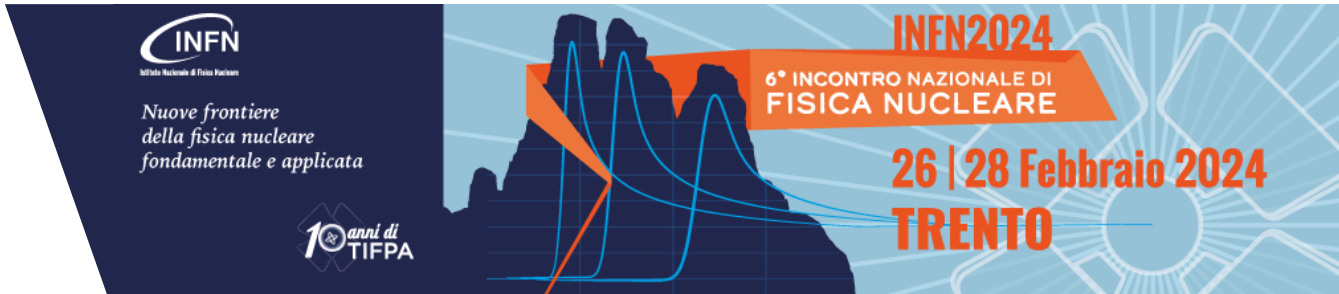
XpCalib

A proton computed tomography system for proton treatment planning

Elena Fogazzi on behalf of the XpCalib collaboration



Proton treatment planning: general workflow

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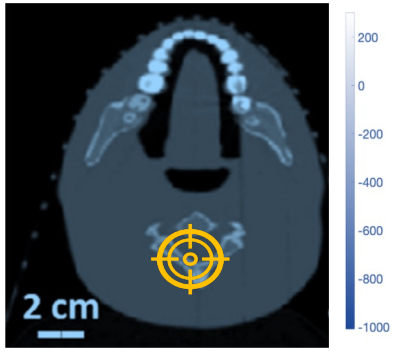
X-rays computed tomography



HU

Photon attenuation coefficient map (Hounsfield unit)

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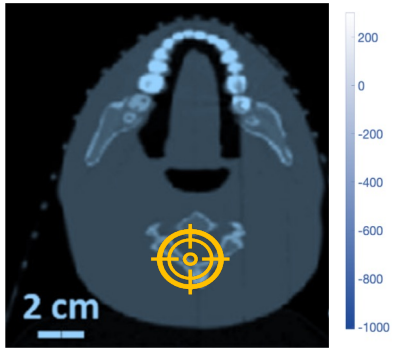
X-rays computed tomography

Treatment Planning System



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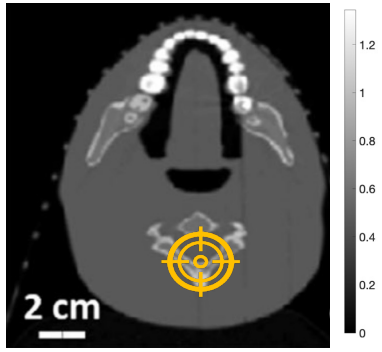


RSP

Computed relative stopping power (RSP) map

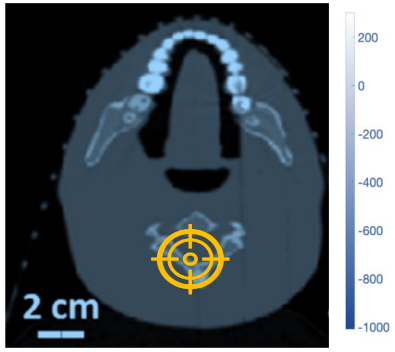
HU-RSP conversion

Proton treatment planning: general workflow

X-rays computed tomography

Treatment Planning System

Farace P et al., Med. Phys. (2021)



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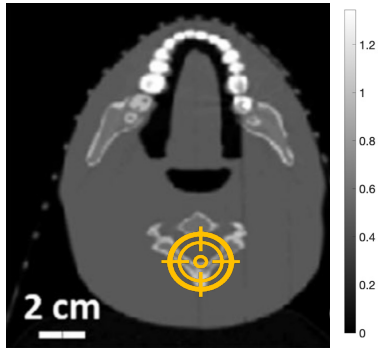

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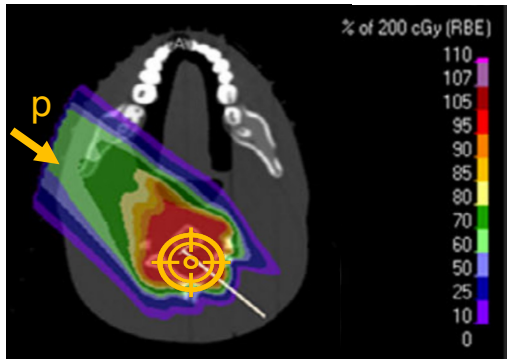

Computed dose distribution

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Proton treatment planning: general workflow

X-rays computed tomography → Treatment Planning System → Proton treatment

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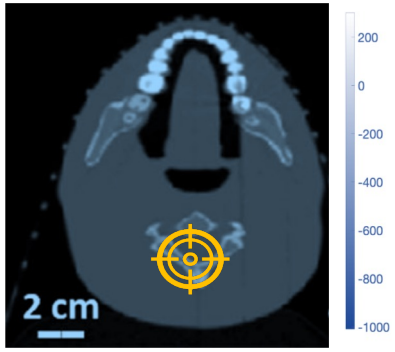

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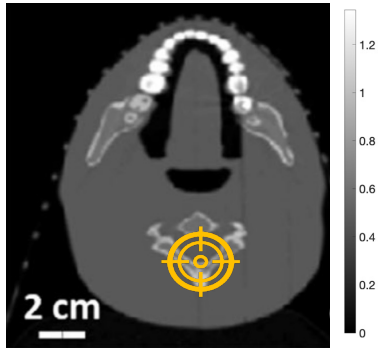

