UNIVERSITY of MARYLAND
SCHOOL OF MEDICINE

Calibrating CT scanners for Patient Dose Calculations in Proton Beam Radiotherapy

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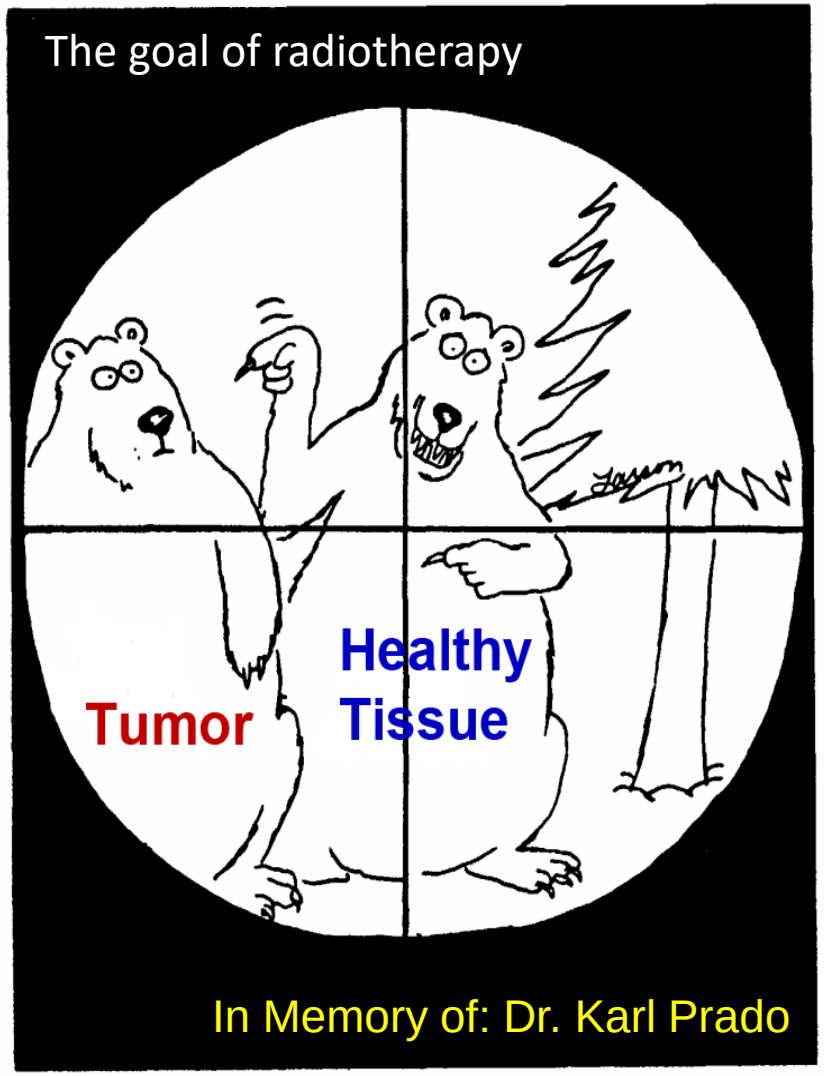
Jerimy C. Polf

Department of Radiation Oncology
Maryland Proton Treatment Center
University of Maryland School of Medicine

Overview

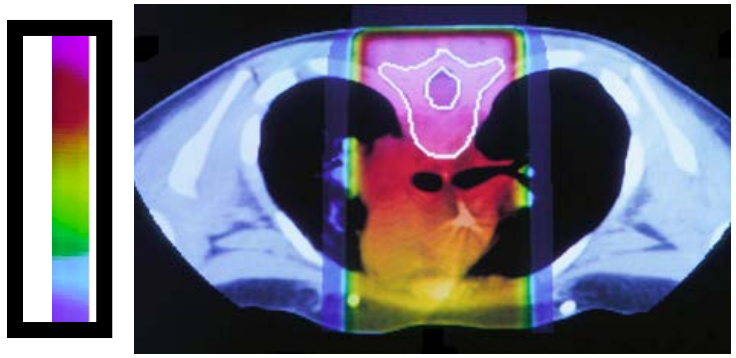
- Proton Therapy
- Calibrating CT scanners for proton dose calculations
- CT calibration uncertainties: “what are the error bars”
- Future trends: Dual Energy CT
- Conclusions/Need for standards



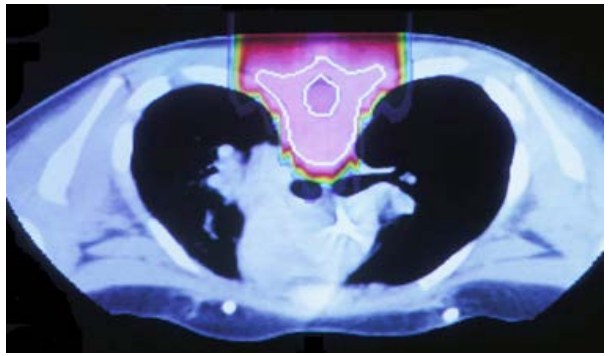
Disclosures:
National Institutes of Health; National Cancer Institute
R01CA187416.
- Prompt gamma imaging for proton radiotherapy treatment verification.

Overview

X-Rays



PROTONS



- Protons Stop!

- Photons don’t!

