Imaging/Imagine Needs for Proton Therapy: Treatment Planning

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Scripps

A World of Healing

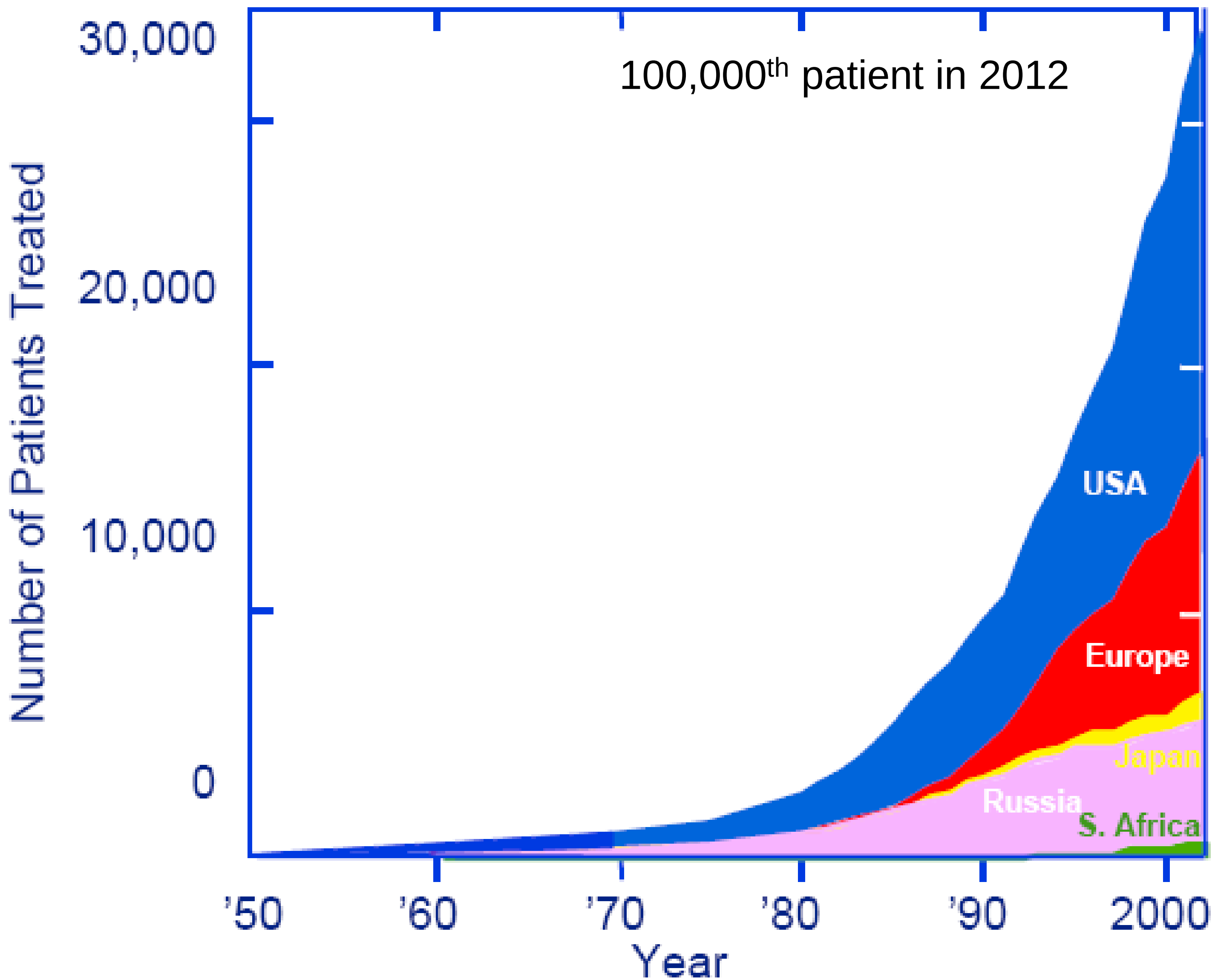
Disclosure

- Software licensing agreement with Varian Medical Systems through MD Anderson Cancer Center

Goals

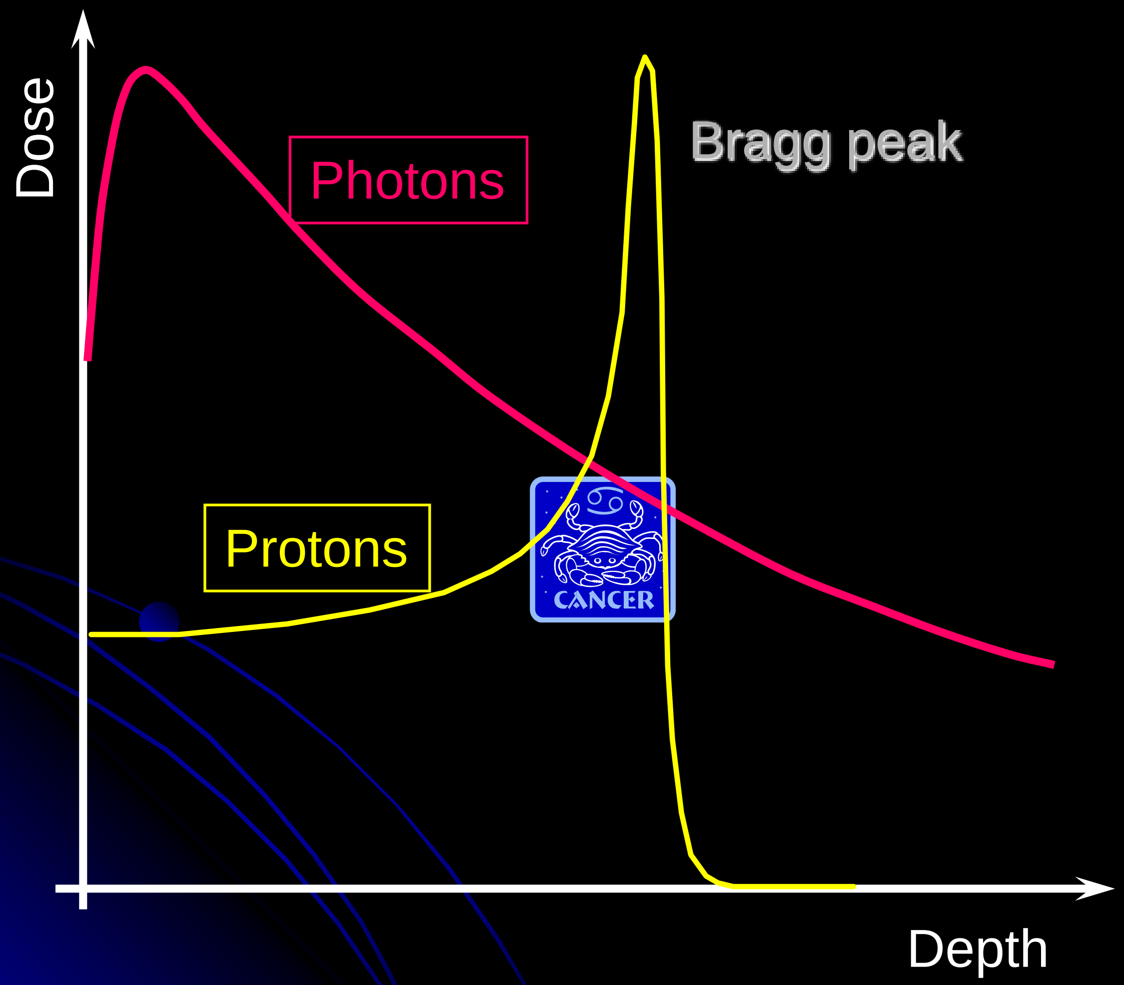
- Evaluating imaging needs for treatment planning
- Comparison of the use of images in planning between photons and protons
- Uncertainties in CT imaging to stopping power conversion
- A wish list

Growth of Proton Treatments

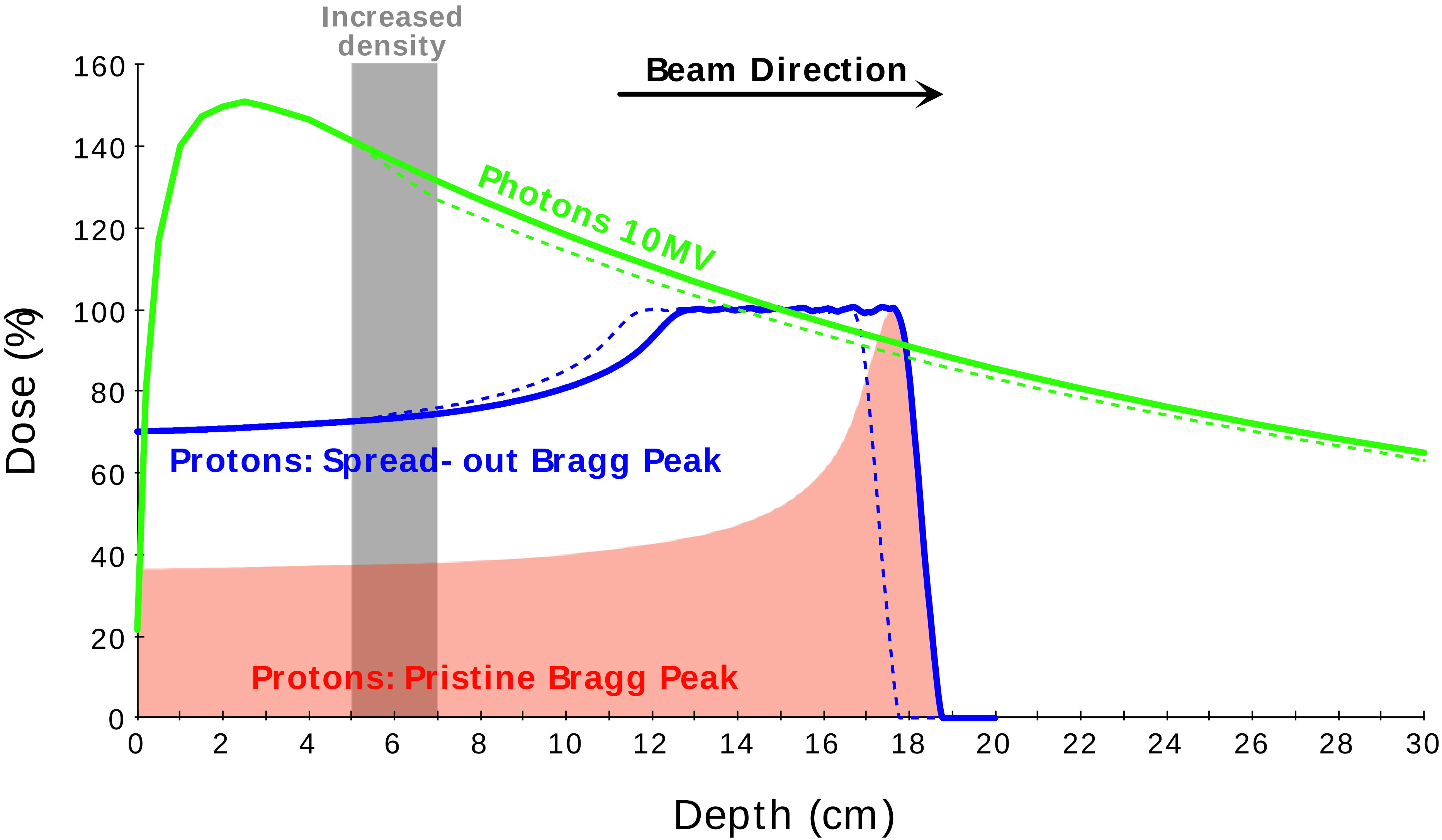


Proton Therapy Centers in US

Why protons?



Range Uncertainties



The Goal of Treatment Planning

Goal: To design a treatment plan based on an anticipated patient treatment

- **Requirements**
  - Delineate target and normal structures
  - Accurate modeling for the patient
  - Accurate dose calculation
  - Evaluating simulation results

The Goal of Treatment Planning

- Imaging Needs
  - Target and normal structure delineation
  - Accurate modeling for the patient
    - Imaging the patient in treatment position
  - Accurate dose calculation
    - Simulate deliverable dose distributions
  - Evaluating simulation results
    - Present DVHs, Isodose lines, PTV or other plan robustness parameters etc.