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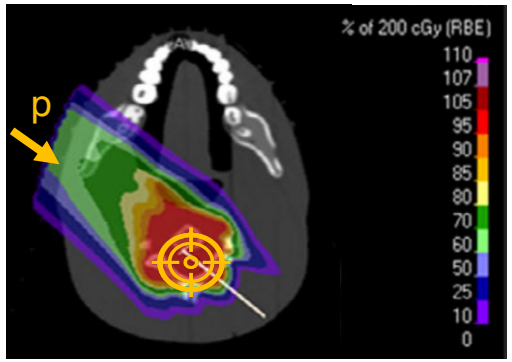

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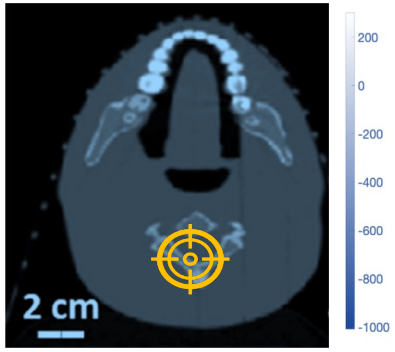

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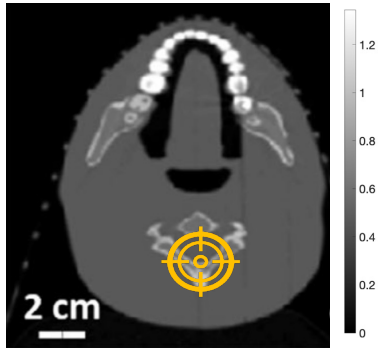

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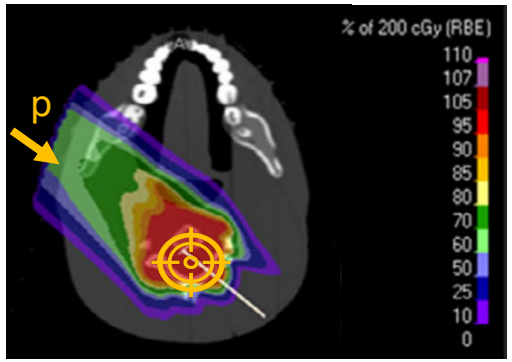
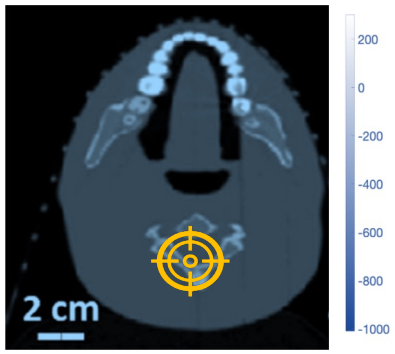


Computed dose distribution

Uncertainties

HU-RSP conversion

Proton treatment planning: uncertainties



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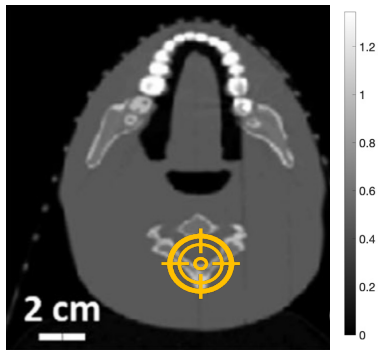


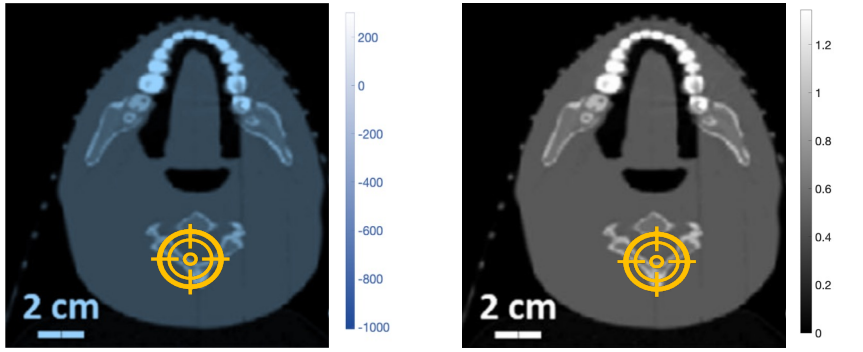
RSP

Computed relative stopping power (RSP) map

Uncertainties

HU-RSP conversion
through the tissue substitute
or the stoichiometric method

Proton treatment planning: uncertainties



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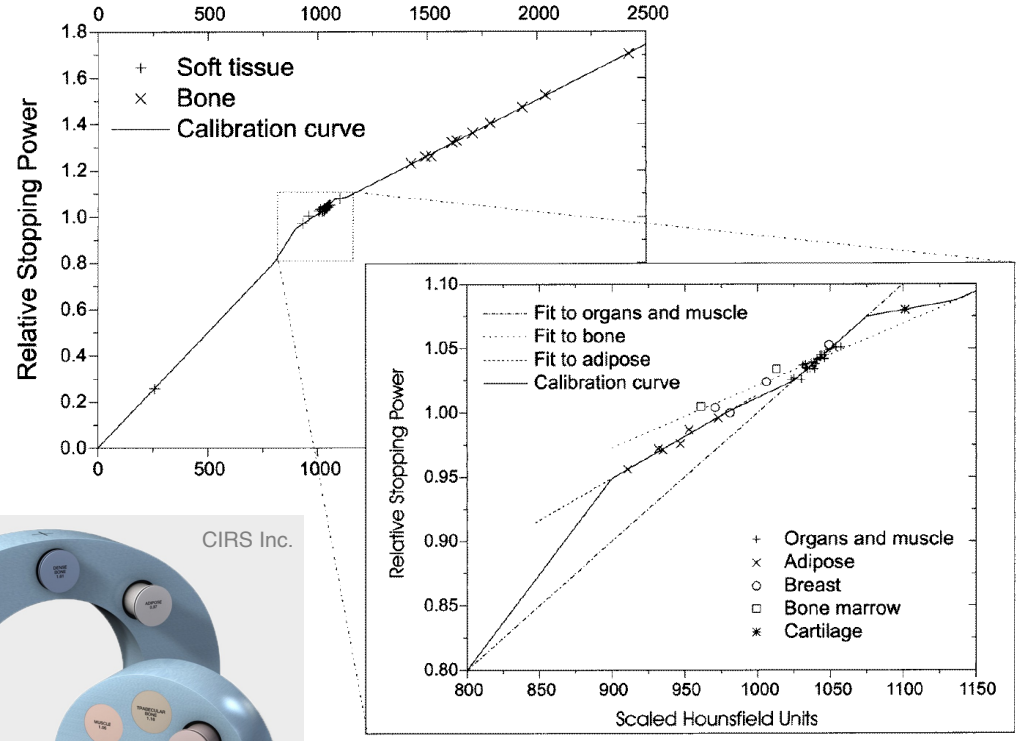
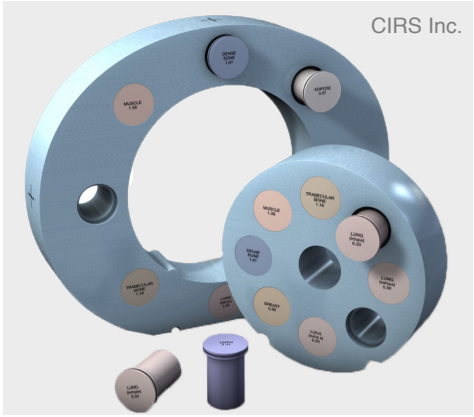




