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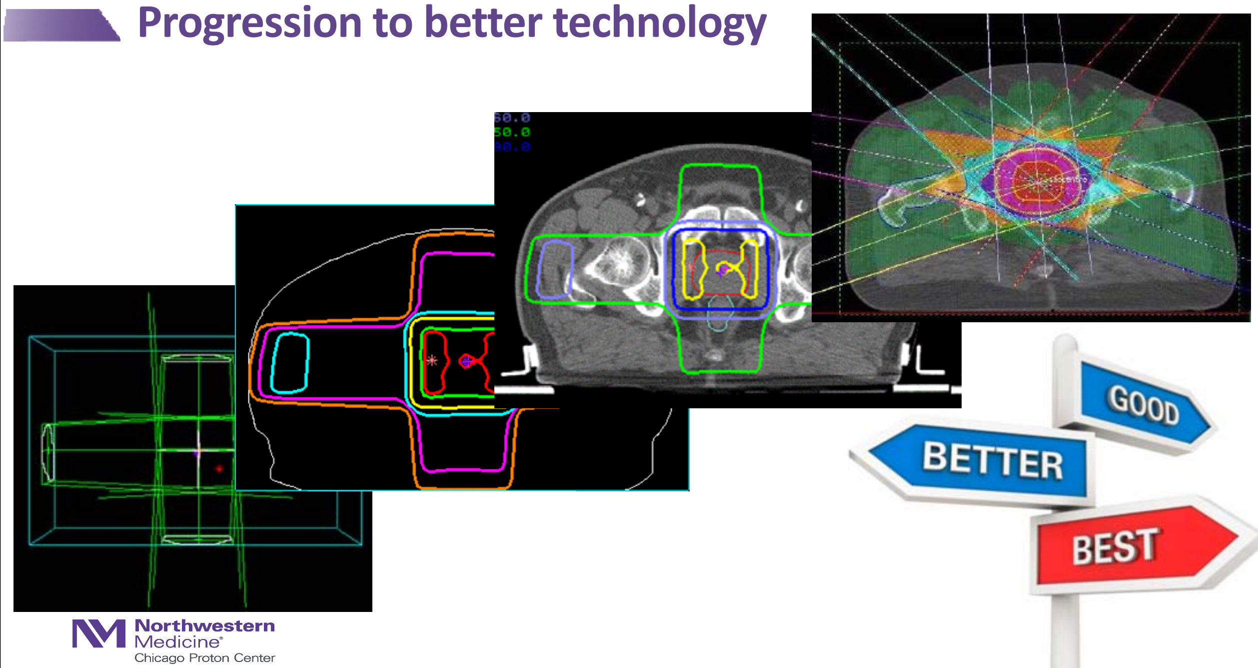
AAPM 2017 JUL 30–AUG 3
CONNECTING OUR PATHWAYS, UNIFYING OUR PROFESSION.
59TH ANNUAL MEETING & EXHIBITION | DENVER, CO

Transitioning to PBS Proton Therapy From IMRT or Passive Scattered-Based Proton Therapy

Mark Pankuch, PhD
Northwestern Medicine
Chicago Proton Center

July 31, 2017

Progression to better technology



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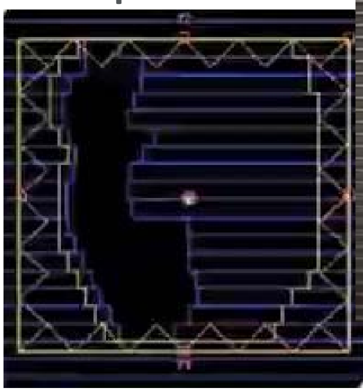
Adoption of new methods for IMRT

VMAT

Dynamic MLC

Step and Shoot



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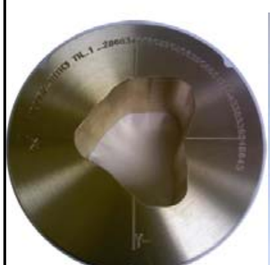
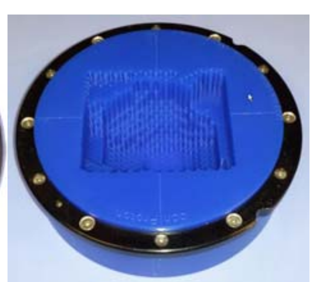
Protons are in the middle of this evolution

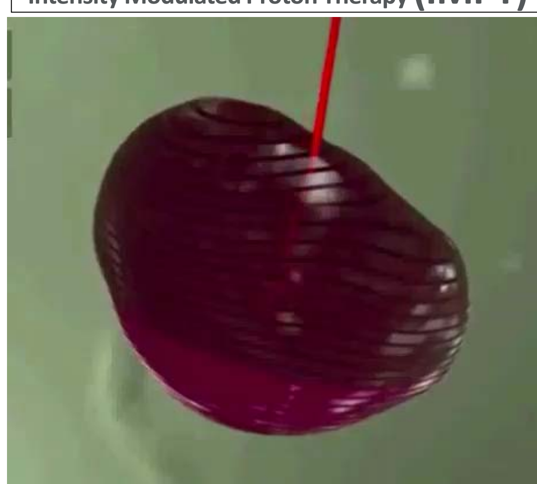
Intensity Modulated Proton Therapy (IMPT)

Aperture

Compensator







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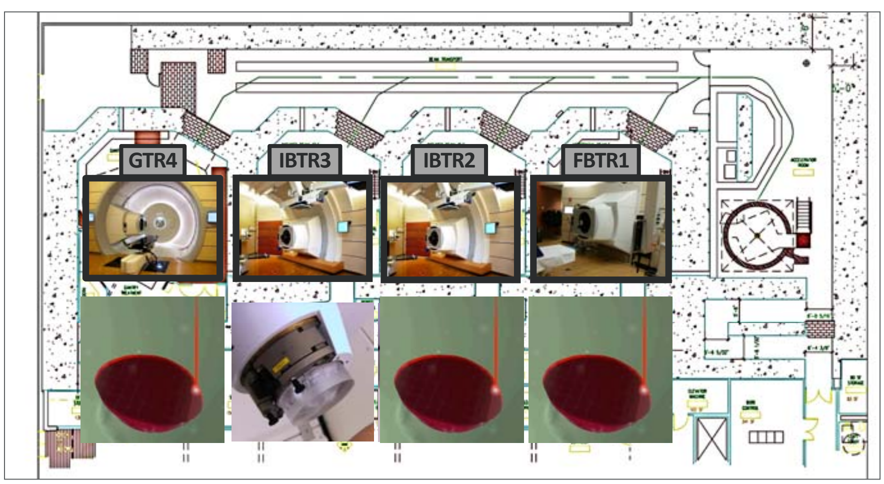

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Radiation Therapy is continually evolving

- Proton Vendors can now provide a delivery method that offers some dosimetric advantages over IMRT and Aperture / Compensator based delivery.
  - Intensity Modulated Proton Therapy (IMPT)
- The full potential of proton therapy can only be realized with IMPT methods.
  - Higher Quality and "Safer" plans
  - More treatment sites
- A process must be defined to develop and implement this new technology.

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A Vision for the Discovery Benefit

- Defining, discovering and understanding new capabilities
  - Treatment delivery
  - Planning
- Understanding the limitations and safety concerns
  - Technology has changed
  - A need torRe-evaluate all safety concerns (margins, robustness)
  - Defining the new tools needed
- Developing methods to implement these new capabilities
  - Site specific benefits
- Providing Clinical Evidence

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Step 1 :

Defining, discovering and understanding new capabilities of Pencil Beam Scanning

step 1

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New Capabilities : What are we gaining ?

	3-D X-Ray	IMRT	Aperture /Comp Proton	IMPT
Collimation : Lateral Control	✓	✓	✓	✓
Intensity Control		✓		✓
Dose Control with Depth			✓	✓✓

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Pencil Beam Scanning: Intensity Modulated Proton Therapy

What benefits can we exploit when using this type of delivery method??

- Spot by spot control of Bragg Peak
  - Position (Direction perpendicular to beam direction)
  - Energy (Layer by layer control in the depth direction)
  - Intensity (Optimized using inverse planning methods)

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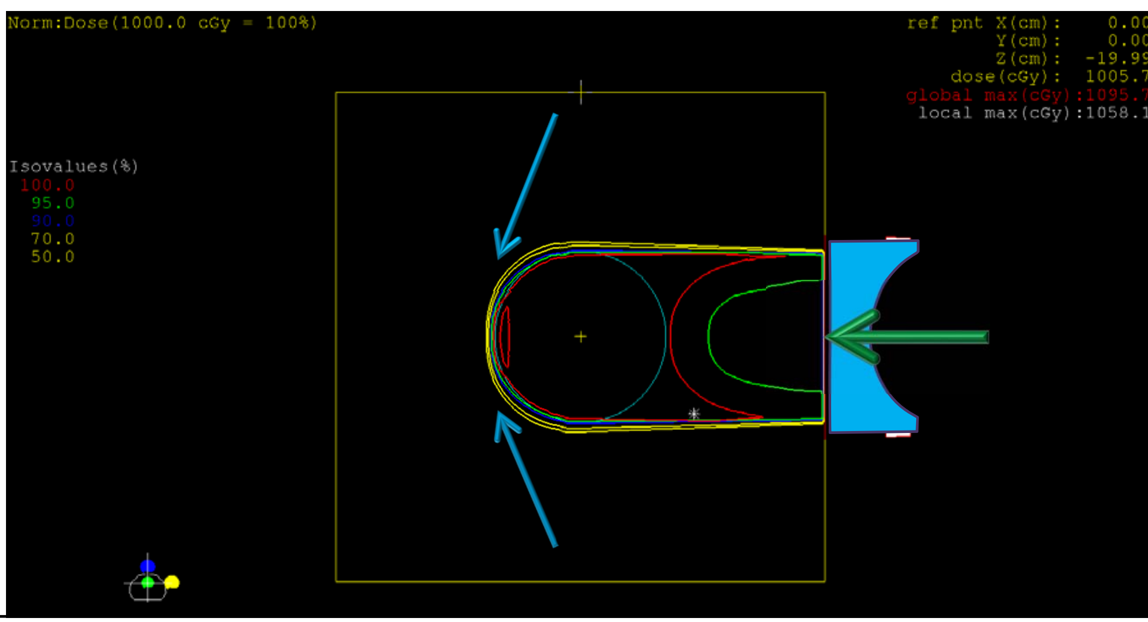
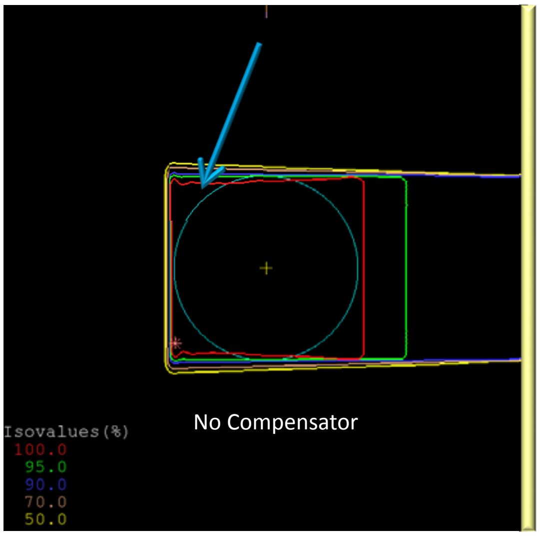
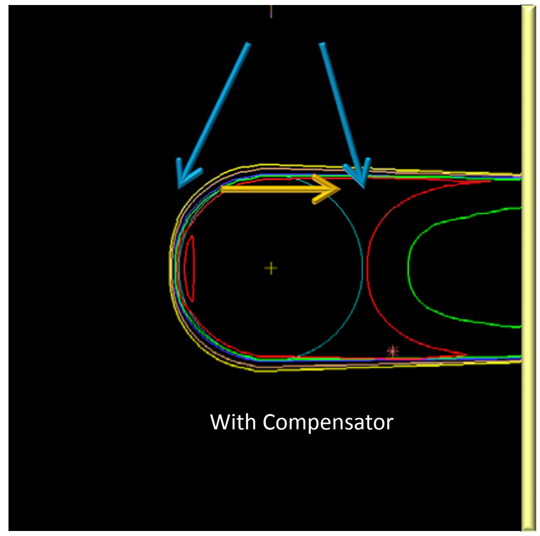
Use of a Compensator for distal shaping



