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Basics of Proton Therapy

Proton Treatment Planning and Beam Optimization

SAM Educational Session, WE-D-BRB-2

Mark Pankuch, PhD
Northwestern Medicine Chicago Proton Center

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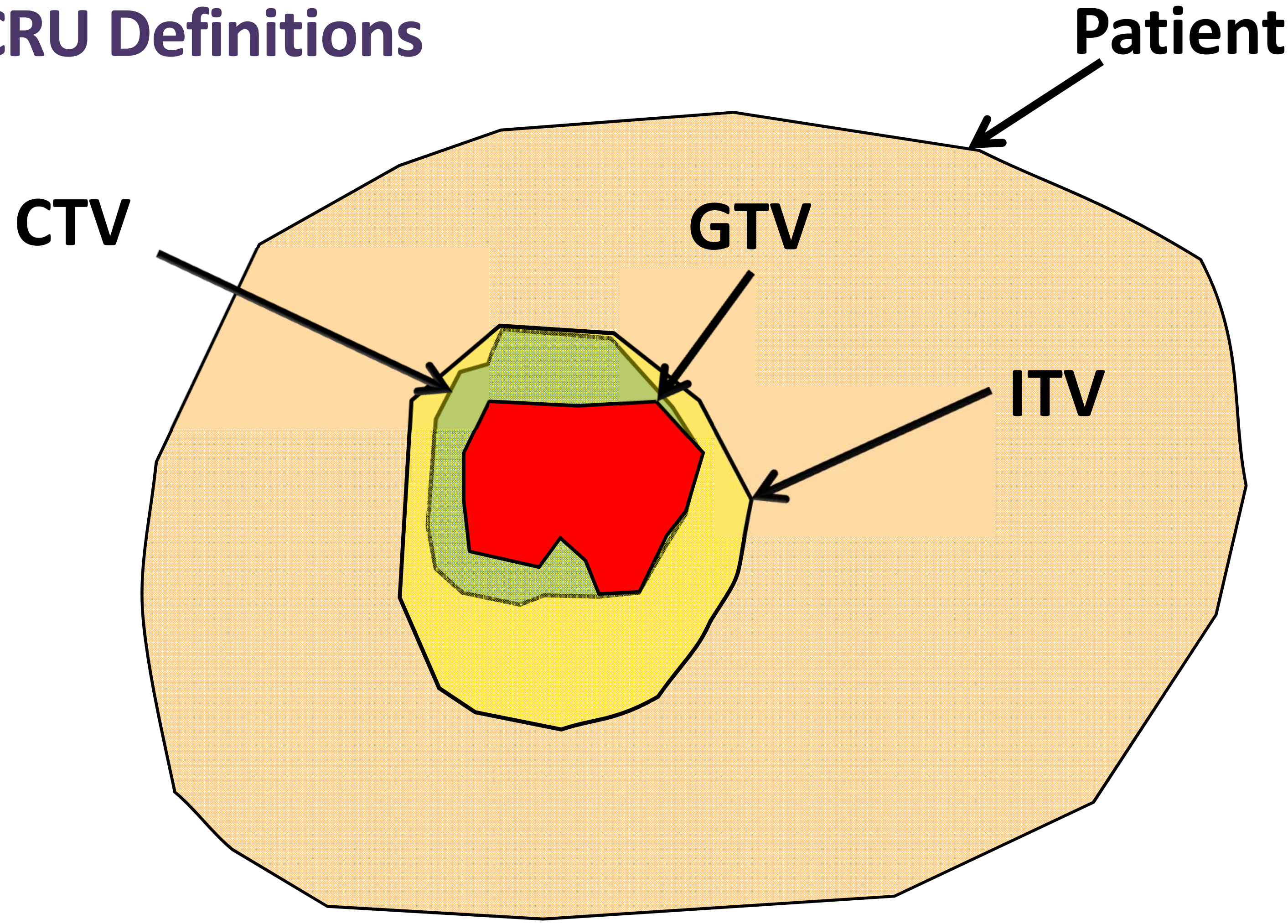
Today's objectives

- Review the concepts of CTV / ITV / PTV when treating with protons
- Discuss the general planning parameters used in proton planning
- Present Aperture / Compensator, forward based, treatment planning methods
- Discuss the methods and clinical benefits of Intensity Modulated Proton Therapy (IMPT)

ICRU Definitions



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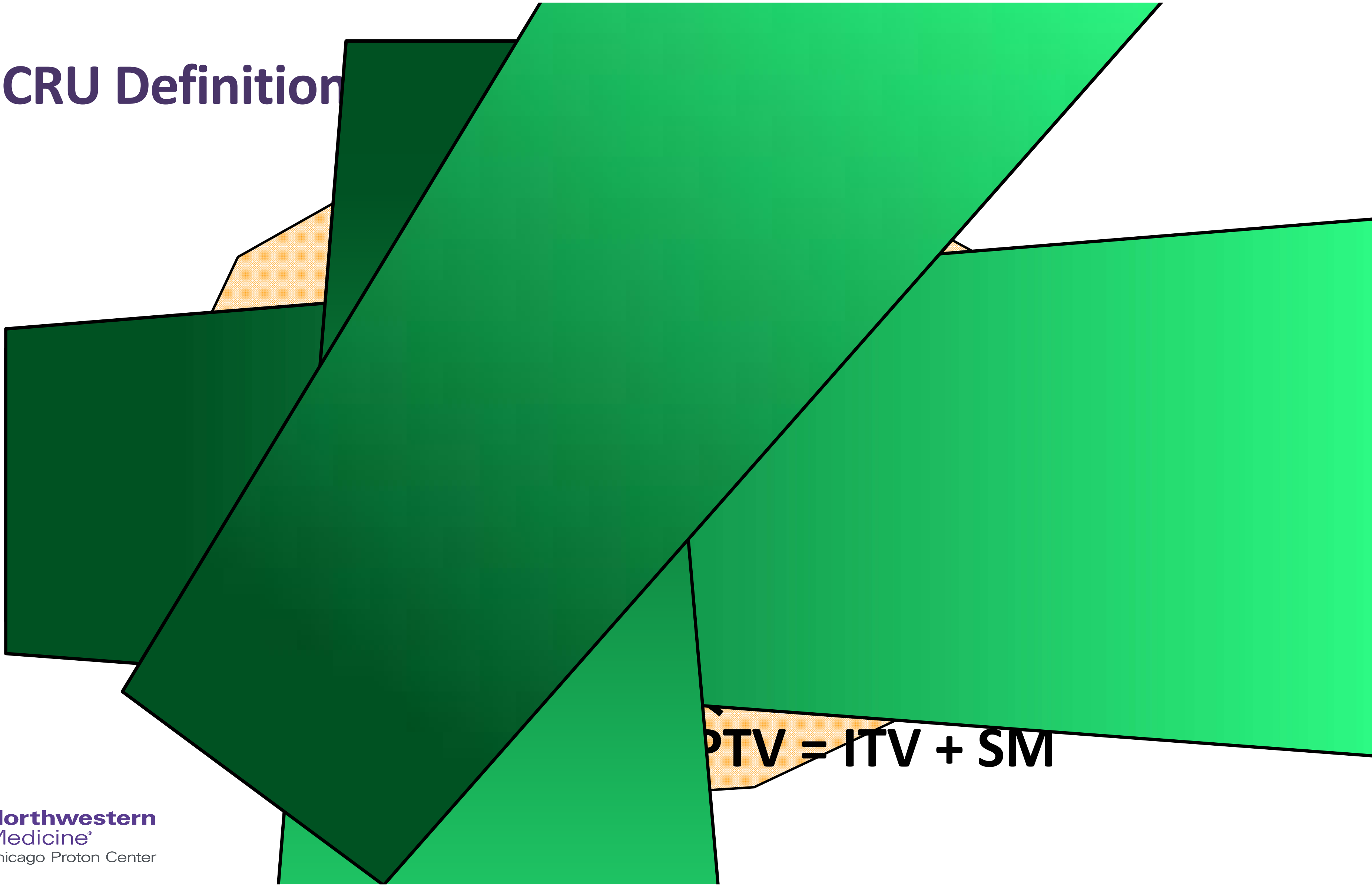
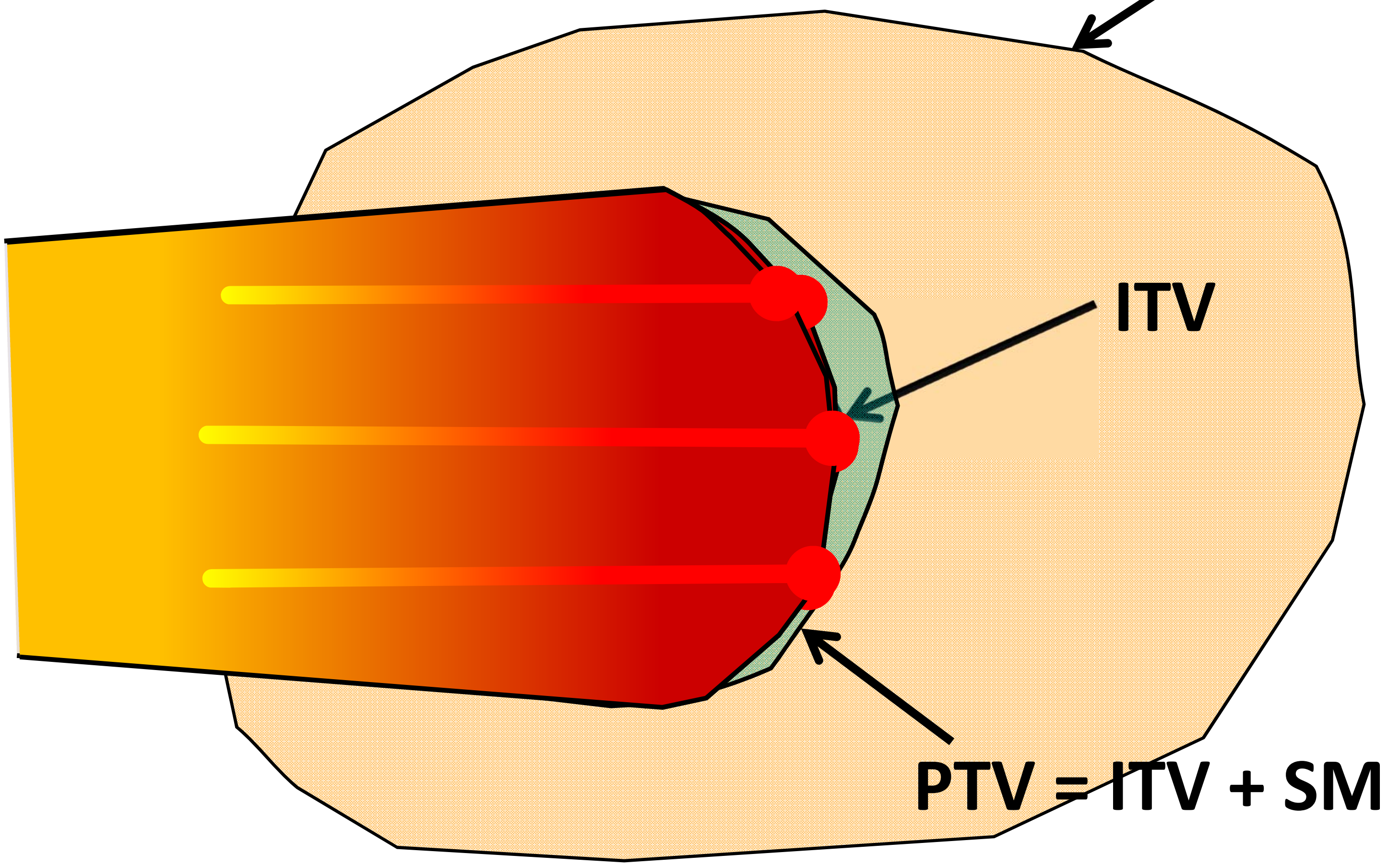
ICRU Definition



ICRU Definitions



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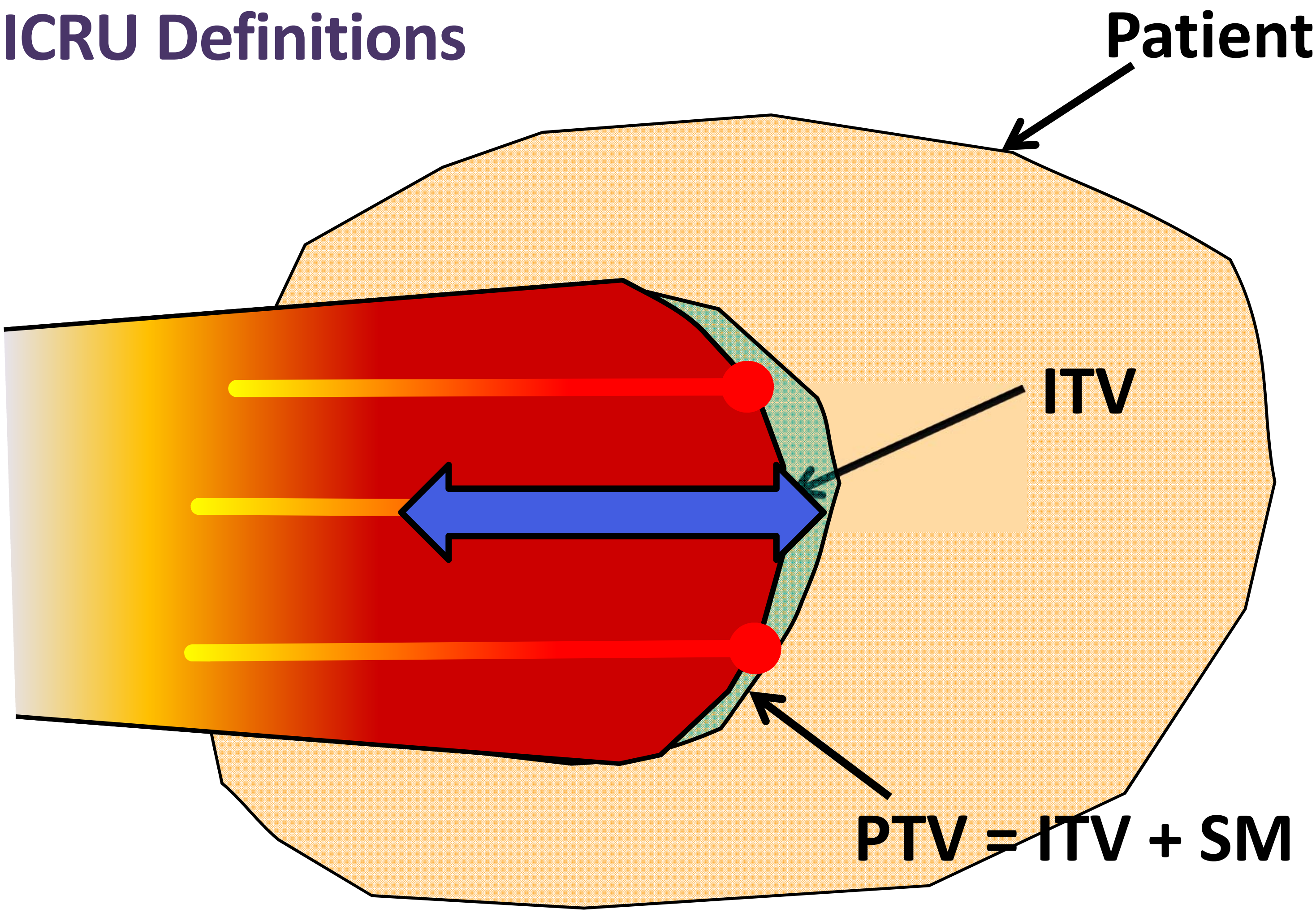
ICRU Definitions



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So….

Distal margins of Protons fields need to consider potential path length differences (Smearing and Robustness)

But are there other considerations for the distal edge margins??

What about

Proton Range Uncertainties ??

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Where do range uncertainties come from and how big are they??

- It depends on who you ask……

Paganetti, Phys. Med Biol (57), 2012

Moyers : Ion Stopping Powers and CT Numbers

Table 7. Summary of estimated uncertainties in treatment planning due to CT numbers and stopping powers

Cause	Uncertainty Before Mitigation	Mitigation	Uncertainty After Mitigation	Possible Future Uncertainty
Scanner calibration for standard conditions	±0.3% day-to-day	Patient-specific scaling	±0.0%	±0.0%
kVp, filter, and FOV selection	±2.0% PMMA, PC > ± 2.0% bone	Use only calibrated conditions	±0.0%	±0.0%
Volume and configuration scanned	±2.5%	Patient-specific scaling	±0.0%	±0.0%
Position in scan	±1.5% water ±2.5% tissue > ± 3.0% bone	—	±1.5% water* ±2.5% tissue > ± 3.0% bone*	±0.5% water^{DE}* ±0.8% tissue^{DE} > ± 1.0% bone^{DE}*
Metal implants	100%	z ≤ 22 – MVXCT z > 22 - substitution	±5.0% metal*	±5.0% metal*
Stopping power of water	±1.0%	—	±1.0%	±0.5%
RLSP of tissues and devices	±0.0 to 3.0%	Contour and substitute	±1.0%	±1.0%
WEQ *vs.* RLSP (soft tissues only)	±1.6%	—	±1.6	±1.6
Energy dependence of RLSP for low Z	±1.2%	—	±1.2	±0.5^{MC}
Total (soft tissues only)	—	—	±3.5	±2.2

Abbreviations: DE, dual-energy CT; MC, Monte Carlo calculations.
*Not considered in total.

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Moyers, Medical Dosimetry(35), 2010

Yang : Comprehensive analysis of proton range uncertainties related to patient stopping power ratio estimation using the stoichiometric calibration

Table 8. Estimates of uncertainties (1σ) in patient SPR estimation in current clinical practice.