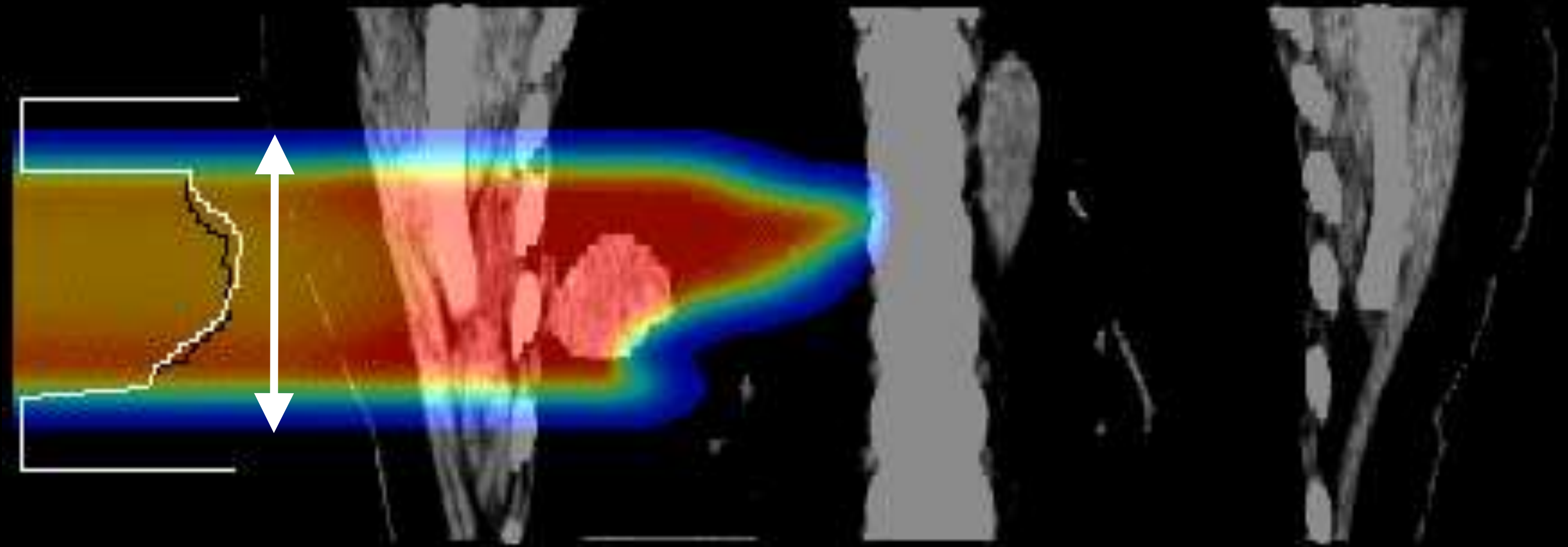
Imaging for Target Delineation

- No difference from photon therapy

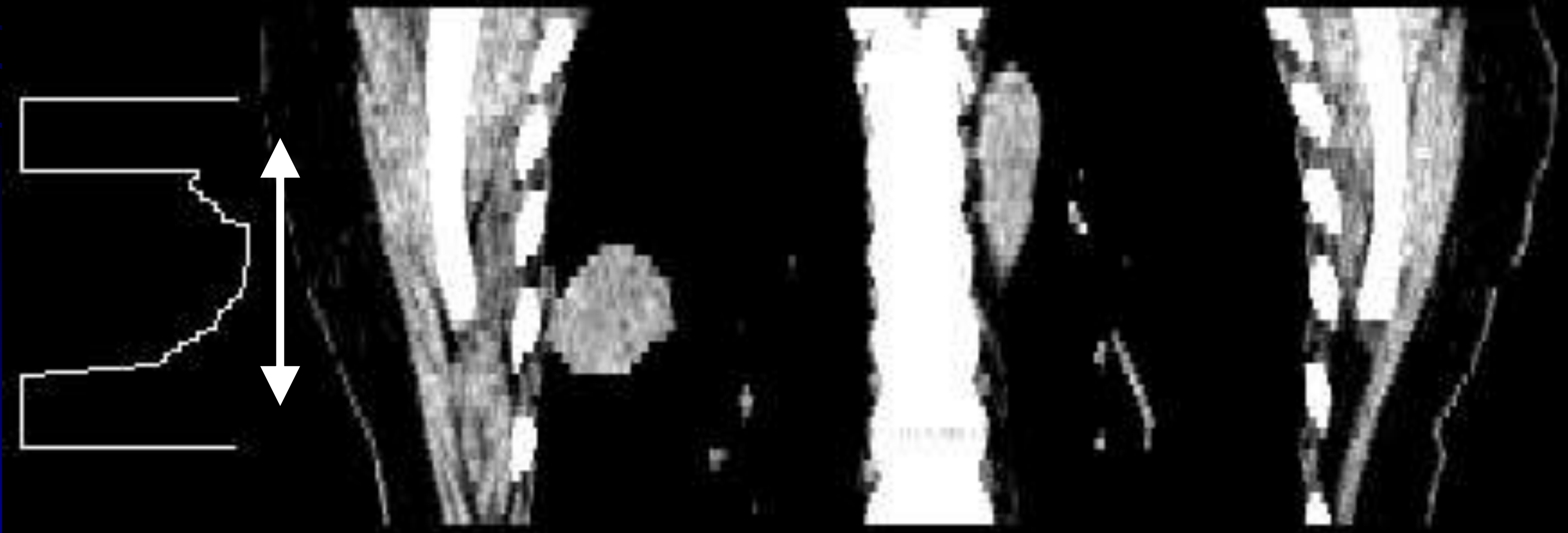
Imaging Patient in Treatment Condition

Organ Motion

Impact of motion to proton dose distribution

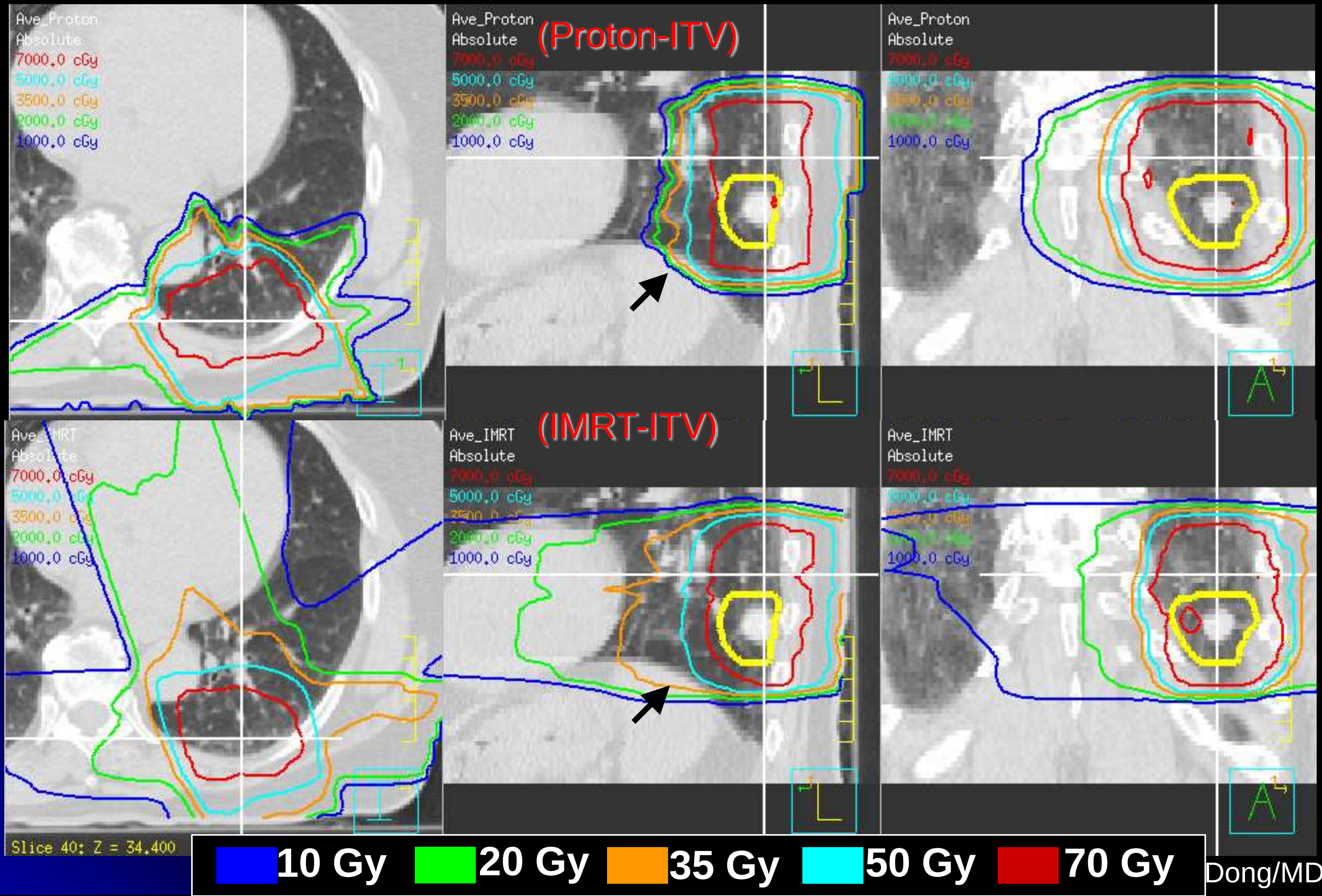


Gated treated on exhale



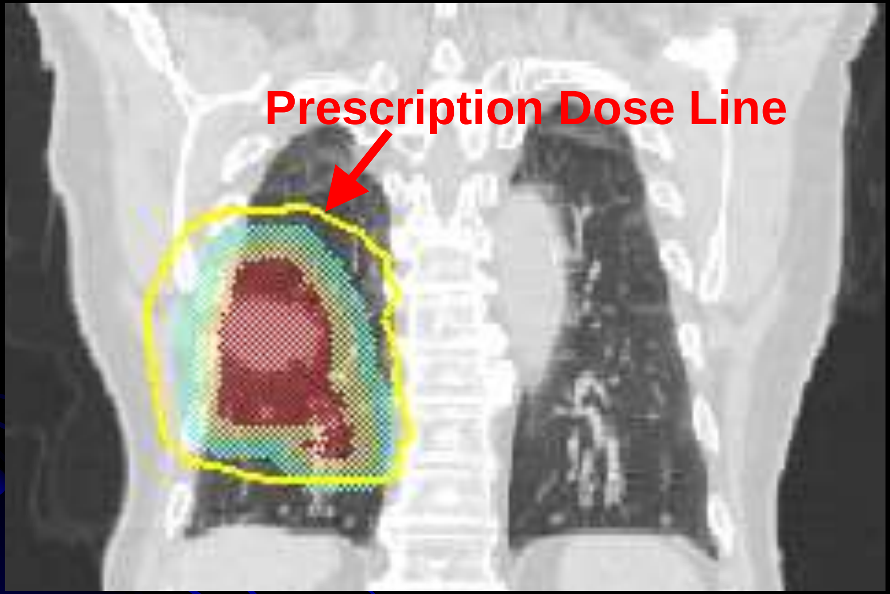
Tsunashima/Dong

Protons are more sensitive to motion than IMRT

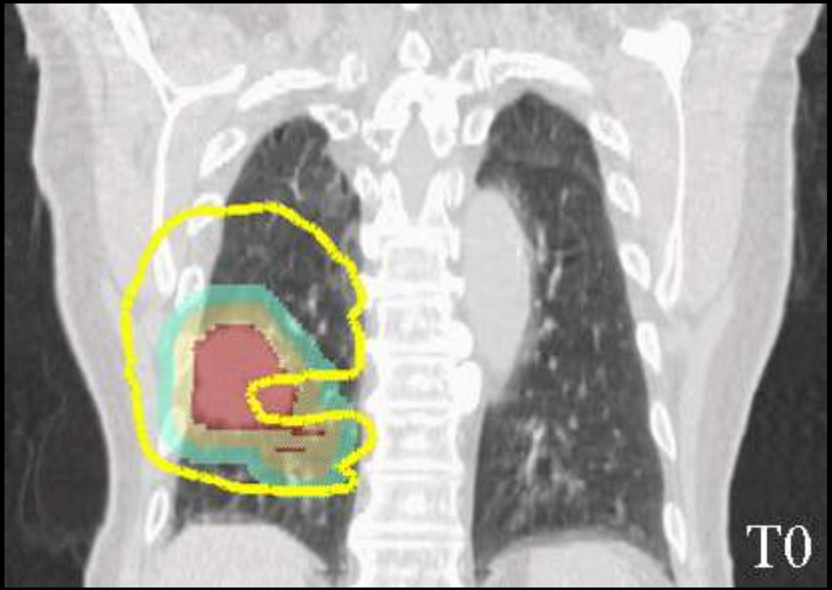


Dong/MDACC

Every Proton Plan is a 4D Plan



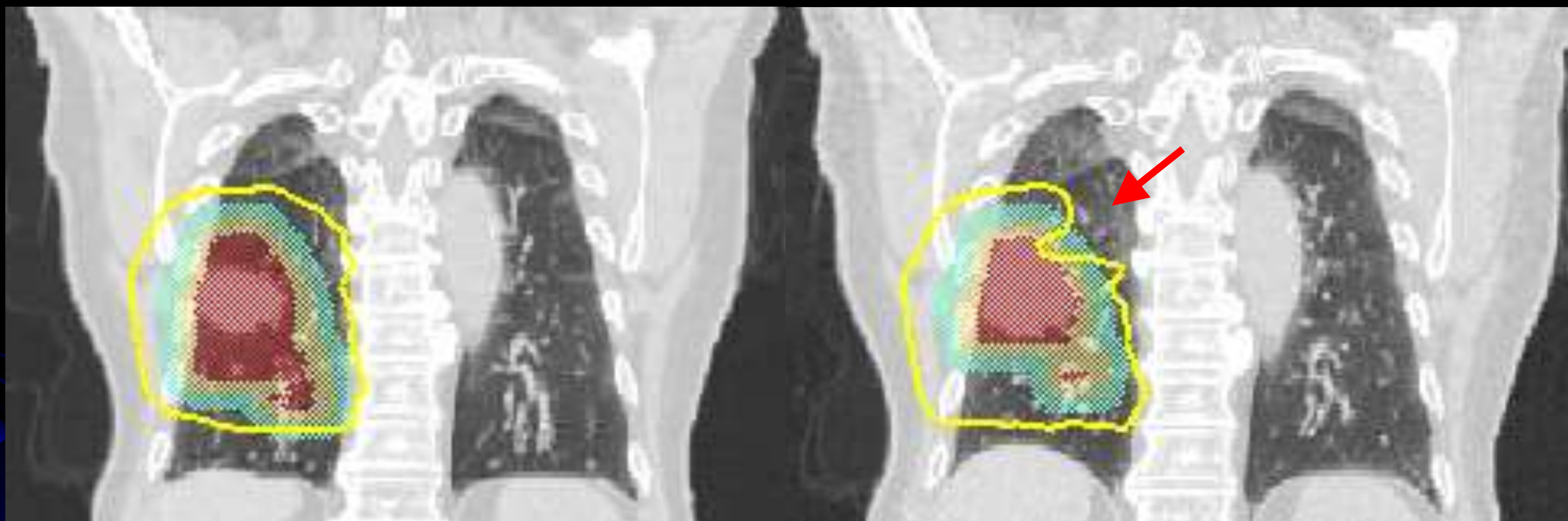
Treatment planned based on single Free-breathing (FB) CT image (conventional approach)



The same treatment plan calculated on 4D CT images

