Particle versus photon imaging for proton radiotherapy - an experimental comparison

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Which imaging modality provides the highest RSP accuracy?

- Photon CT
  1) Single-energy CT
  2) Dual-energy CT
- Particle CT
  3) Proton CT
  4) Helium CT

Which imaging modality provides the highest RSP accuracy?

1) Design a **tissue phantom**, collect and prepare tissue samples.
2) Perform **reference RSP** measurements.
3) Photon CT imaging: Collect **SECT and DECT** images, estimate the RSPs and compare to reference RSP.
4) Particle CT imaging: Collect **proton and helium CT** images, compare RSPs to photon CT and reference RSP.

All in one day!!

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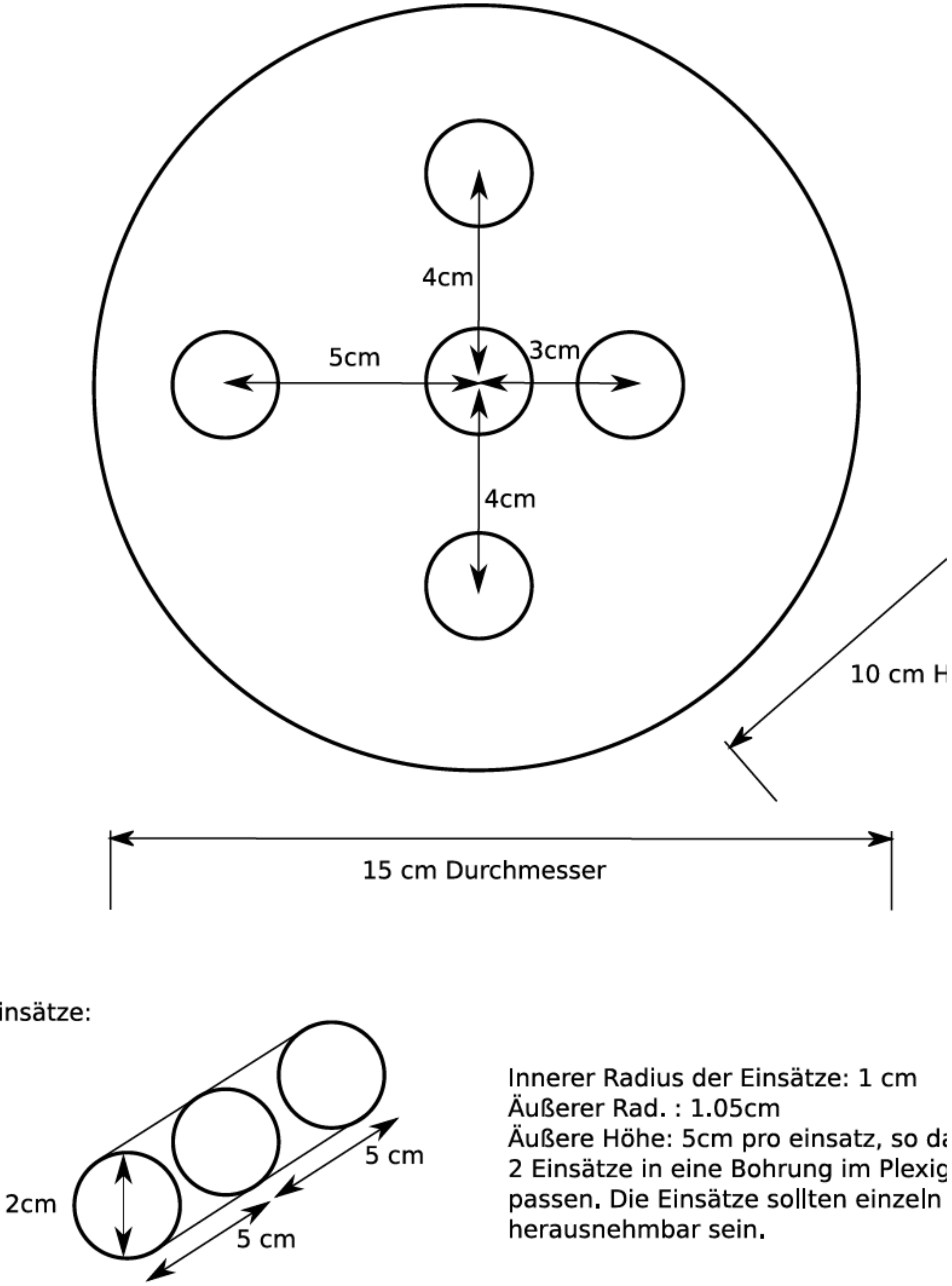
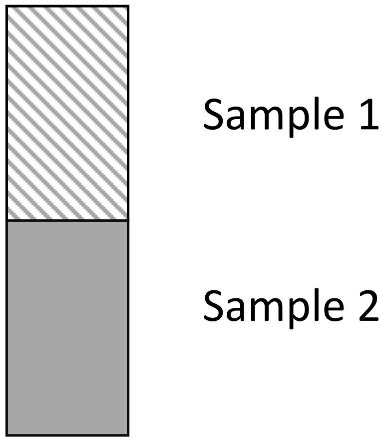


Tissue phantom design

- PMMA cylinder
  - 15 cm diameter
  - 10 cm high
  - Cylindrical holes to insert 3D printed containers
  - Holds 10 containers in one scan



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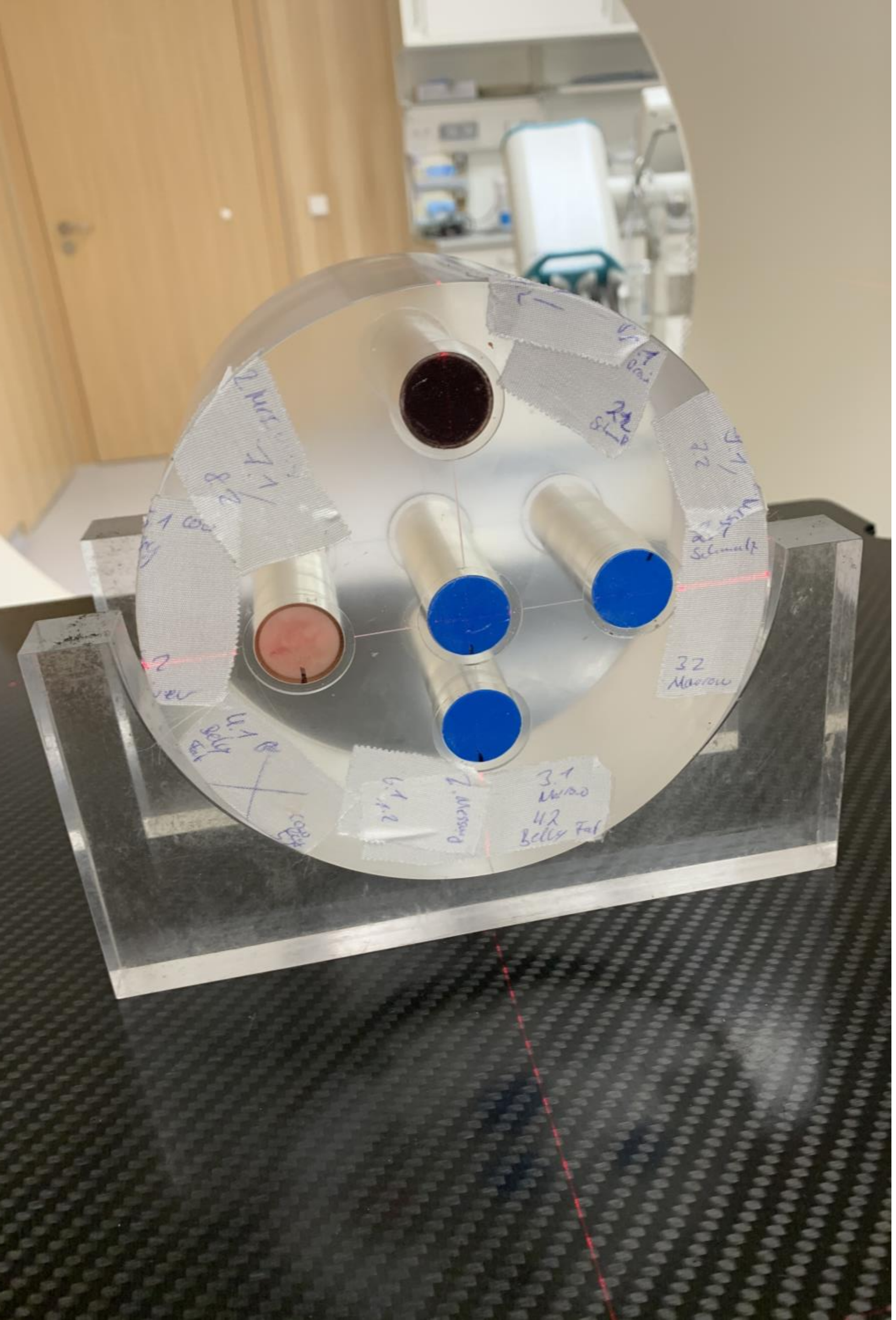

Tissue phantom design

- PMMA cylinder
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Tissue sample preparation

- 17 porcine and bovine samples including:
  - Lung
  - Fat
  - Marrow
  - Blood
  - Muscle
  - Brain
  - Kidney
  - Liver
  - Trabecular bone
  - Cortical bone

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Tissue sample preparation

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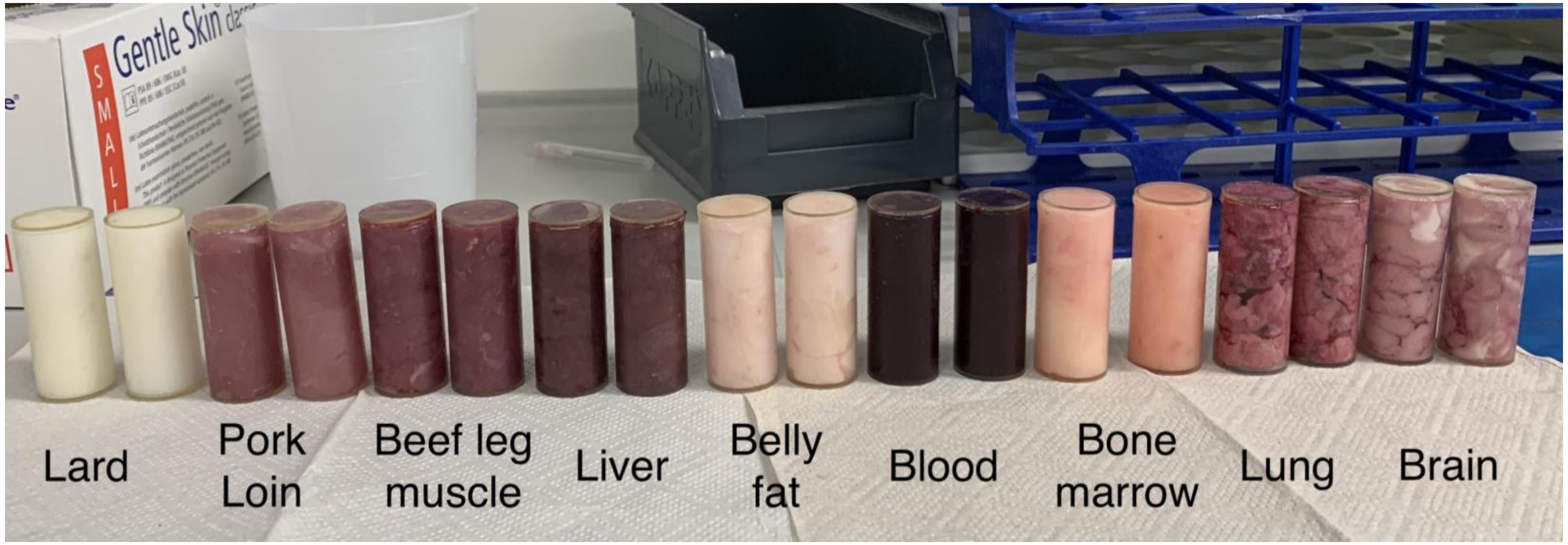

Which imaging modality provides the highest RSP accuracy?