Uncertainty source	Uncertainties in SPR estimation (1σ)		
	Lung (%)	Soft (%)	Bone (%)
Uncertainties in patient CT imaging	3.3	0.6	1.5
Uncertainties in the parameterized stoichiometric formula to calculate theoretical CT numbers	3.8	0.8	0.5
Uncertainties due to deviation of actual human body tissue from ICRU standard tissue	0.2	1.2	1.6
Uncertainties in mean excitation energies	0.2	0.2	0.6
Uncertainties due to energy dependence of SPR not accounted by dose algorithm	0.2	0.2	0.4
Total (root-sum-square)	5.0	1.6	2.4

Yang, Phys. Med. Biol, (57) 2012

Paganetti : Range uncertainties in proton therapy and the role of Monte Carlo simulations

Source of range uncertainty in the patient	Range uncertainty without Monte Carlo	Range uncertainty with Monte Carlo
Independent of dose calculation		
Measurement uncertainty in water for commissioning	± 0.3 mm	± 0.3 mm
Compensator design	± 0.2 mm	± 0.2 mm
Beam reproducibility	± 0.2 mm	± 0.2 mm
Patient setup	± 0.7 mm	± 0.7 mm
Dose calculation		
Biology (always positive) ^	+ ~0.8%	+ ~0.8%
CT imaging and calibration	± 0.5%[a]	± 0.5%[a]
CT conversion to tissue (excluding I-values)	± 0.5%[b]	± 0.2%[g]
CT grid size	± 0.3%[c]	± 0.3%[c]
Mean excitation energy (I-values) in tissues	± 1.5%[d]	± 1.5%[d]
Range degradation; complex inhomogeneities	−0.7%[e]	± 0.1%
Range degradation; local lateral inhomogeneities *	± 2.5%[f]	± 0.1%
Total (excluding *, ^)	2.7% + 1.2 mm	2.4% + 1.2 mm
Total (excluding ^)	4.6% + 1.2 mm	2.4% + 1.2 mm

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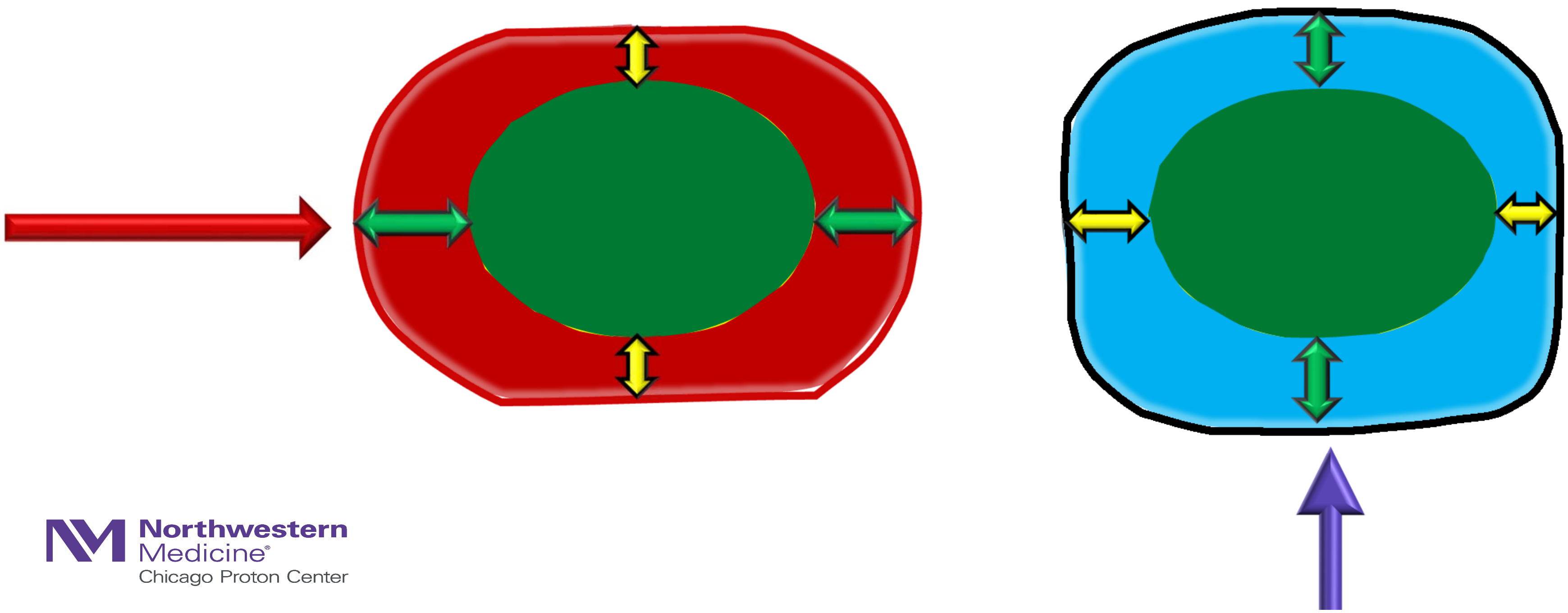
Paganetti, Phys. Med Biol (57), 2012

Setup and Range Uncertainty with Protons : Field Specific Margins

Perpendicular Expansion
Avoid a geometric miss
Physical Distance
(cm)

Parallel Expansion
Avoid a range miss
Radiobiological Depth
(Water Equiv. Thickness)



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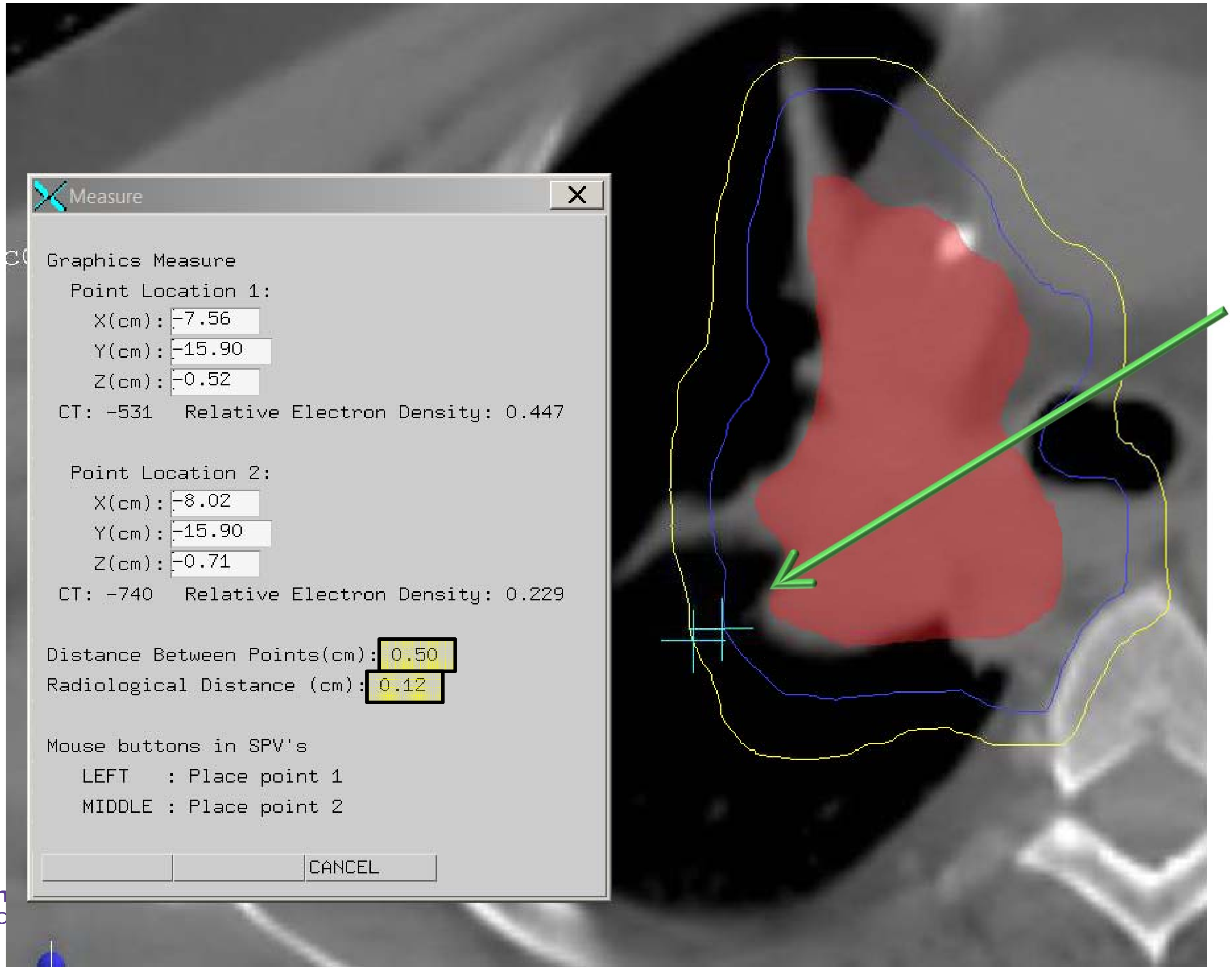
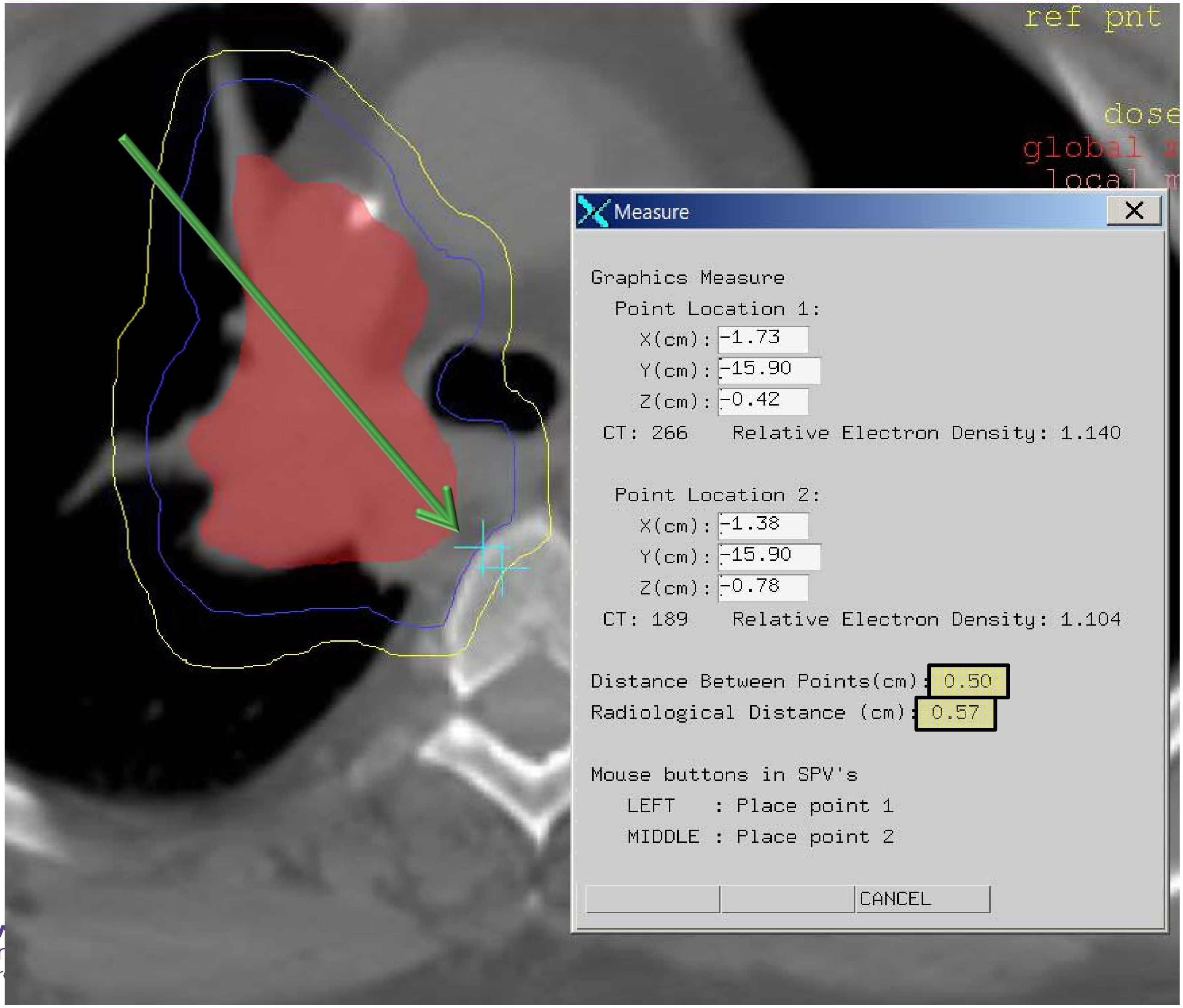

Measure
Graphics Measure
Point Location 1:
X(cm): -7.56
Y(cm): -15.90
Z(cm): -0.52
CT: -531 Relative Electron Density: 0.447
Point Location 2:
X(cm): -8.02
Y(cm): -15.90
Z(cm): -0.71
CT: -740 Relative Electron Density: 0.229
Distance Between Points(cm): 0.50
Radiological Distance (cm): 0.12
Mouse buttons in SPV's
LEFT : Place point 1
MIDDLE : Place point 2
CANCEL



ref pnt
dose
Measure
Graphics Measure
Point Location 1:
X(cm): -1.73
Y(cm): -15.90
Z(cm): -0.42
CT: 266 Relative Electron Density: 1.140
Point Location 2:
X(cm): -1.38
Y(cm): -15.90
Z(cm): -0.78
CT: 189 Relative Electron Density: 1.104
Distance Between Points(cm): 0.50
Radiological Distance (cm): 0.57
Mouse buttons in SPV's
LEFT : Place point 1
MIDDLE : Place point 2
CANCEL

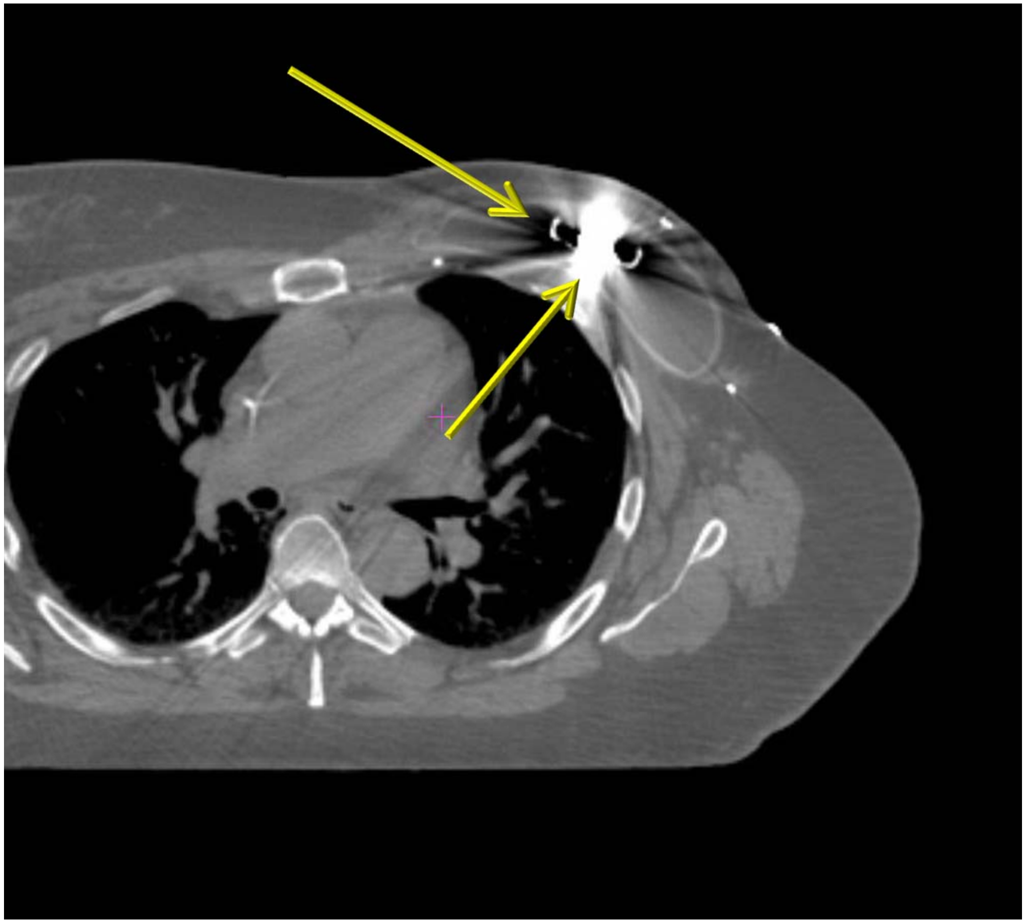
CT is the Patient "Map" : Areas of Specific Concern for Protons