Distal conformity using a Compensator





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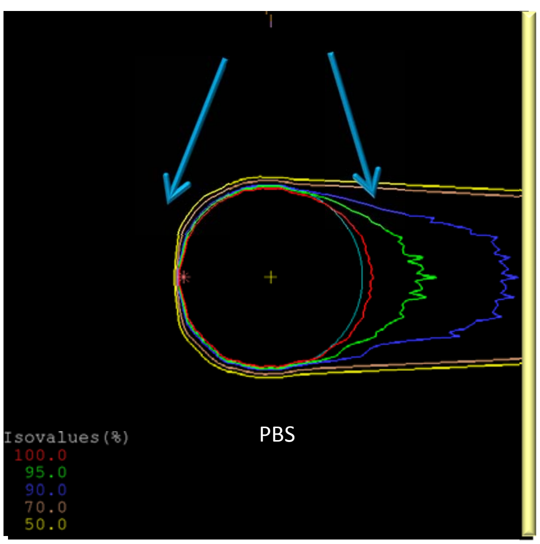
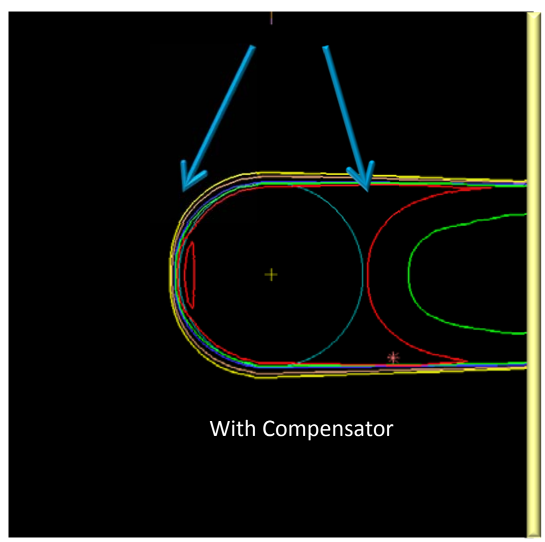
The addition of Proximal Conformity





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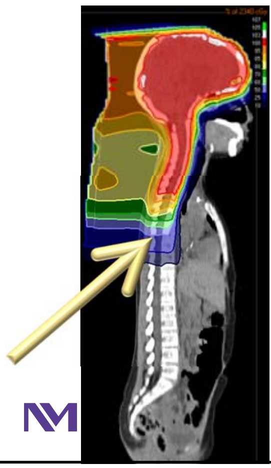
Intensity Control : Matching Fields

A Simple Scanning Beam Treatment Technique for CSI

Annelise Giebeler, Andrew Chang, Luis Perles, Lei Dong, and Atmaram S. Pai Panandiker
Affiliations of Authors: Scripps Proton Therapy Center, San Diego, CA



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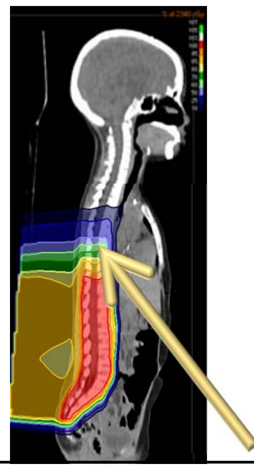

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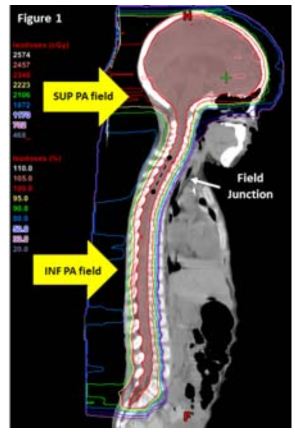
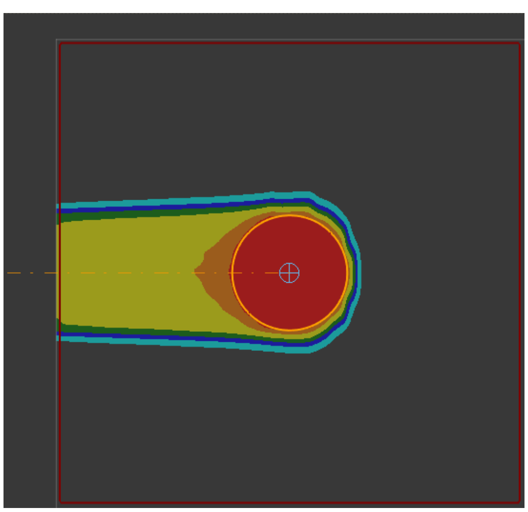
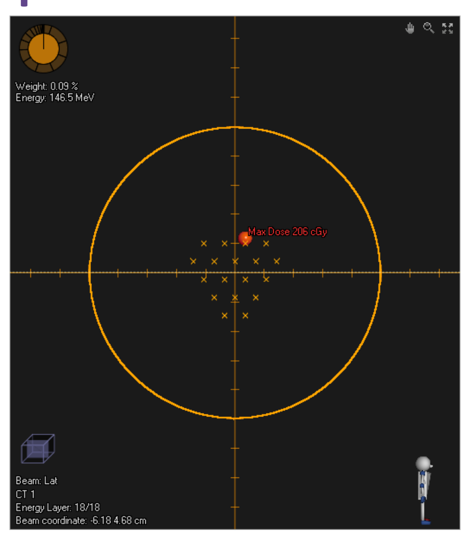


Spot / Layer Patterns for a Sphere



Dose Distribution



Beam's Eye View

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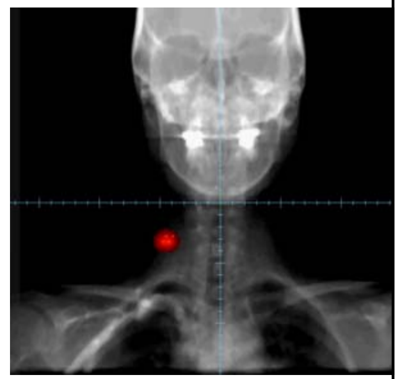
How can we obtain these complex, 3-D spot patterns?

- Inverse planning techniques
  - Iterative minimizations of cost function.
    - Cover target areas
    - Minimize dose to organs at risk
  - Unlimited potential for computing and mathematical "tricks"
    - Minimizing the effects of positional errors and range errors directly into the cost function
    - Including effects of motion into the cost function
    - Multi Criteria Optimization (MCO)
  - Single Field Optimized (SFO) / Multi Field Optimized (MFO)



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IMPT Optimization Methods

Single Field Optimization (SFO)

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

Multi Field Optimization (MFO)

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

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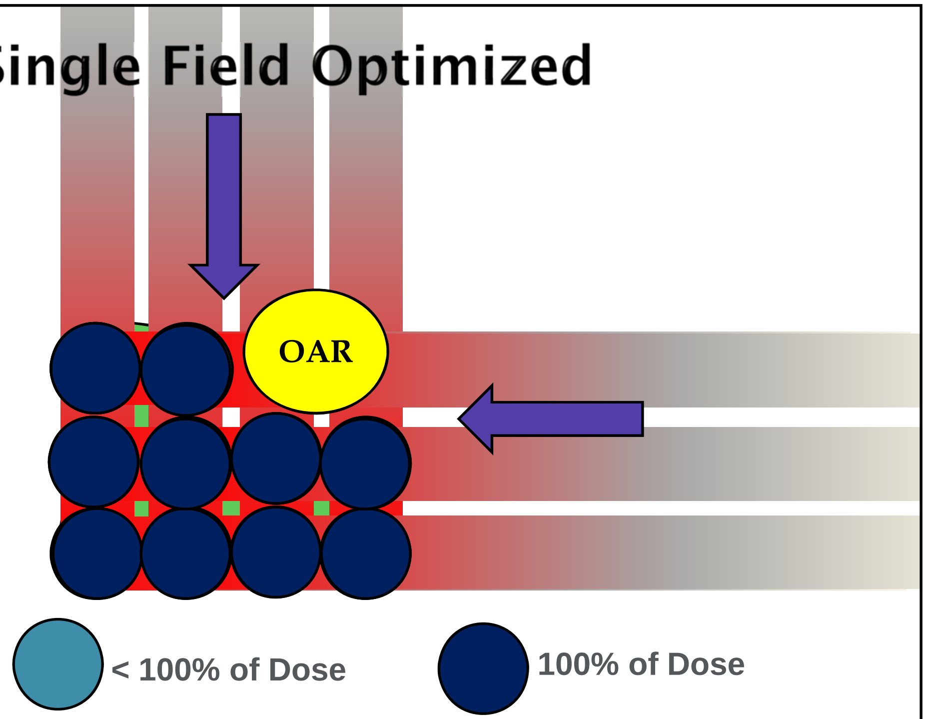
Single Field Optimized



