Proton Treatment Planning: Double Scattering

Brian Winey, PhD
Physicist, MGH
Assistant Professor, HMS

MASSACHUSETTS GENERAL HOSPITAL
RADIATION ONCOLOGY
HARVARD MEDICAL SCHOOL

Conflict of Interest

- Funding received from NCI and Elekta.

Acknowledgements

- Many at MGH and MDACC

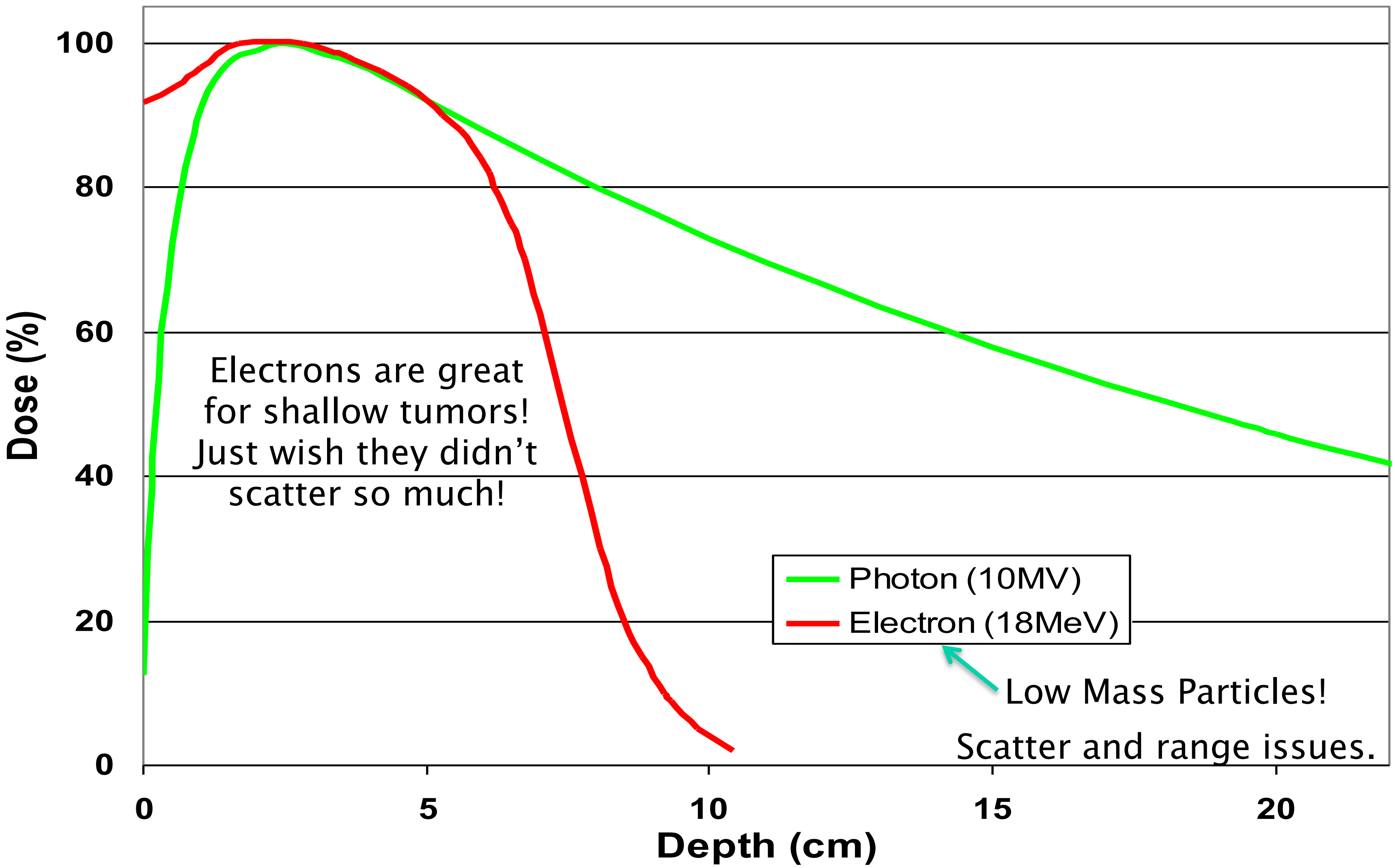
What is our goal?

1. Enough radiation to kill all the tumor cells
2. ZERO radiation to any non-tumor cells.

Particles are best!

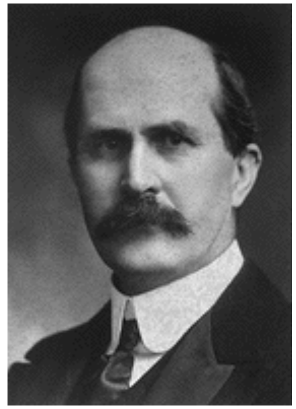
- But, who has a particle accelerator?

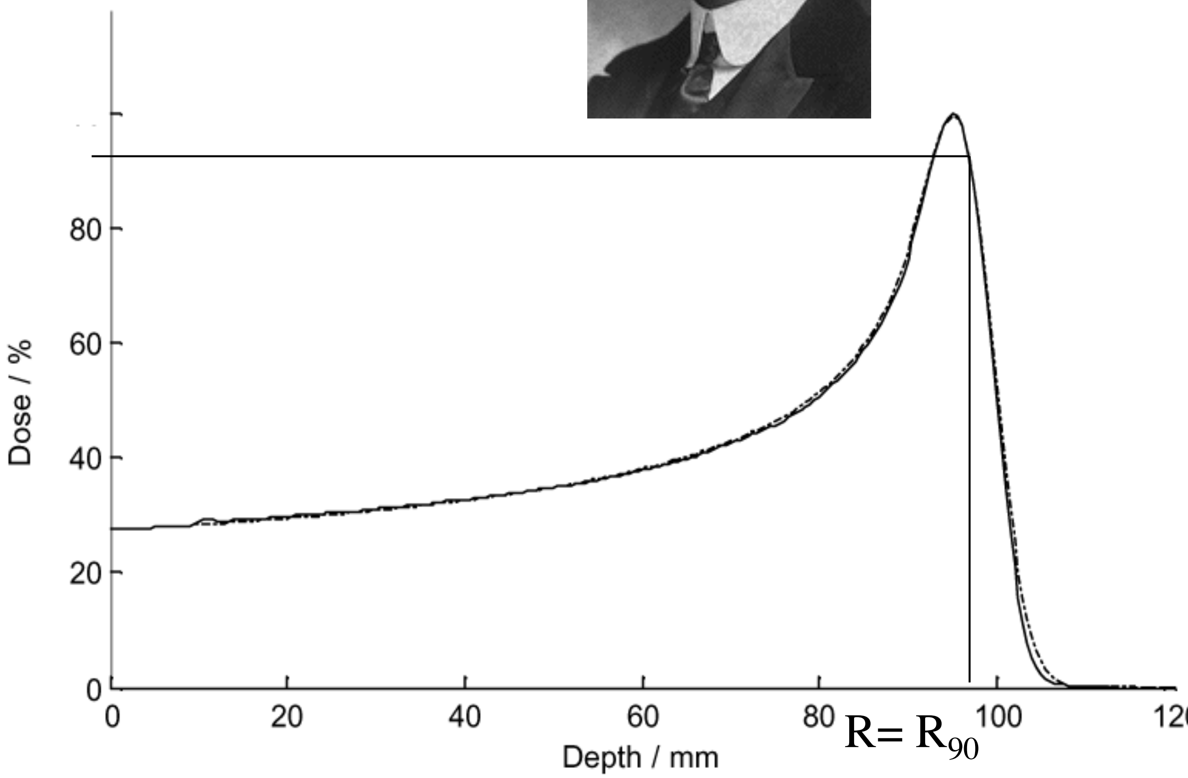
Photons and Electrons



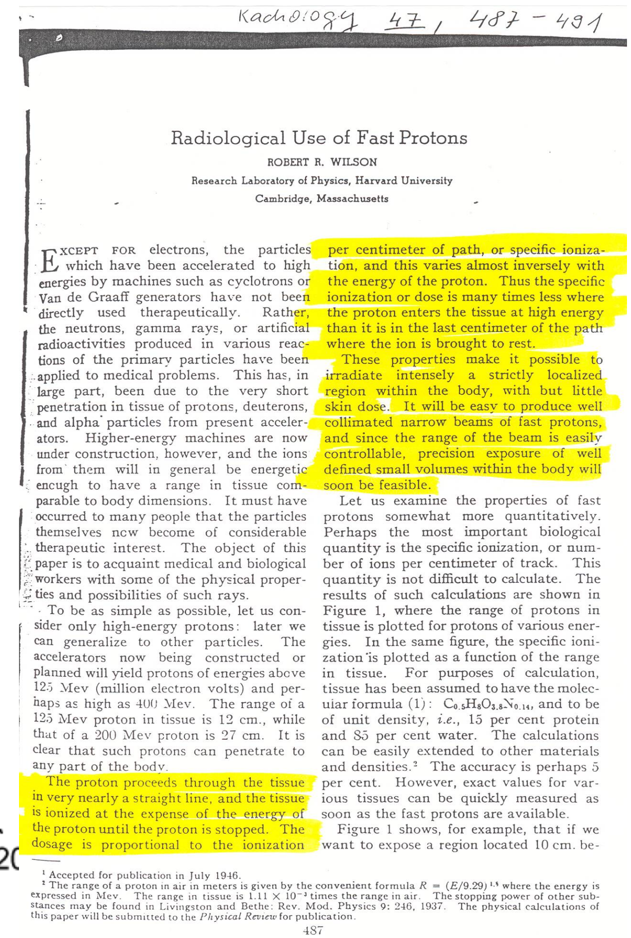
Bragg Peak

William Henry Bragg
1862-1942
Nobel Prize 1915





"Radiological Use of Fast Protons"
By Robert R. Wilson, Harvard,
1946, *Radiology*



Radiology 47, 487 - 491

Radiological Use of Fast Protons

ROBERT R. WILSON

Research Laboratory of Physics, Harvard University

Cambridge, Massachusetts

EXCEPT FOR electrons, the particles which have been accelerated to high energies by machines such as cyclotrons or Van de Graaff generators have not been directly used therapeutically. Rather, the neutrons, gamma rays, or artificial radioactivities produced in various reactions of the primary particles have been applied to medical problems. This has, in large part, been due to the very short penetration in tissue of protons, deuterons, and alpha particles from present accelerators. Higher-energy machines are now under construction, however, and the ions from them will in general be energetic enough to have a range in tissue comparable to body dimensions. It must have occurred to many people that the particles themselves now become of considerable therapeutic interest. The object of this paper is to acquaint medical and biological workers with some of the physical properties and possibilities of such rays.

To be as simple as possible, let us consider only high-energy protons: later we can generalize to other particles. The accelerators now being constructed or planned will yield protons of energies above 125 Mev (million electron volts) and perhaps as high as 400 Mev. The range of a 125 Mev proton in tissue is 12 cm., while that of a 200 Mev proton is 27 cm. It is clear that such protons can penetrate to any part of the body.

The proton proceeds through the tissue in very nearly a straight line, and the tissue is ionized at the expense of the energy of the proton until the proton is stopped. The dosage is proportional to the ionization per centimeter of path, or specific ionization, and this varies almost inversely with the energy of the proton. Thus the specific ionization or dose is many times less where the proton enters the tissue at high energy than it is in the last centimeter of the path where the ion is brought to rest.

These properties make it possible to irradiate intensely a strictly localized region within the body, with but little skin dose. It will be easy to produce well collimated narrow beams of fast protons, and since the range of the beam is easily controllable, precision exposure of well defined small volumes within the body will soon be feasible.

Let us examine the properties of fast protons somewhat more quantitatively. Perhaps the most important biological quantity is the specific ionization, or number of ions per centimeter of track. This quantity is not difficult to calculate. The results of such calculations are shown in Figure 1, where the range of protons in tissue is plotted for protons of various energies. In the same figure, the specific ionization is plotted as a function of the range in tissue. For purposes of calculation, tissue has been assumed to have the molecular formula (1): $C_{0.5}H_8O_{3.8}N_{0.14}$, and to be of unit density, *i.e.*, 15 per cent protein and 85 per cent water. The calculations can be easily extended to other materials and densities.[2] The accuracy is perhaps 5 per cent. However, exact values for various tissues can be quickly measured as soon as the fast protons are available.

Figure 1 shows, for example, that if we want to expose a region located 10 cm. be-

[1] Accepted for publication in July 1946.

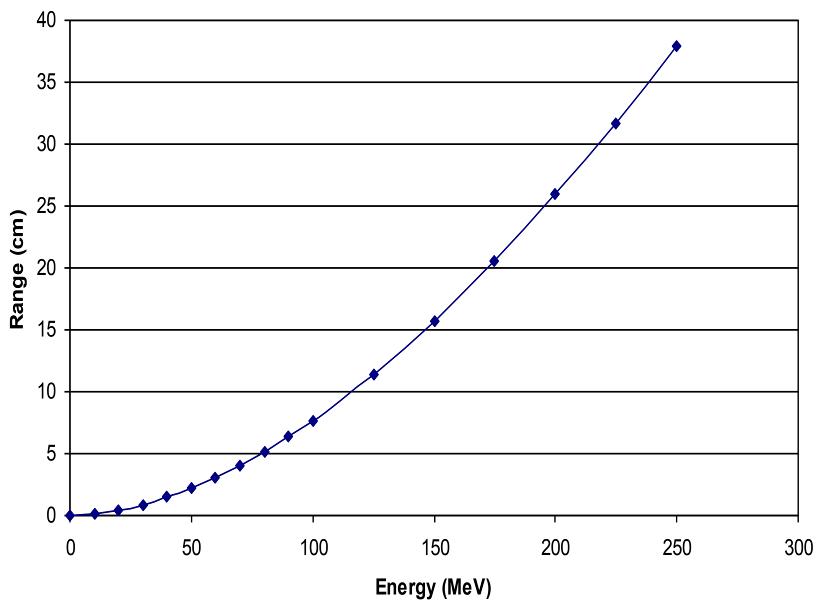
[2] The range of a proton in air in meters is given by the convenient formula $R = (E/9.29)^{1.5}$ where the energy is expressed in Mev. The range in tissue is 1.11×10^{-3} times the range in air. The stopping power of other substances may be found in Livingston and Bethe: Rev. Mod. Physics 9: 246, 1937. The physical calculations of this paper will be submitted to the *Physical Review* for publication.

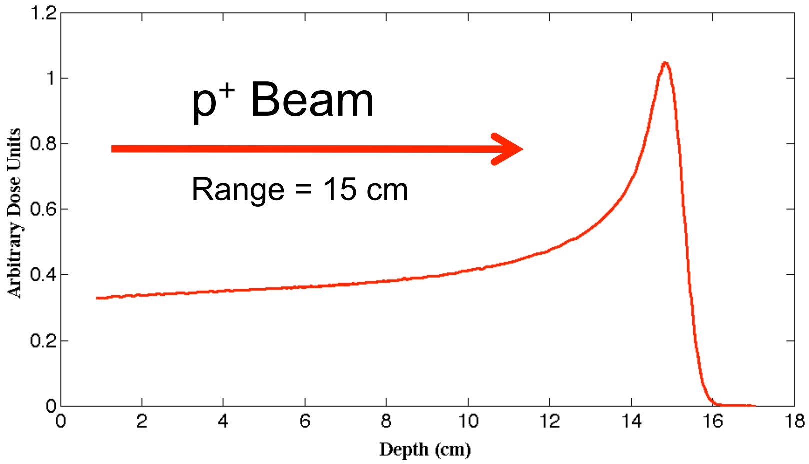
Stanley Rosenthal, Ph.D.

Bragg Peak

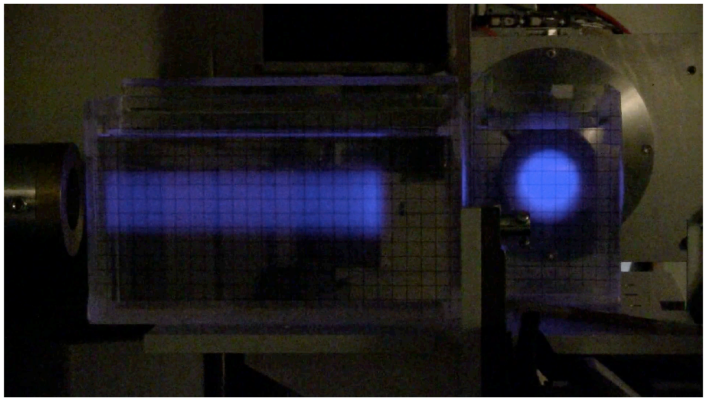
- Bethe-Bloch Equation
- Energy dependent range