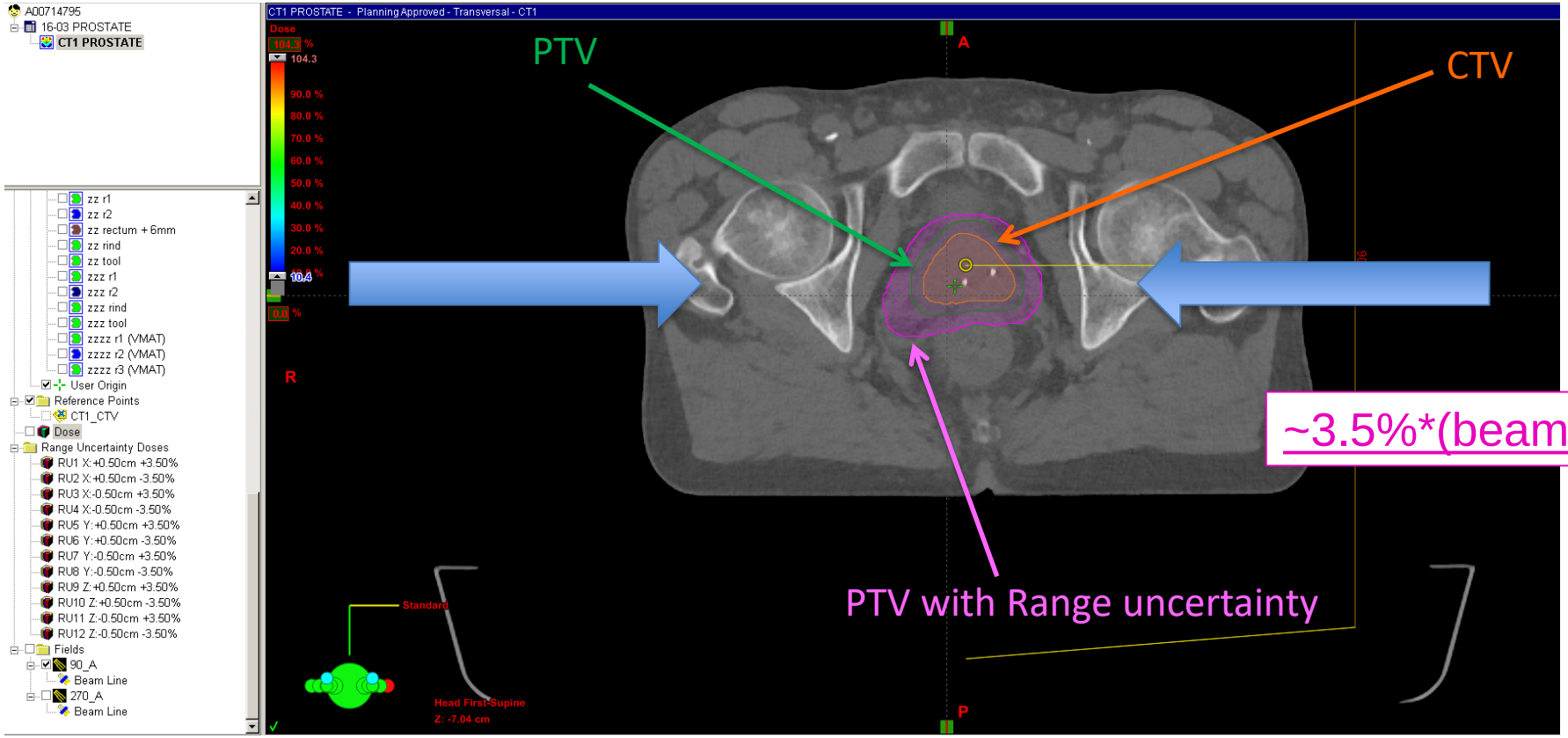
Treatment Planning Process: Expanding Margins

Define our Clinical Target Volume (CTV): the tumor + microscopic disease

Oncologist writes a prescription: 72 Gy in 40 treatment fractions.

Planning Target Volume (PTV): account for setup uncertainty, etc.

Expand PTV to account for range uncertainty



~3.5%*(beam range) + 2 mm

Managing Uncertainties

1. **Dose Calculation**
2. **Treatment Delivery**

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, *PMB* (2012)

Range uncertainty formula:

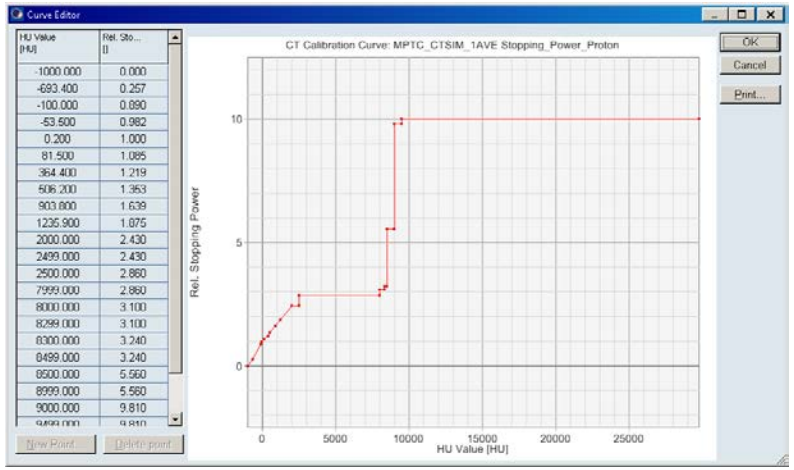
~3.5%*(beam range) + 1-2 mm

Managing Uncertainties: CT calibration

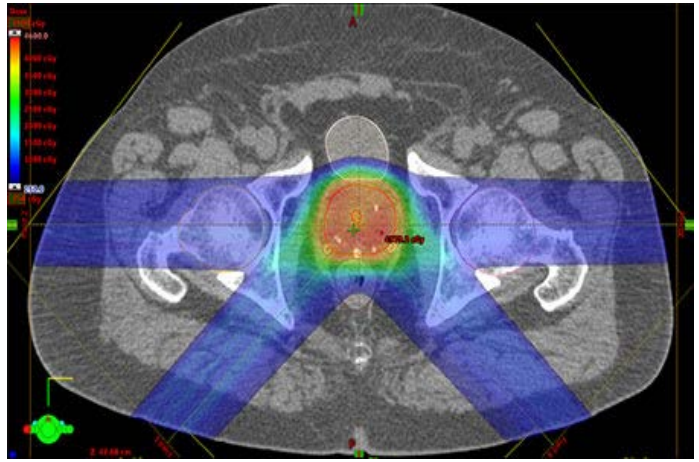
What we need for dose calculation:

- Proton RT
  - Density and Stopping Power Ratios (SPR)

    (or relative stopping power)



$$Stop \quad \mathrm{SPR} = \rho^{tissue} \cdot \frac{(\sum wZ/A)_{tissue}}{(\sum wZ/A)_{\mathrm{water}}} \cdot \frac{\left\{\ln\left(\frac{2m_e c^2\beta^2}{I_{tissue}(1-\beta^2)}\right)-\beta^2\right\}}{\left\{\ln\left(\frac{2m_e c^2\beta^2}{I_{\mathrm{water}}(1-\beta^2)}\right)-\beta^2\right\}}, \quad \left.\right\}-\beta^2\Big\}$$

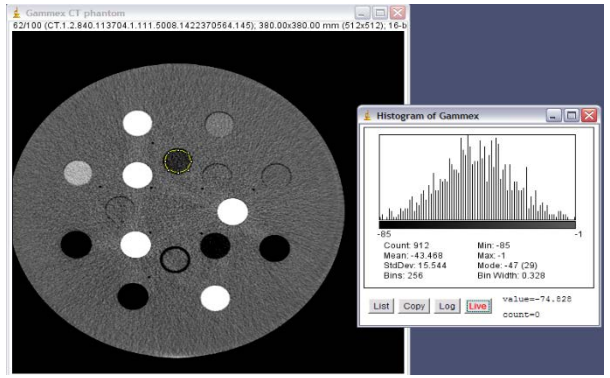


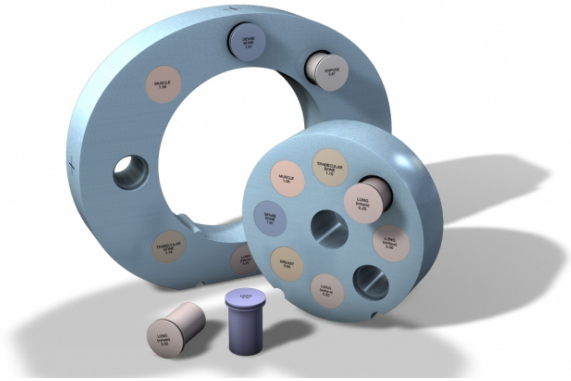
For protons the accepted clinical method for this
Is the "*Stoichiometric Method*".