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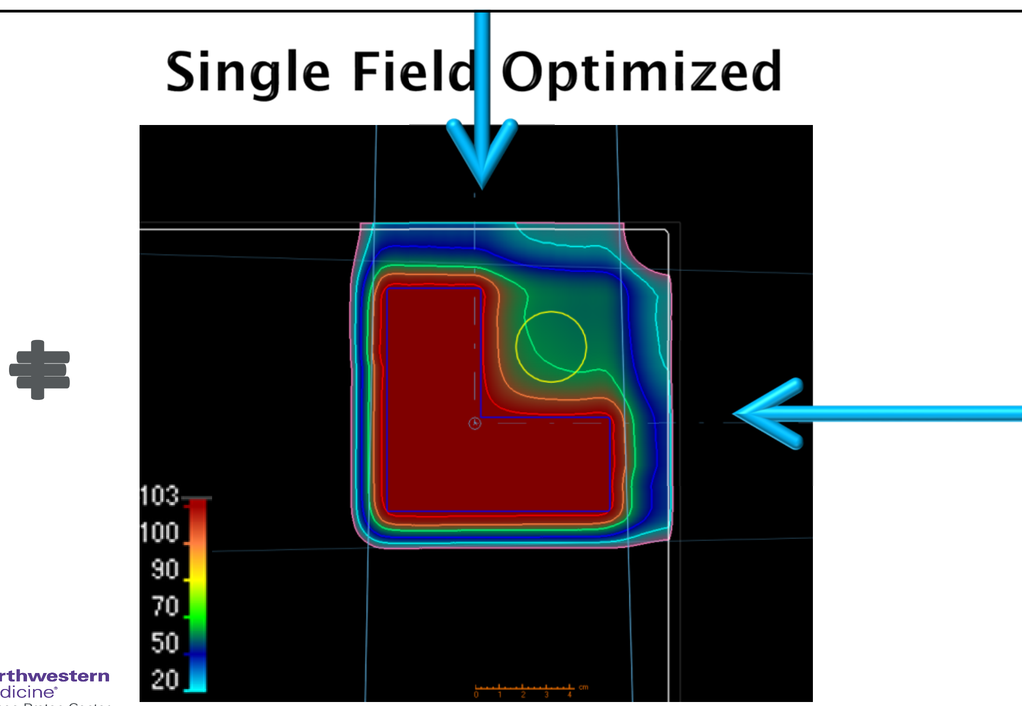
Single Field Optimized



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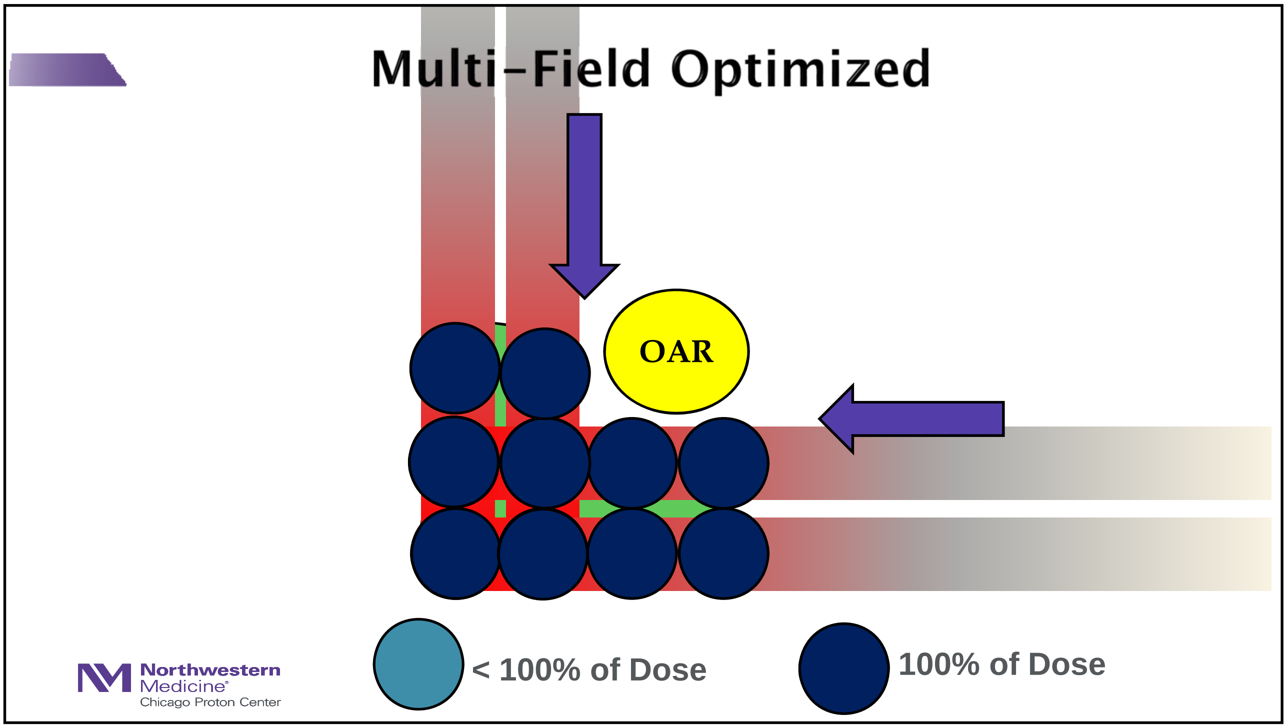
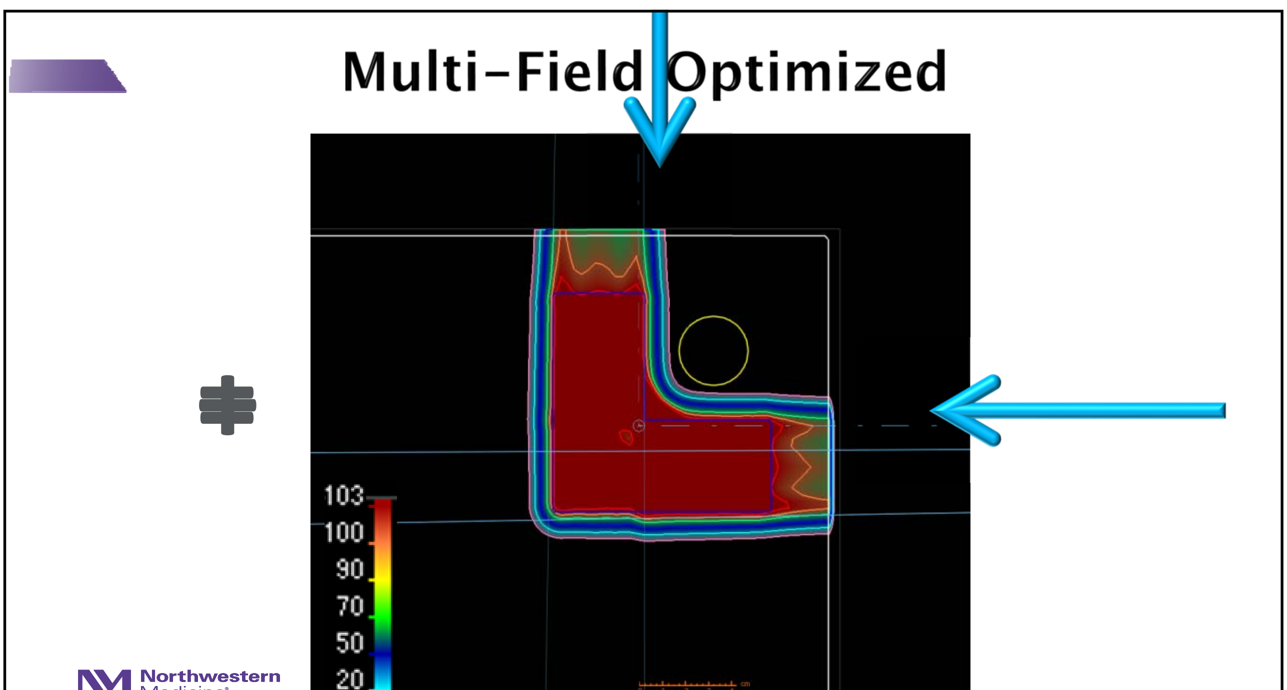
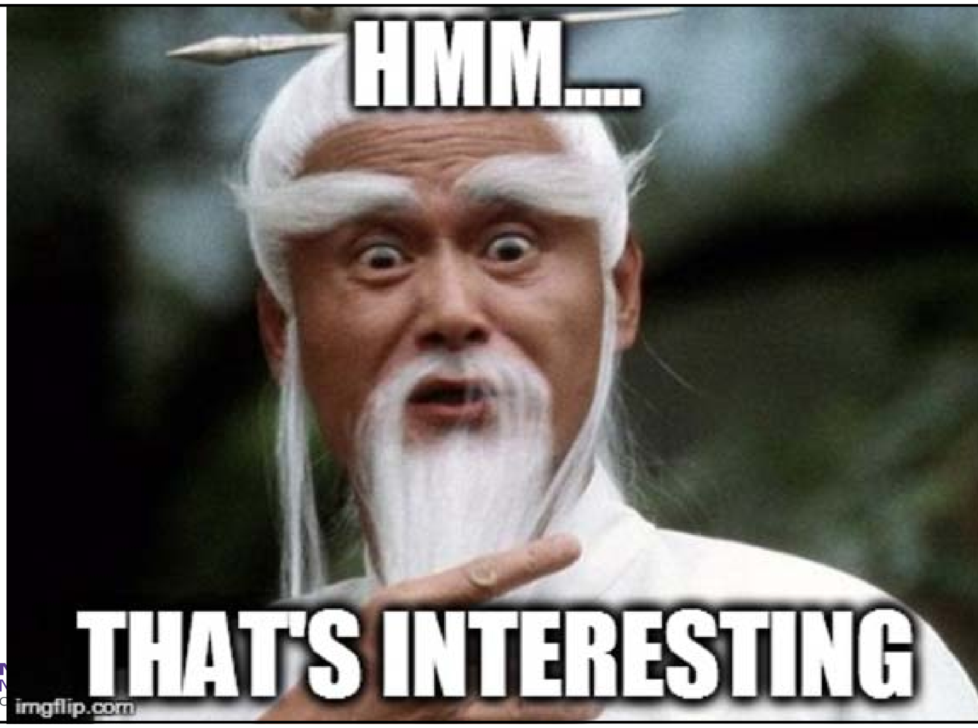
Clinical Radiation Oncology, 3rd Addition





Clinical Radiation Oncology, 3rd Addition



Step 2 :

Understanding the limitations and safety concerns of Pencil Beam Scanning Methods