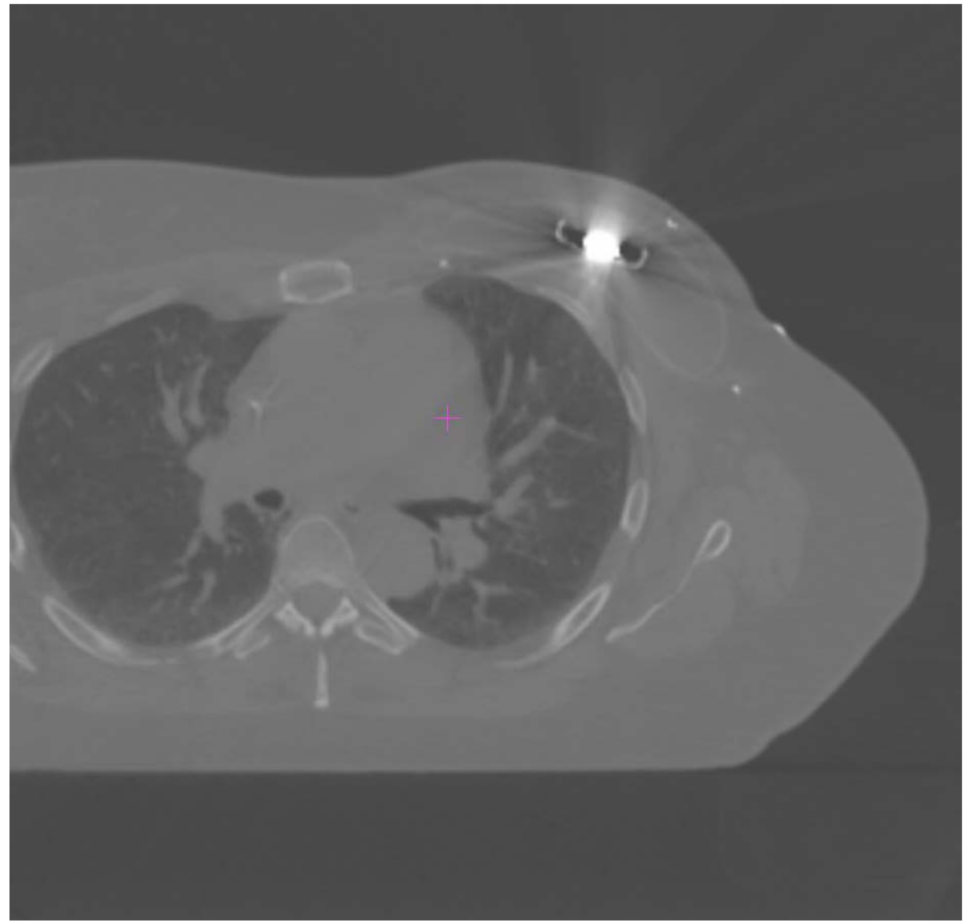
- Conversion from HU to RSP has inherent problems
  - Noise
  - Beam hardening

- Trying to make our CT scanner a spectrometer
  - Two tissues can have same HU but different RSP

- Anything not natural can have large errors.
  - Contrast
  - Fillings
  - Implants

Chestwall Expander





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Breast Prosthesis

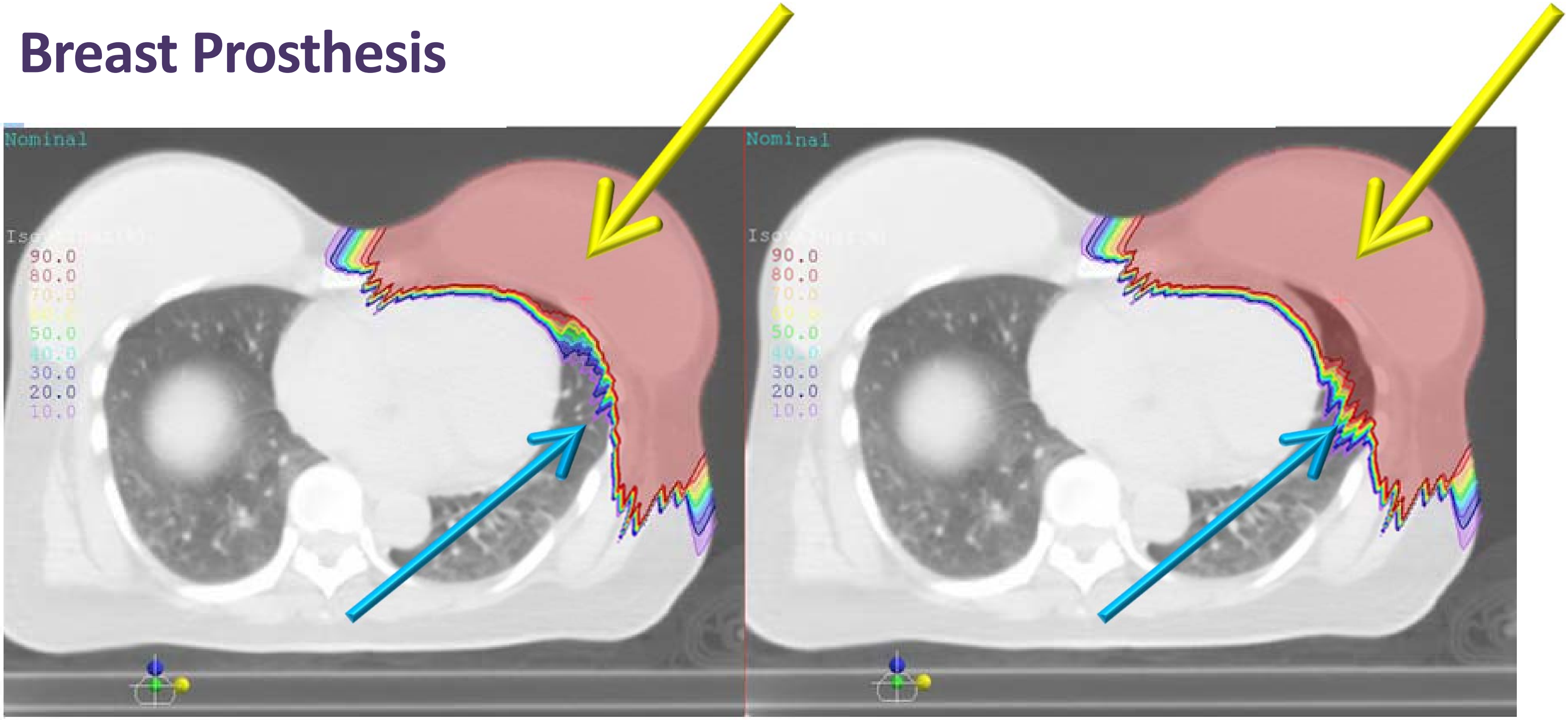

Fig. 3: Treatment plan for patient with silicone breast prosthesis. (a) Planned dose distribution without RLSP reassignment. (b) Delivered dose distribution if planned without proper pRLSP assignment.

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Moyers et.al Med Dosim. 2014 Spring;39(1):98-101.

Is there any hope for improvements?

- Dual Energy CT (kV / MVCT)
- Proton activation (PET/SPECT) Tomography
- Prompt Gamma verification
- Proton Radiography
- Proton Tomography

Treatment Planning Methods depend on Proton Delivery Methods

Double-Scatter (DS)	Uniform Scanning (US)	Pencil Beam Scanning (PBS)	Intensity Modulated Proton Therapy (IMPT)

Aperture / Compensator Based Planning

Inversed planned proton spot intensity optimization

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Aperture / Compensator based Planning Strategies

- Cover the target with appropriate margins

- Spare the critical structures

- Plan with fields that deliver the most “robust” plan

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Tools to do our job

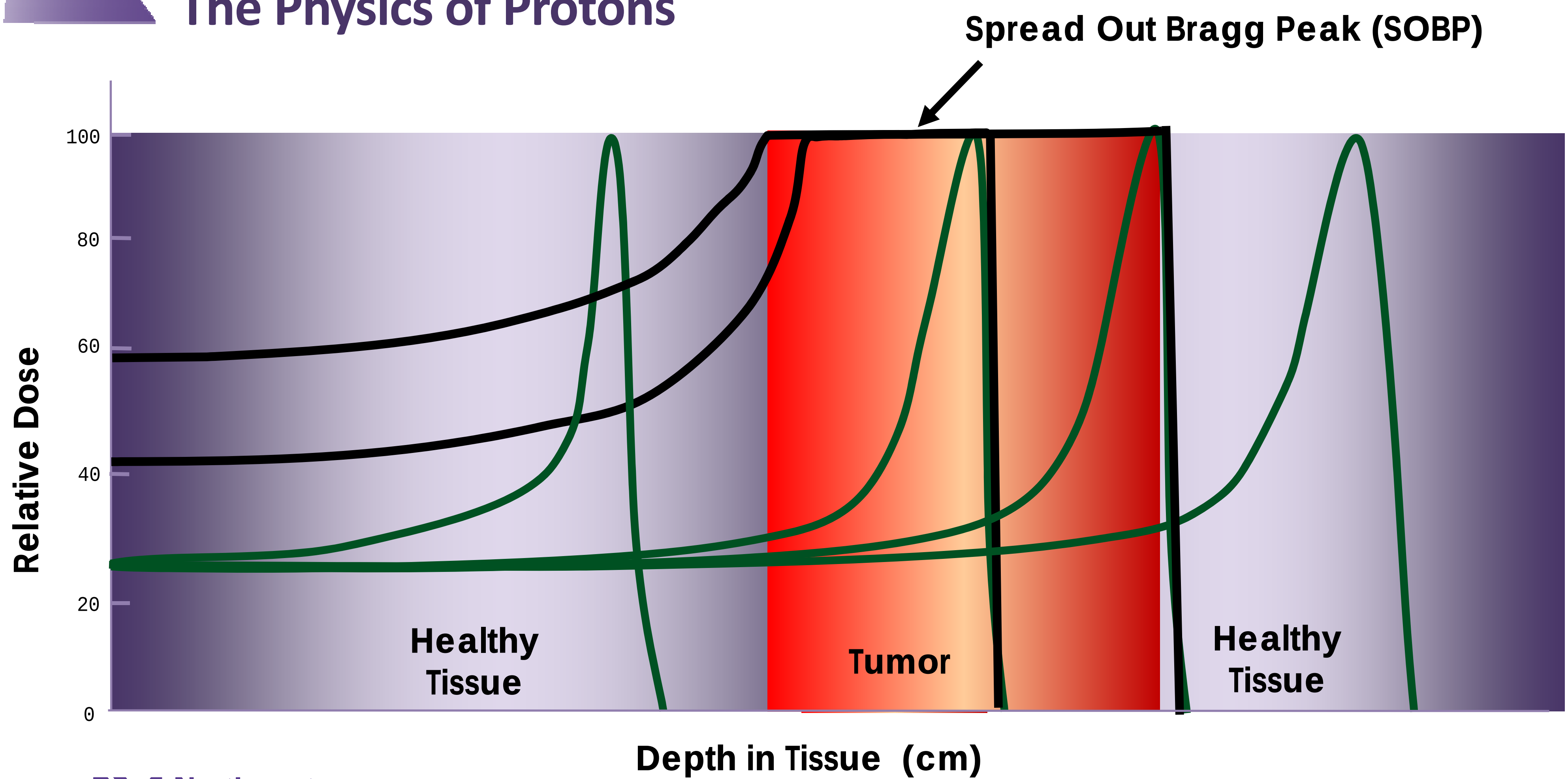
– Range : The depth of the Bragg peak (Distal 90%)

– Modulation : The spread of the Bragg peak

– Apertures : Shaping the beam perpendicular to the path

– Compensators : Distal Shaping

The Physics of Protons



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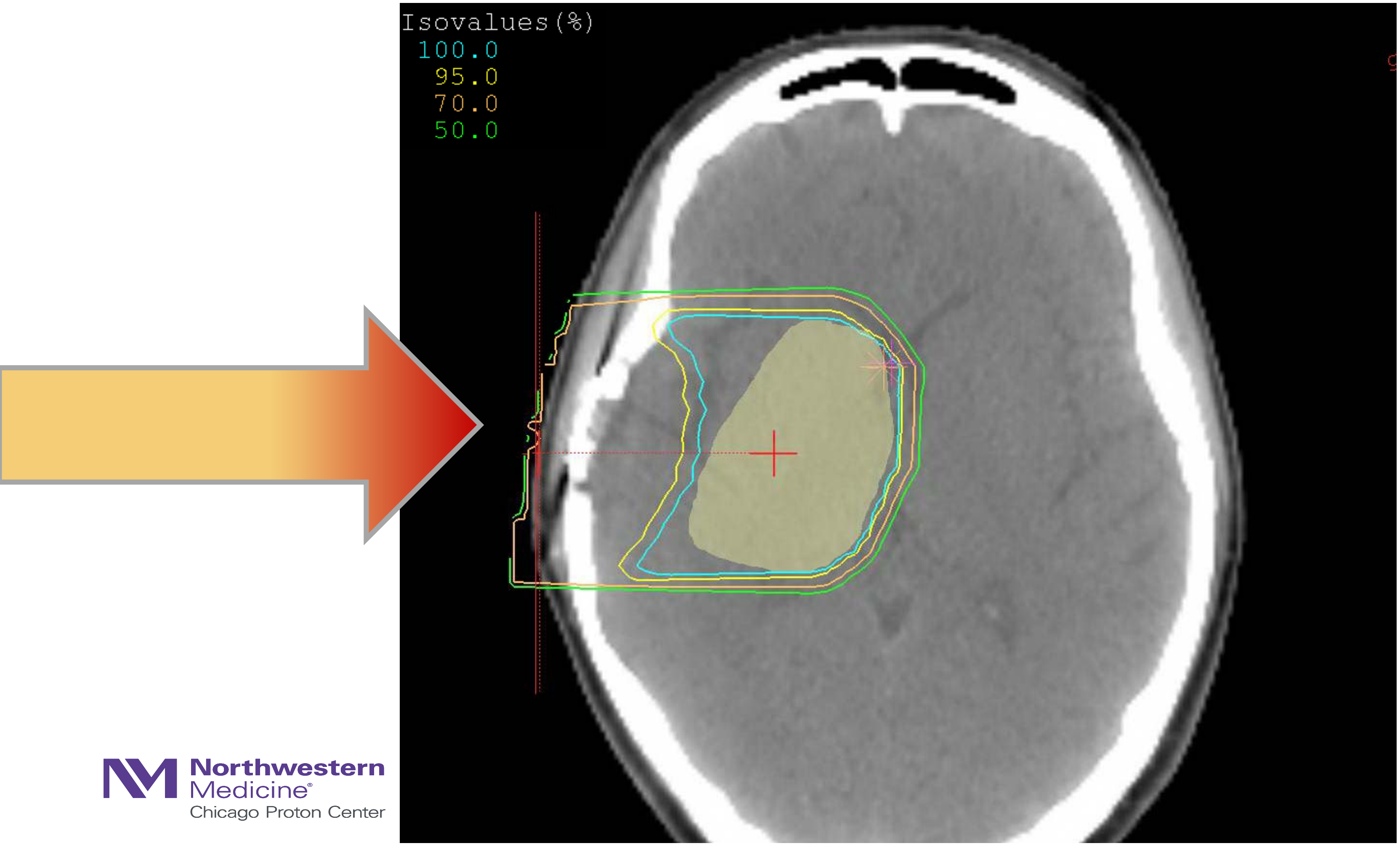
Range and Modulation



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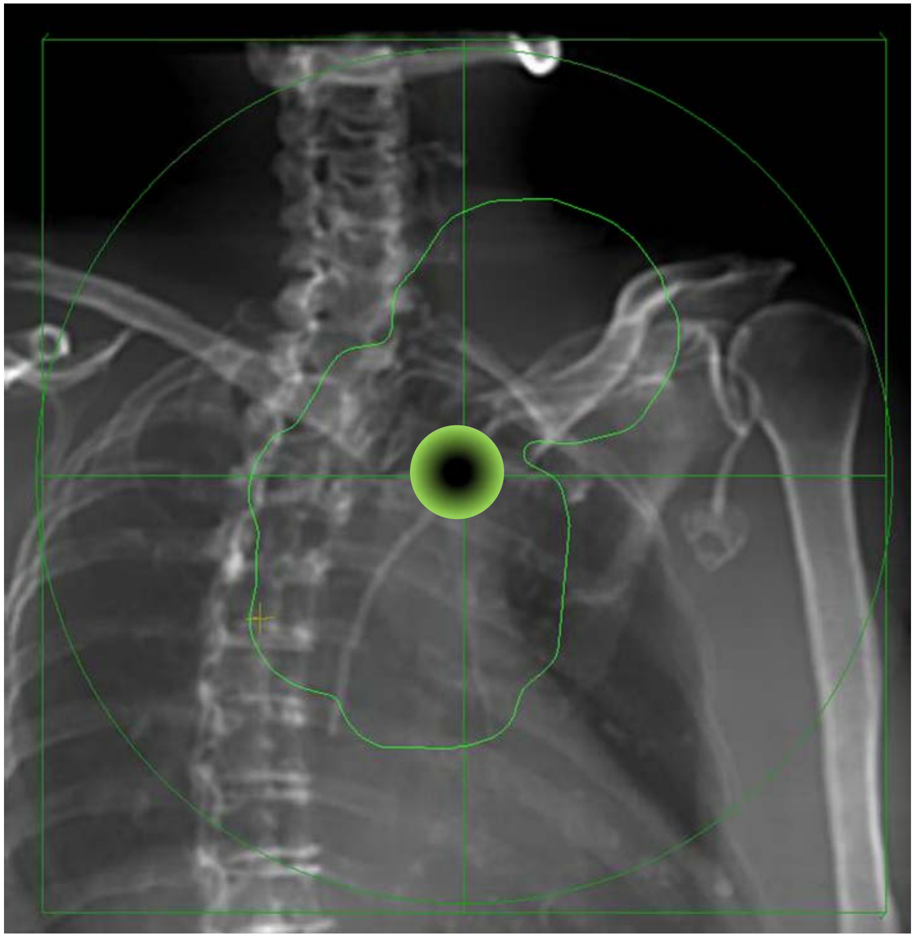
Spreading the beam across the field