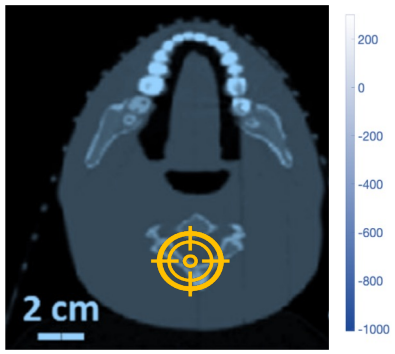
The **proton range error** due to the HU-RSP conversion could be as large as ~3 mm

	Soft tissue			Bone			Total
	Amount (cm)	wer[a] (cm)	Abs. error (cm)	Amount (cm)	wer[a] (cm)	Abs. error (cm)	Abs. error (cm)
Brain	10	10.3	0.11	1	1.8	0.03	0.14
Prostate (lateral beam)	15	15.5	0.17	5	9	0.16	0.33

[a] Water equivalent range.

Schaffner B. and Pedroni E., Phys. Med. Biol. (1998)

Proton treatment planning: uncertainties



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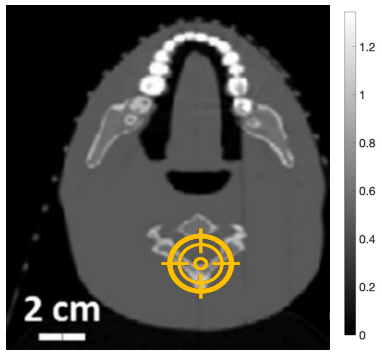

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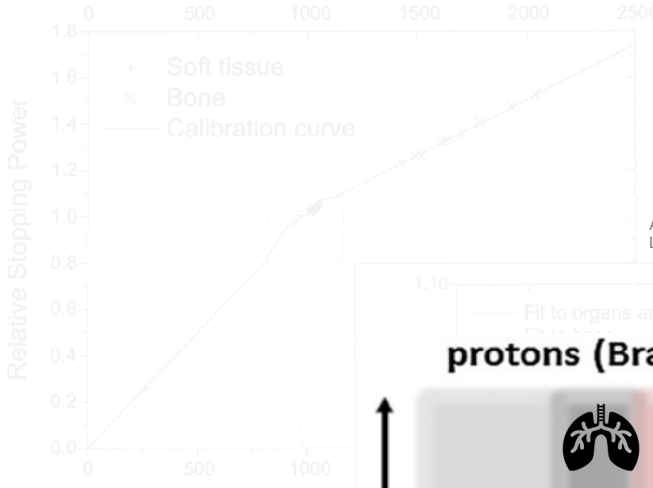
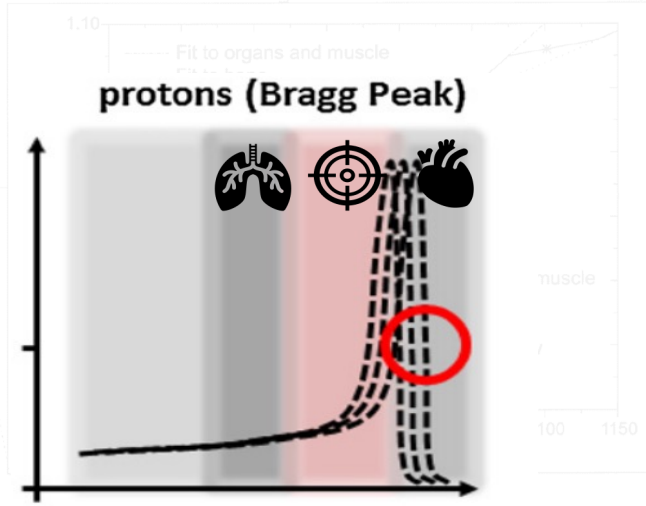


Adapted from Antje-Christin Knopf and Antony Lomax 2013 Phys. Med. Biol. 58 R131



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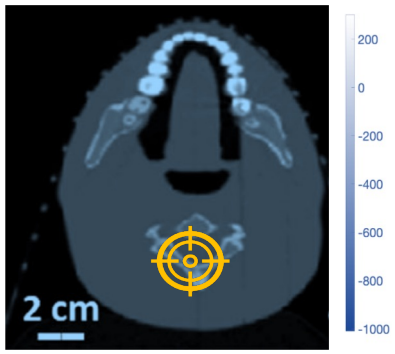

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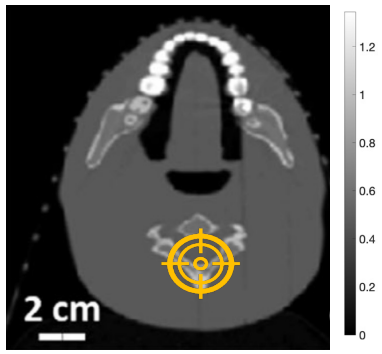