Source: NIST database

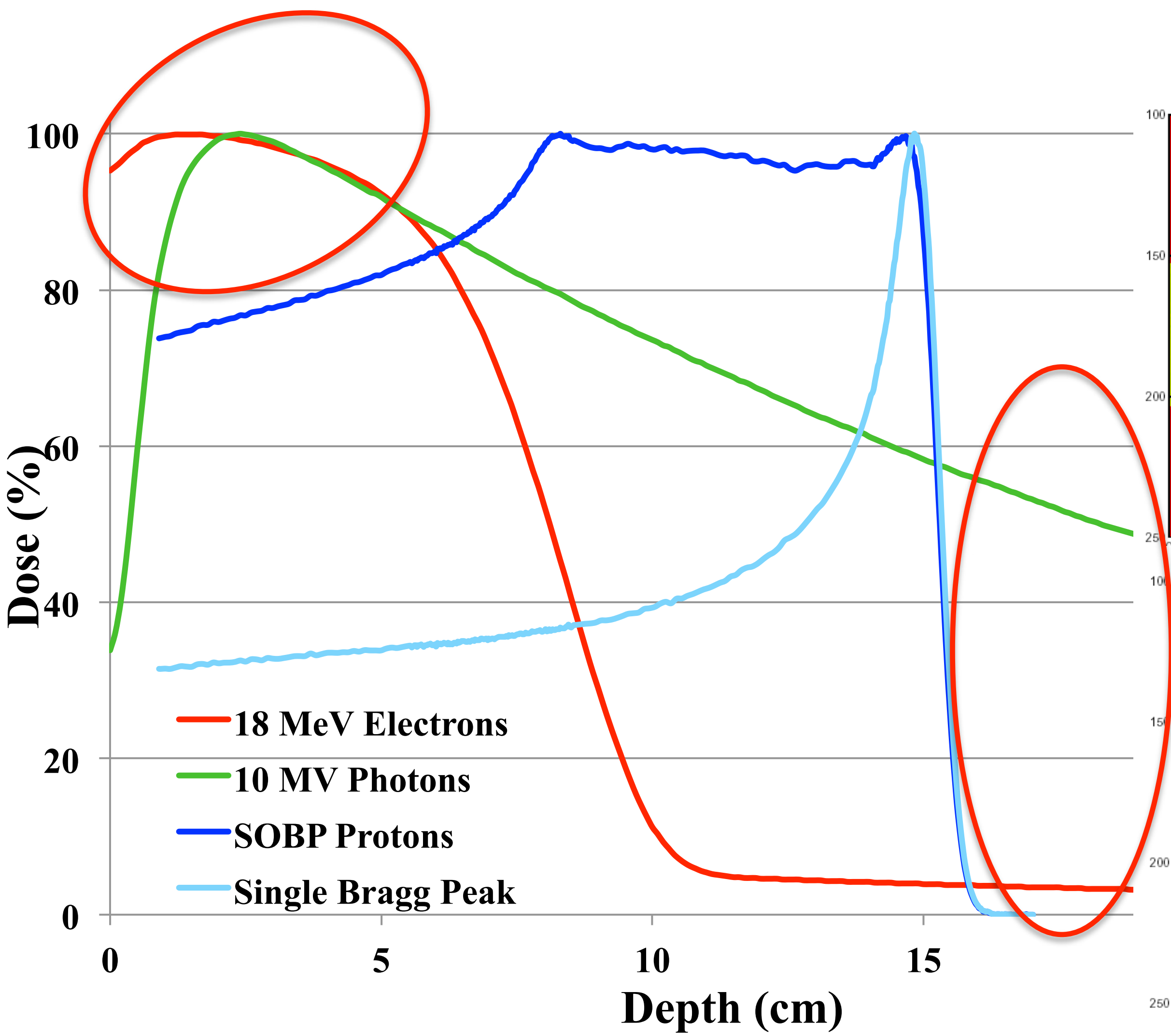


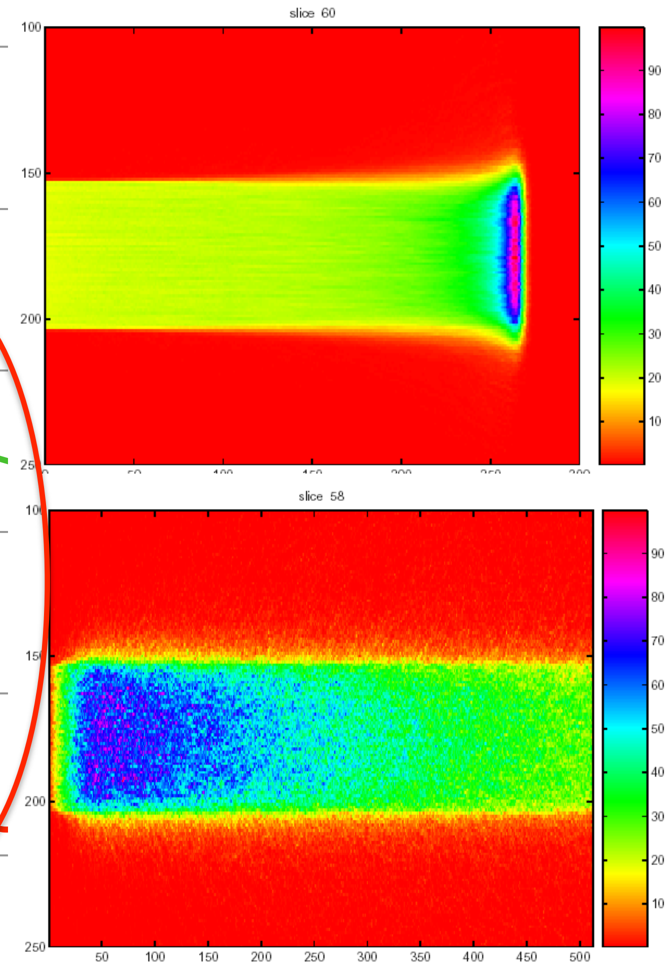


Scintillation Image

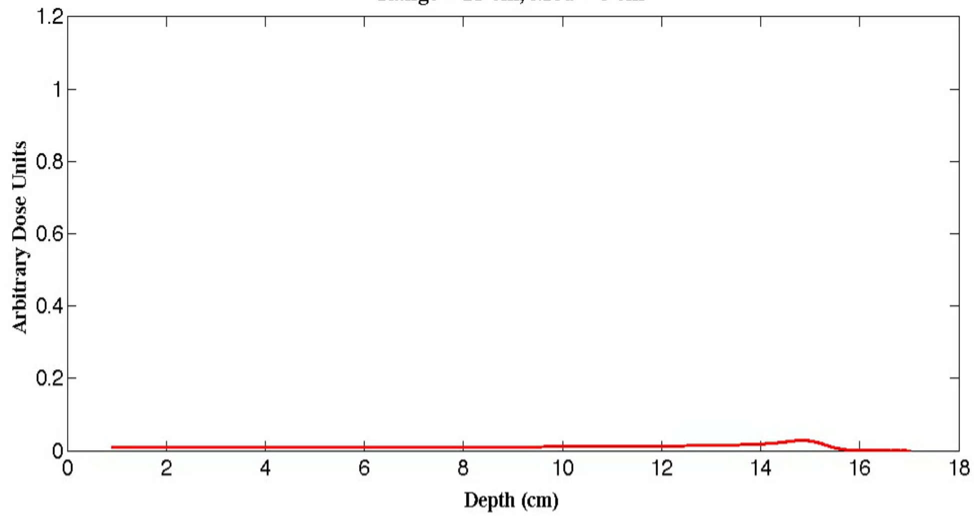


Dose Comparisons

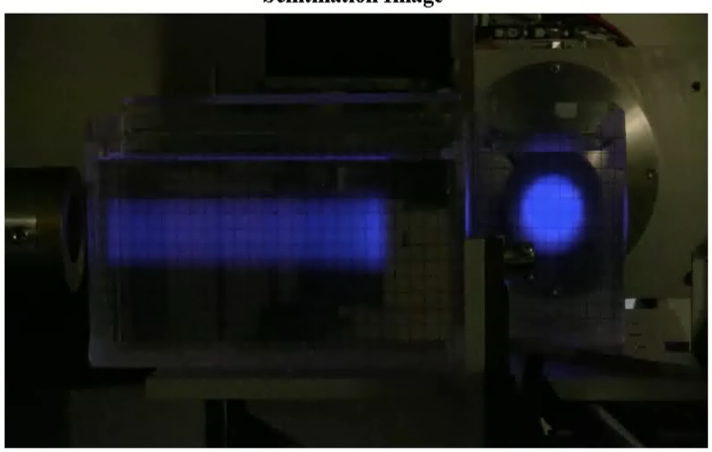




Spread Out Bragg Peak (SOBP)

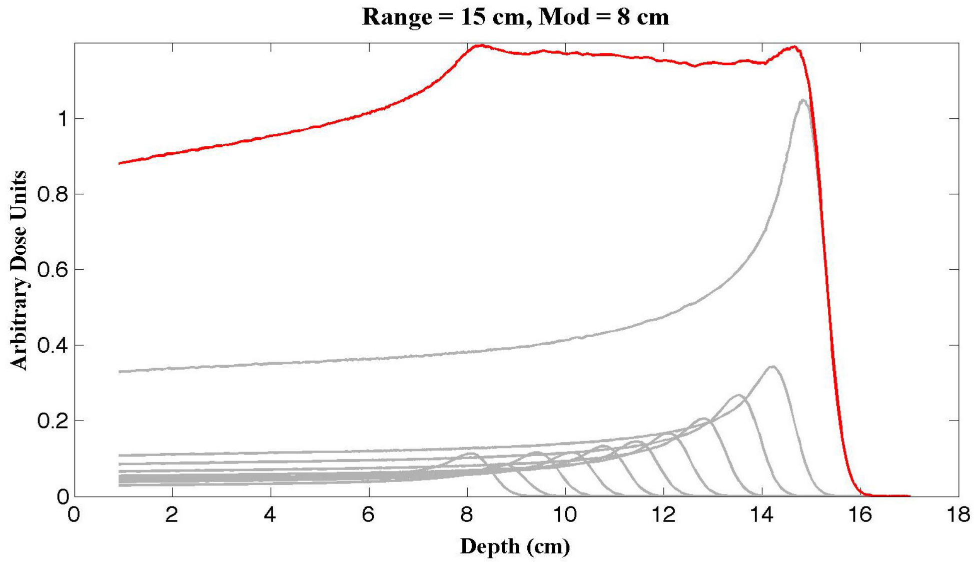


Scintillation Image



- Multiple Methods to Create SOBP (Doesn't have to be flat!)
- Need an energy modulation system
- Synchrotron
- Binary absorbers systems
- Modulator Wheels
- Energy selection systems
- Reams of paper
- Legos
- Etc.

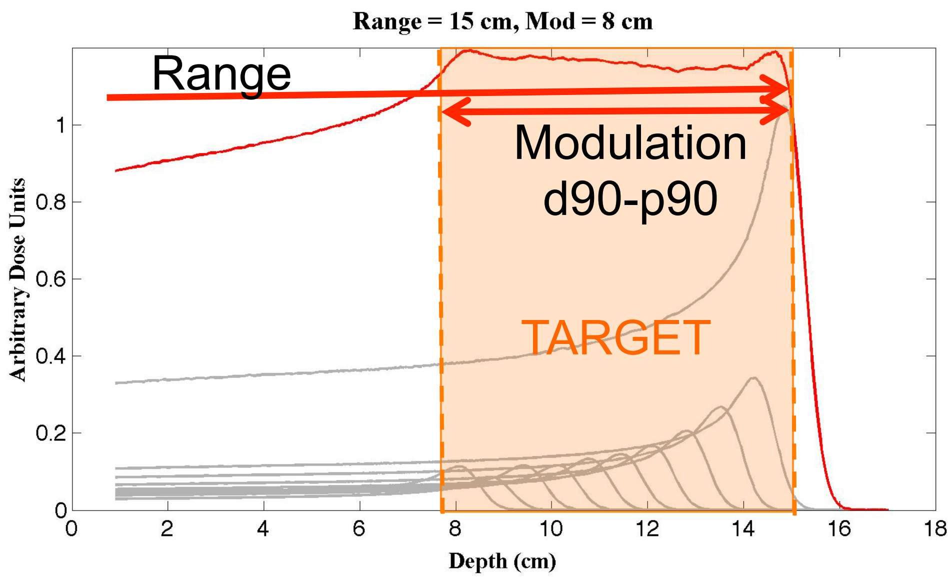
Spread Out Bragg Peak (SOBP)



Scintillation Image

- Multiple Methods to Create SOBP (Doesn't have to be flat!)
- Need an energy modulation system
- Synchrotron
- Binary absorbers systems
- Modulator Wheels
- Energy selection systems
- Reams of paper
- Legos
- Etc.

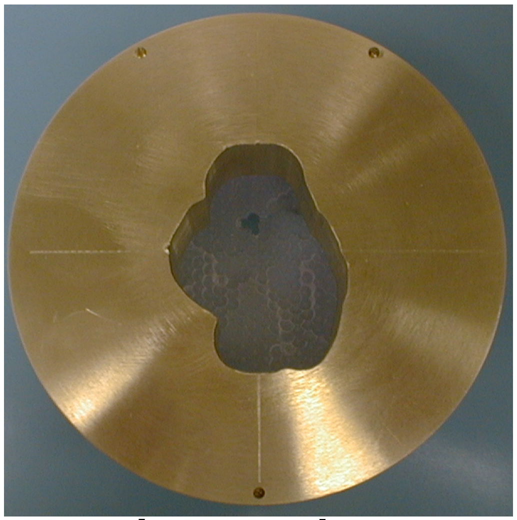
Patient Specific Target



Works great for cube shaped tumors!

Patient and field specific hardware

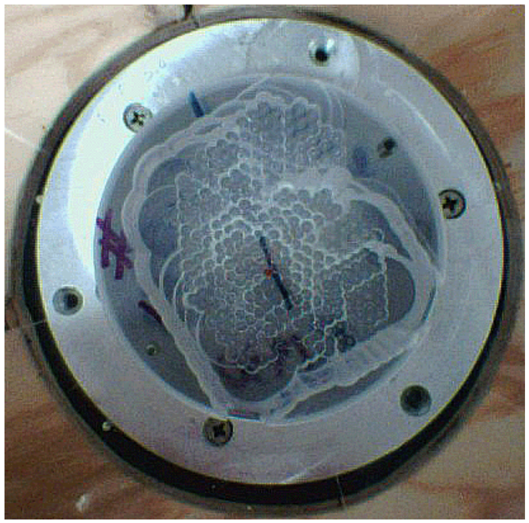
Aperture



Lateral conformation

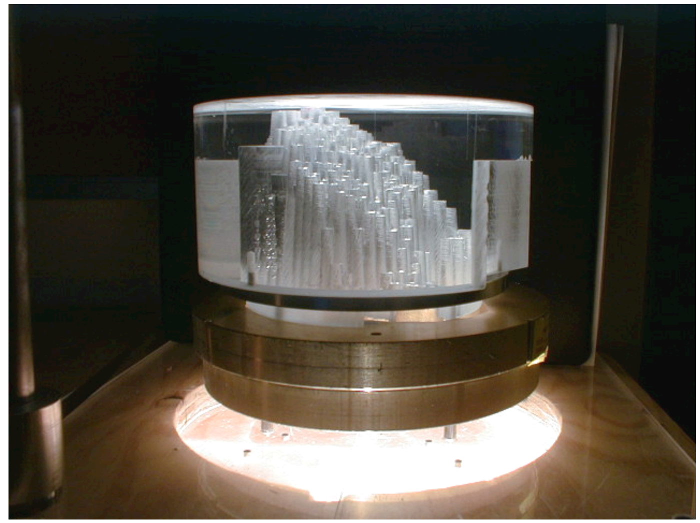
+

Range Compensator



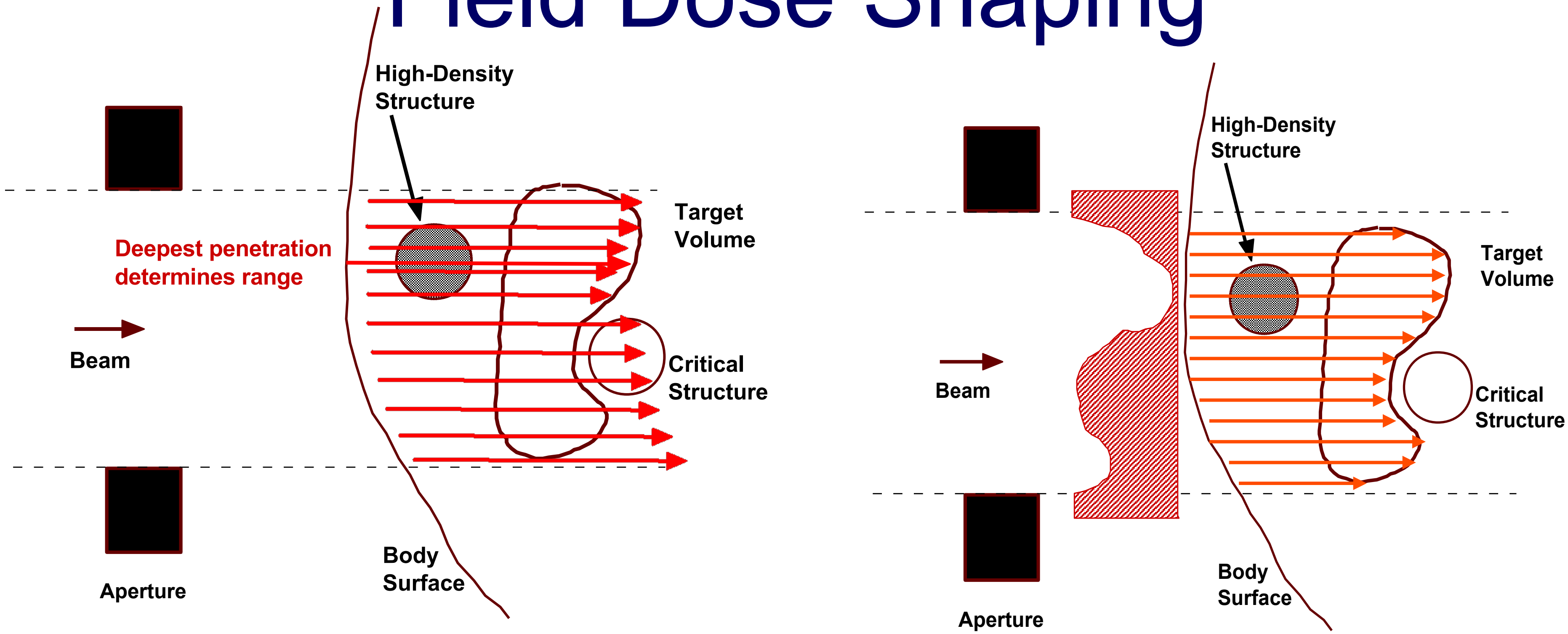
Distal conformation

=

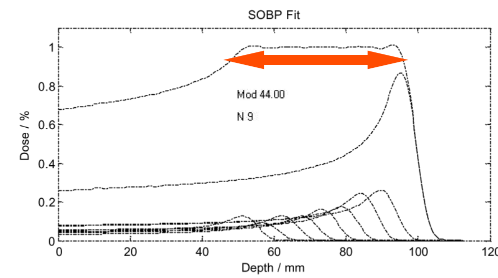


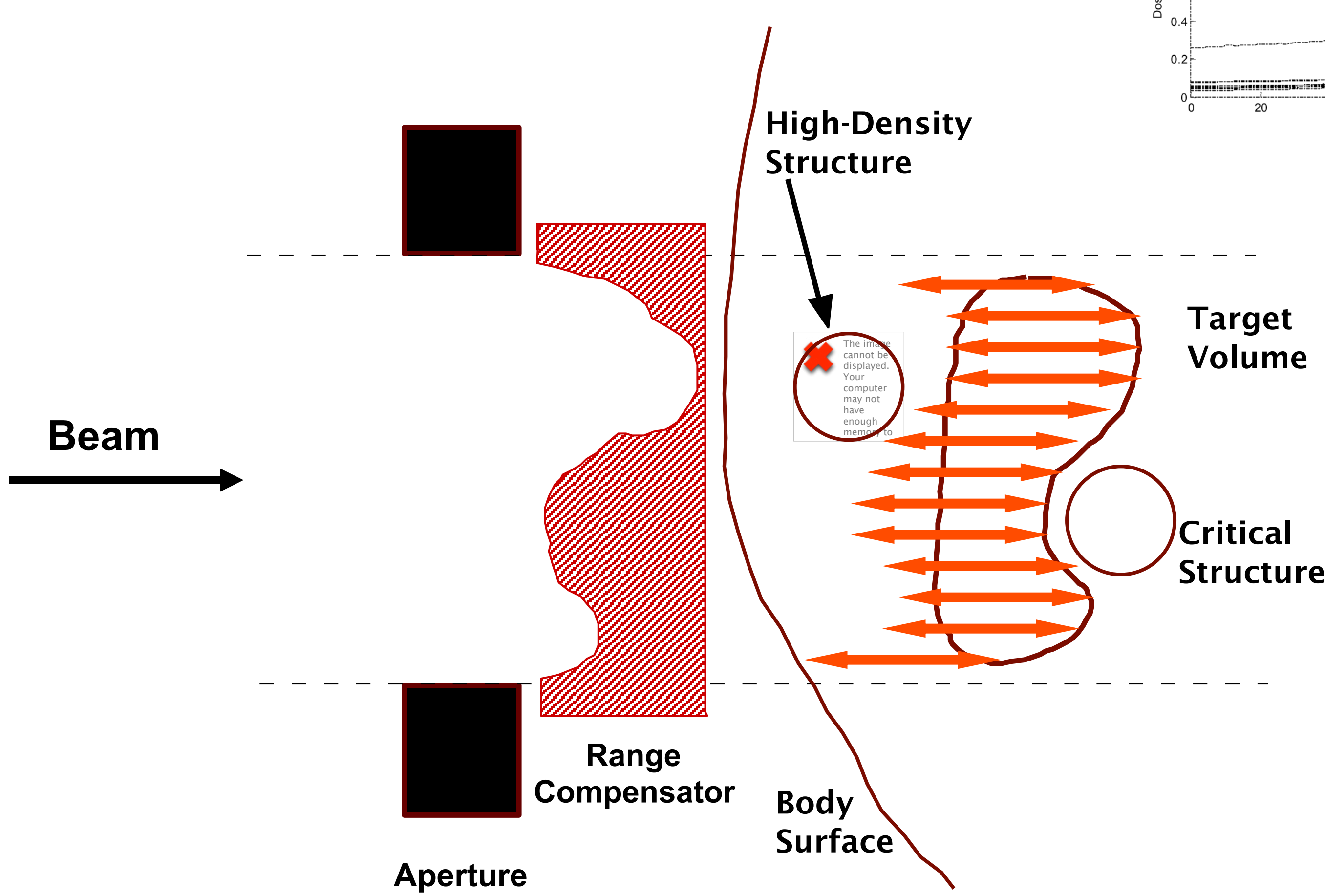
Martijn Engelsman, Ph.D.

