MAYO CLINIC

Imaging for Proton Treatment Planning

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AAPM Annual Meeting, 2018

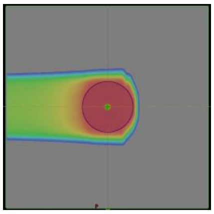
Acknowledgements

- Amanda Deisher, Mayo Clinic
- Edgar Gelover Reyes, Johns Hopkins (formerly Mayo)
- Vicki Taasti, Memorial Sloan Kettering

Outline

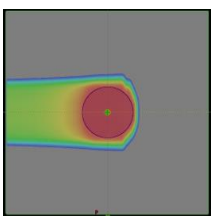
- Impact of Geometric Errors
- Calibrating CT for Proton Dose Calculation
- Potential Improvements in Stopping Power Measurements
- Clinical Examples of Anatomical Changes

Setup and Volume Variations

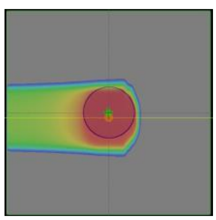


Nominal Plan

Setup and Volume Variations

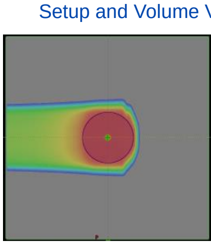


Nominal Plan



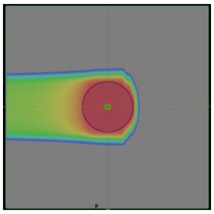
Lateral Shift in BEV

Setup and Volume Variations

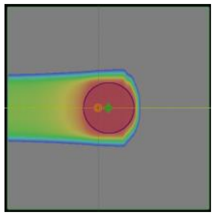


Nominal Plan

Setup and Volume Variations

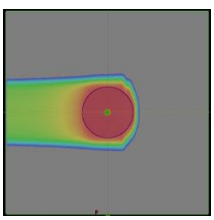


Nominal Plan

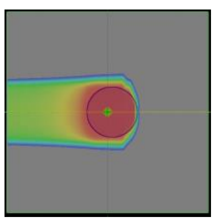


Long Shift in BEV

Setup and Volume Variations

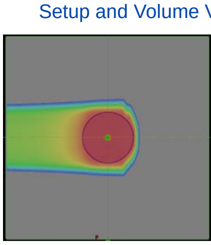


Nominal Plan

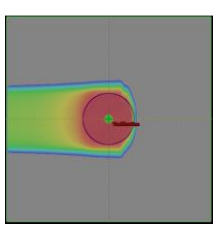


Internal Target Shift

Setup and Volume Variations

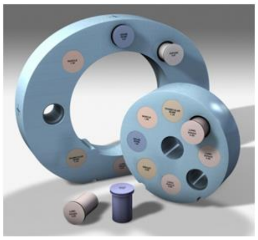


Nominal Plan



3% Error in RSP

Photon Planning: Relative Electron Density



- Scan commercial phantom with known RED
- Measure HU in scan
- Enter HU-RED curve in photon planning system

Proton Planning: Stopping Power

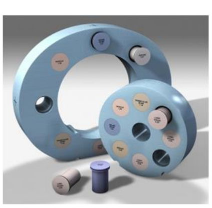
- Proton stopping power comes from Bethe-Bloch equation:

$$S = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

- n is electron density of the medium
- I is ionization potential of the medium
- HU – RSP degeneracies
- Phantom materials are not like human tissues
- Stoichiometric Calibration Process

Stoichiometric Calibration

1. Measure HU of materials with known RED



- Plugs have well known RED values
- Elemental composition not tissue equivalent
- Scan one plug at a time in center of phantom
- Use fixed, clinical CT protocol

Schneider et al., PMB 1996

Stoichiometric Calibration

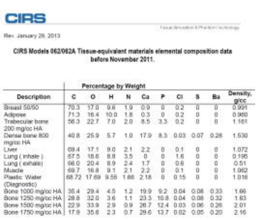
2. Parameterize CT Scanner by Fitting HUs

$$\mathrm{HU}_{\mathrm{sc}} = \rho_{e-}^{\mathrm{rel}}(A \cdot \tilde{Z} + B \cdot \hat{Z} + C)$$

- $\tilde{Z}$ and $\hat{Z}$ are material properties for photoelectric and Compton
- Scanner parameters:
  - A: photoelectric
  - B: Compton
  - C: Klein-Nishina

Schneider et al., PMB 1996

Stoichiometric Calibration


CIRS

Rev. January 29, 2013

CIRS Models 062/062A Tissue-equivalent materials elemental composition data before November 2011.

