PROTON TREATMENT PLANNING

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Today's objectives

- Discuss the general planning concepts used in proton planning
- Review the unique handling of CTV / ITV / PTV when treating with protons
- Pencil Beam distributions and PBS optimization

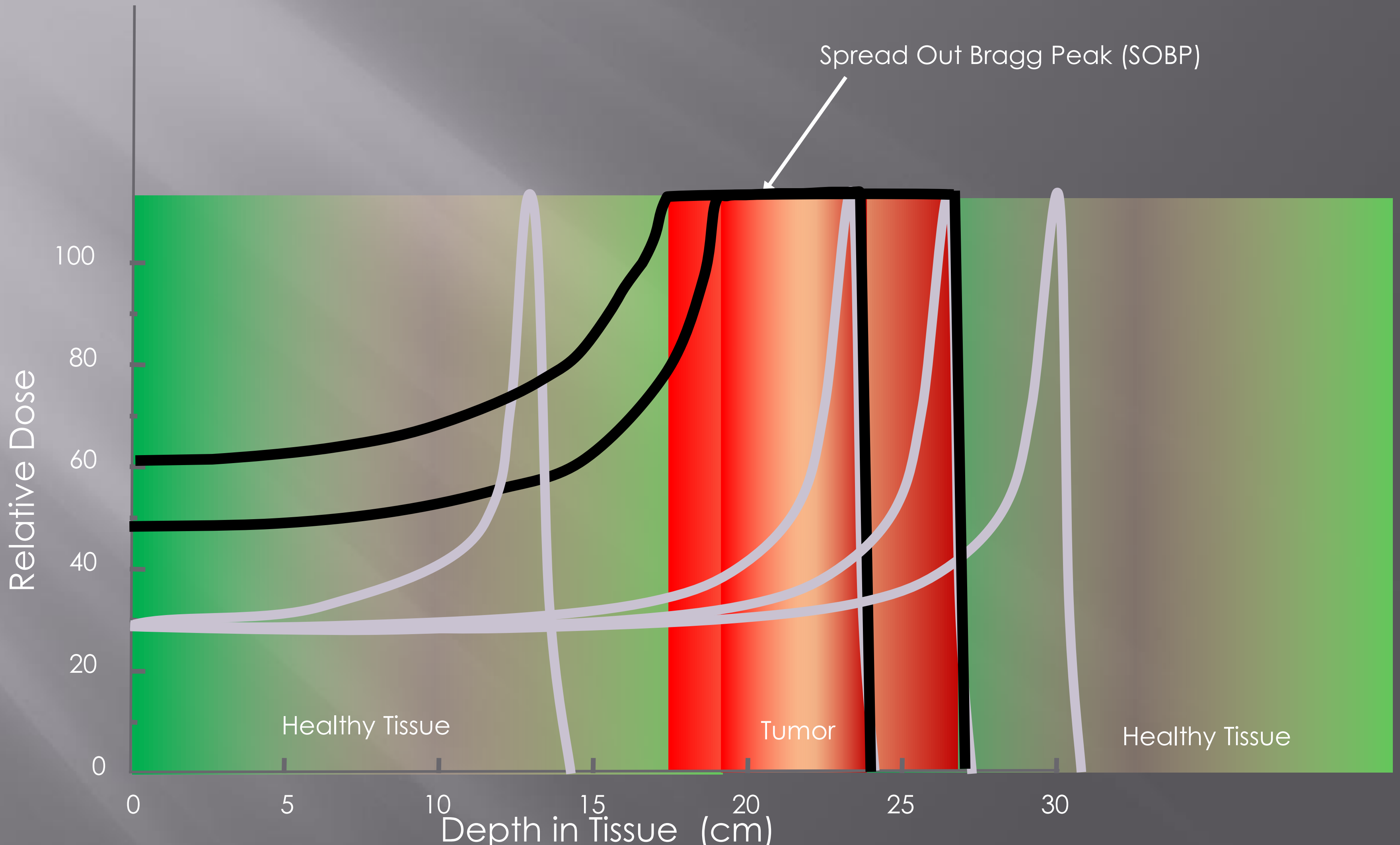
Planning Strategies 101–Protons

- Cover the target with appropriate margins
- Spare the critical structures
- Plan with fields that deliver the most "robust" plan

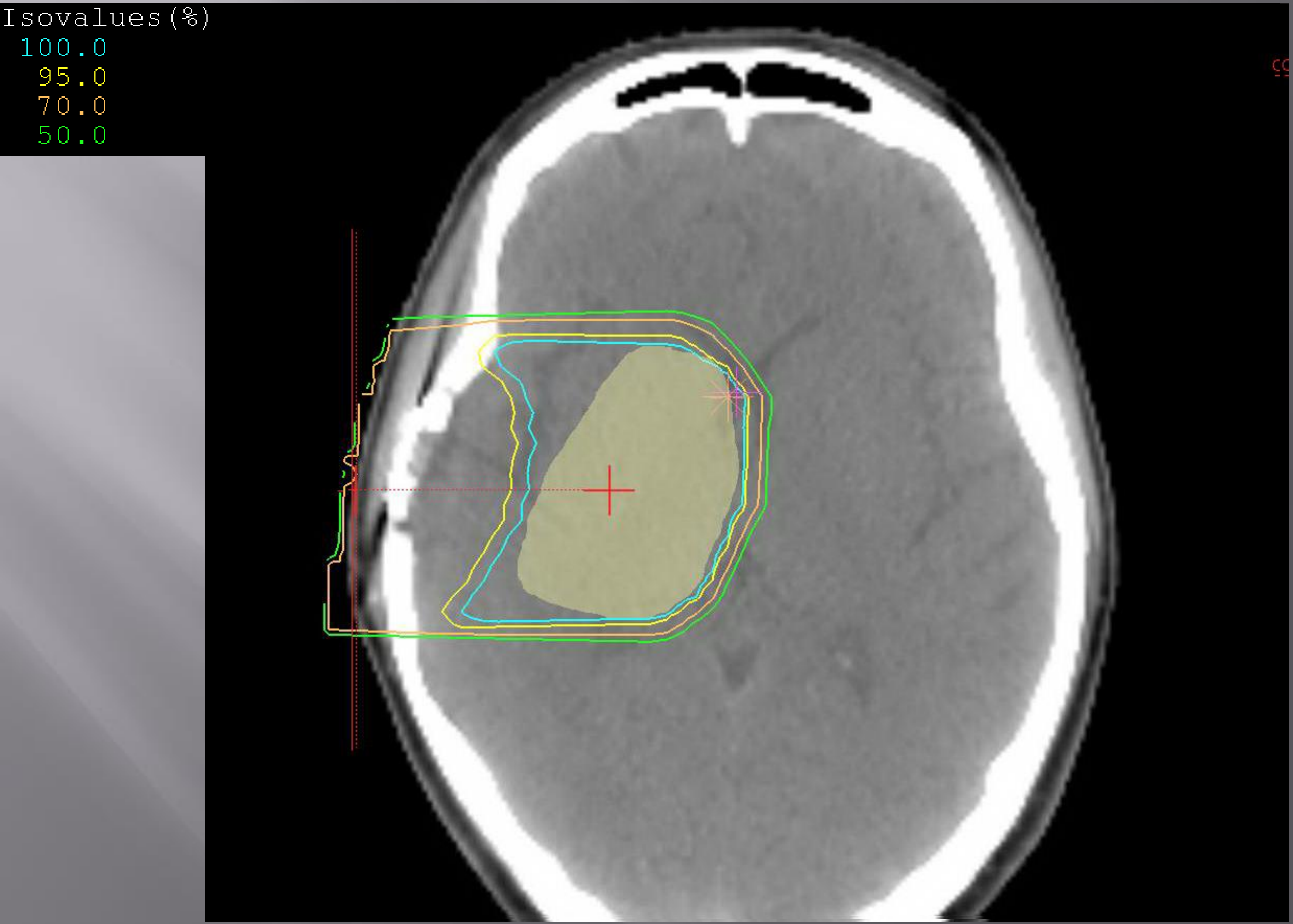
Tools to do our job

- Protons
  - Range : The depth of the Bragg peak (D90%)
  - Modulation : The spread of the Bragg peak
  - Compensators : Distal Shaping
  - Patch Fields : Distal Edge to Lateral Edge Matching
  - IMPT : Inverse planning method