Field Dose Shaping



Field specific dose delivery

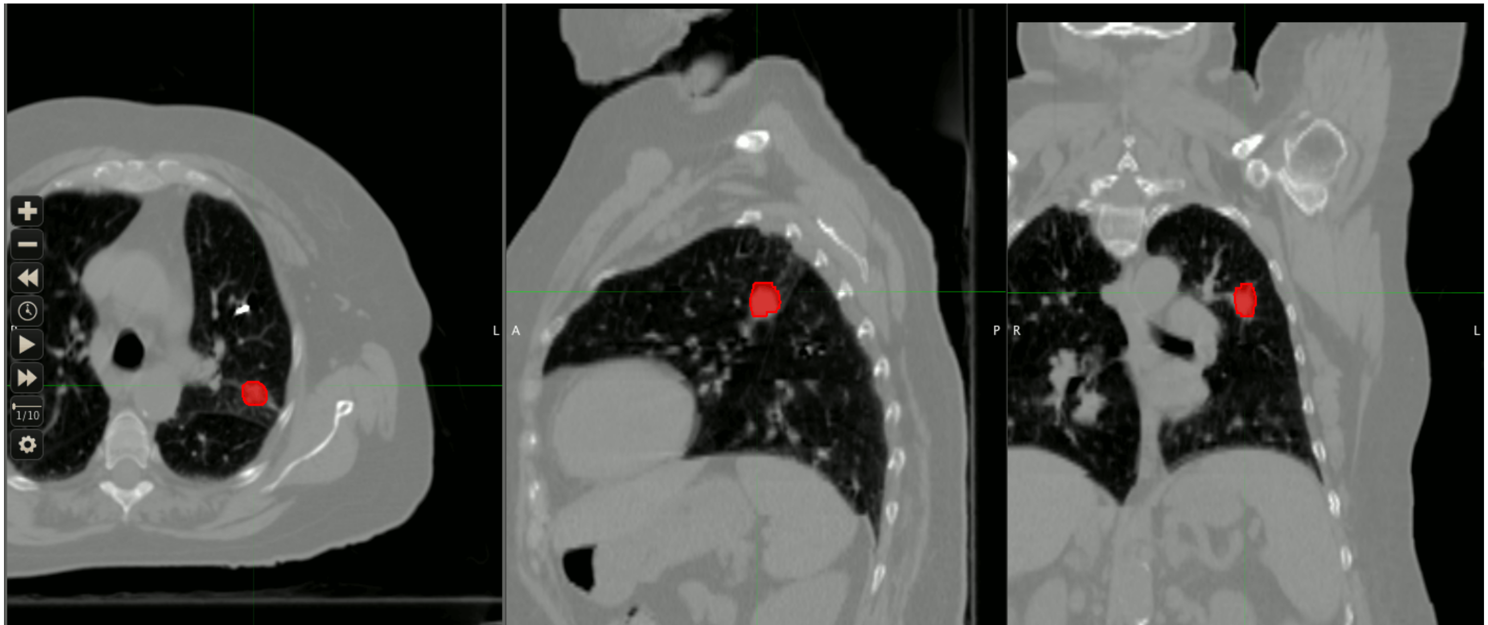


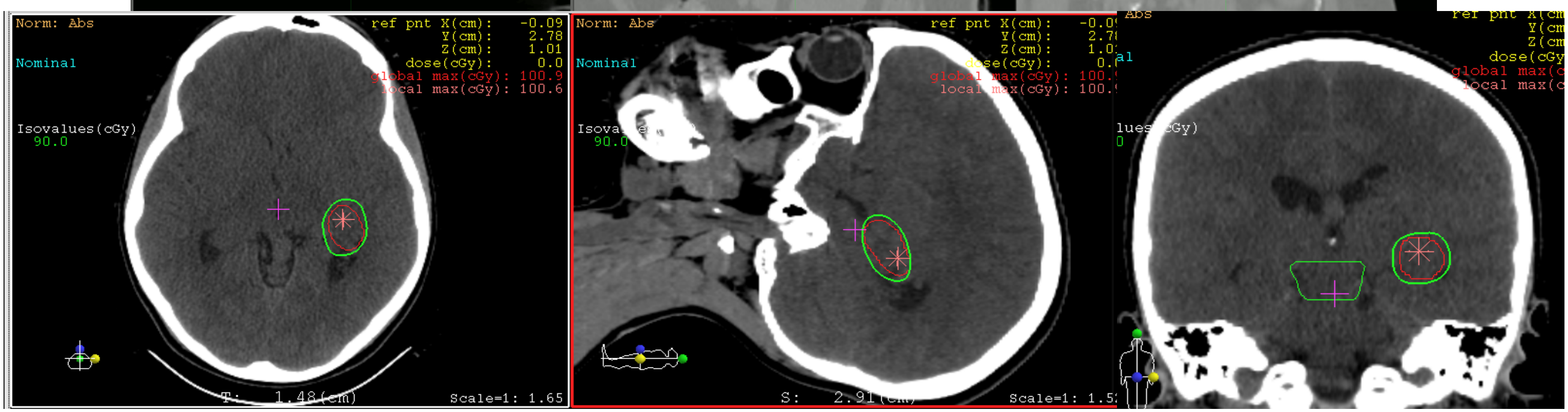


Martijn Engelsman, Ph.D.

Therefore…

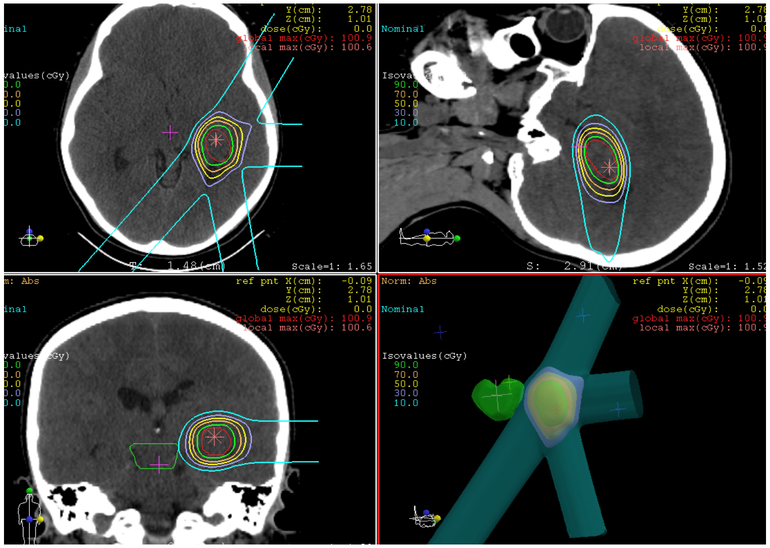
Perfect Radiation Treatment!

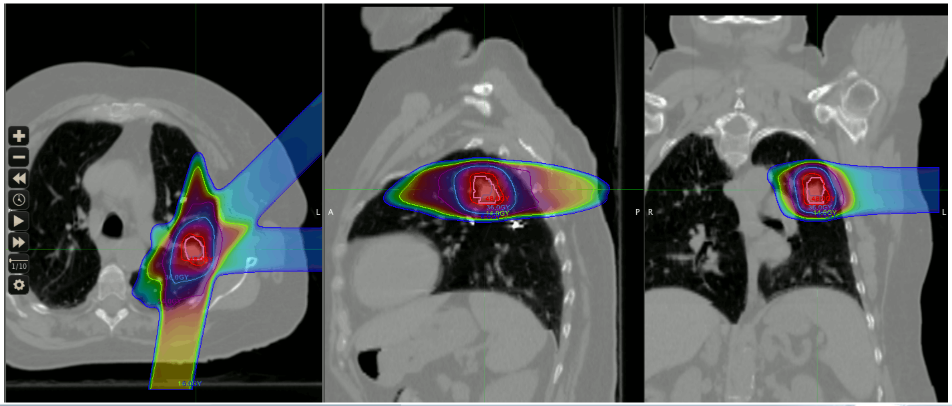




Not the whole story…

- Uncertainties!
  - Range:
    - Physics
    - Anatomy
    - Setup
    - CT
    - Motion
  - Scattering
  - Calibrations





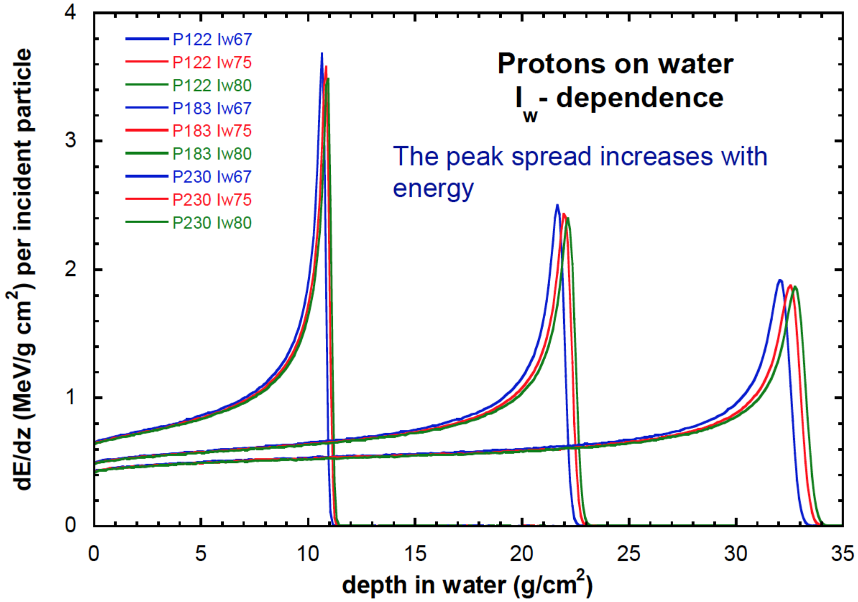
Range Uncertainties:

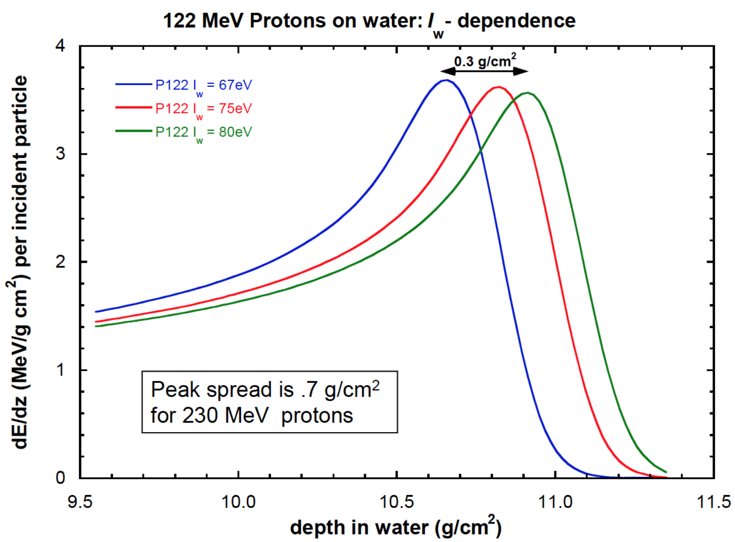
Source of range uncertainty in the patient Estimates excluding worst cases!	Range uncertainty without Monte Carlo [% or mm]	Range uncertainty with Monte Carlo [% or mm]
Independent of dose calculation:		
Measurement uncertainty in water for commissioning	± 0.3 mm	± 0.3 mm
Compensator design	± 0.2 mm	± 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% [f]	+ ~0.8% [f]
CT imaging and calibration	± 0.5%	± 0.5%
CT conversion to tissue (excluding I-values)	± 0.5% [a]	± 0.2% [c]
CT grid size	± 0.3%	± 0.3%
Mean excitation energy (I-values) in tissues	± 1.5% [b]	± 1.5% [b]
Range degradation; complex inhomogeneities (negative)	- 0.7% [d]	± 0.1 %
Range degradation; local lateral inhomogeneities *	± 2.5% [e]	± 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

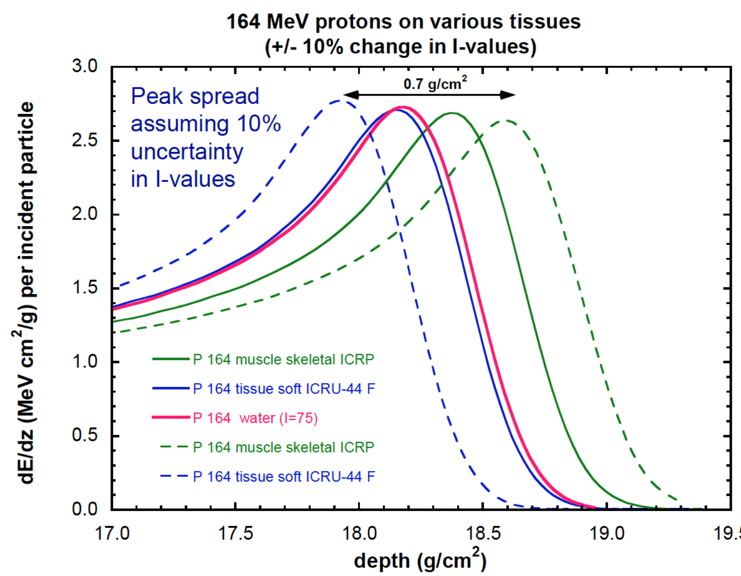
Paganetti *et al.*

[a] (Schaffner and Pedroni, 1998)
[b] (ICRU, 1993; Bichsel and Hiraoka, 1992; Kumazaki *et al.*, 2007)
[c] (Espana Palomares and Paganetti, 2010)
[d] (Sawakuchi *et al.*, 2008; Bednarz *et al.*, 2010; Urie *et al.*, 1986)
[e] (Bednarz *et al.*, 2010)
[f] (Paganetti and Goitein, 2000; Robertson *et al.*, 1975; Wouters *et al.*, 1996)

I-Value→**SPR**←HU



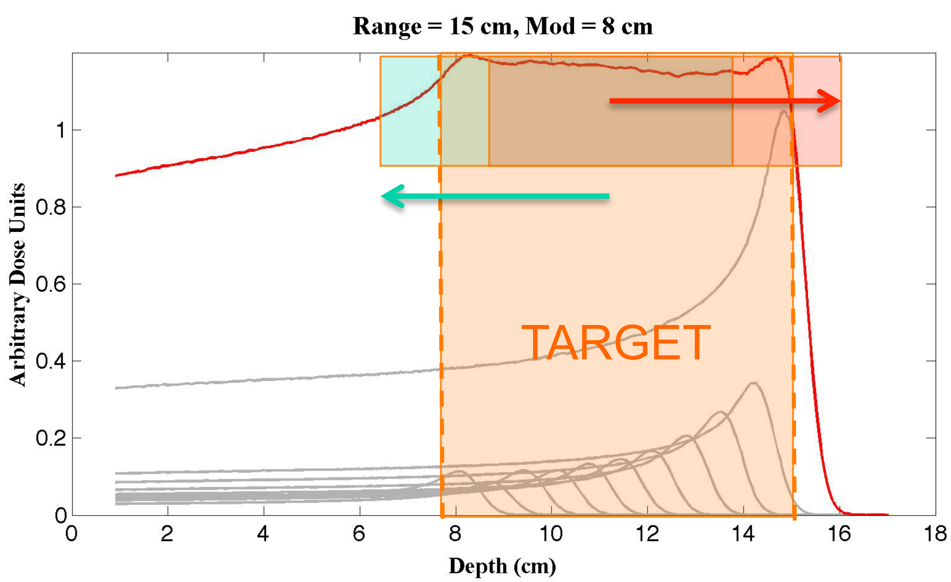




Need SPR measurements!

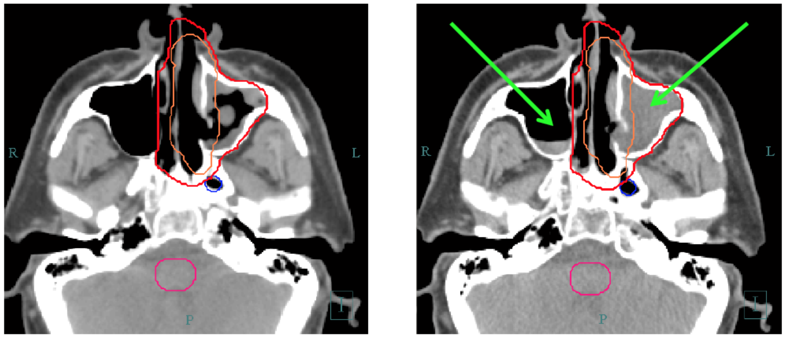
P Andreo, Phys Med Biol, 2009

Downside of Distal Edge



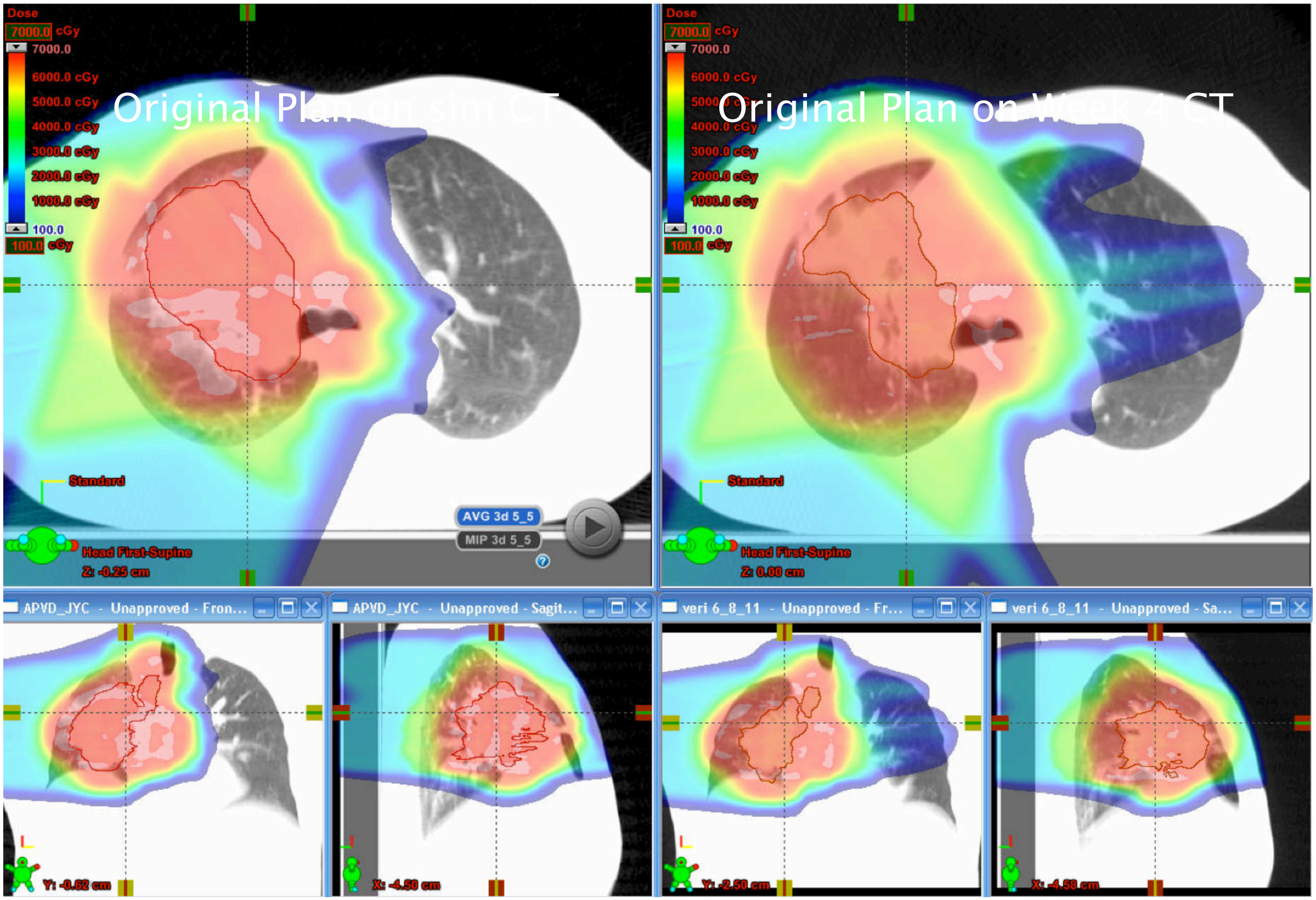
Proton range changes

- Breathing motion
- Lung density changes
  - Sub-clinical pneumonitis
- Patient weight gain / loss
- Fluids in sinuses
- Non-reproducible arm positions
- Setup Uncertainties



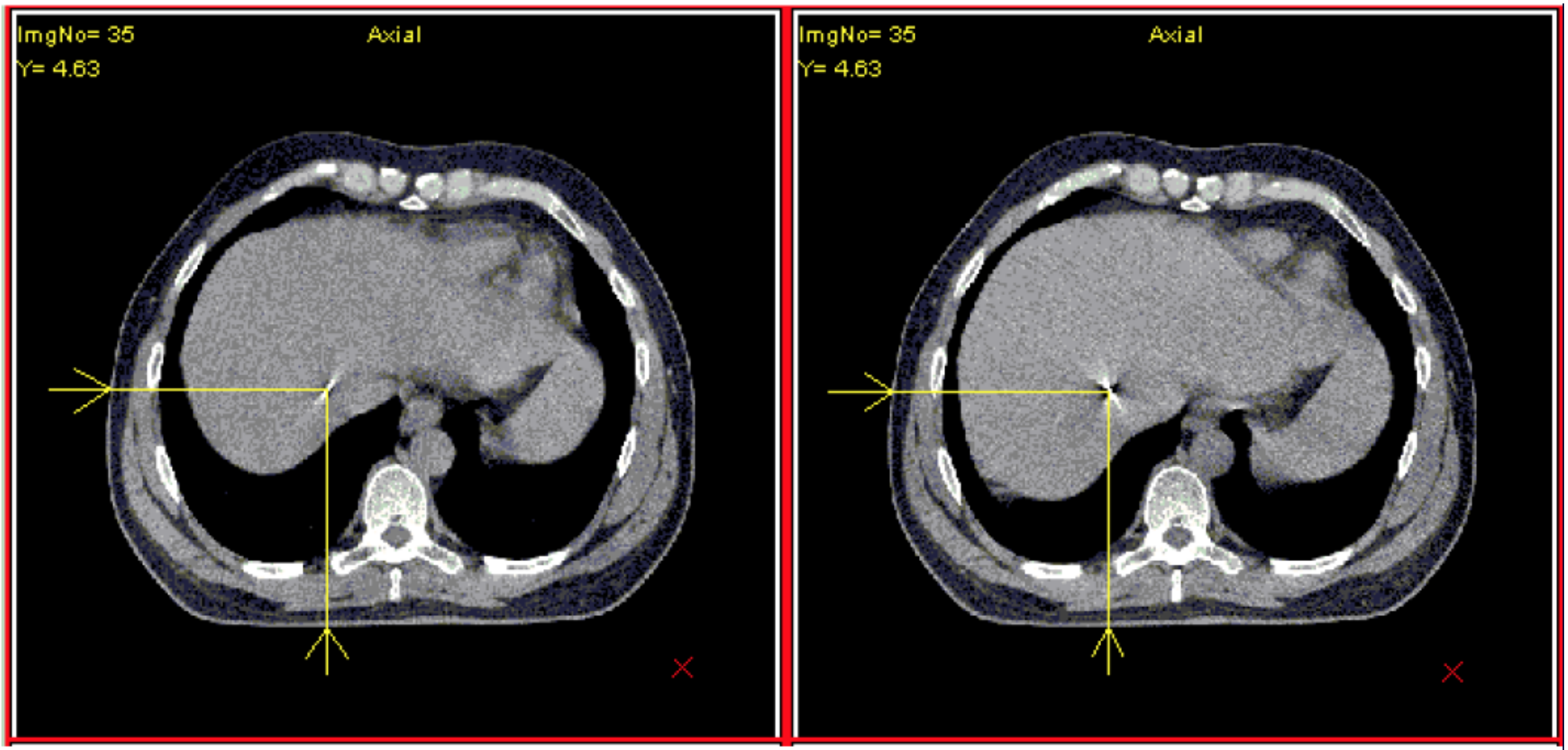
Lei Dong, Ph.D.