Y. Kang et al. IJROBP. **67**, 906-914 (2007).

Impact of Organ Motion on Proton Dose Distribution



Treatment planned based on single Free-breathing (FB) CT image (conventional approach)

Final composite dose distribution after deformable image registration

Y. Kang et al. IJROBP. **67**, 906-914 (2007).

Imagine Patient in Treatment Condition

Treatment Couch and Immobilization Devices

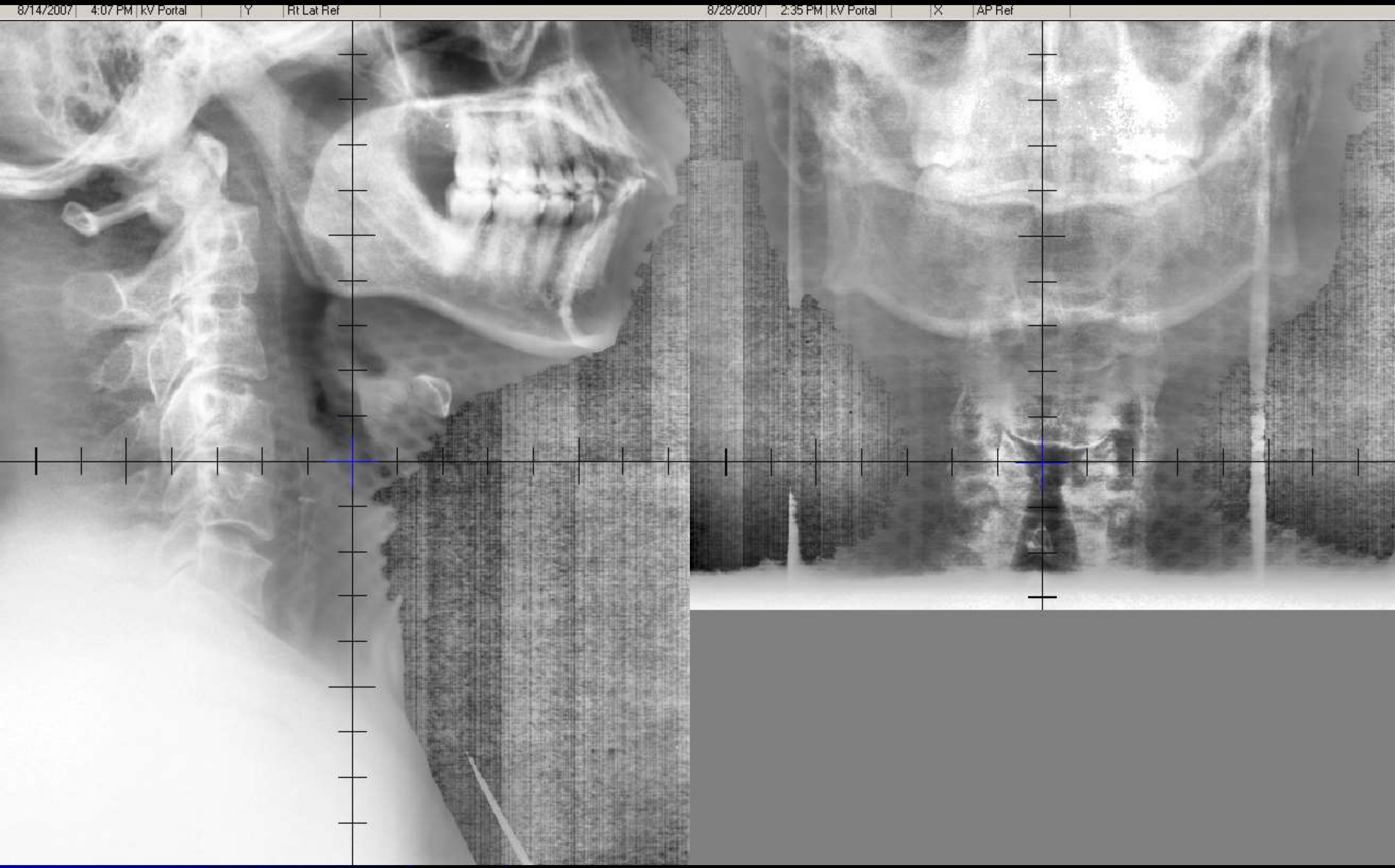








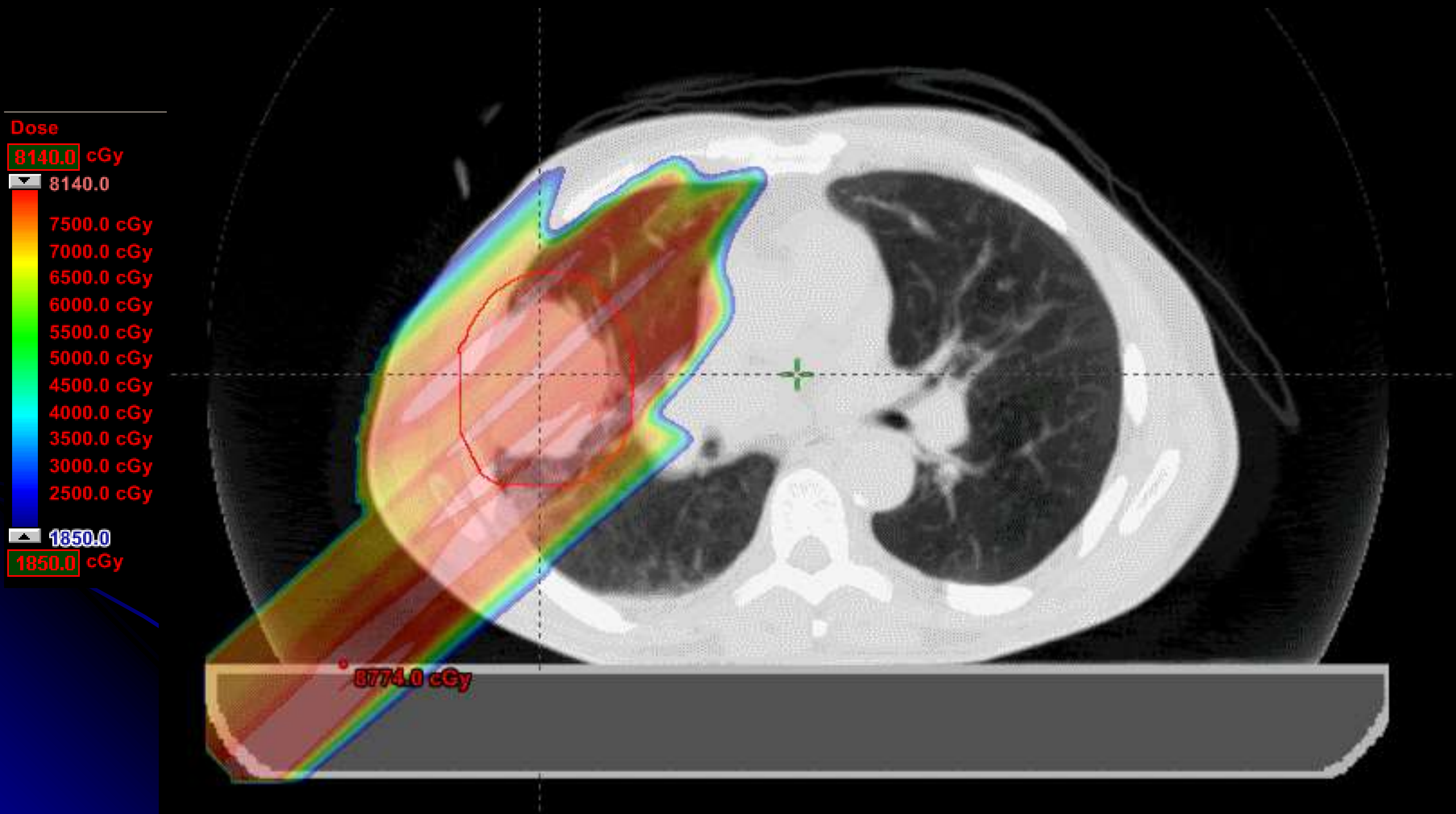
Setup Error and Positional Variation of Immobilization Device



Mitigation

- Avoiding sharp edges in immobilization devices
- Avoiding beam passing through the immobilization device