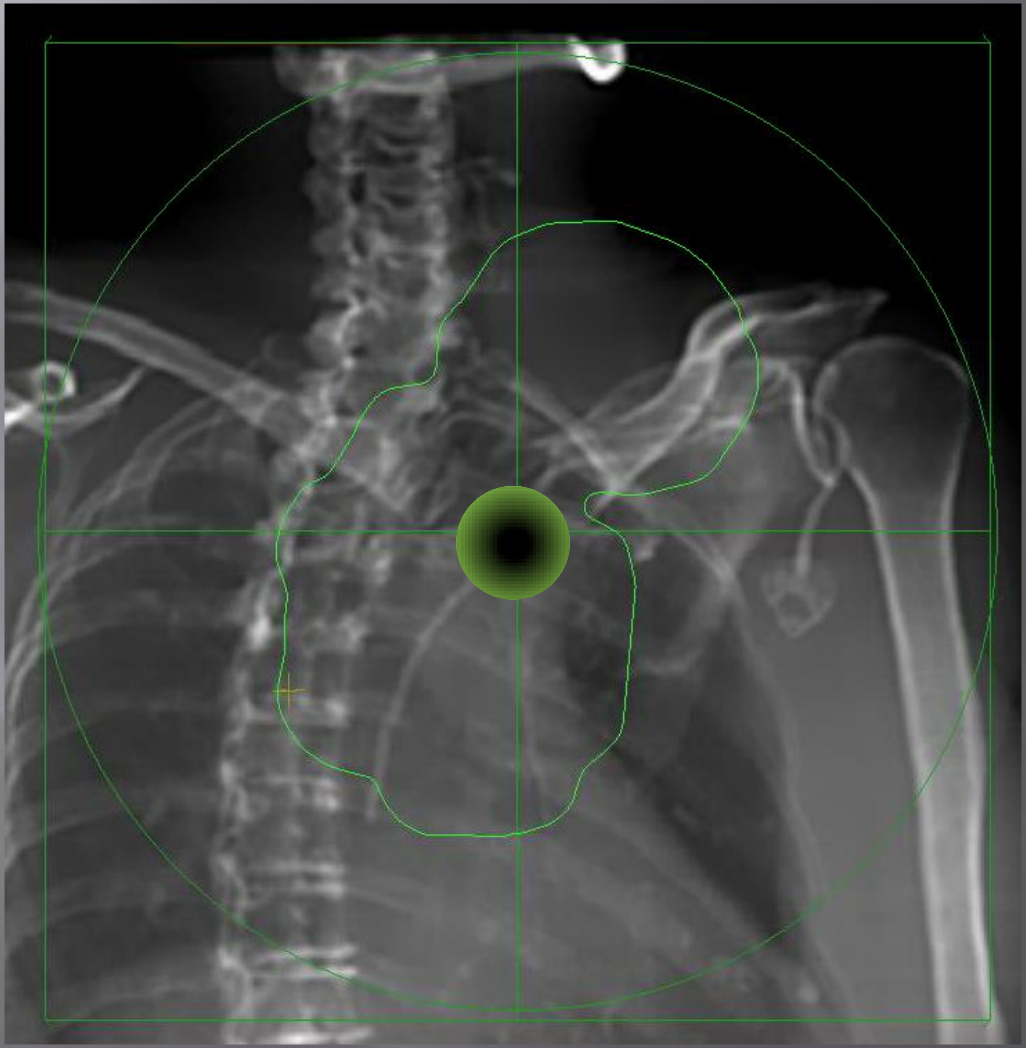
The Physics of Protons



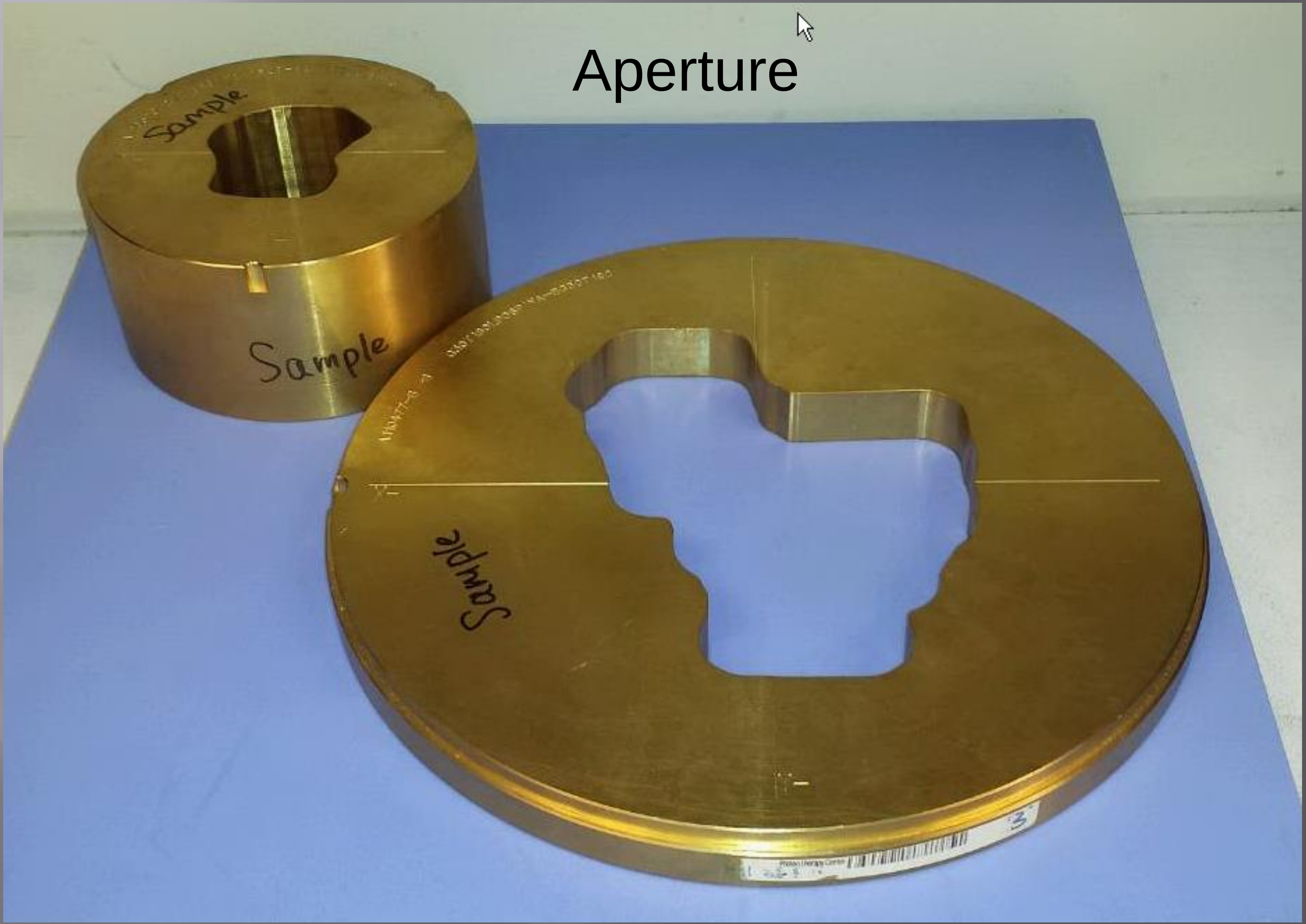
Range and Modulation



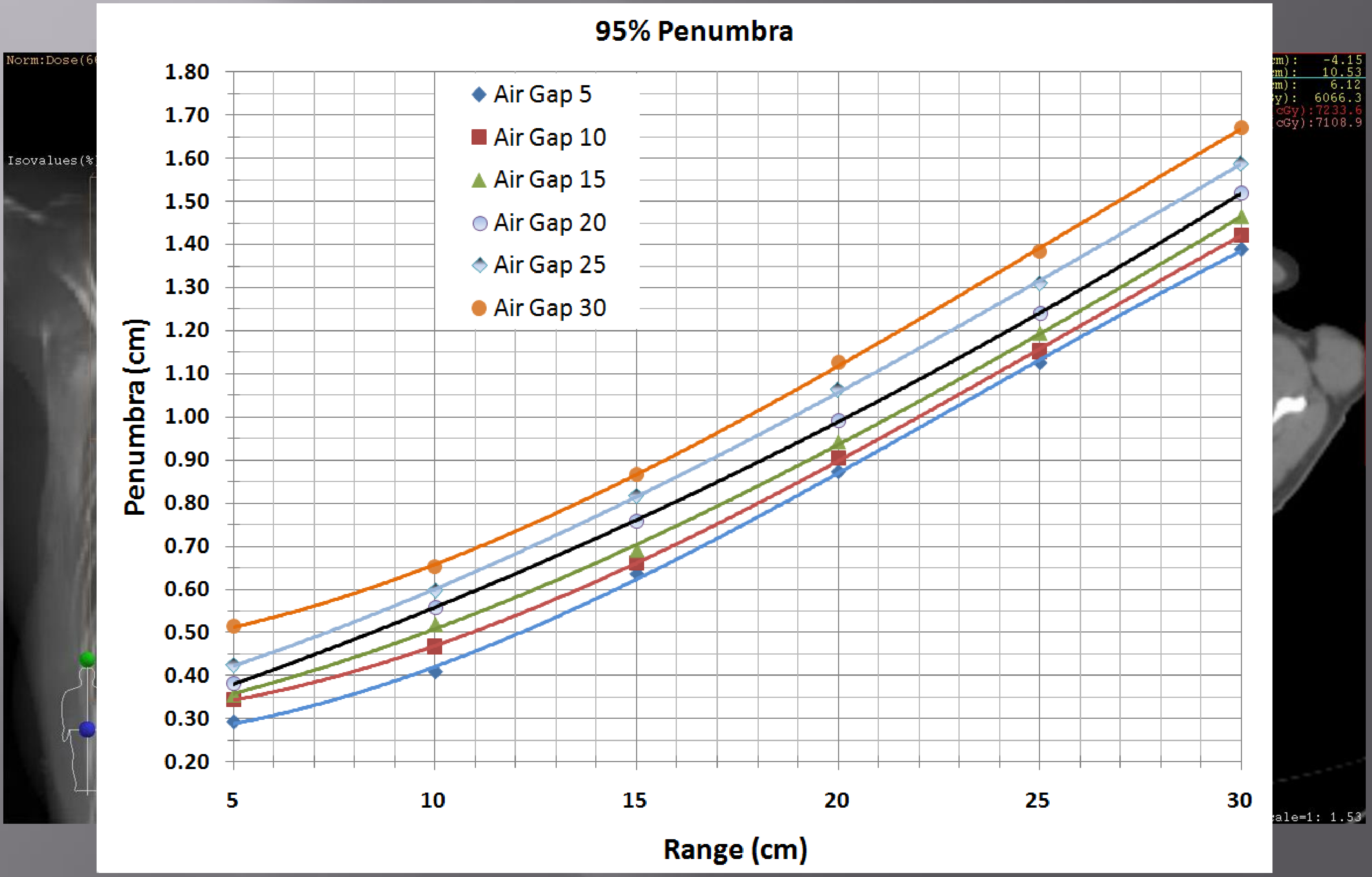
Spreading the beam across the field



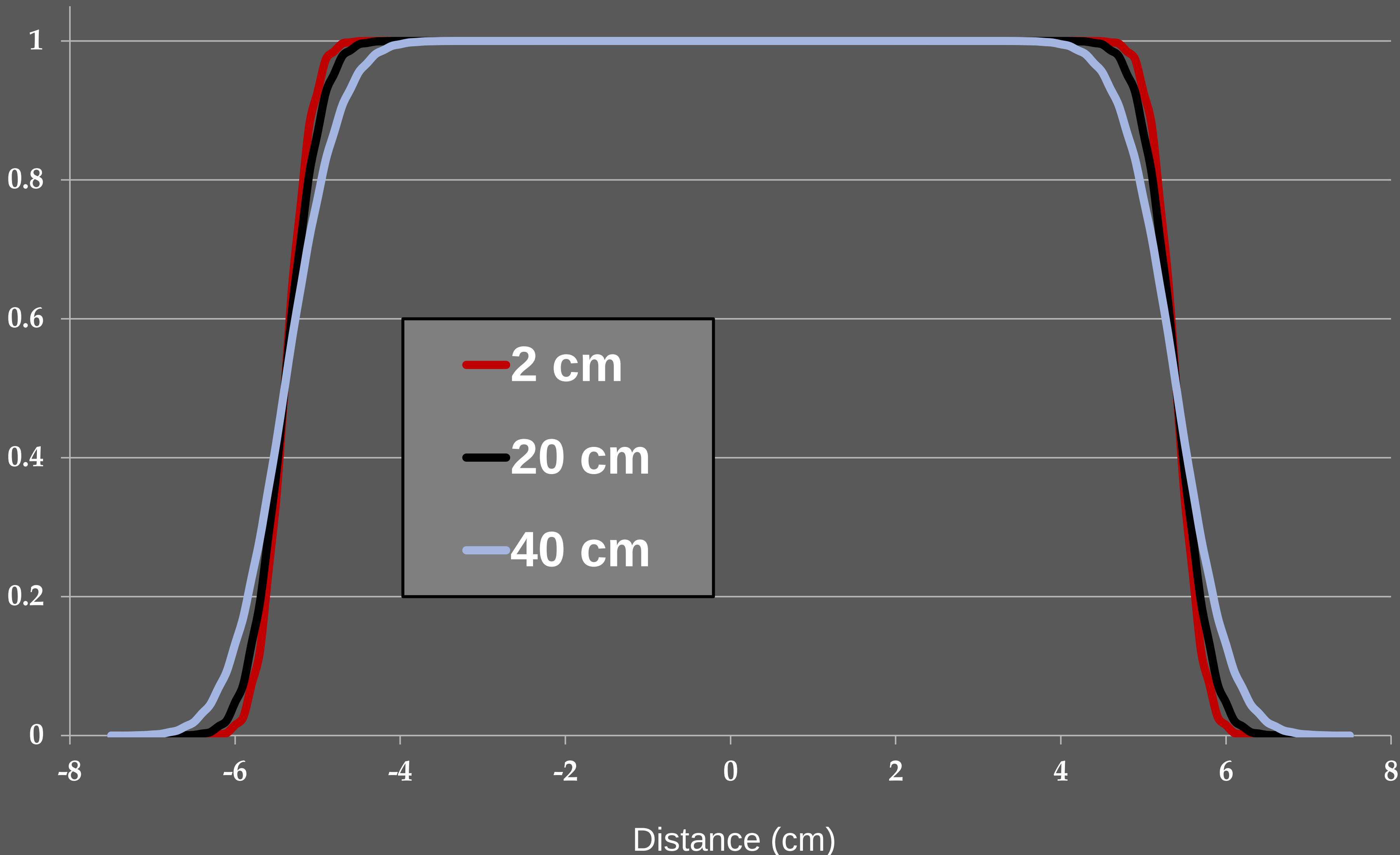
Patient Specific Devices



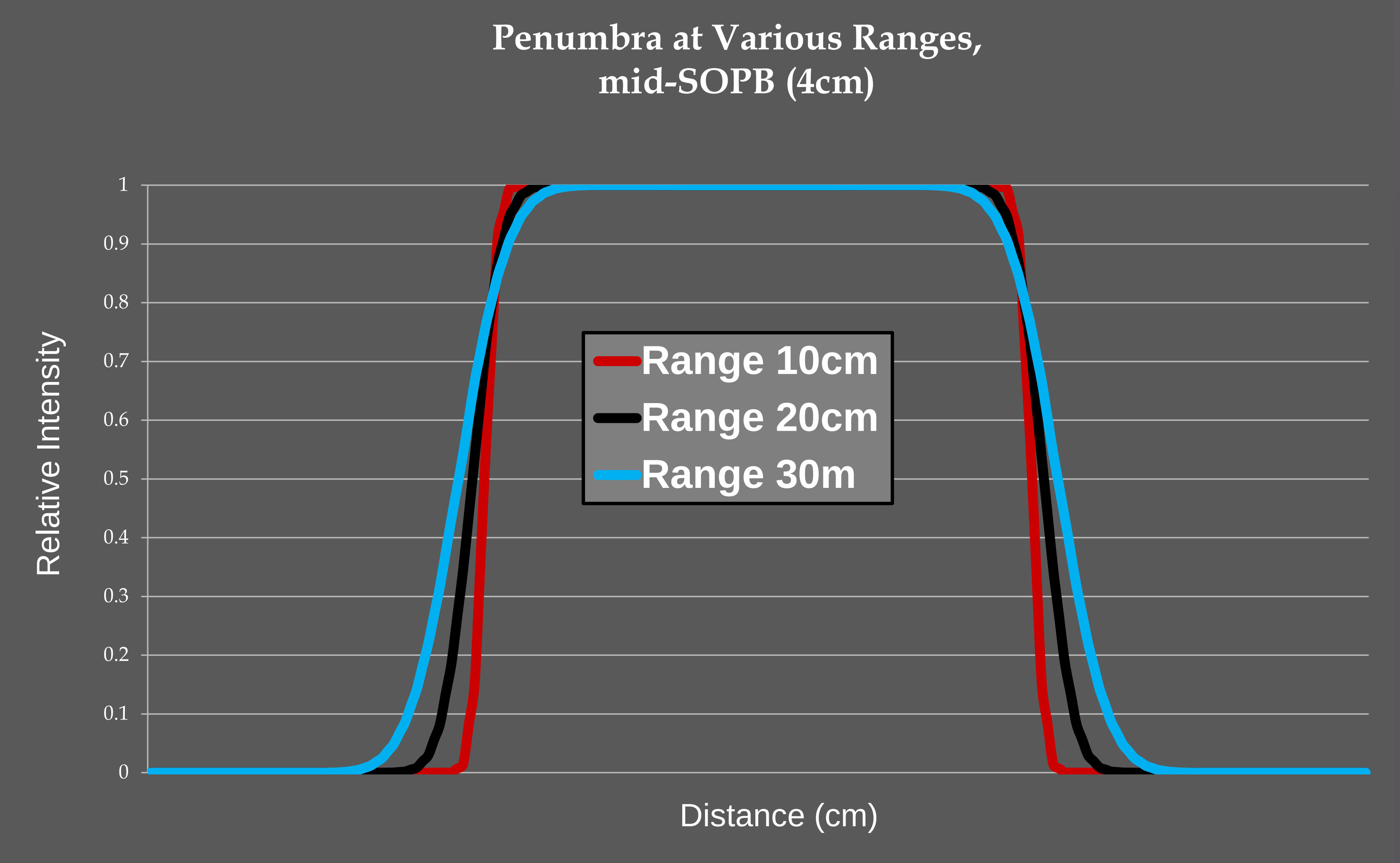
Aperture Design



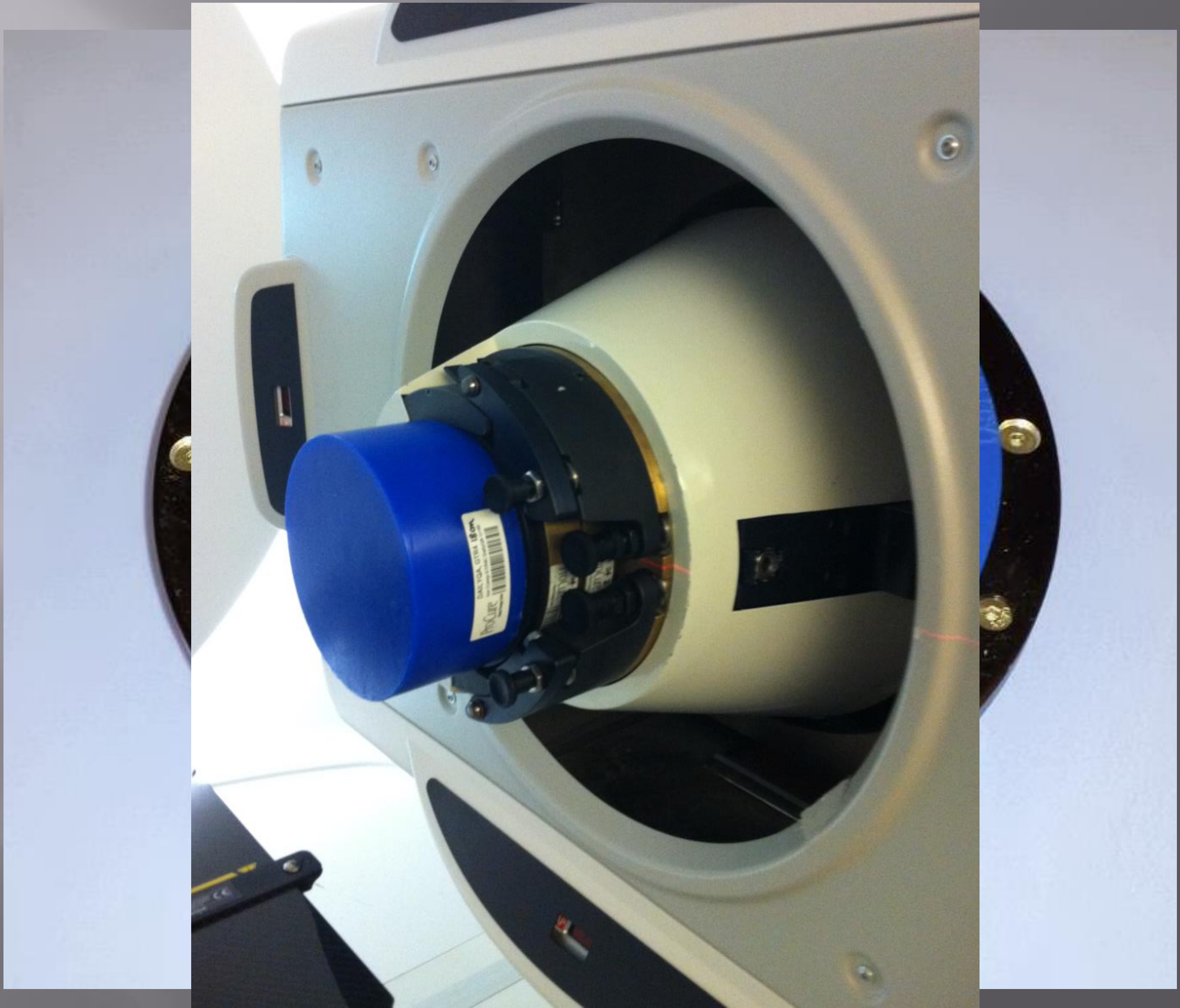
Penumbra at Various Air Gaps



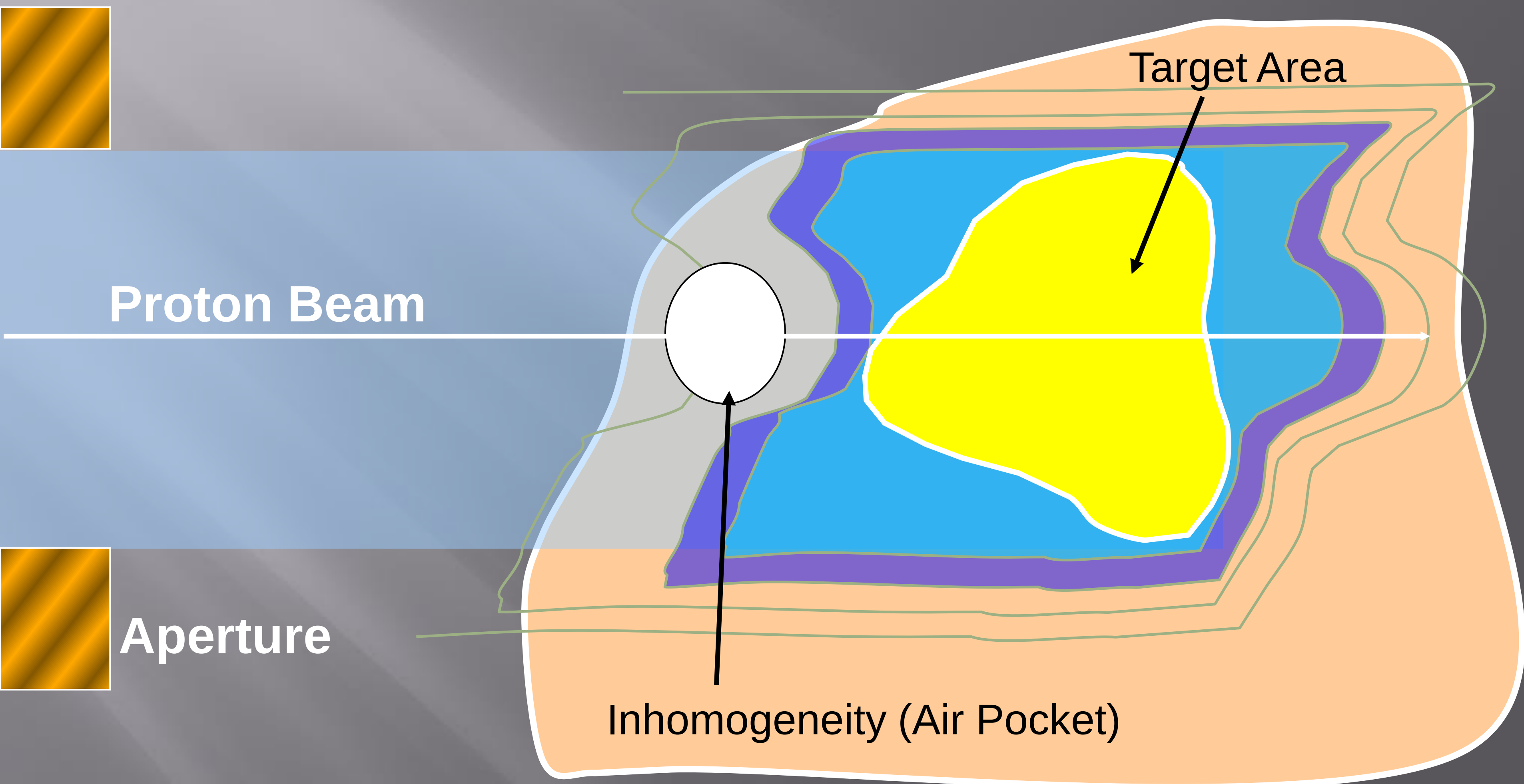
Penumbra as Mid SOBP at various ranges



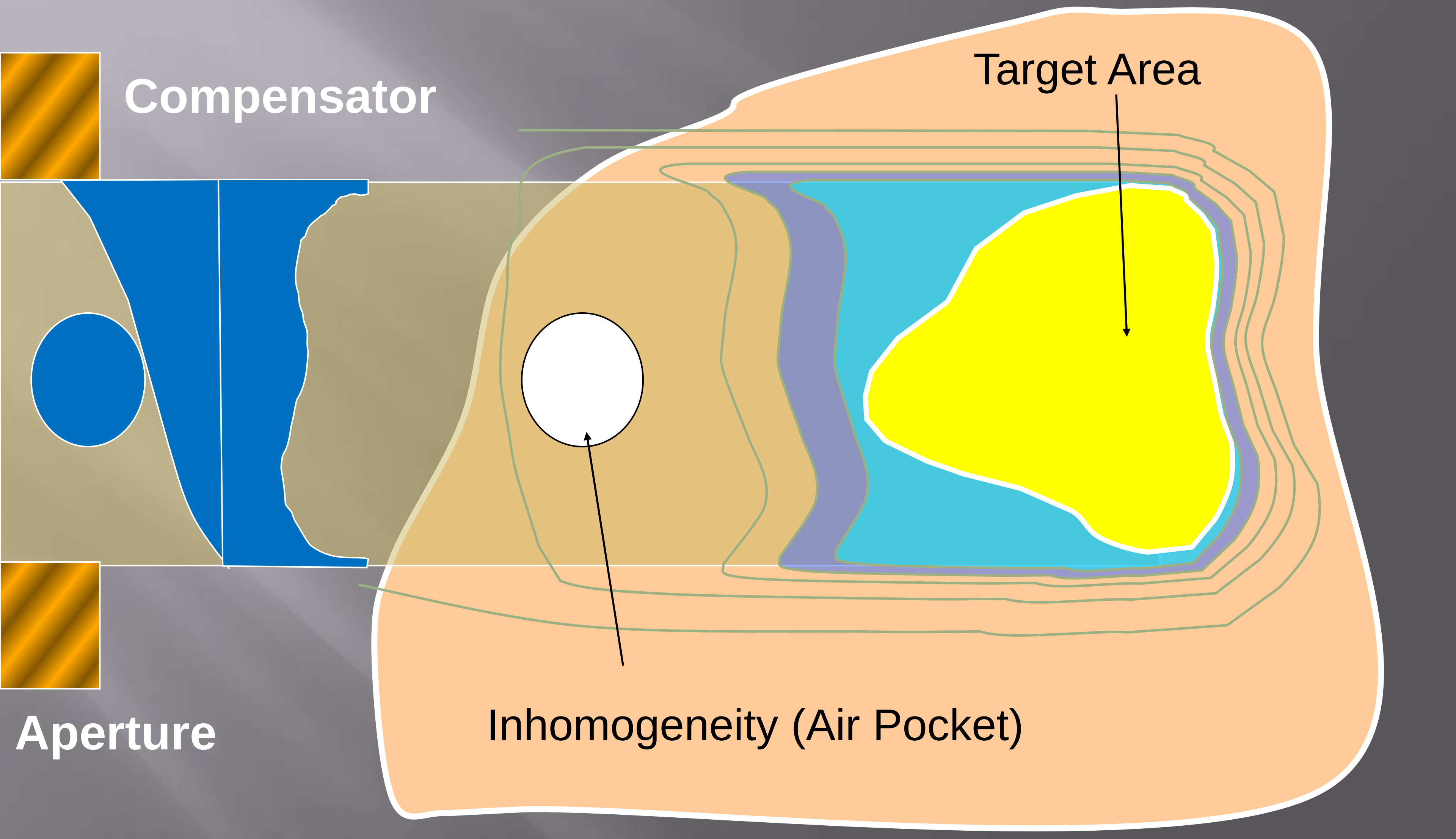
Compensators



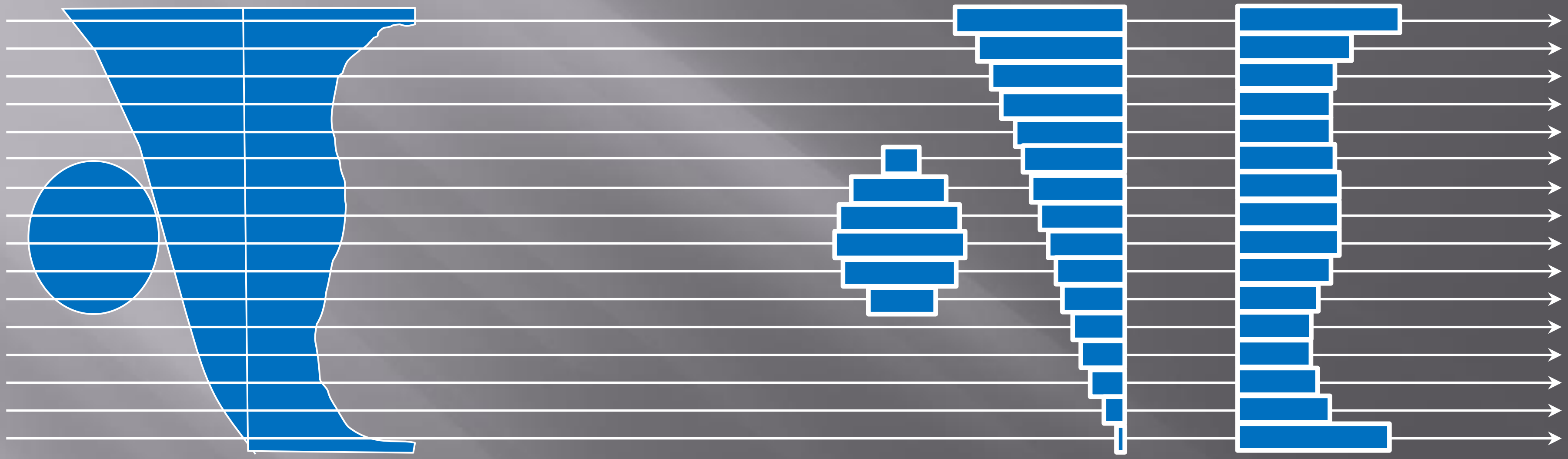