Large Lung Tumors Can Shrink During Treatment



Lei Dong, MDACC, Weekly 4D-CT

Range Variations with Breathing



0% Phase

RL D=11.18 R=10.68
PA D=12.28 R=8.75

50% Phase

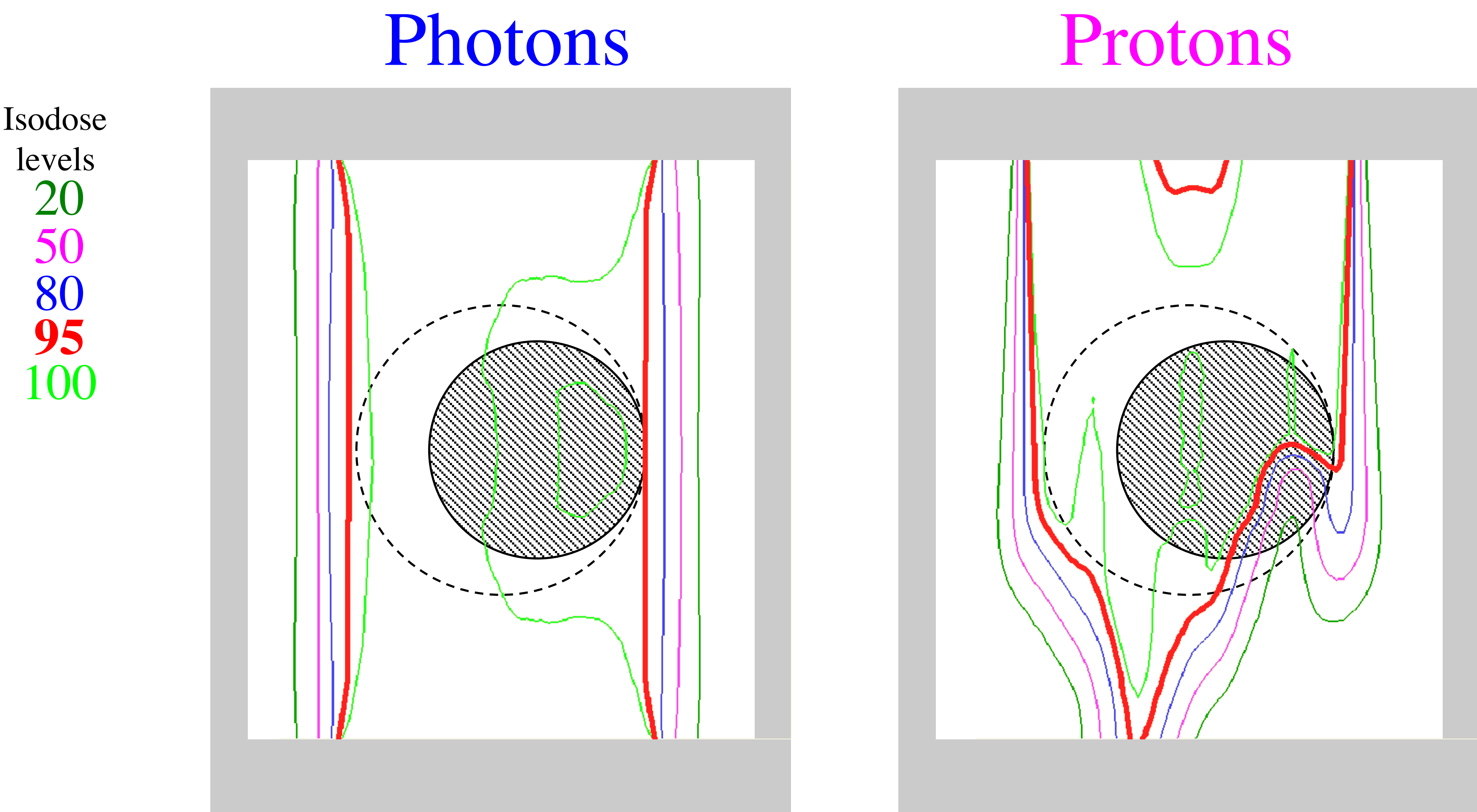
RL D=11.20 R=10.96
PA D=12.21 R=10.01

H-M. Lu, Ph.D.

Chest Wall thickness varies during respiration affecting a large region

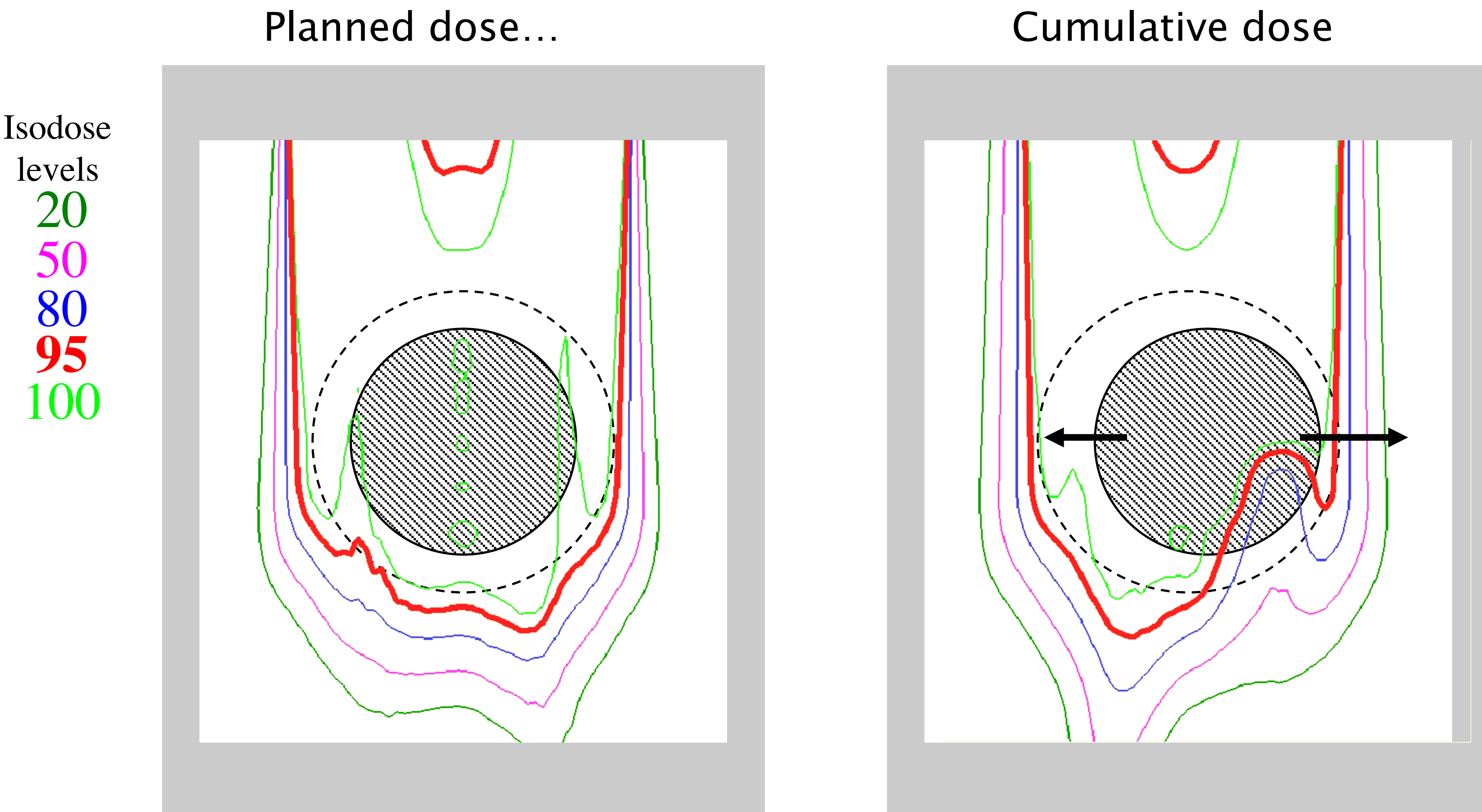
GTY Chen, Ph.D.

Radiotherapy in lung

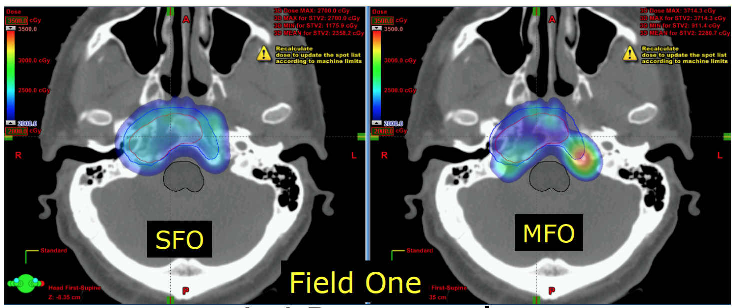


Martijn Engelsman, Ph.D.

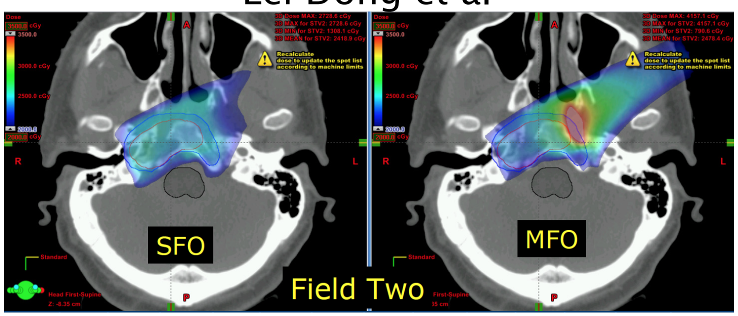
Range sensitivity



Intrafractional Motion

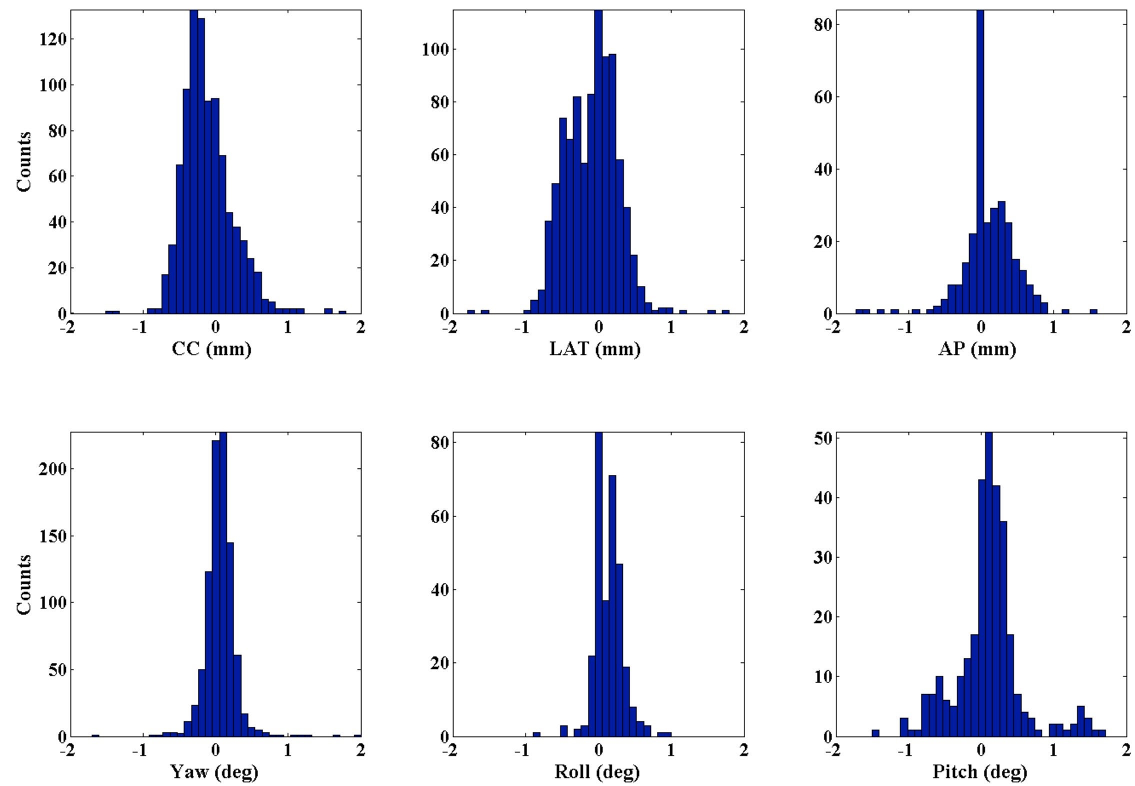


Lei Dong et al

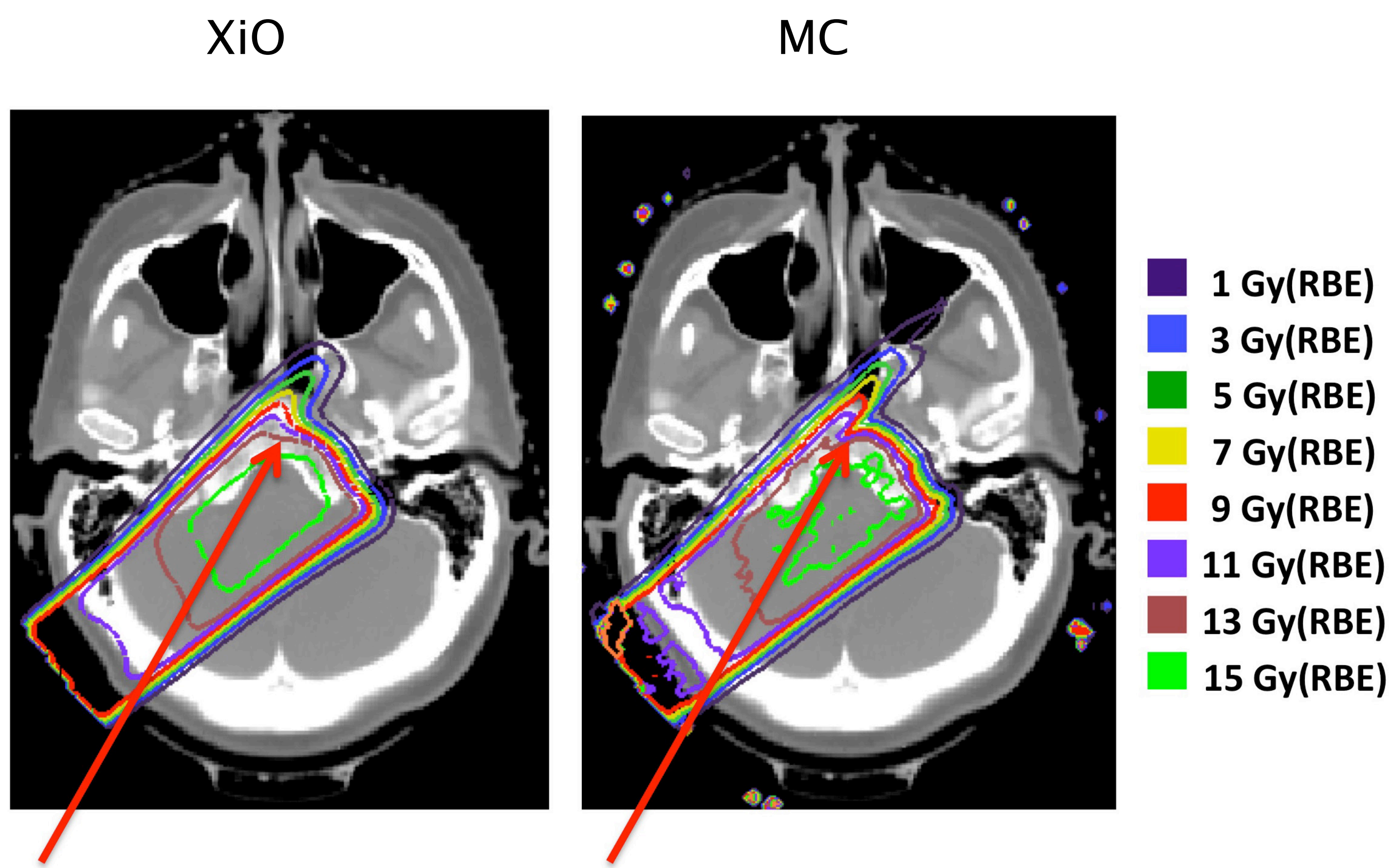


Impact on MFO Planning?