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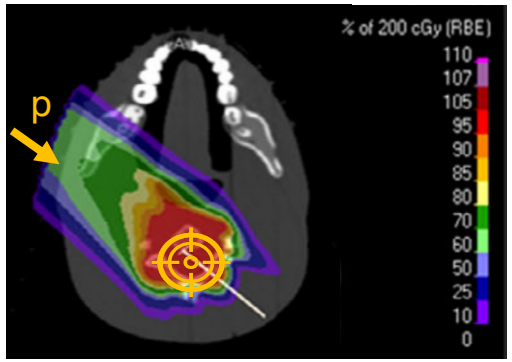

Computed dose distribution

Uncertainties

For this reason, the volume to be irradiated is enlarged by a **safety margin:** tipically +3.5% range + 1mm

- xCT calibration and imaging
- Radiobiological characterization
- Organ motion and anatomical changes
- Dose calculation

Proton treatment planning: uncertainties

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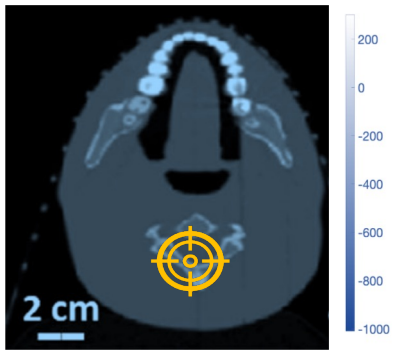

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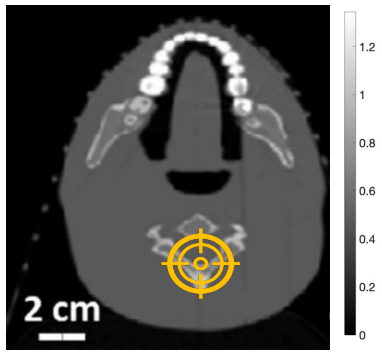

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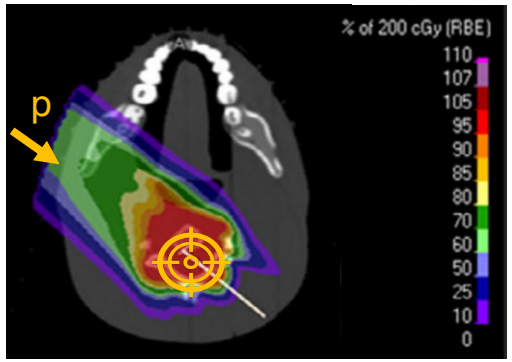


Computed dose distribution

Uncertainties

For this reason, the volume to be irradiated is enlarged by a **safety margin:** tipically +3.5% range + 1mm

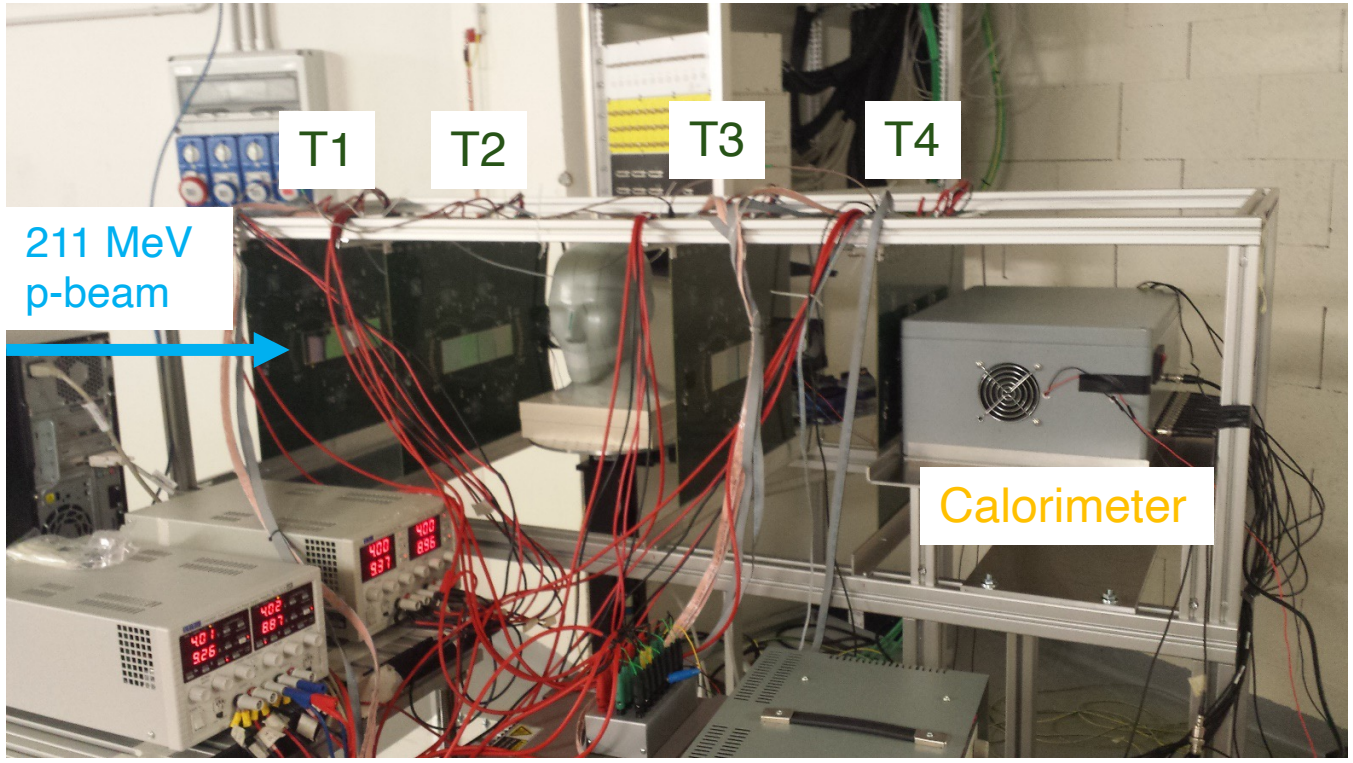
NEW!