No Compensator



With Compensator

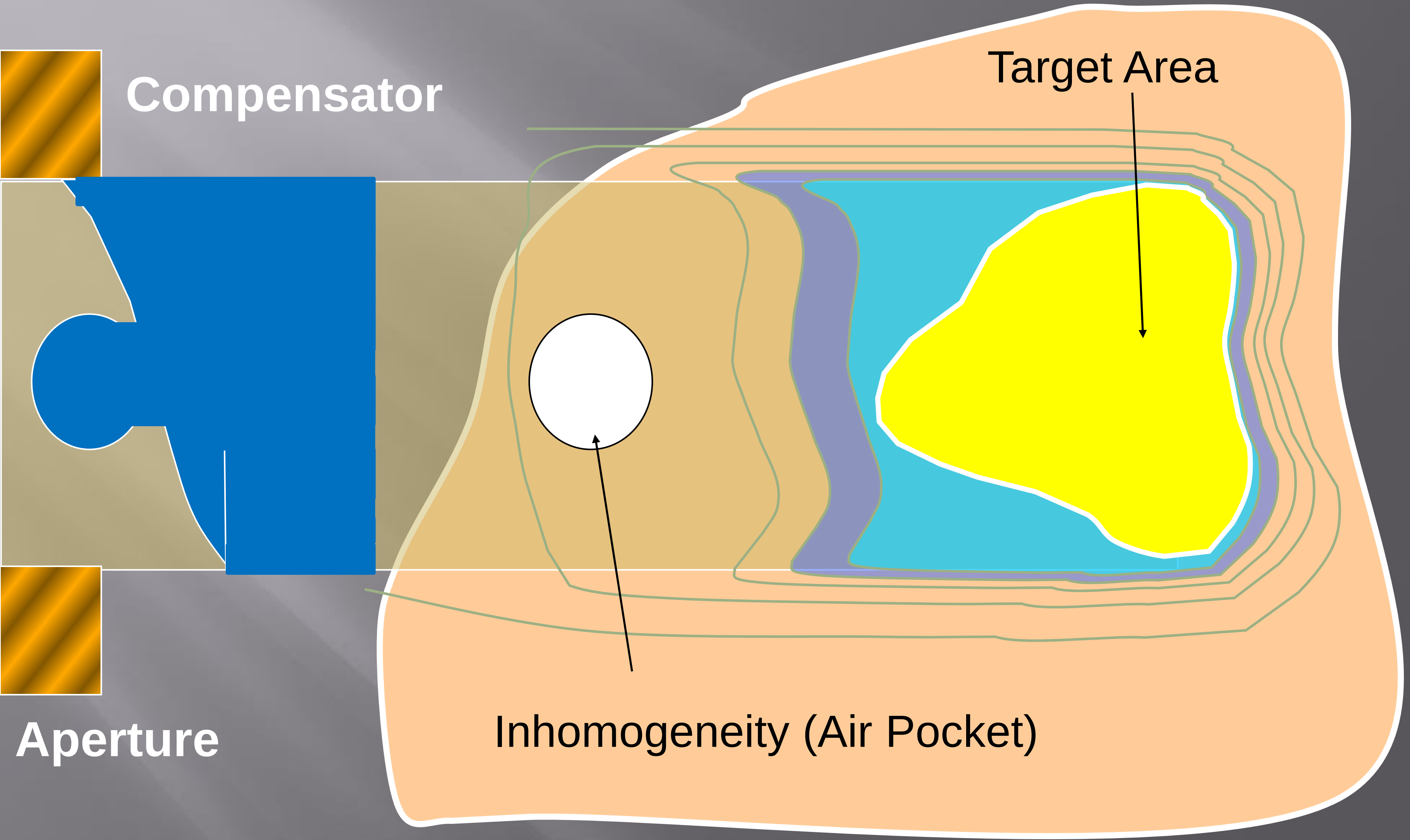


Design of the compensator

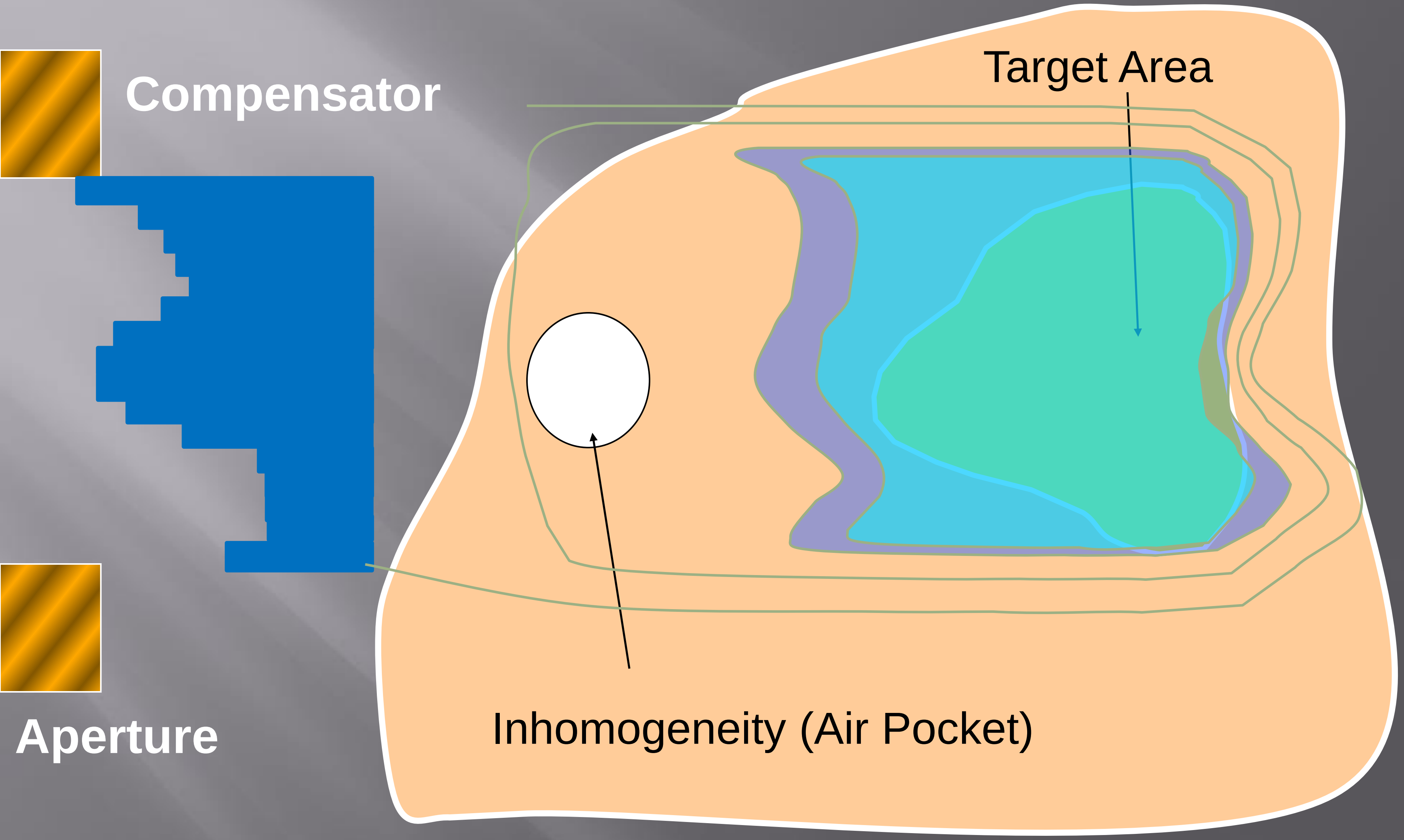


Design of the compensator

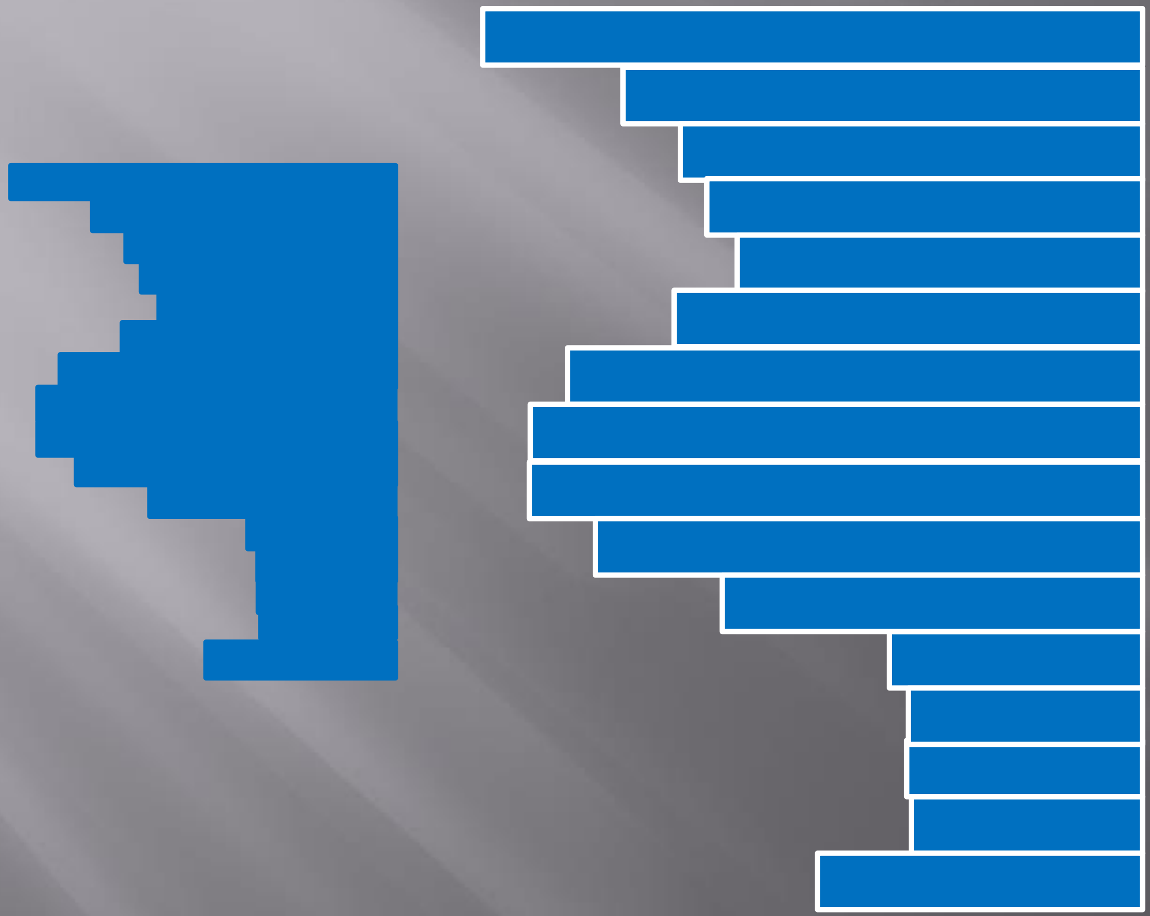
With Discrete Compensator



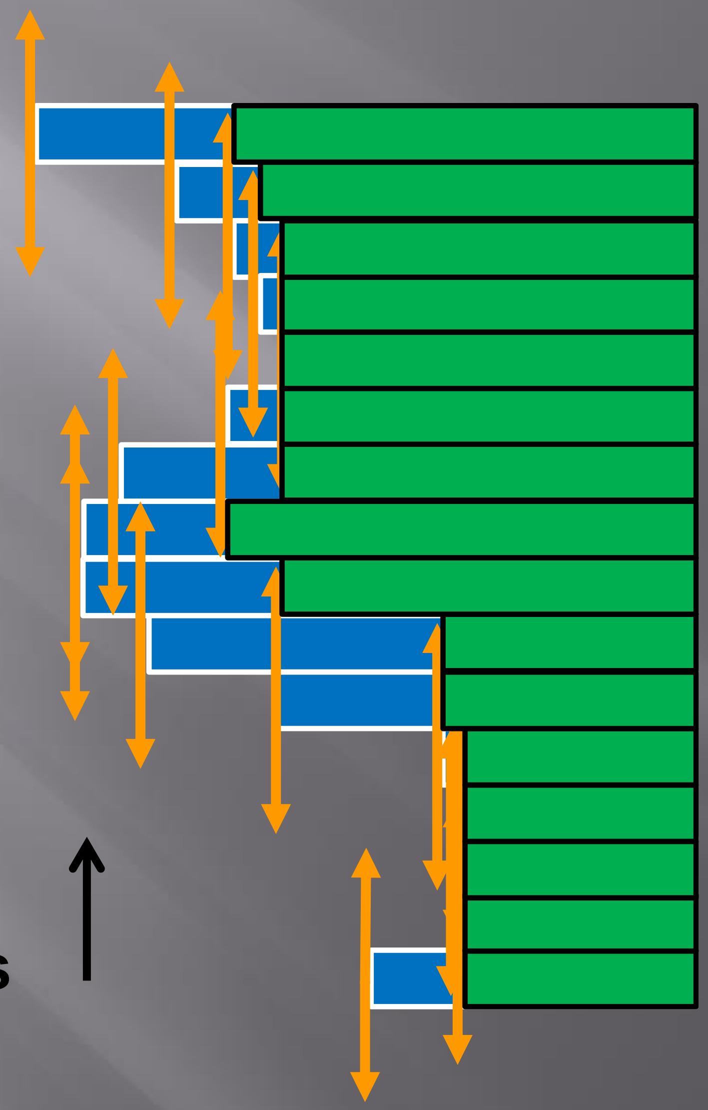
With Discrete Compensator



Smearing

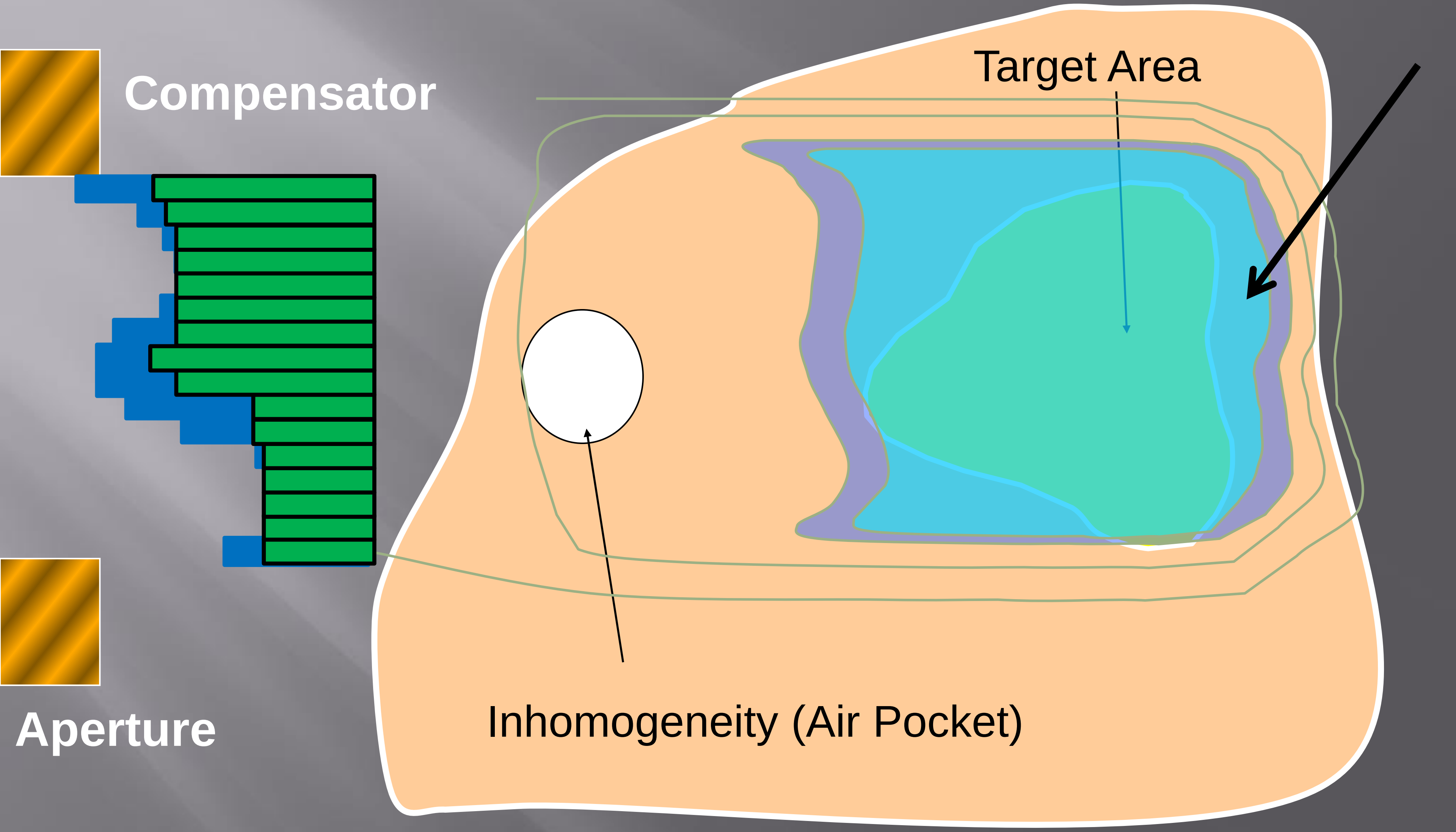


Smearing



Smearing Radius

With Discrete Compensator



Smearing

- Sacrificing distal conformity to ensure you have enough range (and Modulation) to cover the target