Cranial Intrafractional Motion



Setup Uncertainty



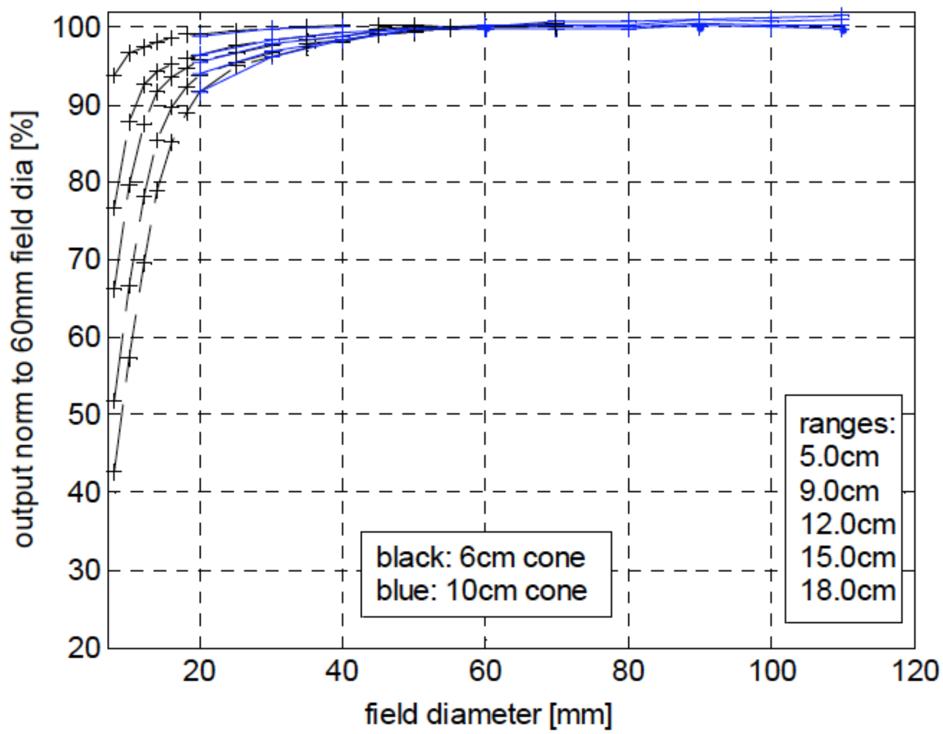
(Paganetti *et al.*, 2008)

Perils Due to MCS

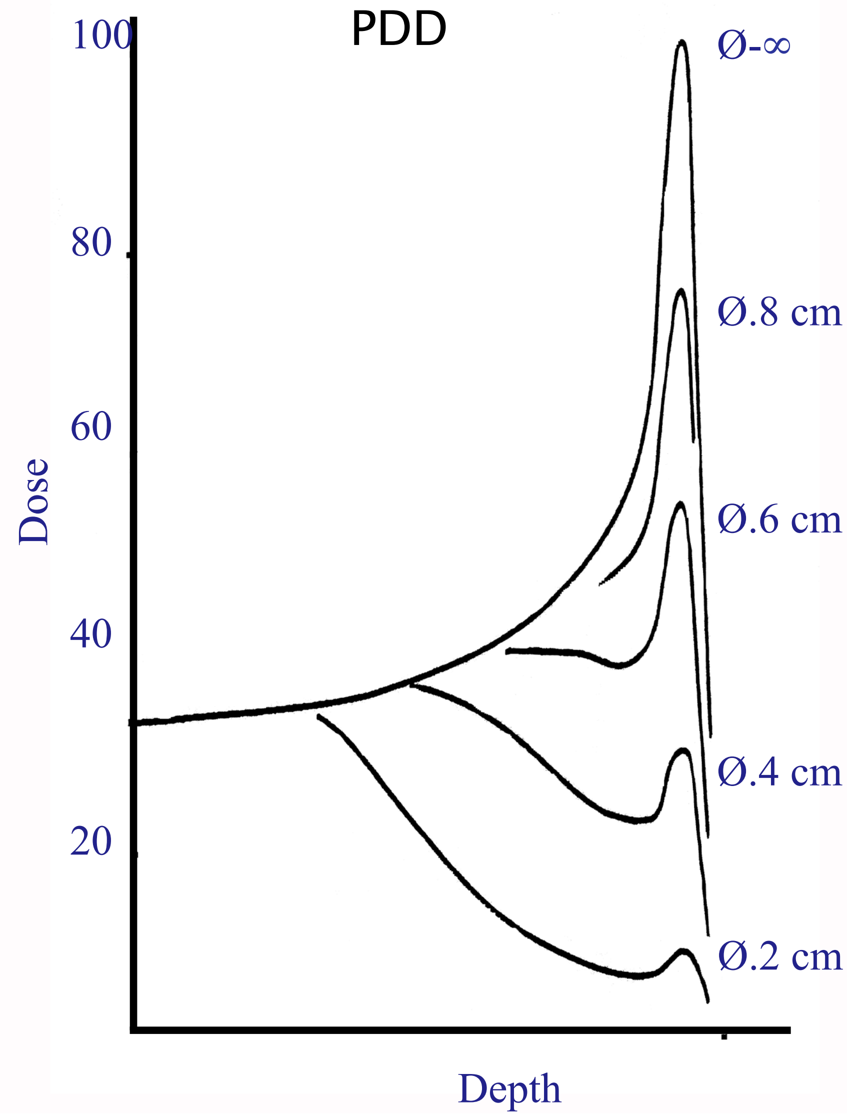
- Range Uncertainties, especially along a heterogeneous boundary
- Motion Uncertainties in Heterogeneous Materials
- Differences in Output, PDD, and Penumbra compared to Photons

Field Size Effects: MCS

Output



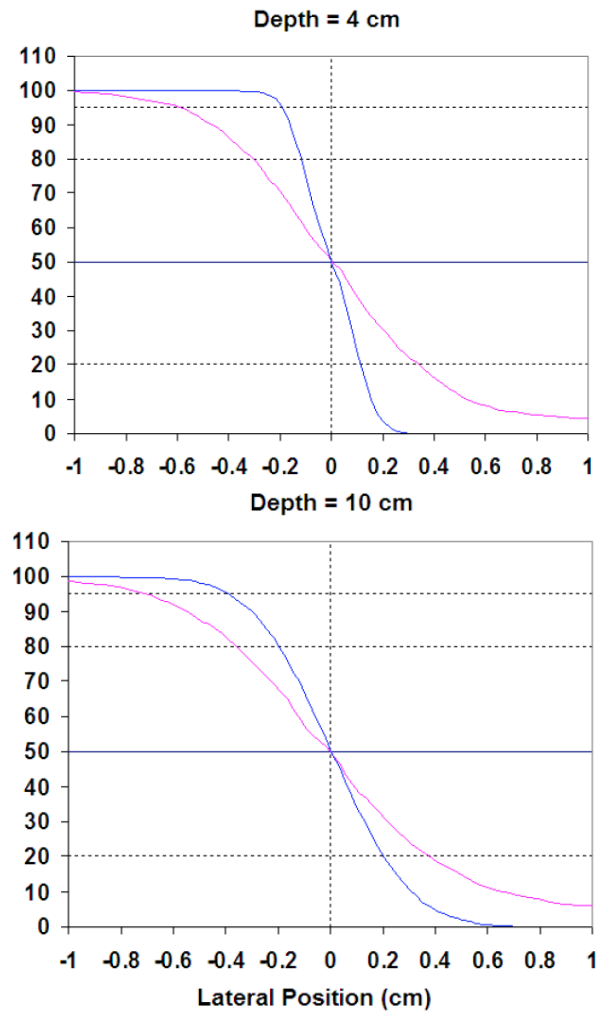
Greatest effects: Large Depth, Small Field



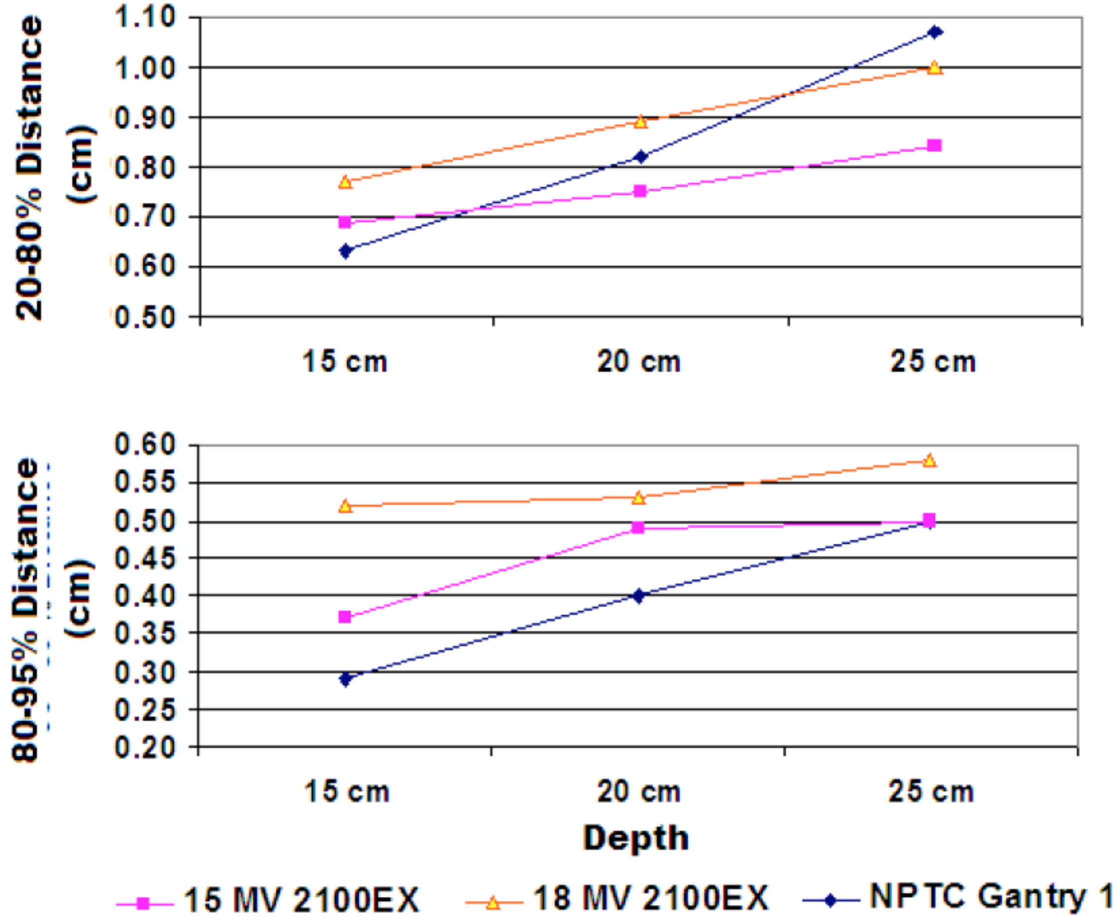
J. Daartz, MGH

Preston & Kohler, Harvard

Penumbra

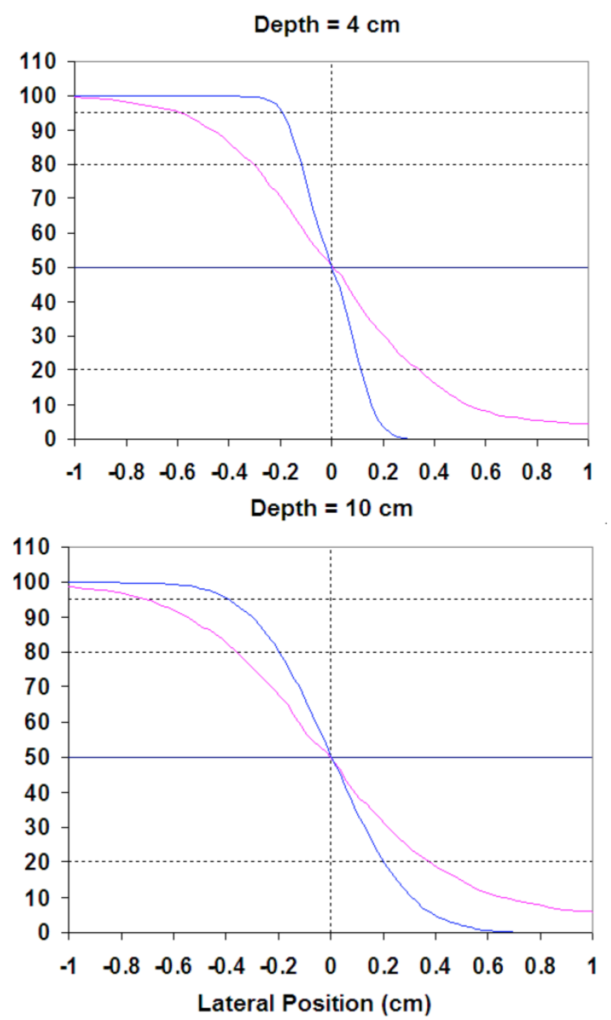


Depth = 4 cm
110
100
90
80
70
60
50
40
30
20
10
0
-1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1
Depth = 10 cm
Lateral Position (cm)



20-80% Distance (cm)
1.10
1.00
0.90
0.80
0.70
0.60
0.50
15 cm
20 cm
25 cm
80-95% Distance (cm)
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
Depth
15 MV 2100EX
18 MV 2100EX
NPTC Gantry 1

Penumbra:



- Sharper at Shallow Depths
- More Sensitive to Setup Uncertainty
- Less Sharp at Greater Depths

Calibrations

- Some centers measure all field outputs: dependent on range, mod, field size, aperture, range compensator, patient scatter
- Model based: *Kooy, et al, PMB 2005*

INSTITUTE OF PHYSICS PUBLISHING

Phys. Med. Biol. **50** (2005) 5847–5856

The prediction of output factors for spread-out proton Bragg peak fields in clinical practice

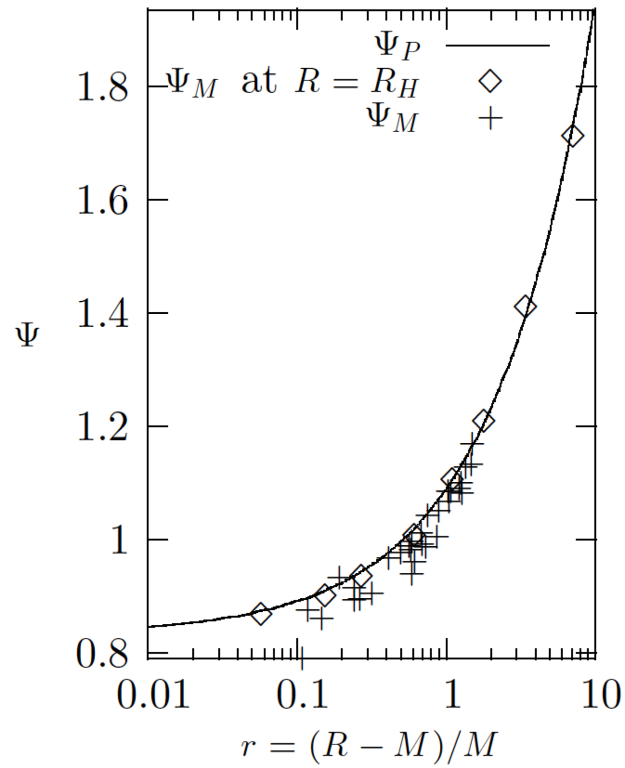
Hanne M Kooy[1], Stanley J Rosenthal[1], Martijn Engelsman[1], Alejandro Mazal[2], Roelf L Slopsema[1], Harald Paganetti[1] and Jacob B Flanz[1]

Calibrations

$$\Psi(r) = \frac{\mathrm{CF} \times \Psi_c \times D_{0,c}}{100/(1 + a_0 r^{a_1})}$$

$$\Psi'(R, M) = (s_0 + s_1(R - R_{\mathrm{L}})) \times \Psi(r)$$

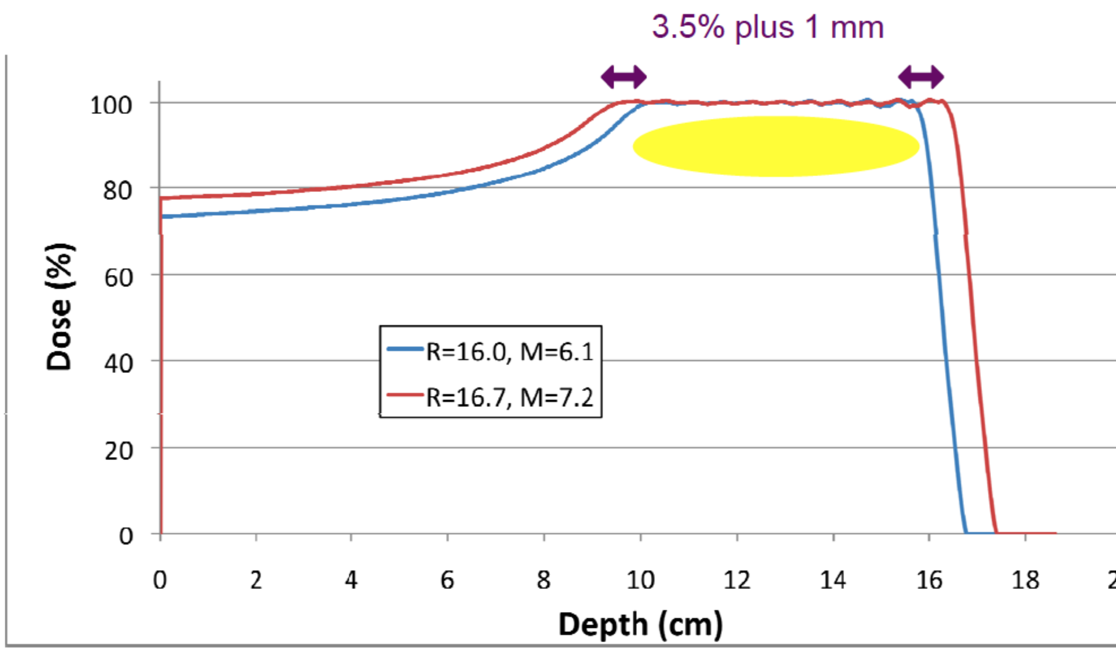
Option	a_0	a_1	CF	s_0	s_1	R_{L}	RMS (%)
B3	0.3375	0.7405	0.9970	0.963	0.0196	7.49	2.5
B4	0.3667	0.6963	1.0234	0.946	0.0208	9.55	3.5
B5	0.3552	0.6081	0.9532	0.928	0.0218	11.65	1.4
B6	0.2338	0.8990	1.0549	0.986	0.0070	15.54	0.6
B7	0.1461	0.7843	1.1849	0.952	0.0090	19.83	1.7

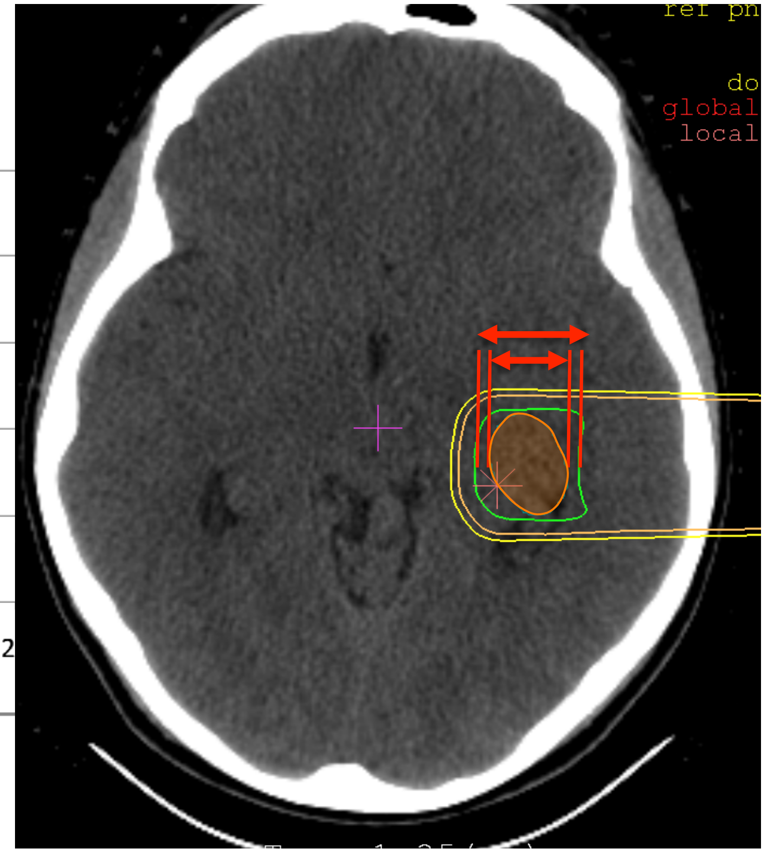


Treatment Planning Perspectives

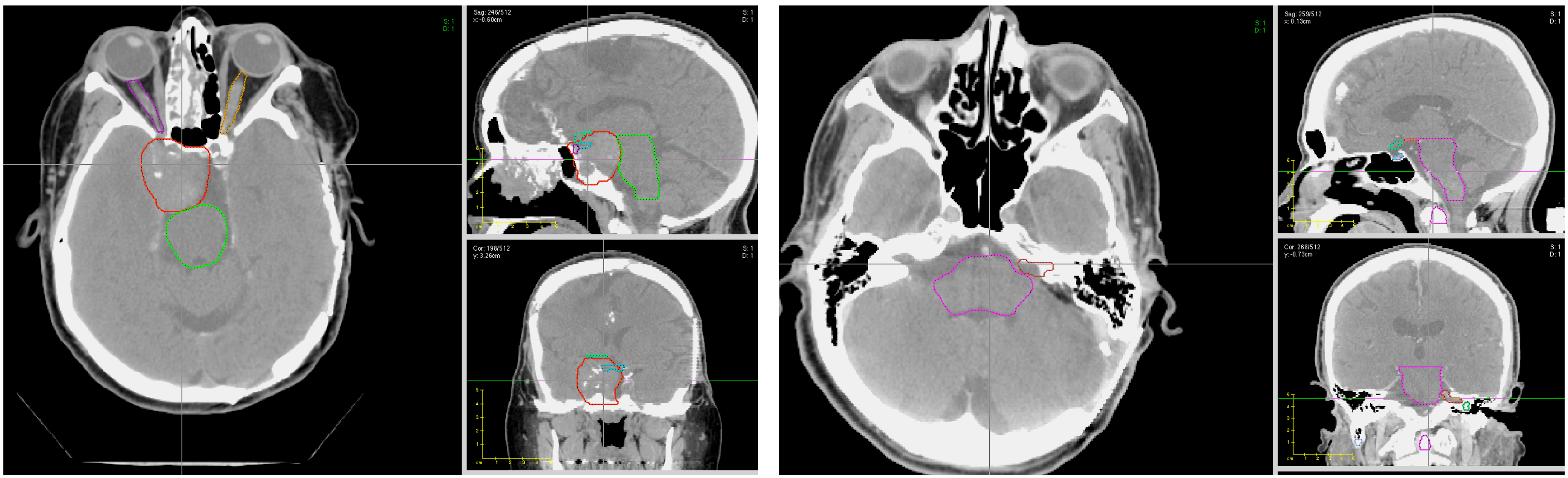
- What do we do with all of this information:
  - Margins: Distal/Proximal and Lateral
  - Beam angle selection
  - Smearing
  - Feathering
  - Gating
  - OARs