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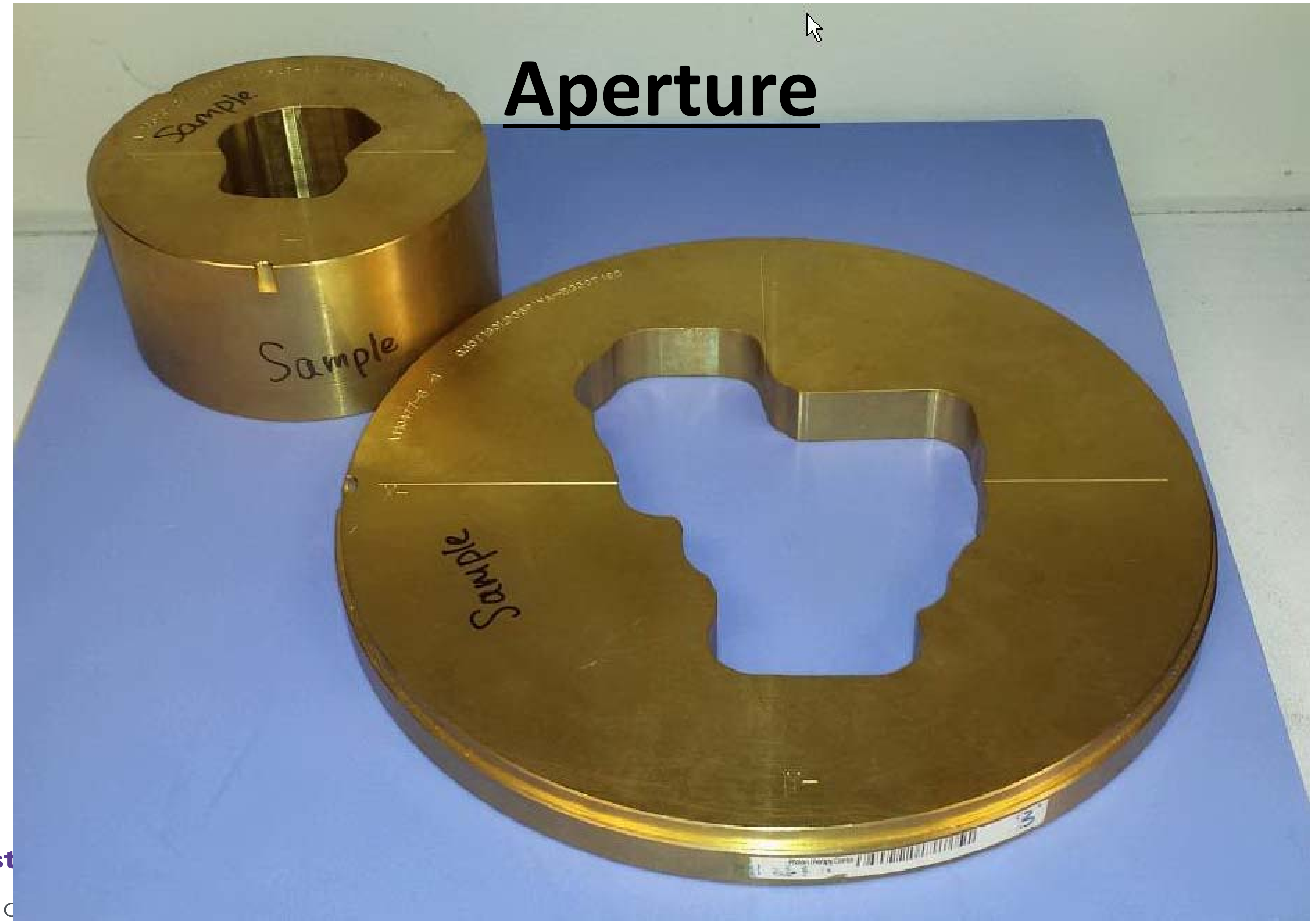
Patient Specific Devices



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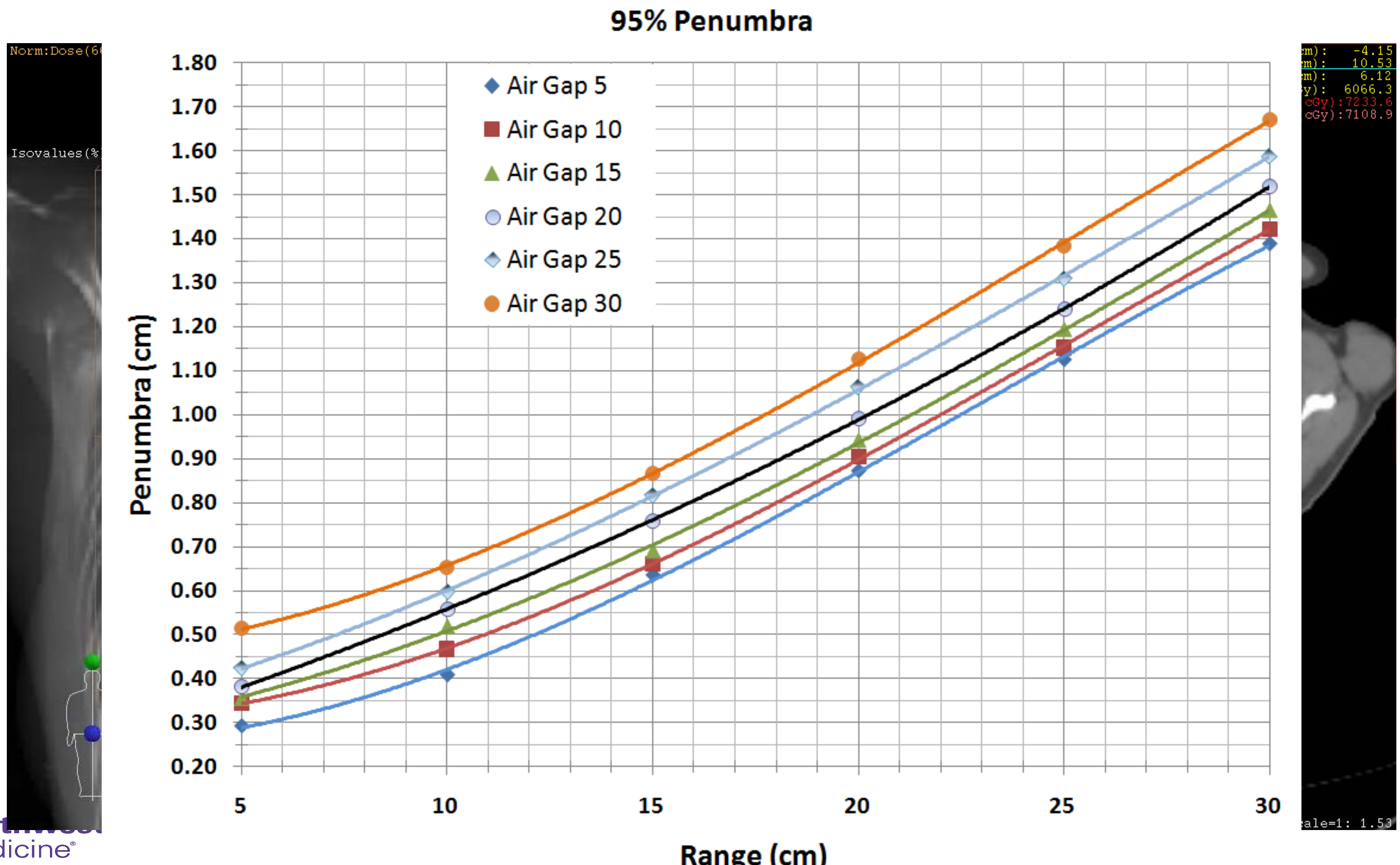
Aperture Design



Brass Aperture mounted in Treatment Snout

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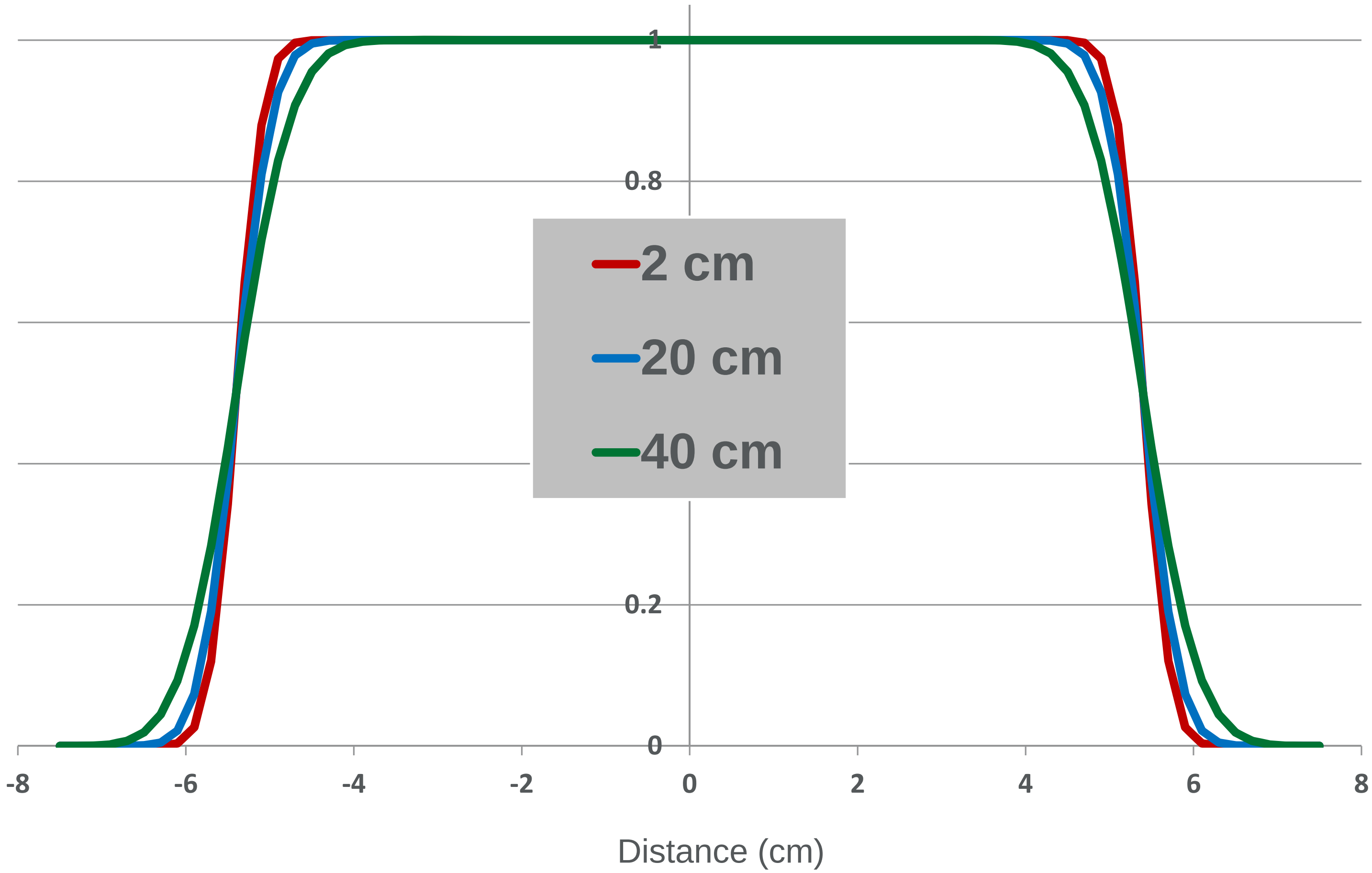
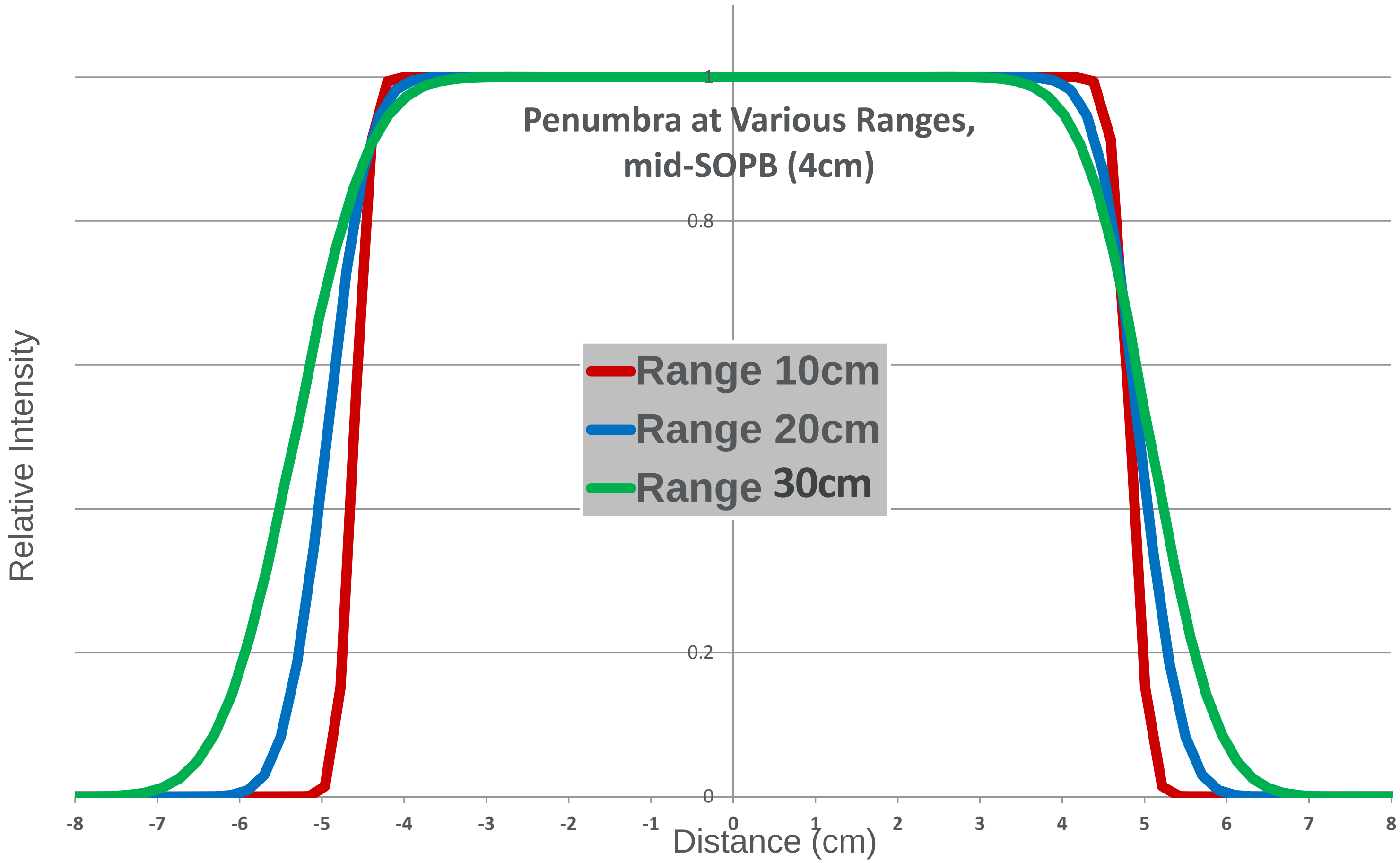
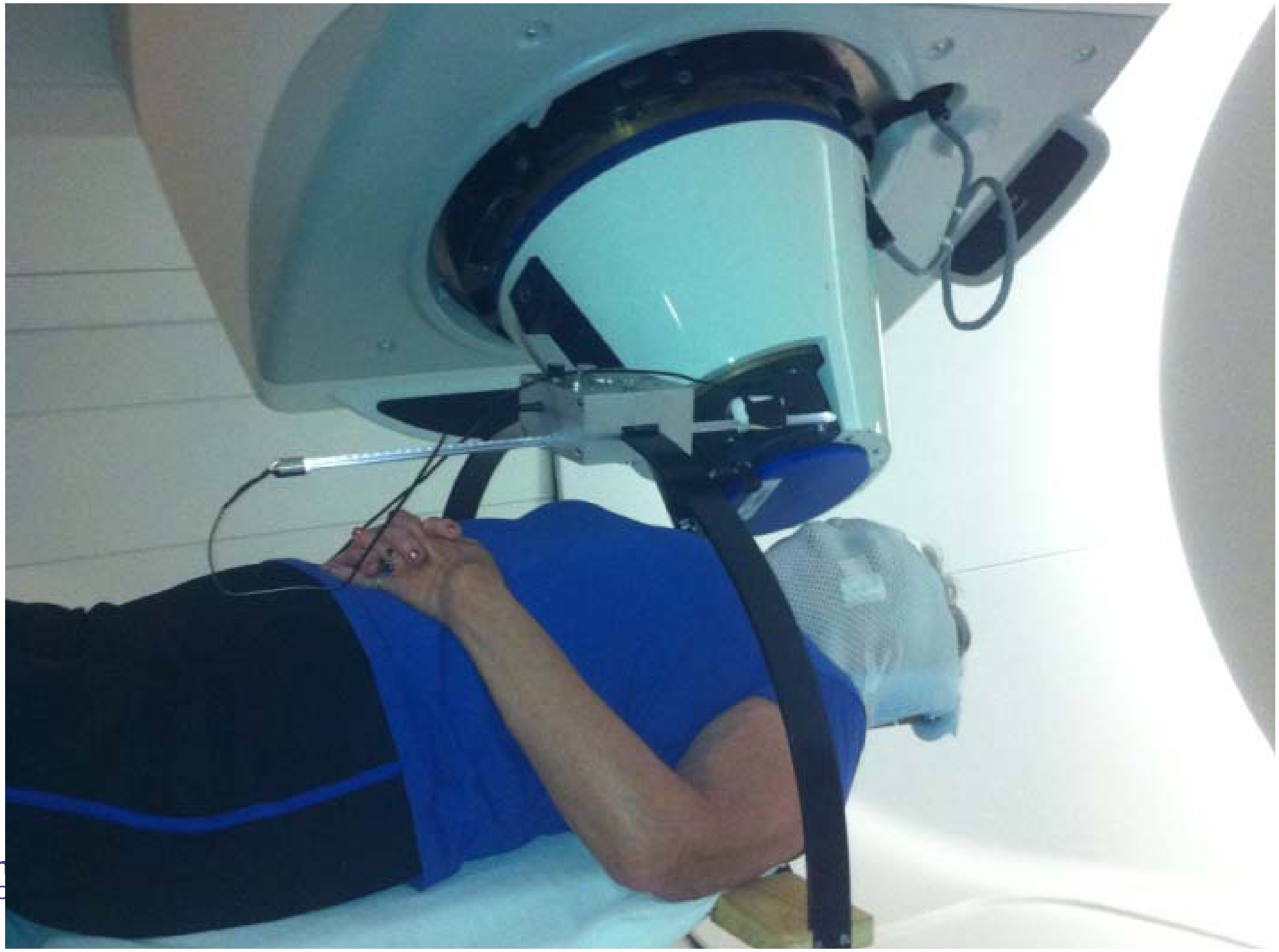
Penumbra at Various Air Gaps