[Schnieder et al, PMB, **41** (1996)]

Managing Uncertainties: CT calibration

1. *Acquire CT scan* of phantom with tissue equivalent materials with *known density and elemental compositions*.
2. *Measure HUs* for each tissue equivalent material.
3. Use measured HUs to *determine coefficients (A, B, C)* for "*stoichiometric parameterization equation*."
4. Using stoichiometric parameterization, *calculate HUs* for a full range of tissues using their published elemental compositions and physical densities.
5. *Calculate the stopping power ratio (SPR)* for each tissue based on known elemental composition and electron densities.
6. *Plot calculated HU vs. calculated SPR* of each tissue.
7. *Fit line through the HU vs SPR data* to be used for treatment planning.





Managing Uncertainties: CT calibration

calculate tissue HU values.

$$HU_i + 1000 = 1000 \times \mu_i^{rel} = A(\rho_{e_i}^{rel} \tilde{Z}_i^{3.62}) + B(\rho_{e_i}^{rel} \hat{Z}_i^{1.86}) + C(\rho_{e_i}^{rel})$$

Using tissue composition data from ICRU 46 and 49, We calculate both "Z_{eff}" values and ρ^{rel}_e.

Plug into Stoichiometric formula, and calculate HU for each tissue.

Tissue	Calculated HU	
	BODY 120KVP	HN 120KVP
Adipose Tissue ICRU 49	-91.10	-90.84
Adipose Tissue	-48.08	-44.04
Average soft tissue (male)	12.05	23.55
Average soft tissue (female)	1.05	10.95
Blood	43.47	59.10
Brain	27.65	41.77
Breast-50/50	-51.60	-46.51
Breast-33/67	-72.92	-70.48
Eye lens	40.67	54.12
GI Tract	15.76	28.69
Heart-bloodfilled	43.85	59.33
Kidney	33.24	47.70
Liver-healthy	41.80	56.88
Liver-cirrhotic	21.87	34.50
Lung-inflated	-680.27	-706.52
Lymph	19.86	33.95
Muscle-striated (ICRU 49)	24.16	38.34
Muscle-skeletal (ICRU 49)	22.90	37.06
Muscle-Skeletal (adult)	32.48	46.89
Ovary	35.25	50.02
Pancreas	33.06	46.60
Skin	62.86	77.73
Spleen	42.93	58.19
Testis	26.52	40.60
Thyroid	54.58	74.41
Bladder-empty	27.19	41.78
Bladder-filled	22.08	36.95
Water	-5.99	6.33
Cartlidge	81.45	101.85
Cortical Bone (ICRU 49)	1058.51	1238.64
Cortical Bone	1138.03	1333.82
Cranium	745.28	876.44
Femur	407.35	485.64
Mandible	831.36	976.20
Rib-2nd&6th	490.19	579.11
Rib-10th	629.77	741.64
Sacrum (male)	338.68	402.82
Sacrum (female)	464.06	548.43
Vertebrae-C4	502.05	592.85
Vertebrae-L3	391.25	464.45
RedMarrow	7.94	17.48
Yellow Marrow	-40.97	-38.16

	H	C	N		ρ_e	ρ_s
Adipose tissue	11.4	59.8	0.	0	0.951	0.979
Blood	10.2	11.0	3.	5	1.050	1.053
Brain	10.7	14.5	2.	7	1.035	1.040
Breast	10.6	33.2	3.	3	1.014	1.029
Cell nucleus	10.6	9.0	3.	3	0.994	0.996
Eye lens	9.6	19.5	5.	0	1.055	1.060
GI tract	10.6	11.5	2.	3	1.024	1.028
Heart	10.3	12.1	3.	5	1.051	1.054
Kidney	10.3	13.2	3.	3	1.041	1.045
Liver	10.2	13.9	3.	3	1.050	1.054
Lung (deflated)	10.3	10.5	3.	4	1.041	1.044
Lung (inflated)				9	0.258	0.258
…						
…						
Skeleton—sacrum	7.4	30.2	3.	413	1.244	1.238
Skeleton—spongiosa	8.5	40.4	2.	260	1.150	1.156
Skeleton—vertebral column (C4)	6.3	26.1	3.	609	1.355	1.337
Skeleton—vertebral column (D6, L3)	7.0	28.7	3.	477	1.278	1.267

Managing Uncertainties: CT calibration

calculate tissue SPR values.

$$\mathrm{SPR} = \rho^{tissue} \cdot \frac{(\sum wZ/A)_{tissue}}{(\sum wZ/A)_{\mathrm{water}}} \cdot \frac{\left\{\ln\left(\frac{2m_e c^2\beta^2}{I_{tissue}(1-\beta^2)}\right)-\beta^2\right\}}{\left\{\ln\left(\frac{2m_e c^2\beta^2}{I_{\mathrm{water}}(1-\beta^2)}\right)-\beta^2\right\}},$$

