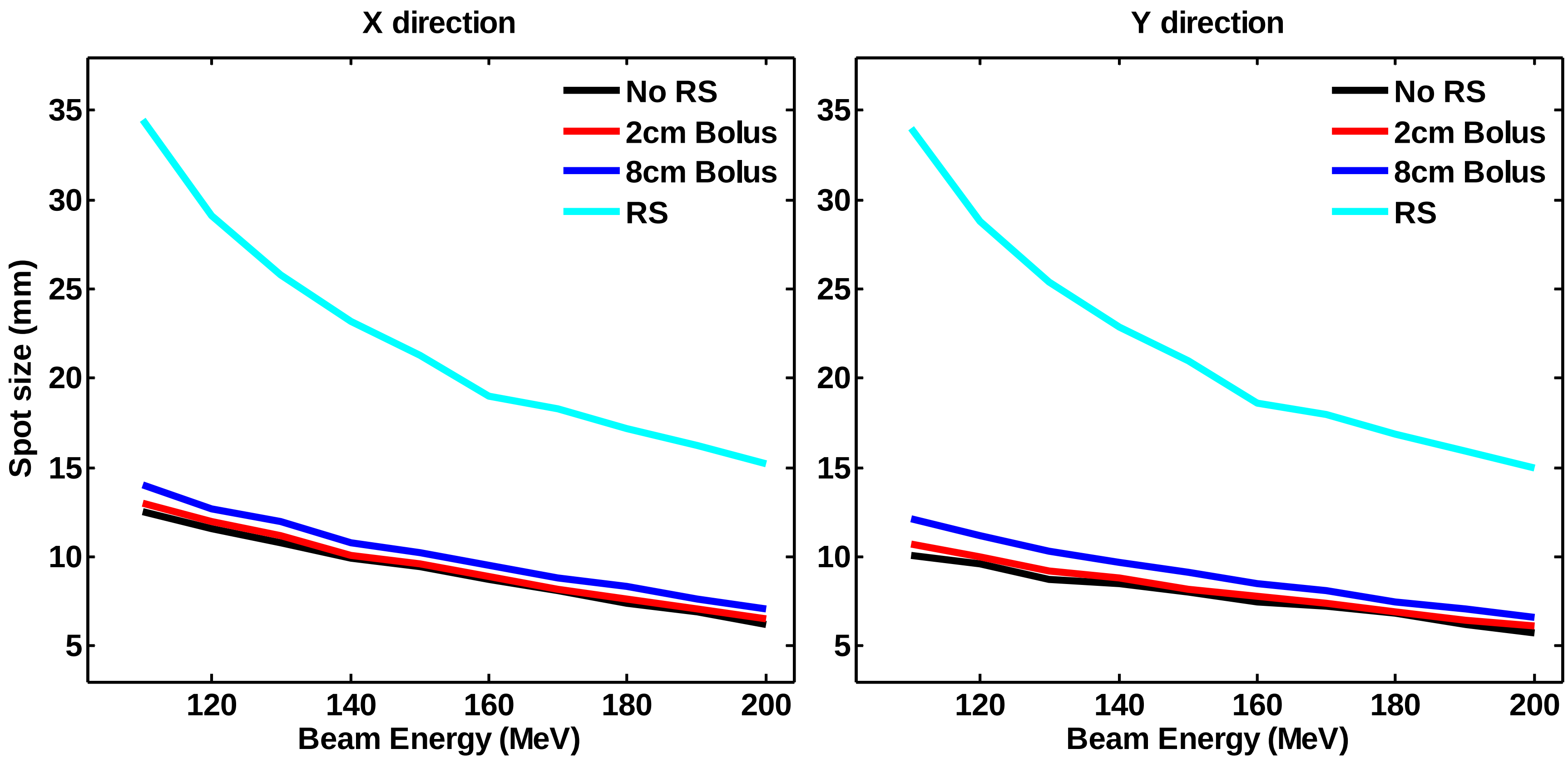
Spot size&Interplay

- **Small spots:** $\sigma\sim$ 5 mm vs. **Big spots:** $\sigma\sim$ 10 mm



Big spots can correct for Interplay due to motion perpendicular to the beam.

Spot Size Integrity vs Air gap.