Typical Planning (DS): Range Uncertainty



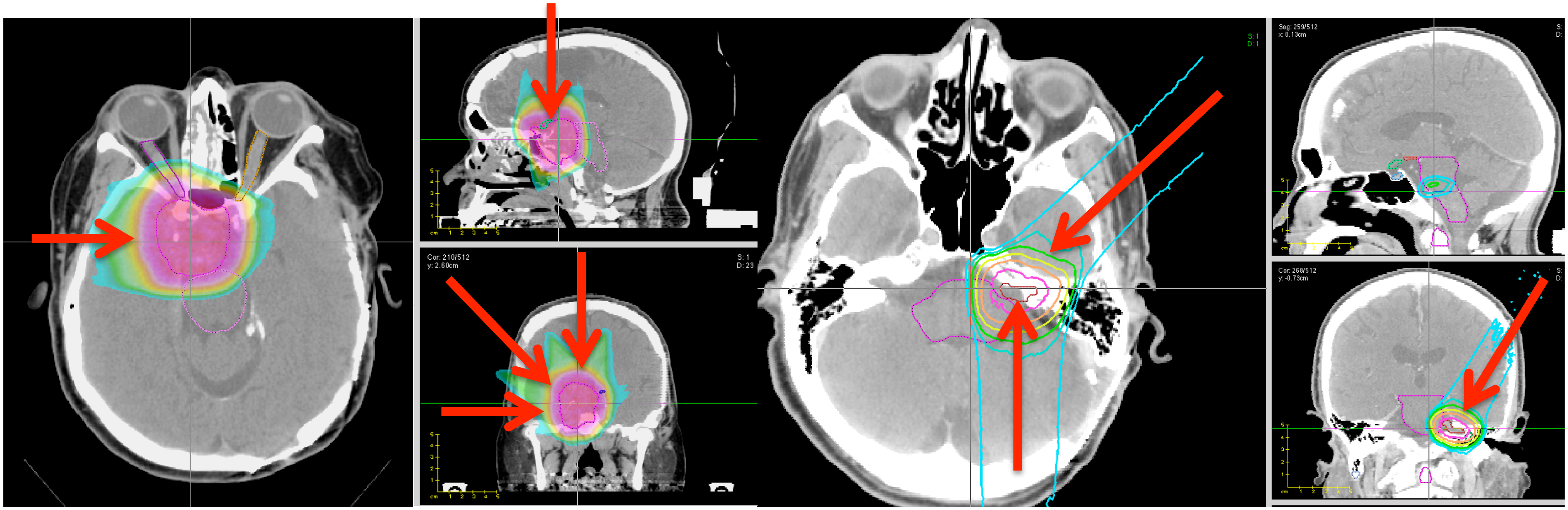


Beam Angle Selection



Two Case Examples: Which beam angles would you use?

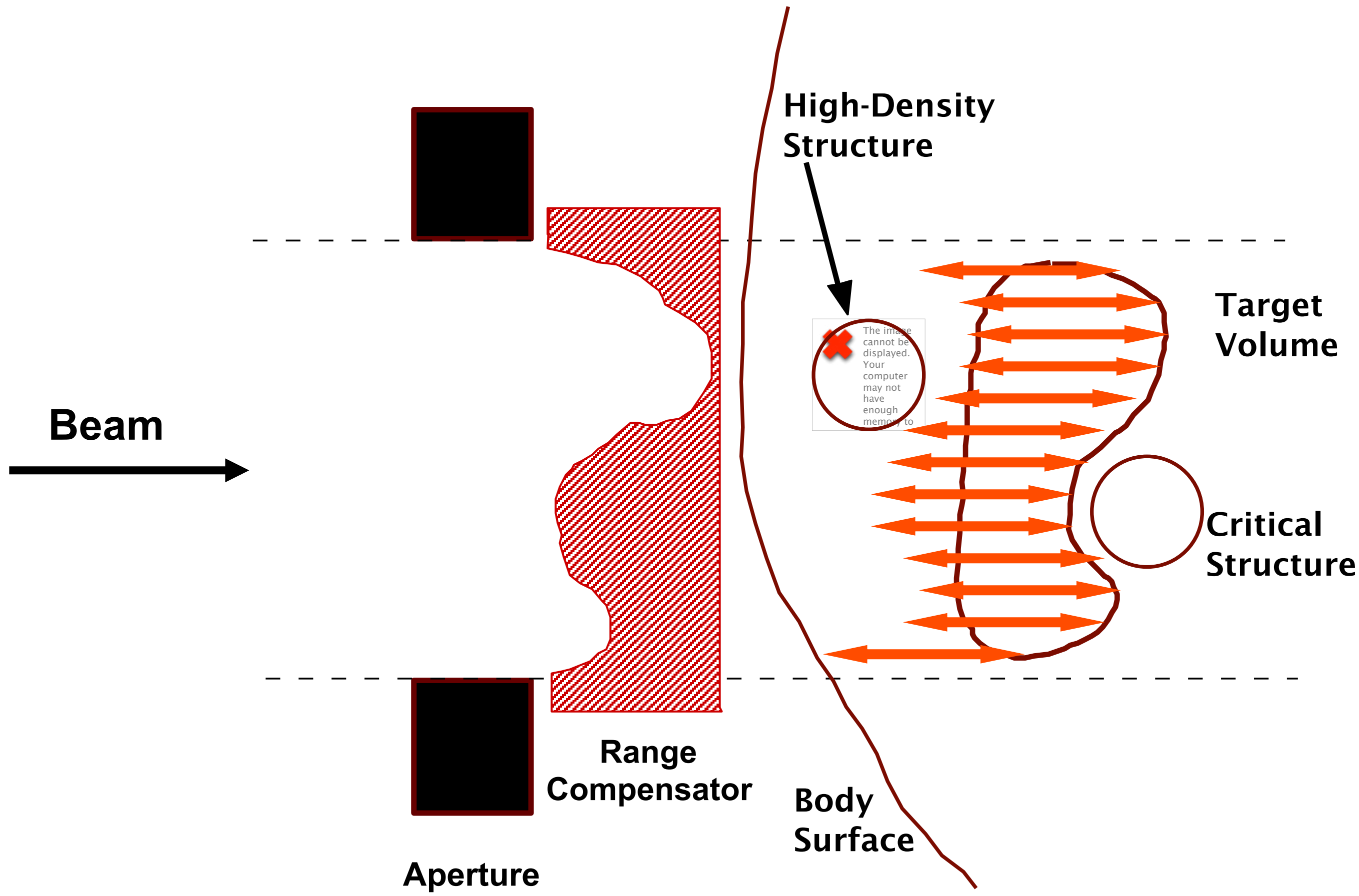
Beam Angle Selection



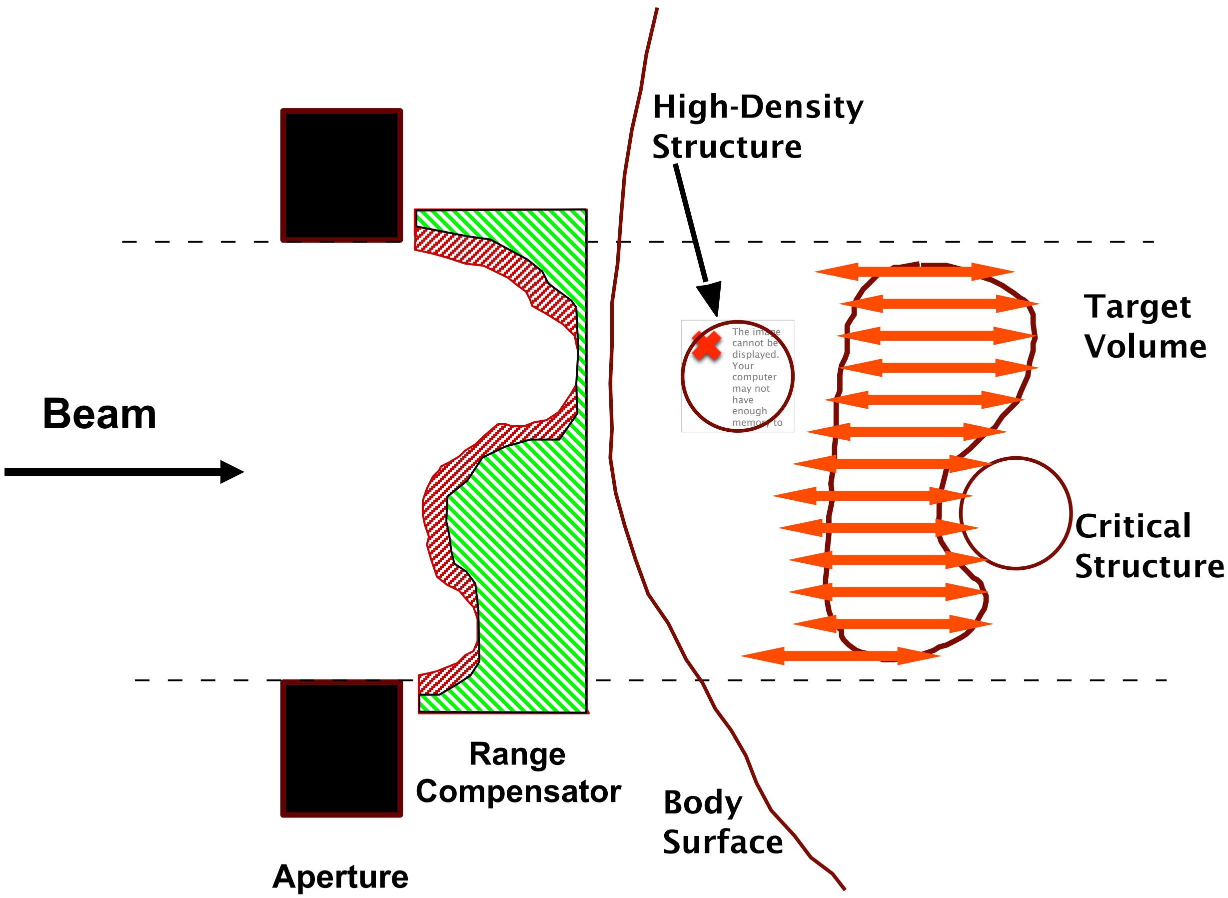
1. Avoid beam entrance angles along and through heterogeneous boundaries
2. Avoid distal edge sparing.
3. <u>Use multiple beams to reduce uncertainty of a single beam!</u>

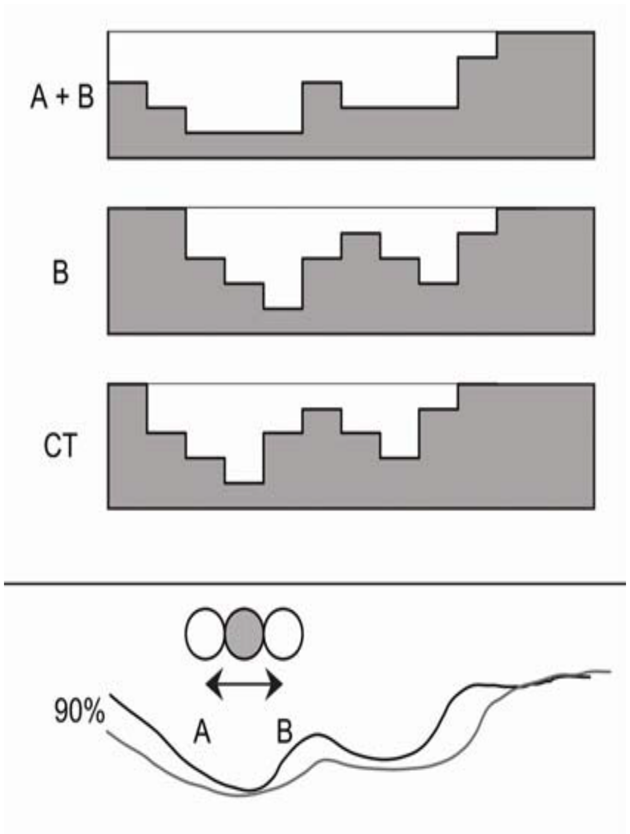
Typical Planning (DS): Setup Uncertainty