ICRU 46 tissue composition values

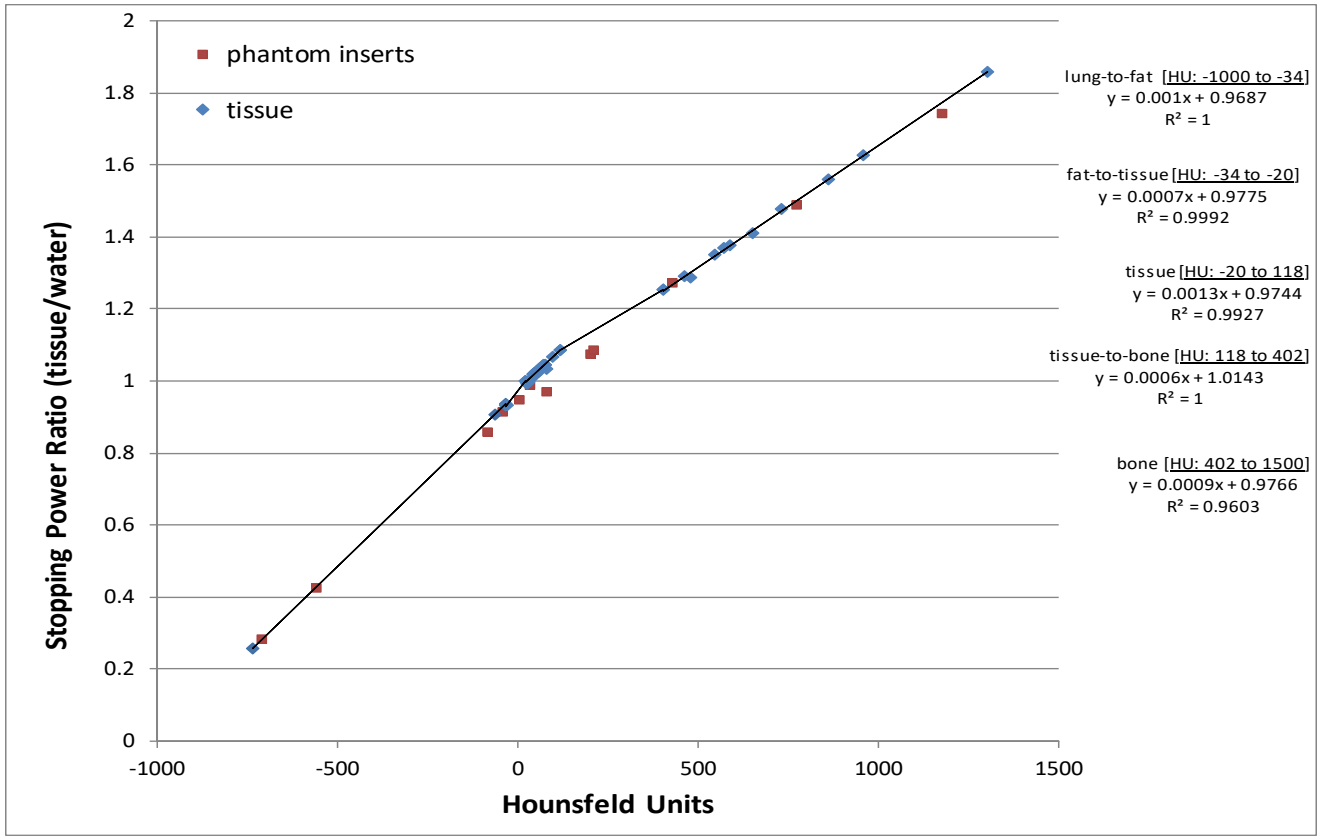
	H	C	N	O	Ca	P	Na	Mg	S	Cl	K	Fe	I	ρ	H	ρ_e	ρ_s
Adipose tissue	11.4	59.8	0.7	27.8			0.1		0.1	0.1				0.95	930	0.951	0.979
Blood	10.2	11.0	3.3	74.5		0.1	0.1		0.2	0.3	0.2	0.1		1.06	1055	1.050	1.053
Brain	10.7	14.5	2.2	71.2		0.4	0.2		0.2	0.3	0.3			1.04	1037	1.035	1.040
Breast	10.6	33.2	3.0	52.7		0.1	0.1		0.2	0.1				1.02	1003	1.014	1.029
Cell nucleus	10.6	9.0	3.2	74.2		2.6			0.4					1.00	1003	0.994	0.996
Eye lens	9.6	19.5	5.7	64.6		0.1	0.1		0.3	0.1				1.07	1050	1.055	1.060
GI tract	10.6	11.5	2.2	75.1		0.1	0.1		0.1	0.2	0.1			1.03	1023	1.024	1.028
Heart	10.3	12.1	3.2	73.4		0.1	0.1		0.2	0.3	0.2	0.1		1.06	1055	1.051	1.054
Kidney	10.3	13.2	3.0	72.4	0.1	0.2	0.2		0.2	0.2	0.2			1.05	1043	1.041	1.045
Liver	10.2	13.9	3.0	71.6		0.3	0.2		0.3	0.2	0.3			1.06	1053	1.050	1.054
Lung (deflated)	10.3	10.5	3.1	74.9		0.2	0.2		0.3	0.3	0.2			1.05	1044	1.041	1.044
Lung (inflated)														0.26	259	0.258	0.258
…																	
…																	
Skeleton—sacrum	7.4	30.2	3.7	43.8	9.8	4.5		0.1	0.2	0.1	0.1	0.1		1.29	1413	1.244	1.238
Skeleton—spongiosa	8.5	40.4	2.8	36.7	7.4	3.4	0.1	0.1	0.2	0.2	0.1	0.1		1.18	1260	1.150	1.156
Skeleton—vertebral column (C4)	6.3	26.1	3.9	43.6	13.3	6.1	0.1	0.1	0.3	0.1	0.1	0.1		1.42	1609	1.355	1.337
Skeleton—vertebral column (D6, L3)	7.0	28.7	3.8	43.7	11.1	5.1		0.1	0.2	0.1	0.1	0.1		1.33	1477	1.278	1.267

Managing Uncertainties: CT calibration

This is the “HU-to-SPR curve” that you
Put into your treatment planning system
For proton dose calculations.

How accurate is this curve?

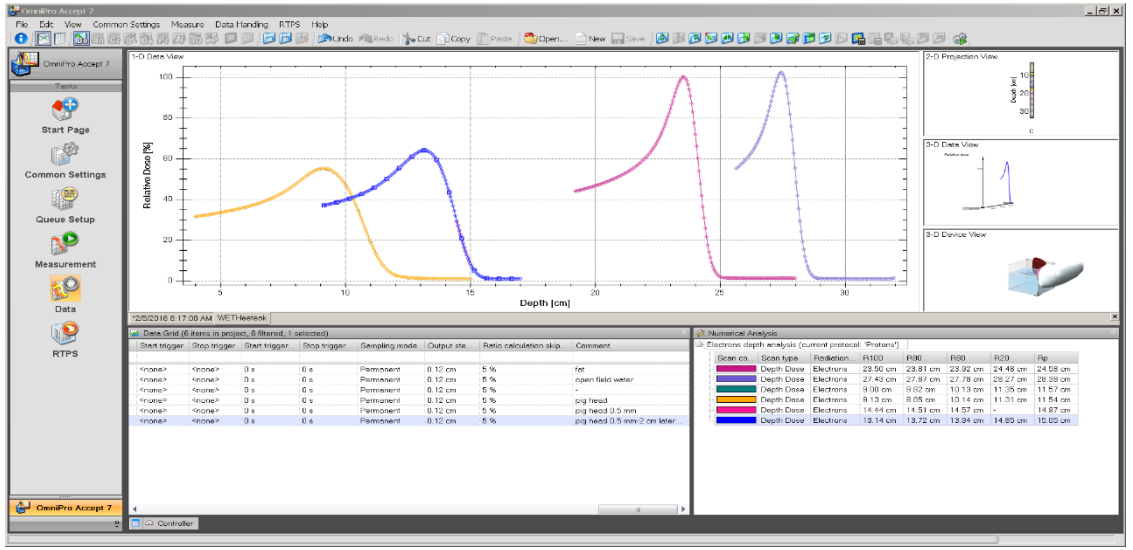
Inaccurate calibration = Inaccurate beam range



Managing Uncertainties: CT calibration

1) Measured the “water equivalent thickness” (WET) through several pig tissues.