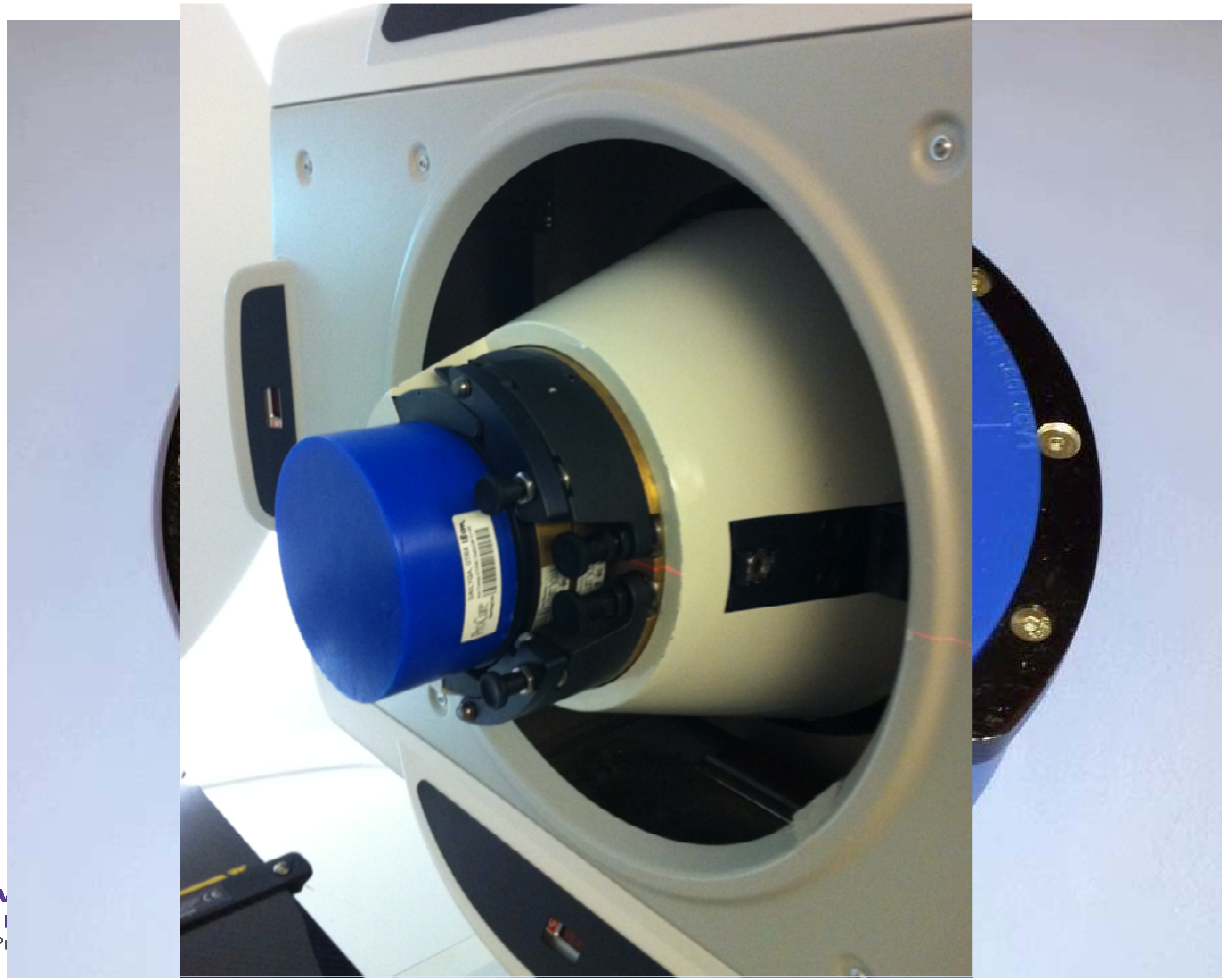
Penumbra as Mid SOBP at various ranges



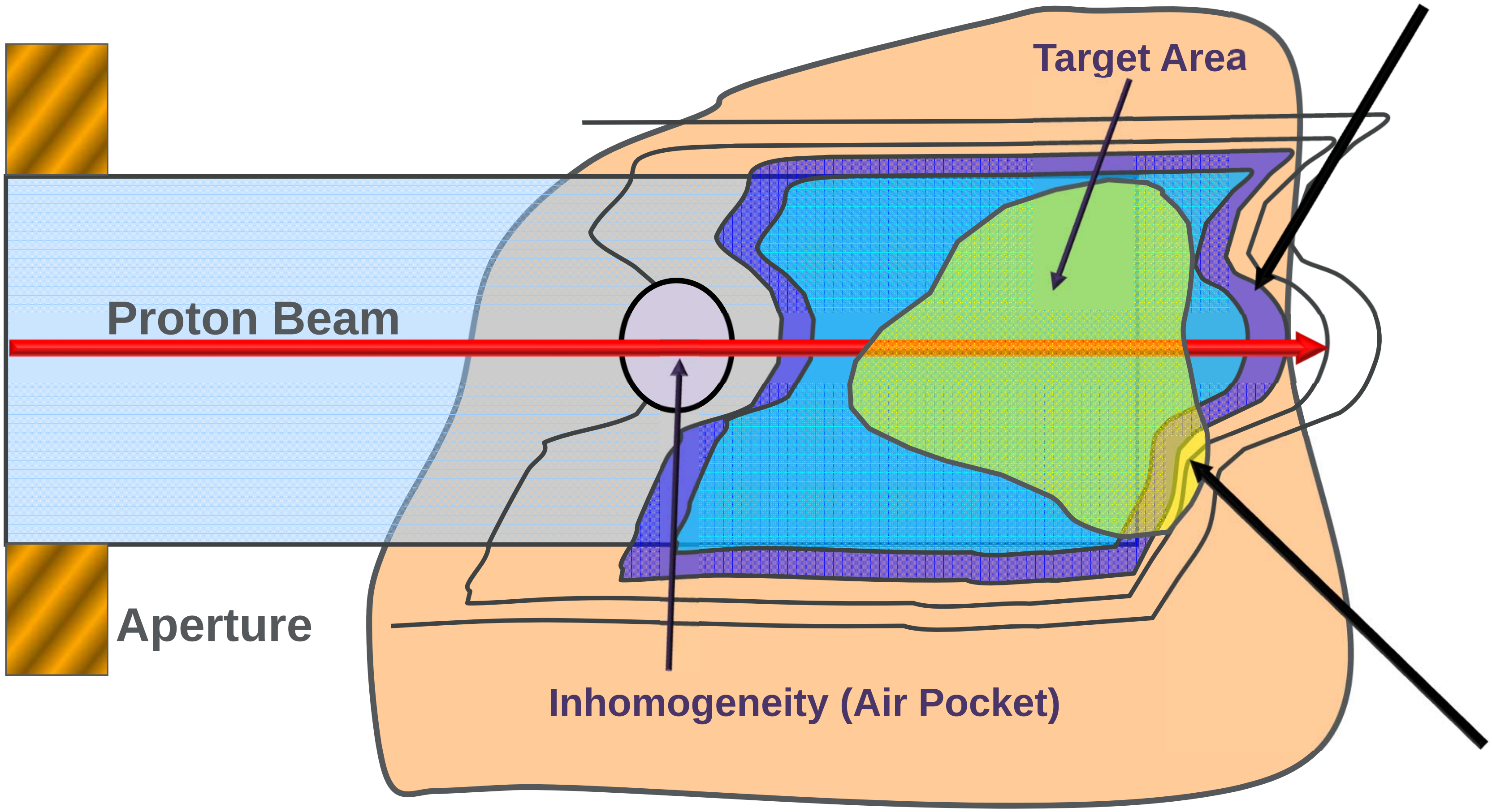
For treatments, the snout is extended to be close to the patient
Reduced Air Gap = smaller penumbra



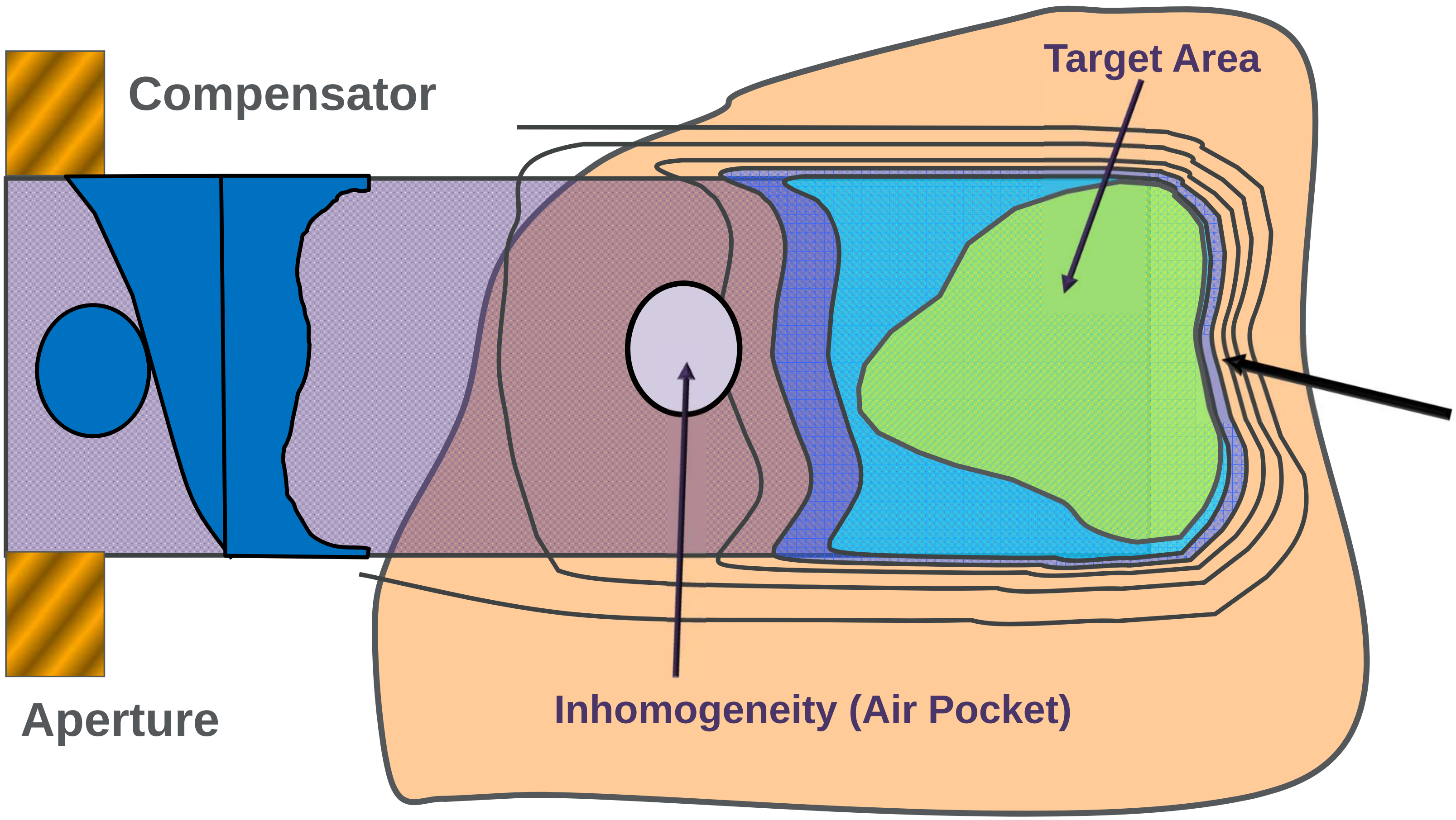
Compensators for Distal Shaping



No Compensator



With Compensator



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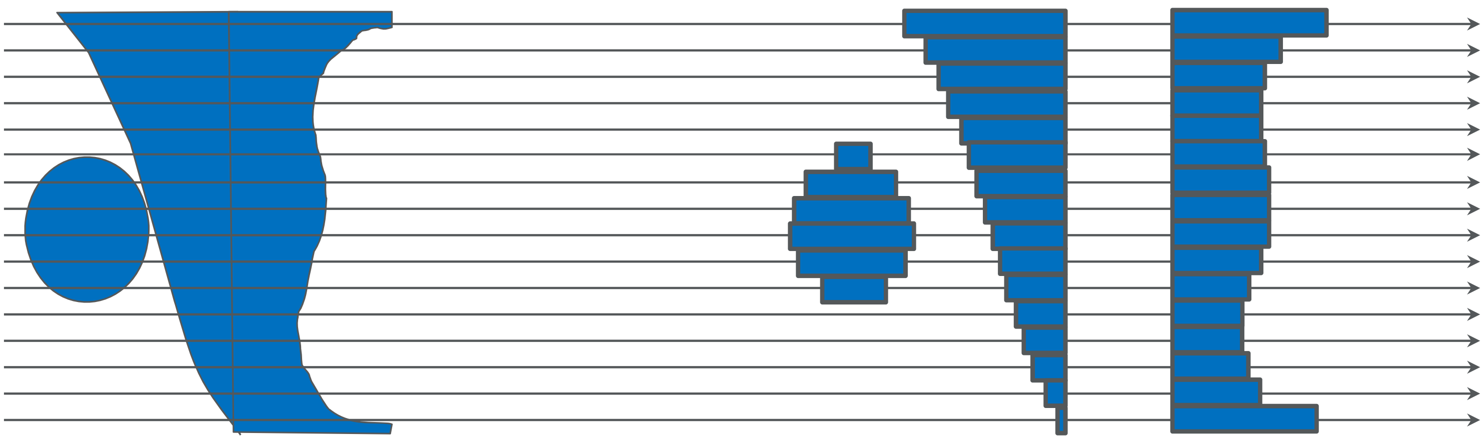
Design of the compensator



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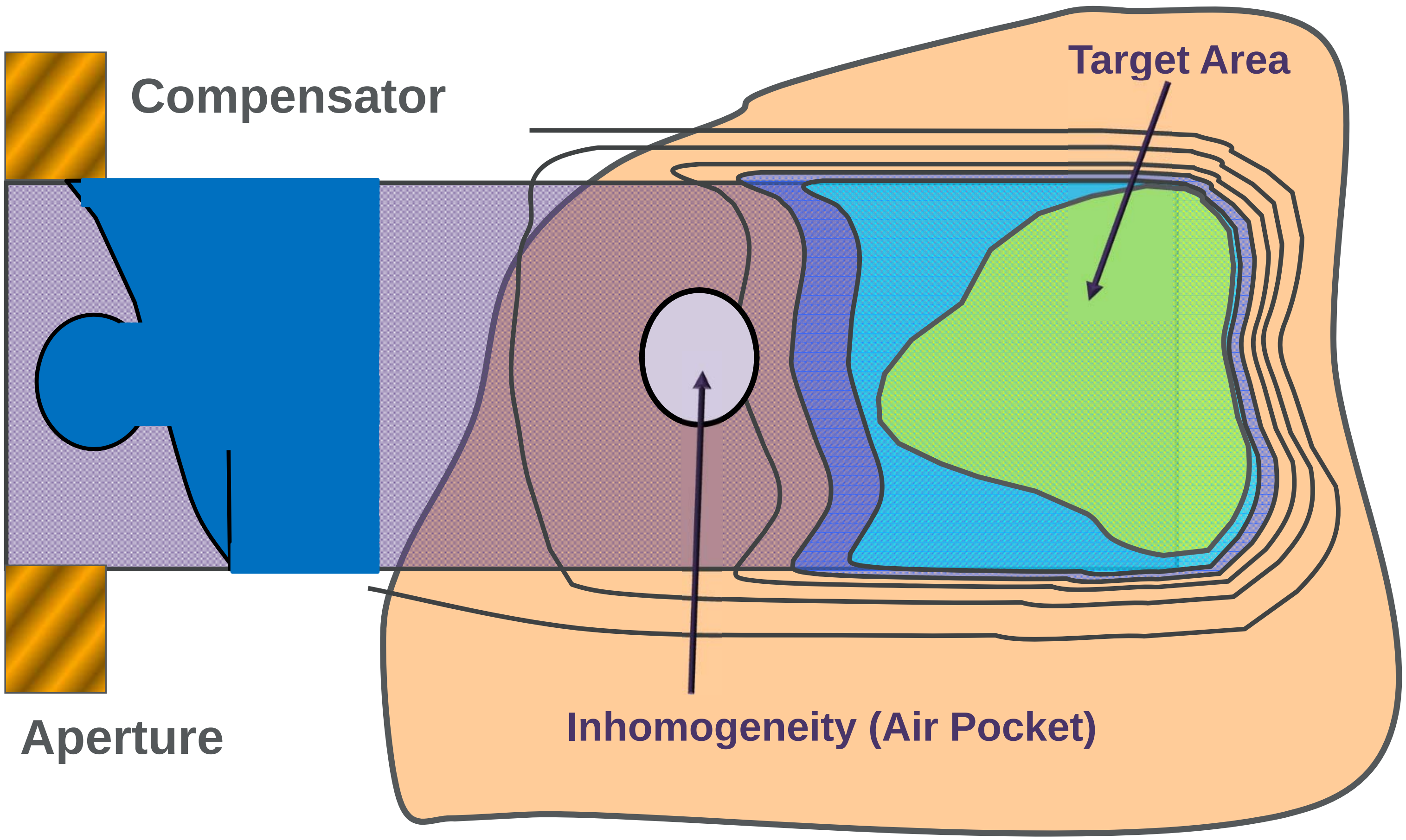
Design of the compensator