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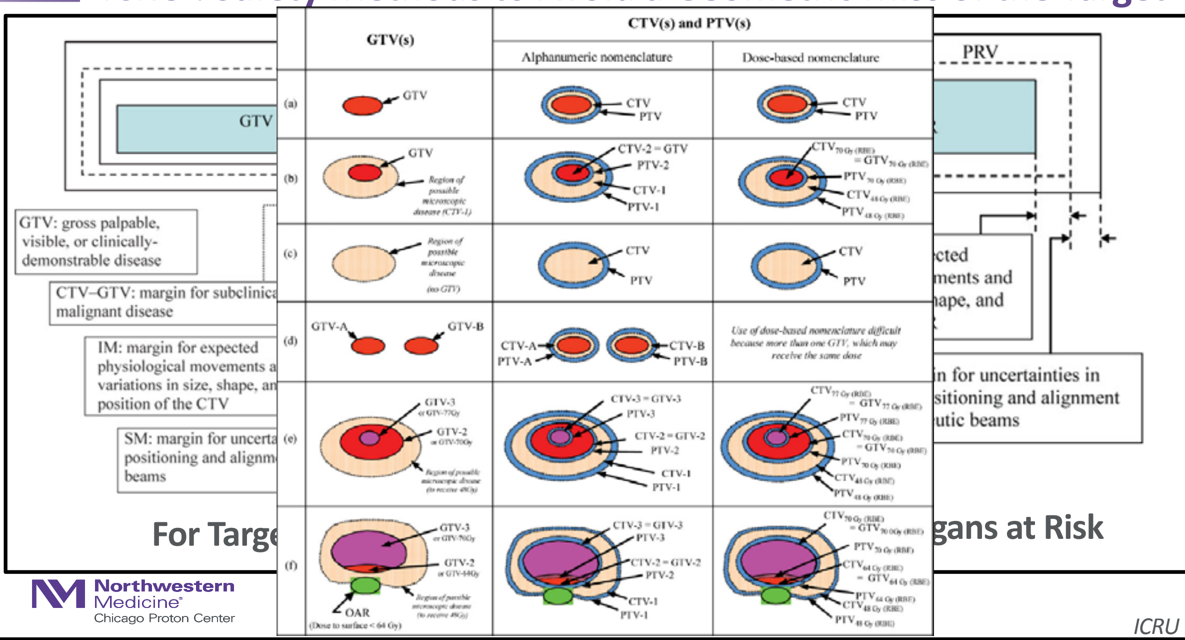
ICRU : Safety Methods to Avoid a Geometric Miss of the Target



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ICRU 78

With Protons : We must always consider for Range Uncertainty

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

Paganetti, Phys. Med Biol (57), 2012

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

	Uncertainties in SPR estimation (1σ)		
Uncertainty source	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

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.

Moyers, Medical Dosimetry(35), 2010

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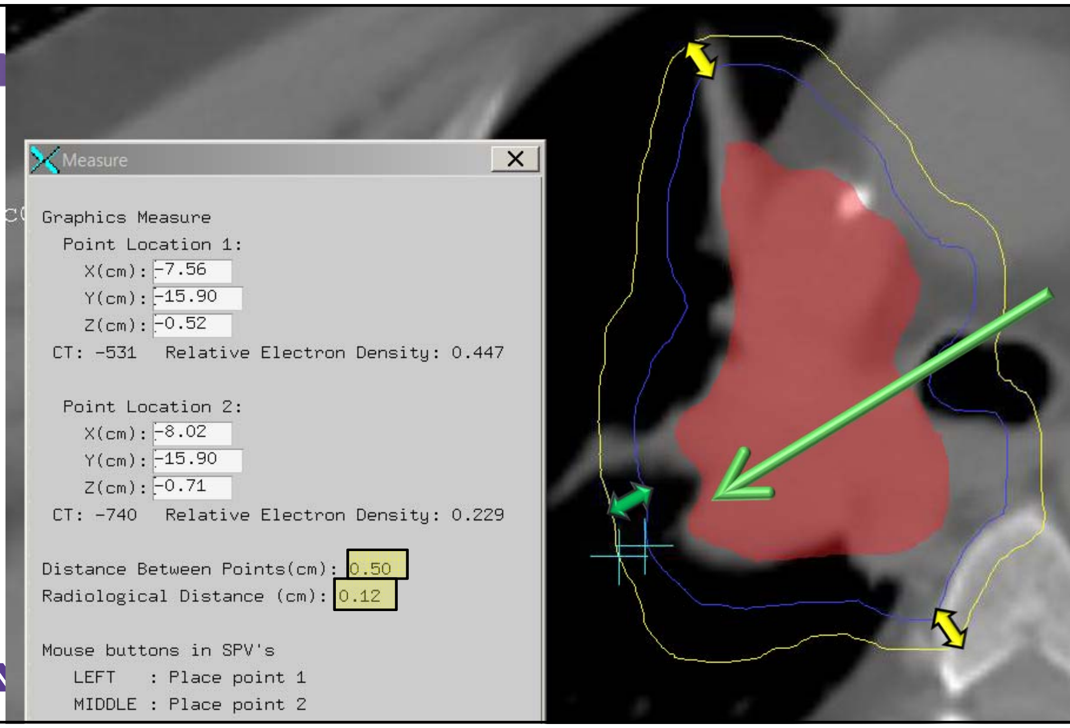
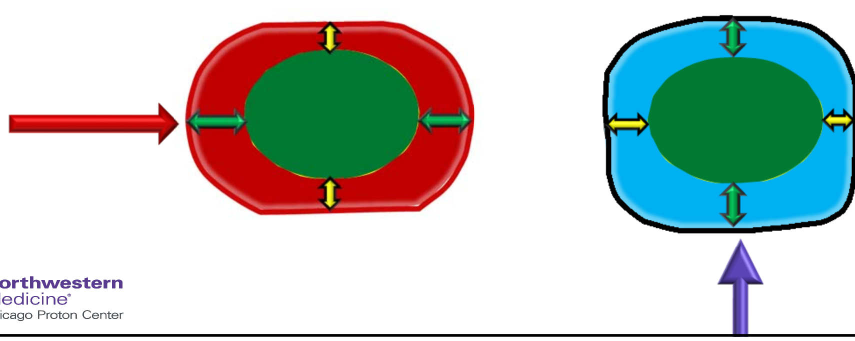


Margins for Setup and Range Uncertainty with Protons

Perpendicular Expansion
Avoid a geometric miss
Physical Distance
(cm)

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



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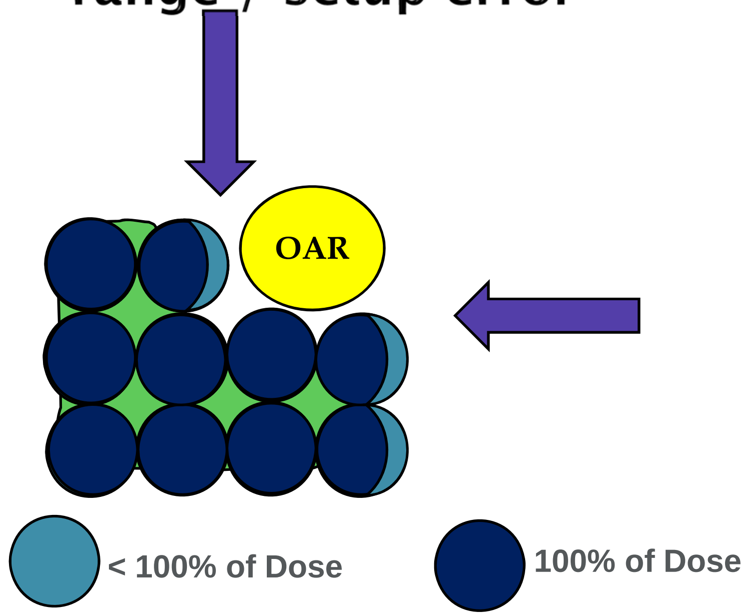
Single Field Optimized with a range / setup error



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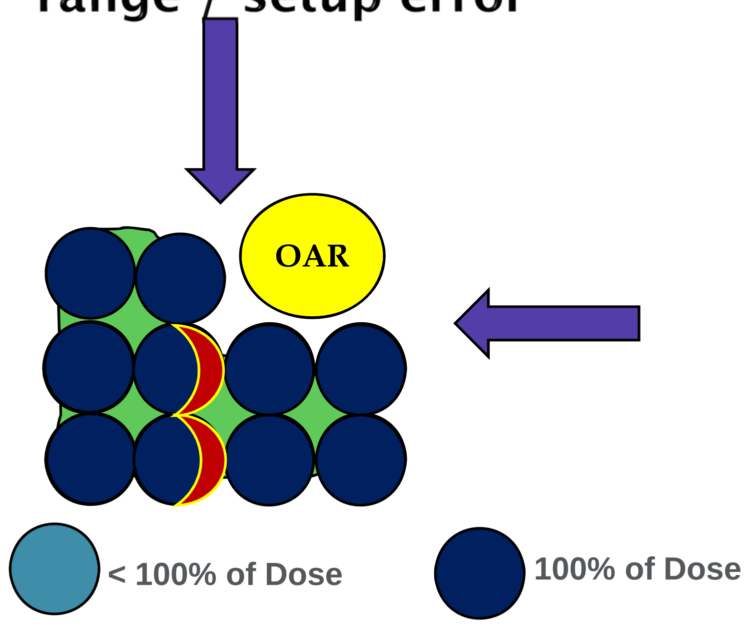
Multi Field Optimized with a range / setup error



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IMPT Optimization Methods

Single Field Optimization (SFO)	Multi Field Optimization (MFO)
Uniform Dose is delivered to the entire target by each field individually	Spot weights of all fields are optimized together. The spot weight of one field may rely on another field's dose to create an integrated uniform target dose
Less sparing of critical structures	Better for sparing critical structures
Less sensitive to Set-up/Range errors	More sensitive to Set-up/Range errors

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Understanding the limitations and safety concerns

"Robustness"

Quantify the effects of:

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

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Robustness for PBS Plans

- Two methods to do this:
  - Prospectively : Robustness Planning / Optimization
  - Retrospectively : Robustness Evaluation
- Adequate tools are required!!