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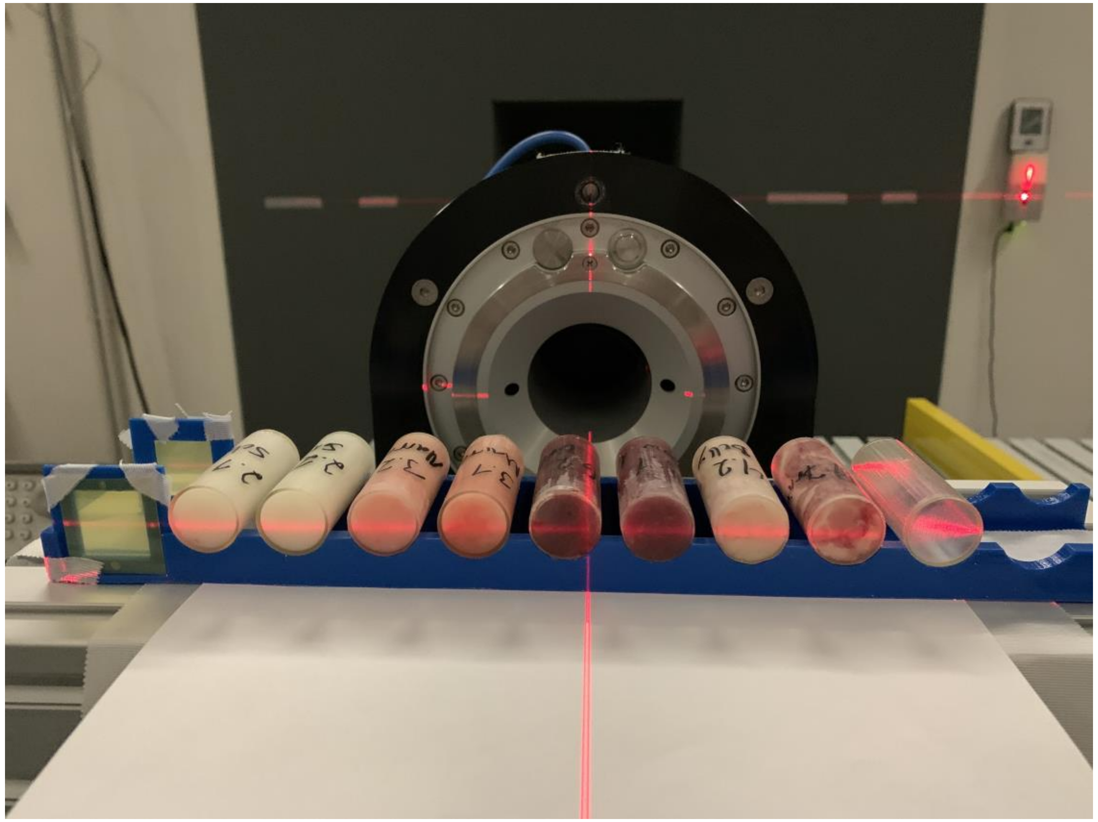
Reference RSP measurements



- Samples in 3D printed containers
  - Placed on a 3D printed holder and a translational stage

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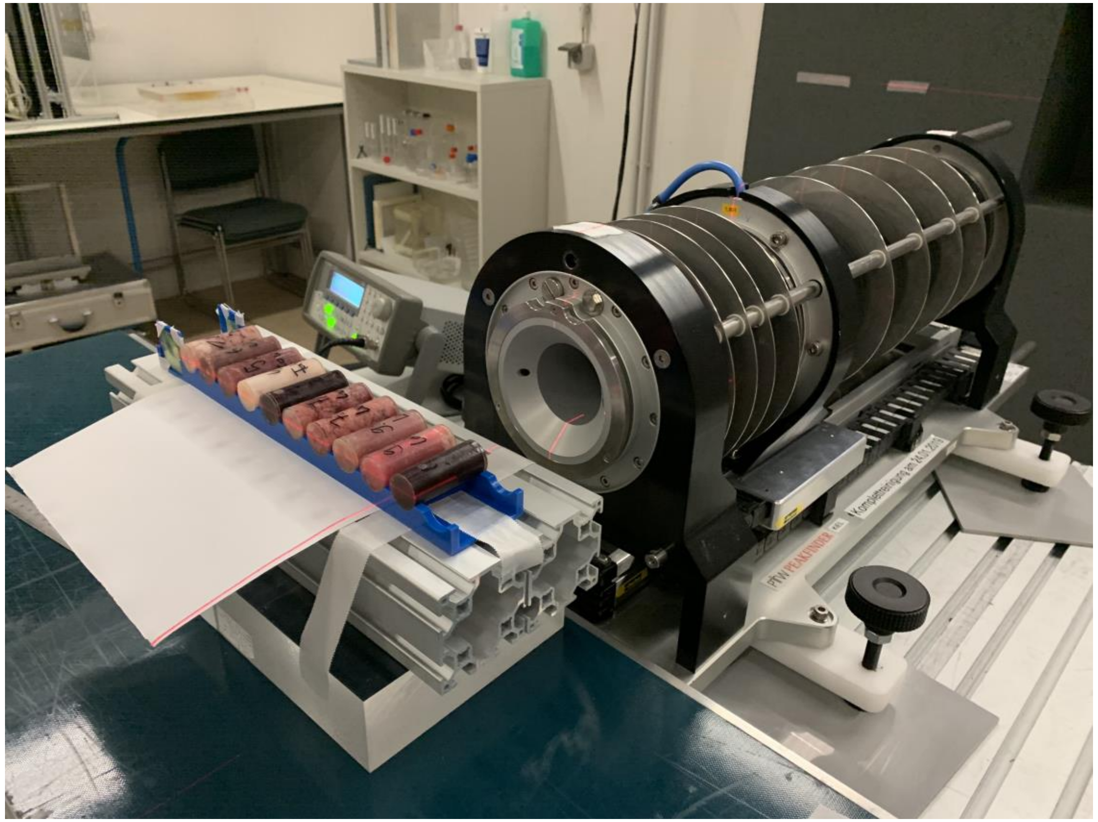
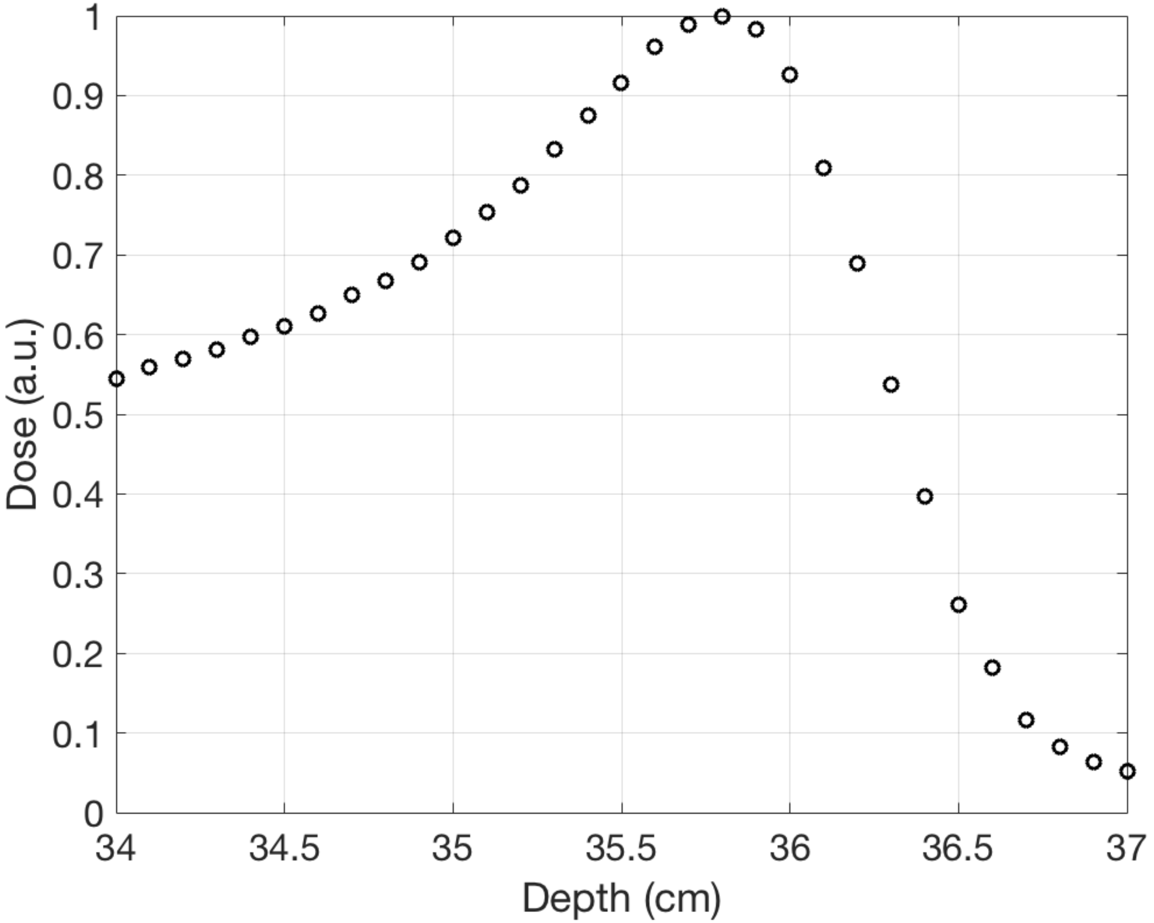
Reference RSP measurements



- Samples in 3D printed containers
  - Placed on a 3D printed holder and a translational stage
- PTW *PeakFinder*
  - Adjustable water column for peak detection measurements
- Clinical carbon beam
  - Narrow peak, low scattering

Reference RSP measurements



- For each tissue sample and empty container: measure a depth dose curve

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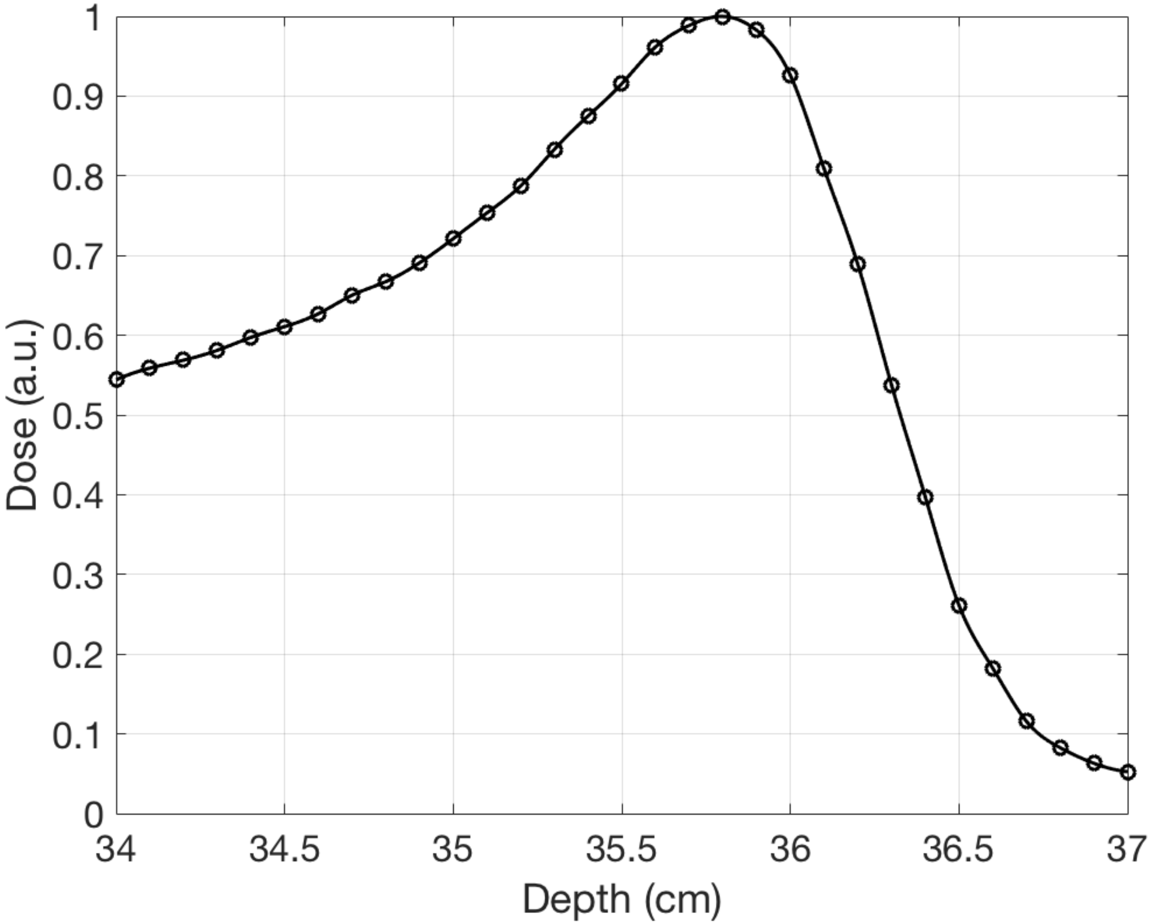
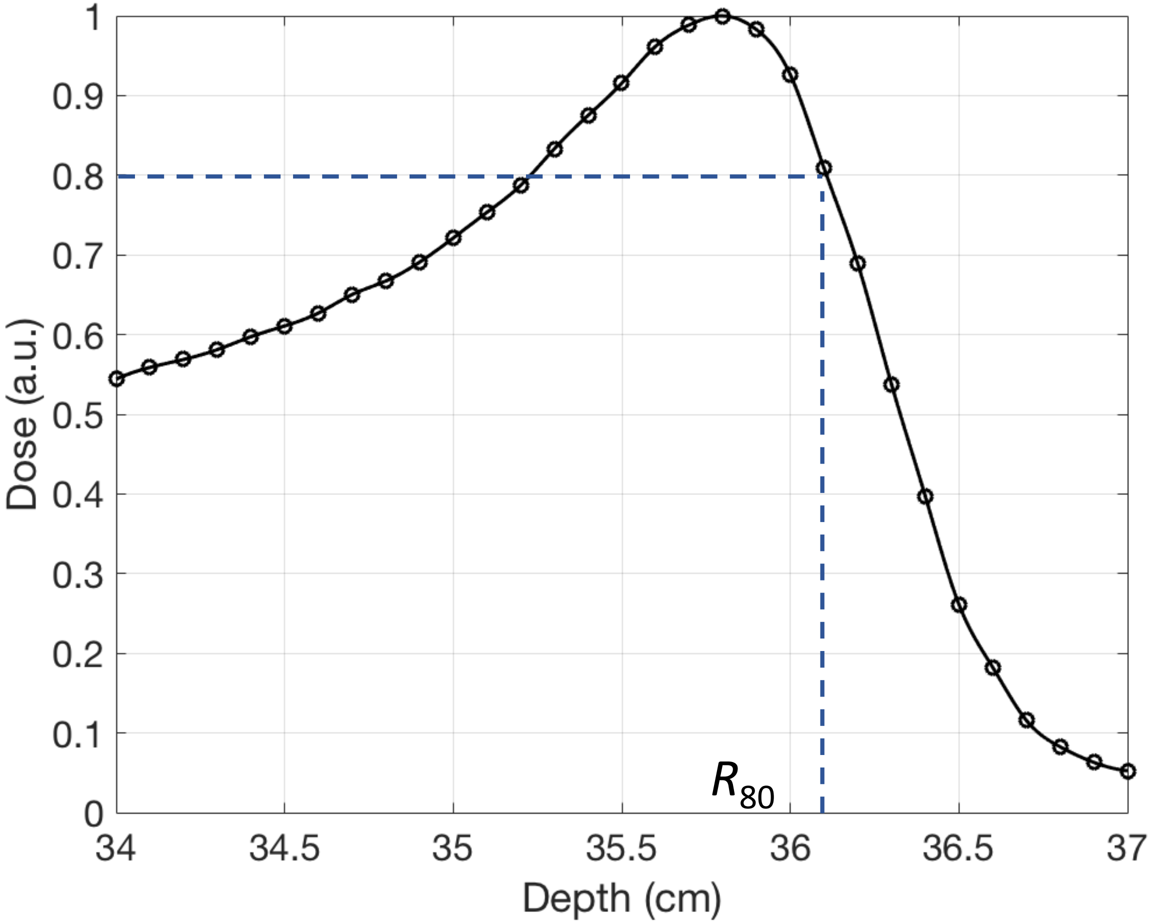
Reference RSP measurements



