Evaluation of Proton Dose Accuracy Improvements with Dual-Energy CT

Sina Mossahebi, Pouya Sabouri, Maida Ranjbar, Joshua Strauss, Matthew O'Neil, Jainil Shah, Jerimy Polf

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

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Disclosures

- Partially supported by Siemens Healthineers

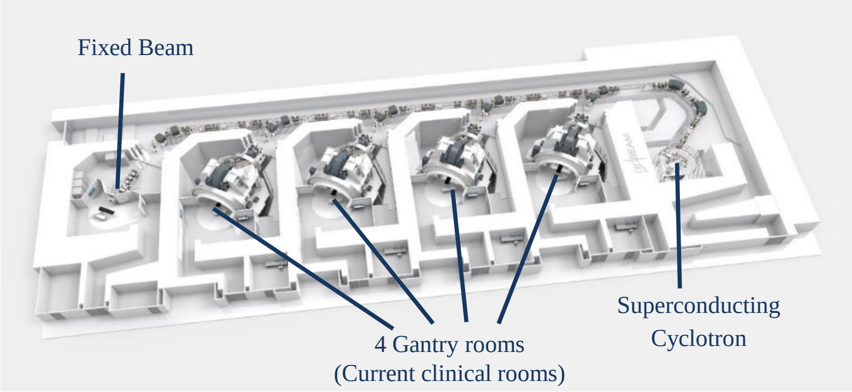
  SECT vs. DECT Comparison Study

Maryland Proton Treatment Center (MPTC)
University of Maryland

Varian ProBeam

5 room facility (4 gantries, 1 fixed beam)

- First treatment in February 2016
- 4 of 5 treatment rooms open and treating



Siemens Definition Edge DECT
Dual Spiral & TwinBeam

Siemens Aera MRI Scanner
1.5 T

University of Maryland School of Medicine

Outline

Introduction

- Proton Therapy
- Proton Therapy Uncertainties
    - Range Uncertainty
- Single Energy CT
- Dual Energy CT

Methods

- Creating Stopping Power Ratio images from DECT
- SPR Image Analysis for Non-Biological Tissue
- SPR and Dose Measurements
    - Tissue surrogate plugs
    - Biological tissue samples
    - Non-biological samples

Results & Conclusions

- Results

  SPR and Dose Measurements
    - Tissue surrogate plugs
    - Biological tissue samples
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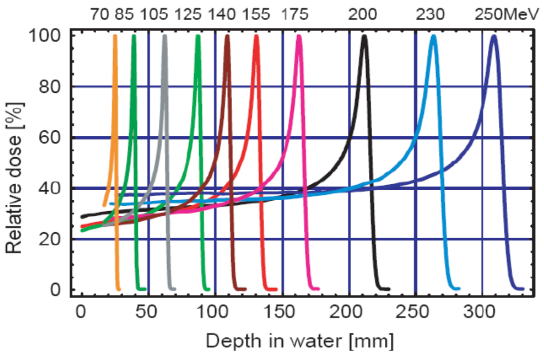
Introduction

Proton Radiotherapy Overview

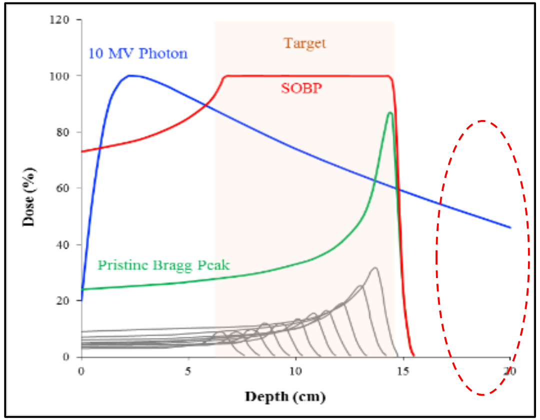
- Proton is a charged particle that continuously loses energy as it penetrates the body
- Range depends on Energy



Due to the finite range of the proton beam (Bragg Peak)

→ No exit dose!

→ Better normal tissue sparing

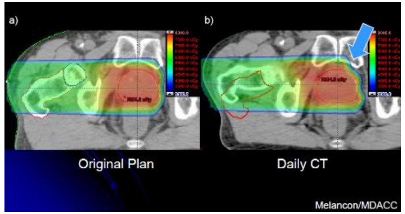


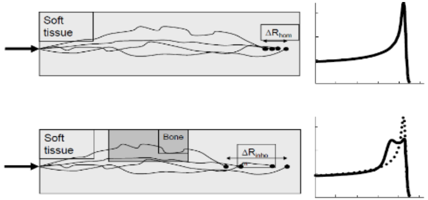
Proton Therapy Uncertainties

Range uncertainty: 3.5% of range

Uncertainty to estimate stopping power ratio from CT Hounsfield units (HU)

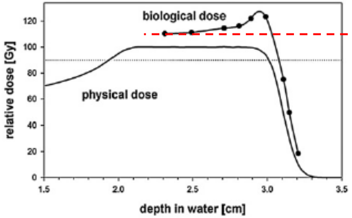
Sensitivity to anatomical changes





Lomax, AAPM SS 2003

RBE uncertainty at end of range



Choose generic RBE value of 1.1

ICRU Report 78

Motion during treatment and …

Proton Therapy Uncertainties

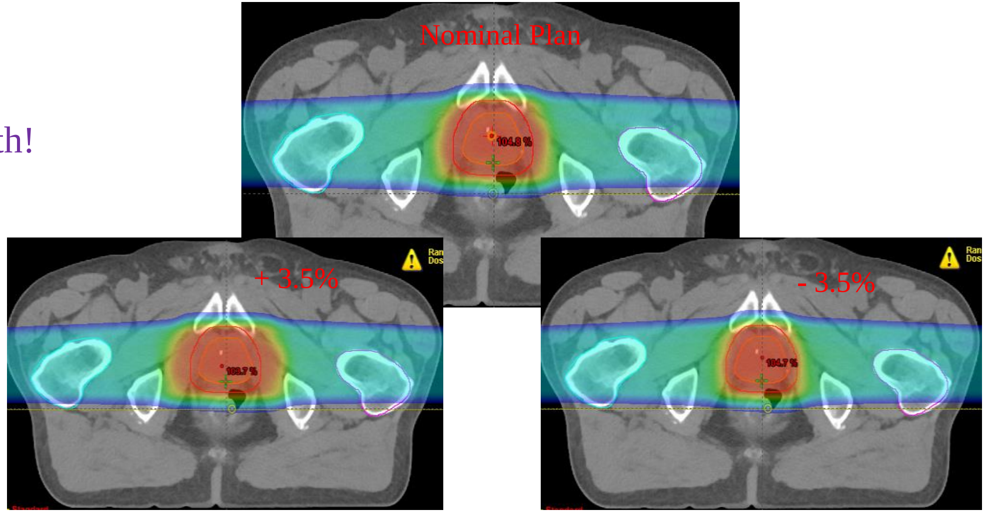
Range uncertainty

Stopping power determine how "fast" proton loses energy

- CT HU to stopping power ratio calibration has about 3.5% uncertainty
- Translates into 3.5% range uncertainty

3.5 mm at a range of 10 cm
7 mm at a range of 20 cm
} Depends on depth!