With Discrete Compensator



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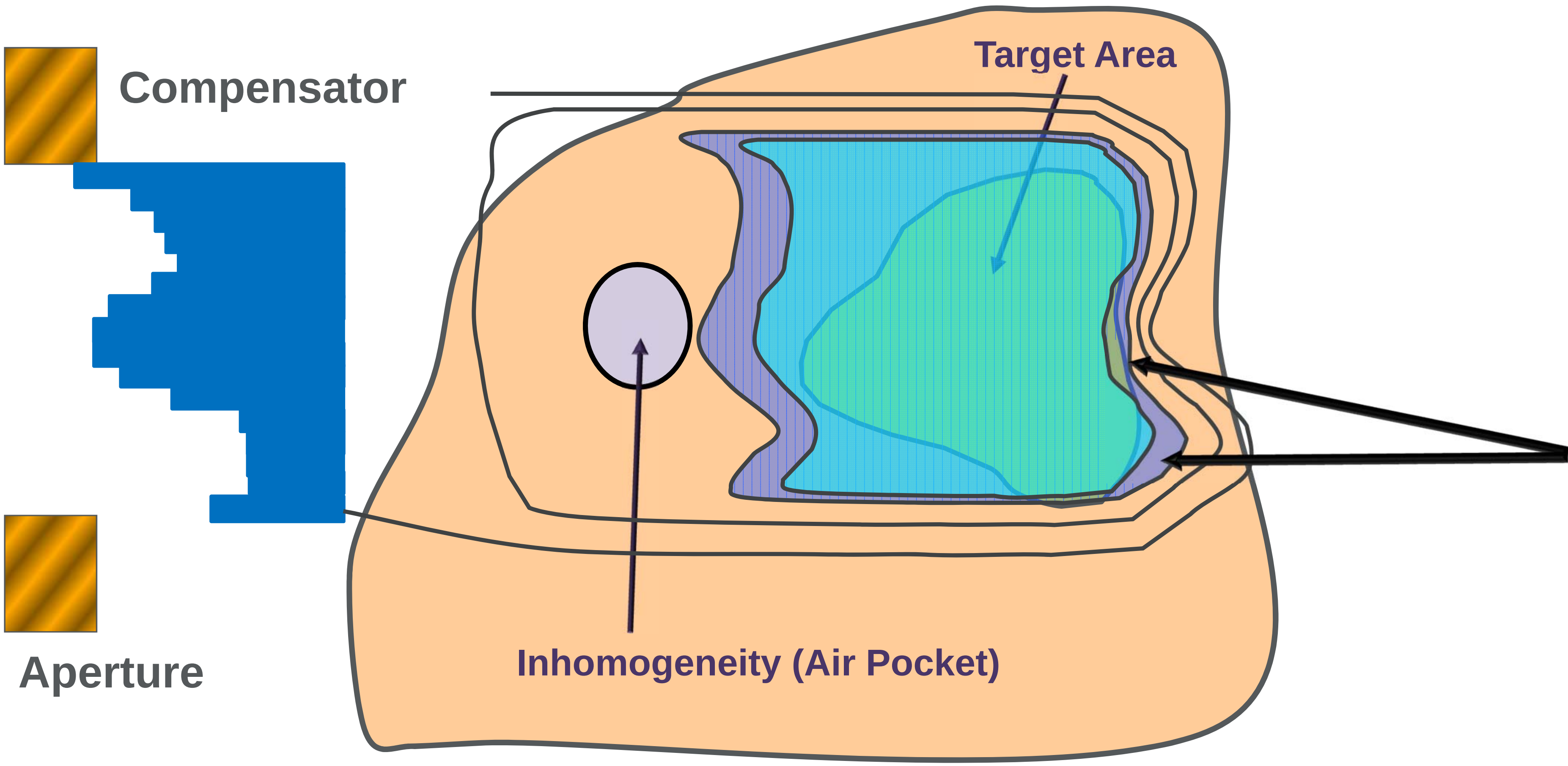
With Discrete Compensator



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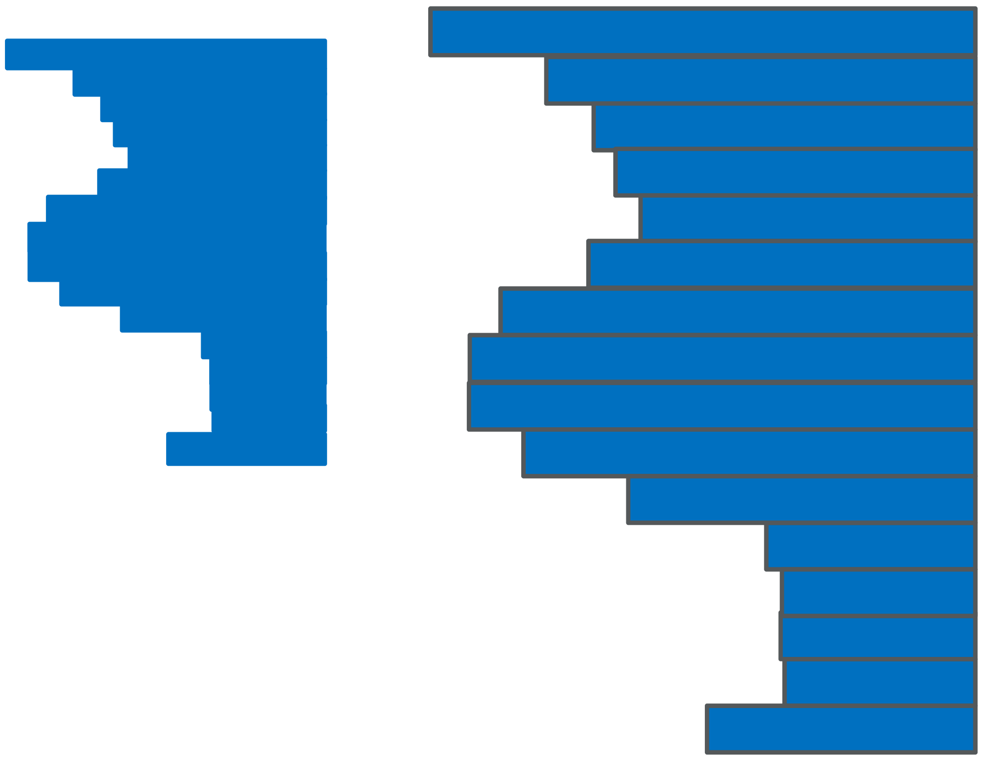
Smearing



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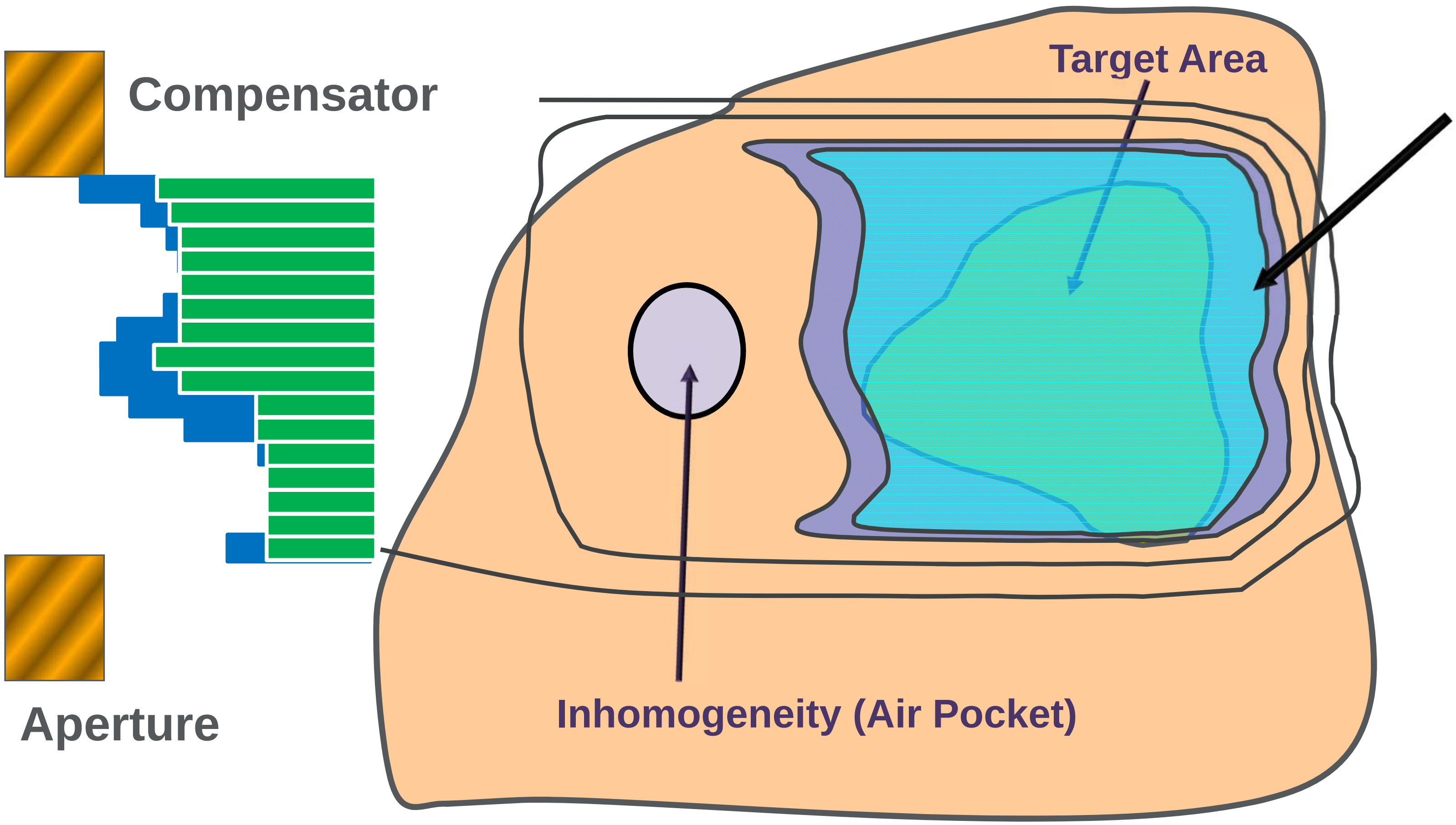
With Discrete Compensator

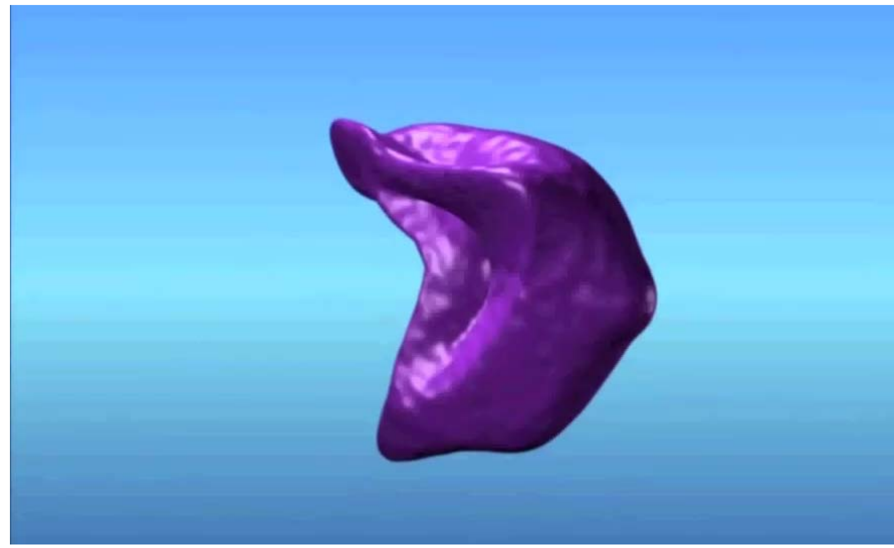


Smearing

- Sacrificing distal conformity to ensure you have enough range (and modulation) to cover the target in the case of anticipated misalignments
- Accounts for the fact that treatment path lengths may be different than planned path lengths due to set-up errors and internal motion.
- Can easily be built into compensator design
- Is not directly "mechanically" accounted for in IMPT (No compensator)

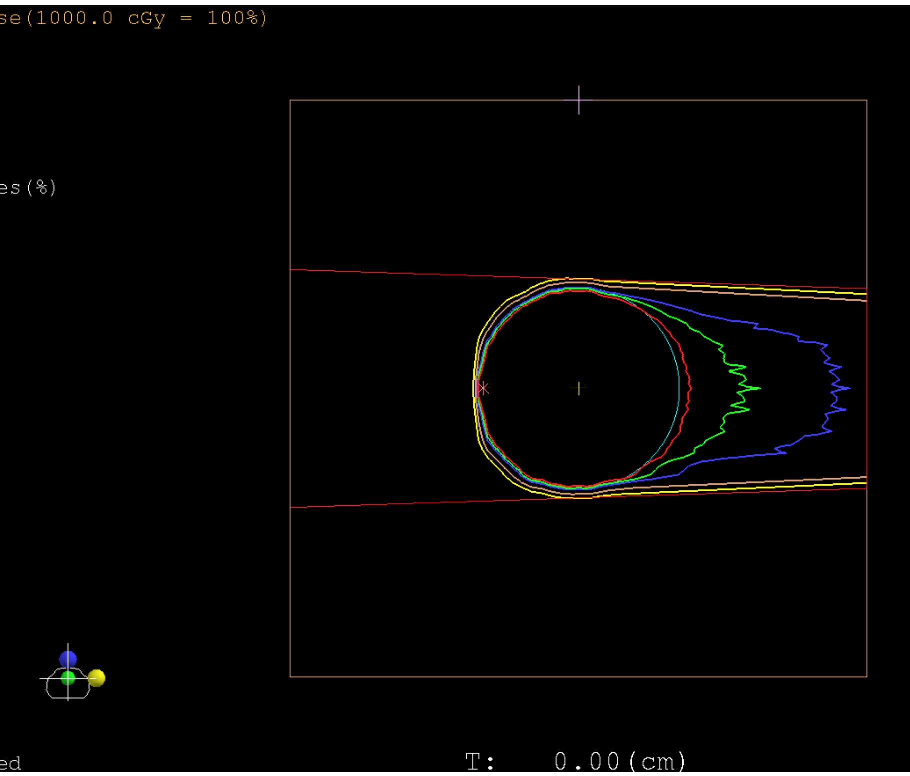
Intensity Modulated Proton Therapy (IMPT)

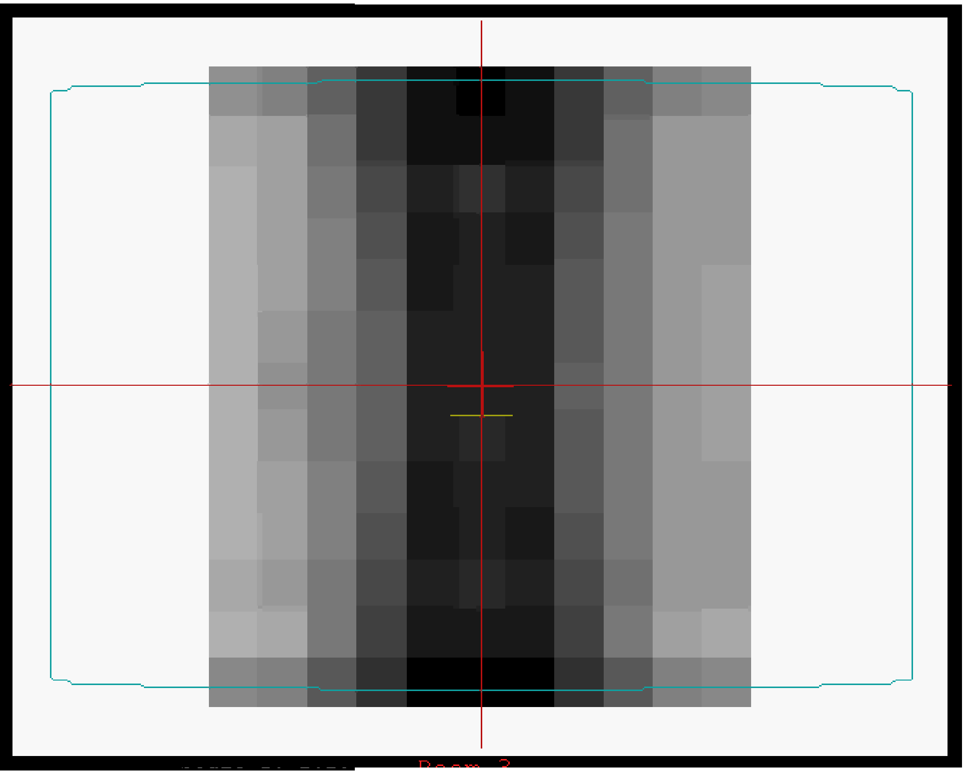
- Layers of spot patterns delivered over the target volume
- Variable Intensity Control
  - Dose uniformity
  - Simultaneous Intergraded Boost
- Distal AND Proximal conformity
- The ability to perform Single Field or Multi-Field Optimizations