Description	C	O	H	N	Ca	P	Cl	S	Ba	Density, g/cc
	Percentage by Weight									
Breast 50/50	70.3	17.0	9.6	1.9	0.9	0	0.2	0	0	0.991
Adipose	71.3	16.4	10.0	1.8	0.3	0	0.2	0	0	0.960
Trabecular bone 200 mg/cc HA	56.3	22.7	7.0	2.0	8.5	3.3	0.2	0	0	1.161
Dense bone 800 mg/cc HA	40.8	25.9	5.7	1.0	17.9	8.3	0.03	0.07	0.28	1.530
Liver	69.4	17.1	9.0	2.1	2.2	0	0.1	0	0	1.072
Lung (inhale)	67.5	18.6	8.8	3.5	0	0	1.6	0	0	0.195
Lung (exhale)	66.0	20.4	8.9	2.4	1.7	0	0.6	0	0	0.51
Muscle	69.7	16.8	9.1	2.1	2.2	0	0.1	0	0	1.062
Plastic Water (Diagnostic)	68.72	17.69	9.55	1.66	2.18	0	0.15	0	0	1.016
Bone 1000 mg/cc HA	35.4	29.4	4.5	1.2	19.9	9.2	0.04	0.08	0.33	1.66
Bone 1250 mg/cc HA	28.8	32.0	3.6	1.1	23.3	10.8	0.04	0.08	0.32	1.83
Bone 1500 mg/cc HA	22.9	33.9	2.9	0.9	26.7	12.4	0.03	0.06	0.26	2.01
Bone 1750 mg/cc HA	17.9	35.6	2.3	0.7	29.6	13.7	0.02	0.05	0.20	2.16

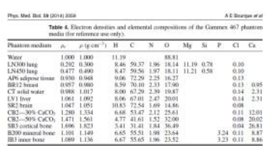
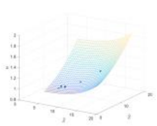

Phys. Med. Biol. 59 (2014) 2059 A E Bourque et al

Table 4. Electron densities and elemental compositions of the Gammex 467 phantom media (for reference use only).

Phantom medium	ρ_e	ρ (g cm^{-3})	H	C	N	O	Mg	Si	P	Cl	Ca
Water	1.000	1.000	11.19			88.81					
LN300 lung	0.292	0.300	8.46	59.37	1.96	18.14	11.19	0.78		0.10	
LN450 lung	0.477	0.490	8.47	59.56	1.97	18.11	11.21	0.58		0.10	
AP6 adipose tissue	0.930	0.948	9.06	72.29	2.25	16.27				0.13	
BR12 breast	0.957	0.980	8.59	70.10	2.33	17.90				0.13	0.95
CT solid water	0.988	1.017	8.00	67.29	2.39	19.87				0.14	2.31
LV1 liver	1.061	1.092	8.06	67.01	2.47	20.01				0.14	2.31
SR2 brain	1.047	1.051	10.83	72.54	1.69	14.86				0.08	
CB2—30% $CaCO_3$	1.280	1.334	6.68	53.47	2.12	25.61				0.11	12.01
CB2—50% $CaCO_3$	1.471	1.561	4.77	41.61	1.52	32.00				0.08	20.02
SB3 cortical bone	1.696	1.823	3.41	31.41	1.84	36.49				0.04	26.81
B200 mineral bone	1.101	1.149	6.65	55.51	1.98	23.64			3.24	0.11	8.87
IB3 inner bone	1.089	1.136	6.67	55.65	1.96	23.52			3.23	0.11	8.86

Stoichiometric Calibration



Parameter	Value
K^{ph}	8.68×10^{-6} (-1.668×10^{-5}, 3.404×10^{-5})
K^{coh}	0.003356 (-0.003138,0.00985)
K^{KN}	0.8814 (0.717,1.046)