Limits Plan Quality & Robustness!



More dose to normal tissue **Less target coverage**

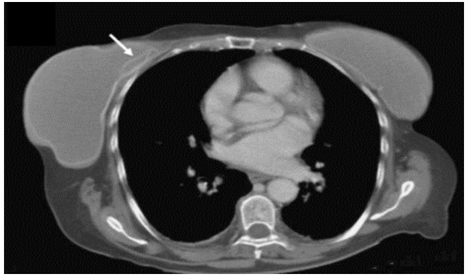
Proton Therapy Uncertainties

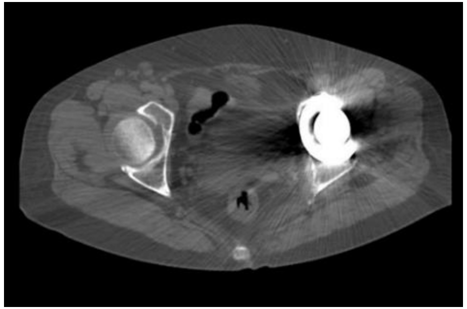
Single energy CT (SECT) is commonly used in radiation therapy.

- SECT stoichiometric calibration curve does not work well for non-biological tissue
- Manual measurement – Density override technique is required

Implants made of “non-tissue” materials:

- Dental implants
- Breast implants
- Chemo ports
- Hip prosthesis
- Spinal hardware
- Surgical clips
- Pacemakers / ICDs
- etc.





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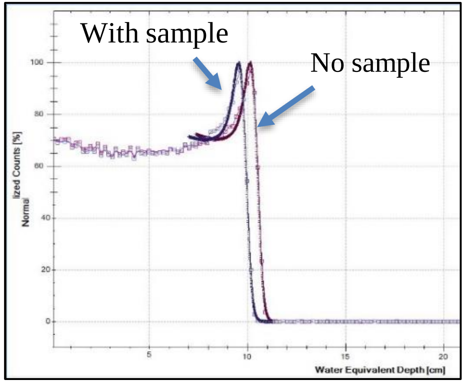

Calculate water equivalent thickness (WET) of the sample

WET = range in water (no sample) – range in water (with sample)

$$\mathrm{SPR} = \frac{\text{Sample WET}}{\text{Sample thickness}}$$

Example: $$\mathrm{SPR} = \frac{0.64\ cm}{0.4\ cm} = 1.6$$

Proton Therapy Uncertainties

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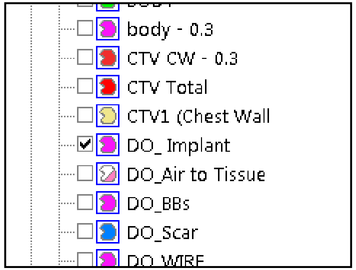
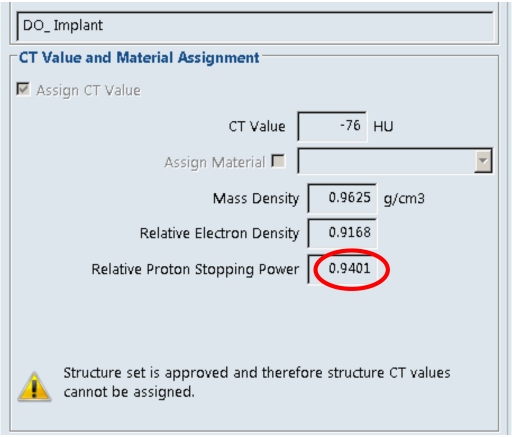
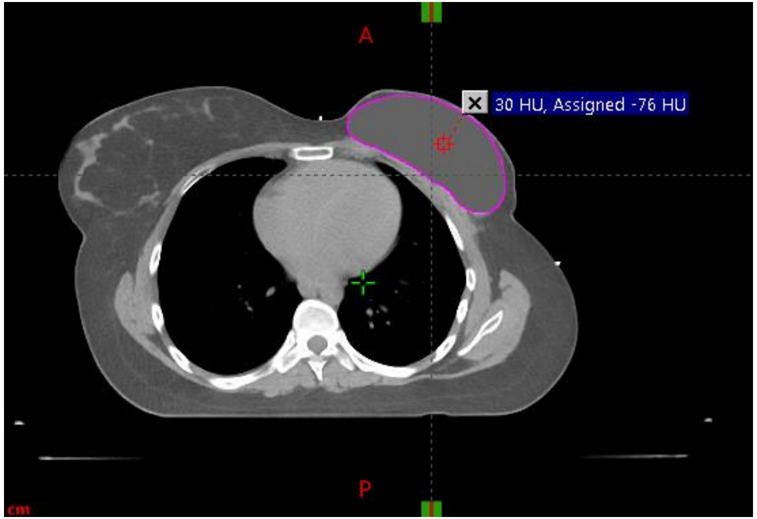
Material	SPR	HU			
		MPTC HN	MPTC AVG	MPTC BODY	UMMS
Sientra Silicone Gel Breast Implant (20645-450MPNU)	0.94	-73	-74	-76	







Proton Therapy Uncertainties

Single energy CT (SECT) is commonly used in radiation therapy.

- SECT stoichiometric calibration curve does not work well for non-biological tissue
- Manual measurement – Density override technique is required

Why is calibration uncertain?

- HU and SPR are both dominated by electron density ratio

But elemental composition also matters, not a perfect relationship

- Same SPR can have different HU values
- Same HU can have different SPR values

Proton Therapy Uncertainties

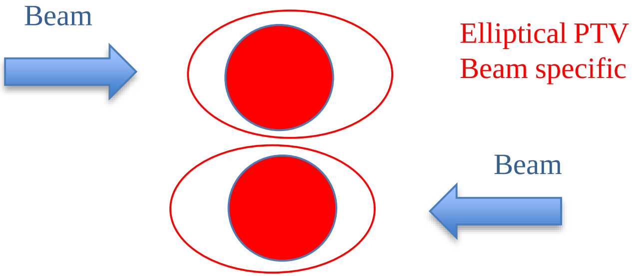
Range uncertainty

Management:

1) Use margins = 3.5% range + 1mm

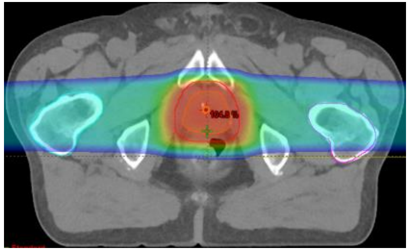
   Larger distal margin than proximal margin

   For prostate @ 20 cm depth: margin= 8 mm



2) Do not stop beam in front of organs at risk

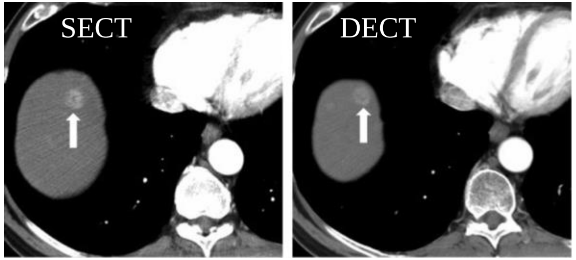
   This is why lateral beams are used to treat prostate in proton therapy



Can it be reduced?