Movie clip from Varian ProBeam : https://www.youtube.com/watch?v=AQTE7UqbjoY

Spot Intensity for SFUD plan





BEV of the spot intensity patterns

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Spot Positions and Intensity

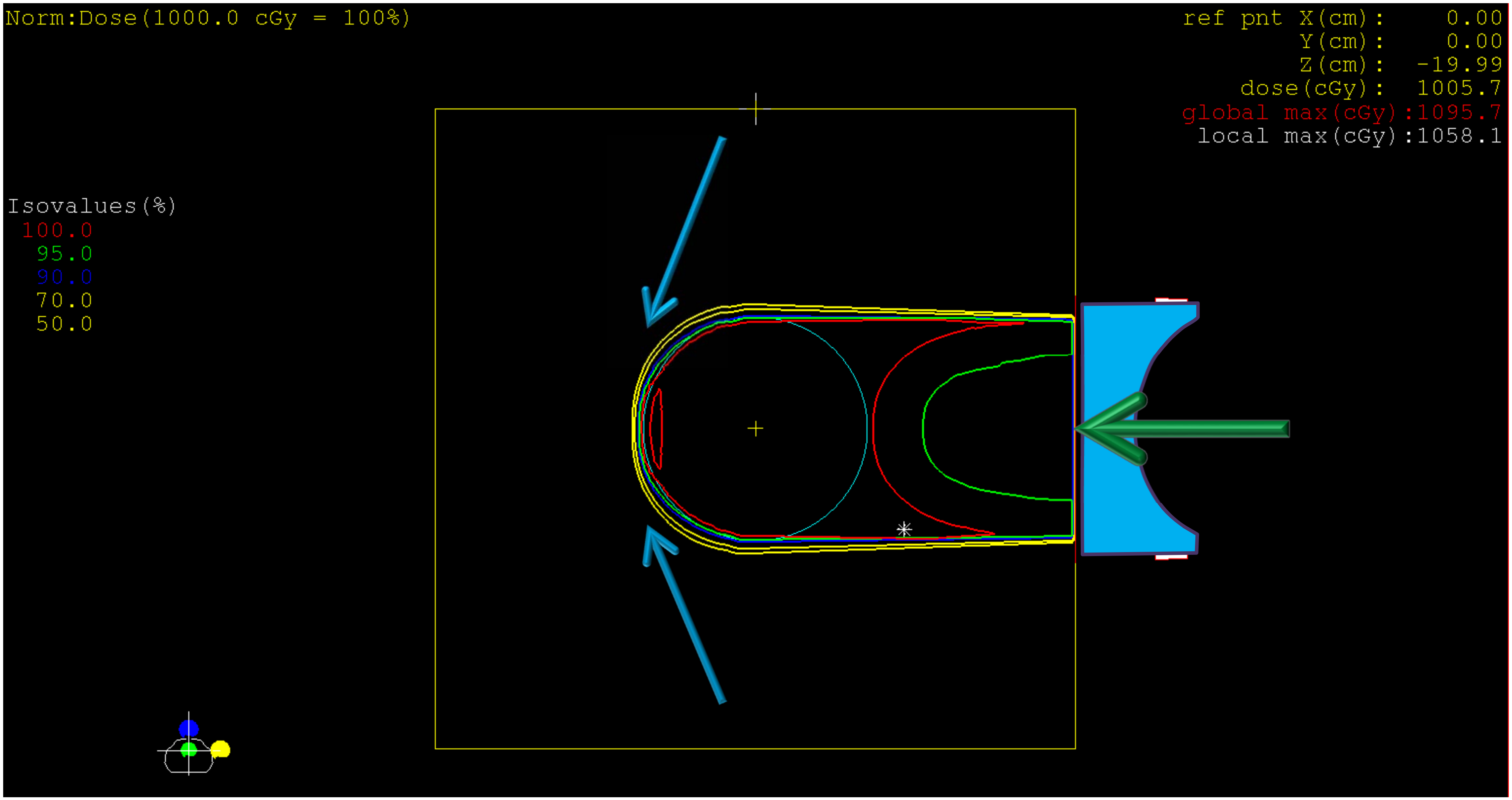
- Impossible to manually define spot positions and intensities and hope they relate to each other.
- Inverse planning is required
- Objective function is defined
- An iterative process is used to minimize the objective function

Objectives/Constraints | Beams | Energy Layers | Beam Computation Settings | Beam Weighting

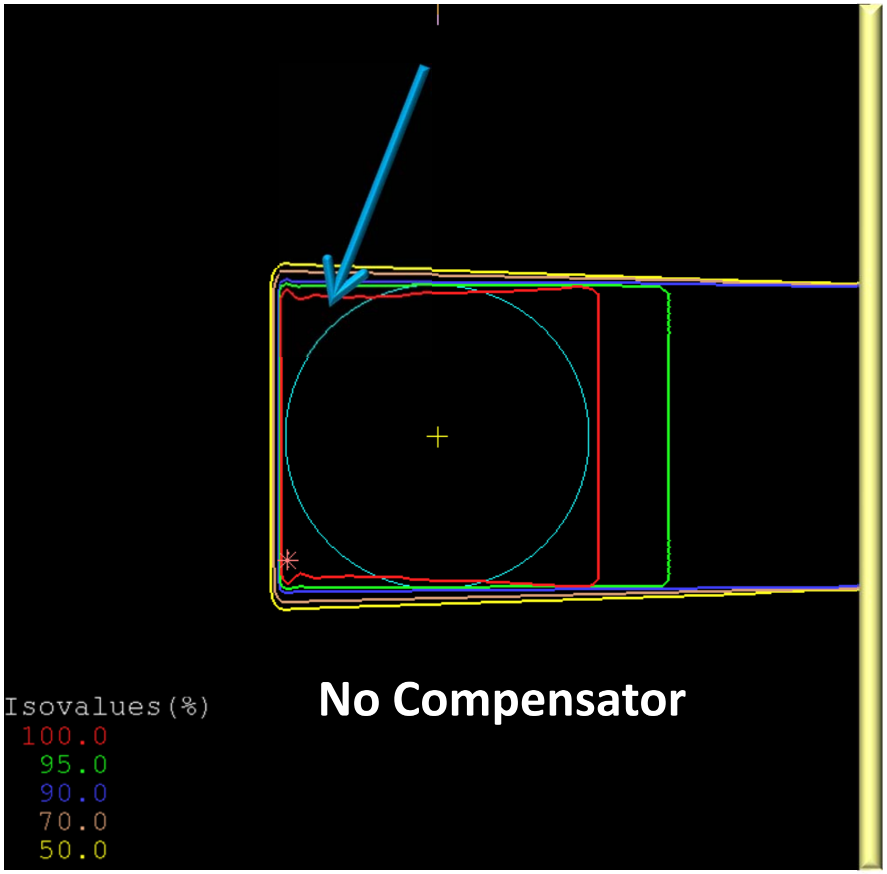
Add... | Edit... | Delete | Load template... | Create template... | Add MCO function

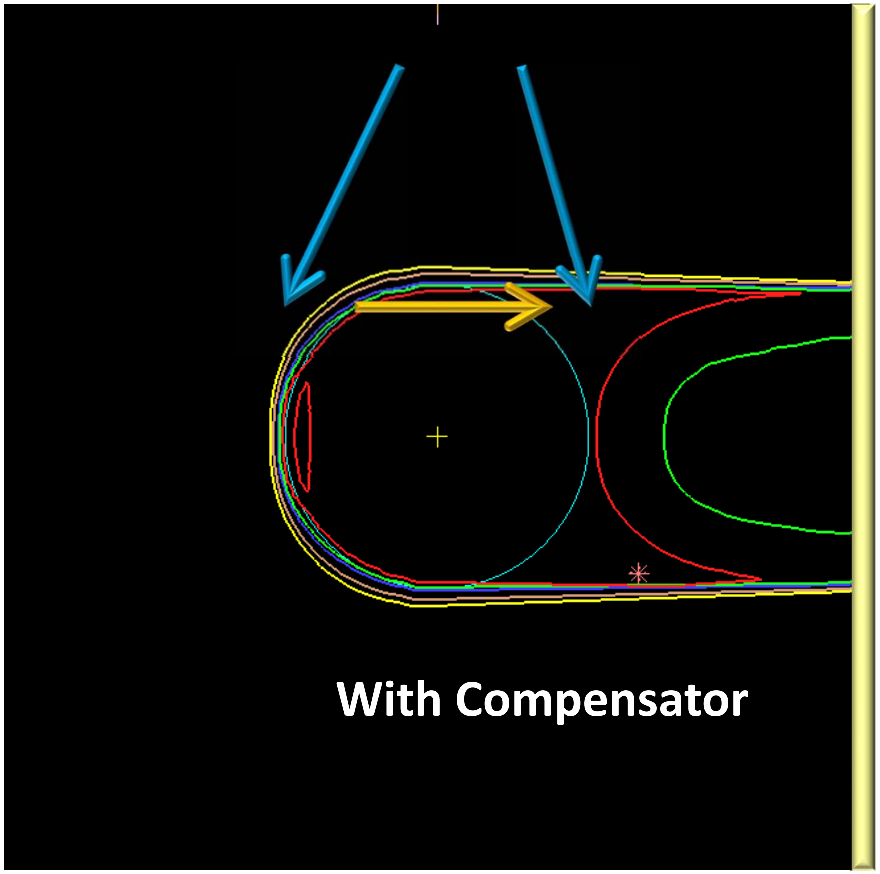
Function	Constraint	Dose	ROI	Description	Robust	Weight	Value
Physical Composite Objective							0.9345
Min Dose		Plan	CTV_NWM	Min Dose 6300 cGy	★	500	0.6437
Max Dose		Plan	Chiasm	Max Dose 5400 cGy	★	1000	0.1342
Max Dose		Plan	BrainStem	Max Dose 5550 cGy	★	4000	0.0712
Min Dose		Beam Set	CTV_NWM	Min Dose 6300 cGy, All beams		1	0.0269
Max DVH		Plan	Brain	Max DVH 5000 cGy to 3% volume		150	0.0192
Max Dose		Plan	OpticNerve_L	Max Dose 5400 cGy	★	1500	0.0146
Max Dose		Plan	Brain	Max Dose 6200 cGy		350	0.0109
Max Dose		Plan	100 SPLASH	Max Dose 6300 cGy		100	0.0053
Max Dose		Plan	CTV_NWM	Max Dose 6600 cGy		600	0.0045
Max Dose		Plan	OpticNerve_R	Max Dose 5400 cGy	★	1500	0.0036

Use of a Compensator for distal shaping



Distal conformity using a Compensator





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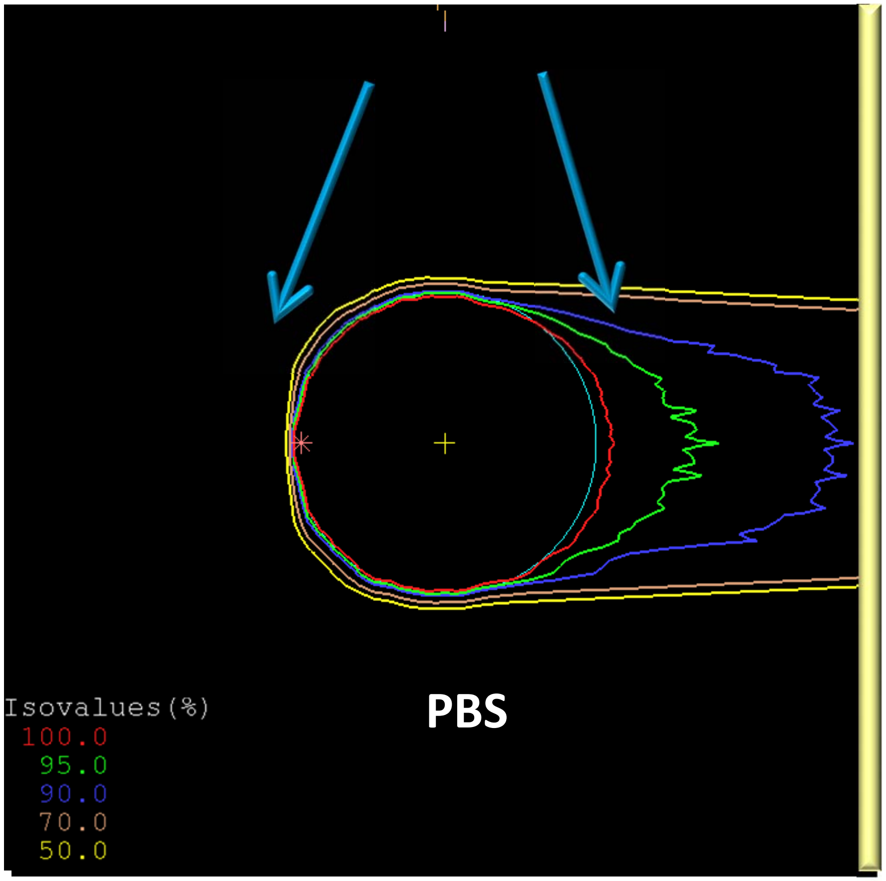
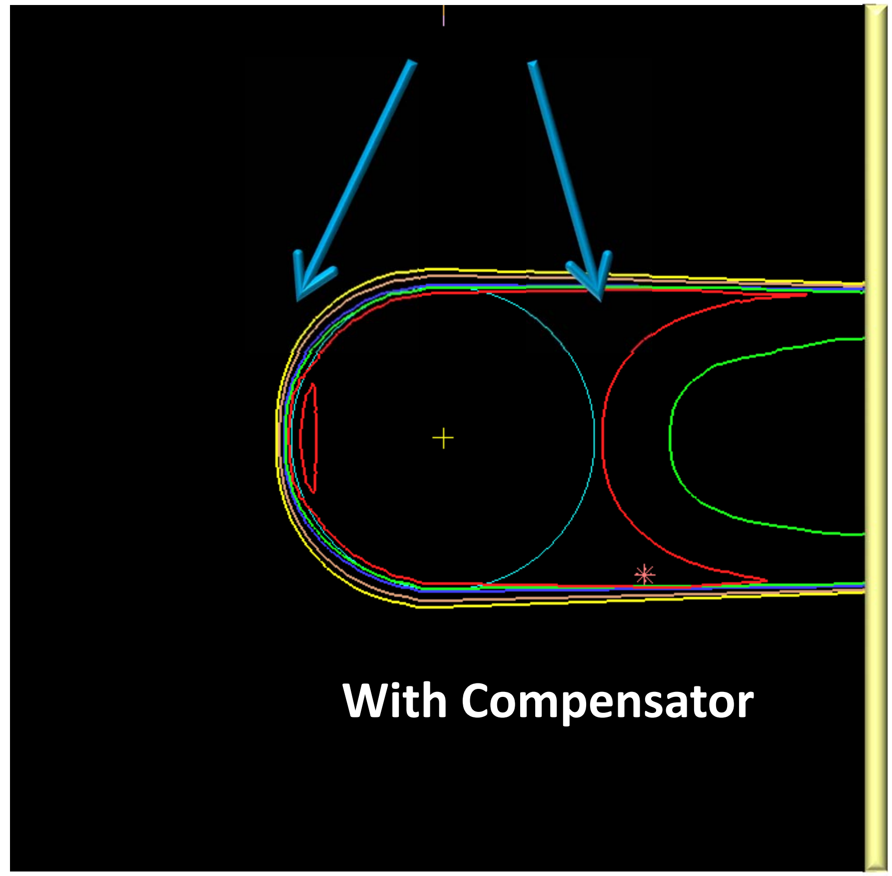
Advantage of PBS : The addition of Proximal Conformity





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IMPT Optimization Methods

Single Field Optimization (SFO)