- Accounts for the fact that treatment path lengths may be different than planned path lengths due to set-up errors.
- Can easily be built into compensator design
- Not directly accounted for in PBS

Question 1

The concept of smearing is used in compensator based proton therapy to account for :

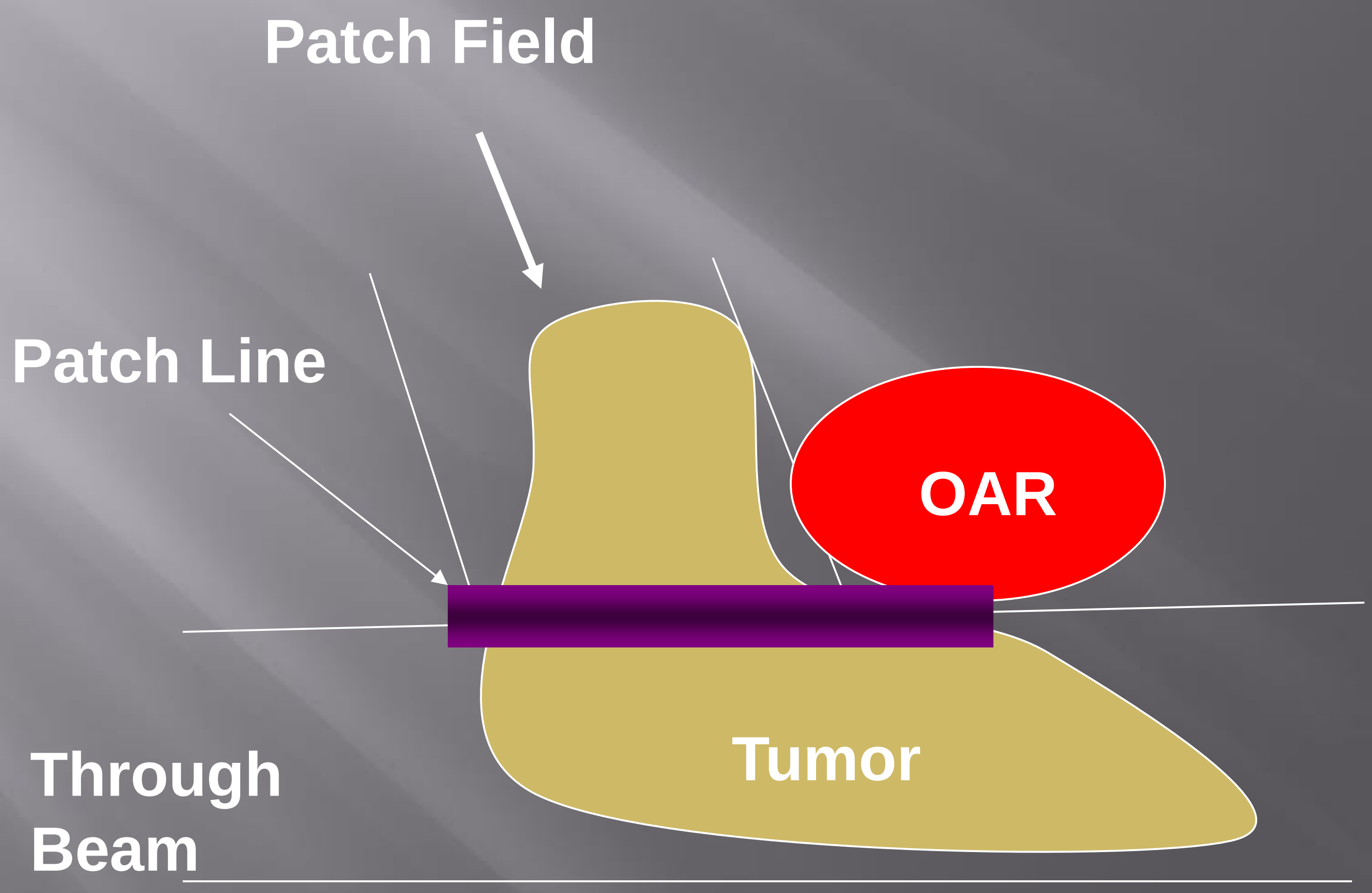
a) Possible compensator thickness errors generated by the milling process

b) Inaccurate stopping power data of compensator materials

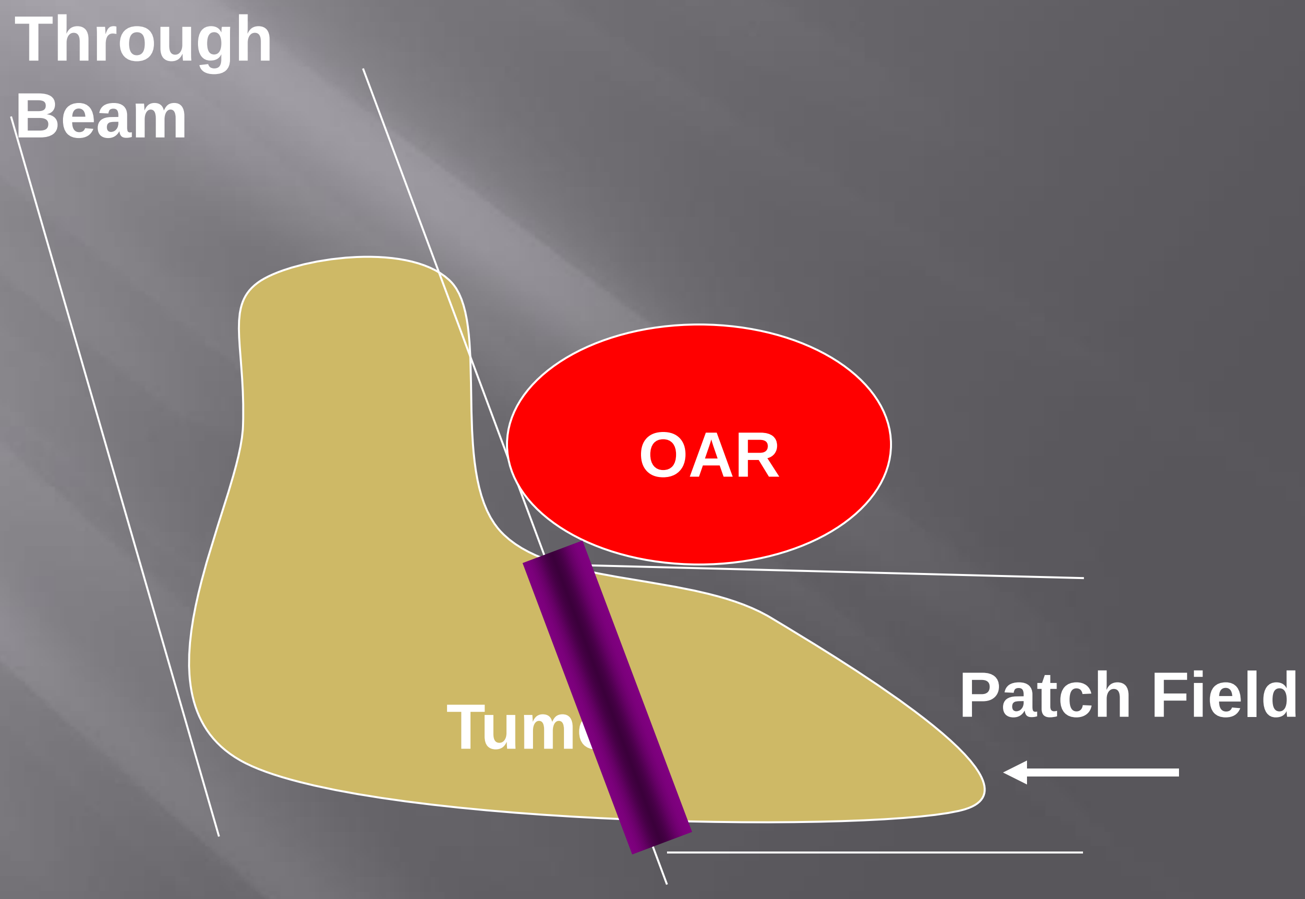
c) Daily patient set-up uncertainties and possible movement of anatomical inhomogeneities during treatment