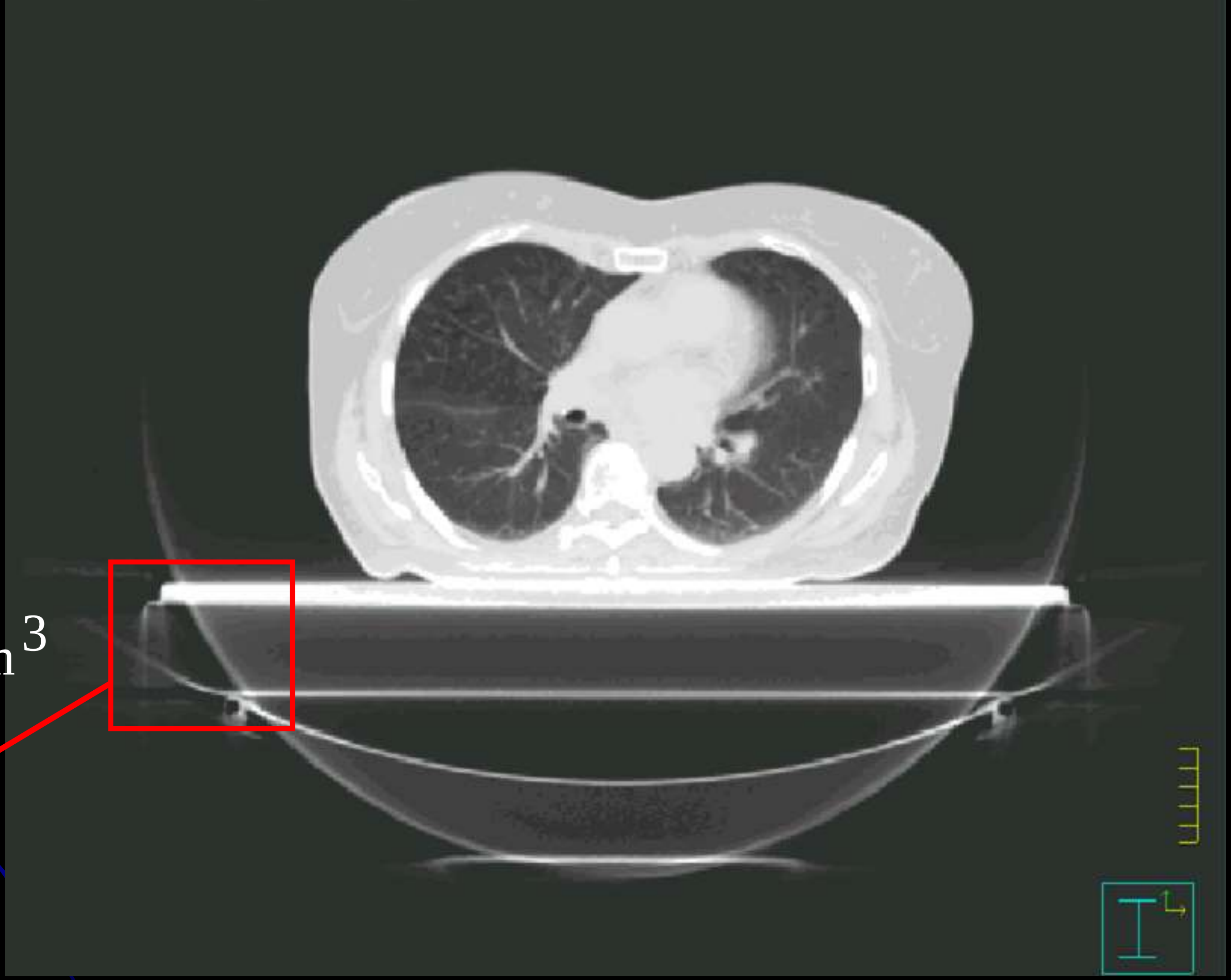
Couch Edge or Dense Immobilization Device

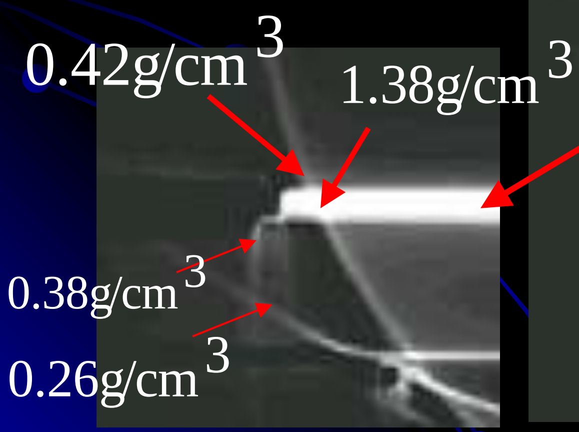


H. Yu et al.

Modeling the treatment couch

CT Imaging Artifacts



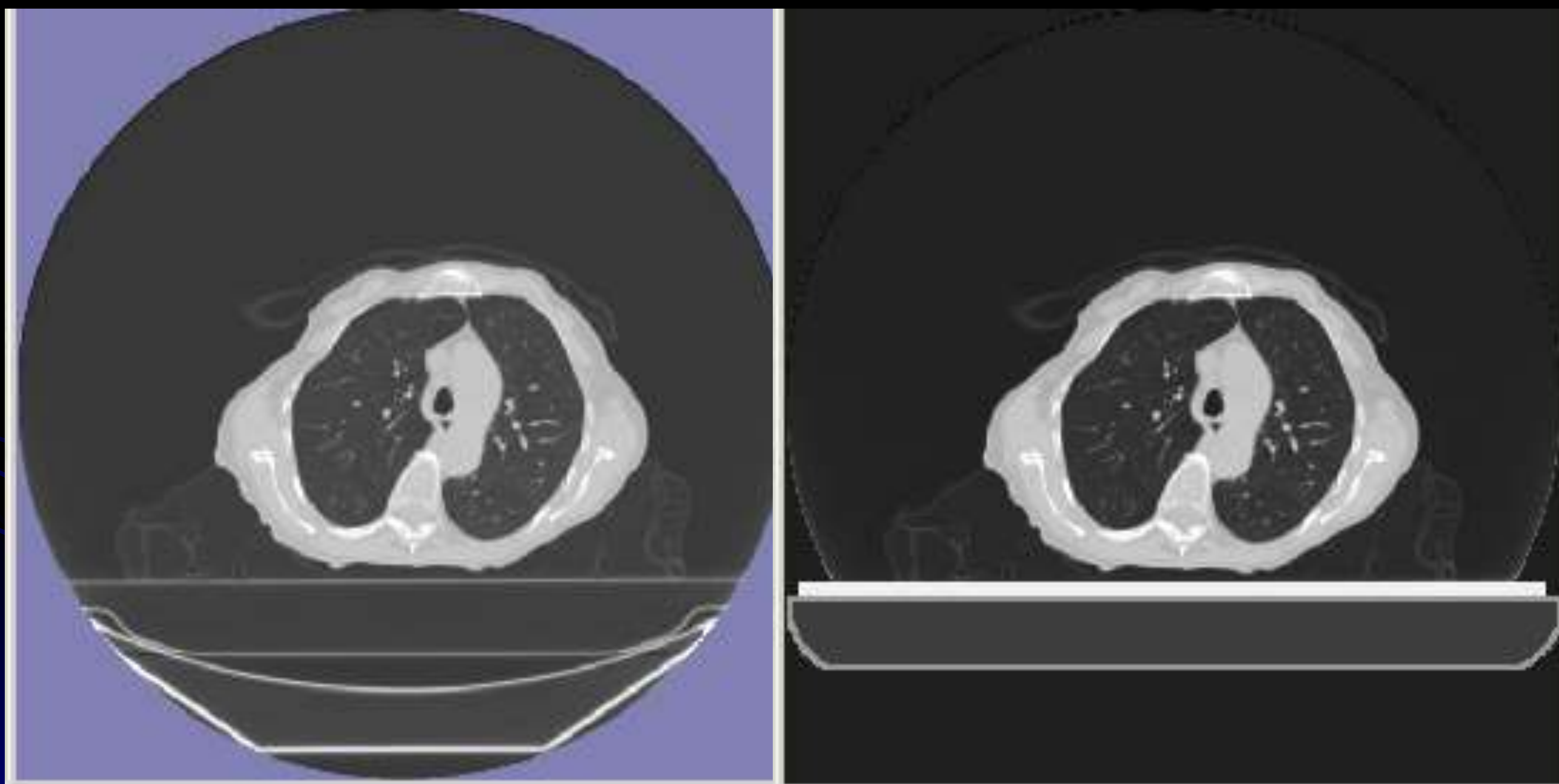


CT artifacts

The digital template of the couch support

- Water-Equivalent-Thickness (WET) was measured experimentally from the change in the distal edge position of a proton beam
- HU numbers were assigned to the geometry template obtained in previous CT scans