Proton Computed Tomography (pCT) would allow solving this issue, by **measuring 3D RSP maps** for a given tissue

- ~~xCT calibration and imaging~~
- Radiobiological characterization
- Organ motion and anatomical changes
- Dose calculation

INFN pCT apparatus

Manufactured by INFN-Florence and Catania (2014-2017), running since 2018.
Now installed at the Trento Proton Therapy Center's experimental beam line



Scaringella M., et al., *Phys. Med. Biol.* (2023)

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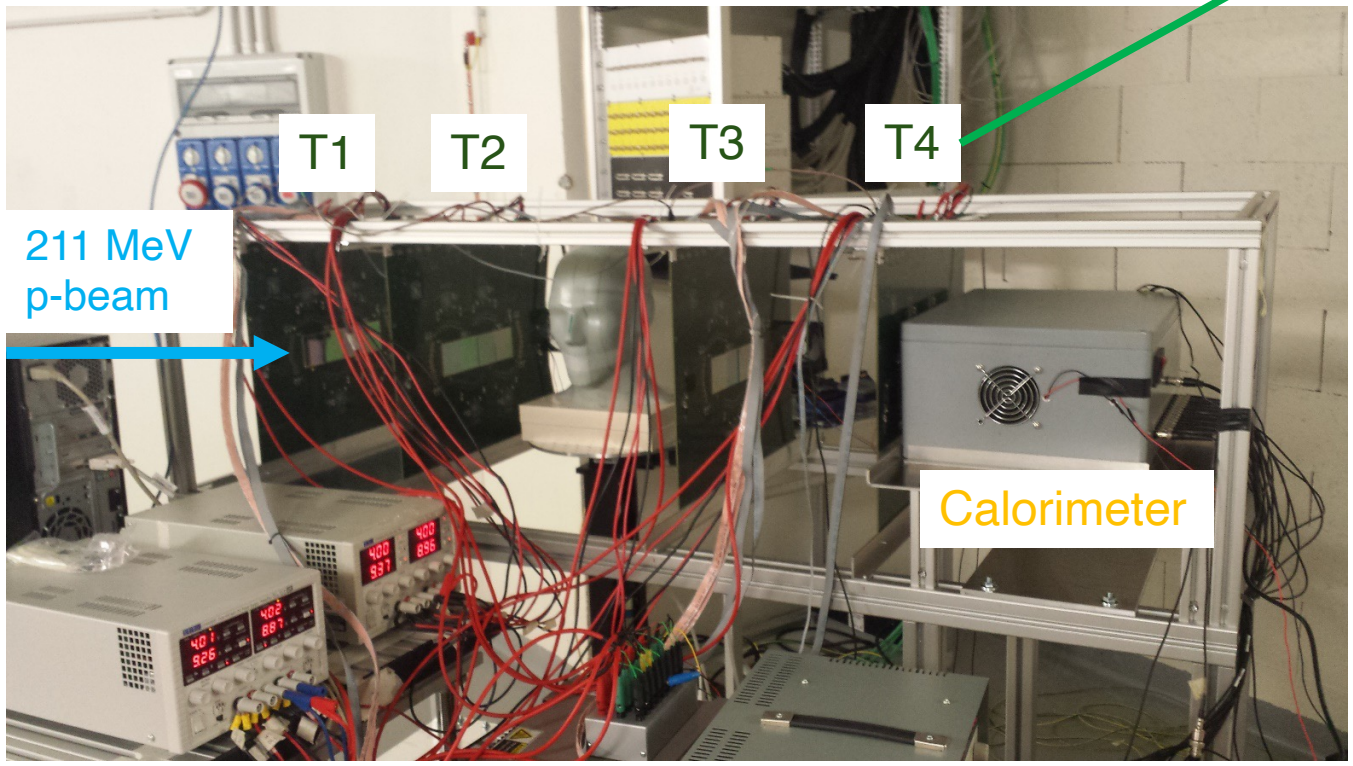

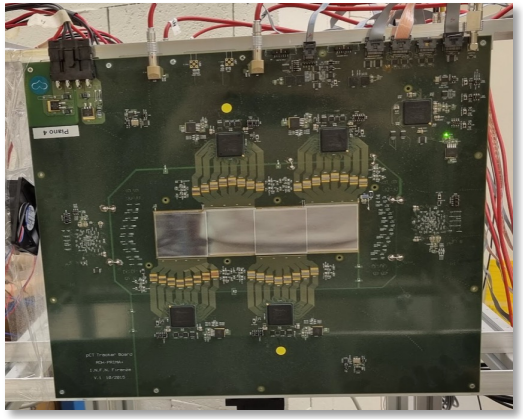

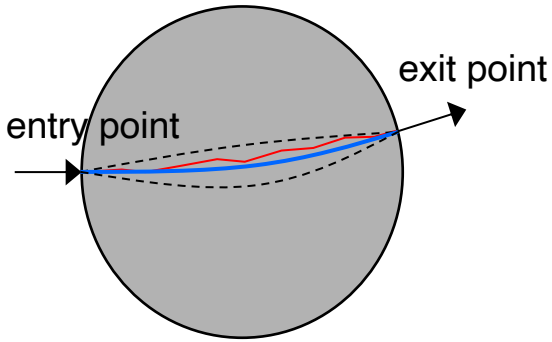

Proton true trajectory

MLP trajectory with confidence limits

1) **Tracker** to measure the proton Most Likely Path (MLP)
→ 4 Silicon microstrip tracker planes
- 5x20cm^2 field of view
- 80/100 kHz sustained acquisition rate

Scaringella M., et al., *Phys. Med. Biol.* (2023)

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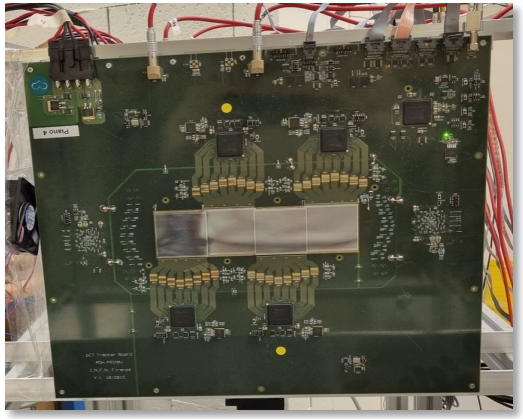