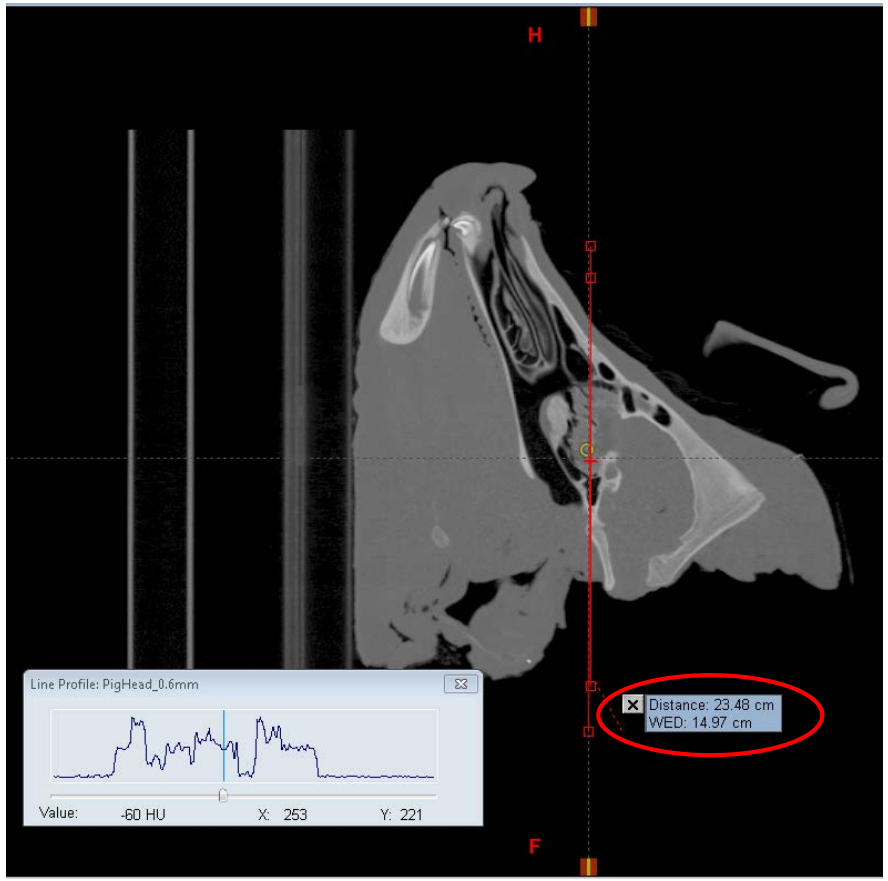
WET = Beam range without sample – beam range with sample



Managing Uncertainties: CT calibration

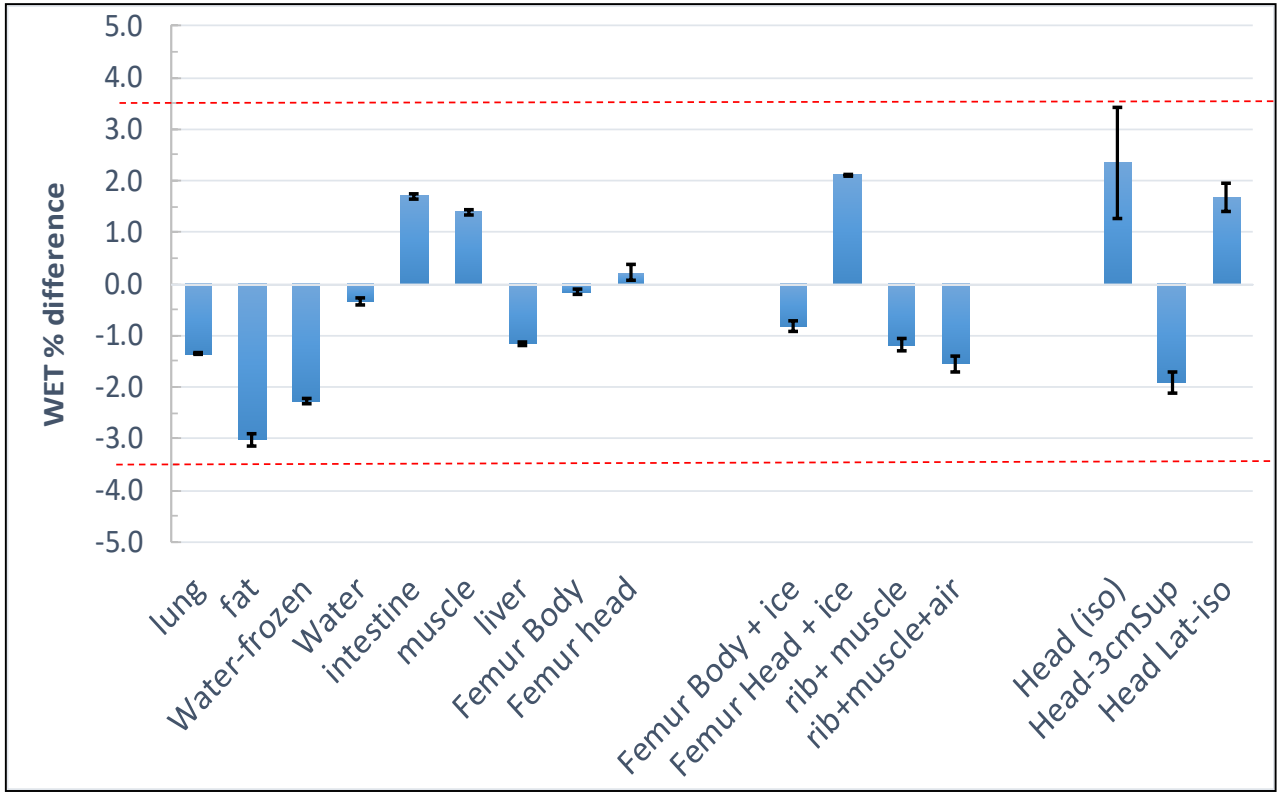
2) Compared them to WET values through the tissues calculated by Treatment Planning System(TPS).