Final values: $K^{ph}=3.404\times10^{-5}$,$K^{coh}=0.0002$ and $K^{KN}=0.8814$

Stoichiometric Calibration

3. Calculate Predicted HU for ICRU Tissues

$$HU_{sc} = \rho_{e-}^{rel}(A \cdot \tilde{Z} + B \cdot \hat{Z} + C)$$

	H	C	N	O	Ca	P	Na	Mg	S	Cl	K	Fe	I	ρ	ρe	SPw
Adipose	11.4	59.8	0.7	27.8			0.1		0.1	0.1				0.95	0.951	0.979
Blood	10.2	11	3.3	74.5		0.1	0.1		0.2	0.3	0.2	0.1		1.06	1.05	1.053
Brain	10.7	14.5	2.2	71.2		0.4	0.2		0.2	0.3	0.3			1.04	1.035	1.04
Breast	10.6	33.2	3	52.7		0.1	0.1		0.2	0.1				1.02	1.014	1.029
Cell	10.6	9	3.2	74.2		2.6			0.4					1	0.996	0.996
Eye	9.6	19.5	5.7	64.6		0.1	0.1		0.3	0.1				1.07	1.056	1.06
GI	10.6	11.5	2.2	75.1		0.1	0.1		0.1	0.2	0.1			1.03	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	1.051	1.054
Kidney	10.3	13.2	3	72.4	0.1	0.2	0.2		0.2	0.2	0.2			1.05	1.041	1.045
Liver	10.2	13.9	3	71.6		0.3	0.2		0.3	0.2	0.3			1.06	1.05	1.054
Lung	10.3	10.5	3.1	74.9		0.2	0.2		0.3	0.3	0.2			1.05	1.041	1.044
Lymph	10.8	4.1	1.1	83.2			0.3		0.1	0.4				1.03	1.029	1.027
Muscle	10.2	14.3	3.4	71		0.2	0.1		0.3	0.1	0.4			1.05	1.04	1.044
Ovary	10.5	9.3	2.4	76.8		0.2	0.2		0.2	0.2	0.2			1.05	1.043	1.046
Pancreas	10.6	16.9	2.2	69.4		0.2	0.2		0.1	0.2	0.2			1.04	1.036	1.041
Cartilage	9.6	9.9	2.2	74.4		2.2	0.5		0.9	0.3				1.1	1.083	1.081
Red	10.5	41.4	3.4	43.9		0.1			0.2	0.2	0.2	0.1		1.03	1.023	1.041
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	1.15	1.156
Yellow	11.5	64.4	0.7	23.1			0.1		0.1	0.1				0.98	0.982	1.013
Skin	10	20.4	4.2	64.5		0.1	0.2		0.2	0.3	0.1			1.09	1.078	1.084
Spleen	10.3	11.3	3.2	74.1		0.3	0.1		0.2	0.2	0.3			1.06	1.051	1.054
Testis	10.6	9.9	2	76.6		0.1	0.2		0.2	0.2	0.2			1.04	1.032	1.035
Thyroid	10.4	11.9	2.4	74.5		0.1	0.2		0.1	0.2	0.1		0.1	1.05	1.041	1.045
Skeleton—cortical	3.4	15.5	4.2	43.5	22.5	10.3	0.1	0.2	0.3					1.92	1.781	1.714
Skeleton—cranium	5	21.2	4	43.5	17.6	8.1	0.1	0.2	0.3					1.61	1.517	1.48
Skeleton—femur	7	34.5	2.8	36.8	12.9	5.5	0.1	0.1	0.2	0.1				1.33	1.279	1.269
Skeleton—humerus	6	31.4	3.1	36.9	15.2	7	0.1	0.1	0.2					1.46	1.389	1.37
Skeleton—mandible	4.6	19.9	4.1	43.5	18.7	8.6	0.1	0.2	0.3					1.68	1.577	1.534
Skeleton—ribs	6.4	26.3	3.9	43.6	13.1	6	0.1	0.1	0.3	0.1	0.1			1.41	1.367	1.329
Skeleton—ribs	5.6	23.5	4	43.4	15.6	7.2	0.1	0.1	0.3	0.1	0.1			1.52	1.441	1.413
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	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	1.15	1.156
Skeleton—vertebral	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	1.355	1.337
Z	1	6	7	8	20	15	11	12	16	17	19	26	53			
Aw	1.0079	12.011	14.006	15.999	40.08	30.973	22.989	24.312	32.065	35.45	39.098	55.845	126.904			