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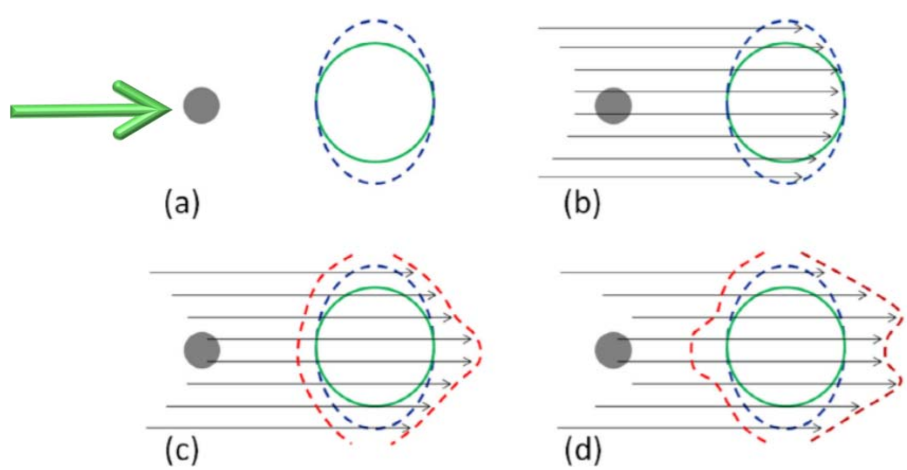
For SFO: Beam Specific PTV : bs(PTV)



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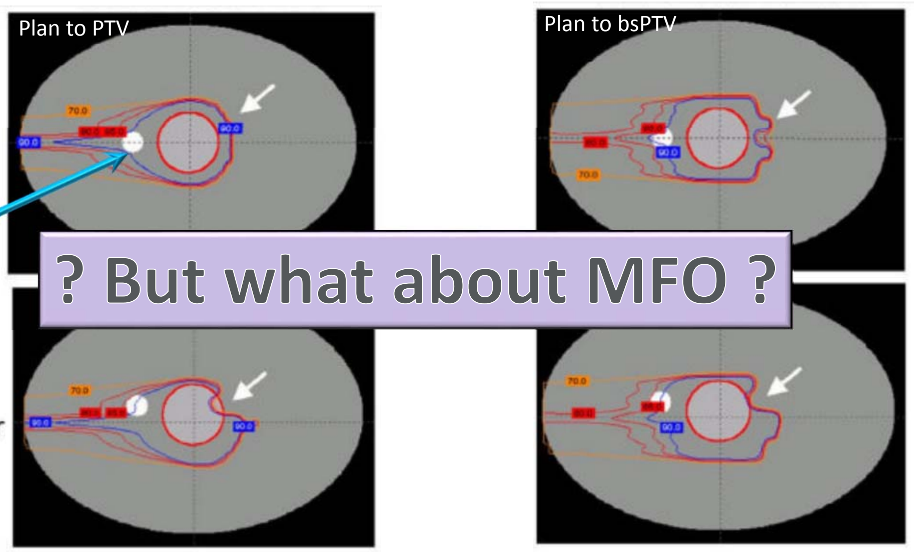
P. Park et al Int J Radiat Oncol Biol Phys. 2012

The Effect of Set-up Errors on SFO Plan

Normal Condition

Setup and Motion error



? But what about MFO ?

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Park et al. Int J Radiat Oncol Biol Phys. 2012

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

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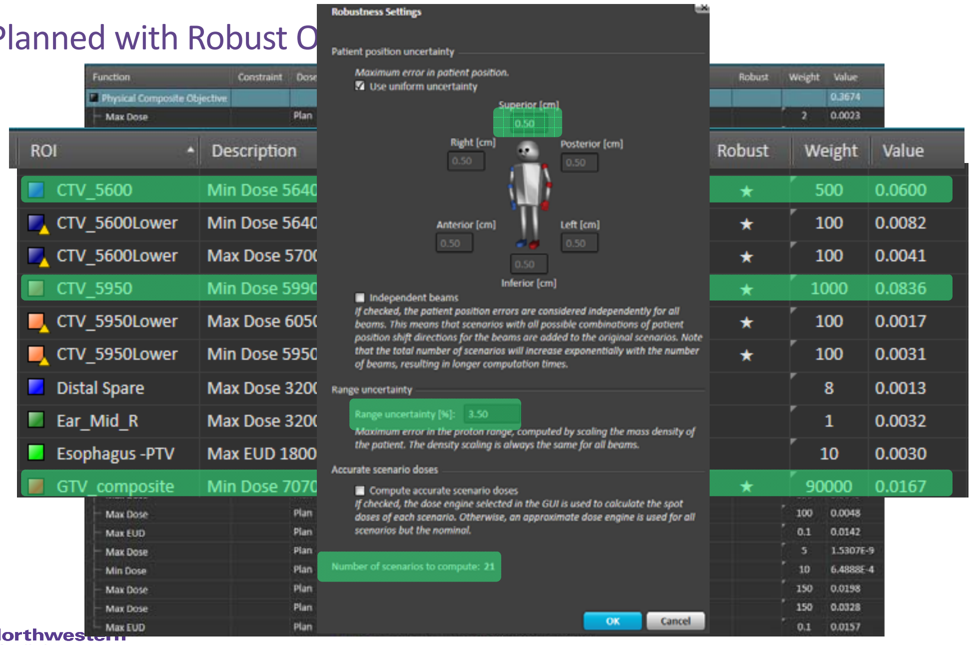
Planned with Robust O



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Robustness Evaluation

Quantify the differences in quality between the planned and the delivered dose in the presence of uncertainties

Robust Plan Evaluation includes :

– Calculation and Evaluation of many "Worst case" scenarios
  - Systematic offset of HU conversion

    (-3.5% , + 3.5%)

  - Systematic offset of set-up error

    (x= +/- 3mm, y= +/- 3mm, z= +/- 3mm)

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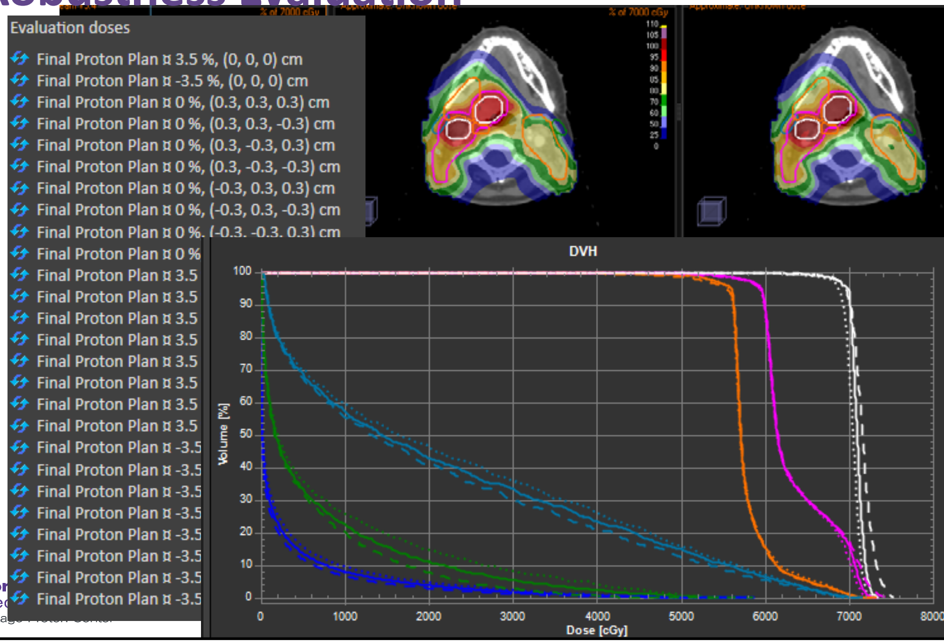
Lomax Phys. Med. Biol 2008

Robustness Evaluation



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This concept of "Robustness" and the Quality of a "Robustness Evaluation" really has limitations

- Impossible to look at all potential scenarios
- Combinations of Random AND Systematic errors
  - Set-up errors are random
  - Range errors are systematic
    - Range errors are NOT uniformly distributed
    - Beam Hardening
    - Tissue Dependent
- Only as good as the patient model that you give it.
  - What if the patient changes??

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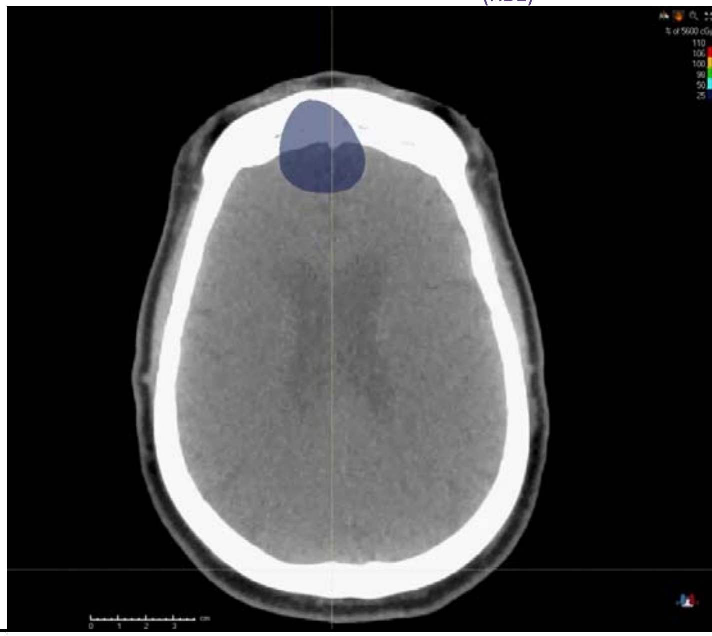
Adaptive Planning : Naso-pharynx to 56Gy$_{(RBE)}$



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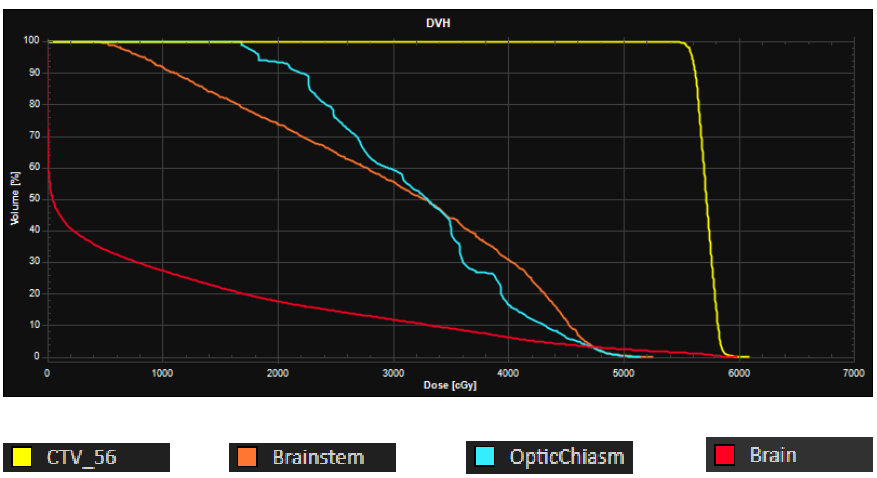
Approved Plan : Naso-pharynx



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Large Change in Target Region Anatomy