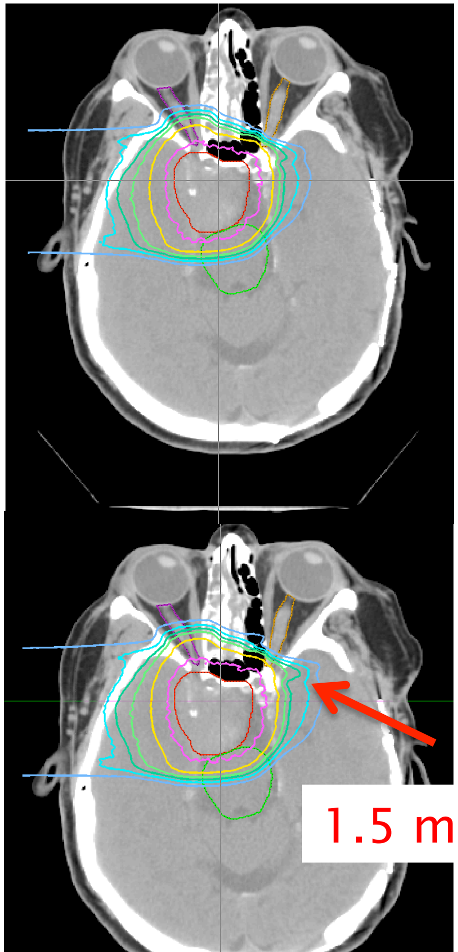
Smearing the range compensator



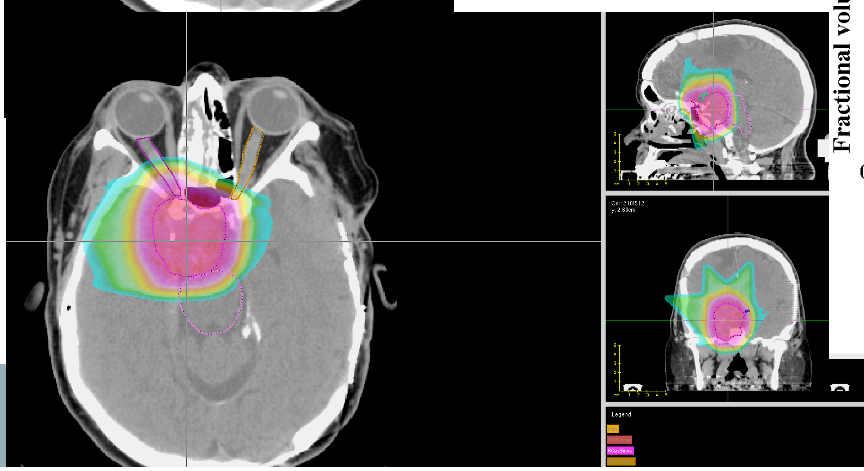
Smearing the range compensator

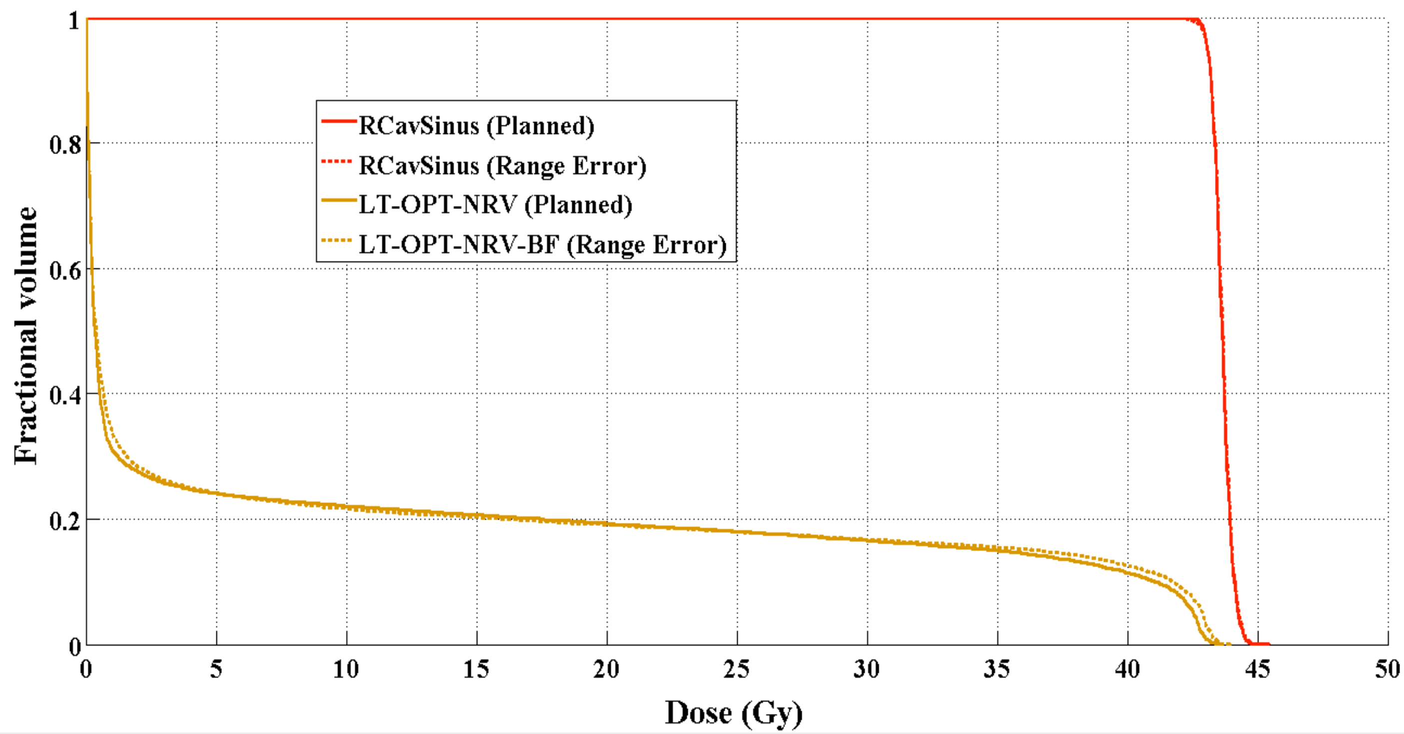


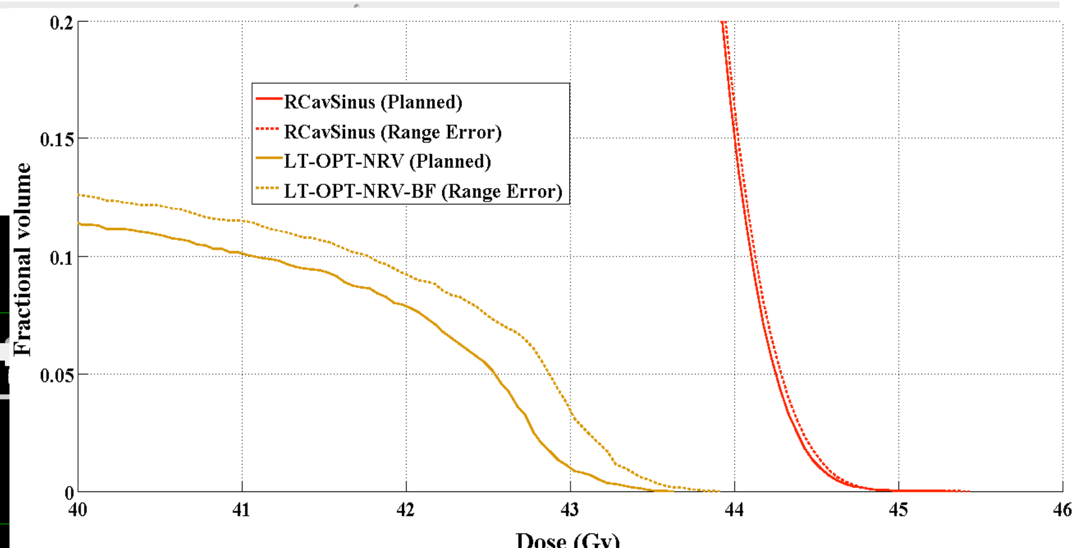




1.5 mm setup error





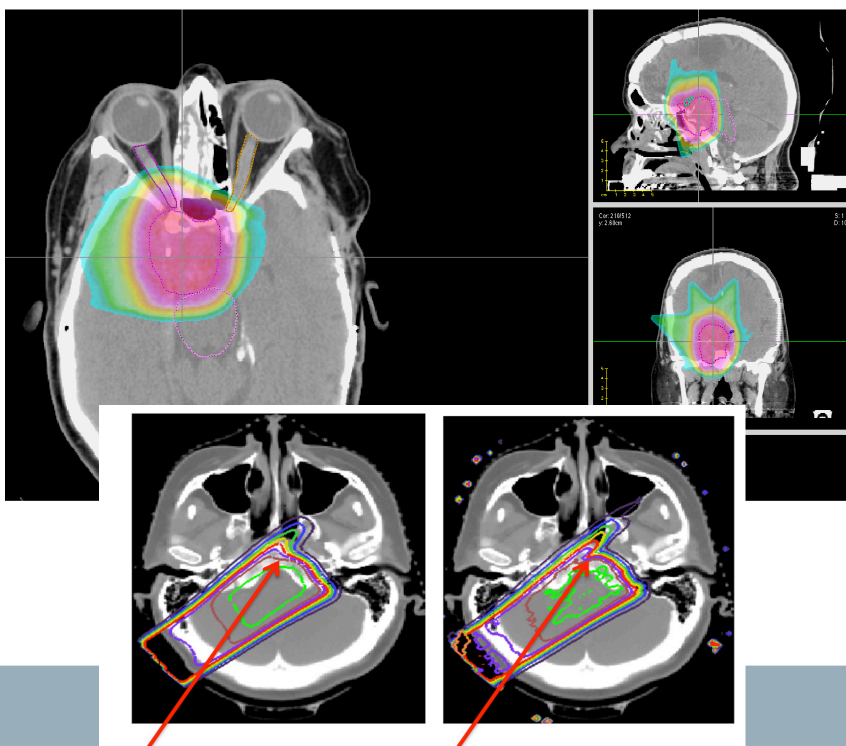


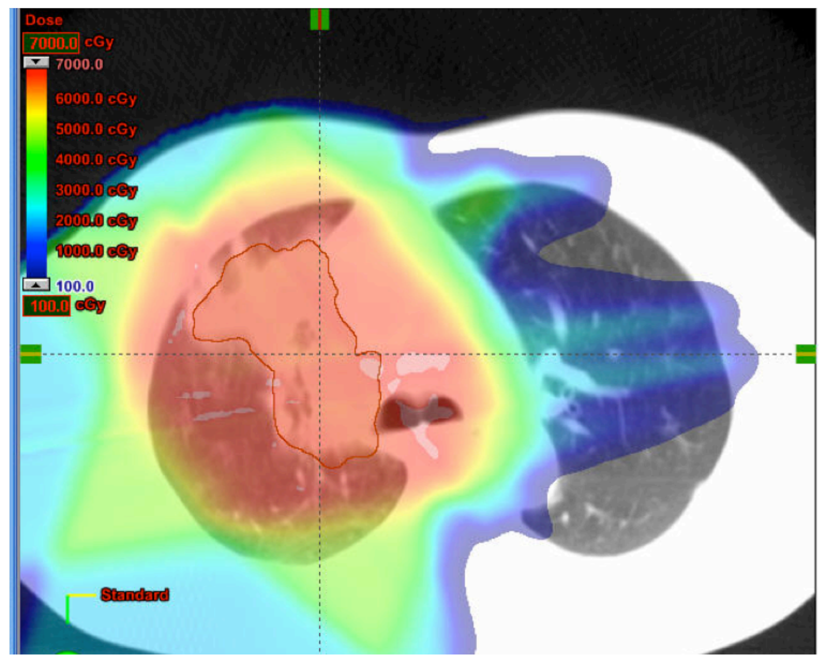
Gating

- Gating can greatly reduce the range uncertainties of targets close to the diaphragm where motion is typically the greatest

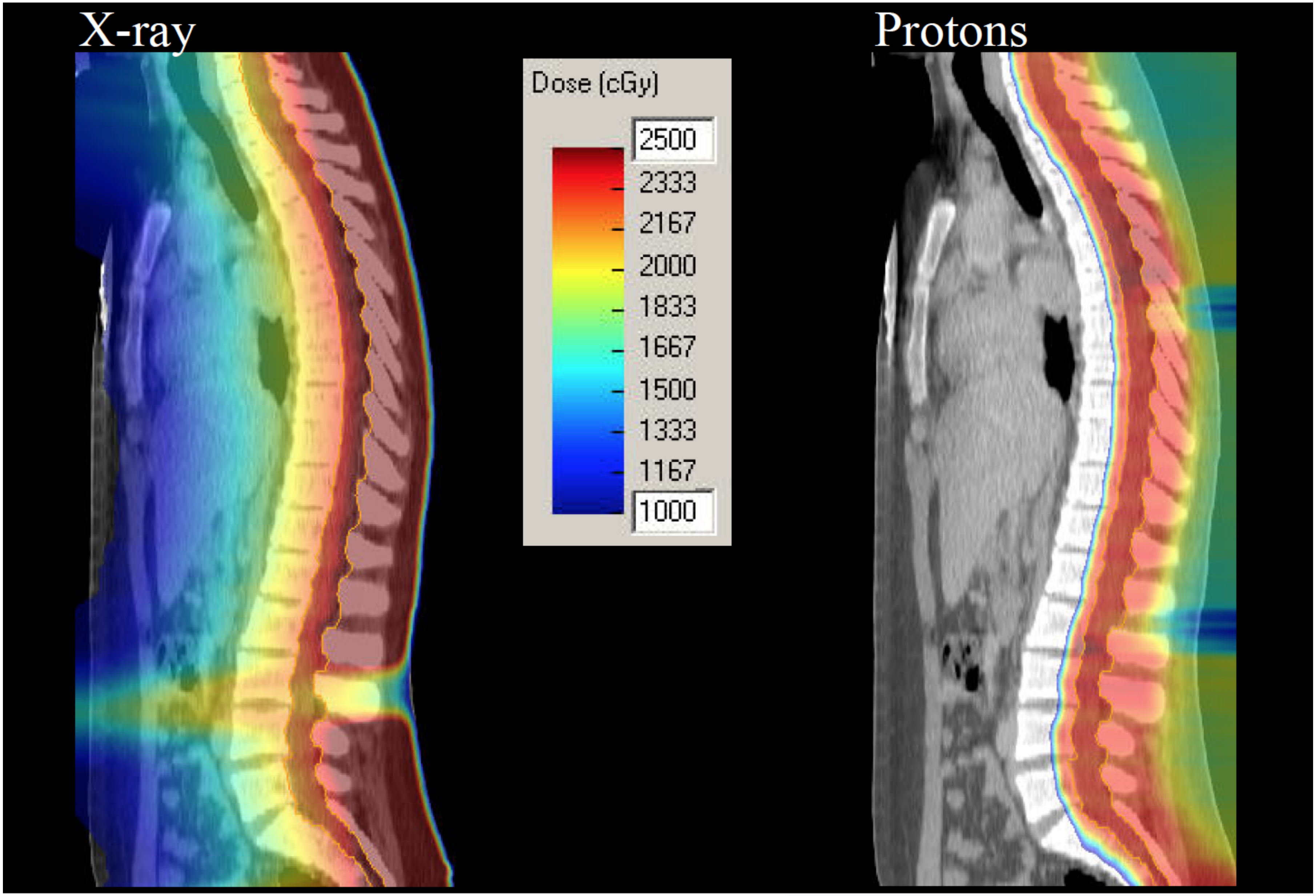
OARs

- AVOID distal edge sparing!
- If unavoidable, use multiple fields to spread the risk and reduce the dose to the OAR if there is an error.

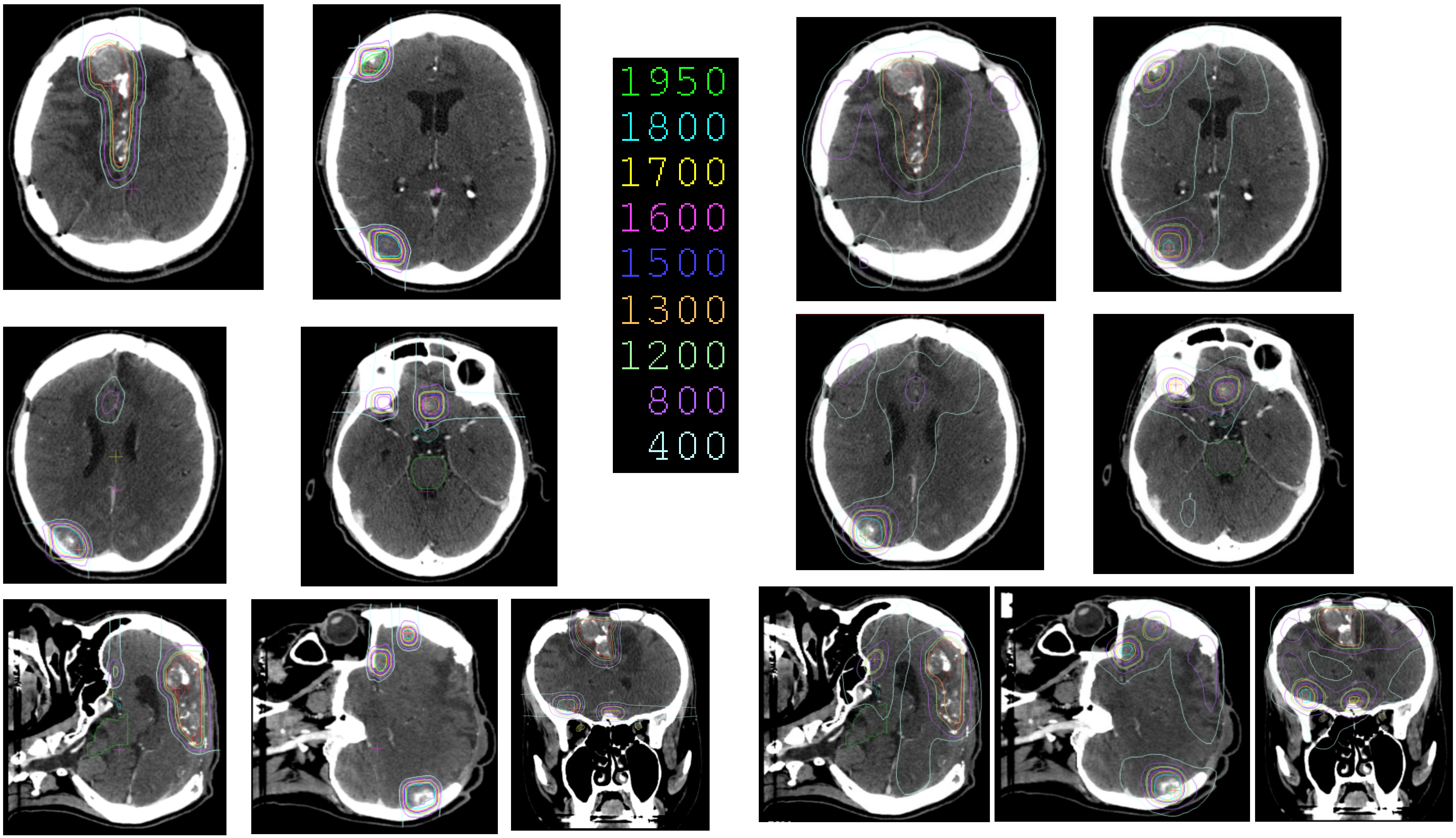




Plan Examples:
Protons versus Photons


X-ray
Protons
Dose (cGy)
2500
2333
2167
2000
1833
1667
1500
1333
1167
1000

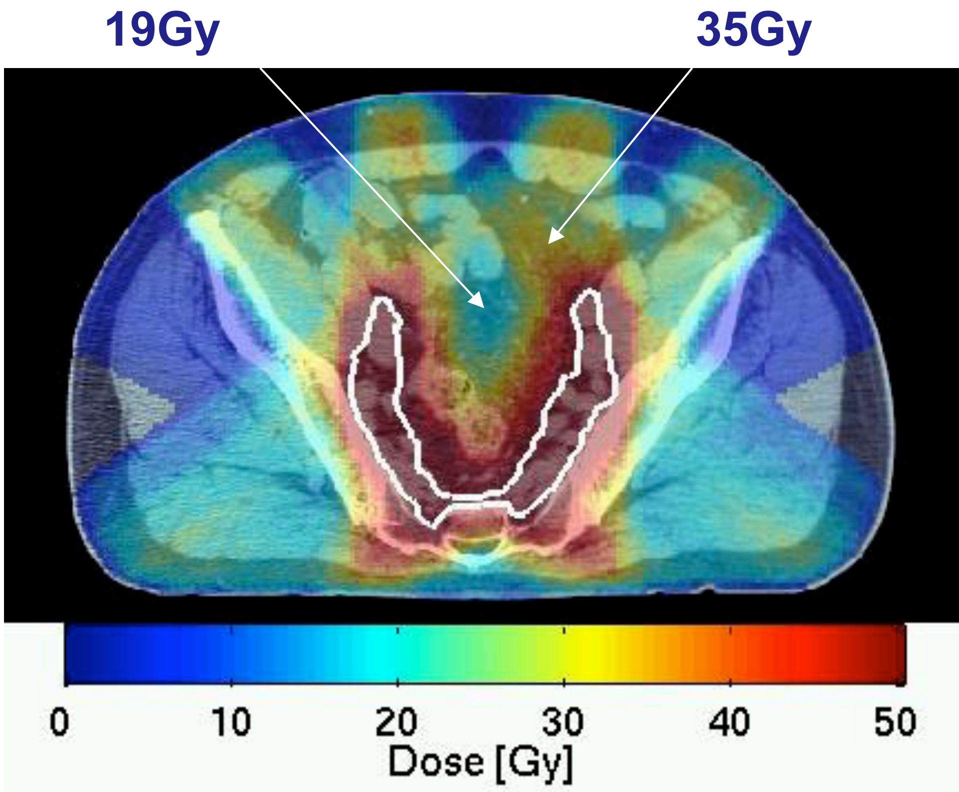
Multiple Atypical Meningioma



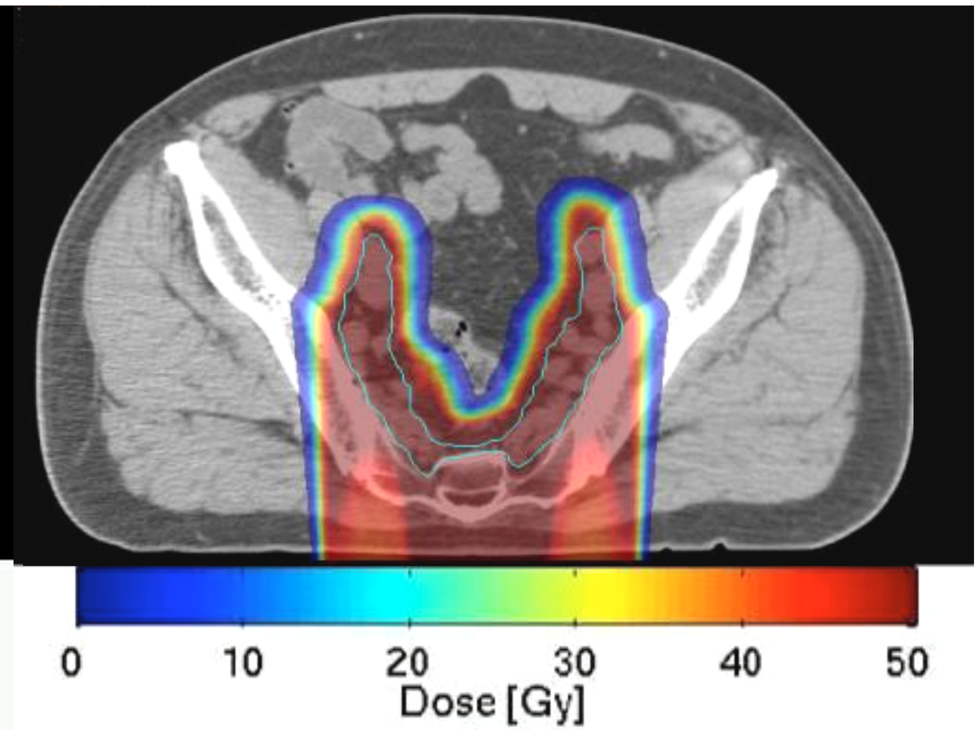
Protons

X-Rays

Sacral Sarcoma



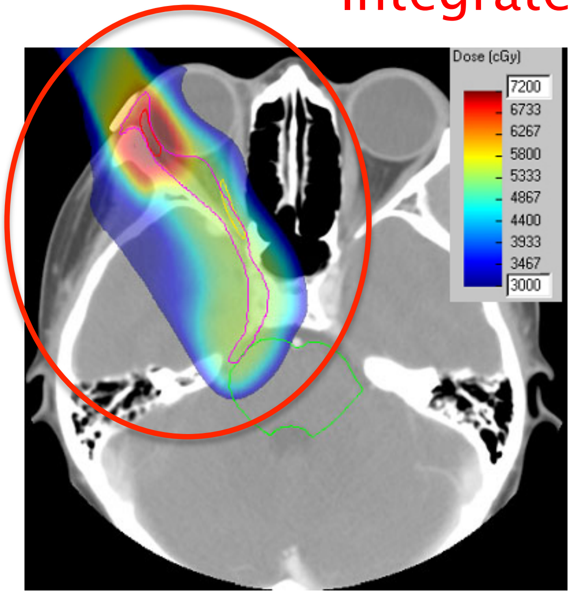
IMRT

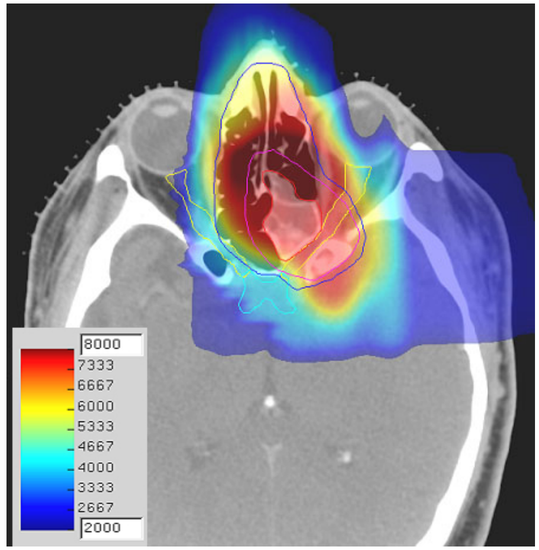


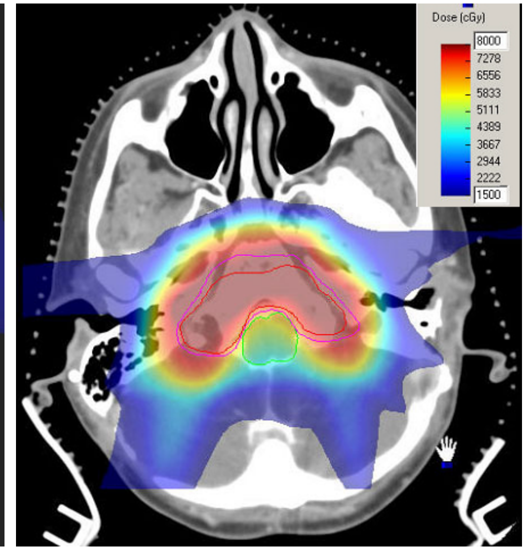
Protons

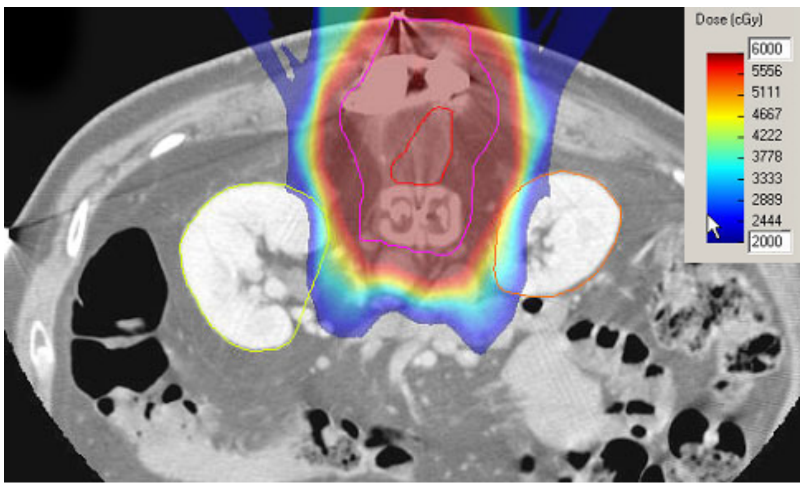
Martijn Engelsman, Ph.D.
MASSACHUSETTS GENERAL HOSPITAL
RADIATION ONCOLOGY
HARVARD MEDICAL SCHOOL