- Better CT: Dual Energy CT (DECT)
- Direct measurement of range (prompt gamma, proton radiography)
- …

Dual Energy CT



Enhance the soft tissue contrast → Good for contouring

What we are more interested in proton therapy other than soft tissue enhancement capabilities, DECT:

- Can provide information about the composition of materials
- Can be used to directly calculate the SPR from CT images
- Accurate calculation of SPR → better proton range estimation

Purpose

Evaluate potential improvements associated with DECT to estimate SPR for biological and non-biological tissue samples.

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How to Calculate SPR from the Patient CT Images using DECT

- **To calculate SPR, you need two information:**
  - Electron density ratio
  - Mean excitation energy (mean value of the ionization and excitation potentials)

Stopping Power Ratio

Mean Excitation Energy

$$\left(\frac{S}{\rho}\right)^{m}_{water} = \frac{\rho_e^m}{\rho_e^{water}} \times \frac{\ln\left[\frac{2m_e c^2\beta^2}{I_m(1-\beta^2)}\right] - \beta^2}{\ln\left[\frac{2m_e c^2\beta^2}{I_{water}(1-\beta^2)}\right] - \beta^2}$$

Electron Density Ratio

Hünemohr et al, PMB, 59, 2014

Creating SPR images from DECT

DECT outputs using *Syngo.via* software:

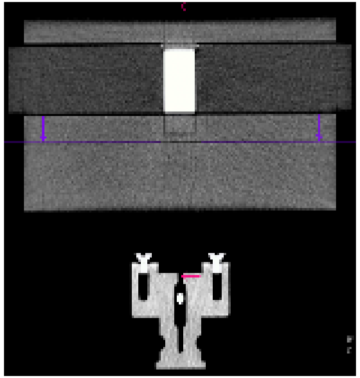
Relative Electron Density and Z_{eff} using *Syngo.via* software

Relative electron density (RED)

Each pixel value is in
Units of HU

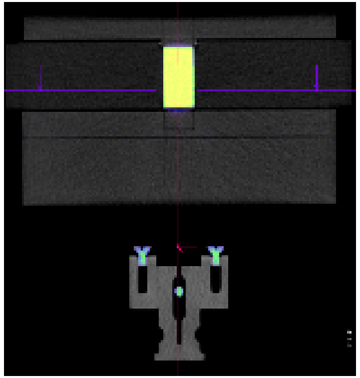
Proportional to RED

$$\left(\frac{\rho_e}{\rho_{e,water}}\right) = \left(\frac{HU}{1000}\right) + 1$$



Effective atomic number (Z_{eff})

Each pixel value is in
Units of Z_{eff}



But, to calculate SPR we need Relative Electron Density and **Mean Excitation Energy (I_m)**

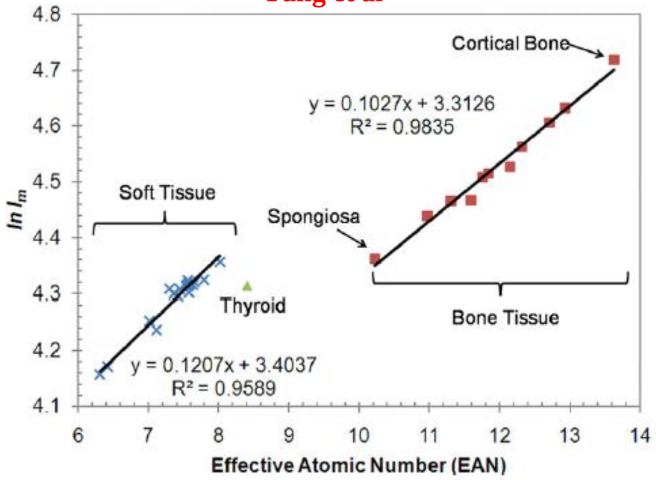
Creating SPR images from DECT

Need to convert Z_{eff} to I_m

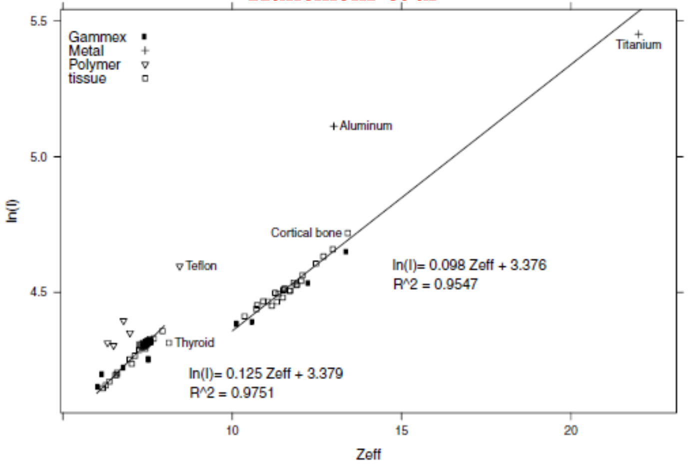
We started with two models:

- Yang Model
- Hünemohr Model

Yang et al



Hünemohr et al



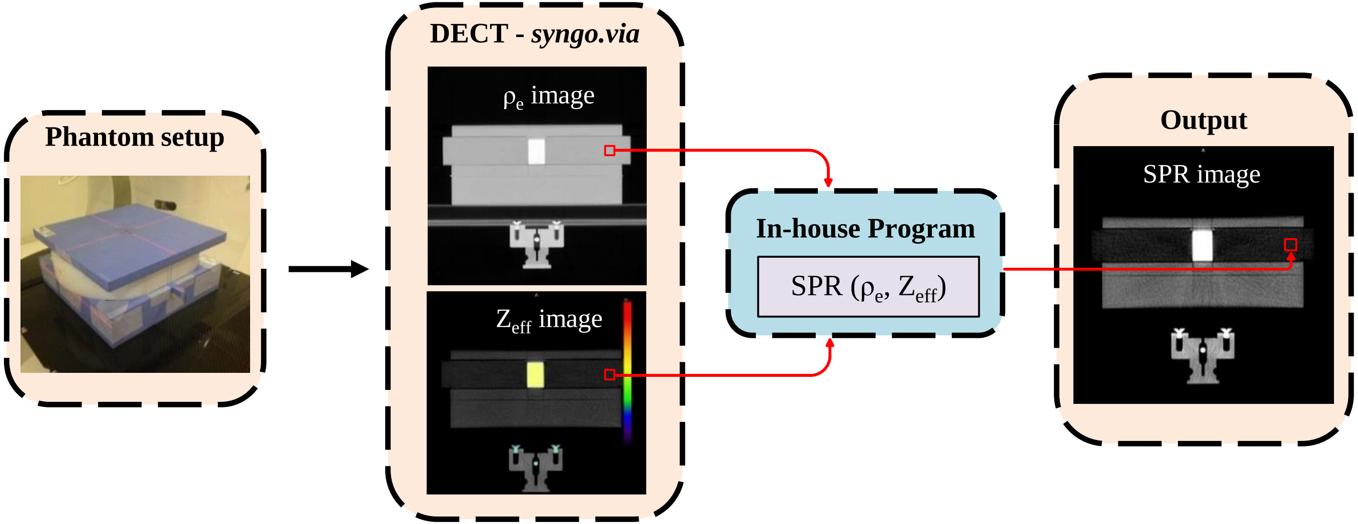
Yang et al, PMB, 55, 2010
Hünemohr et al, PMB, 59, 2014