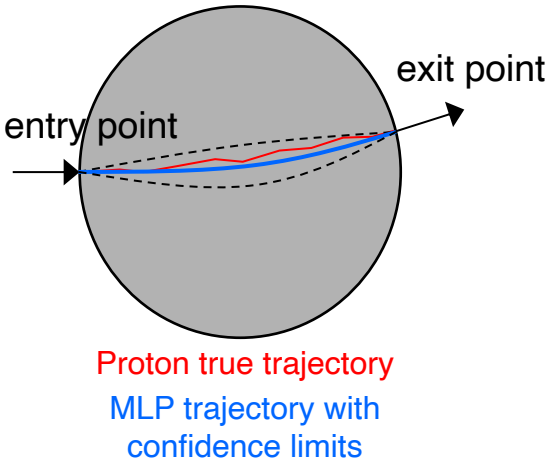

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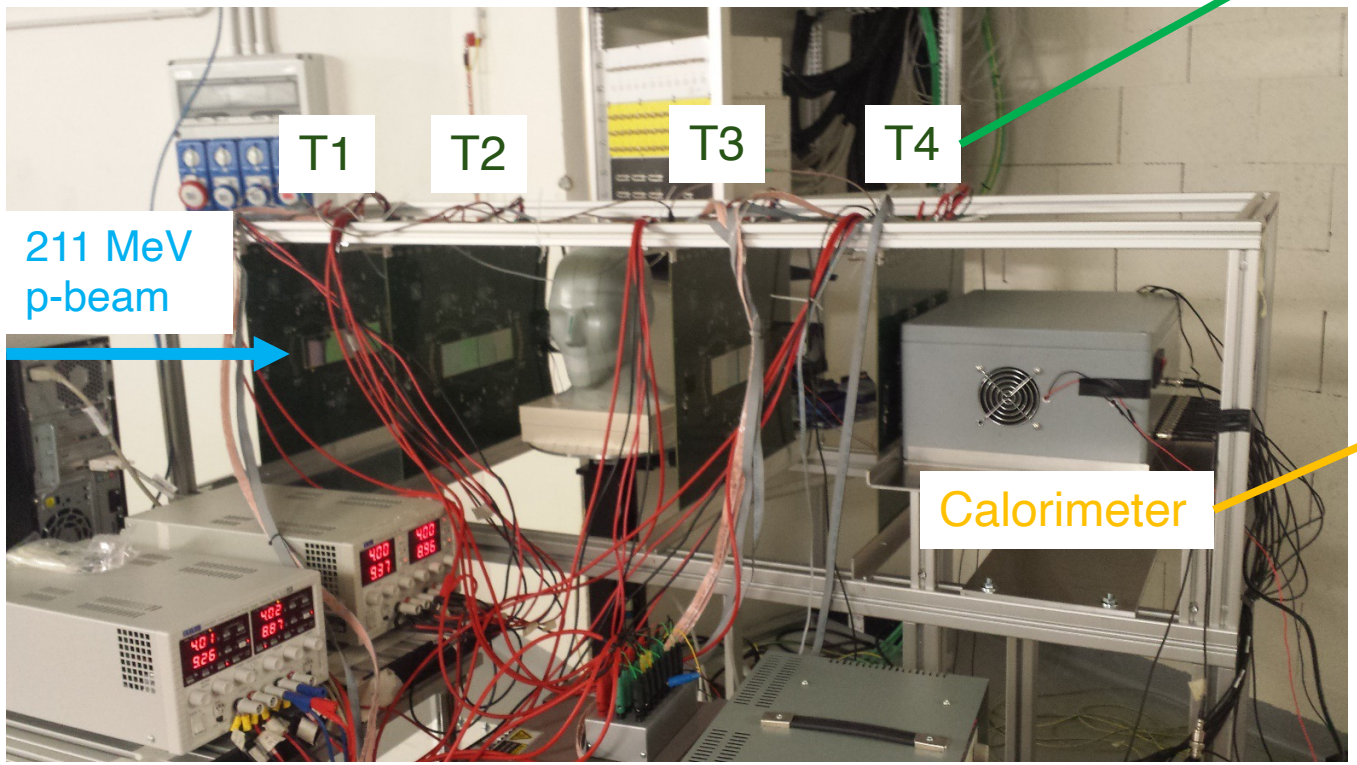

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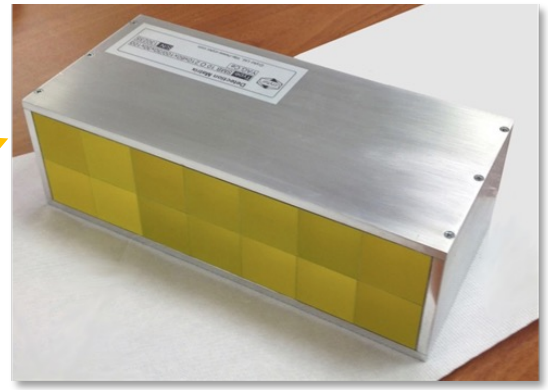

2) **Calorimeter** to assign an energy loss to each proton track
→ 2x7 YAG:Ce Crystals Array, 3x3x10cm^3 each
- 70 ns scintillating light decay time
- ~1% energy resolution @ 200 MeV