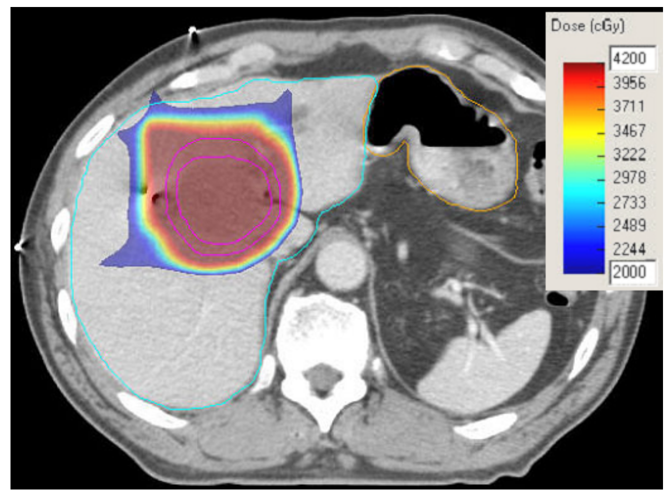
Integrated Boost







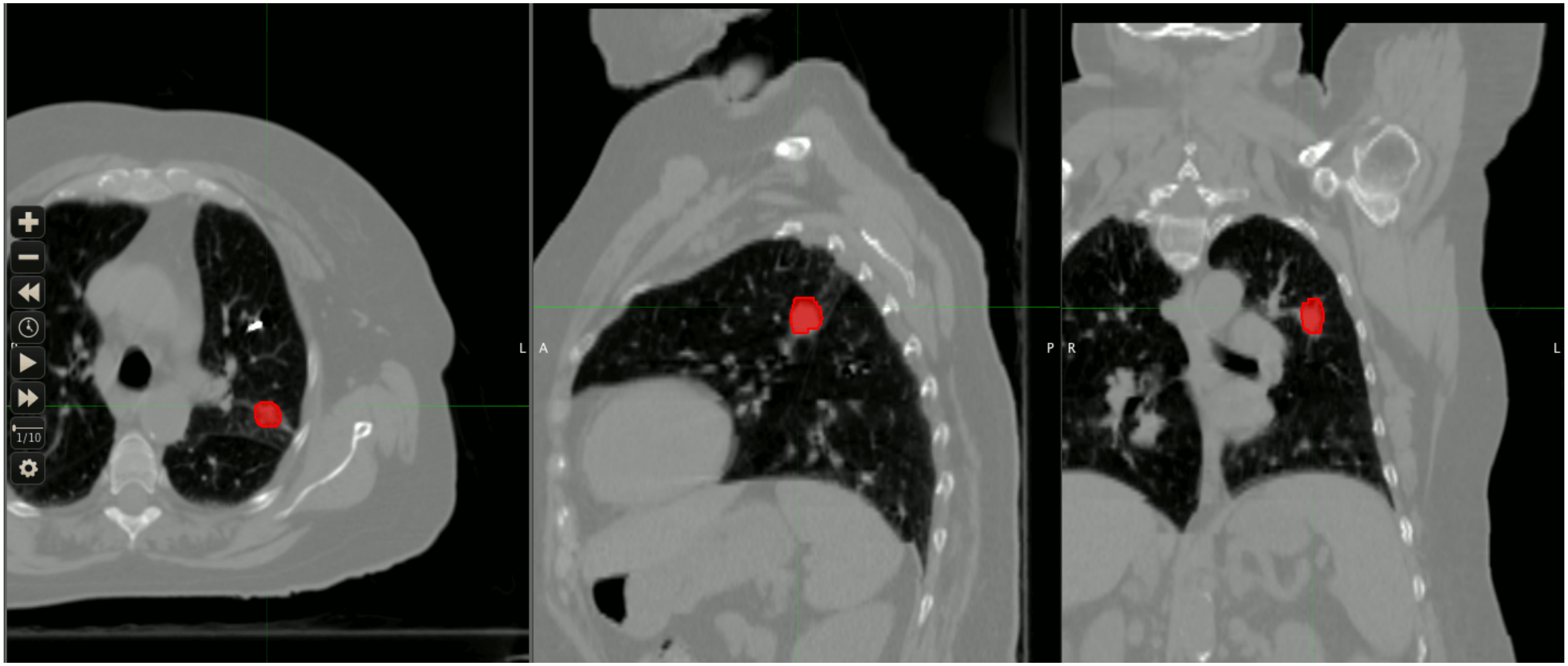




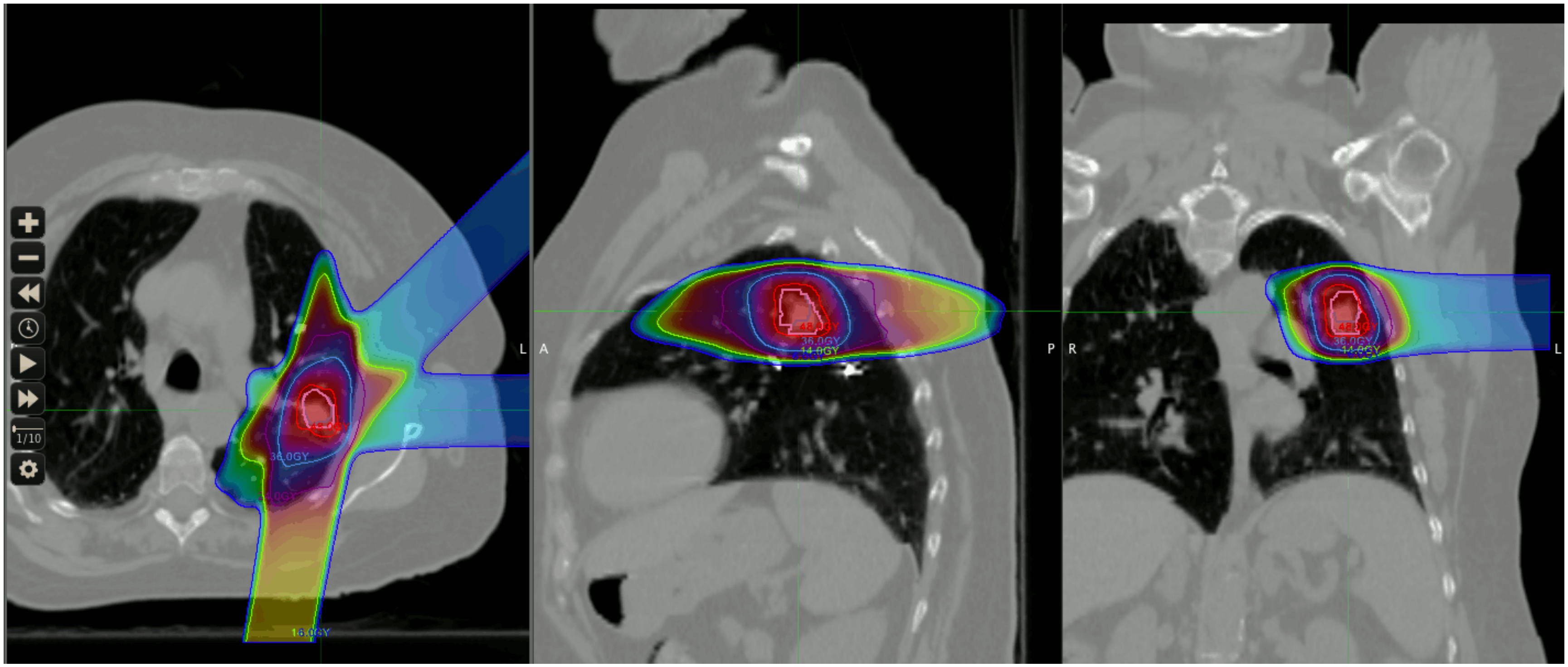
Ideal Motion Scenario

- Perfect Tracking of the CTV
- No Interplay
- Complete knowledge of range variations: intrafraction and interfraction

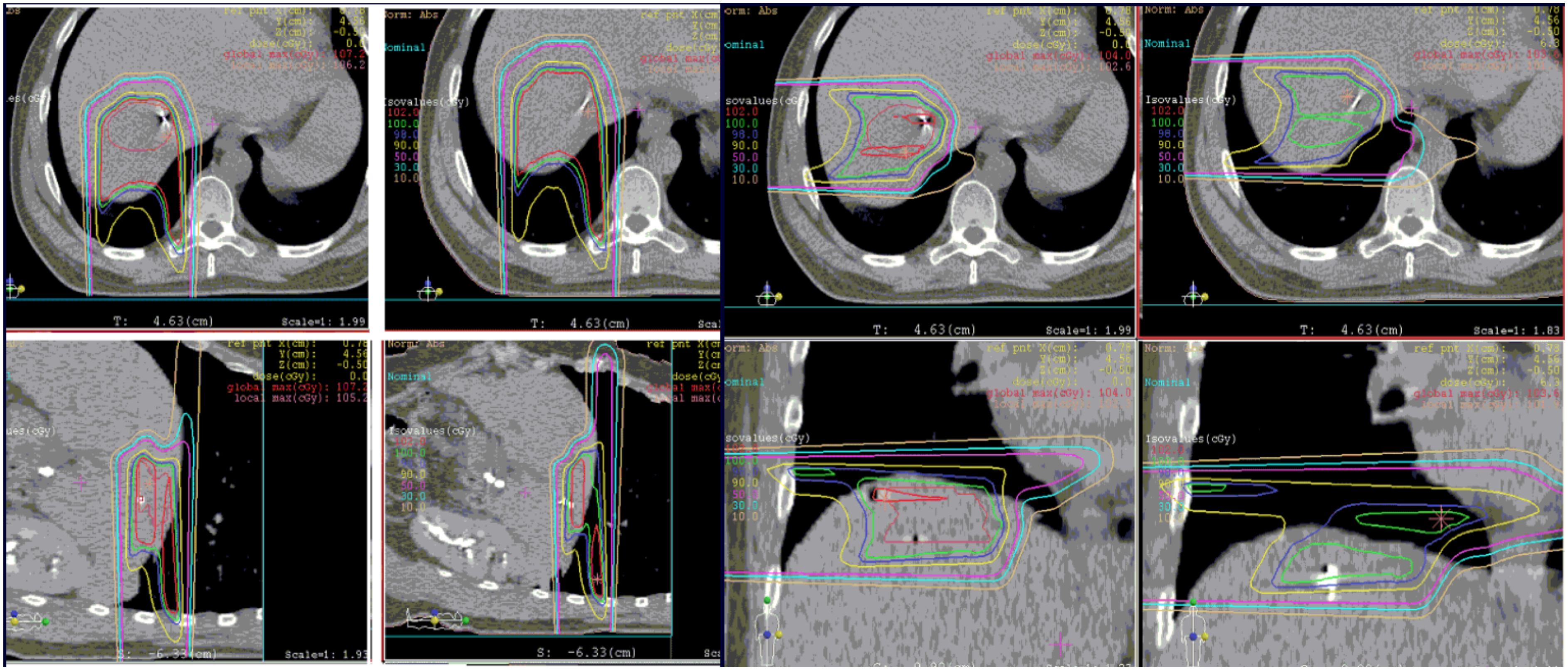
Ideal Lung Scenario



Large Margins: Range, Motion, Smearing



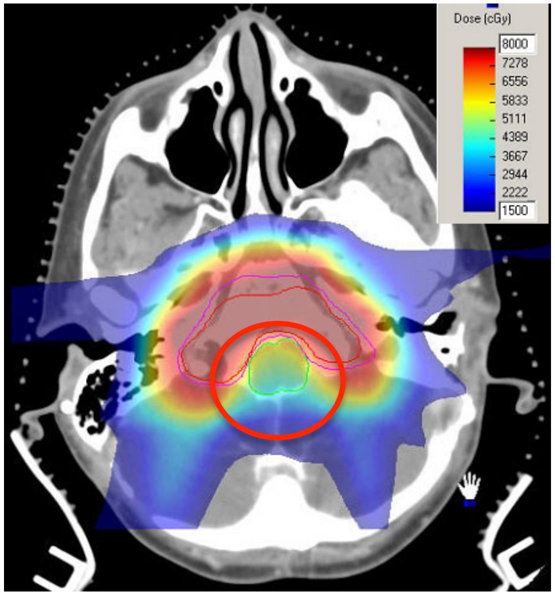
Liver Motion

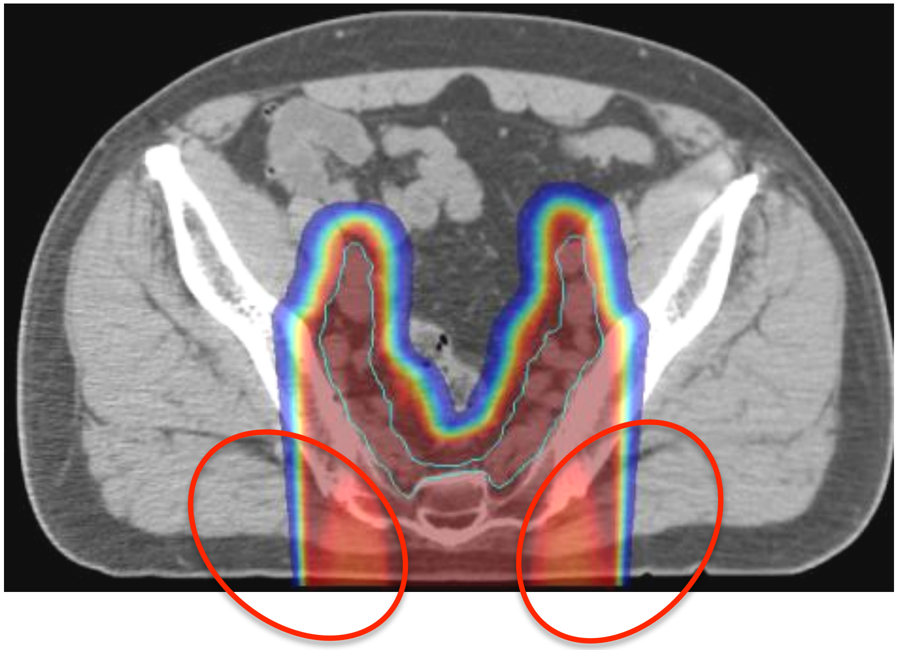


H-M Lu, Ph.D

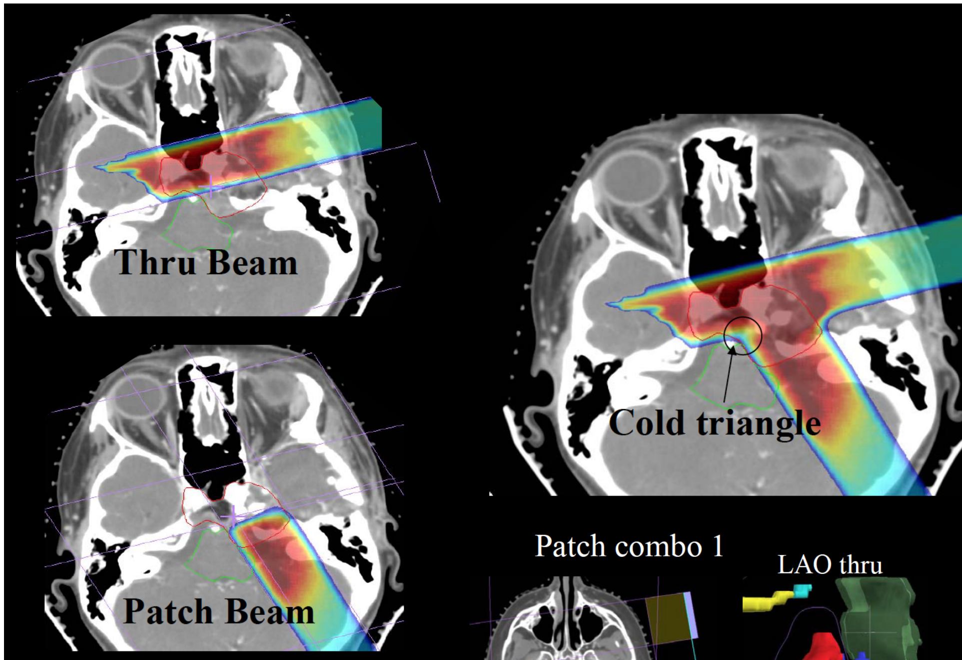
Complex Geometries

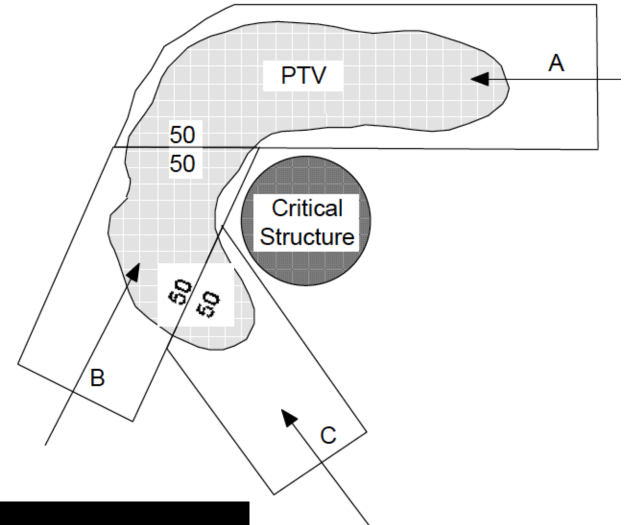
- Double Scattering has trouble with concave geometries



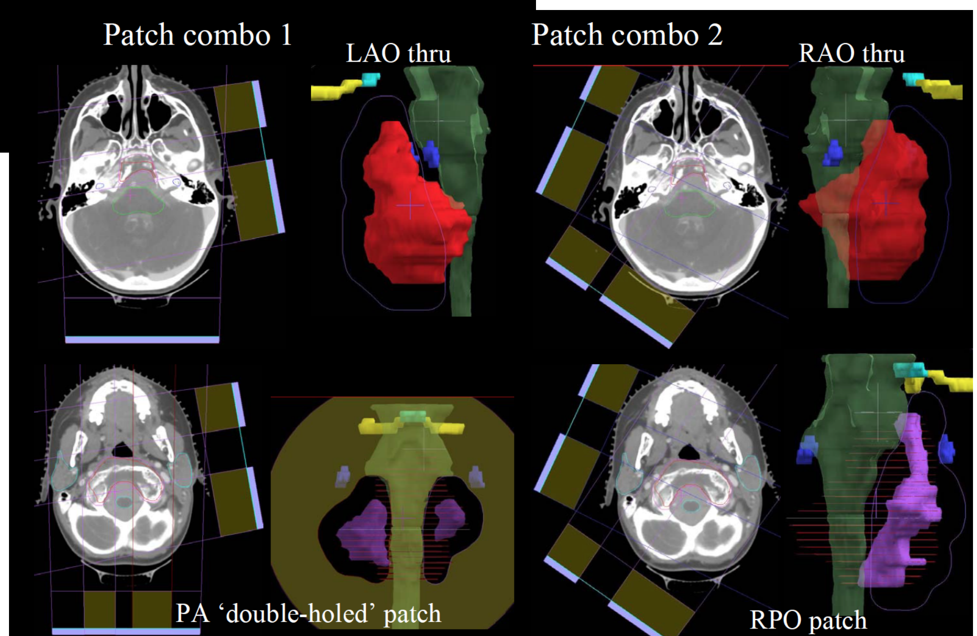


Patching





Feathering



Judy Adams

Conclusions

- Distal Danger!
  - Range uncertainties: OARs, Motion (Breathing and otherwise)
- Use Appropriate Margins (Distally, Proximally and Laterally) and Smearing
- Use Beam Angles that minimize heterogeneous boundaries and range variations
- Use Beam angles that minimize distal edge sparing
- Beware of Small Fields-difficult to measure and model
- Use Multiple beams to reduce risk
- Understand your patient setup and immobilization