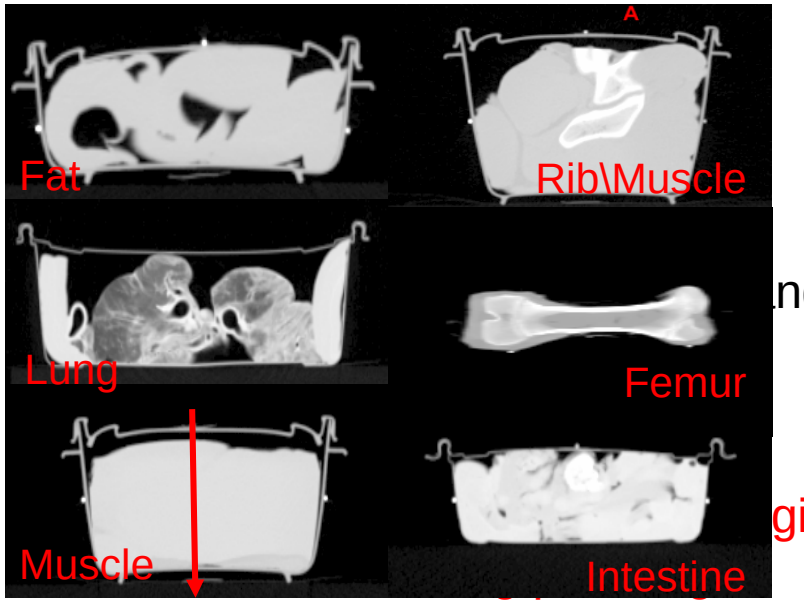
WET(TPS) = thickness*SPR



Managing Uncertainties: CT calibration

WET % difference = {[WET(TPS) – WET(Measured)]/WET(Measured)}*100





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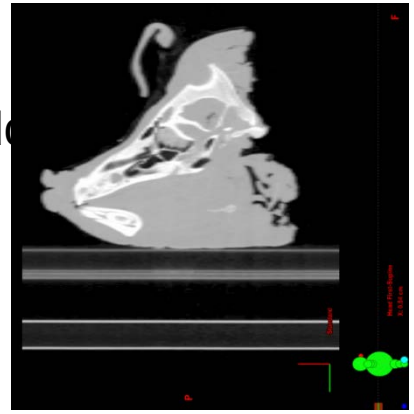
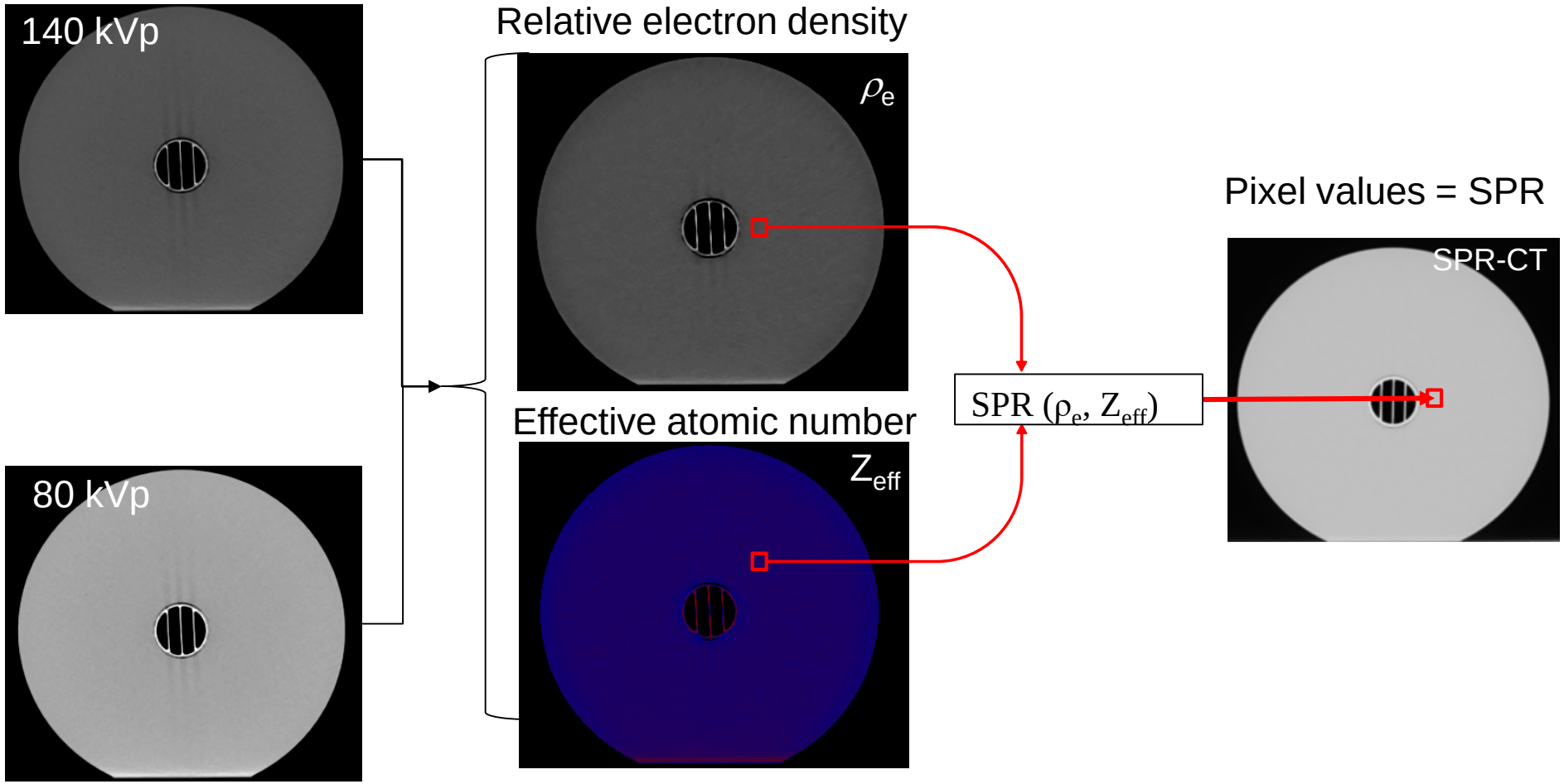
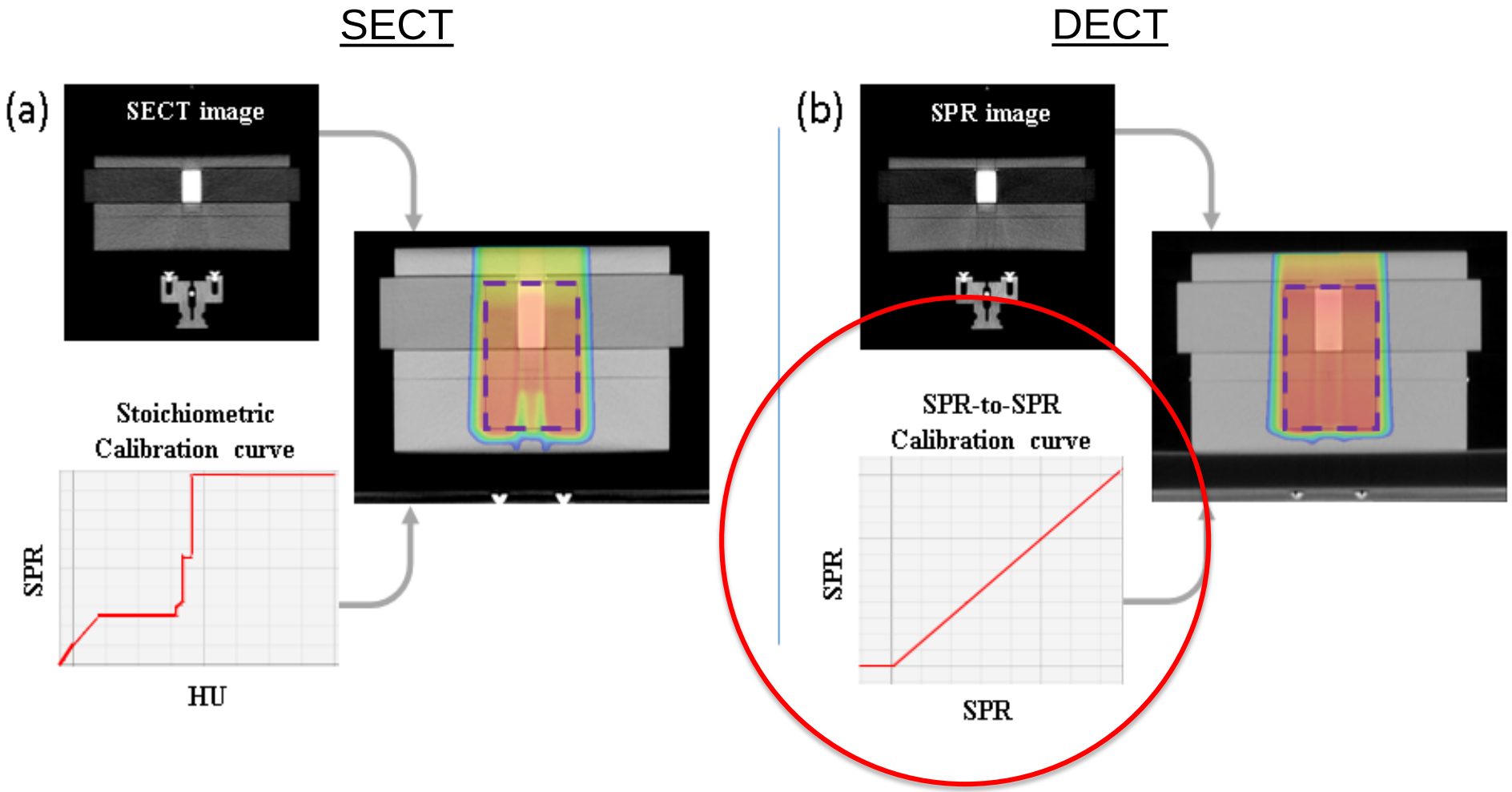