Creating SPR images from DECT

Using in-house program, SPR images were created by

- Combining electron density (ρ_e) and effective atomic number (Z_{eff}) images
- Using SPR equation for both models

$$\left(\frac{S}{\rho}\right)^{m}_{water} = \frac{\rho_e^m}{\rho_e^{water}} \times \frac{ln\left[\frac{2m_e c^2\beta^2}{I_m(1-\beta^2)}\right] - \beta^2}{ln\left[\frac{2m_e c^2\beta^2}{I_{water}(1-\beta^2)}\right] - \beta^2}$$

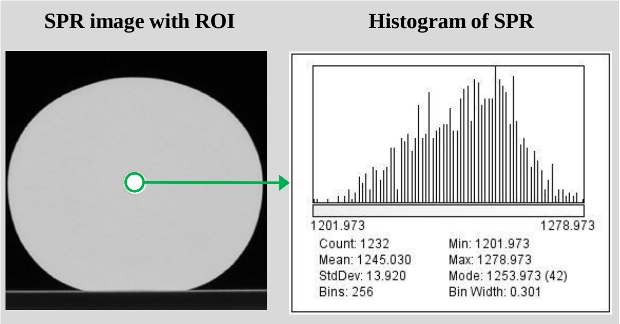


Yang et al, PMB, 55, 2010
Hünemohr et al, PMB, 59, 2014

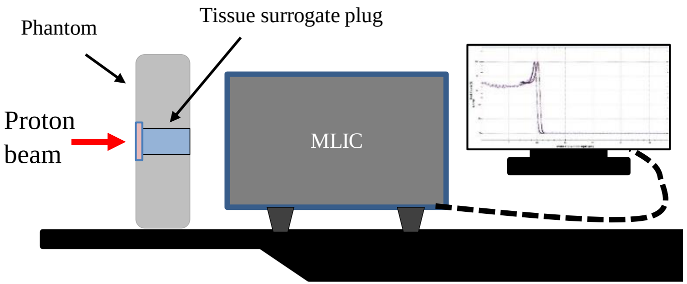
Validating SPR values from DECT

26 tissue surrogate plugs were used from Gammex and CIRS phantoms

For each plug, SPR value was determined from SPR image created from DECT

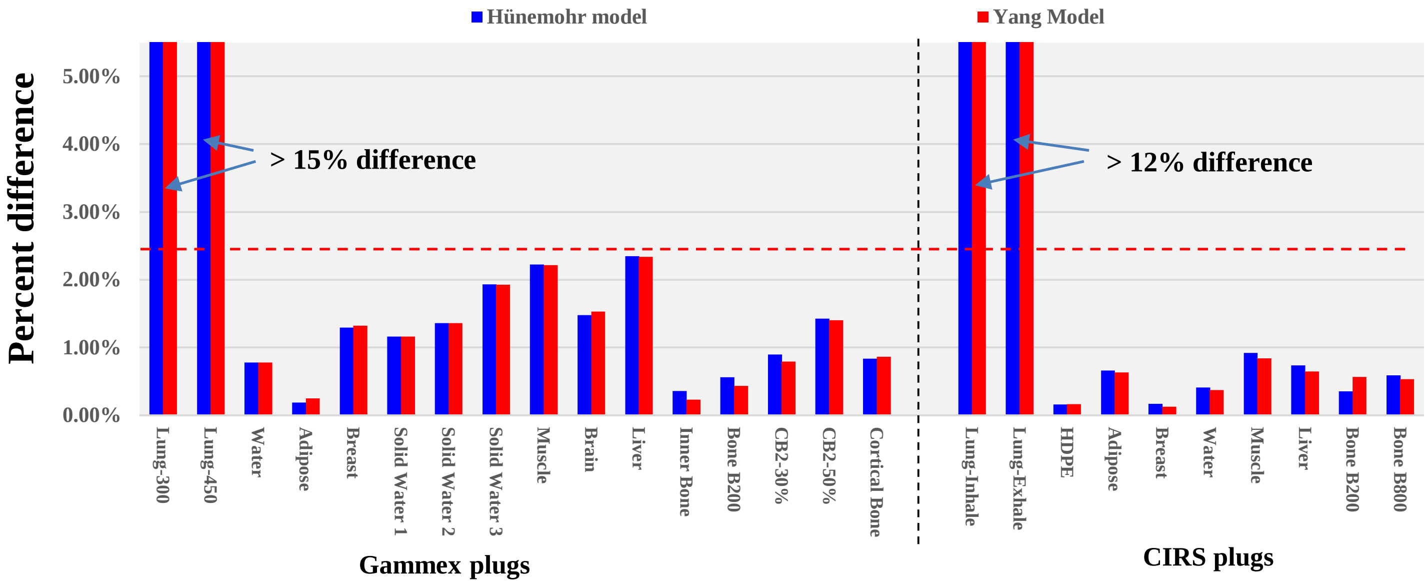


And compared to the measured SPR value from multi-layer ion chamber (Giraffe)



Validating SPR values from DECT

For all tissues (except lung): %Difference < 2.5%



Why it's not good for lung?!

High %diff of lung values are due to the limitation of *Syngo.via* software for low density materials (Z_{eff}=0)

Optimizing the SPR model from DECT

Based on our measured data, we created a new model (MPTC model)

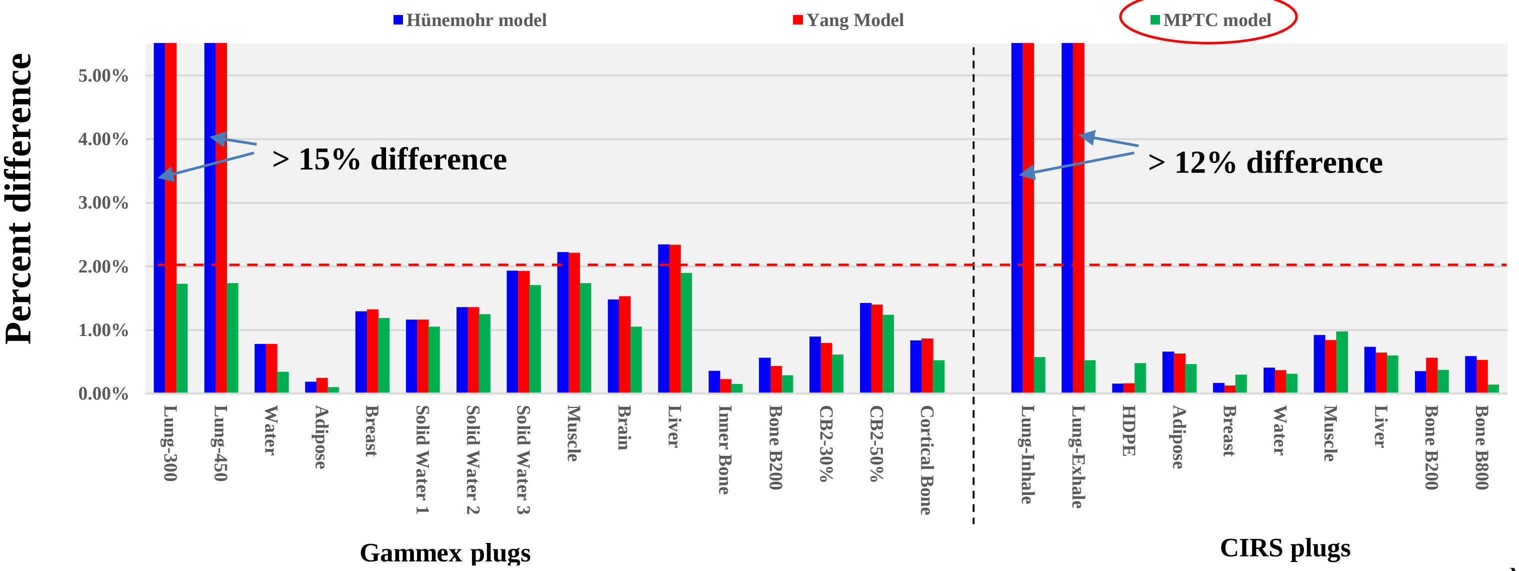
$$SPR = \rho_e; \qquad Z_{eff} \leq 1.0,$$