- For each tissue sample and empty container: measure a depth dose curve
- Interpolate to find the 80% distal fall-off

Reference RSP measurements



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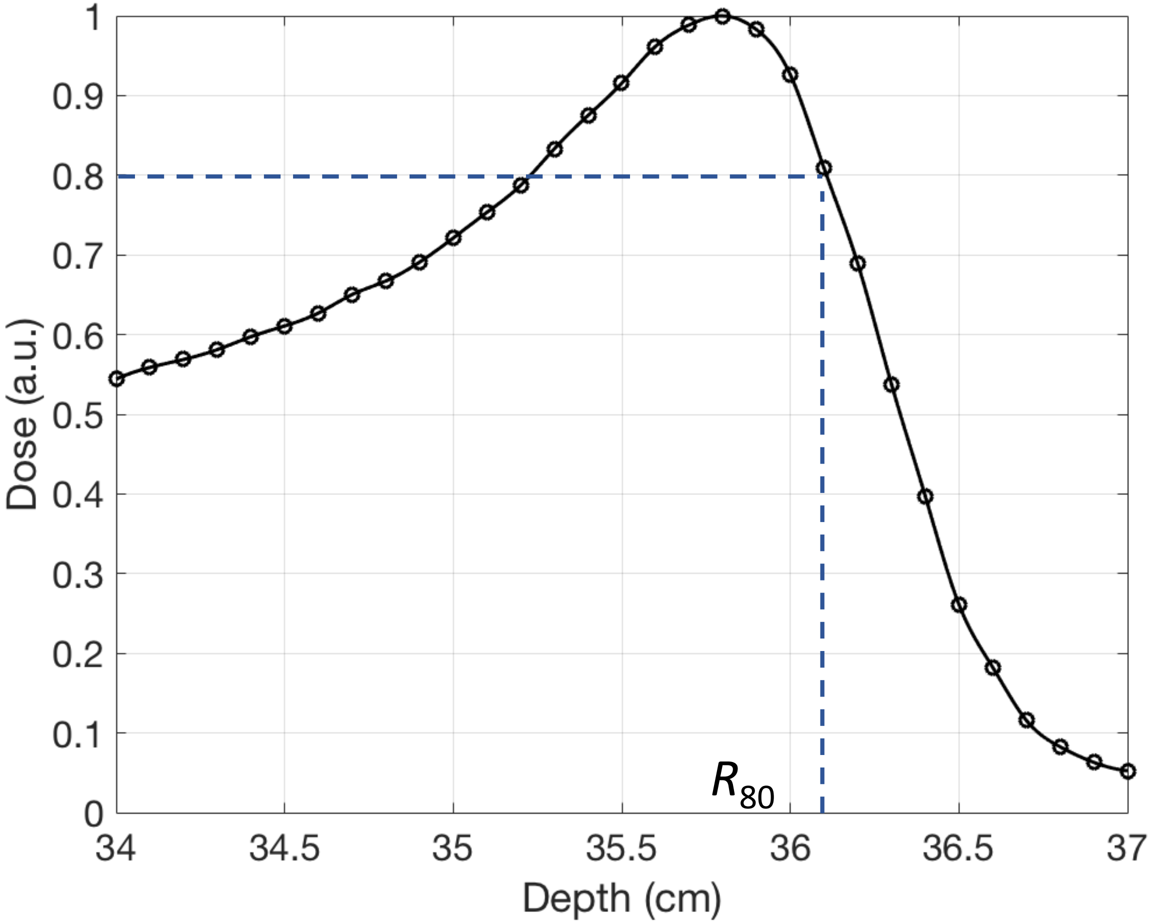
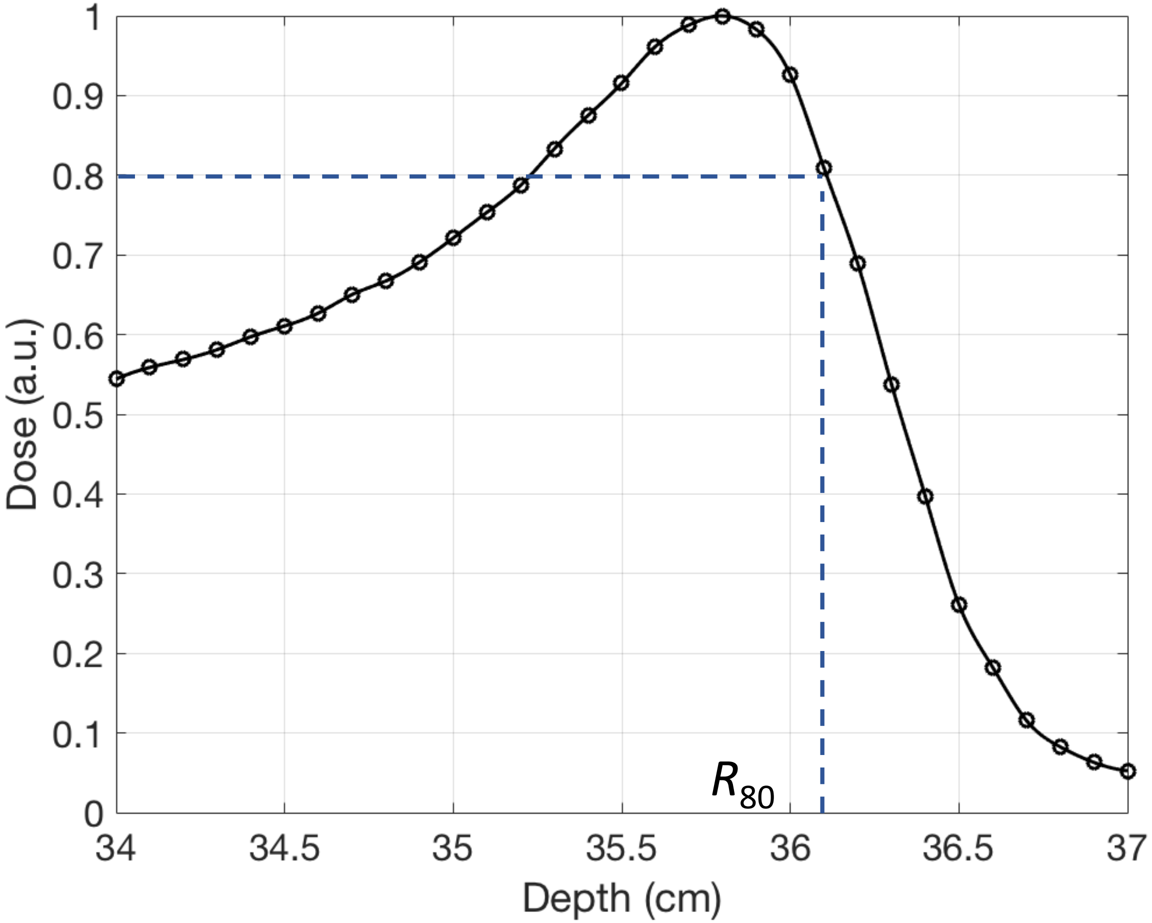


- For each tissue sample and empty container: measure a depth dose curve
- Interpolate to find the 80% distal fall-off

$$\mathrm{WET}_{\mathrm{sample}} = R_{80,\mathrm{empty}} - R_{80,\mathrm{sample}}$$

Reference RSP measurements



- For each tissue sample and empty container: measure a depth dose curve
- Interpolate to find the 80% distal fall-off

$$\mathrm{WET}_{\mathrm{sample}} = R_{80,\mathrm{empty}} - R_{80,\mathrm{sample}}$$

$$\mathrm{RSP}_{\mathrm{sample,ref}} = \frac{\mathrm{WET}_{\mathrm{sample}}}{t}$$

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Reference RSP measurements

Tissue	RSP_{ref}
Lung	0.90 ± 0.04
Belly fat	1.00 ± 0.00
Back fat	0.97 ± 0.01
Marrow	0.93 ± 0.02
Water	1.00 ± 0.00
Blood	1.05 ± 0.00
Cheek muscle	1.05 ± 0.01
Loin 1	1.06 ± 0.00
Loin 2	1.06 ± 0.00
Leg muscle	1.05 ± 0.01
Brain	1.04 ± 0.00
Kidney 1	1.05 ± 0.00
Kidney 2	1.04 ± 0.01
Liver 1	1.06 ± 0.00
Liver 2	1.06 ± 0.00
Trabecular bone	1.19 ± 0.06
Cortical bone	1.78 ± 0.03
Mean error	–
Mean absolute error	–
Root mean square error	–

Which imaging modality provides the highest RSP accuracy?

1) Design a **tissue phantom**, collect and prepare tissue samples.
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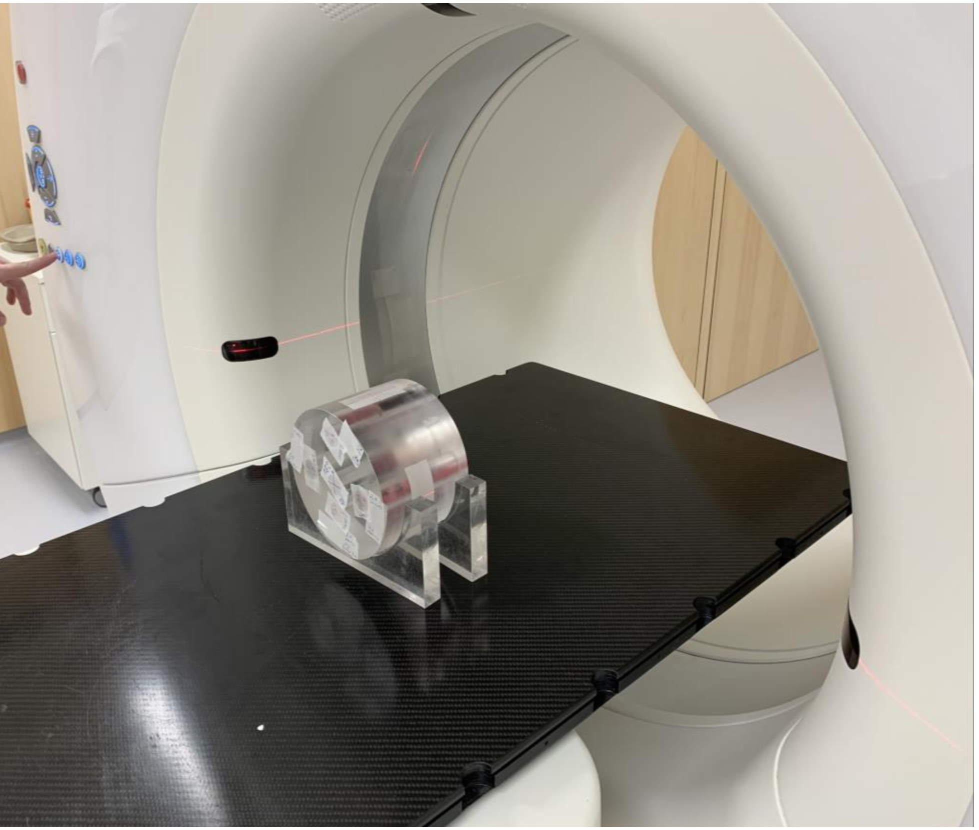
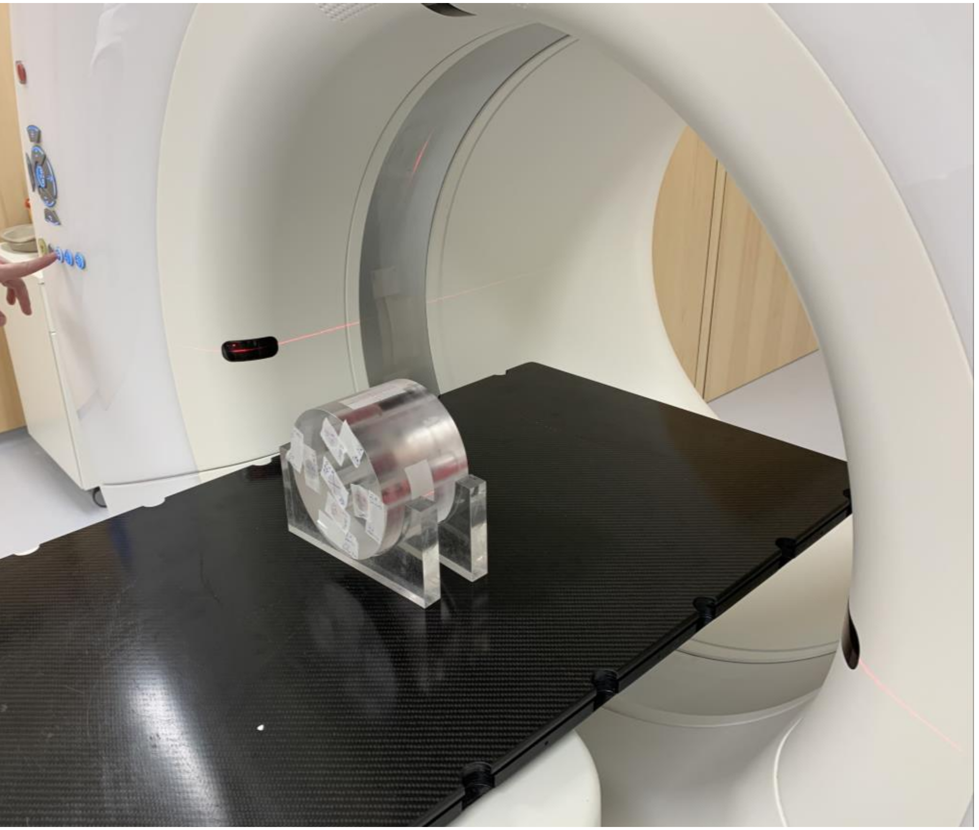
Estimating RSP maps from SECT Images