Managing Uncertainties: CT calibration

Dual energy CT calibration for Proton therapy

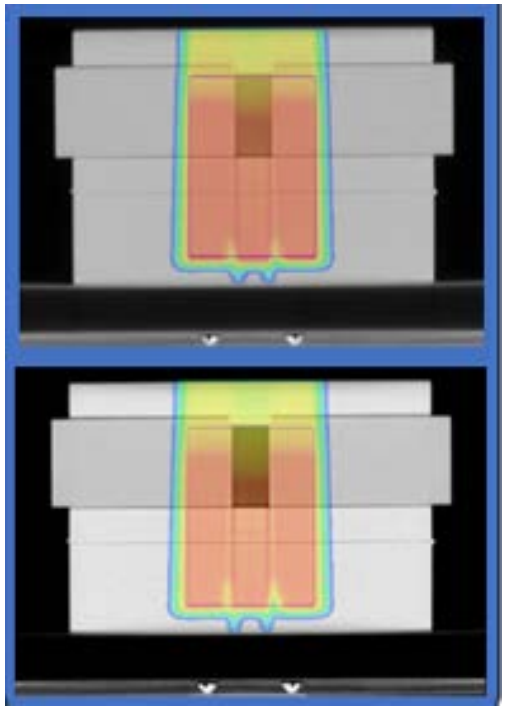


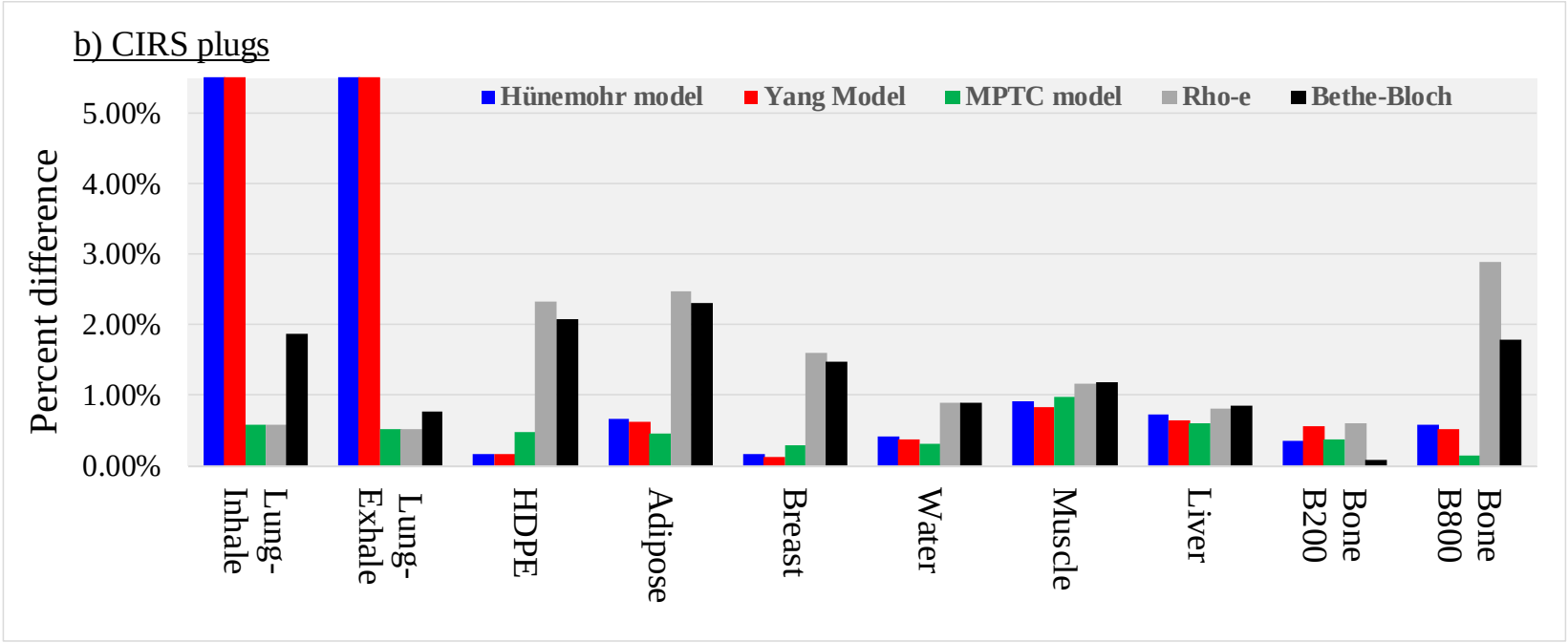
Managing Uncertainties: CT calibration



Managing Uncertainties: CT calibration

WET Measurements: “comparing our error bars”