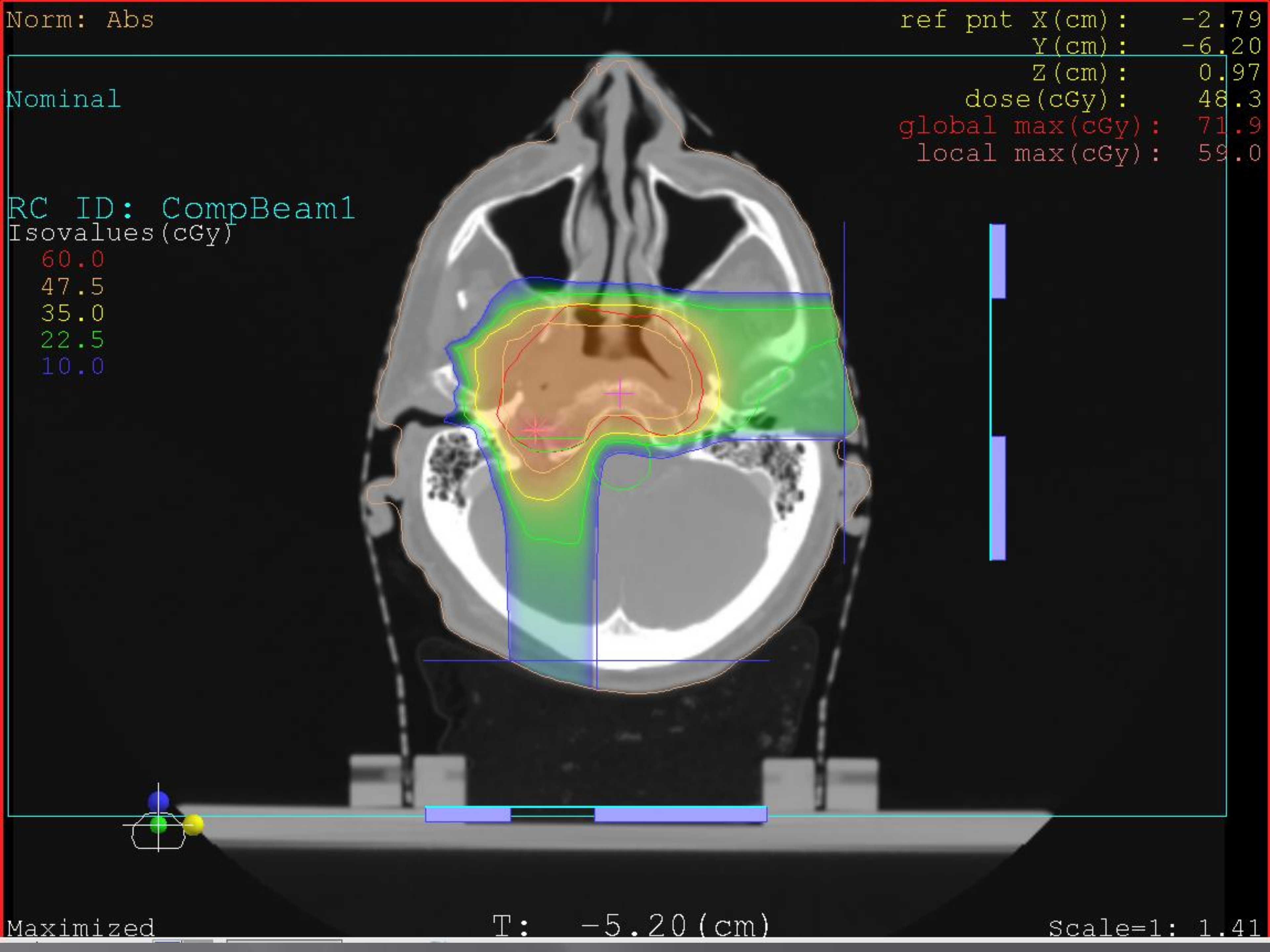
d) All of the above

Patch Field Technique

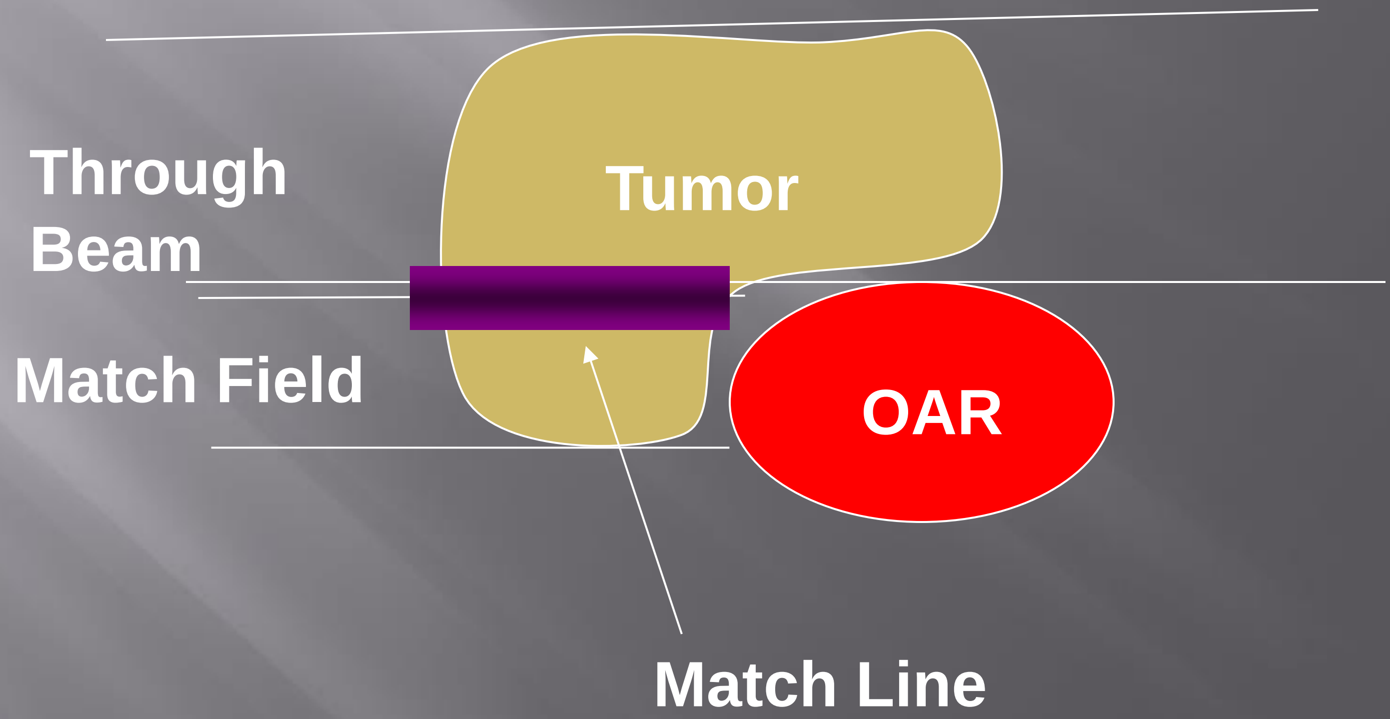


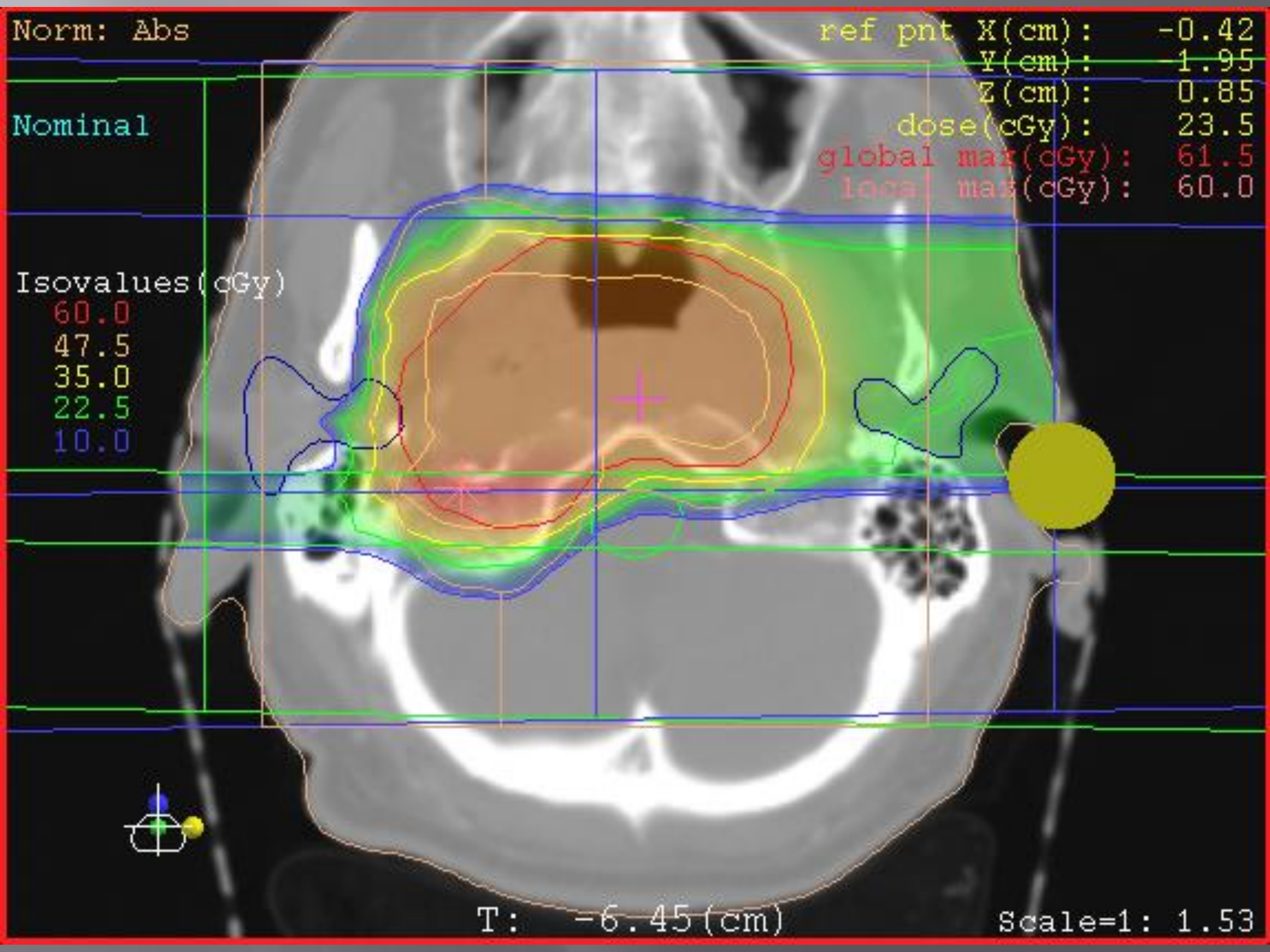
Patch Field Technique
Match-line Change



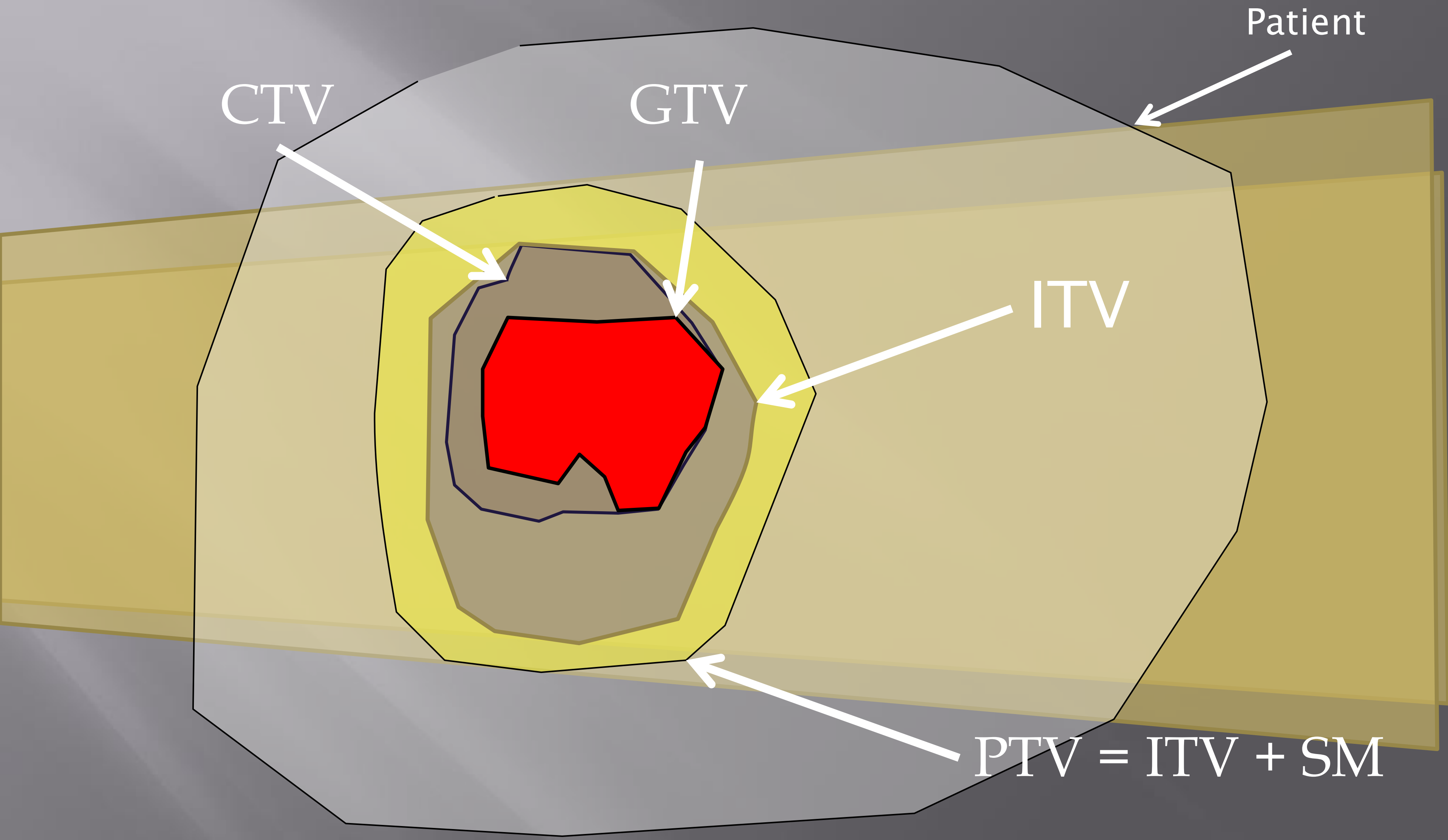

Norm: Abs
ref pnt X(cm): -2.79
Y(cm): -6.20
Z(cm): 0.97
dose(cGy): 48.3
global max(cGy): 71.9
local max(cGy): 59.0
Nominal
RC ID: CompBeam1
Isovalues(cGy)
60.0
47.5
35.0
22.5
10.0
Maximized
T: -5.20(cm)
Scale=1: 1.41

Match Technique

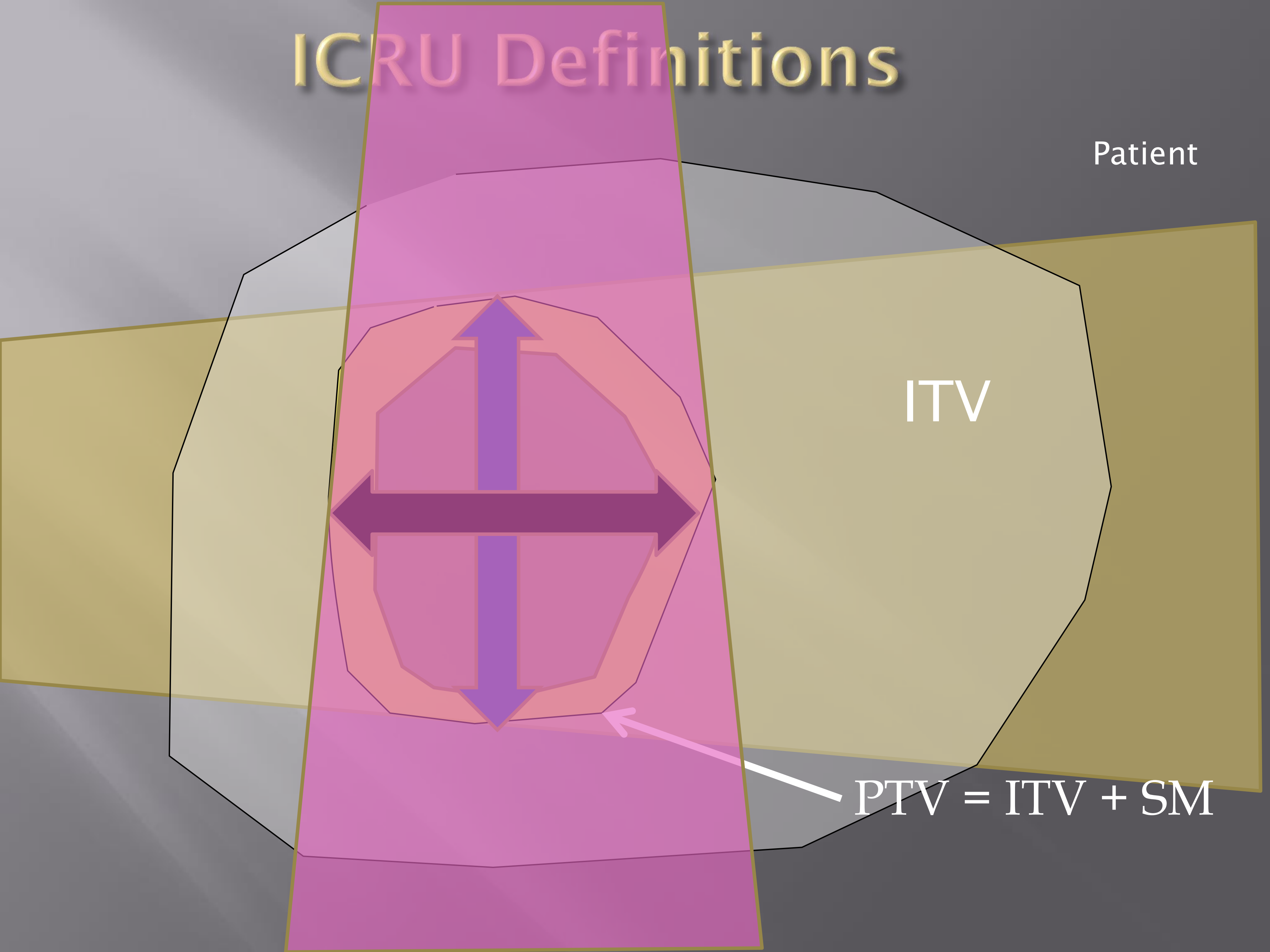



Norm: Abs
ref pnt X(cm): -0.42
Y(cm): -1.95
Z(cm): 0.85
dose(cGy): 23.5
global max(cGy): 61.5
local max(cGy): 60.0
Nominal
Isovalues(cGy)
60.0
47.5
35.0
22.5
10.0
T: -6.45(cm)
Scale=1: 1.53

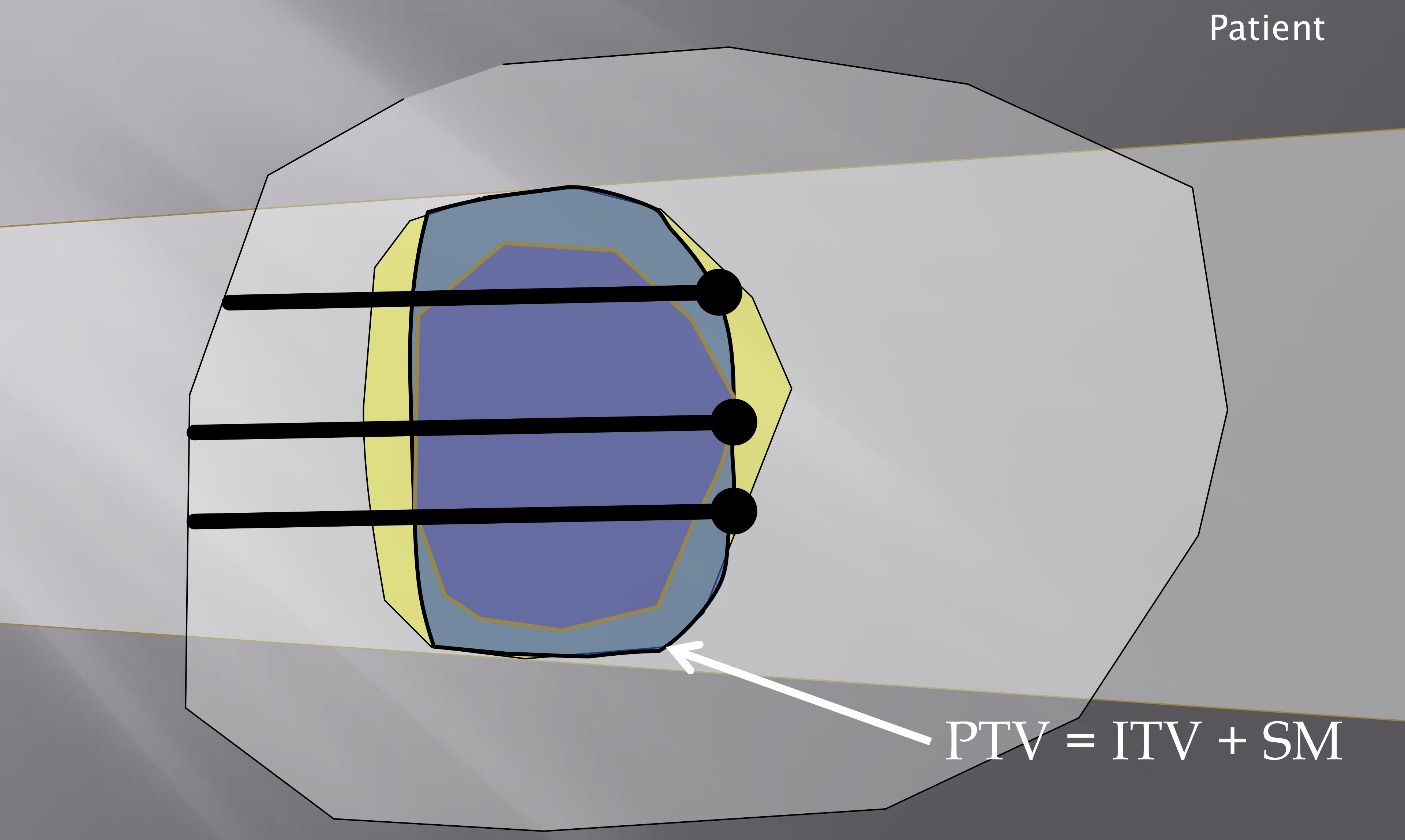
ICRU Definitions



ICRU Definitions



ICRU Definitions



Protons need no distal Set-up margin?