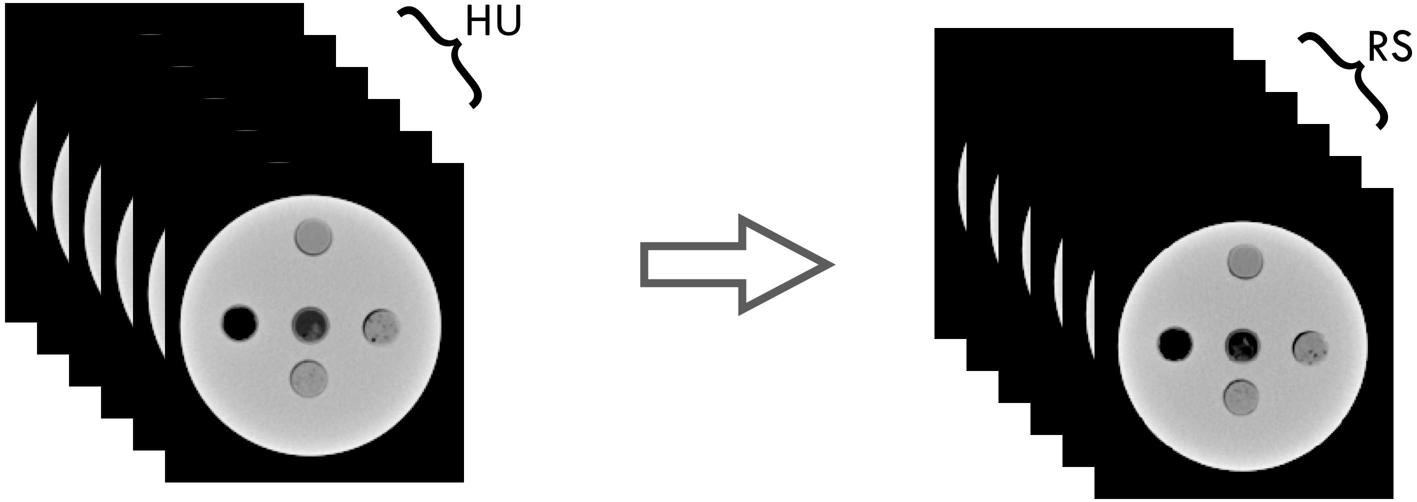


Calibration

- Schneider, U., Pedroni, E. and Lomax, A., 1996. The calibration of CT Hounsfield units for radiotherapy treatment planning. Physics in Medicine & Biology, 41(1), p.111.
- Calibration phantom: Gammex RMI 467 electron density phantom
- Reference tissues: White and Woodard

Estimating RSP maps from SECT Images





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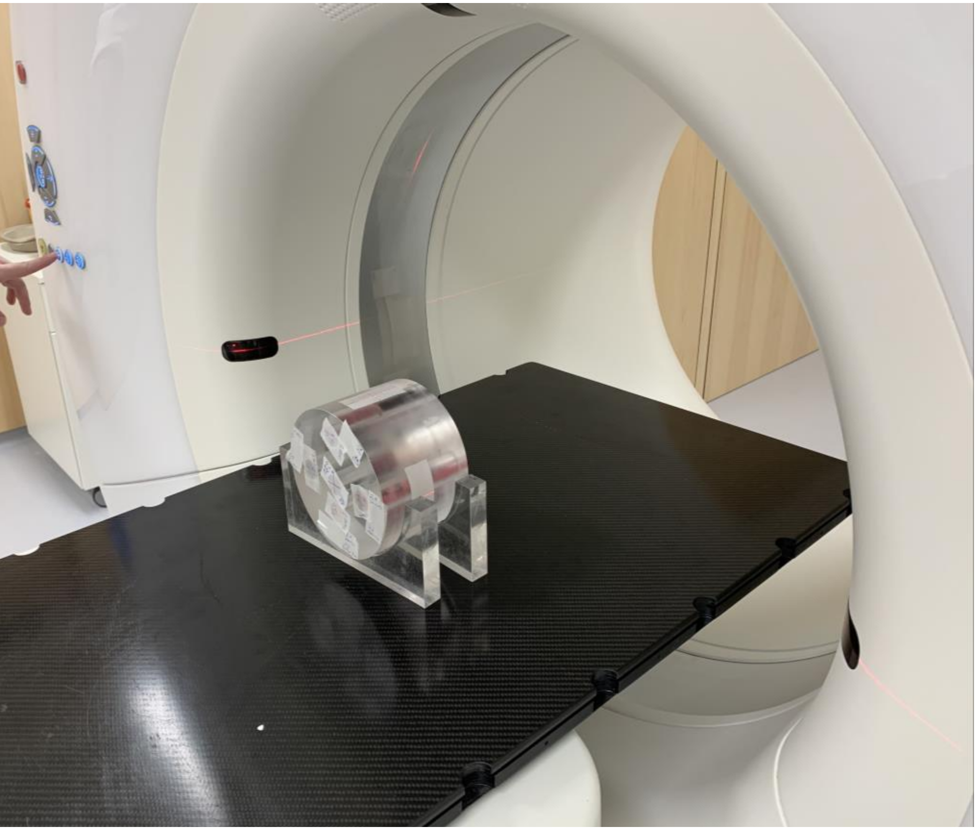
- Calibration phantom: Gammex RMI 467 electron density phantom
- Reference tissues: White and Woodard
- Measure average RSP per sample in VOIs: $\mathbf{RSP_{SECT}}$

Estimating RSP maps from SECT Images



Calibration

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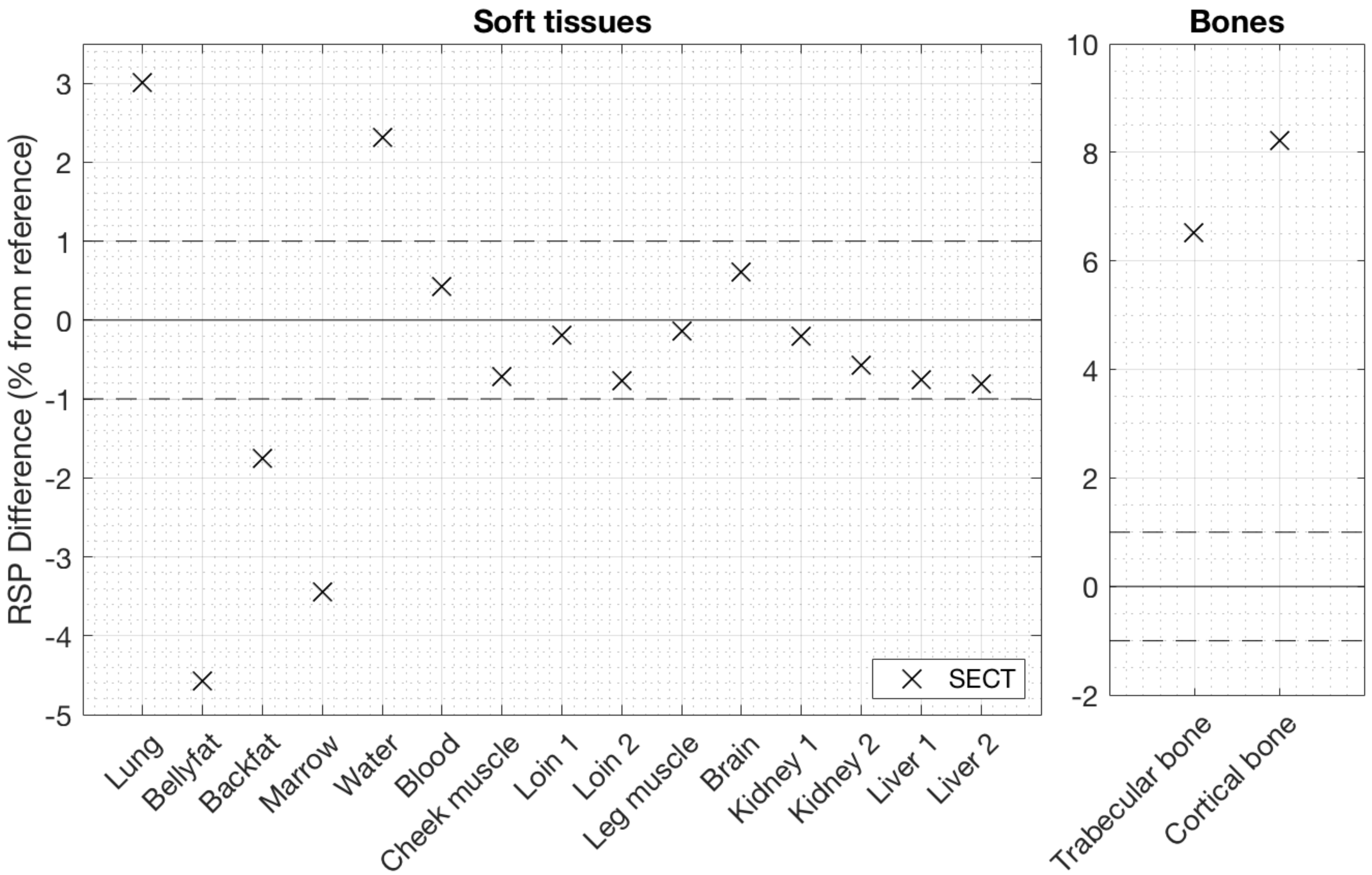
- Calibration phantom: Gammex RMI 467 electron density phantom
- Reference tissues: White and Woodard
- Measure average RSP per sample in VOIs: $\mathbf{RSP_{SECT}}$

$$\Delta\mathrm{RSP}(\%) = \frac{\mathrm{RSP}_{\mathrm{SECT}} - \mathrm{RSP}_{\mathrm{ref}}}{\mathrm{RSP}_{\mathrm{ref}}} * 100$$

SECT-estimated RSP errors



$$\Delta\mathrm{RSP}(\%) = \frac{\mathrm{RSP}_{\mathrm{SECT}} - \mathrm{RSP}_{\mathrm{ref}}}{\mathrm{RSP}_{\mathrm{ref}}} * 100$$

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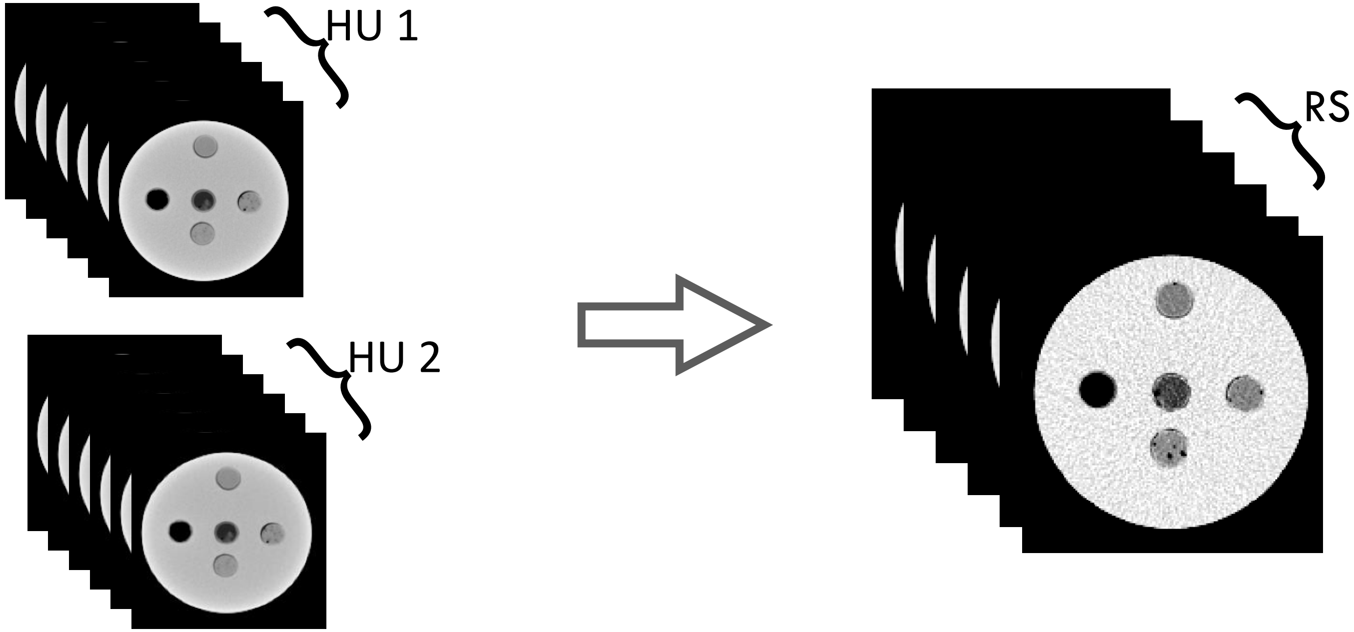
SECT-estimated RSP errors