Replacing CT couch with a treatment couch in CT images



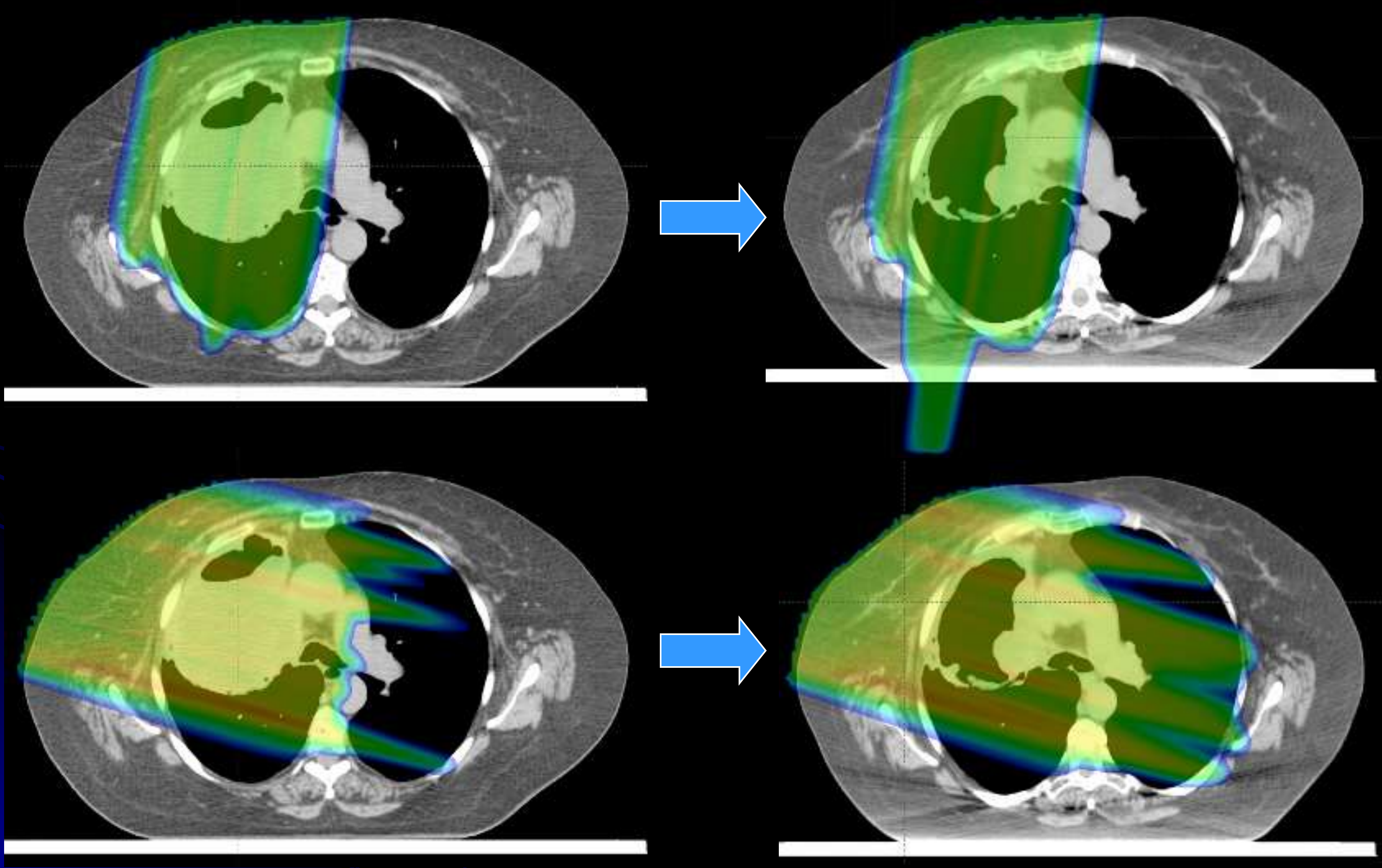
Before

After

Repeat Imaging During Treatment

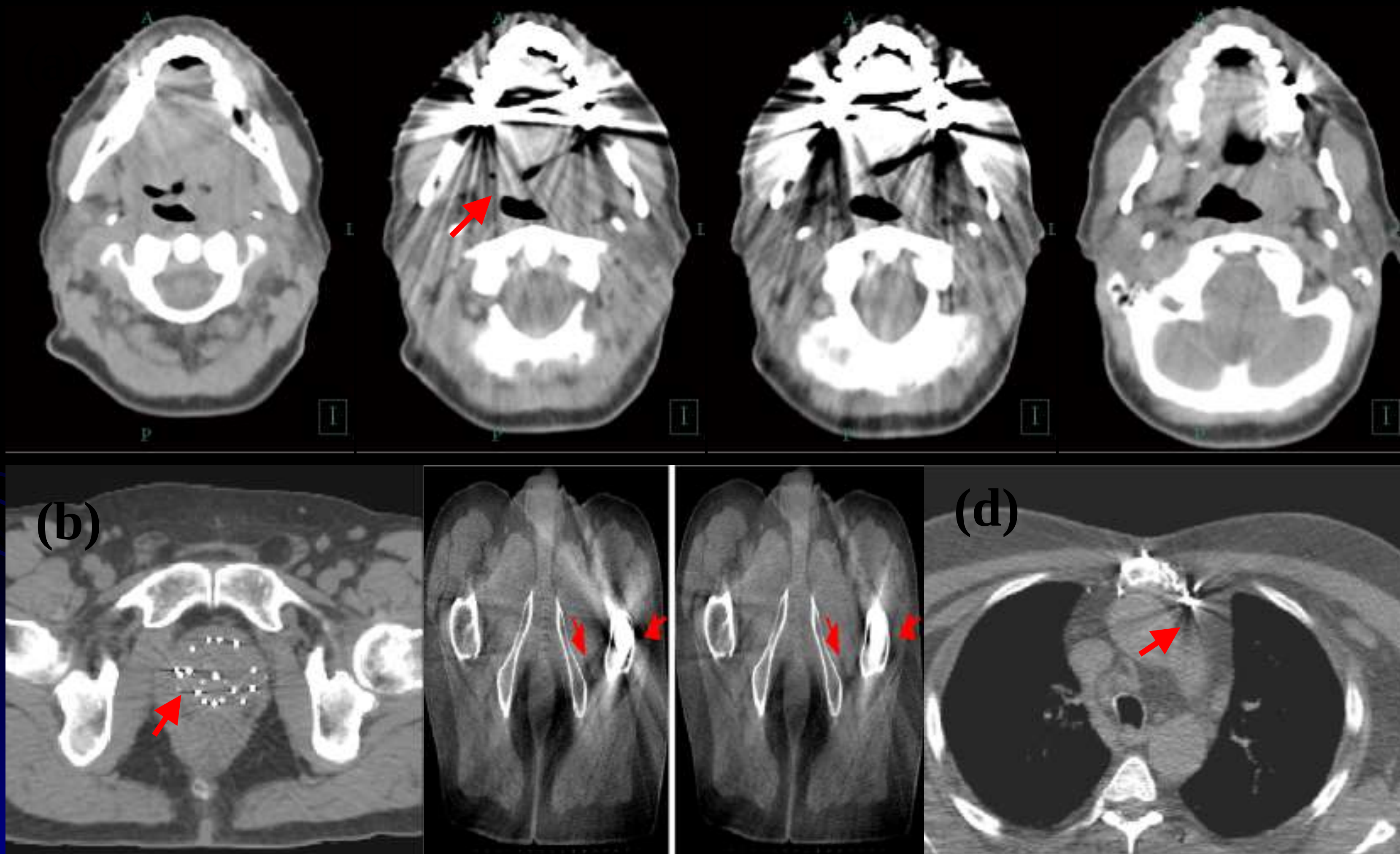
Original Proton Plan

Dose recalculated
on the new anatomy

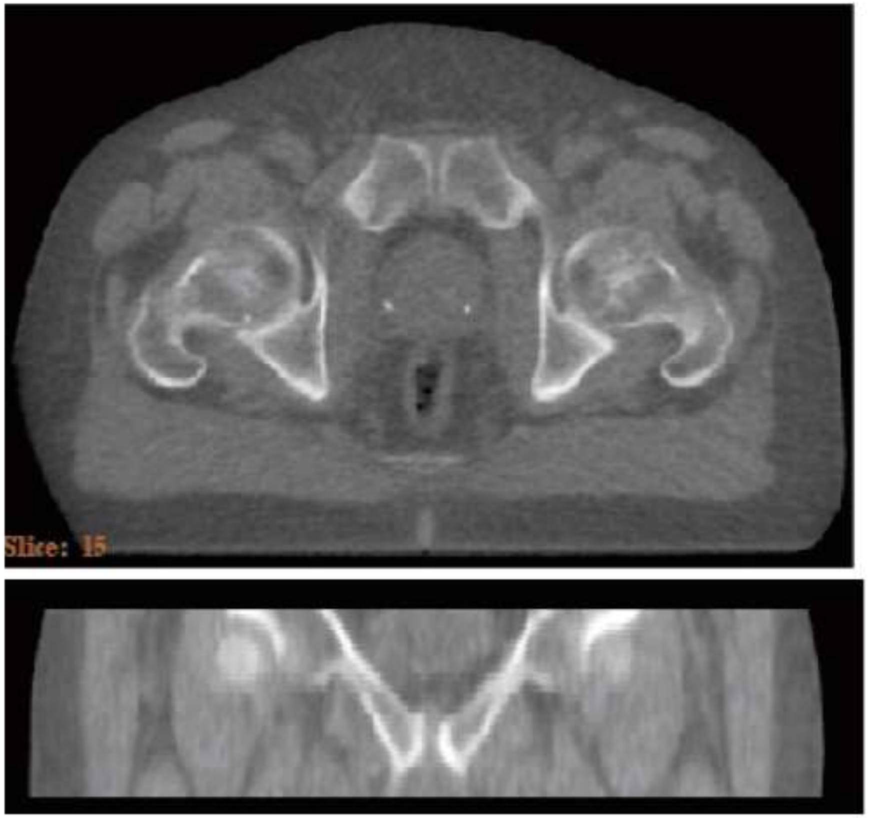


Bucci/Dong et al. ASTRO Abstract, 2007

Metal Artifacts



MV CT Imaging



(a)

(b)

Figure 2. An axial and coronal MVCT slice of a prostate cancer patient (a) and an axial slice of a head and neck patient (b). Bony anatomy and some soft tissue anatomy are visible. The prostate and rectum can be identified in the pelvic anatomy. Structures with less density contrast, e.g., the parotid glands, are harder to distinguish.

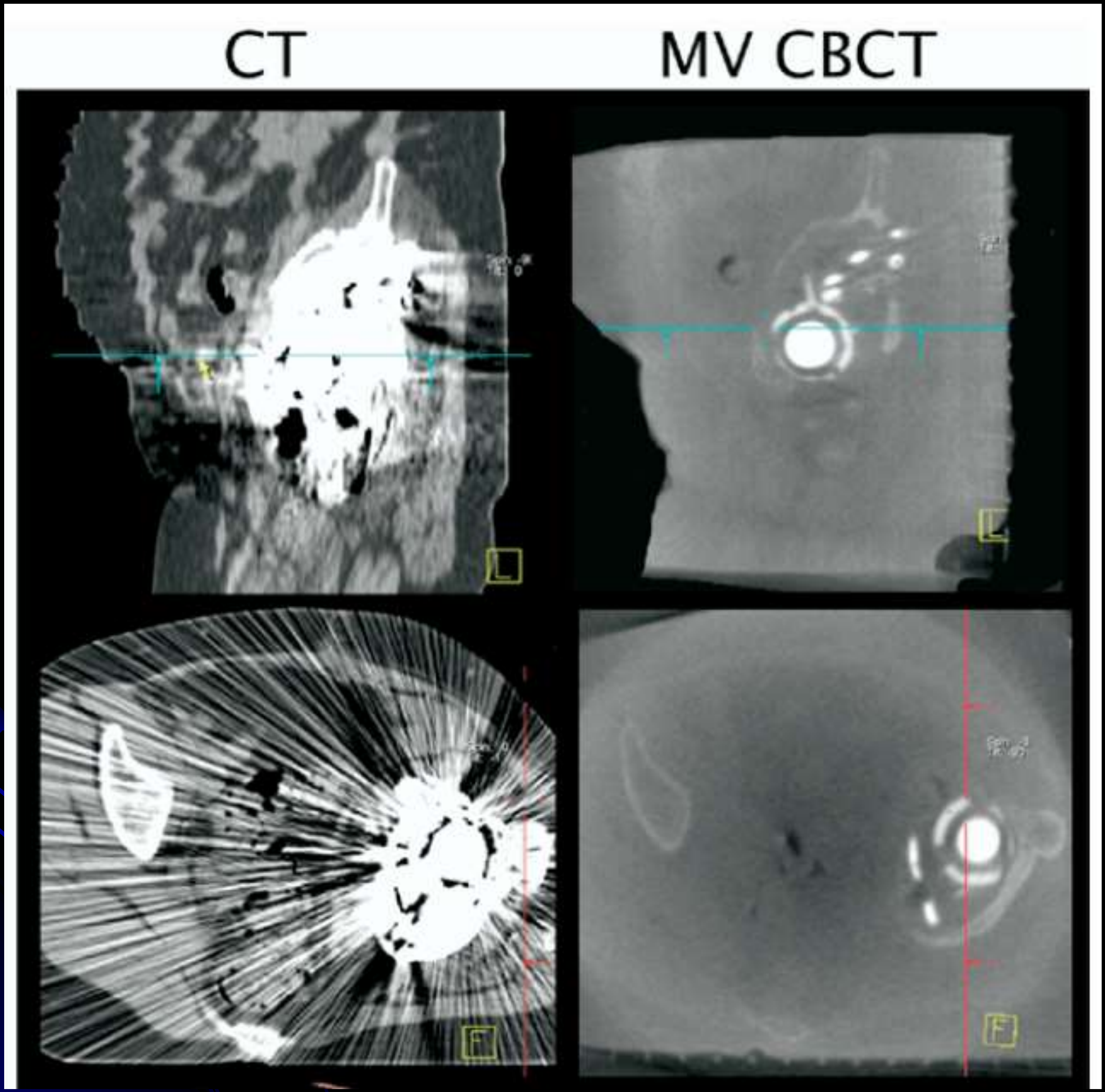
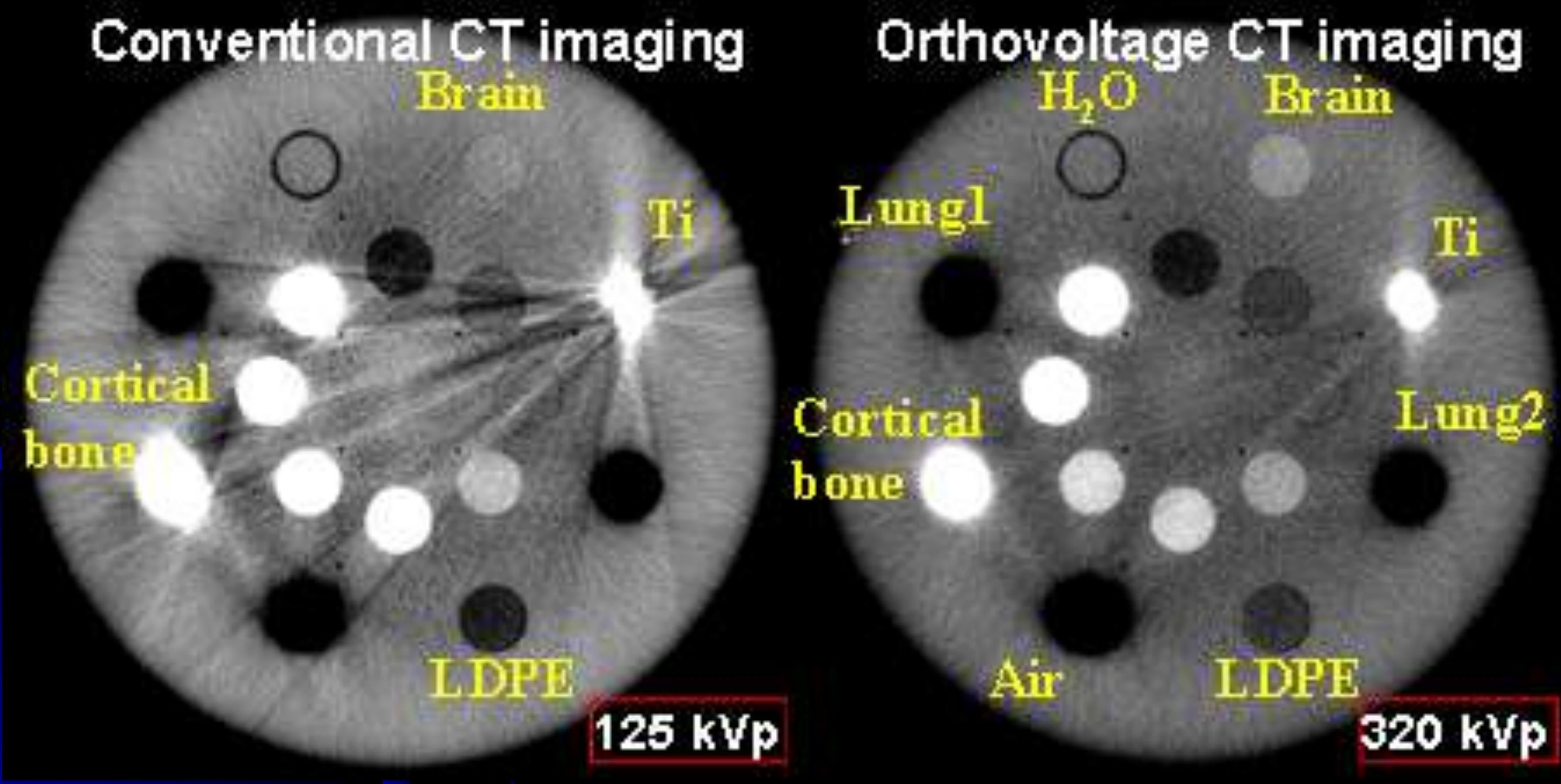


Fig. 5

Morin O, Gillis A, Chen J, *et al.* Megavoltage cone-beam CT: System description and clinical applications. *Med Dosim* 2006;31:51-61.