$$SPR = \rho_e \times \frac{(12.77 - a * Z_{eff}) - C}{8.45}; \qquad 1.0 < Z_{eff} \leq 8.5$$

$$SPR = \rho_e \times \frac{(12.77 - b * Z_{eff}) - D}{8.45}; \qquad 8.5 > Z_{eff}$$

Where
$a = 0.0591$
$b = 0.0947$
$C = 3.893$
$D = 3.6976$

For all tissues: %Difference < 2.0%



Mossahebi et al, IJPT 7(2), 2020

DECT Evaluation

1) **Tissue Surrogate Plugs**

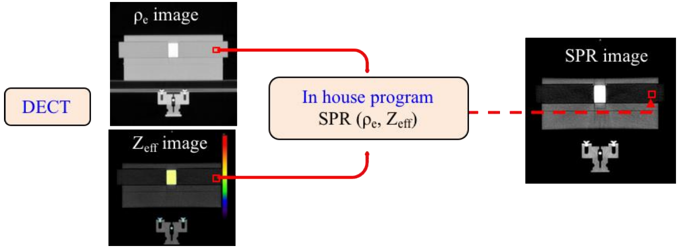
2) **Lung Tissue Sample (Cow and Sheep)**

3) **Other Tissue Samples (brain, liver, foot, belly)**

4) **Breast Implants (2 samples)**

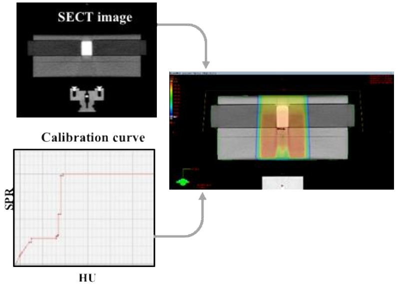
1) Tissue Surrogate Plugs

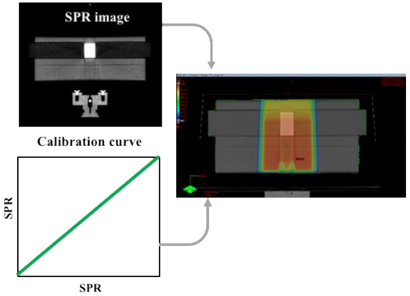
- SECT and DECT scans were acquired for 9 tissue surrogate plugs (CIRS)
- SPR images created
- SPR and SECT images were imported to TPS



Create treatment plans

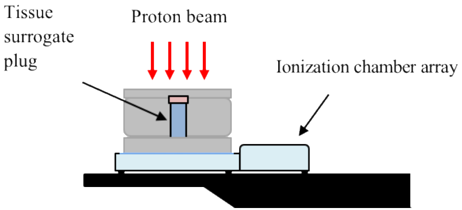
- Single field treatment plans ($10\times10\times10$ cm^3) created on both image sets

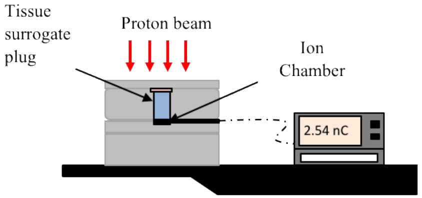




Point and Planar Dose Measurements

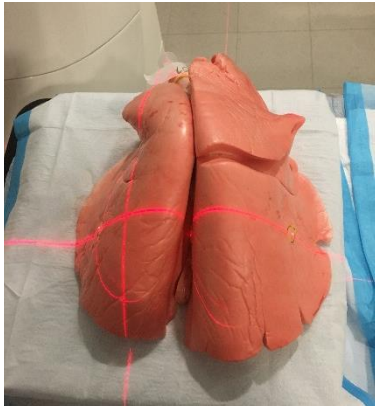
- SOBP field delivered
- Point dose and 2D planar dose were measured





2) Lung Tissue Sample

6 sheep and 1 cow lungs were used in this study



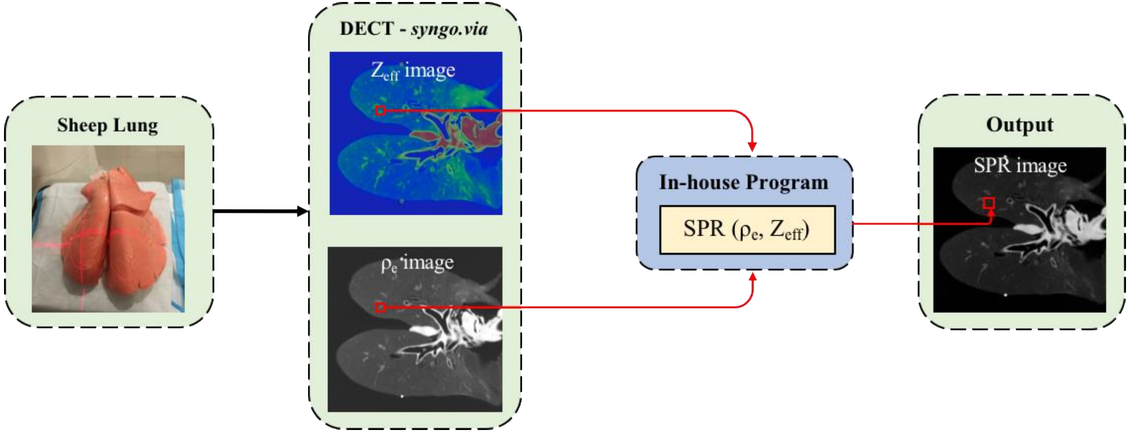
Lungs were partially inflated

DECT and SECT scans acquired

WET and SPR of all lung tissue samples were measured using a MLIC

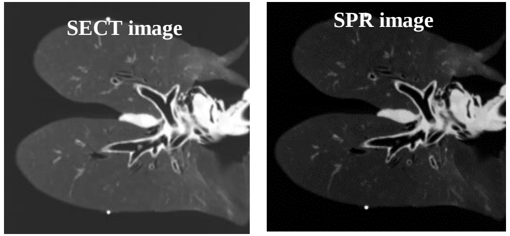
Creating SPR images from DECT

- SPR images were created



- Compared SECT and DECT calculations to measurements

WET & SPR Calculation



← ? →

WET & SPR Measurements

MLIC

3) Other Tissue Samples

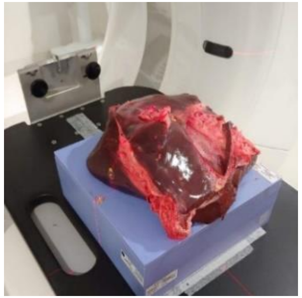
For each sample:

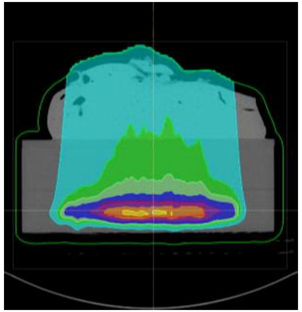
- DECT and SECT scans were acquired
- Treatment plans created and delivered

SPR and Planar Dose Measurements

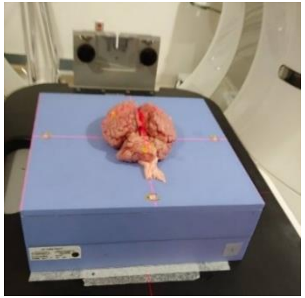
- SPR measured using MLIC
- 2D-planar dose measured using array detector (Matrixx-PT)

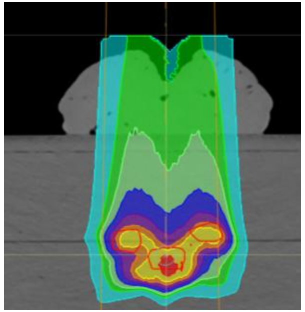
Cow liver



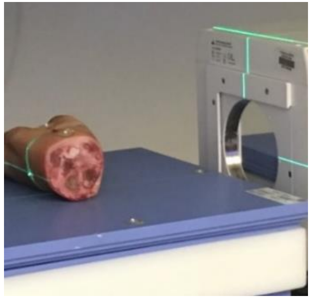


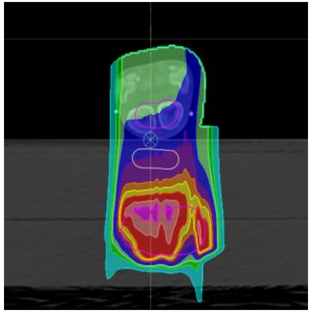
Cow brain



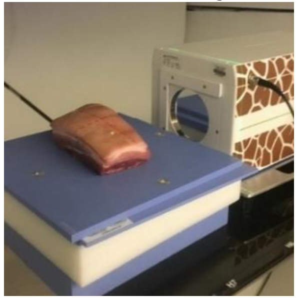


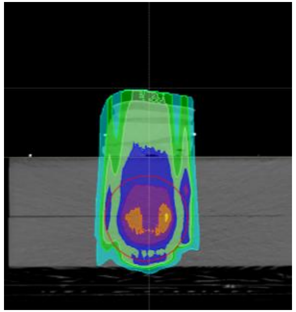
Pork foot





Pork belly





4) Breast Implants

Planar dose measurements

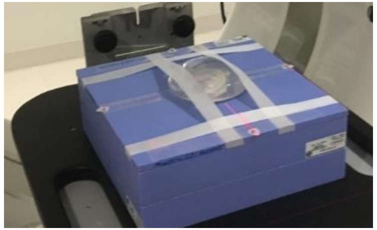
DECT and SECT scans of two commonly used breast implants were acquired

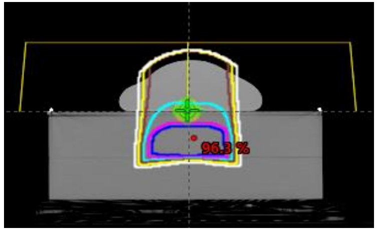
Treatment plans were created and delivered

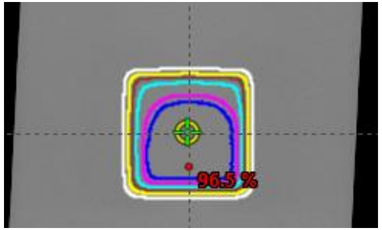
Compared planar dose measurements with TPS dose calculation based on:

- *DECT*
- *SECT*
- *SECT with Density Override (DO)*

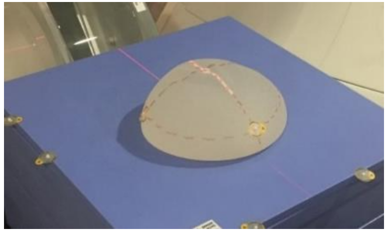
Breast Implant 1

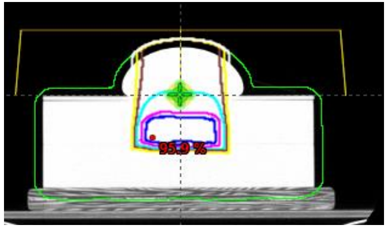


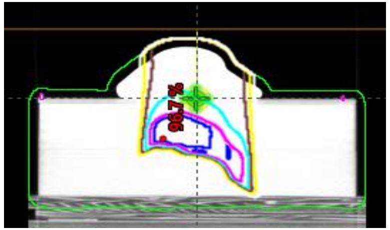




Breast Implant 2







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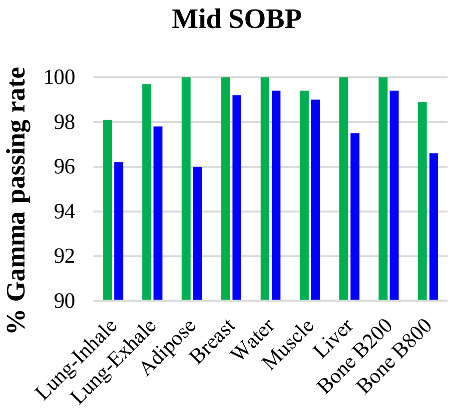
1) Tissue Surrogate Plugs

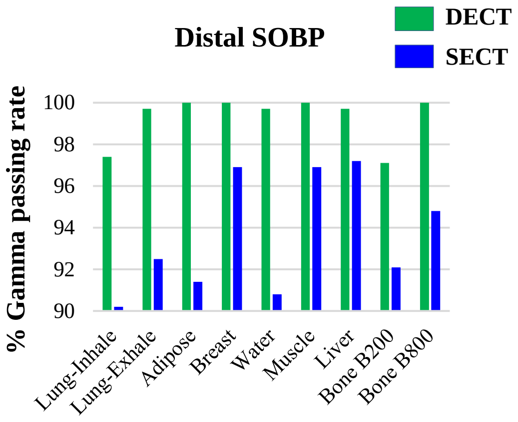
2D Planar dose (gamma analysis)