Tissue	RSP_{ref}	SECT
Lung	0.90 ± 0.04	3.01 ± 11.06
Belly fat	1.00 ± 0.00	-4.57 ± 3.35*
Back fat	0.97 ± 0.01	-1.75 ± 1.97
Marrow	0.93 ± 0.02	-3.44 ± 5.78
Water	1.00 ± 0.00	2.32 ± 0.31
Blood	1.05 ± 0.00	0.43 ± 0.29
Cheek muscle	1.05 ± 0.01	-0.72 ± 1.49
Loin 1	1.06 ± 0.00	-0.20 ± 2.18
Loin 2	1.06 ± 0.00	-0.77 ± 1.51
Leg muscle	1.05 ± 0.01	-0.14 ± 1.68
Brain	1.04 ± 0.00	0.61 ± 0.83
Kidney 1	1.05 ± 0.00	-0.20 ± 3.25
Kidney 2	1.04 ± 0.01	-0.58 ± 4.90
Liver 1	1.06 ± 0.00	-0.75 ± 4.61
Liver 2	1.06 ± 0.00	-0.80 ± 6.31
Trabecular bone	1.19 ± 0.06	6.52 ± 6.86
Cortical bone	1.78 ± 0.03	8.22 ± 5.06†
Mean error	–	**0.42 ± 4.55**
Mean absolute error	–	**2.06**
Root mean square error	–	**3.10**

$$\Delta \mathrm{RSP}(\%) = \frac{\mathrm{RSP}_{\mathrm{SECT}} - \mathrm{RSP}_{\mathrm{ref}}}{\mathrm{RSP}_{\mathrm{ref}}} * 100$$

Estimating RSP maps from DECT Images

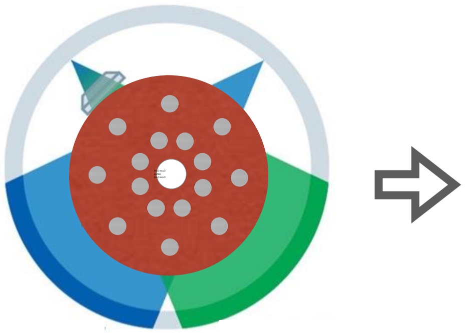


Calibration

- Bourque, A.E., Carrier, J.F. and Bouchard, H., 2014. A stoichiometric calibration method for dual energy computed tomography. Physics in Medicine & Biology, 59(8), p.2059.

Estimating RSP maps from DECT Images

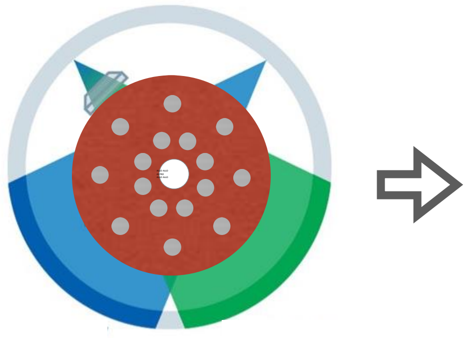
- Parameterize the **CT number *u*** as a function of Z_{med} and the electron density ρ_e



$$u = \rho_{\mathrm{e}} \sum_{m=1}^{M} b_m Z_{\mathrm{med}}^{m-1}$$

Estimating RSP maps from DECT Images

- Parameterize the **CT number *u*** as a function of Z_{med} and the electron density ρ_{e}
- Parameterize the **effective atomic number Z_{med}** as a function of the dual energy index Γ

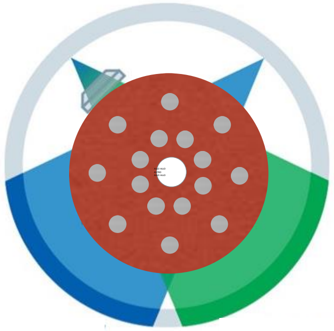


$$u = \rho_{\mathrm{e}} \sum_{m=1}^{M} b_m Z_{\mathrm{med}}^{m-1}$$

$$Z_{\mathrm{med}} = \sum_{k=1}^{K} c_k \Gamma^{k-1}$$

Estimating RSP maps from DECT Images

- Parameterize the **CT number *u*** as a function of Z_{med} and the electron density ρ_e
- Parameterize the **effective atomic number Z_{med}** as a function of the dual energy index Γ
- **Calibrate** (find parameters c_k and b_m) using tissue substitutes with known densities and compositions



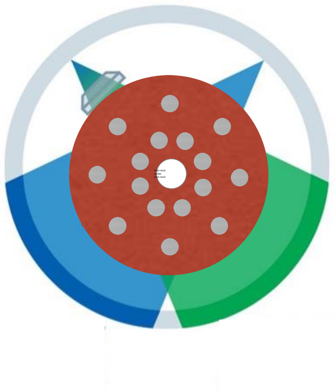
$$u = \rho_e \sum_{m=1}^{M} b_m Z_{\mathrm{med}}^{m-1}$$

$$Z_{\mathrm{med}} = \sum_{k=1}^{K} c_k \Gamma^{k-1}$$

find parameters c_k and b_m

Estimating RSP maps from DECT Images

- Parameterize the **CT number *u*** as a function of Z_{med} and the electron density ρ_e
- Parameterize the **effective atomic number Z_{med}** as a function of the dual energy index Γ
- **Calibrate** (find parameters c_k and b_m) using tissue substitutes with known densities and compositions
- use parameters to find Z_{med} and ρ_e per voxel in a patient scan



$$u = \rho_e \sum_{m=1}^{M} b_m Z_{\text{med}}^{m-1}$$

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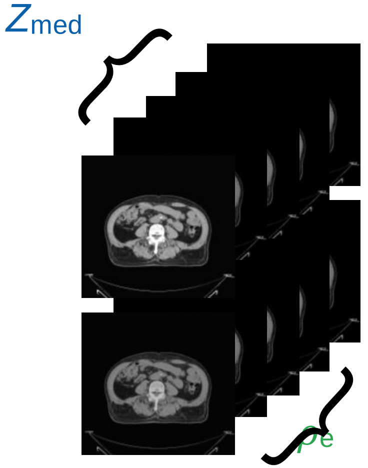
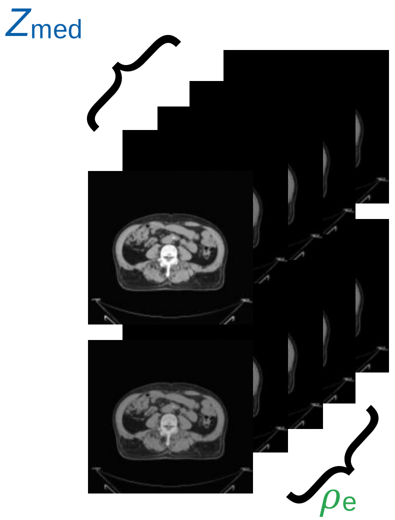
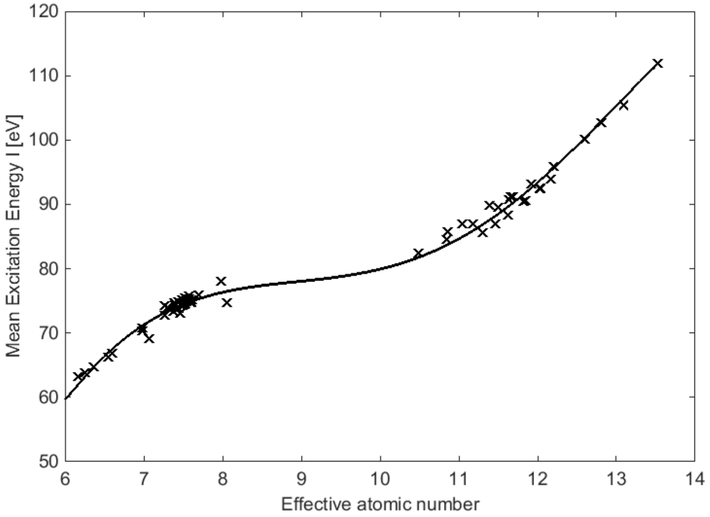
find parameters c_k and b_m



Estimating RSP maps from DECT Images

- Parameterize the **mean excitation energy *I*** as a function of Z_{med}

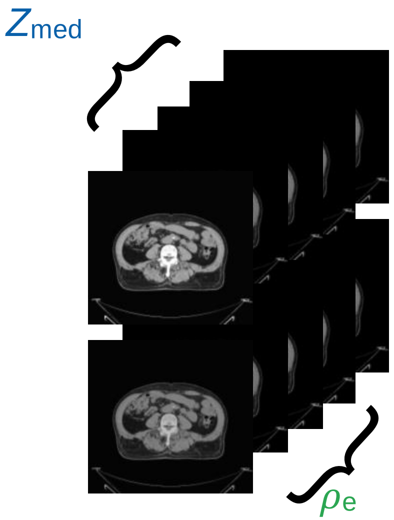


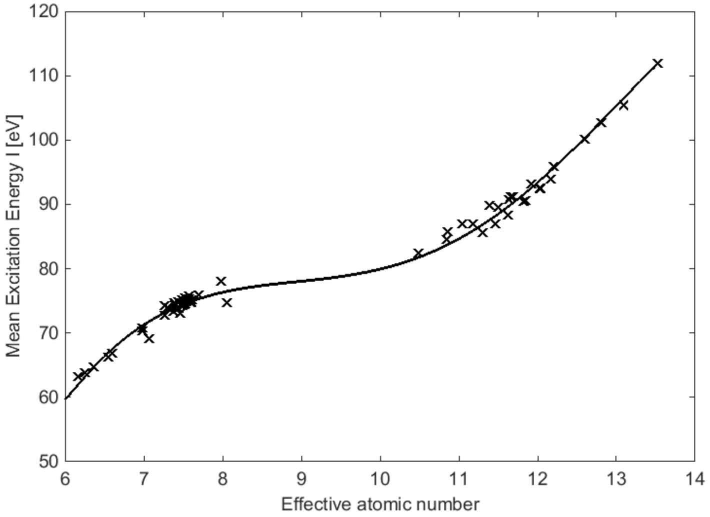


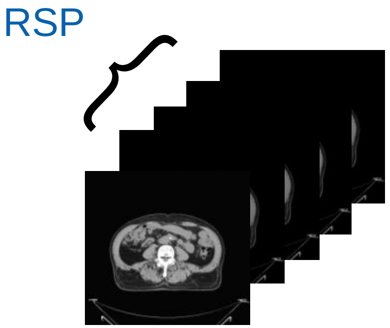
Estimating RSP maps from DECT Images

- Parameterize the **mean excitation energy *I*** as a function of Z_{med}
- Calculate the **RSP** from *I* and ρ_e per voxel using the **Bethe equation**

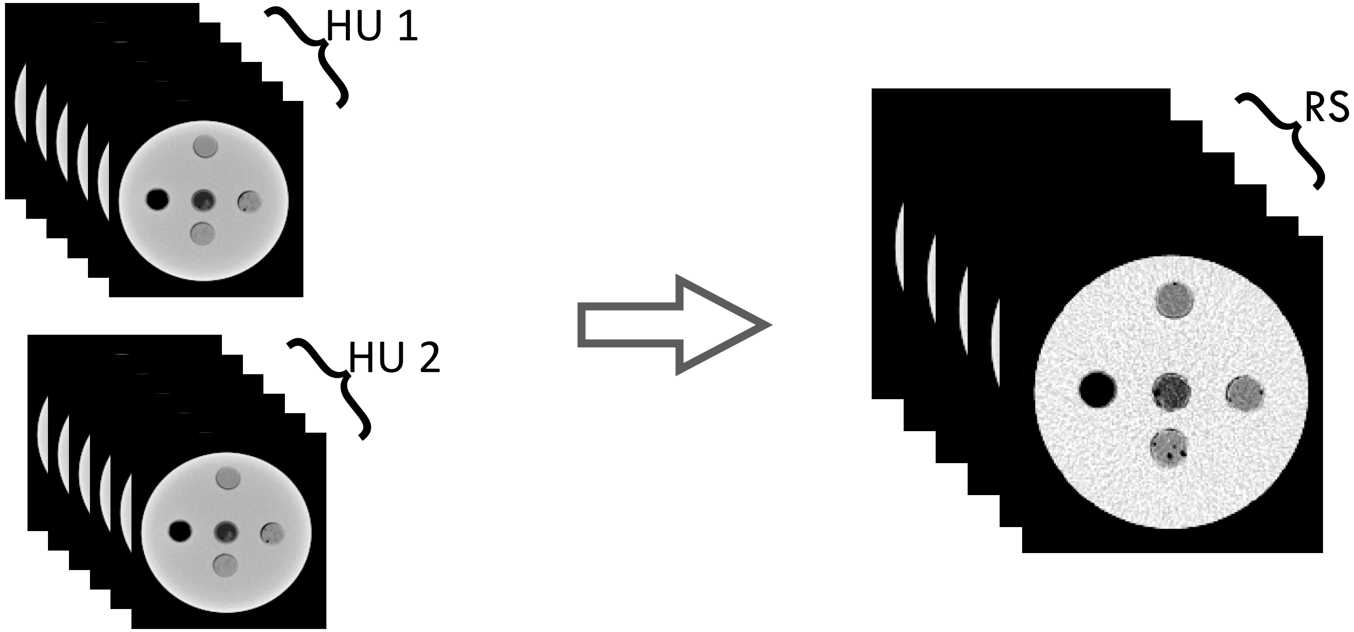
$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \rho_e \frac{k_0 z^2}{\beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2}{I(1-\beta^2)}\right) - \beta^2\right]$$