Uniform Dose is delivered to the entire target by each field individually

Less sparing of critical structures

Less sensitive to Set-up/Range errors

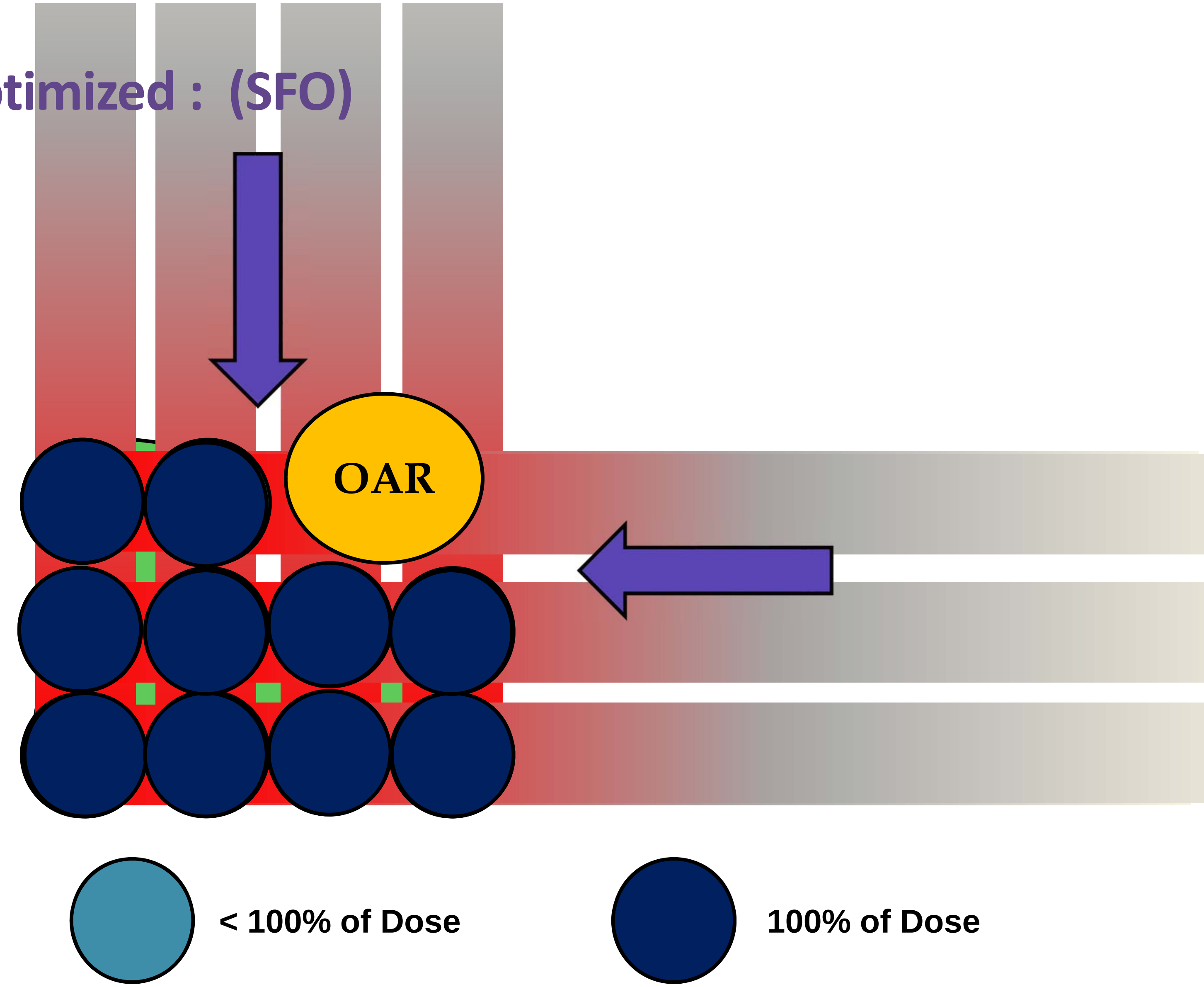
Multi Field Optimization (MFO)

Spot weights of all fields are optimized together. The spot weight of one field will rely on another field's dose to create an integrated uniform target dose

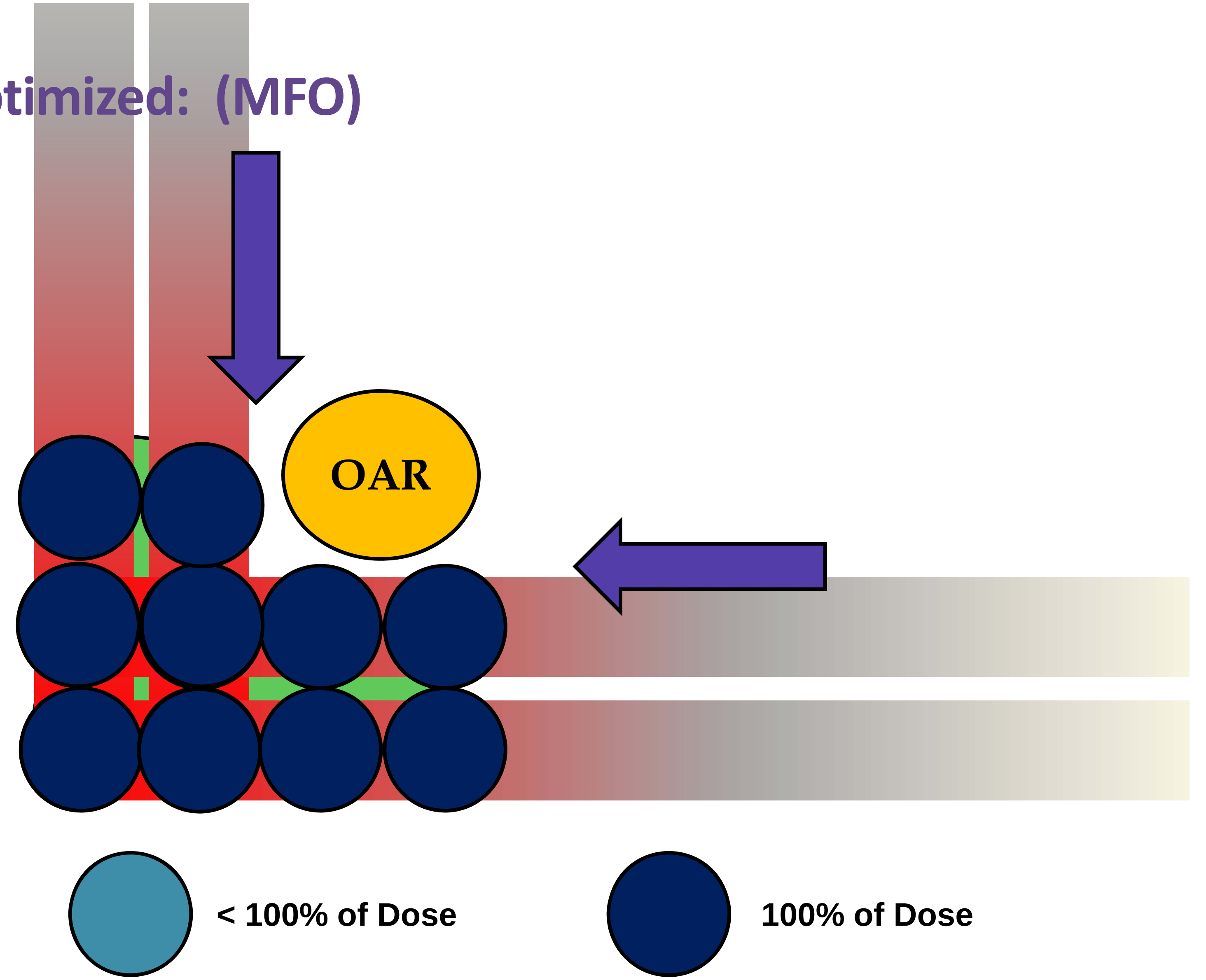
Better for sparing critical structures

More sensitive to Set-up/Range errors

Single Field Optimized : (SFO)



Multi-Field Optimized: (MFO)



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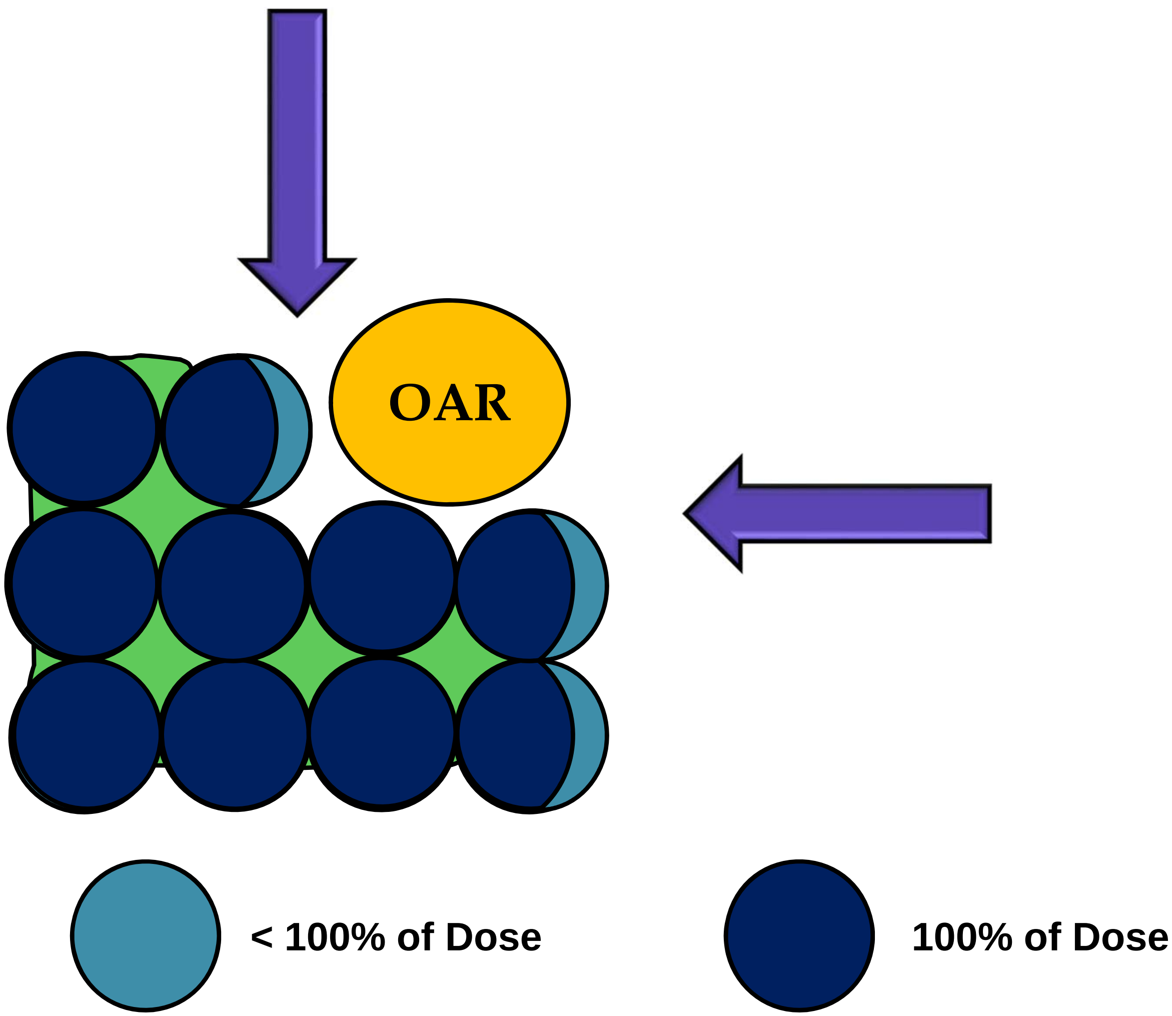
Single Field Optimized with a systematic range error



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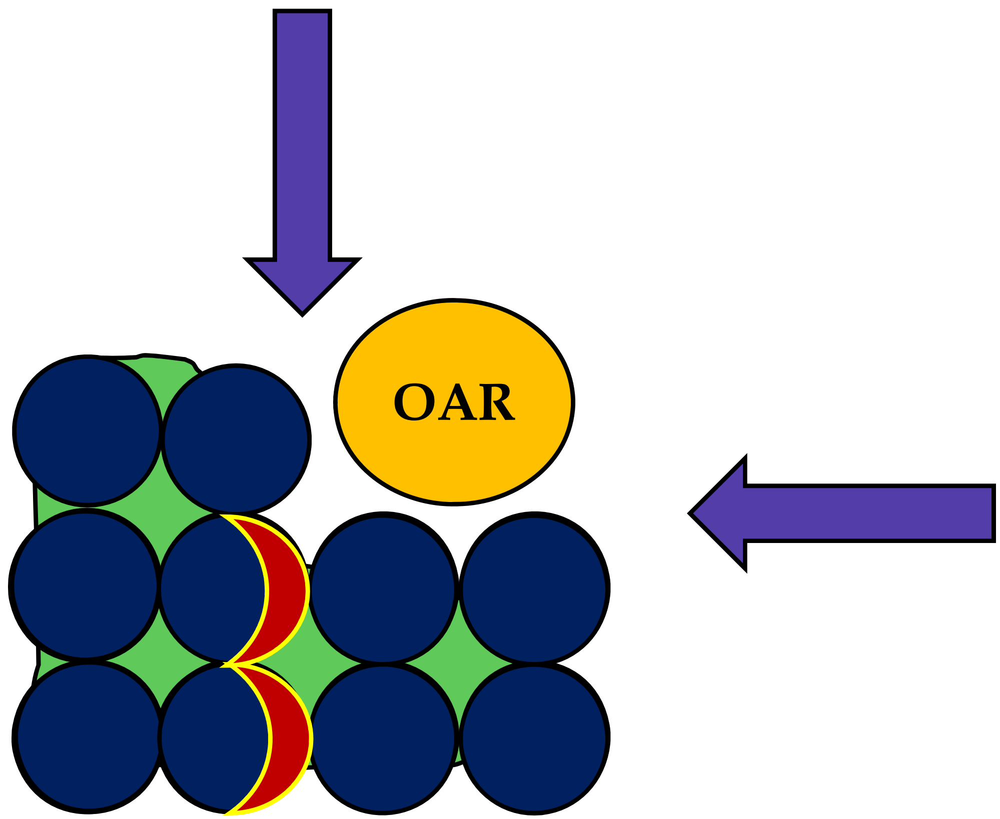
Multi Field Optimized with a systematic range error



< 100% of Dose

100% of Dose

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A need to Quantify and account for the effects of:

“Robustness”

- Non-ideal set-up
- Range uncertainty
- Intra-fraction motion
  - Respiratory motion
- Inter-fraction motion
  - Anatomical consistency

Quantify and account for the effects of:

"Robustness"

- Two methods to do this:
  - Prospectively : Robustness Optimization
  - Retrospectively : Robustness Evaluation

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PBS Robust Optimization

- Add penalties into the cost function for robustness
- Allow the planning system to score robustness on a spot to spot basis AND how one spot will effect the overall sensitivity to potential plan degradation.
- Spots with “poor” robustness (high sensitivity to plan degradation) will be penalized by iteratively decreasing, and potentially, eliminating their intensity

Robustness Evaluation

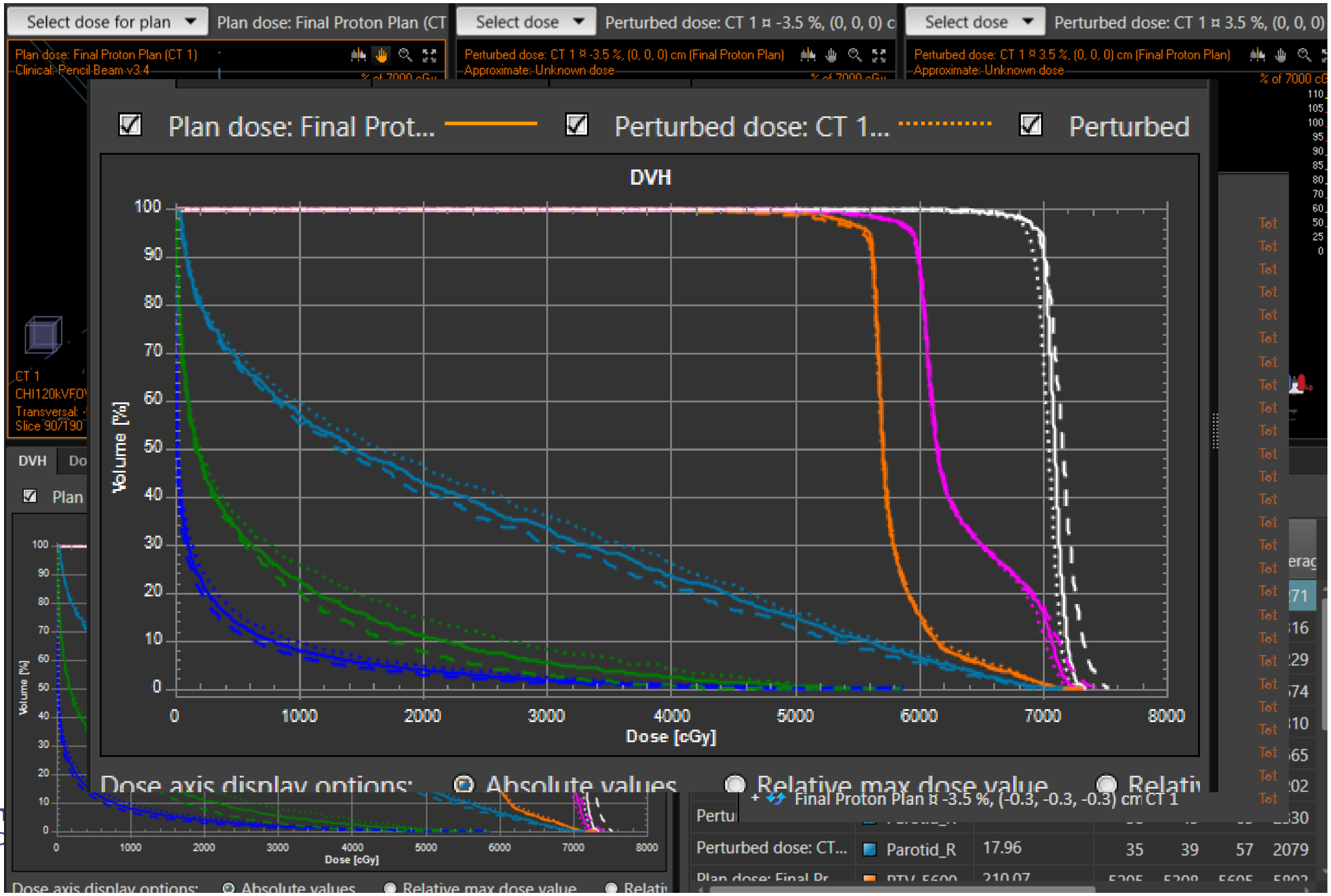
Process of evaluating several potential scenarios to understand potential "worse case" results

- Translate and/or rotate individual fields and recalculate
  - Mimic Set-up errors

- Re-assign systematically shifted HU conversion curves and recalculate
  - Mimic HU conversion errors

- Move Target structures and recalculate
  - Mimic Internal Motion and Anatomical Variances

Robust Evaluations



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In Conclusion …..

- Because the protons stop, the standard planning methods used in photon planning may not be directly applicable.

- Treatment Planning with proton requires several addition consideration.

- The proper application of proton planning techniques can generate some very wonderful treatment plans.

Thanks You for listening!

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