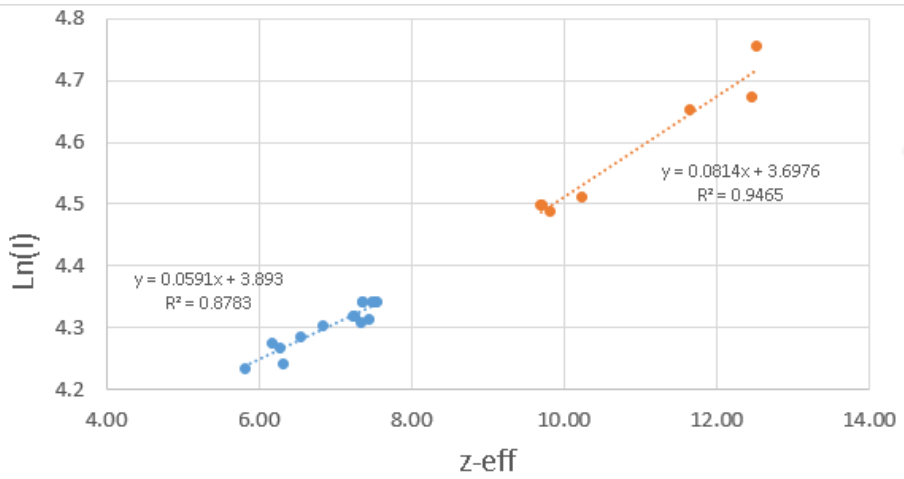


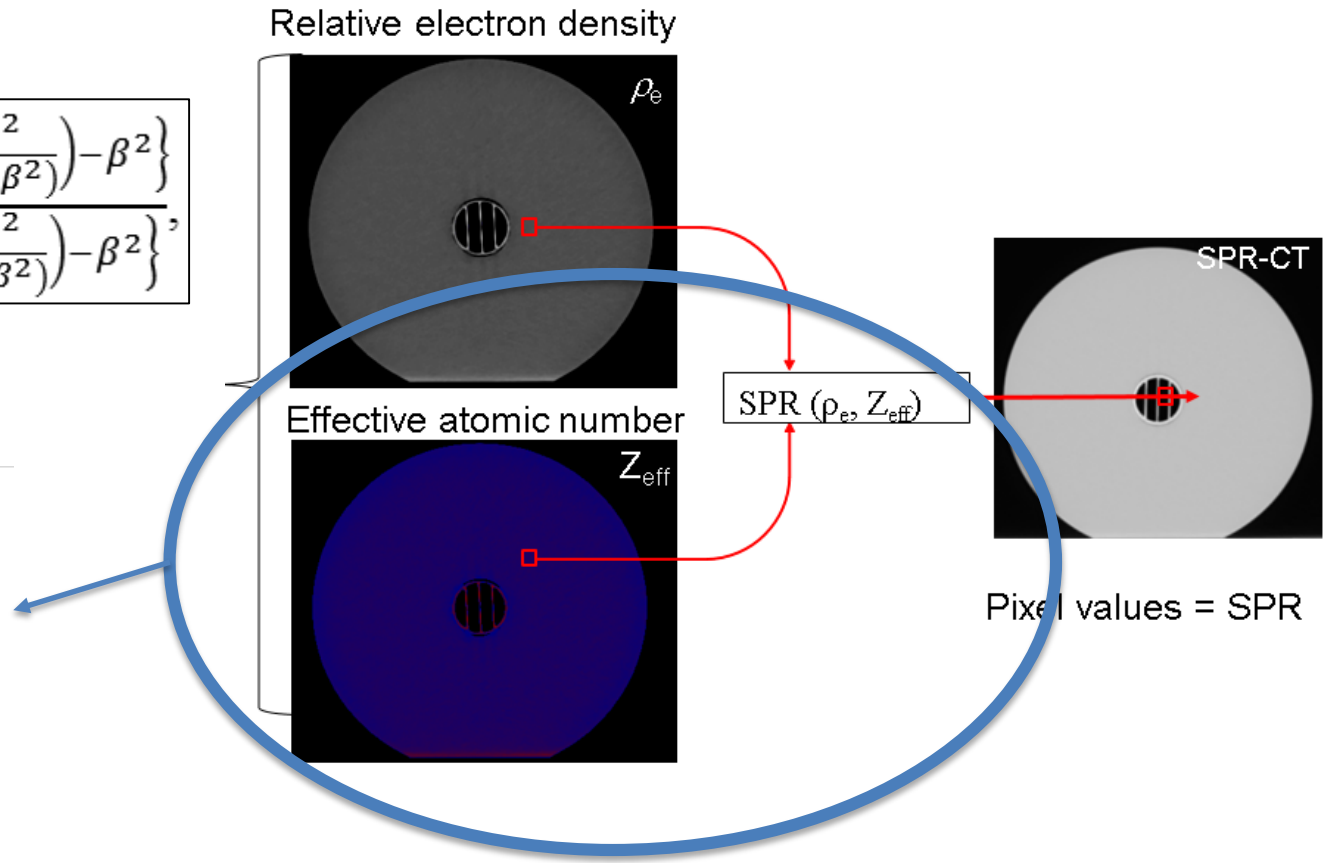


Managing Uncertainties: CT calibration

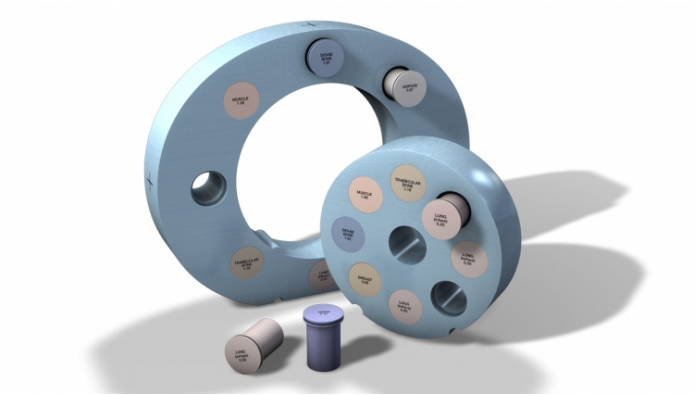
Dual energy CT calibration for Proton therapy

$$SPR = \rho^{tissue} \cdot \frac{(\sum wZ/A)_{tissue}}{(\sum wZ/A)_{water}} \cdot \frac{\left\{\ln\left(\frac{2m_e c^2\beta^2}{I_{tissue}(1-\beta^2)}\right)-\beta^2\right\}}{\left\{\ln\left(\frac{2m_e c^2\beta^2}{I_{water}(1-\beta^2)}\right)-\beta^2\right\}},$$





Needs Statement



<u>CT scanners calibrated using to Relate HU to proton SPR</u>

- Standard reference materials for calibration
  - Known, well controlled composition/density

- Improved empirical values for SPR calculation
  - Mean ionization (I) values in literature: 65 eV up to 82 eV
  - ICRU I-value = 75 eV
  - SPR uncertainty due to I uncertainty: ~1-2%

- Standard methods for evaluating uncertainty of CT calibration for proton radiotherapy