Use of Orthovoltage CT Imaging



Yang, M et al. (2008). "Improving accuracy of electron density measurement in the presence of metallic implants using orthovoltage computed tomography." Medical Physics 35(5): 1932-1941.

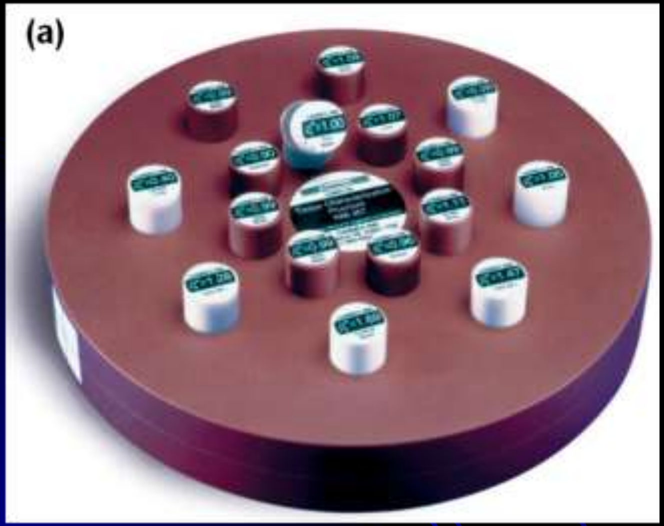
Accurate Dose Calculation

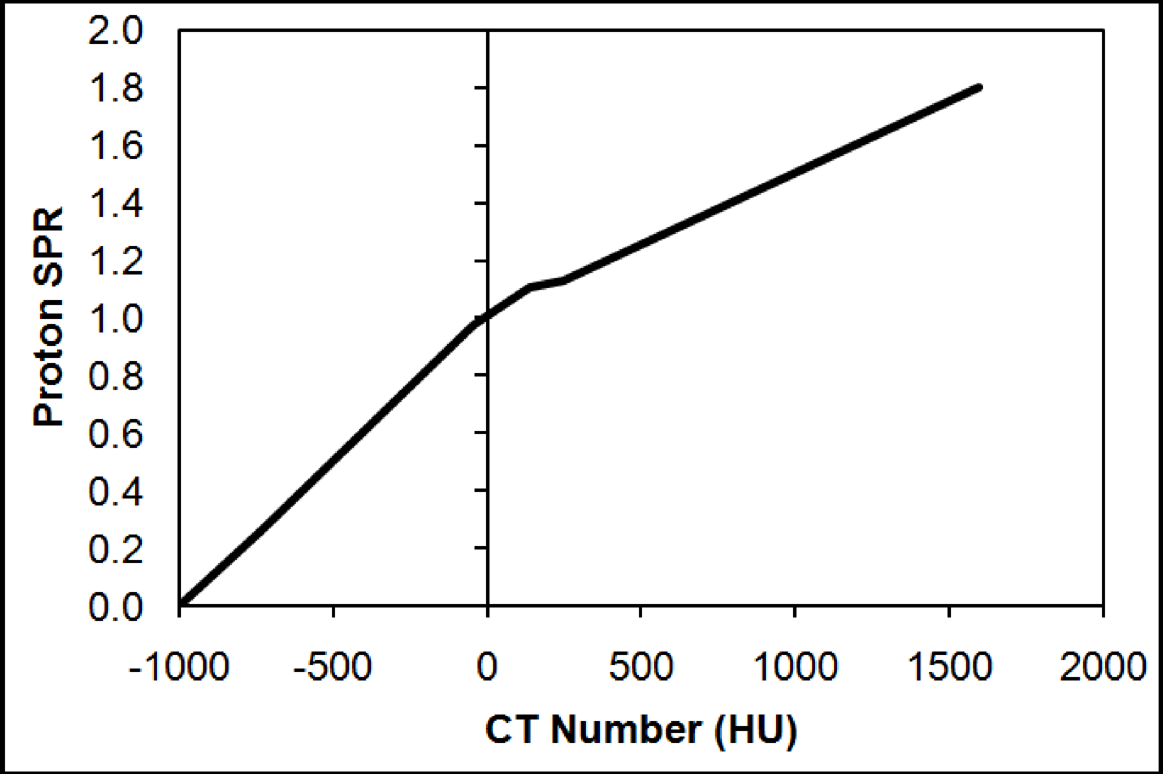
CT number to proton stopping power conversion

Uncertainties in a Proton Plan

- CT imaging to measure stopping power of human tissue
- Dose calculation algorithm
- Setup errors and motion
- Couch or immobilization device in the beam path
- Anatomical changes

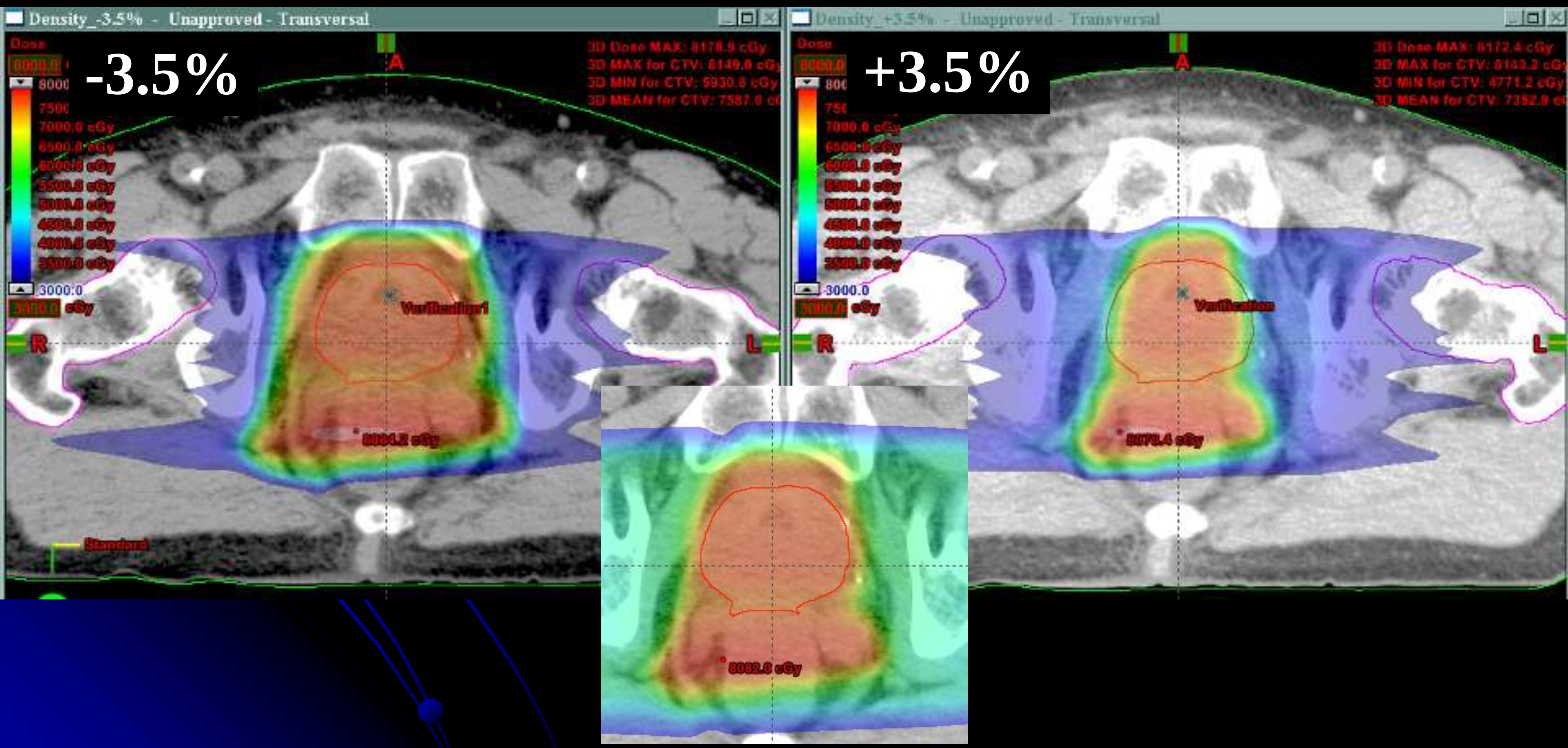
CT calibration to generate proton stopping power ratio





SPR uncertainties have a significant impact on proton dose distributions

Commonly it’s not visible on proton plans

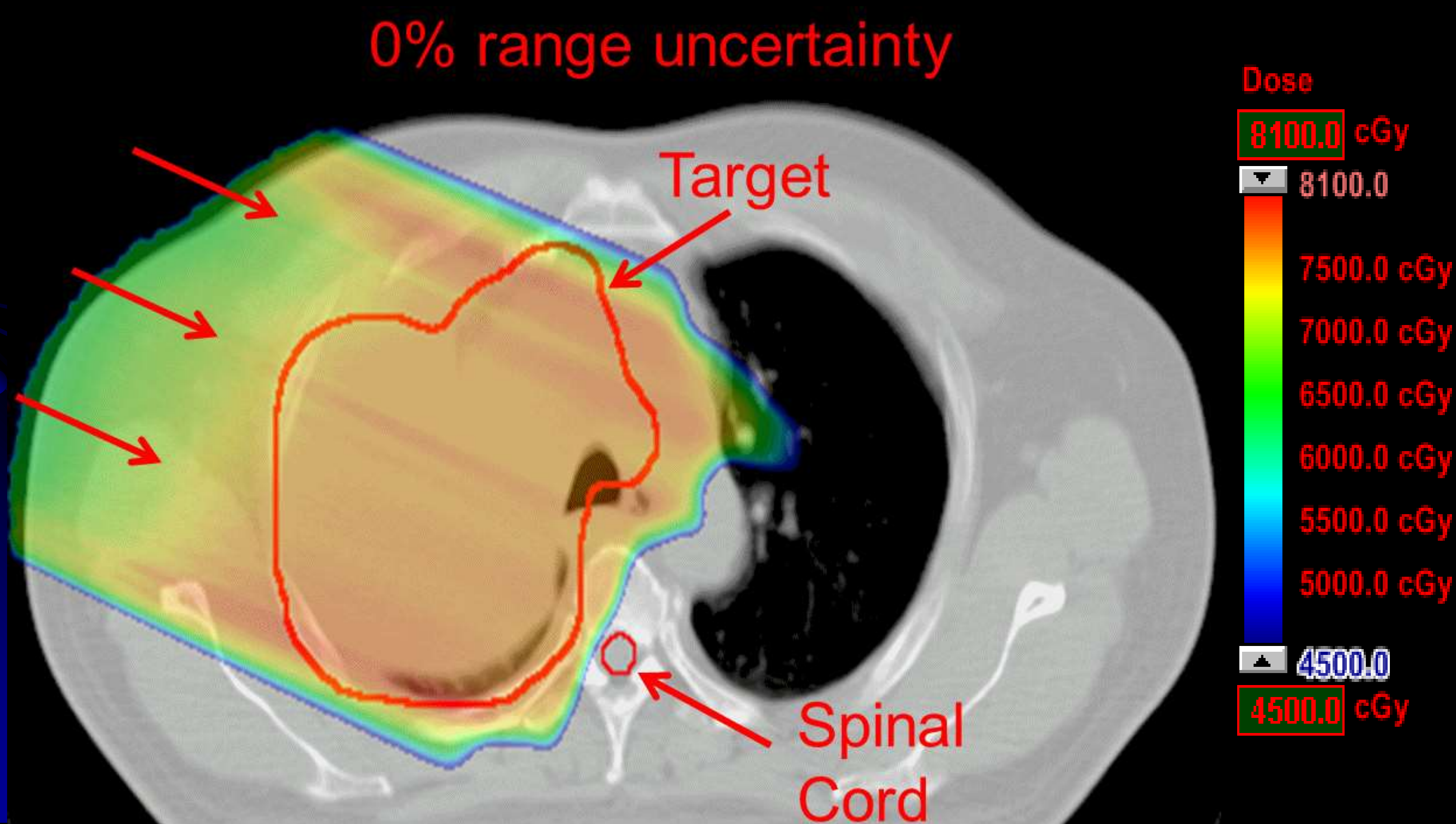


0% uncertainty

Dong

What does the Bragg Peak brag about?