But…. What about Range Uncertainties

Where do range uncertainties
com ey??

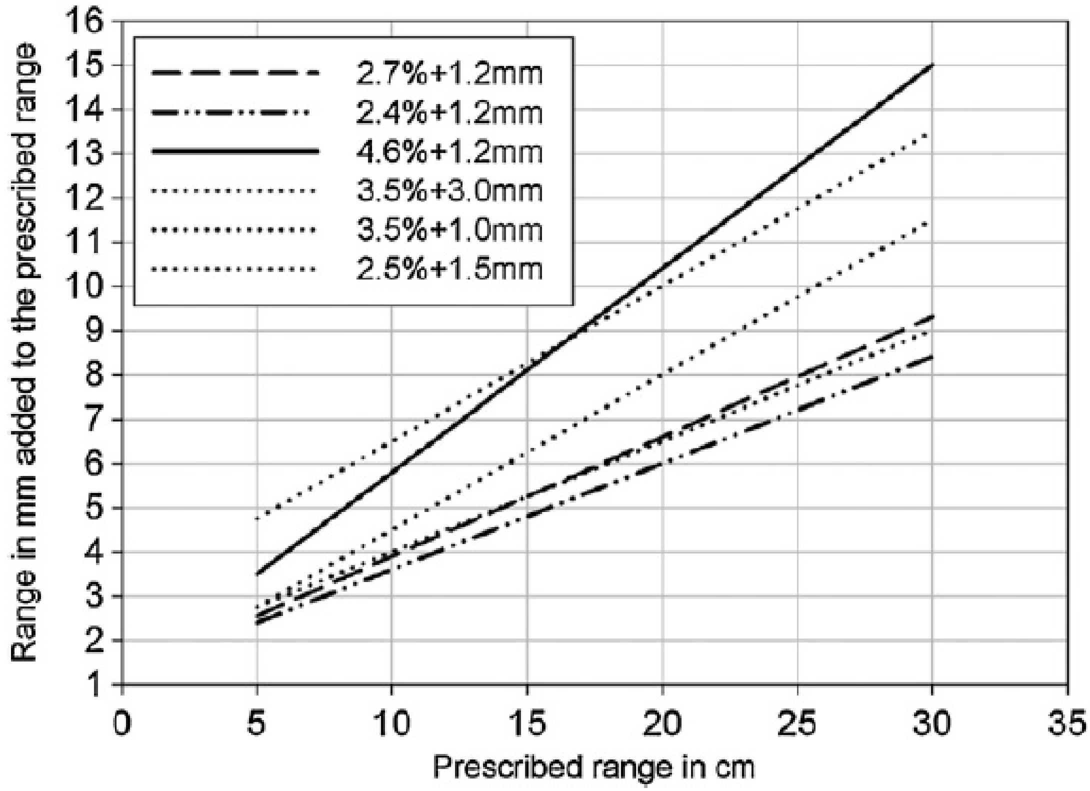


Figure 12. Dotted lines: typically applied range uncertainty margins in proton therapy treatment planning as currently typically applied at the MGH (3.5% + 1 mm), the MD Anderson Proton Therapy Center in Houston (3.5% + 3 mm), the Loma Linda University Medical Center (3.5% + 3 mm), the Roberts Proton Therapy Center at the University of Pennsylvania (3.5% + 3 mm) and the University of Florida Proton Therapy Institute (2.5% + 1.5 mm). Note that these centers may apply bigger margins in specific treatment scenarios. Dashed line: estimated uncertainty without the use of Monte Carlo dose calculation. Solid line: estimated uncertainty for complex geometries without the use of Monte Carlo dose calculation. Dashed-dotted line: estimated uncertainty with the use of Monte Carlo dose calculation.

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.

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.

	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

Table 9. Median, 90th percentile and 95th percentile of composite range uncertainties and the corresponding percentile when the range uncertainty is 3.5% at different clinical sites.

	Composite range uncertainty (%)			Percentile when range uncertainty = 3.5%
Tumor site	Median	90th percentile	95th percentile	
Prostate	1.3	2.5	3.0	98%
Lung	1.5	2.9	3.4	96%
Head and neck	1.3	2.6	3.0	98%

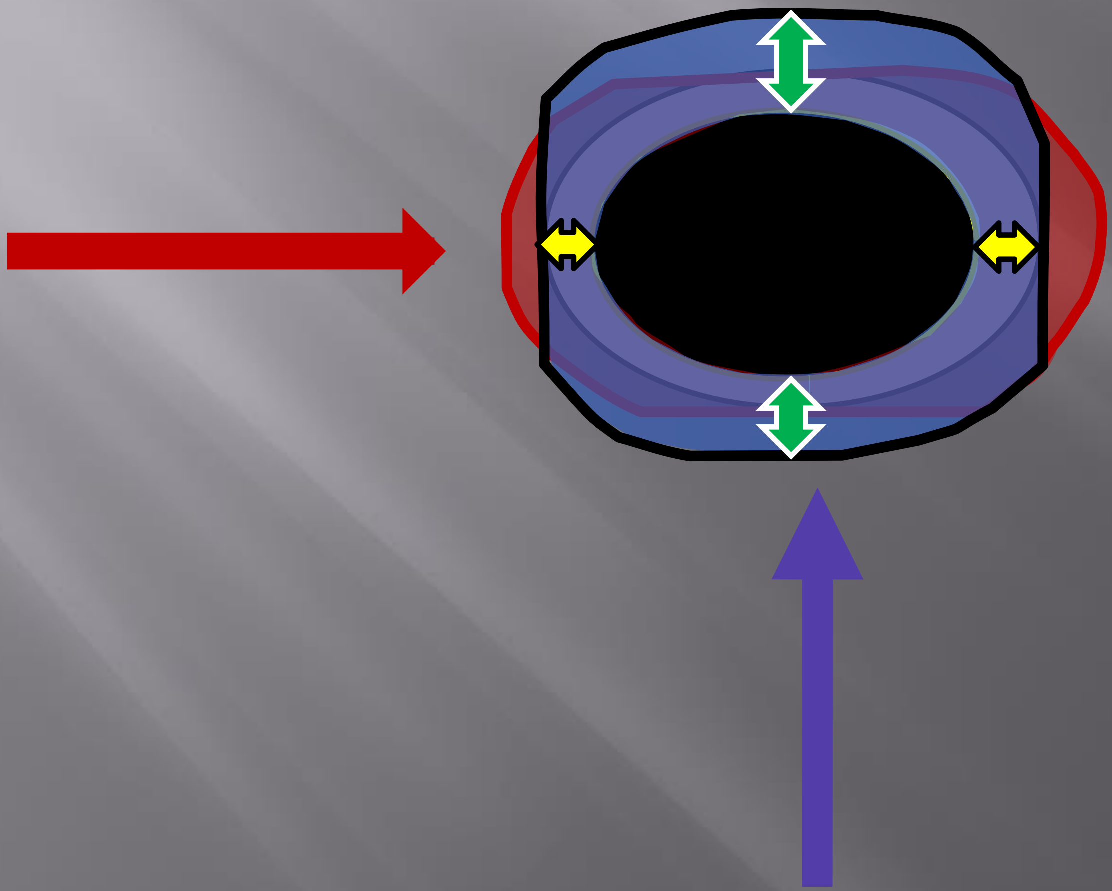
Yang, Phys. Med. Biol, (57) 2012

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

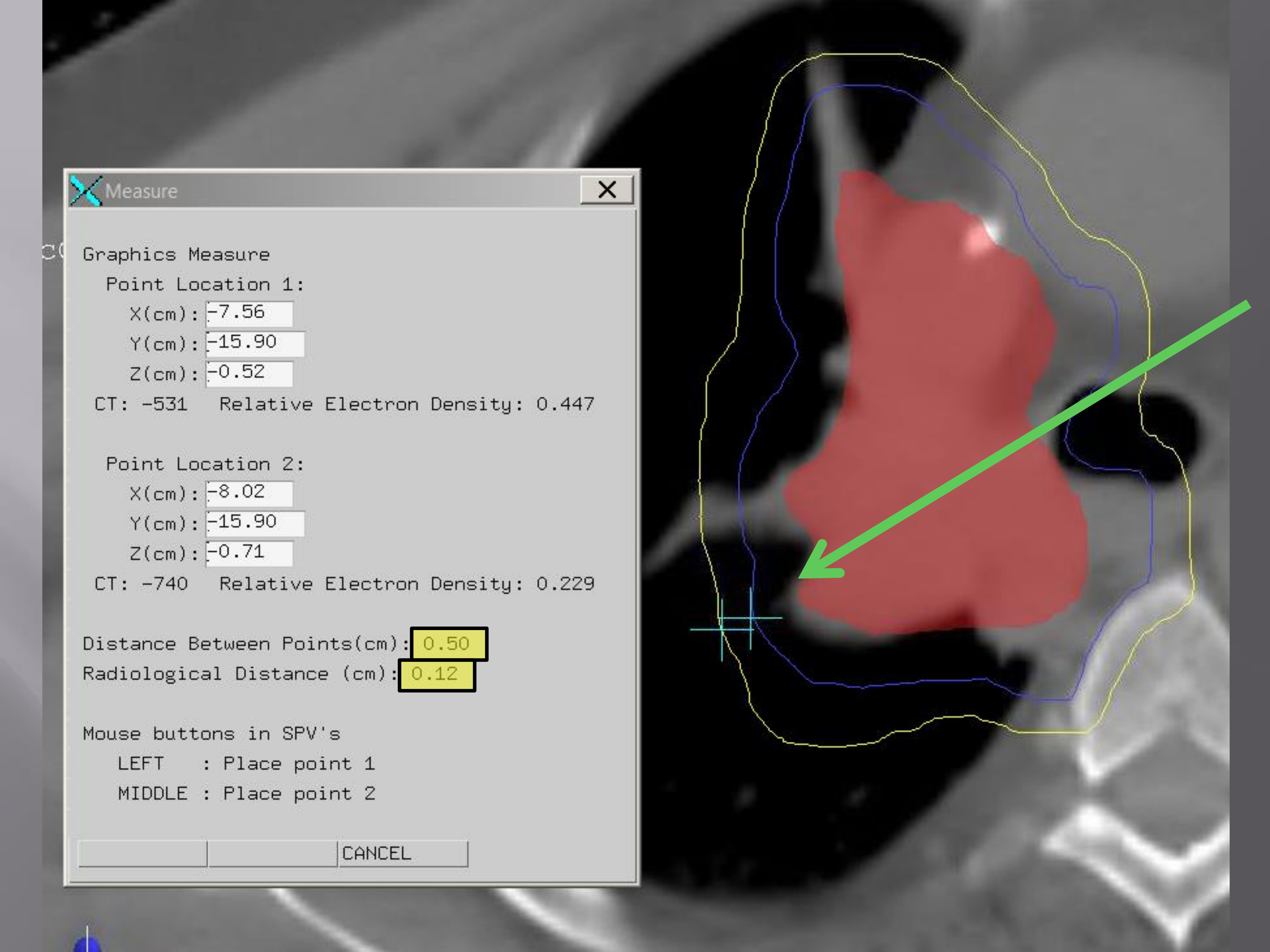
Paganetti, Phys. Med Biol (57), 2012

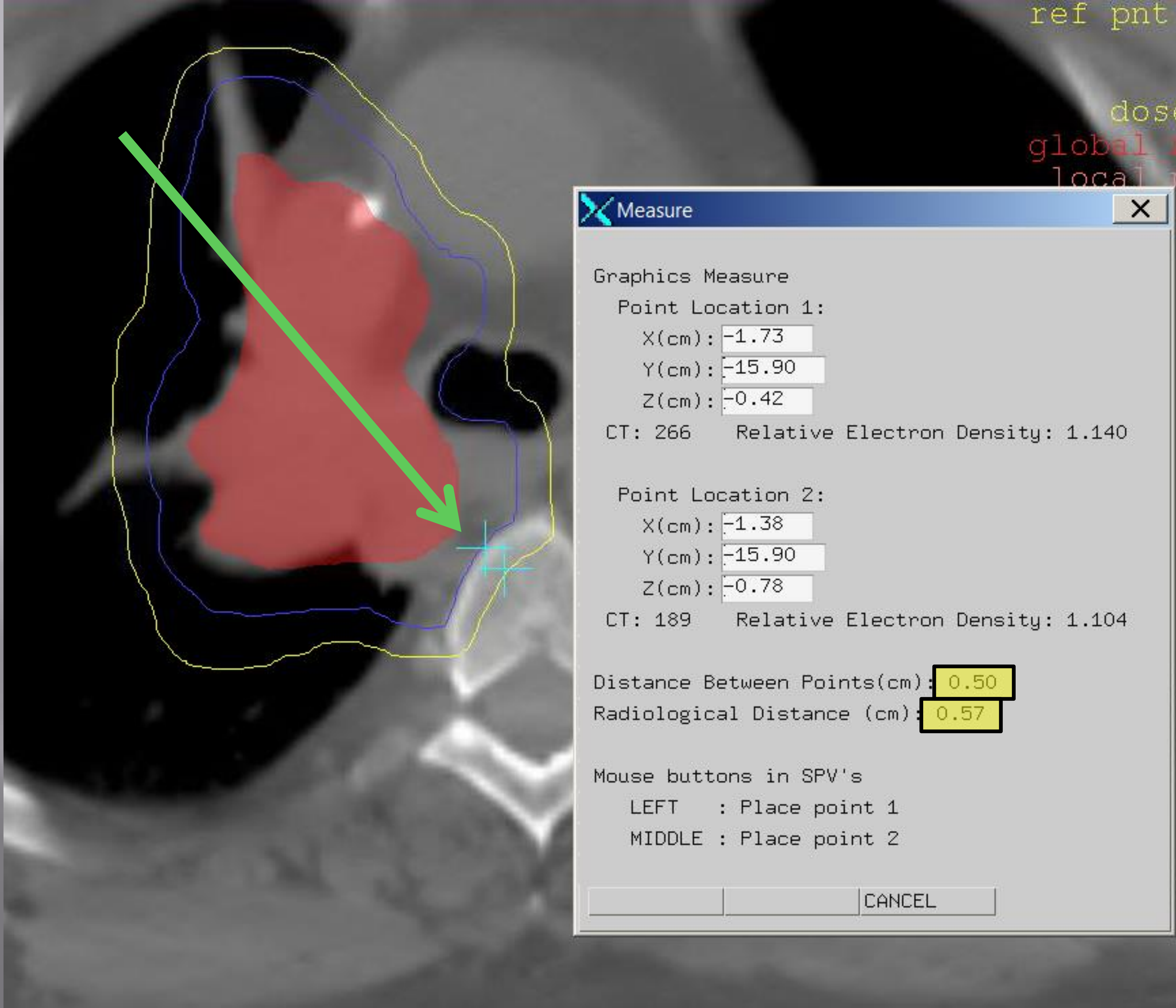
Adding the Uncertainty with Protons



Physical Distance (cm)

Radiobiological Depth (WET)


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

Question 2

Why is the standard PTV concept NOT fully applicable to proton therapy?

a) Targets treated with protons tend to have no setup and intra-fraction changes in the target volume .

b) The use of smearing negates the need for lateral margins in proton therapy.