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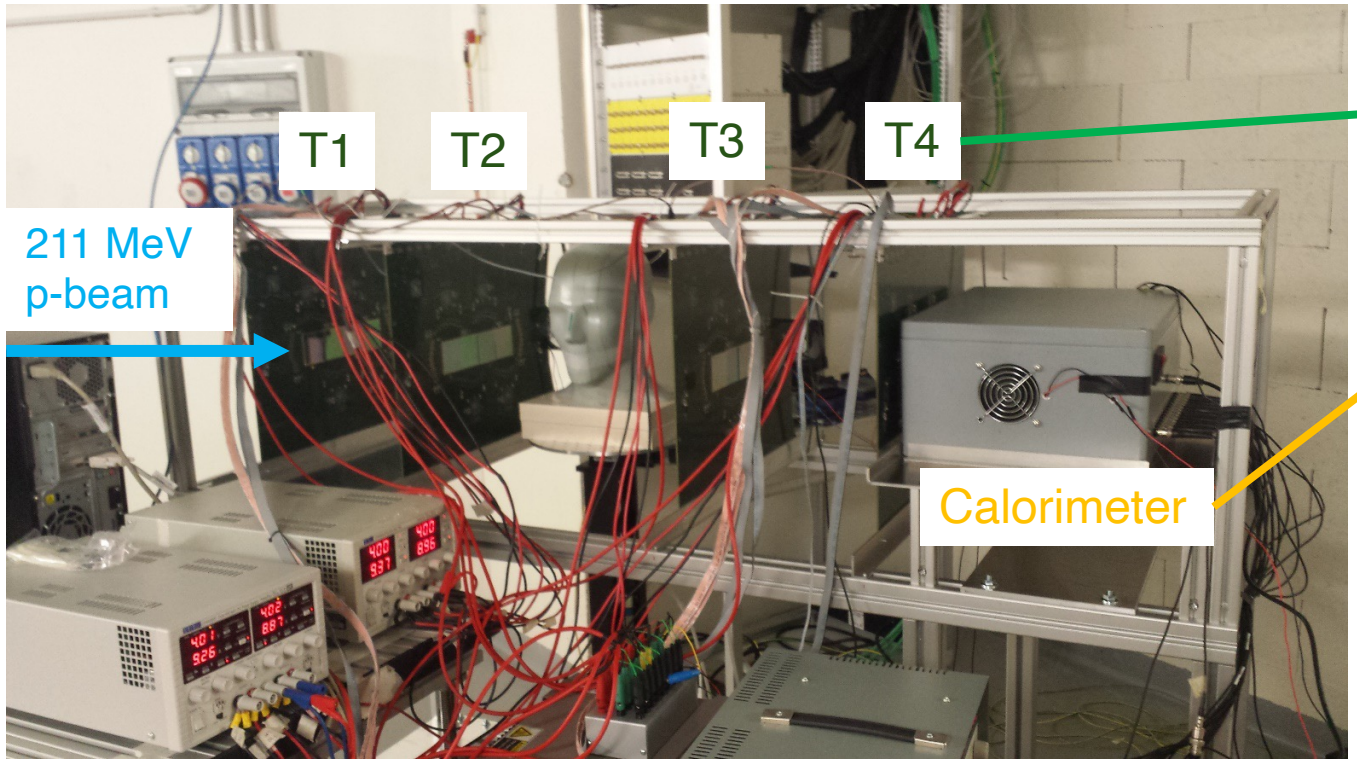


Scaringella M., et al., *Phys. Med. Biol.* (2023)

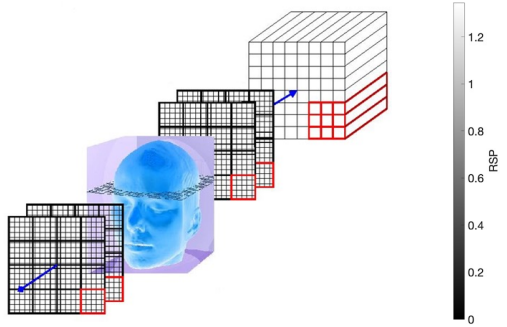
Image reconstruction

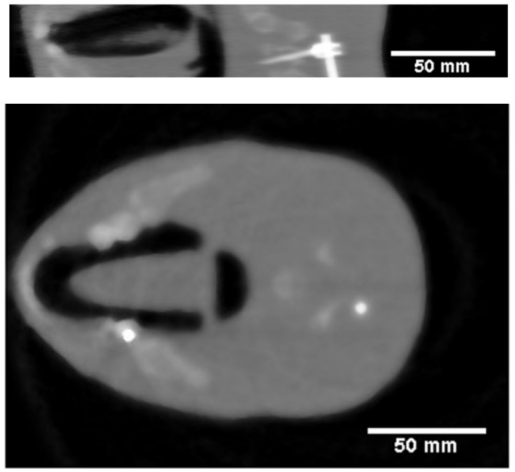
Filtered backprojection algorithm* developed
at CREATIS Research Lab, Lyon

$$\int_{\Gamma_i} \mathrm{RSP}(\boldsymbol{x})\mathrm{d}\boldsymbol{x} \approx \int_{E_i^{\mathrm{out}}}^{E_i^{\mathrm{in}}} \frac{\mathrm{d}E}{S_{\mathrm{water}}(E)}$$

Rit S et al., *Med Phys* (2013)

→ 3D RSP MAP





XpCalib experiment

(2021-2023, CSN5-INFN)

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TIFPA — Trento Institute for Fundamental Physics and Applications

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Azienda Provinciale per i Servizi Sanitari
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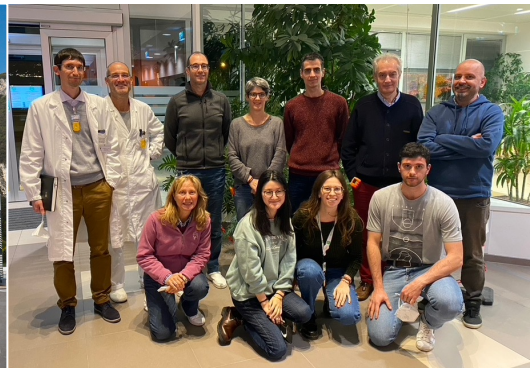
Trento PT centre