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Stoichiometric Calibration

4. Calculate Relative Stopping Power for Reference Tissues

$$S_p = \rho_{e-}^{rel} \cdot \frac{\left\{\ln\left[\frac{2m_e c^2 \beta^2}{\langle I_{mat}\rangle(1-\beta^2)}\right] - \beta^2\right\}}{\left\{\ln\left[\frac{2m_e c^2 \beta^2}{\langle I_{water}\rangle(1-\beta^2)}\right] - \beta^2\right\}}$$

- I is ionization potential for material
- I is assumed to be ~ 75 eV for water
- More uncertainty in I for other materials

Schneider et al., PMB 1996

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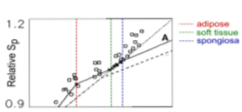
Stoichiometric Calibration

5. Plot Relative Stopping Power vs. Calc. CT



- Nominally fit to bi-linear curve
- More segments used in soft tissue region to cover tissues with differing H composition

Schneider et al., PMB 1996

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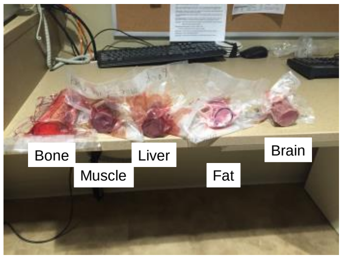
Experimental Verification of HU to RSP

Every chef and every proton physicist should be friends with their butcher



Experimental Verification of HU to Sp

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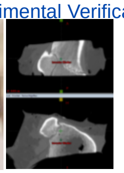
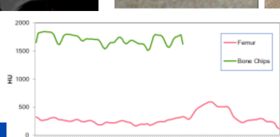
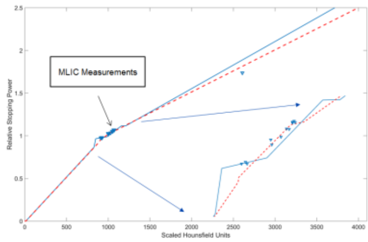
Experimental Verification of HU to Sp

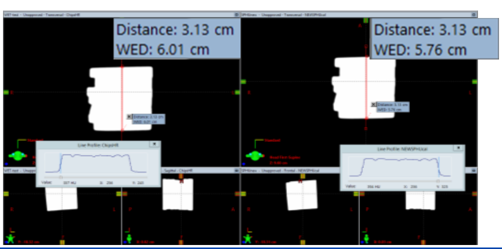




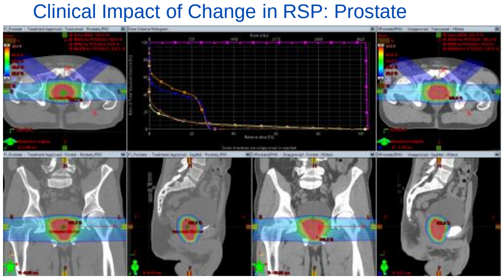
Experimental Modification of HU/RSP



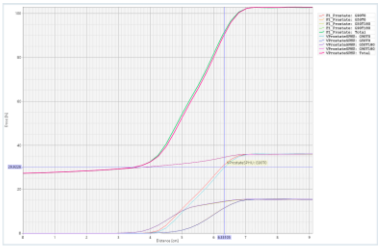
Experimental Modification of HU/RSP



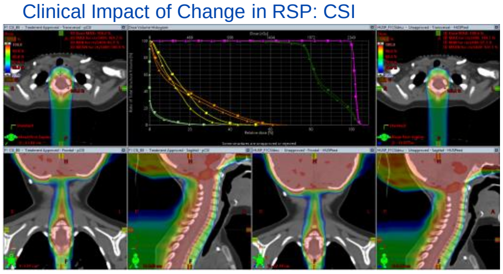
Clinical Impact of Change in RSP: Prostate