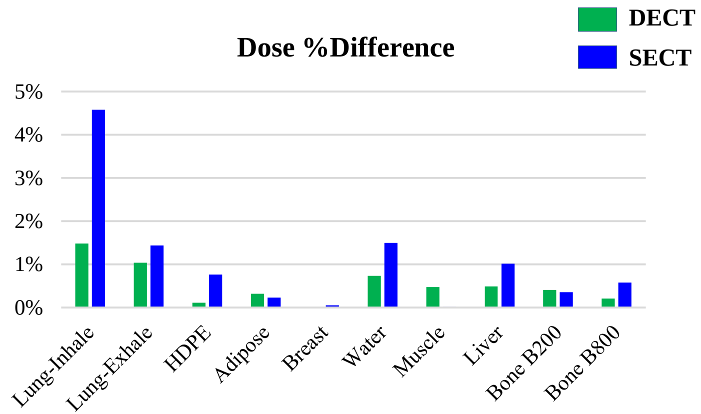
For all plugs at both distal and mid SOBP depths, higher passing rates were observed using DECT

Point dose

Agreement between TPS calculated dose and measurements were within **1.0% (DECT) and 1.5% (SECT)** except for lung-inhale



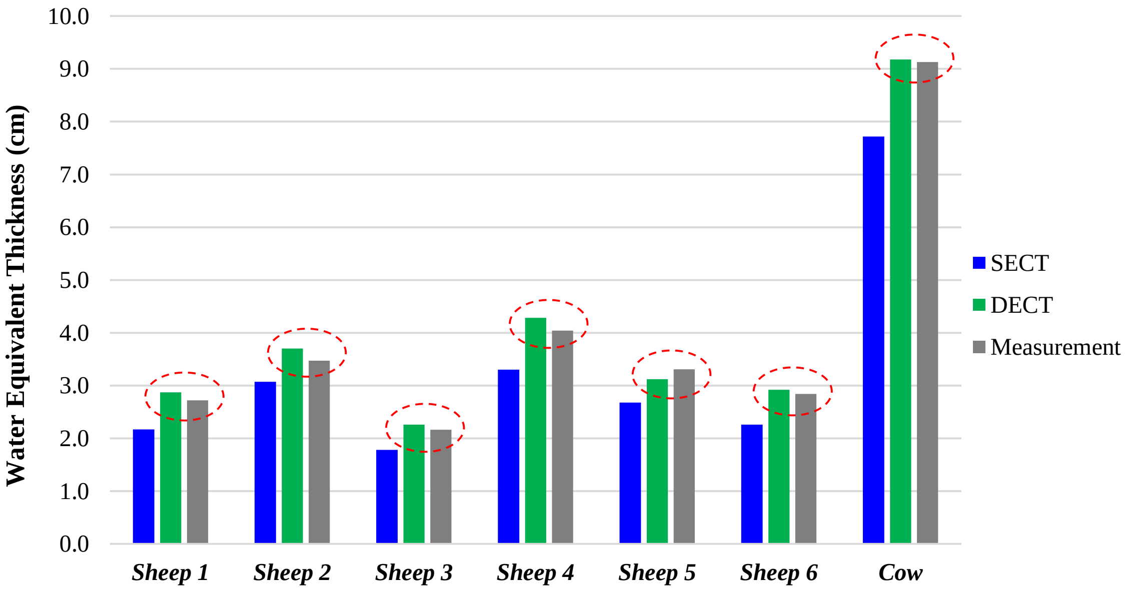




* Gamma analysis criteria 3mm/3%

2) Lung Tissue Samples

Water equivalent thickness



Better agreement observed for DECT calculated WET values

DECT:

ΔWET_{max} = 2.4 mm

ΔWET_{avg} = 1.5 mm

SECT:

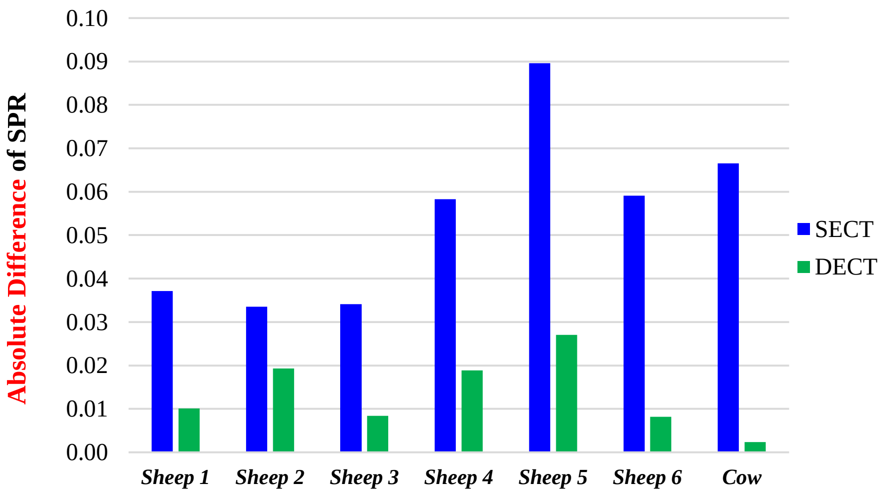
ΔWET_{max} = 7.7 mm

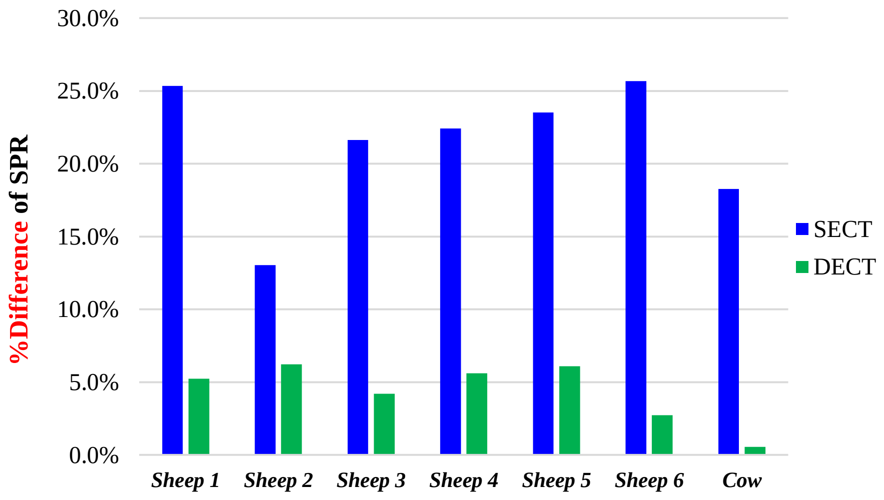
ΔWET_{avg} = 3.3 mm

2) Lung Tissue Samples

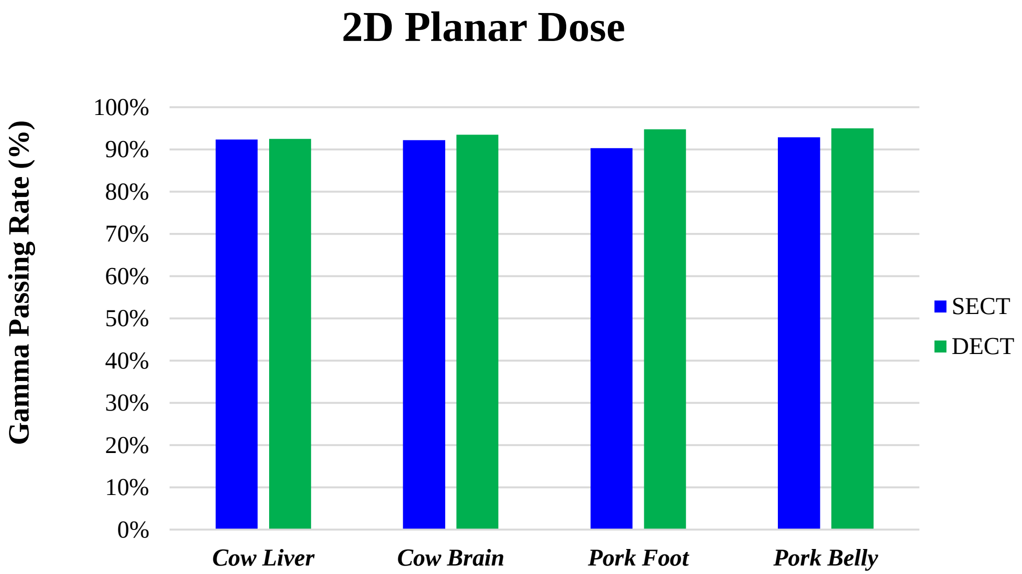
Stopping Power Ratio

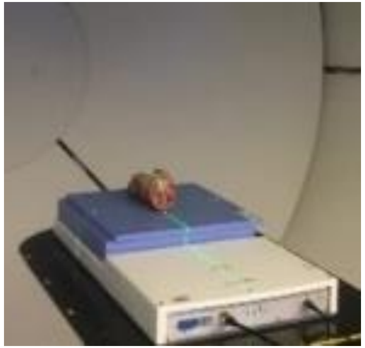
For all lung tissue samples, **DECT calculated SPRs** were within **0.03 (6.2%)** of measurements, and showed better agreement compared to SECT calculation **0.09 (26.0%)** .





3) Other Tissue Samples

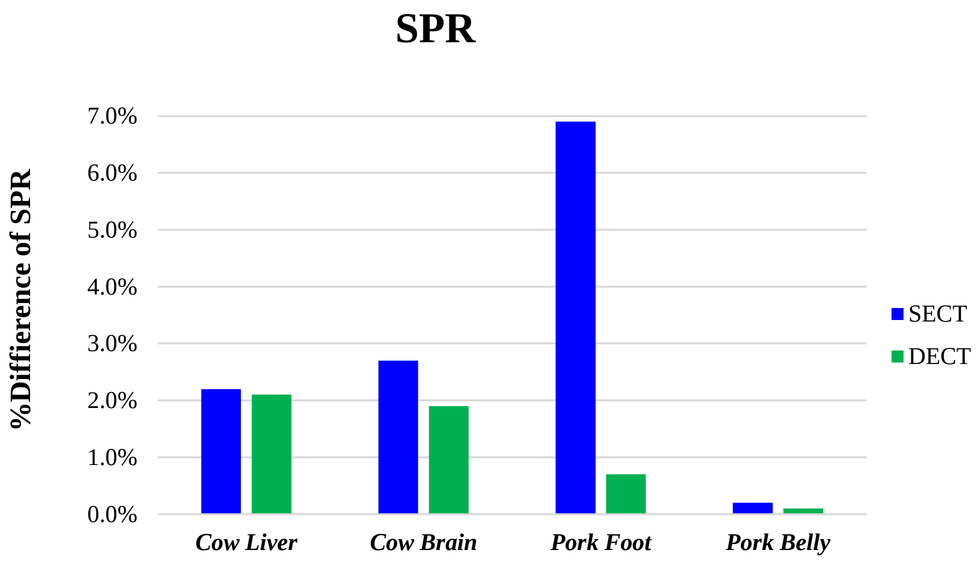




* Gamma analysis criteria 3mm/3%

- **No significant difference in gamma passing rates** between DECT and SECT was observed.

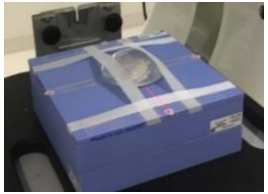
3) Other Tissue Samples

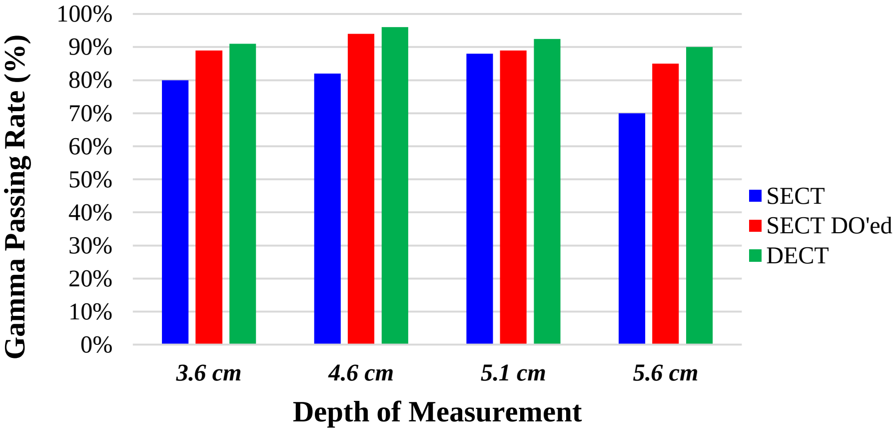


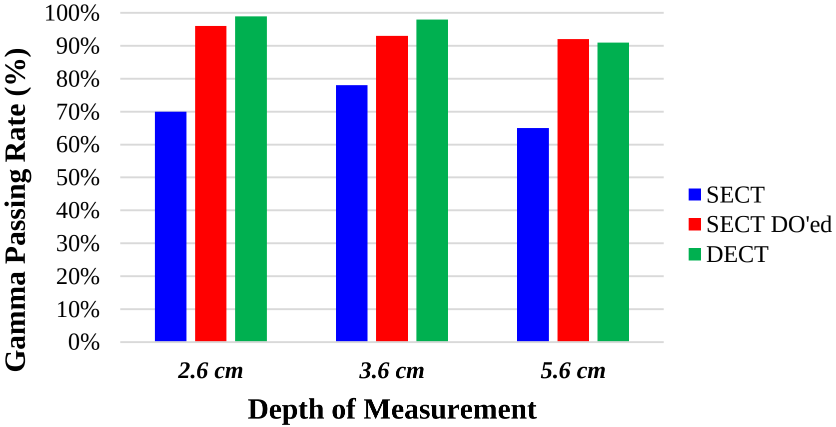
- SPR calculation**: DECT showed better agreement with the measurements**.
- Largest difference between DECT and SECT calculation was observed for pork foot.

4) Breast Implants

2D Planar dose (gamma analysis)







* Gamma analysis criteria 2mm/2%

For all depths, DECT performed better than SECT or SECT density-override (clinical approach).

Conclusions

- We used SPR images created from DECT scans for dose calculations in a clinical proton treatment planning system.

- Better agreement with measurement was observed for calculated SPR using DECT image.
  - SPR images constructed from DECT can improve the accuracy of SPR predictions particularly for low density materials.
  - Use of DECT for other biological tissues results in negligible differences in calculated TPS dose
  - For non-biological tissues, significant differences in TPS dose accuracy was observed

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Thank you!