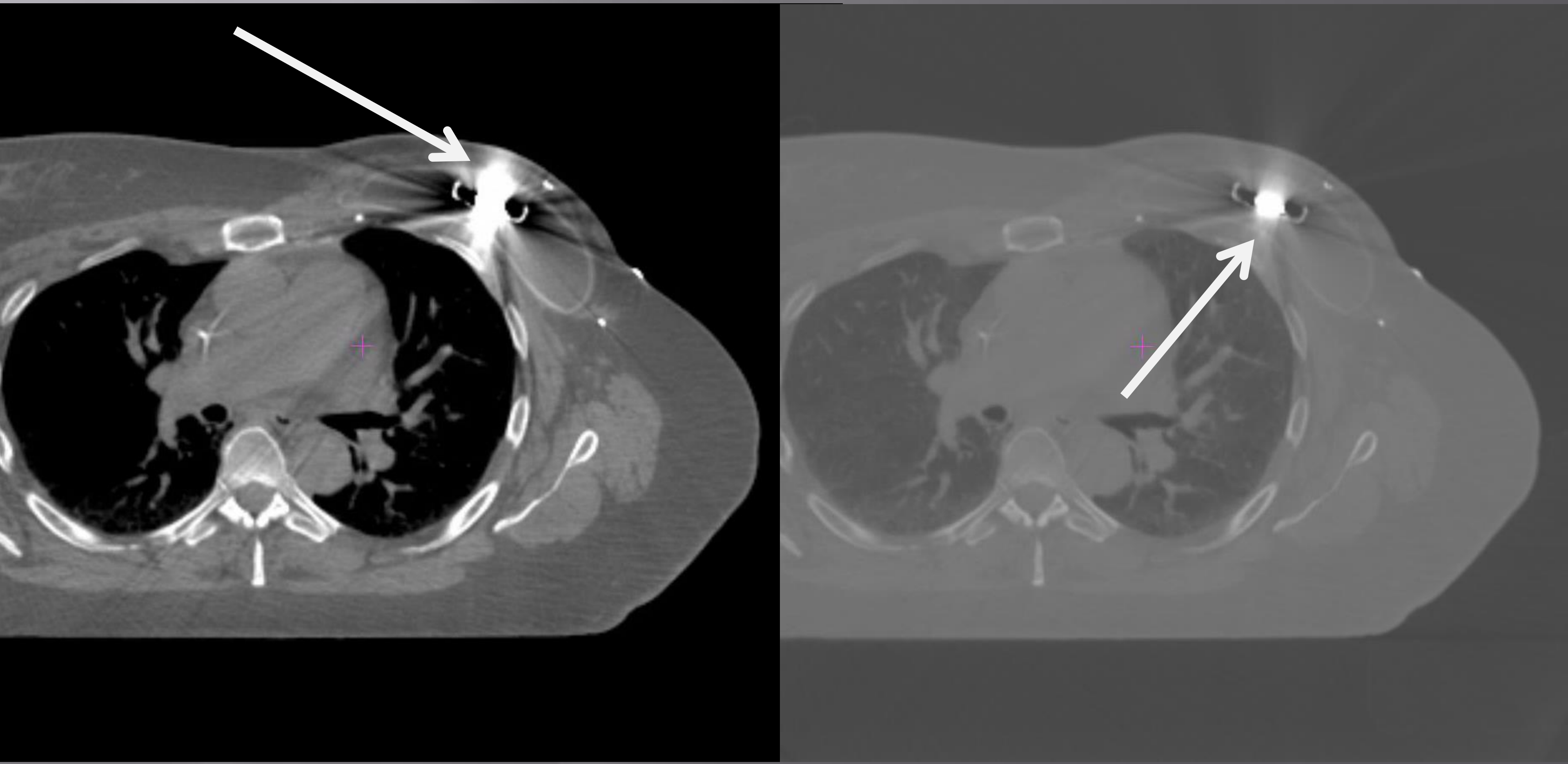
c) For protons, distal and proximal margins around the target are required to account for range uncertainties which are not accurately achieved using a standard PTV.

d) None of the above.

HU Unit conversions

- 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



Breast Prosthesis

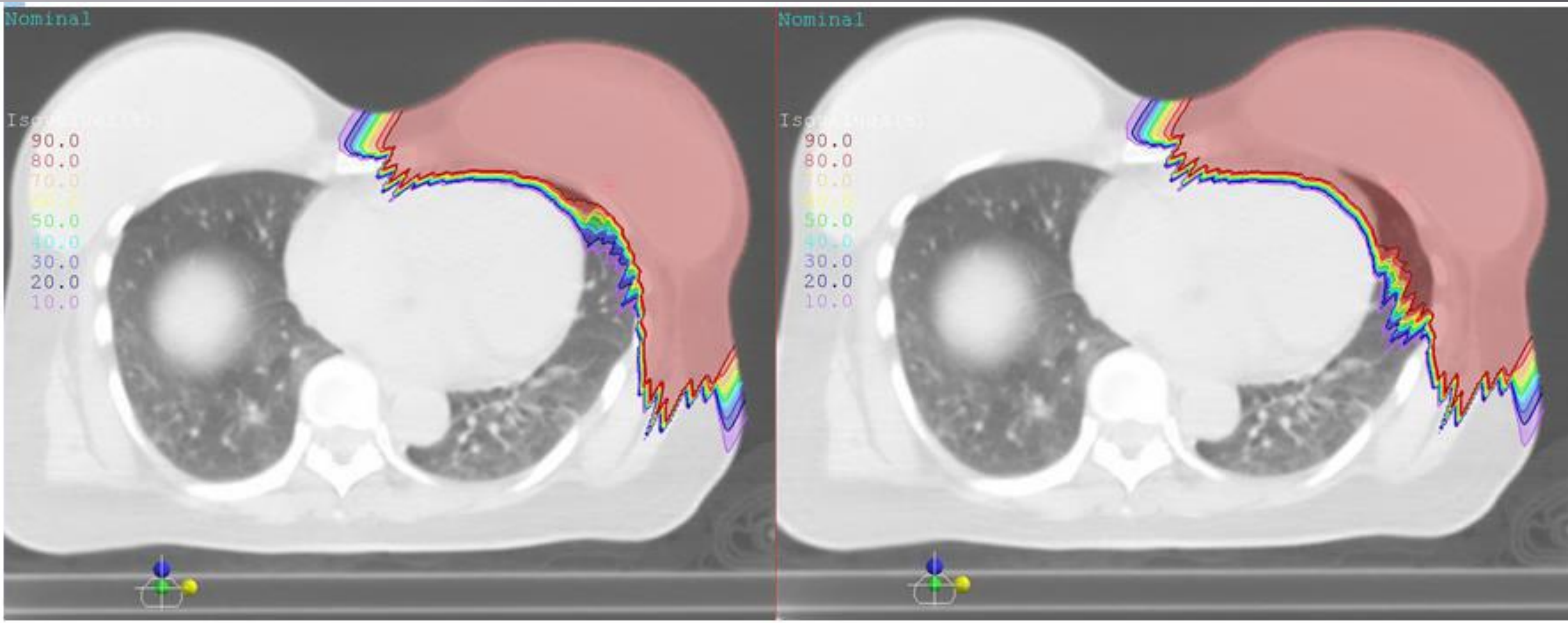
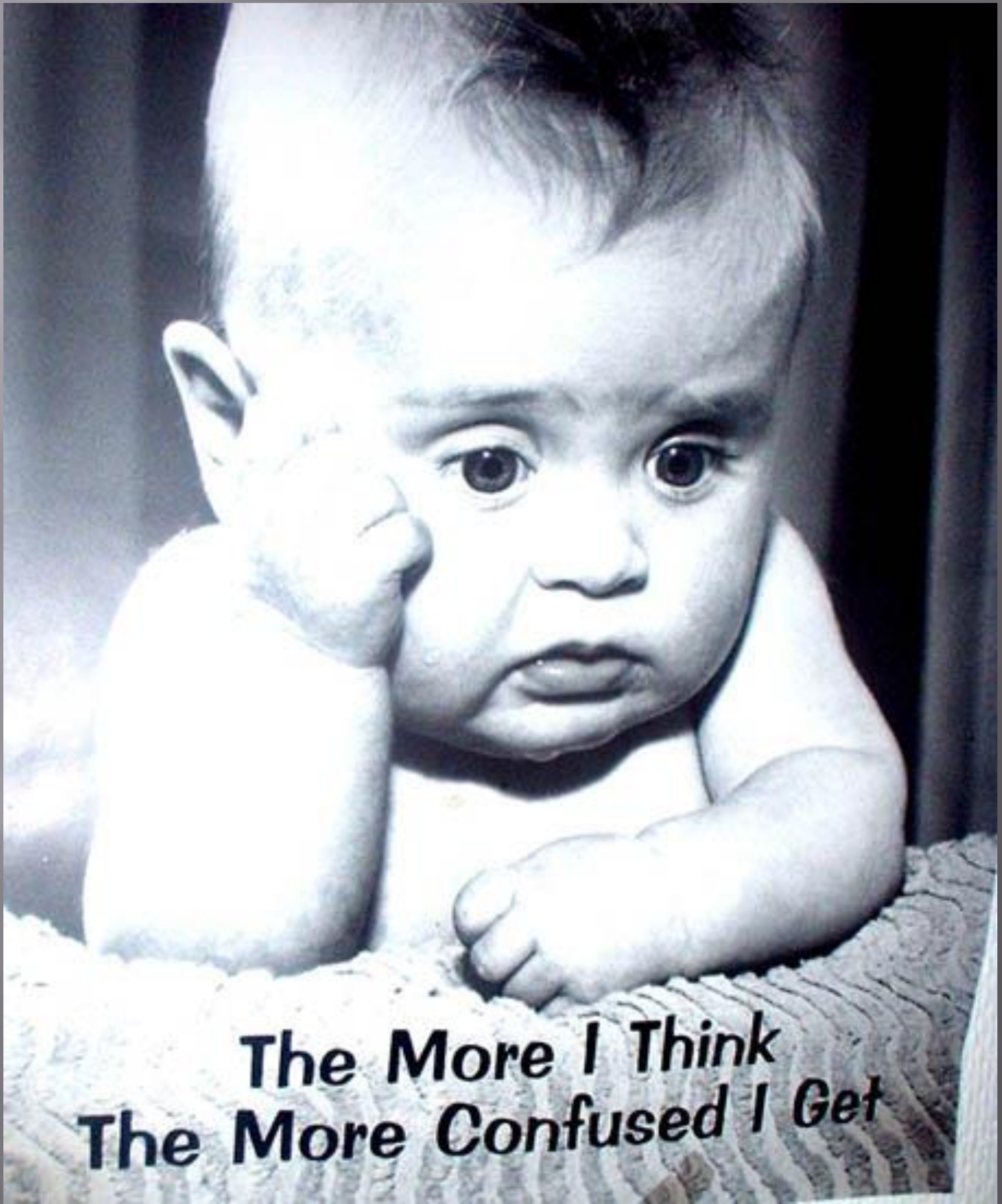


Fig. 3: Treatment plan for patient with silicone breast prosthesis. (a) Planned dose distribution without RLSP reassignment. (b) Delivered dose distribution if planned without proper pRLSP assignment.

Is there any hope for improvements?

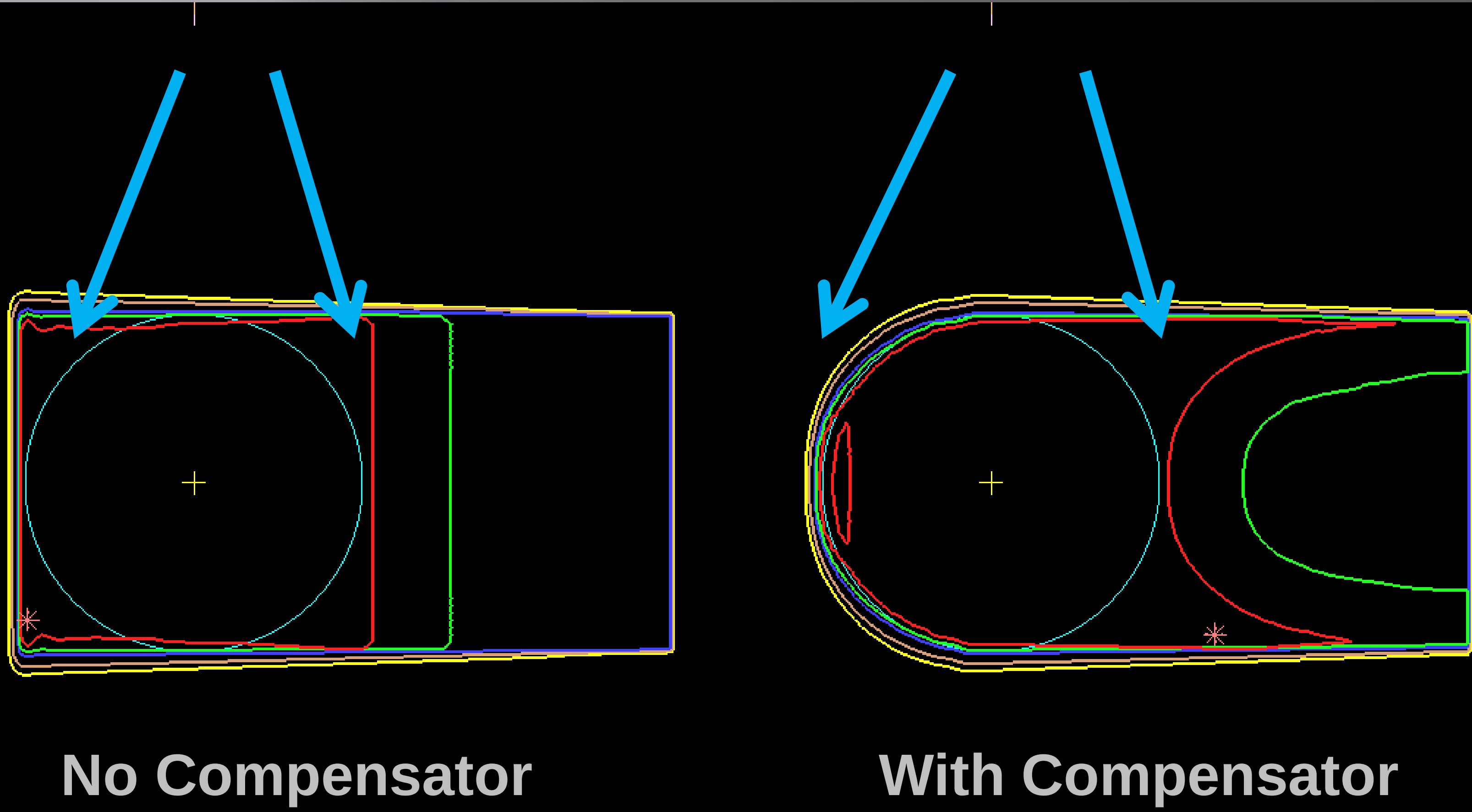
- MVCT
- Proton activation (PET/SPECT) Tomography
- Prompt Gamma verification
- Proton Tomography / radiography


The More I Think
The More Confused I Get

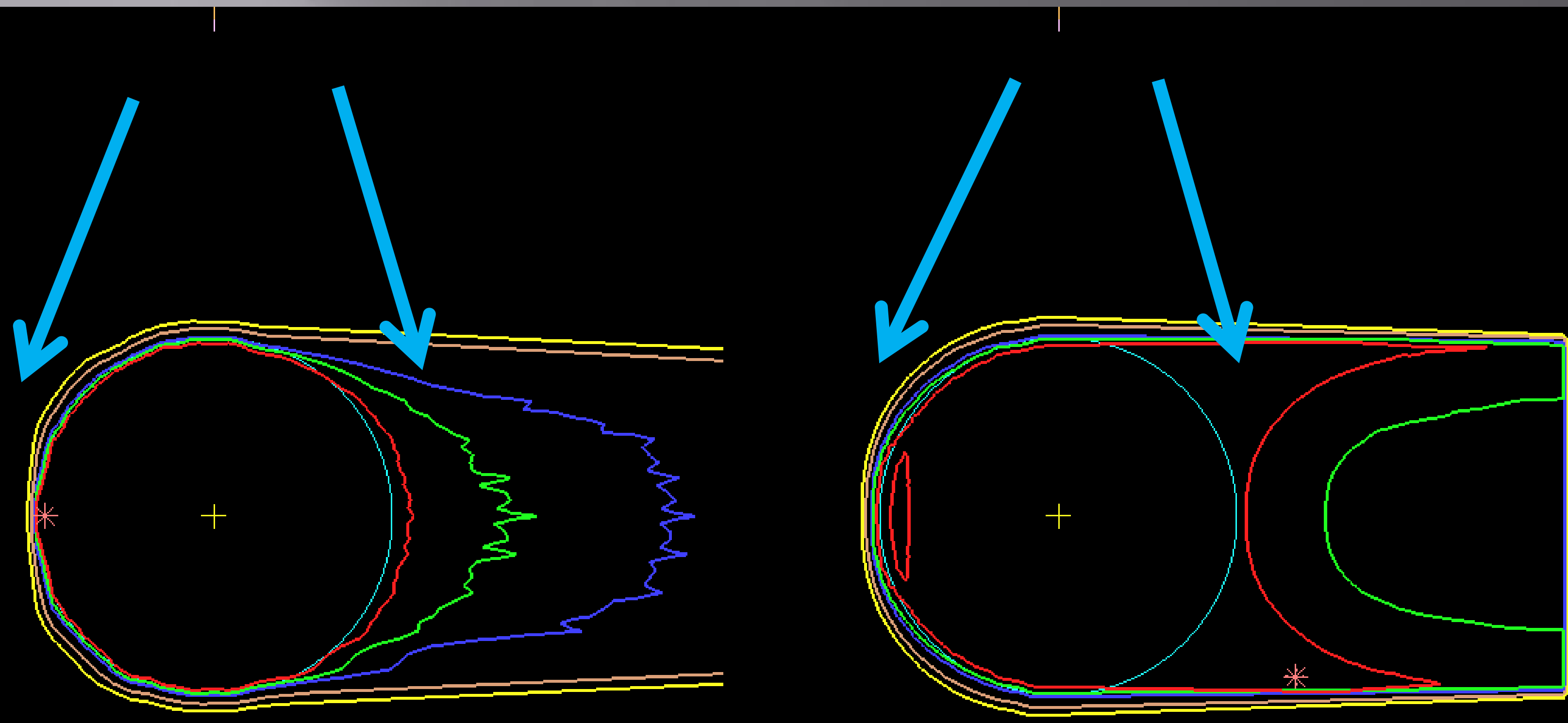
DS/US vs. PBS


Norm:Dose(1000.0 cGy = 100%)
ref pr
dc
global
local
Isovalues(%)
100.0
95.0
90.0
70.0
50.0