- Uncertainty in SPR estimation
  - Estimated to be 3.5% (Moyers *et al,* 2001, 2009)



Dong

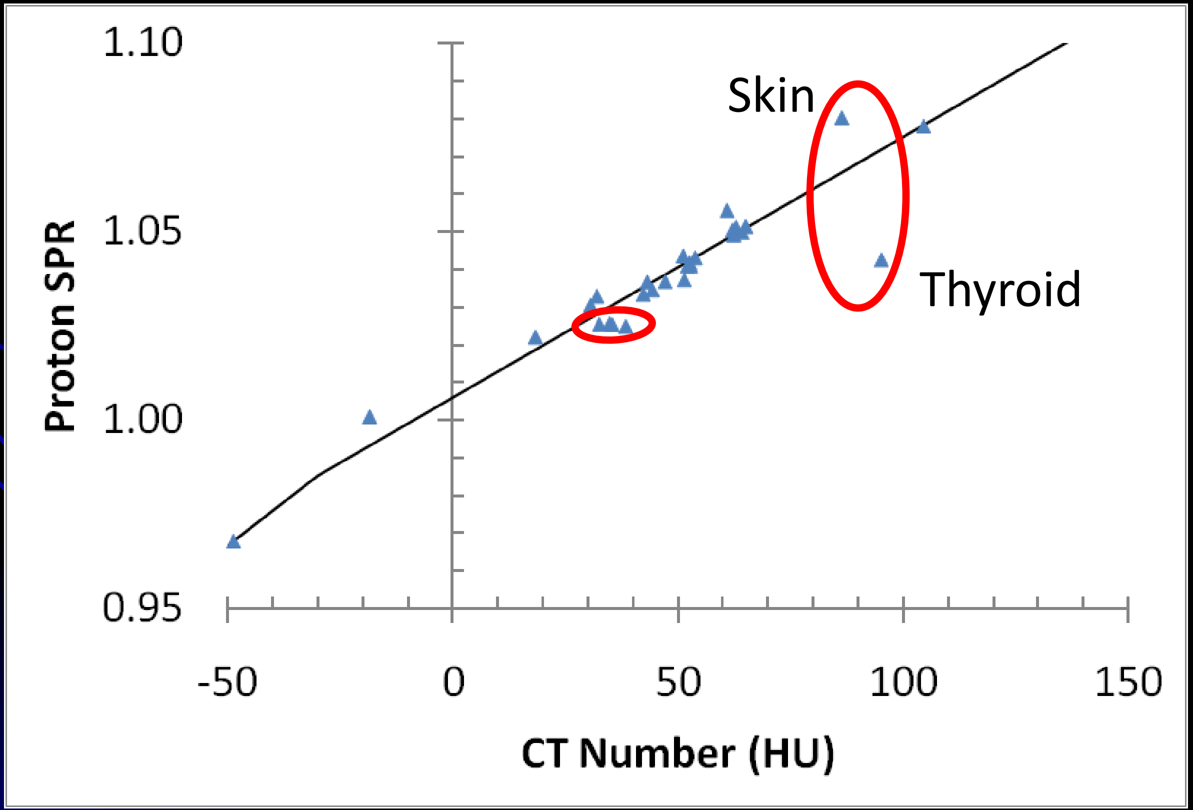
- Proton SPR calculated by the Bethe-Bloch equation:

$$SPR = EDR \times \frac{\ln[2m_e c^2 \beta^2 / I_m (1-\beta^2)] - \beta^2}{\ln[2m_e c^2 \beta^2 / I_{water} (1-\beta^2)] - \beta^2}$$

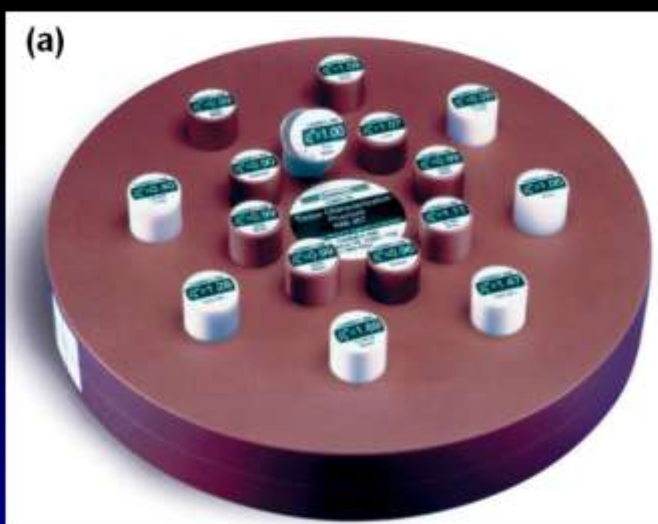
SPR: proton stopping power ratio (relative to water)
EDR: relative electron density
Im: mean excitation energy of the element

Conventional CT-based SPR Estimation

- Degeneracy problem
  - HU (ρ_1, Z_1) = HU (ρ_2, Z_2)
  - SPR$(\rho_1, Z_1) \neq$ SPR(ρ_2, Z_2)



Phantom Composition is Different from Human Tissue!



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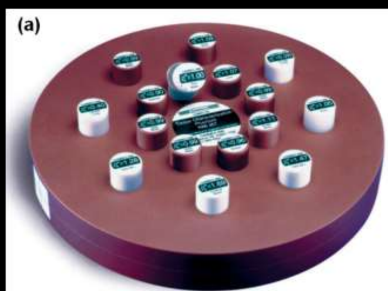
Stoichiometric Calibration Method

Measured CT#s of Human Tissue Substitutes

CT Modeled by a Parameter Set (K^{ph}, K^{coh}, K^{KN})



Elemental Composition of Human Body Tissues

Bethe-Bloch Equation

Predicted CT#s

Calculated SPRs

ICRU Standard Human Tissues

Schneider, et al. *The calibration of CT Hounsfield units for radiotherapy treatment planning*. Phys. Med. Biol. 41 (1996) 111-124.

Examples of ICRU Report #44 Standard Human Tissue Composition

	H	C	N	O	Cl	F	Ca
Atomic Number (Z)	**1**	**6**	**7**	**8**	**17**	**9**	**20**
Atomic Weight (A)	**1.0079**	**12.011**	**14.006**	**15.999**	**35.45**	**18.998**	**40.08**
Rod Material	**Composition in % of weight**						
Adipose (AP6)	8.36%	69.14%	2.36%	16.93%	0.14%	3.07%	0.00%
Breast	8.68%	69.95%	2.37%	17.91%	0.14%	0.00%	0.95%
True Water	11.20%	0.00%	0.00%	88.80%	0.00%	0.00%	0.00%
Liver (LV1)	11.00%	4.10%	1.20%	82.50%	1.20%	0.00%	0.00%
Inner Bone	7.90%	63.79%	4.23%	9.88%	14.20%	0.00%	0.00%
Bone (CB2-50%)	4.77%	41.63%	1.52%	31.99%	0.08%	0.00%	20.03%
Cortical Bone (SB3)	3.10%	31.26%	0.99%	37.57%	0.05%	0.00%	27.03%

Stoichiometric Calibration Method

Relative electron density

$$HU_{sc} = HU + 1000 = \rho_e(A\tilde{Z}^{3.62} + B\hat{Z}^{1.86} + C)$$

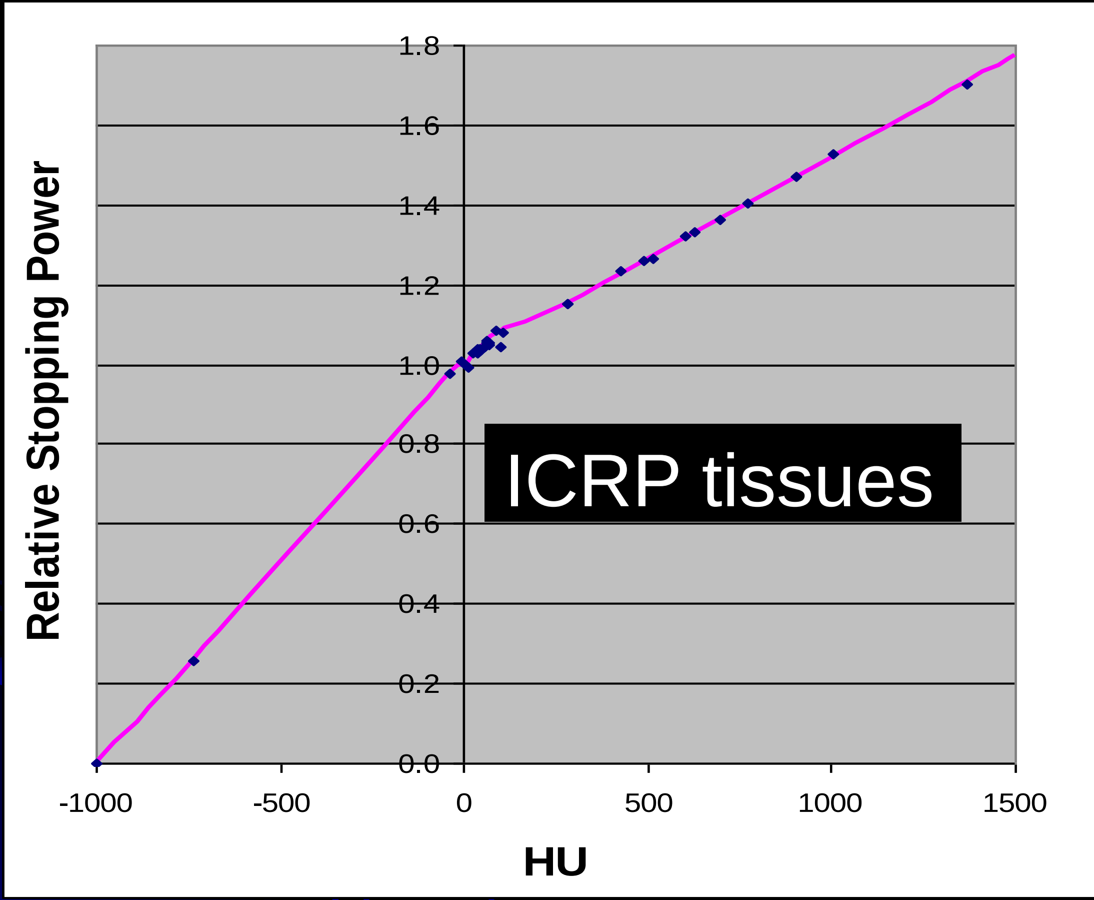
Photoelectric

Incoherent

Coherent

- Linear regression determine A, B & C.
- HU can be calculated for any tissue with known density and composition.

Relative Stopping Power & Calibration Curve



$$S_p = \rho_e K$$

$$K = \frac{L_{tissue}}{L_{water}}$$

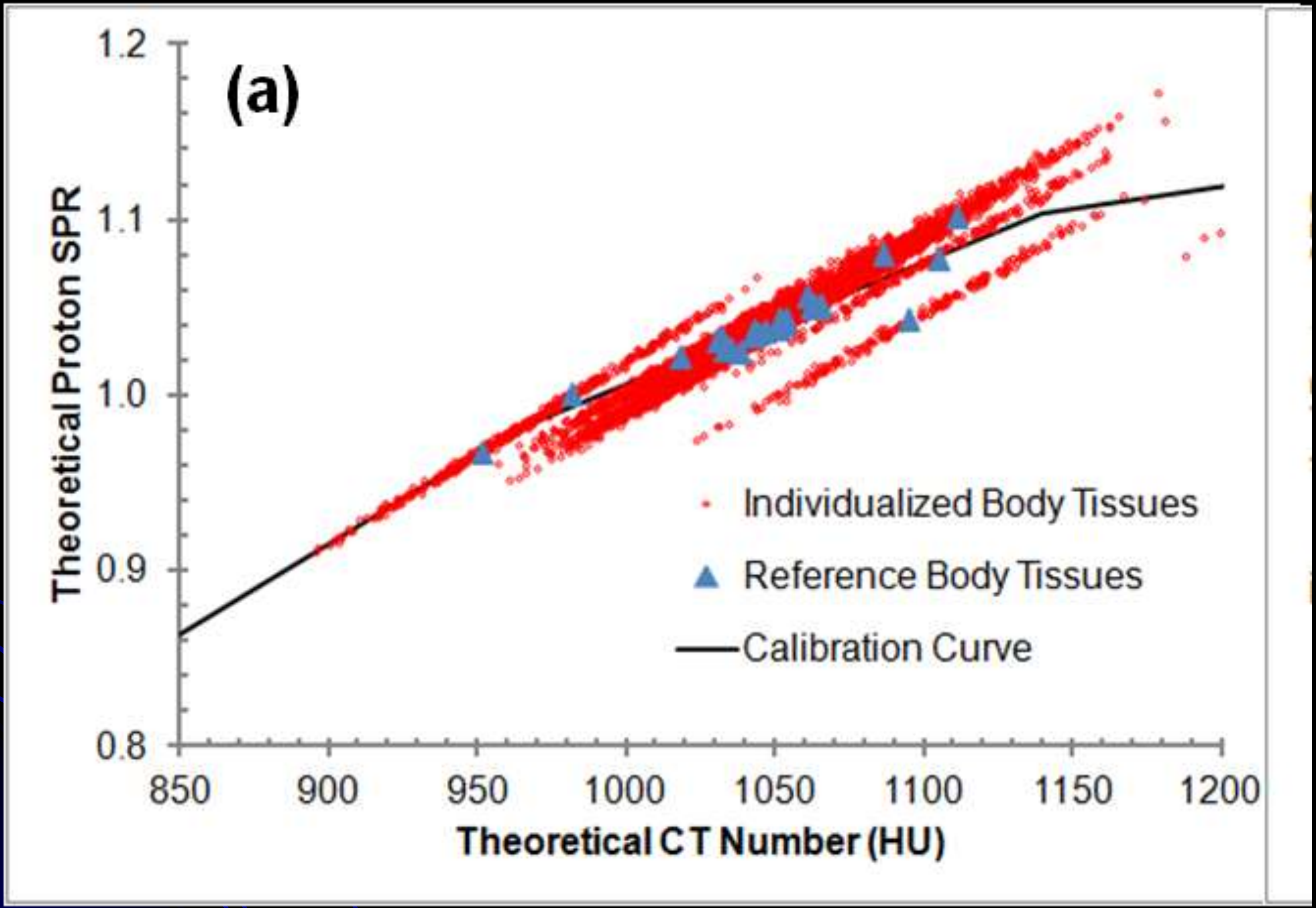
$$L = \log\left(\frac{2m_e c^2 \beta^2}{I(1-\beta^2)}\right) - \beta^2$$

m_e – mass of electron
c – speed of light
β – v/c
v – speed of the proton
I – excitation energy