Estimating RSP maps from DECT Images



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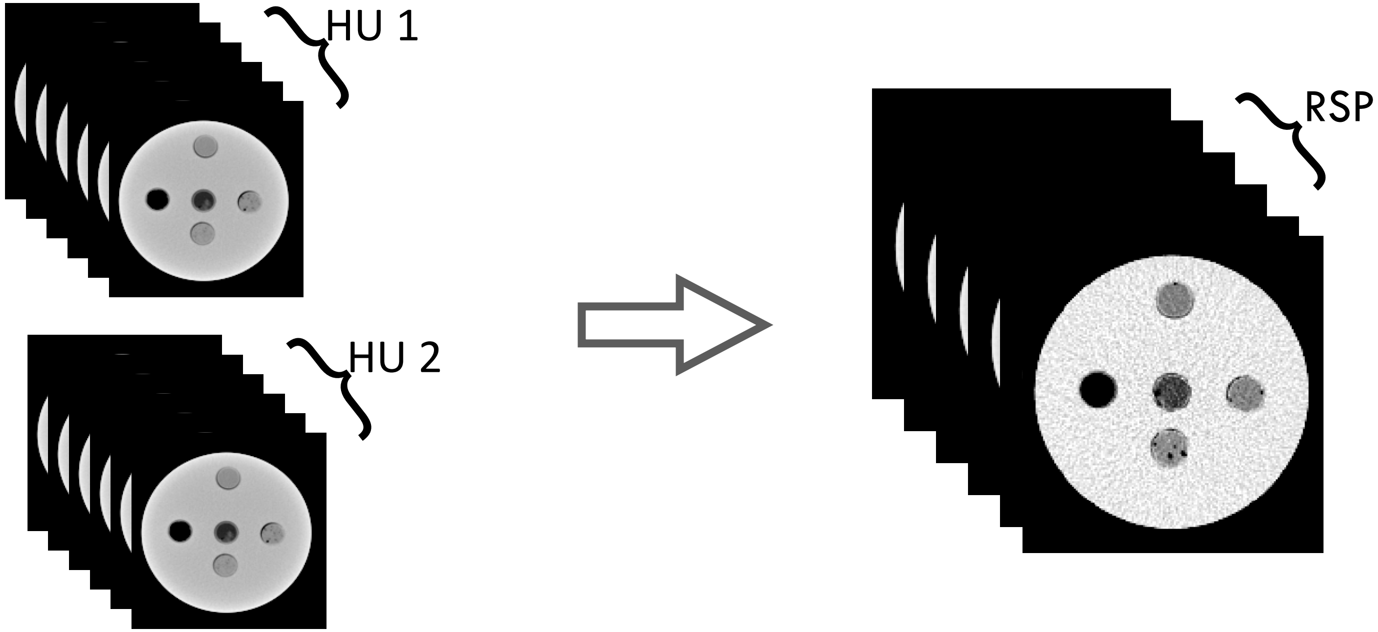
- Calibration phantom: Gammex RMI 467 electron density phantom
- Measure average RSP per sample in VOIs: $\mathbf{RSP_{DECT}}$

Estimating RSP maps from DECT Images



$$\Delta \mathrm{RSP}(\%) = \frac{\mathrm{RSP}_{\mathrm{DECT}} - \mathrm{RSP}_{\mathrm{ref}}}{\mathrm{RSP}_{\mathrm{ref}}} * 100$$

Calibration

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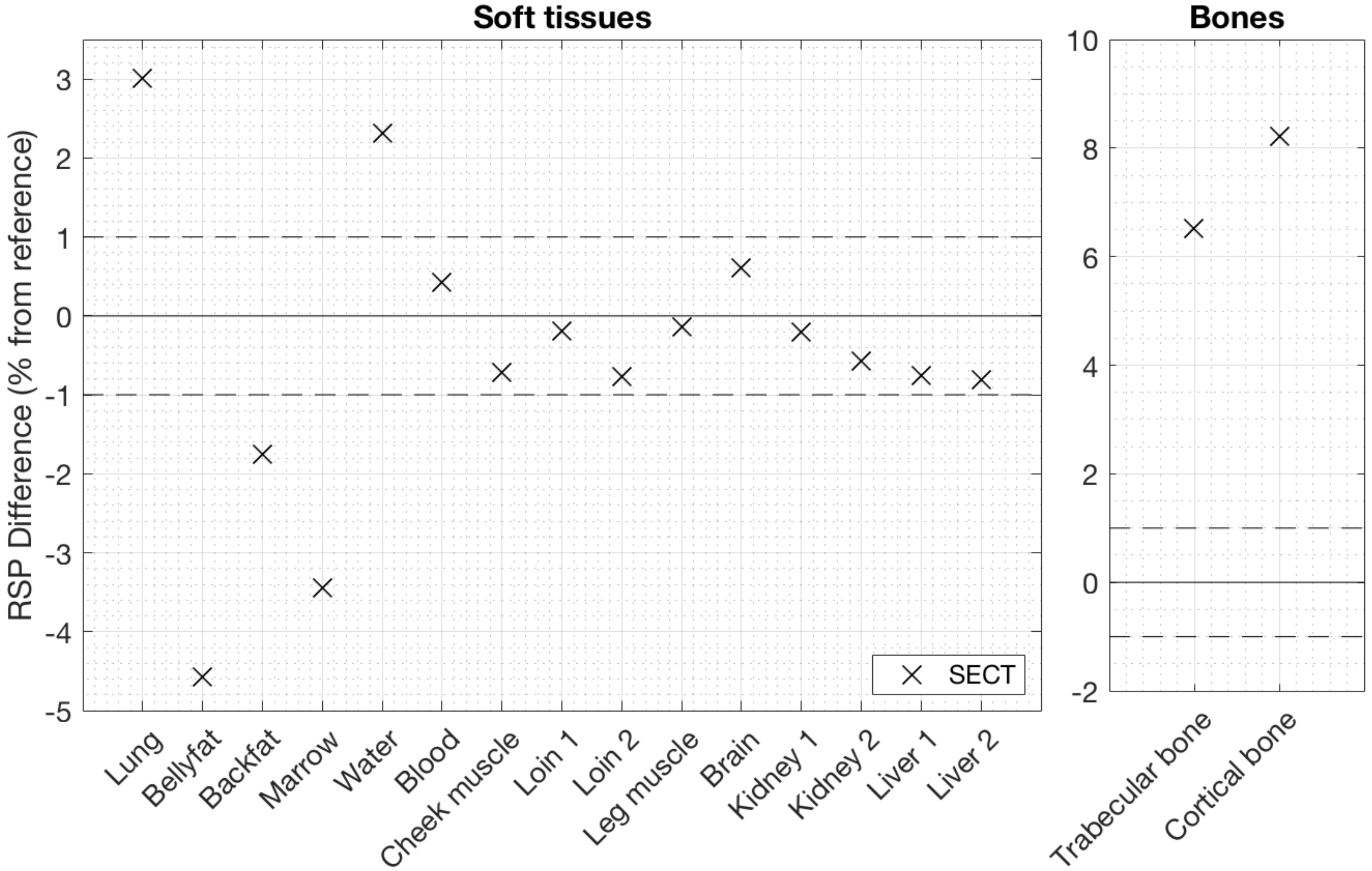
- Calibration phantom: Gammex RMI 467 electron density phantom
- Measure average RSP per sample in VOIs: $\mathbf{RSP_{DECT}}$

SECT-estimated RSP errors



$$\Delta\mathrm{RSP}(\%) = \frac{\mathrm{RSP}_{\mathrm{SECT}} - \mathrm{RSP}_{\mathrm{ref}}}{\mathrm{RSP}_{\mathrm{ref}}} * 100$$

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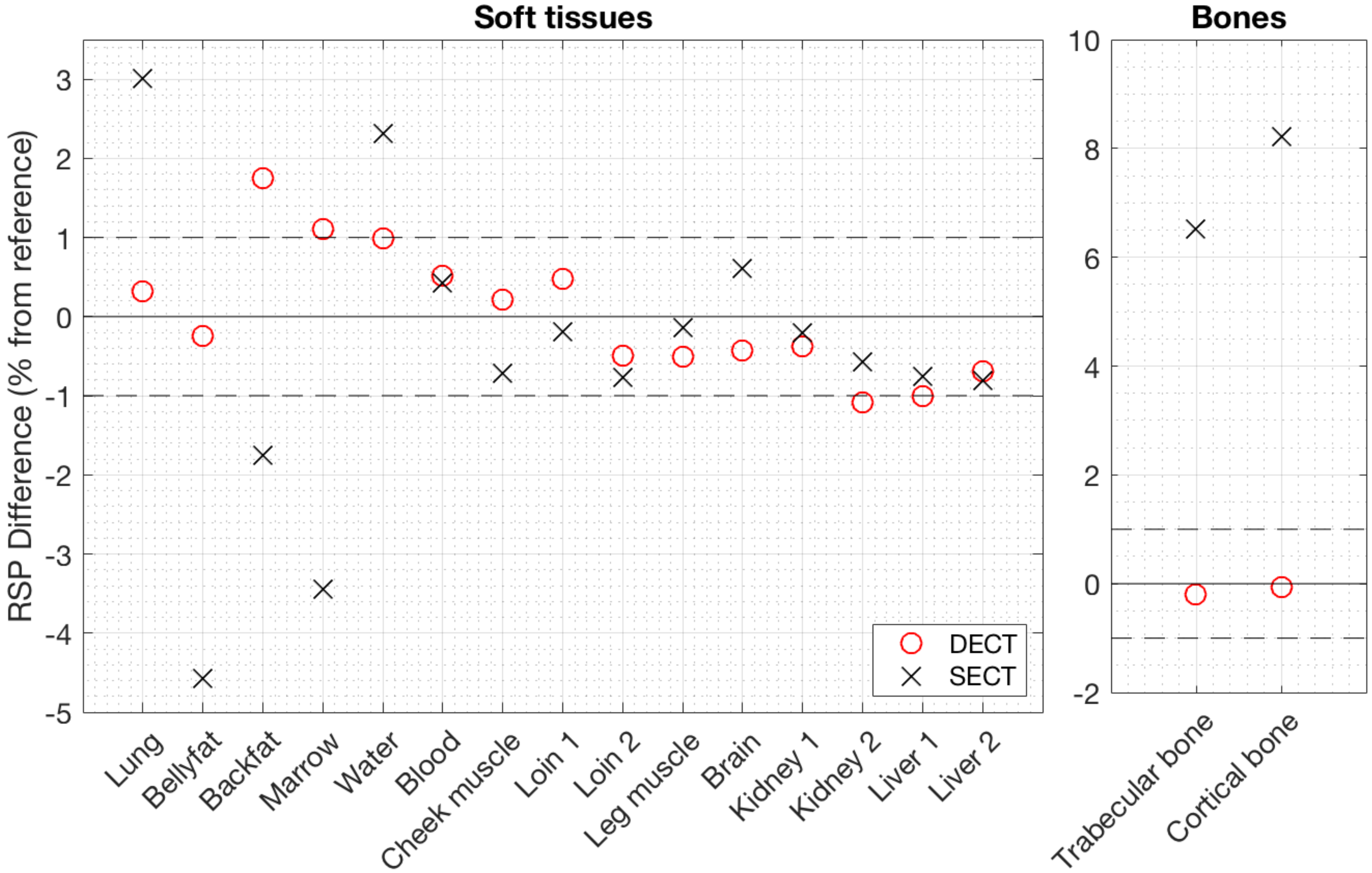
Photon CT estimated RSP errors



$$\Delta\text{RSP}(\%) = \frac{\text{RSP}_{\text{SECT}} - \text{RSP}_{\text{ref}}}{\text{RSP}_{\text{ref}}} * 100$$

$$\Delta\text{RSP}(\%) = \frac{\text{RSP}_{\text{DECT}} - \text{RSP}_{\text{ref}}}{\text{RSP}_{\text{ref}}} * 100$$

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DECT-estimated RSP errors

		% Difference	
Tissue	RSP_{ref}	SECT	DECT
Lung	0.90 ± 0.04	3.01 ± 11.06	0.32 ± 10.87
Belly fat	1.00 ± 0.00	-4.57 ± 3.35*	-0.24 ± 4.24
Back fat	0.97 ± 0.01	-1.75 ± 1.97	1.74 ± 3.30†
Marrow	0.93 ± 0.02	-3.44 ± 5.78	1.11 ± 7.01
Water	1.00 ± 0.00	2.32 ± 0.31	0.99 ± 2.31
Blood	1.05 ± 0.00	0.43 ± 0.29	0.51 ± 1.94
Cheek muscle	1.05 ± 0.01	-0.72 ± 1.49	0.22 ± 2.96
Loin 1	1.06 ± 0.00	-0.20 ± 2.18	0.47 ± 3.57
Loin 2	1.06 ± 0.00	-0.77 ± 1.51	-0.49 ± 2.78
Leg muscle	1.05 ± 0.01	-0.14 ± 1.68	-0.50 ± 2.78
Brain	1.04 ± 0.00	0.61 ± 0.83	-0.43 ± 2.13
Kidney 1	1.05 ± 0.00	-0.20 ± 3.25	-0.37 ± 3.82
Kidney 2	1.04 ± 0.01	-0.58 ± 4.90	-1.09 ± 6.27 *
Liver 1	1.06 ± 0.00	-0.75 ± 4.61	-1.01 ± 5.23
Liver 2	1.06 ± 0.00	-0.80 ± 6.31	-0.69 ± 6.90
Trabecular bone	1.19 ± 0.06	6.52 ± 6.86	-0.19 ± 6.61
Cortical bone	1.78 ± 0.03	8.22 ± 5.06†	-0.07 ± 4.87
Mean error	–	**0.42 ± 4.55**	**-0.02 ± 5.11**
Mean absolute error	–	**2.06**	**0.61**
Root mean square error	–	**3.10**	**0.75**

$$\Delta RSP(\%) = \frac{RSP_{DECT} - RSP_{ref}}{RSP_{ref}} * 100$$

Which imaging modality provides the highest RSP accuracy?