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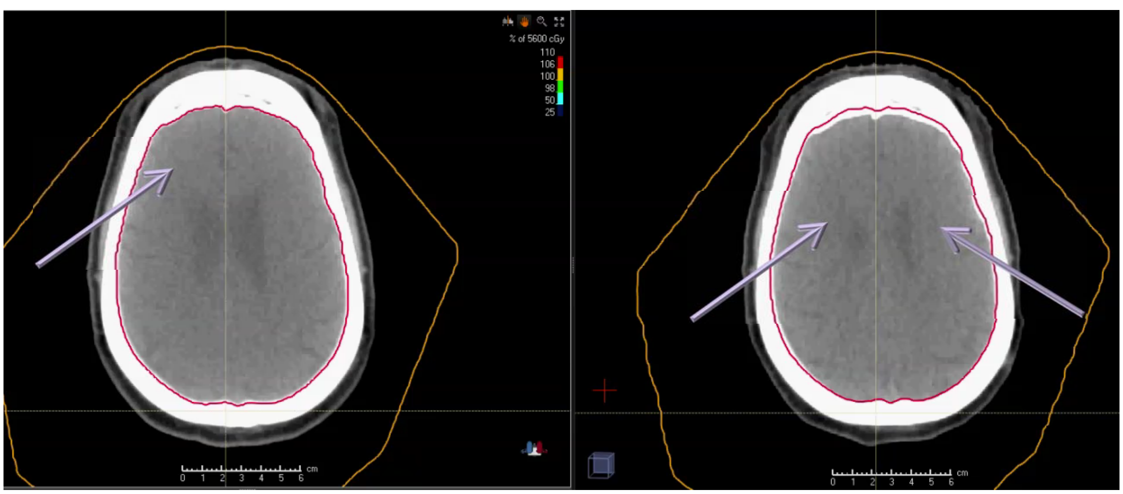
Calculation of Initial Plan on New Image Set



Initial Plan

On Treatment Evaluation

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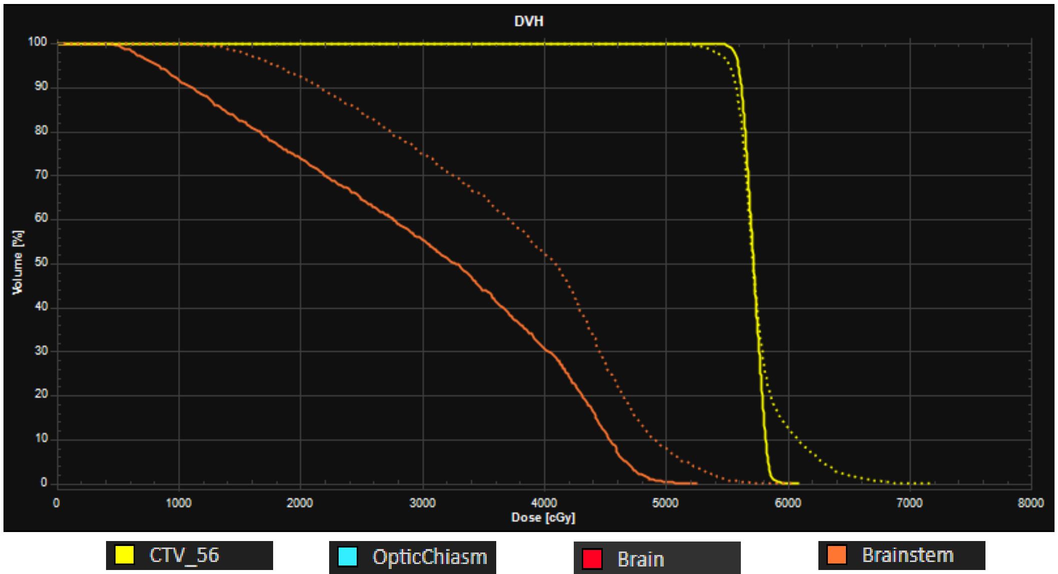

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Step 3 :

Developing methods to implement the new capabilities of Pencil Beam Scanning

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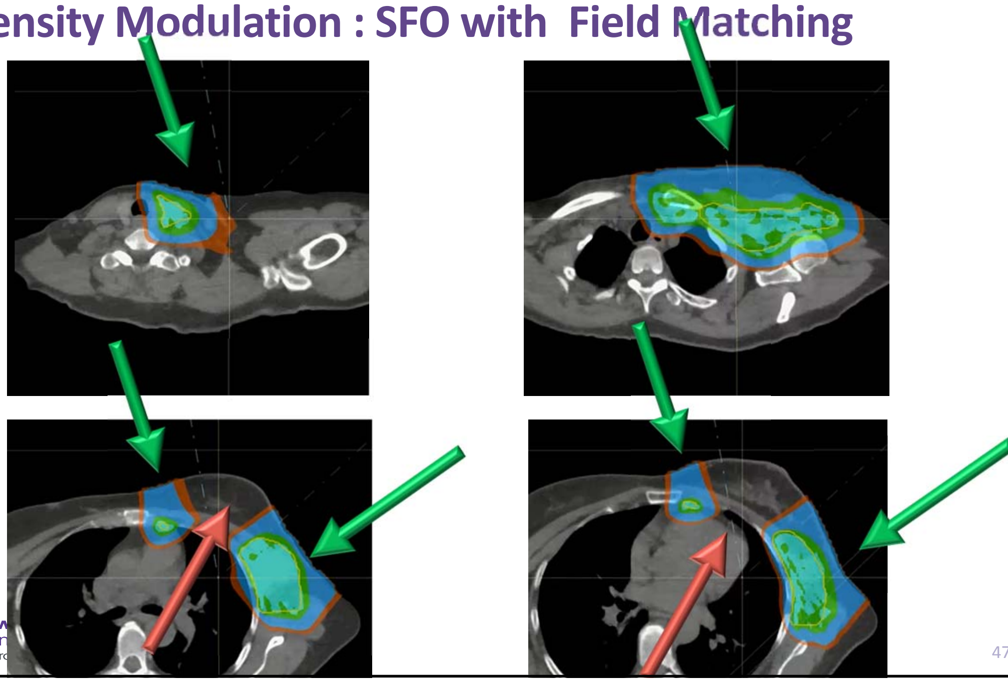
Intensity Modulation : SFO with Field Matching



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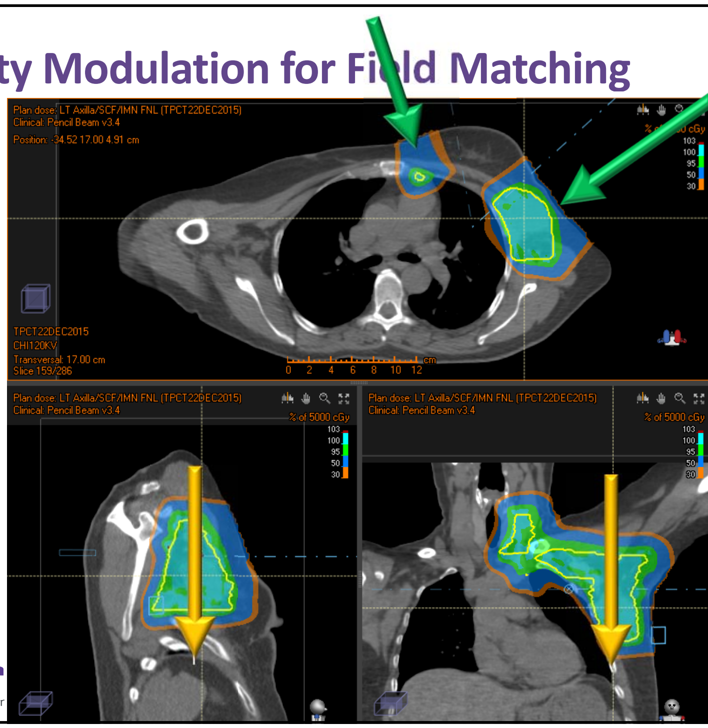
Intensity Modulation for Field Matching



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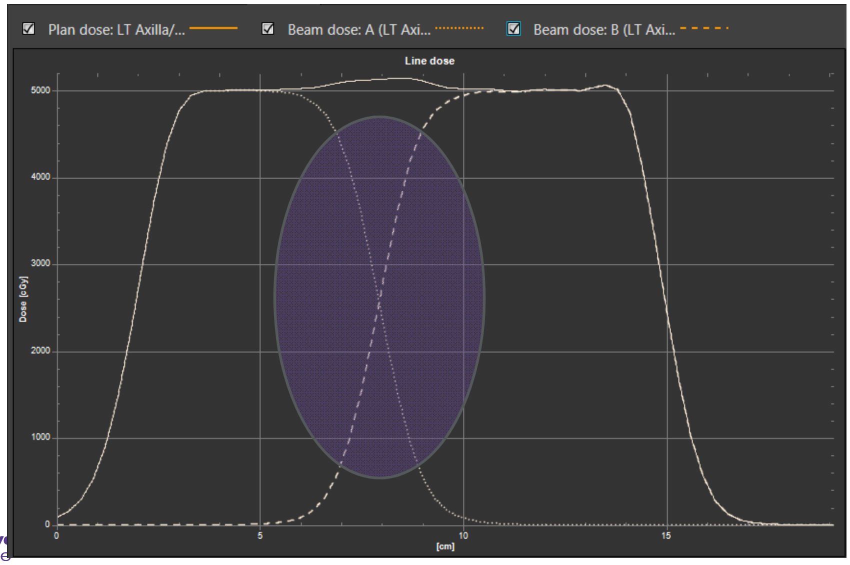
Dose Profiles at Field Junction



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A Head / Neck that requires MFO dose shaping:

- Nasopharynx target with neck nodal irradiation
  - GTV and Regional Lymphatics to 50 $Gy_{(RBE)}$
  - Boost Volume to 70 $Gy_{(RBE)}$

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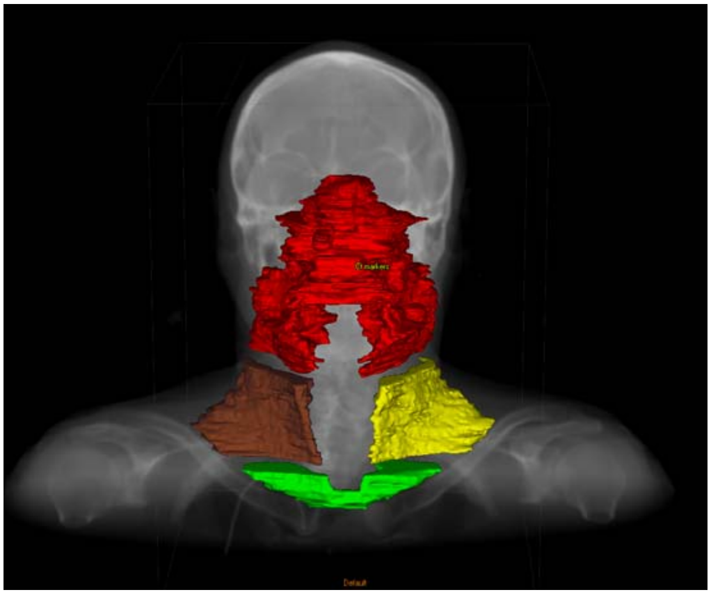
Optimizing IMPT strengths and robustness