Both, Shen et al, IJROBP 2014

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- Scanning Beams and Intensity Modulated Proton Therapy

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- Site Specific Implementation: Technical Protocols.

- Summary.

Site Specific Implementation

Due to uncertainties related to patient, machine , physics and biology, scanning beams require a site specific clinical implementation and *technical protocols* have to be developed.

Technical protocols should address:

- different machine parameters(spot size, delivery time, etc.).
- treatment planning algorithms.
- patient's anatomy changes in the beam(weight lose, air pockets, ports, etc).
- misalignments of the proton beam relative to the patient.
- skin surface or dense bone irregularities near or within the beam path.

Site Specific Implementation

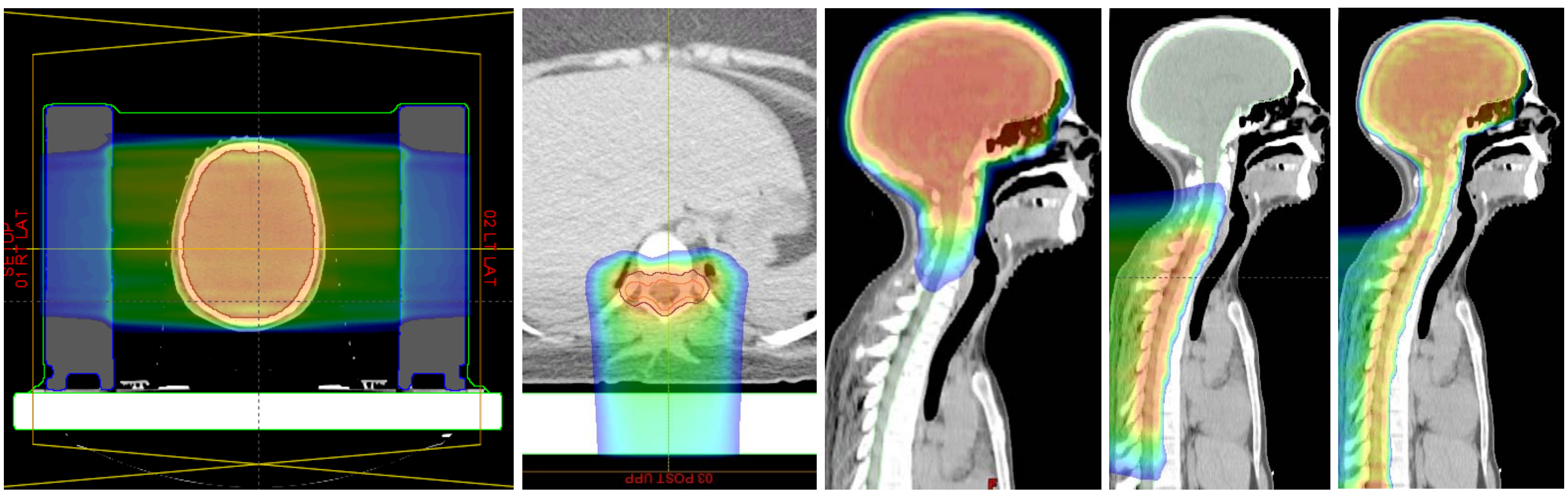
To determine meaningful technical protocols is important:

- **to work with the physicians and the treatment team to acquire and analyze prospective patient data within the treatment environment.**
- **to move consistently from simple to complex treatment sites(prostate, brain, pelvis (GI, GU, GYN), HN, CSI, etc).**
- **to recognize potential problems and address them as necessary.**
- **to perform dose accumulation studies for moving targets.**
- **to review the literature and one's institutional data within the limita-tions imposed by differences in technology, patient population, etc.**