1) Design a **tissue phantom**, collect and prepare tissue samples.
2) Perform **reference RSP** measurements.
3) Photon CT imaging: Collect **SECT and DECT** images, estimate the RSPs and compare to reference RSP.
4) Particle CT imaging: Collect **proton and helium CT** images, compare RSPs to photon CT and reference RSP.

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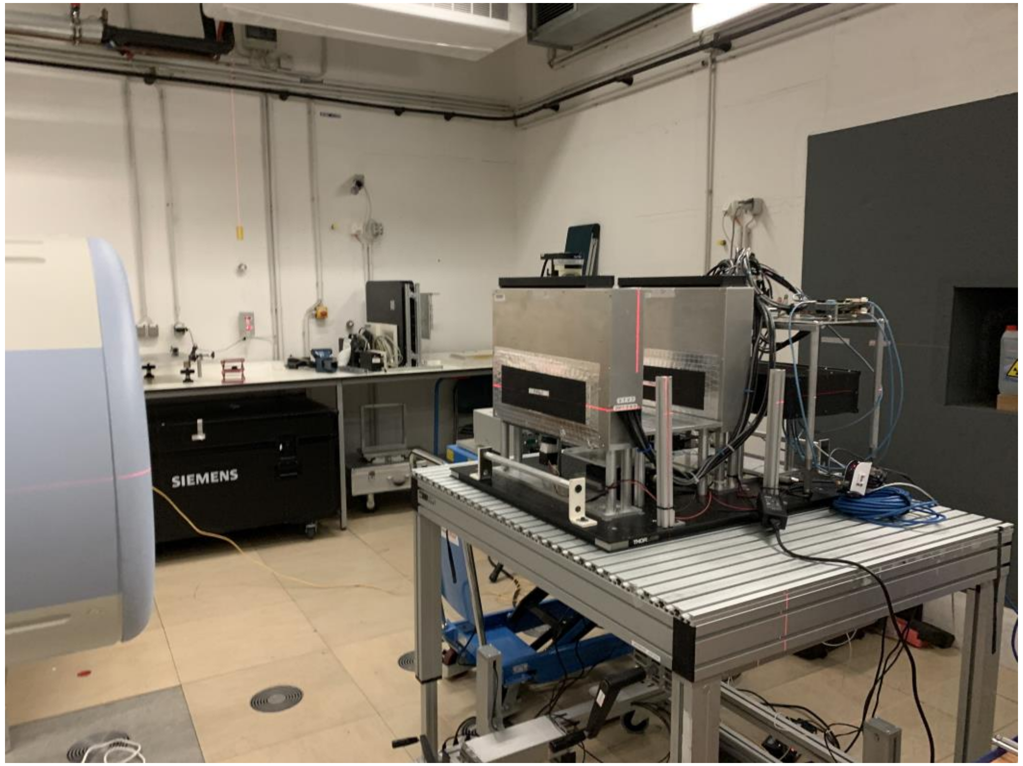
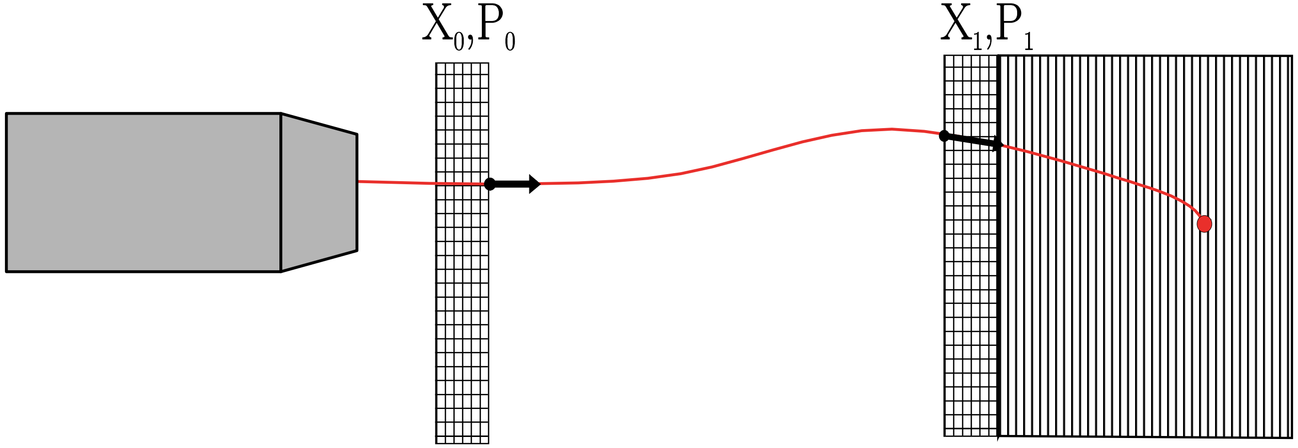
Proton and helium CT collection





- Particle CT directly samples energy loss
- Image blur due to non-linear path of protons
- Helium ions are investigated

$$\Delta\text{RSP}(\%) = \frac{\text{RSP}_{\text{pCT}} - \text{RSP}_{\text{ref}}}{\text{RSP}_{\text{ref}}} * 100$$

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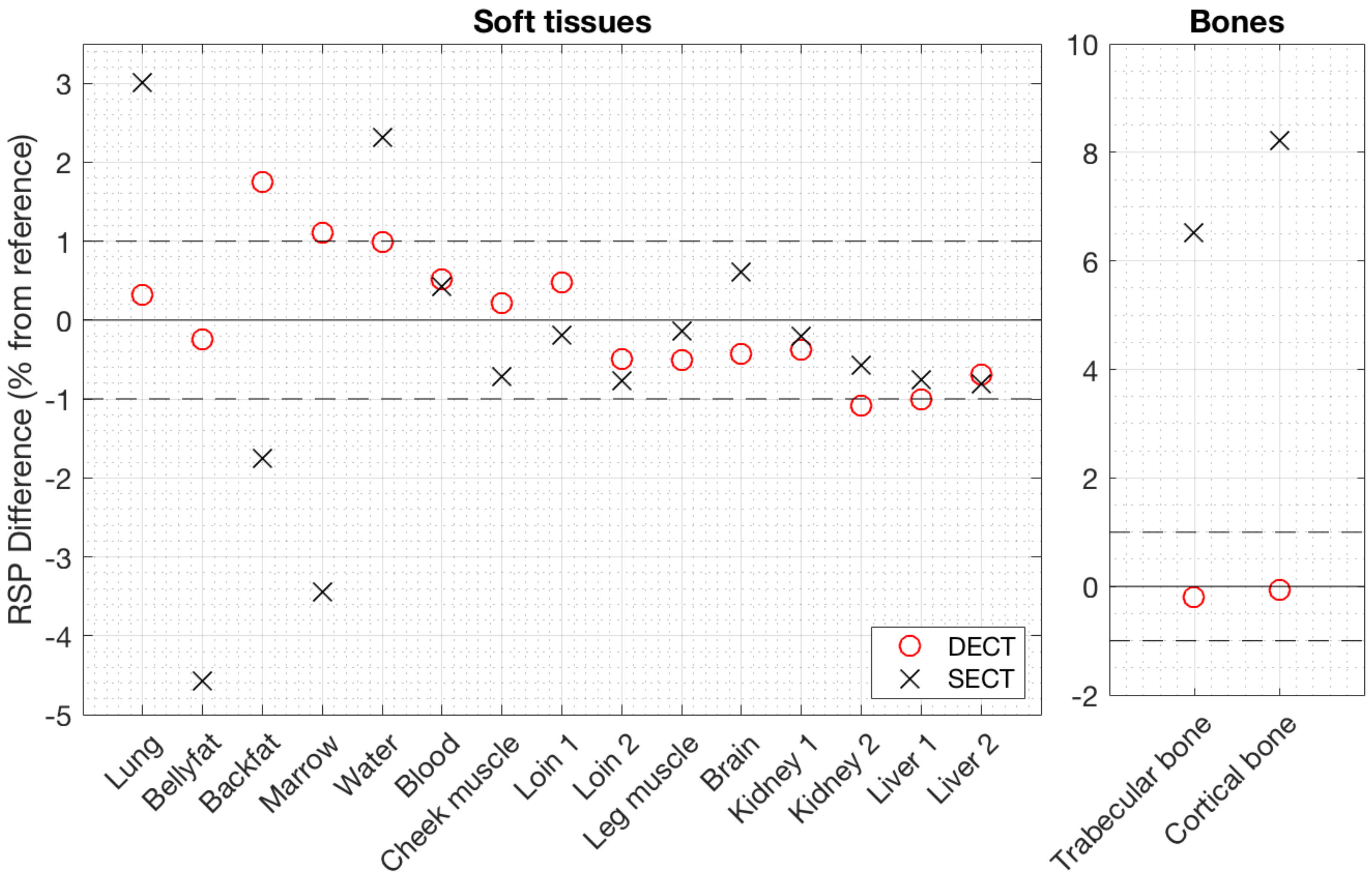
Photon CT estimated RSP errors



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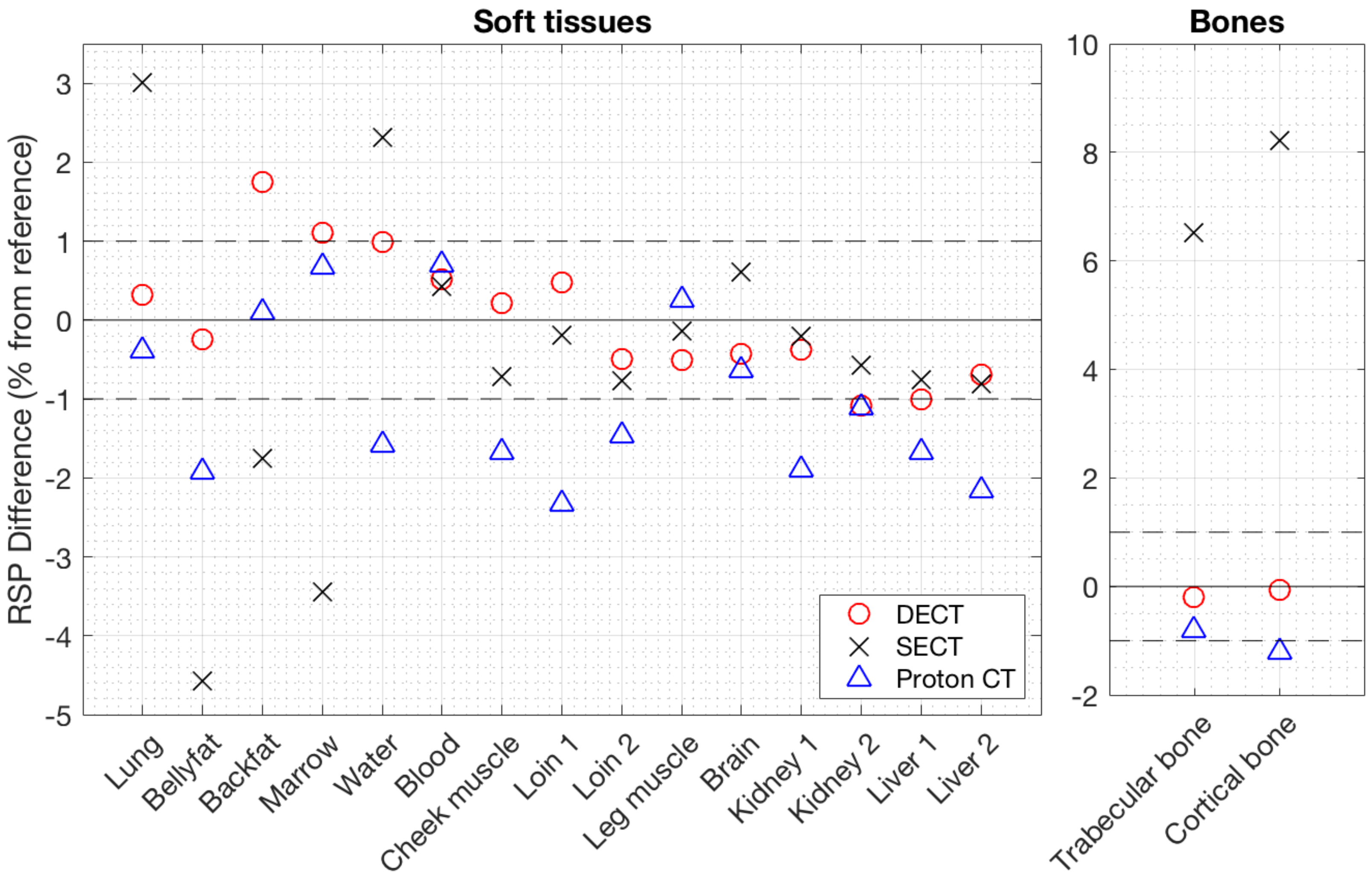
Photon CT vs. Proton CT