Advantage of a Compensator



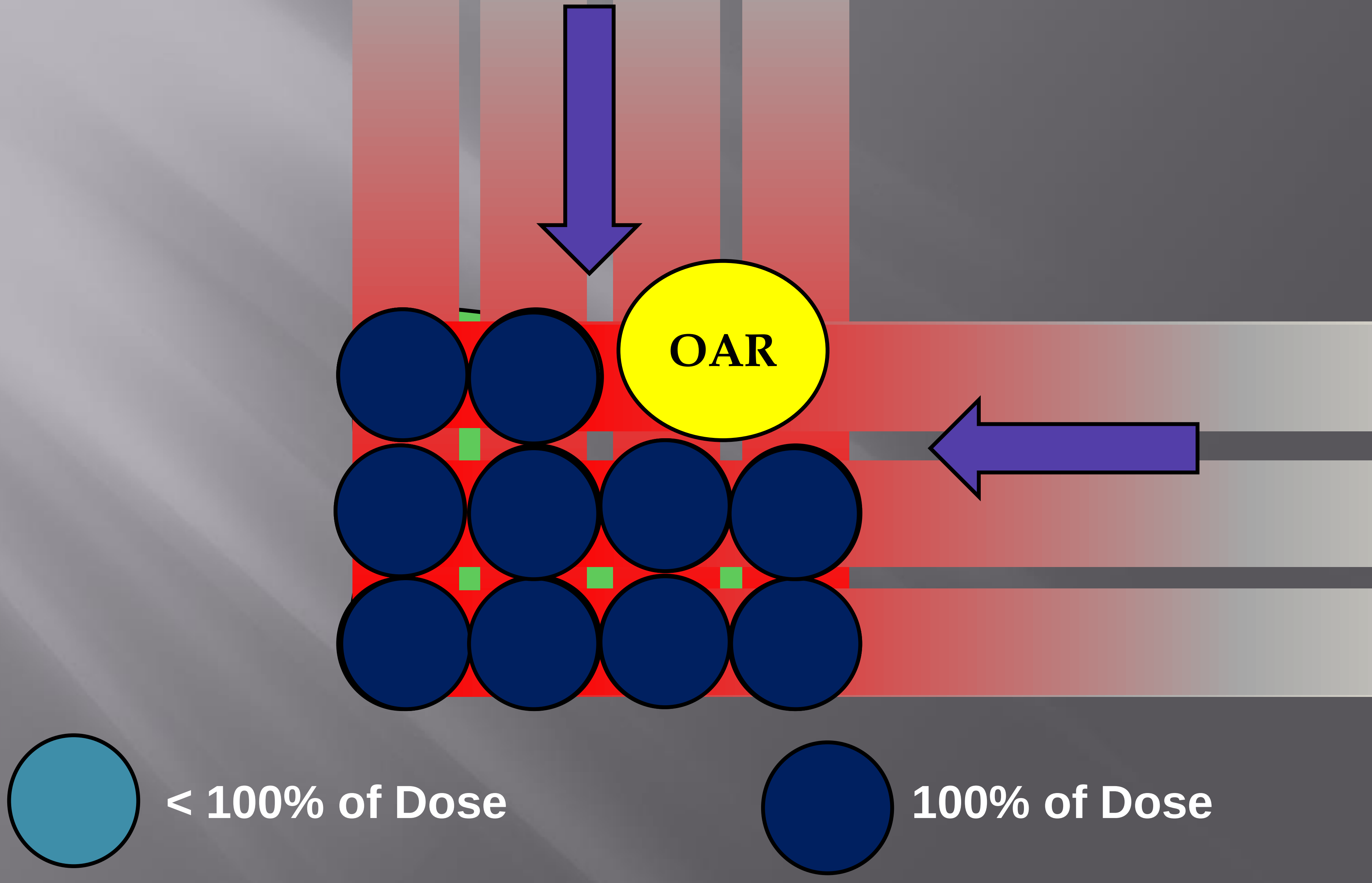
Advantage of PBS



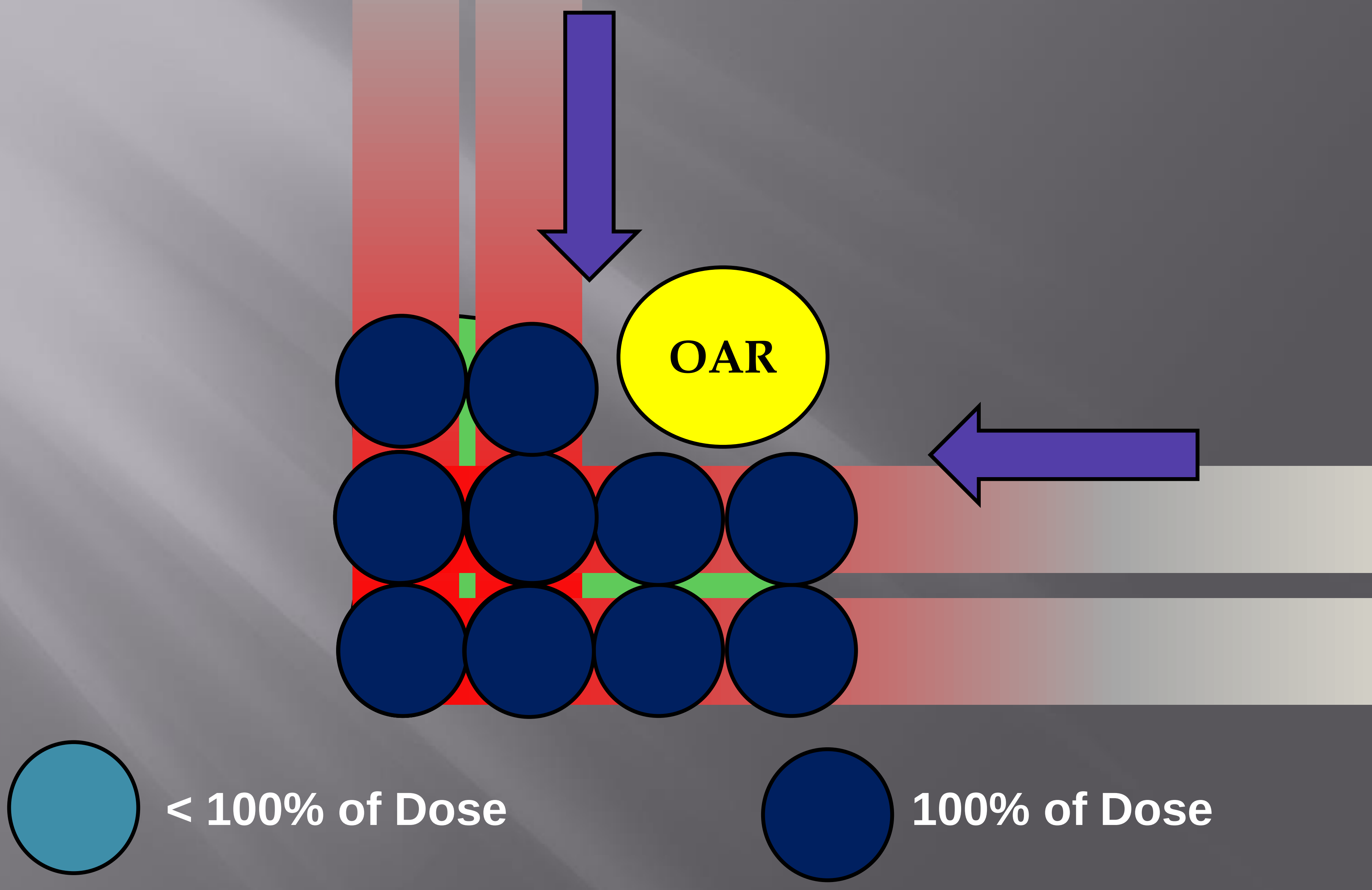
PBS

With Compensator

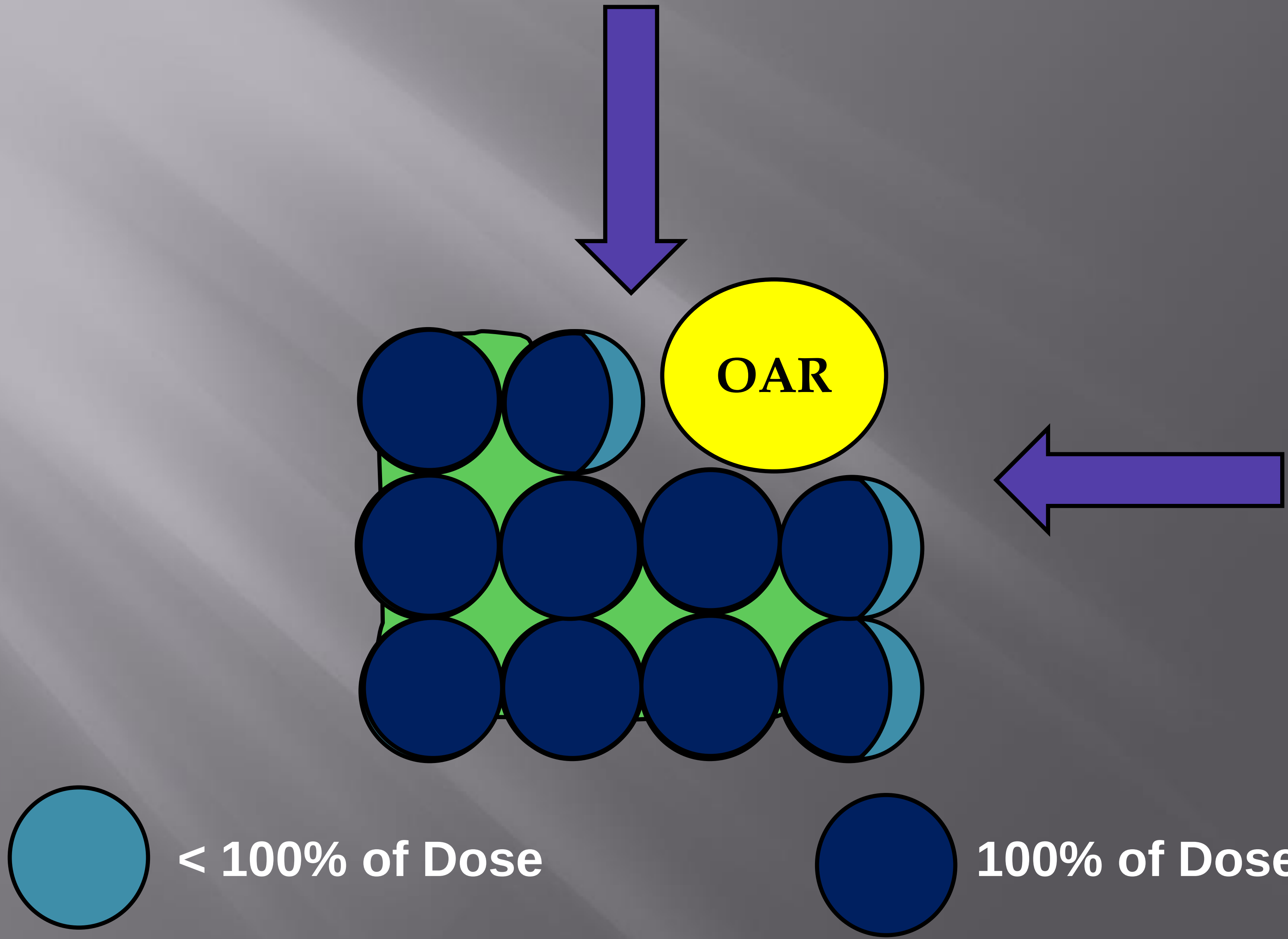
Single Field Uniform Dose



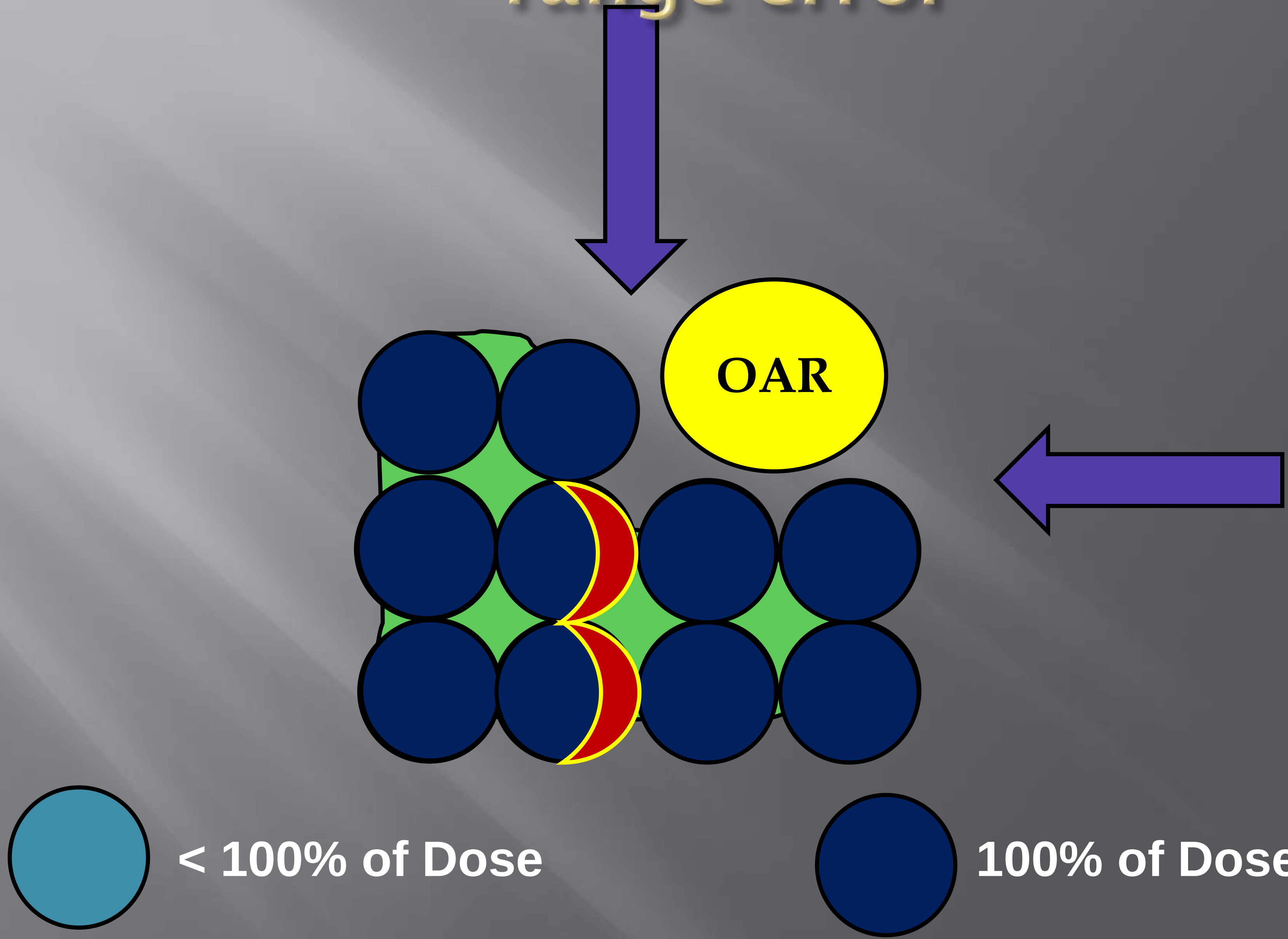
Multi-Field Optimized



SFUD with range error



Multi Field Optimized with a range error



So how can we quantity this?

Robustness analysis

- Move individual fields and recalculate
  - Mimic Set-up errors
- Re-assign shifted HU conversion curves and recalculate
  - Mimic HU conversion errors
- Move Target structures and recalculate
  - Mimic smearing

Is it too hard??
Should we give up??

No way !!

The true benefit of proton is in the difference in integral dose. Make the best of this !!

Where is the community putting efforts to improve proton planning??

- Faster layer switching
- Smaller and variable Spot Size
- Better understanding of Range Uncertainties
- Robustness tools for evaluations, probability DVH
- Robustness penalties included in optimization
- Robustness optimizations using in 4-D evaluations
- Streamlined Verification CT/plans
- Motivation to build strong proton protocols

Thanks You for listening!