Uncertainty Category	Uncertainty Source
CT imaging uncertainties	The deviation of HU value from its calibrated value when imaging a patient.
Uncertainties in predicting theoretical CT numbers using tissue substitute phantoms	This includes the uncertainties in the definition and measurement using CT imaging for a tissue substitute phantom, including the parameterization of equation
Uncertainties to calculate SPRs of human tissues	The uncertainties caused by modeling SPR and variations of tissue composition in patient population.
Uncertainties in mean excitation energies	The value of mean excitation energy is critical in calculating SPR
Uncertainties caused by an assumption used in a dose calculation algorithm	For simplicity, some treatment planning systems ignored the SPR dependency on proton energy.

Comprehensive analysis **of the stoichiometric calibration. Yang M. et al.**

Variations in Human Tissue Composition



Yang, M., X. R. Zhu, et al. (2012). "Comprehensive analysis of proton range uncertainties related to patient stopping-power-ratio estimation using the stoichiometric calibration." Physics in Medicine and Biology **57(13): 4095-4115.**

Uncertainties for Tissue Specific SPR

Uncertainty Source	Uncertainties in SPR Estimation (1σ)		
	Lung	Soft	Bone
CT imaging uncertainties	3.3%	0.6%	1.5%
Uncertainties in predicting theoretical CT numbers using tissue substitute phantoms	3.8%	0.8%	0.5%
Uncertainties to calculate SPR of human tissues	0.2%	1.2%	1.6%
Uncertainties in mean excitation energies	0.2%	0.2%	0.6%
Uncertainties caused by an assumption used in a dose calculation algorithm	0.2%	0.2%	0.4%
Total (root-sum-square)	5.0%	1.6%	2.4%

Comprehensive analysis **of the stoichiometric calibration. Yang M. et al.**

Composite Uncertainties in Typical Cases

Tumor Site	Composite Range Uncertainty			Percentile when Range Uncertainty = 3.5%
	Median	90th Percentile	95th Percentile	
Prostate	1.3%	2.5%	3.0%	98%
Lung	1.5%	2.9%	3.4%	96%
Head & neck	1.3%	2.6%	3.0%	98%

Yang M. et al.

Summary of Uncertainties

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 $> \pm$ 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 $> \pm$ 3.0% bone	—	±1.5% water* ±2.5% tissue $> \pm$ 3.0% bone*	±0.5% water^{DE}* ±0.8% tissue^{DE} $> \pm$ 1.0% bone^{DE}*
Metal implants	100%	$z \leq 22$ – 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, et al. *Ion stopping powers and CT numbers*. Medical Dosimetry,35:179-194, 2010

Summary of CT# Variation

	Tissue Groups	Time and Scanner	Size	Position	Couch Position	Root-Sum-Square (RSS)
CT#	Lung	1.0%	4.4%	2.2%	1.8%	5.3%
	Soft	0.3%	0.5%	0.1%	0.4%	0.7%
	Bone	0.6%	2.4%	1.3%	0.7%	2.9%
SPR	Lung	1.0%	4.5%	2.2%	1.8%	5.4%
	Soft	0.3%	0.3%	0.1%	0.3%	0.5%
	Bone	0.4%	1.6%	0.9%	0.5%	1.9%

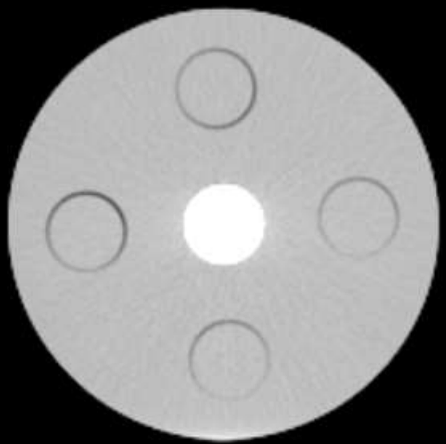
- Patient size is the dominating factor
- Uncertainty is a function of tissue types

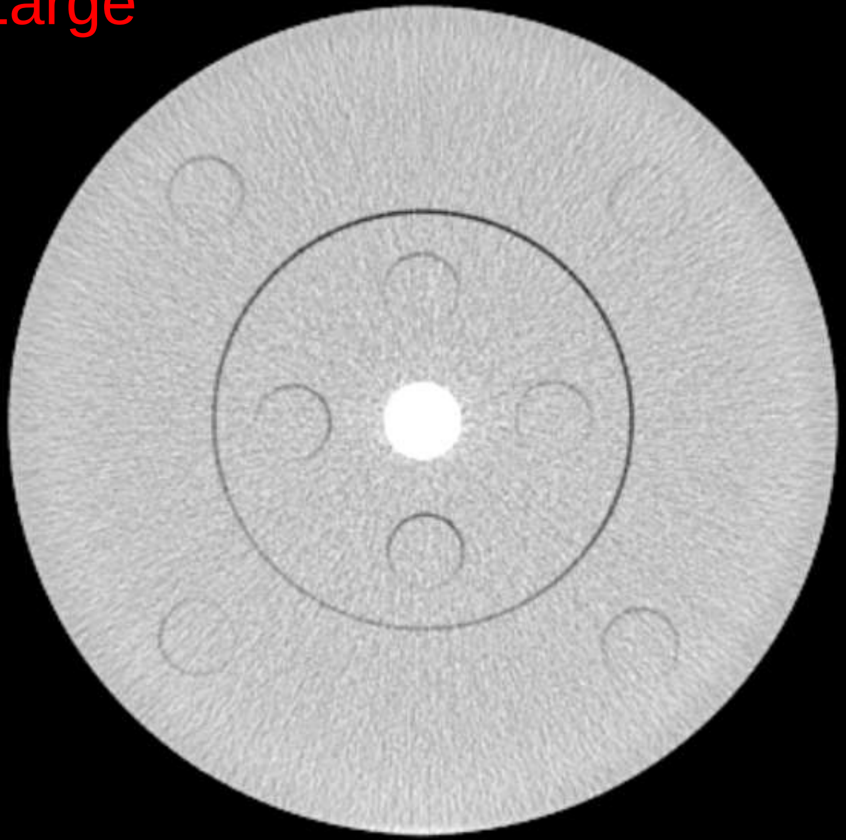
Yang M. et al.

CT Number Uncertainties: Phantom Size

Large

Small





Mitigation of CT imaging uncertainties

- Distal and proximal margins
- Site-specific CT calibration (small phantom vs. large phantom)
- In patient calibration of CT numbers for known anatomy (Moyer et al. 2010)
- Avoiding couch or immobilization device outside CT scanner's FOV

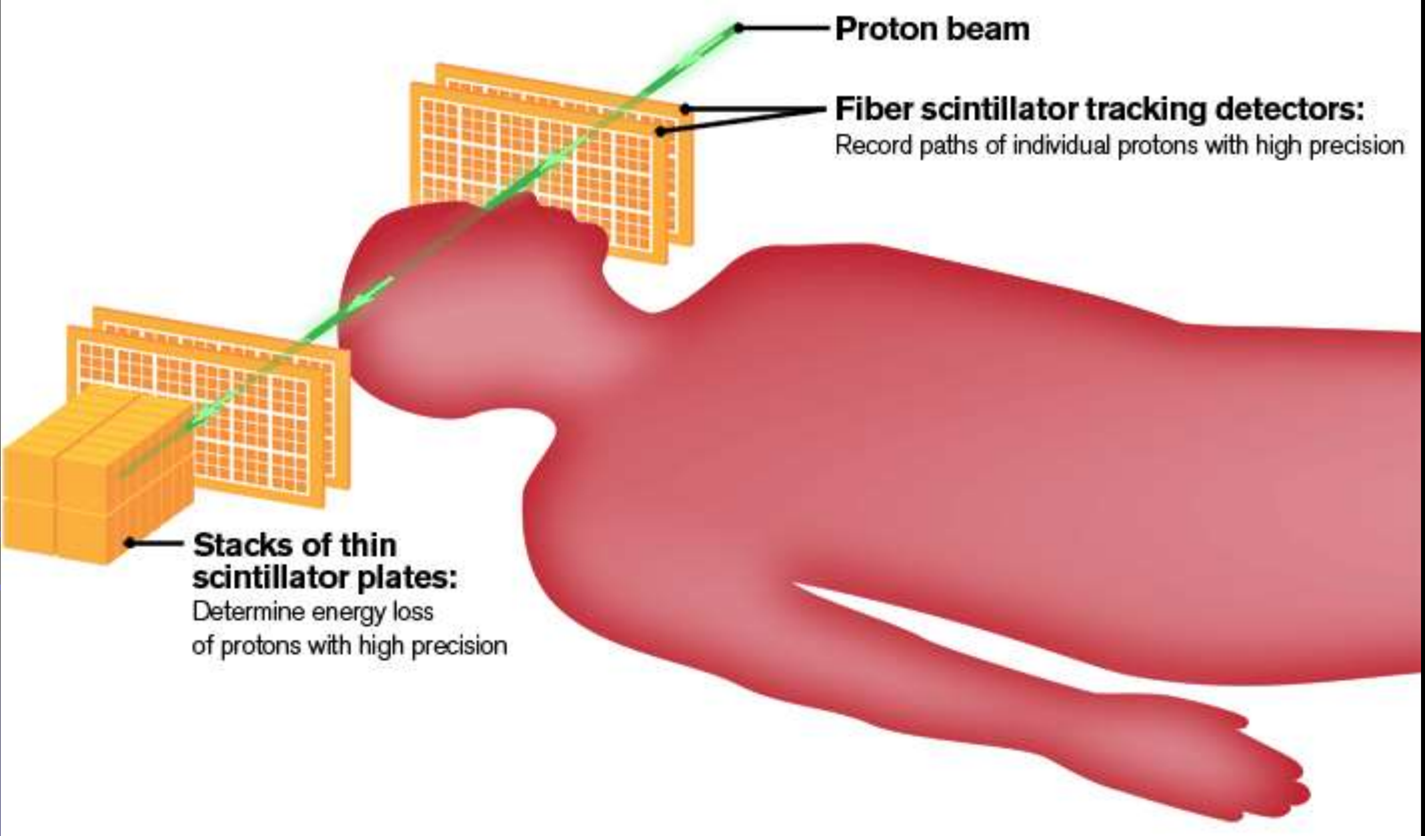
A wish list

- A proton CT to measure SPR in patient
- A MV CT for SPR measurement
- A dual-energy CT to minimize the effect of atomic number
- In-room (4D) CT

kV-MV Dual Energy CT

	SPR Uncertainty (1-SD)			Range Uncertainty (2-SD)		
	Lung	Soft	Bone	Prostate	Lung	HN
kV-MV DECT	3.7%	0.99%	1.4%	1.9%	2.3%	1.9%

A Proton CT Scanner



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Uncertainties in Proton Therapy

- CT imaging to measure stopping power of human tissue
- Dose calculation algorithm
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- Anatomical changes

Summary

The imaging needs for proton therapy are to minimize range uncertainties