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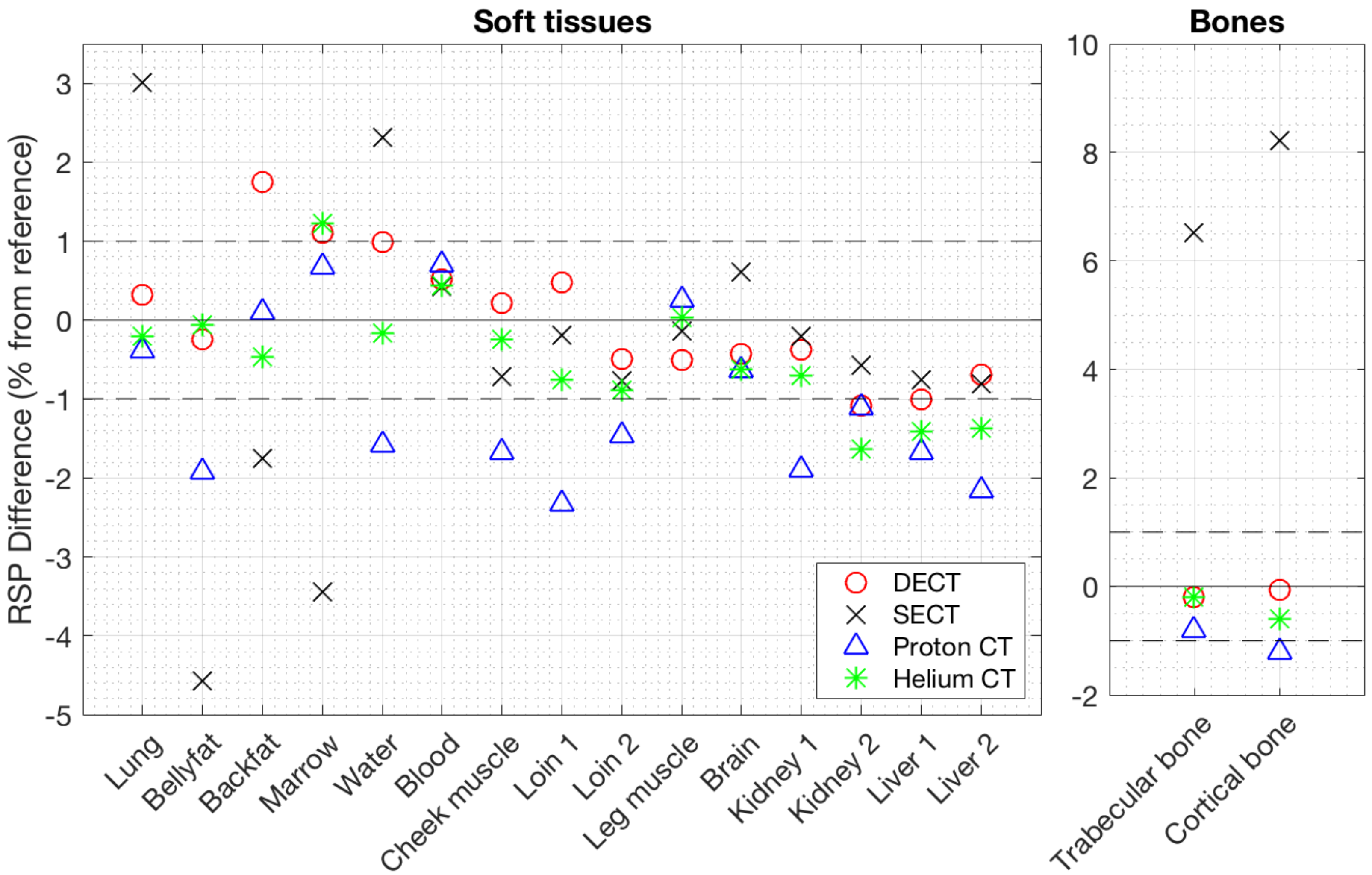
Proton CT estimated RSP errors

		% Difference to reference		
Tissue	RSP_{ref}	SECT	DECT	proton CT
Lung	0.90 ± 0.04	3.01 ± 11.06	0.32 ± 10.87	-0.39 ± 6.89
Belly fat	1.00 ± 0.00	-4.57 ± 3.35*	-0.24 ± 4.24	-1.92 ± 0.83
Back fat	0.97 ± 0.01	-1.75 ± 1.97	1.74 ± 3.30†	0.10 ± 0.95
Marrow	0.93 ± 0.02	-3.44 ± 5.78	1.11 ± 7.01	0.68 ± 4.23
Water	1.00 ± 0.00	2.32 ± 0.31	0.99 ± 2.31	-1.59 ± 0.21
Blood	1.05 ± 0.00	0.43 ± 0.29	0.51 ± 1.94	0.70 ± 0.29†
Cheek muscle	1.05 ± 0.01	-0.72 ± 1.49	0.22 ± 2.96	-1.68 ± 1.12
Loin 1	1.06 ± 0.00	-0.20 ± 2.18	0.47 ± 3.57	-2.33 ± 1.01*
Loin 2	1.06 ± 0.00	-0.77 ± 1.51	-0.49 ± 2.78	-1.47 ± 0.72
Leg muscle	1.05 ± 0.01	-0.14 ± 1.68	-0.50 ± 2.78	0.26 ± 0.95
Brain	1.04 ± 0.00	0.61 ± 0.83	-0.43 ± 2.13	-0.64 ± 0.31
Kidney 1	1.05 ± 0.00	-0.20 ± 3.25	-0.37 ± 3.82	-1.90 ± 0.85
Kidney 2	1.04 ± 0.01	-0.58 ± 4.90	-1.09 ± 6.27 *	-1.12 ± 2.12
Liver 1	1.06 ± 0.00	-0.75 ± 4.61	-1.01 ± 5.23	-1.68 ± 1.50
Liver 2	1.06 ± 0.00	-0.80 ± 6.31	-0.69 ± 6.90	-2.16 ± 5.32
Trabecular bone	1.19 ± 0.06	6.52 ± 6.86	-0.19 ± 6.61	-0.82 ± 5.83
Cortical bone	1.78 ± 0.03	8.22 ± 5.06†	-0.07 ± 4.87	-1.22 ± 1.58
Mean error	–	**0.42 ± 4.55**	**-0.02 ± 5.11**	**-1.01 ± 2.90**
Mean absolute error	–	**2.06**	**0.61**	**1.21**
Root mean square error	–	**3.10**	**0.75**	**1.39**

Photon vs. Particle CT



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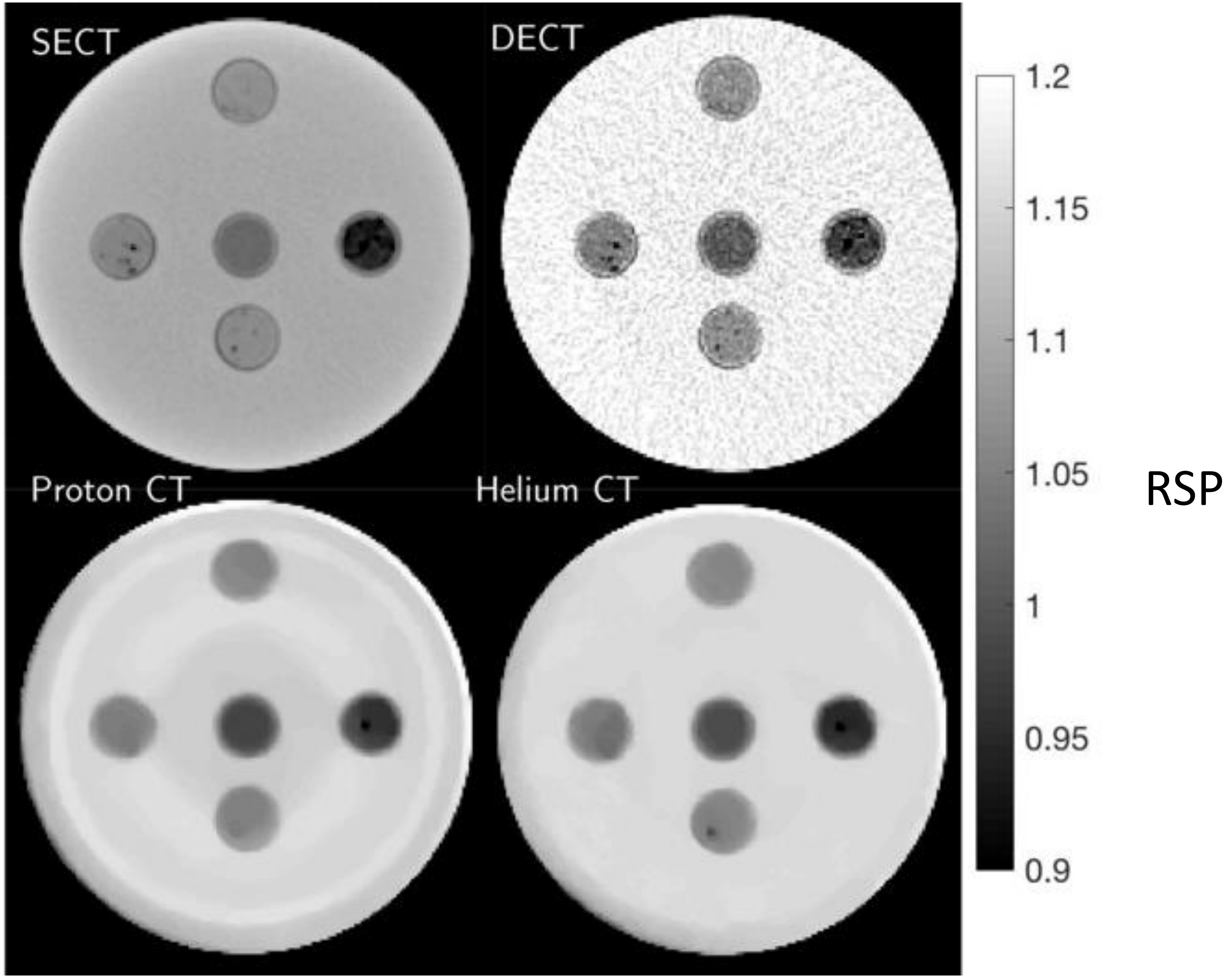
Particle CT

		% Difference to reference			
Tissue	RSP_{ref}	SECT	DECT	proton CT	Helium CT
Lung	0.90 ± 0.04	3.01 ± 11.06	0.32 ± 10.87	-0.39 ± 6.89	-0.21 ± 7.13
Belly fat	1.00 ± 0.00	-4.57 ± 3.35*	-0.24 ± 4.24	-1.92 ± 0.83	-0.07 ± 1.32
Back fat	0.97 ± 0.01	-1.75 ± 1.97	1.74 ± 3.30†	0.10 ± 0.95	-0.47 ± 0.98
Marrow	0.93 ± 0.02	-3.44 ± 5.78	1.11 ± 7.01	0.68 ± 4.23	1.23 ± 3.74†
Water	1.00 ± 0.00	2.32 ± 0.31	0.99 ± 2.31	-1.59 ± 0.21	-0.16 ± 0.25
Blood	1.05 ± 0.00	0.43 ± 0.29	0.51 ± 1.94	0.70 ± 0.29†	0.43 ± 0.18
Cheek muscle	1.05 ± 0.01	-0.72 ± 1.49	0.22 ± 2.96	-1.68 ± 1.12	-0.24 ± 1.17
Loin 1	1.06 ± 0.00	-0.20 ± 2.18	0.47 ± 3.57	-2.33 ± 1.01*	-0.75 ± 1.38
Loin 2	1.06 ± 0.00	-0.77 ± 1.51	-0.49 ± 2.78	-1.47 ± 0.72	-0.89 ± 0.98
Leg muscle	1.05 ± 0.01	-0.14 ± 1.68	-0.50 ± 2.78	0.26 ± 0.95	0.03 ± 1.11
Brain	1.04 ± 0.00	0.61 ± 0.83	-0.43 ± 2.13	-0.64 ± 0.31	-0.63 ± 0.48
Kidney 1	1.05 ± 0.00	-0.20 ± 3.25	-0.37 ± 3.82	-1.90 ± 0.85	-0.70 ± 1.07
Kidney 2	1.04 ± 0.01	-0.58 ± 4.90	-1.09 ± 6.27 *	-1.12 ± 2.12	-1.64 ± 3.34*
Liver 1	1.06 ± 0.00	-0.75 ± 4.61	-1.01 ± 5.23	-1.68 ± 1.50	-1.41 ± 1.40
Liver 2	1.06 ± 0.00	-0.80 ± 6.31	-0.69 ± 6.90	-2.16 ± 5.32	-1.37 ± 5.34
Trabecular bone	1.19 ± 0.06	6.52 ± 6.86	-0.19 ± 6.61	-0.82 ± 5.83	-0.19 ± 6.22
Cortical bone	1.78 ± 0.03	8.22 ± 5.06†	-0.07 ± 4.87	-1.22 ± 1.58	-0.60 ± 2.02
Mean error	–	**0.42 ± 4.55**	**-0.02 ± 5.11**	**-1.01 ± 2.90**	**-0.50 ± 3.06**
Mean absolute error	–	**2.06**	**0.61**	**1.21**	**0.65**
Root mean square error	–	**3.10**	**0.75**	**1.39**	**0.81**



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Conclusion

- We present a first comparison of photon and particle CT for RSP estimation based on fresh tissues
- SECT is highly biased in low- and high density tissues
- DECT offers high accuracy
- Proton CT is currently limited by ring artefacts
- Helium CT provides good RSP accuracy and low noise
- Mind the maturity of systems!

Acknowledgements

Sample preparation
Photon CT
Beam time

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Particle CT equipment

TO MAKE MAN WHOLE
LOMA LINDA UNIVERSITY

Data processing algorithms

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PRT

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