Example: CSI

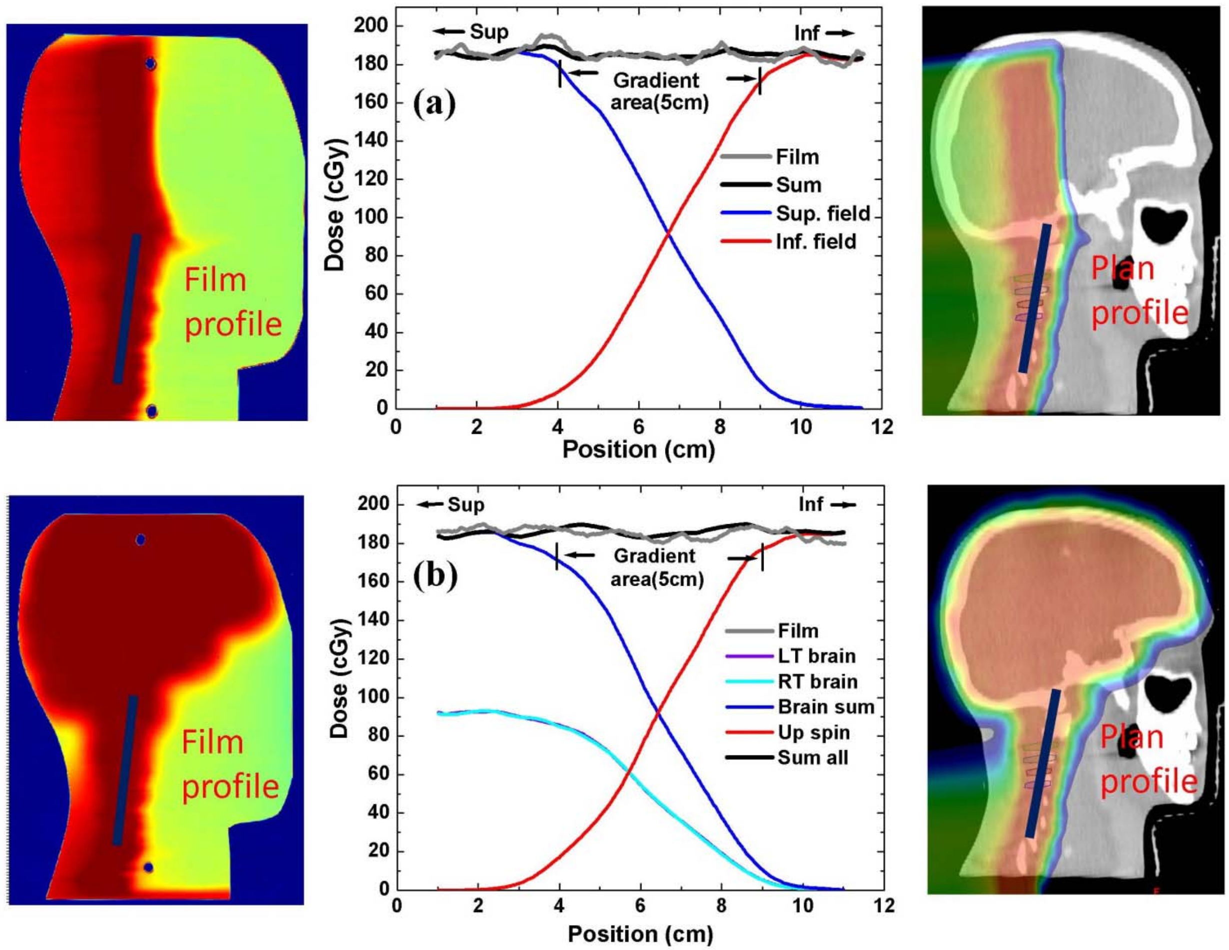
CSI Field Geometry

- ❑ **Two lateral PBS fields are used to treat the brain**
- ❑ **One or more posterior fields are used to treat the spine**
- ❑ **Fields overlap (5-8cm) is needed to generate a high dose low gradient between the fields => safe, smeared field match**



Lin, Both et al..IJROBP 2014

CSI film measurements on field matching



Sagittal dose profiles comparison for:

(a) spinal-spinal and (b) craniospinal junctions.

The blue lines indicated the location to draw the dose profiles.

Summary

- IMPT and SFUD techniques improve conformality and efficiency of proton planning, as require less number of fields and are automated.
- IMPT and SFUD are sensitive to range and set-up uncertainties, however plan robustness is better for SFUD.
- Robust optimization helps, however moving targets require additional forms of management(spot size, minimize motion, rescanning,etc)
- Technical protocols have to be developed for each clinical site implementation as in proton therapy geometry does not equals dose.
- Continue communication between the planning team and clinical team is crucial during treatment for a safe and accurate proton treatment.

Thank you

Acknowledgements:

Penn Radiation Oncology & Collaborators

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