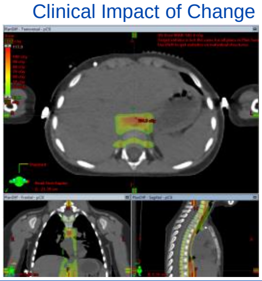
Clinical Impact of Change in RSP: Prostate



Clinical Impact of Change in RSP: CSI



Clinical Impact of Change in RSP: CSI

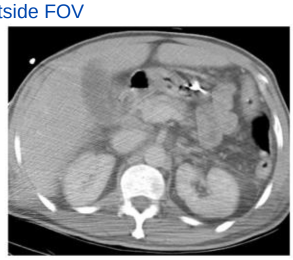


	MCR Curve		New Curve		DVH Report
	Max [Gy]	Mean [Gy]	Max [Gy]	Mean [Gy]	D1% [Gy]
Constrictors	12.58	3.77	11.70	3.02	24
Esophagus	16.03	4.29	15.15	3.81	24

Uncertainties in HU to SP

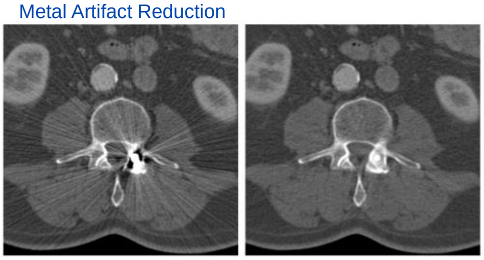
- Fitting experimental results for planning system curve
- Degeneracy in SP values for tissues with same HU
- HU value uncertainty
  - Technique
  - Position in scanner
  - Artifact
- Uncertainties in mean excitation value
- Variations in human tissue composition
- Expected Range Uncertainty: ~3.5% + 1 mm

Patient Outside FOV



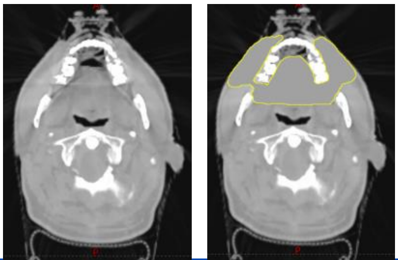
Barrett, Radiographics 2004

Metal Artifact Reduction



Barrett, Radiographics 2004

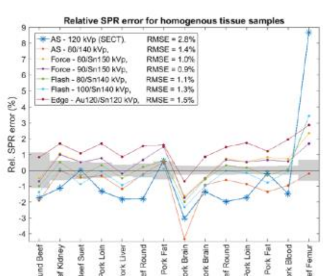
Manual Artifact Reduction



Potential Improvements in RSP Measurement

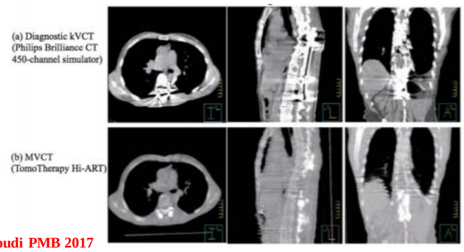
- Dual Energy CT
- MegaVoltage CT
- Proton CT

Dual Energy CT



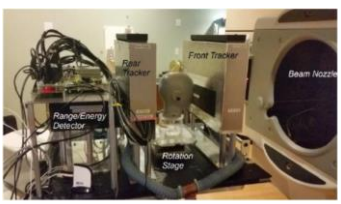
Taasti et al., PMB 2018

MVCT



Giantsoudi PMB 2017

Proton CT

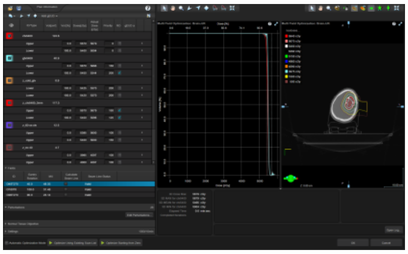


Johnson et al., Physics Procedia, 2017

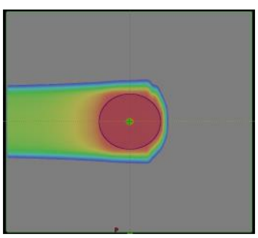
Robust Treatment Planning

- Geometric and range uncertainties are estimated at time of planning
- Treatment plans are optimized in a way to account for range and setup variations
- A robust plan provides CTV coverage and critical organ sparing in presence of errors
- Physicians review coverage of CTV in light of expected variations