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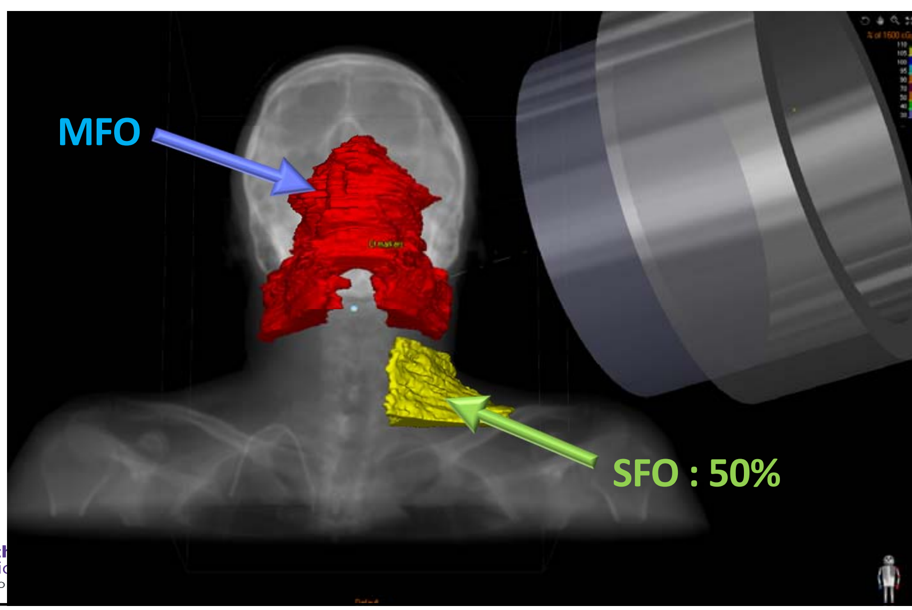
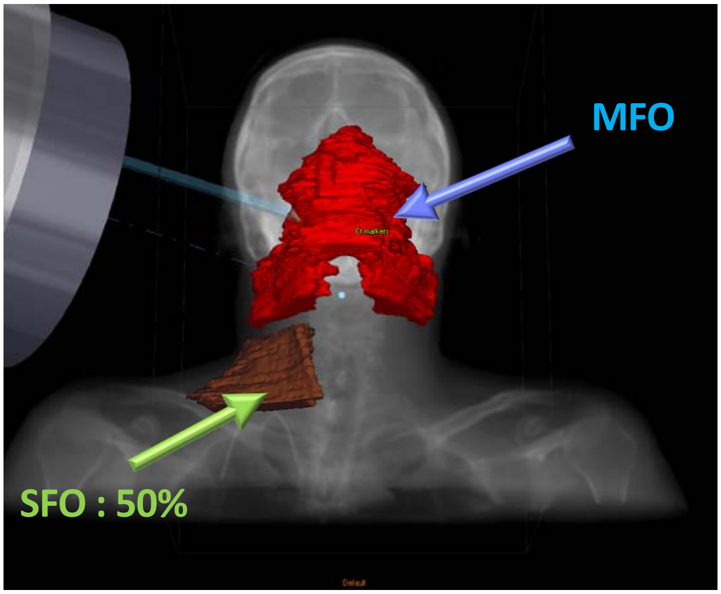
Left Anterior Oblique



Right Anterior Oblique



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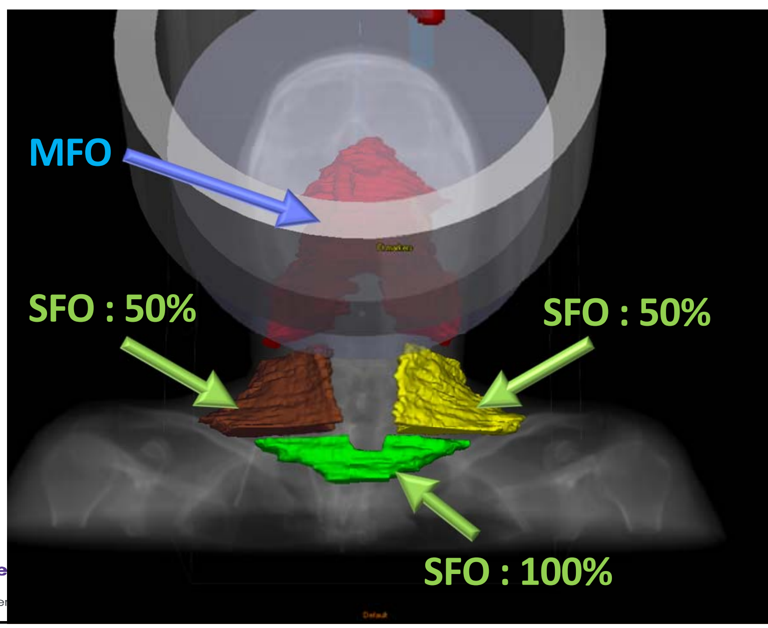
Anterior Superior Oblique



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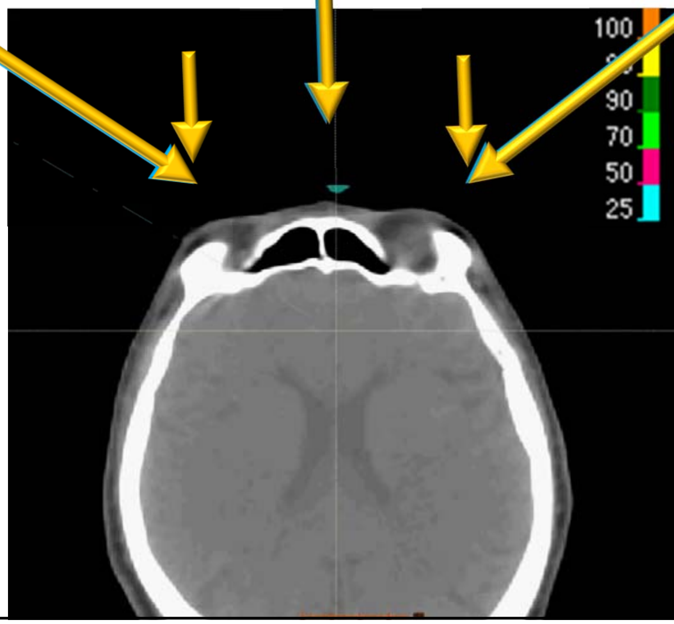
Composite plan to 50 Gy(RBE)



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New capabilities with MFO over SFO

The Problem:

Expander Filling ports

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CTV / CTV_Expander

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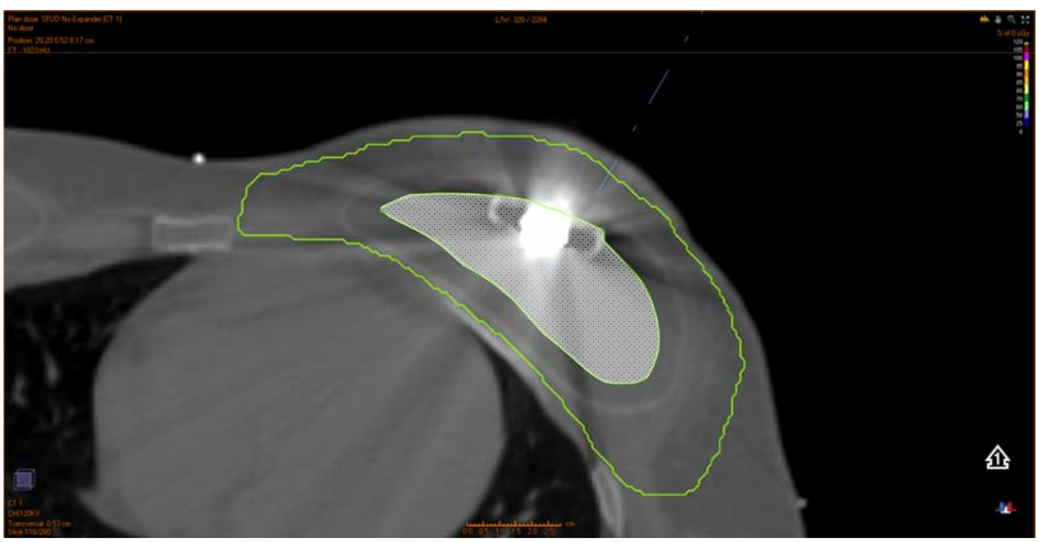
CTV_EXPANDER



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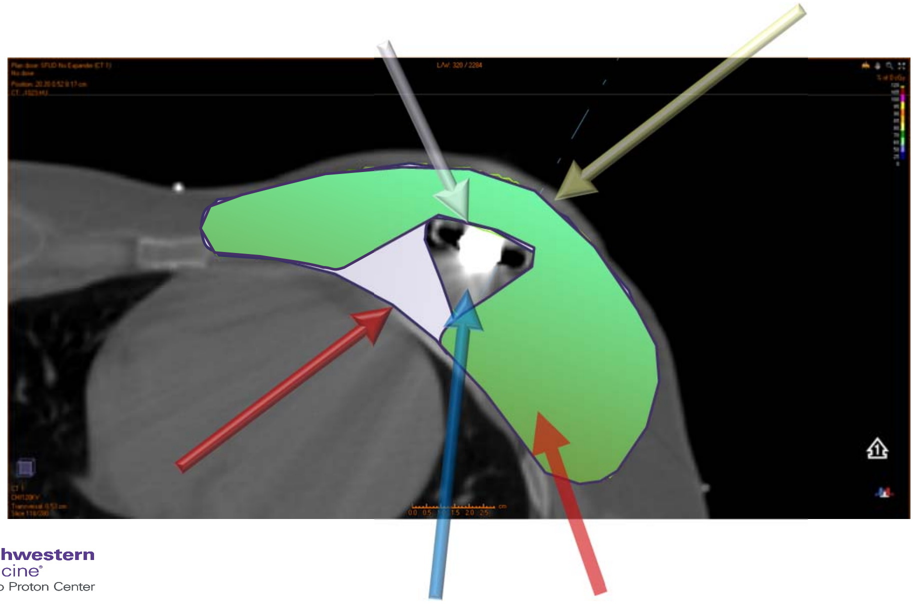
Treat around the port with MFO Methods