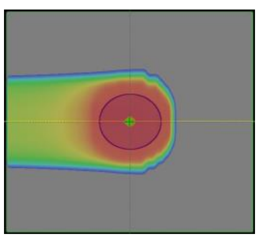
Robust Optimization



Proton Plan Robustness Evaluation

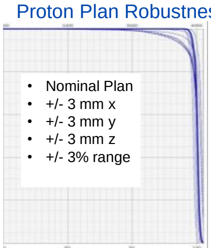


Nominal Plan

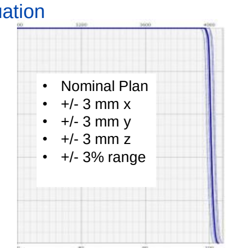


Robust Proton Plan

Proton Plan Robustness Evaluation

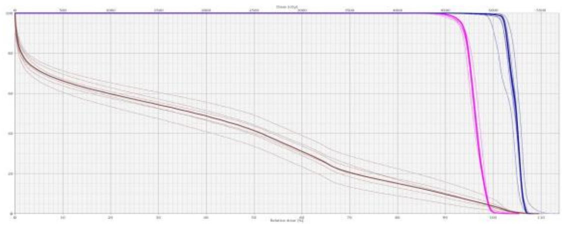


Nominal Plan



Robust Proton Plan

Robust Plan Evaluation



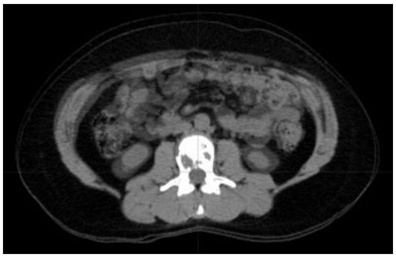
Patient Contour Variations

- Range uncertainty also arises from changes in patient external contour
  - Variations in posterior tissue on immobilization device
  - Folds in posterior neck
  - Excess adipose tissue in pelvis

CT Guided SBRT

Original Plan

CT Guided SBRT



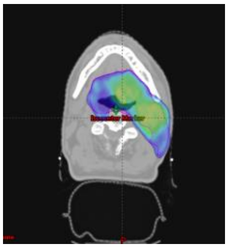
Tx Image Registration

CT Guided SBRT

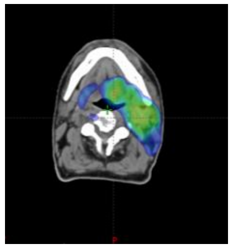
Verification Dose

Posterior Neck Variation

Posterior Neck Variation

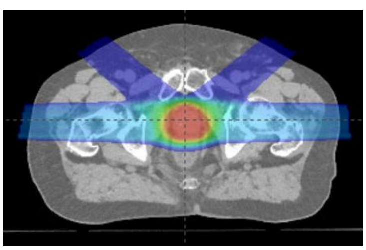


Original Plan

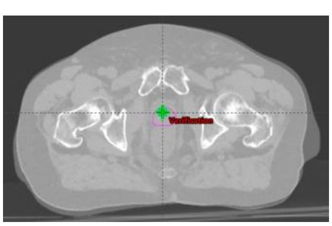


VerificationPlan

Prostate SBRT

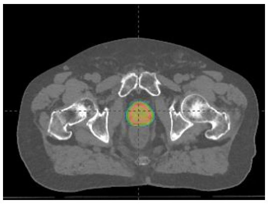


Prostate SBRT

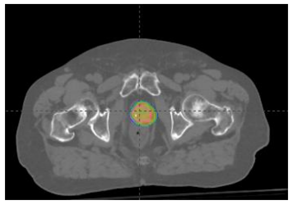


Pre-Treatment Registration

Prostate SBRT Variation



Original Plan



VerificationPlan

Conclusion

- Converting HU to RSP is not trivial
- Increasing our knowledge of stopping power is important, but not the only concern
  - A clinically viable plan already has lots of margin in the beam direction
  - Anatomical variation is a much greater variable than error in stopping power
- Critical to validate anatomy before Tx (Dr. Winey)
- Ideally validate dose after Tx (Dr. Polf)