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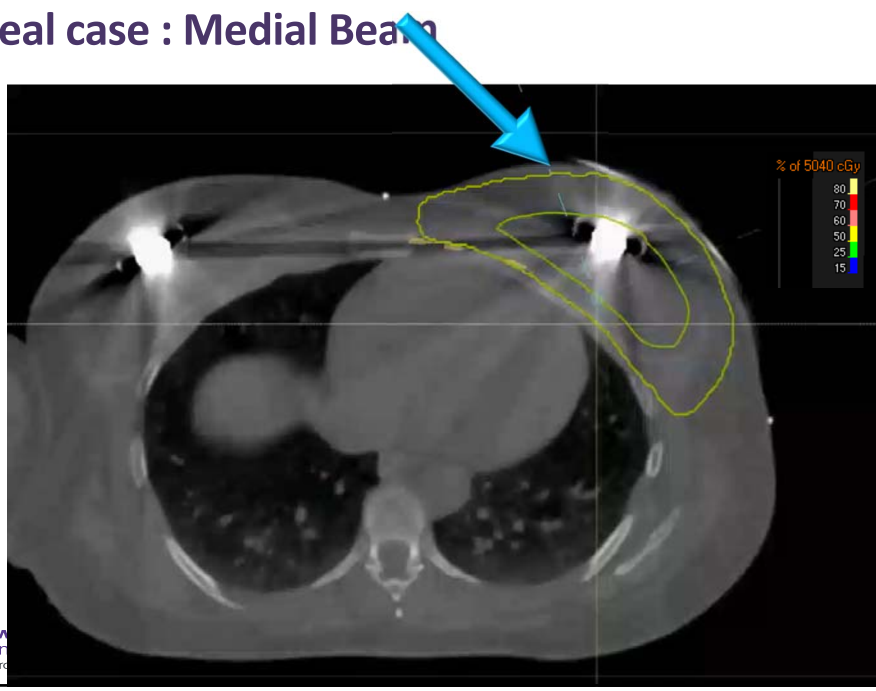
A real case : Medial Beam



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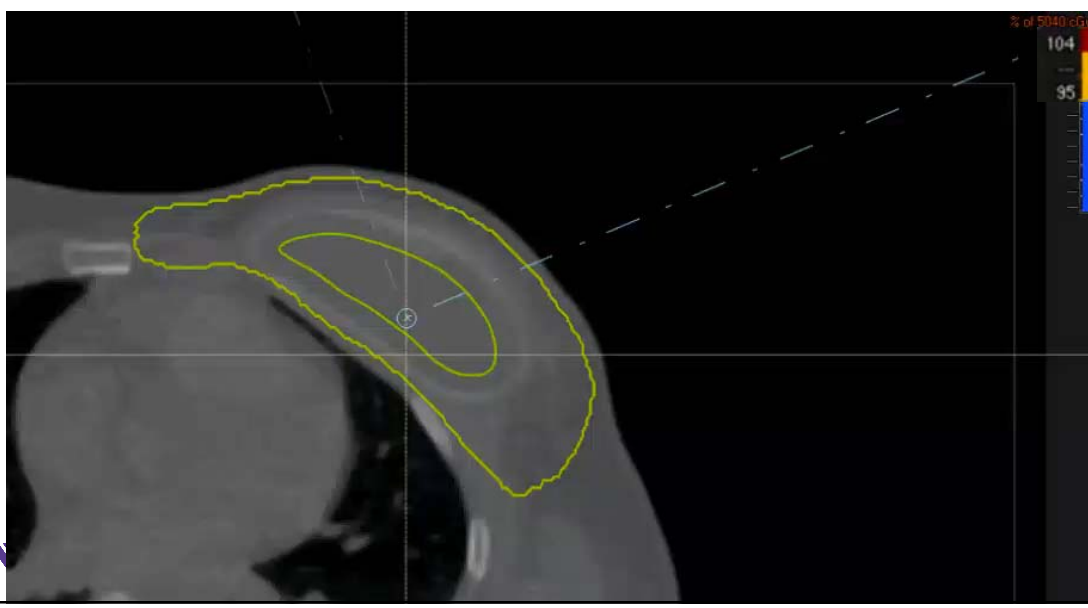
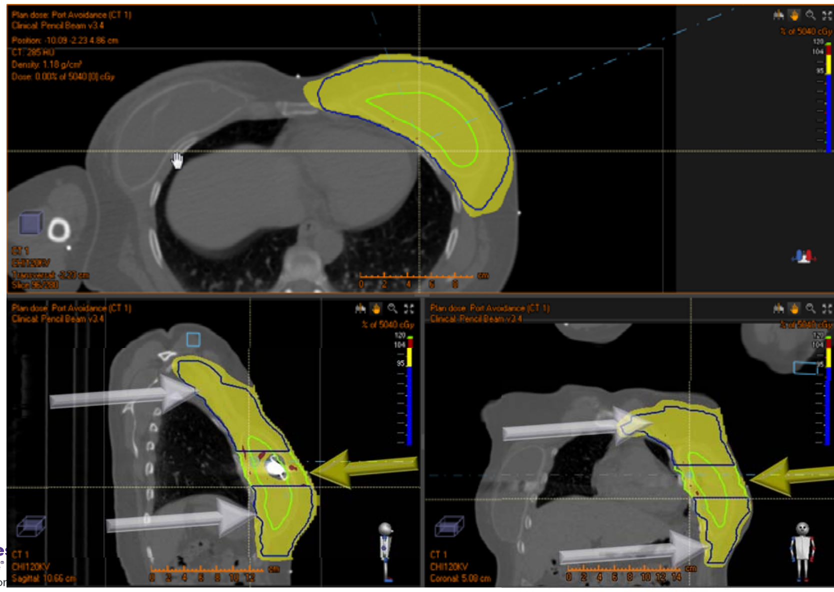
A real case : Lateral Beam

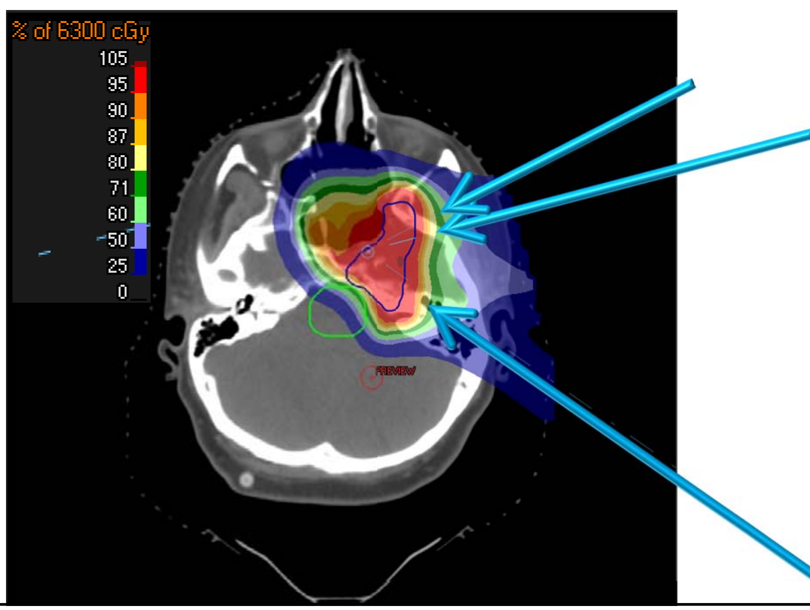
A Real Case : Both Beams



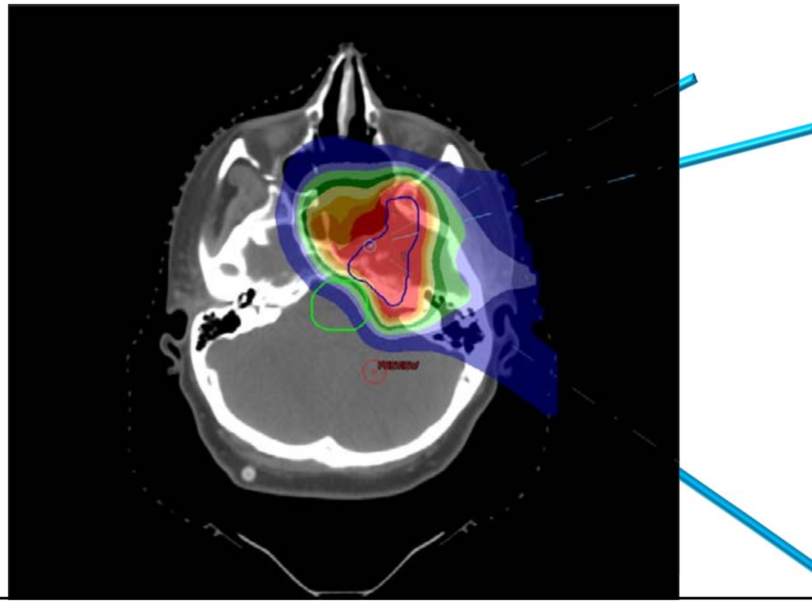
SFO and MFO regions for robustness



Robust Optimization for OAR



Robust Optimization for OAR



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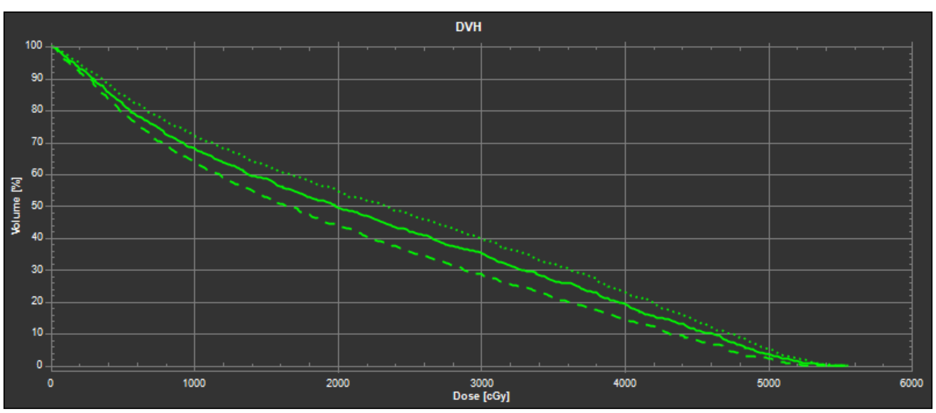
Robust Optimization for OAR



Dose	ROI/POI	Clinical goal	Value
Plan dose: To 63 G...	BrainStem	At most 5700 cGy dose at 0.0 cm^3 volume	5538 cGy
Perturbed dose: CT...	BrainStem	At most 5700 cGy dose at 0.0 cm^3 volume	5568 cGy
Perturbed dose: CT...	BrainStem	At most 5700 cGy dose at 0.0 cm^3 volume	5545 cGy

Where can we exploit the benefits offered by IMPT ?

Benefits of IMPT

- Minimize Integral Dose
- Advanced Dose Shaping
- Field Matching
- Treatment Efficiency

- Pediatric
- Re-treats
- Lt Sided Breast
- Head / Neck
- Esophagus
- Whole Pelvis
- Lung

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A few take-a ways……

- PBS delivery methods have opened up remarkable, new capabilities for Proton Therapy
- The proton community needs to continue to work closely in an effort to find the full potential of PBS methods.
- A collection of the new "tools" is an essential part of clinical implementation of this new opportunity

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