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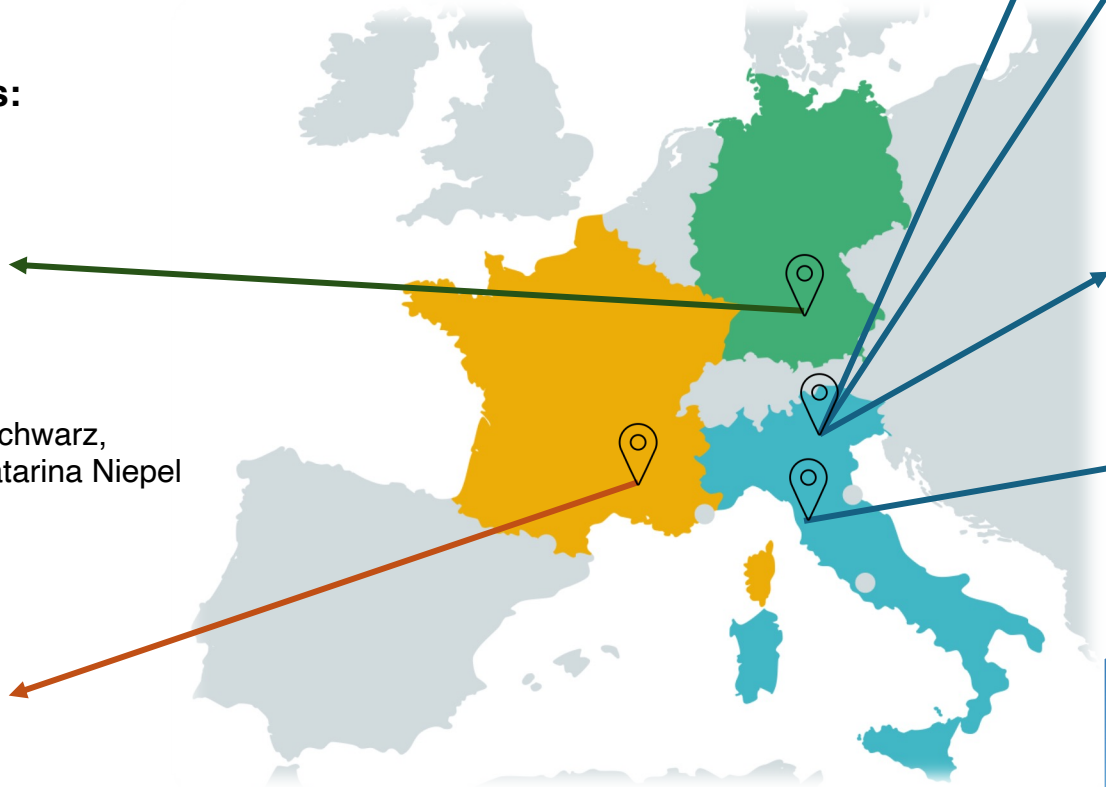
External collaborations:



LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

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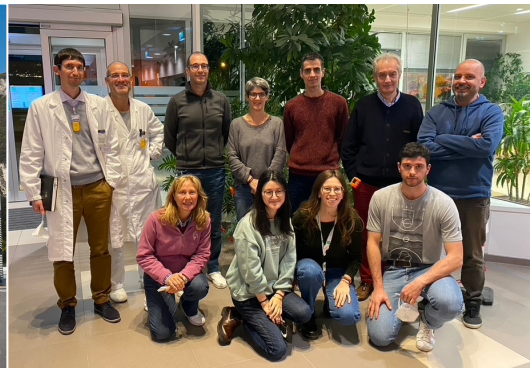
Dr. Simon Rit

Trento PT centre



Investigation of the pCT imaging performances

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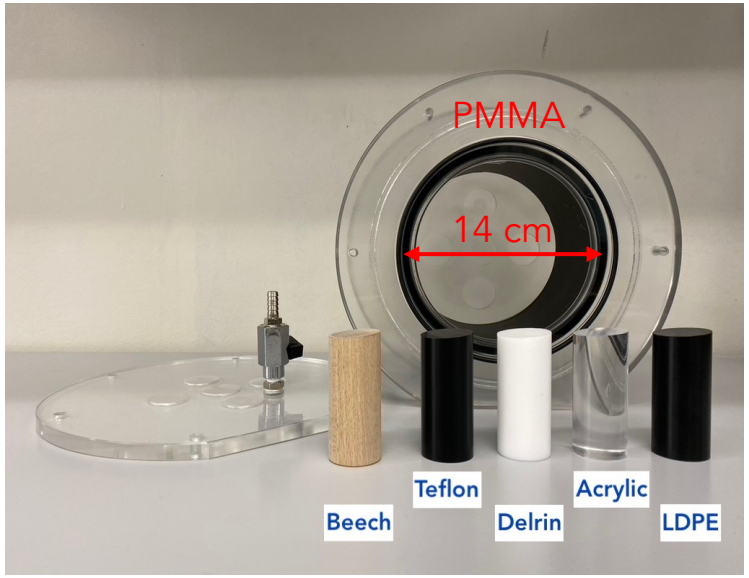
Custom-built phantom made of 5 different cylindrical inserts (Ø=3 cm), and that can be filled with air/water



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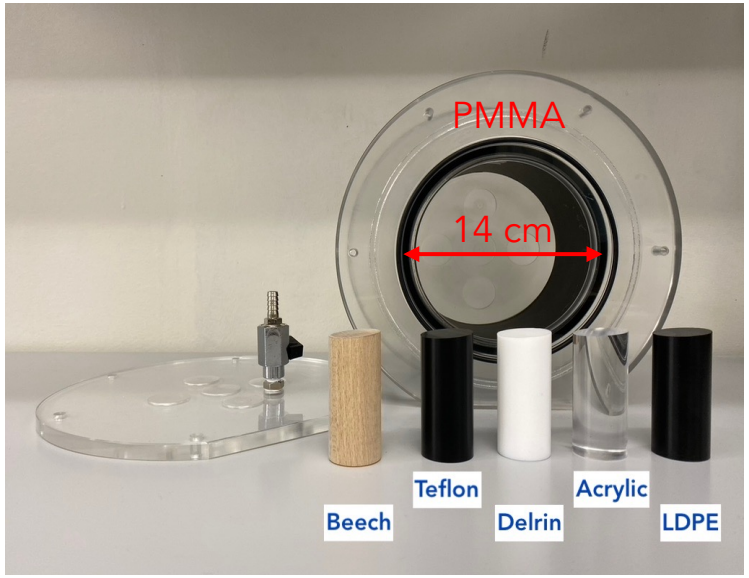
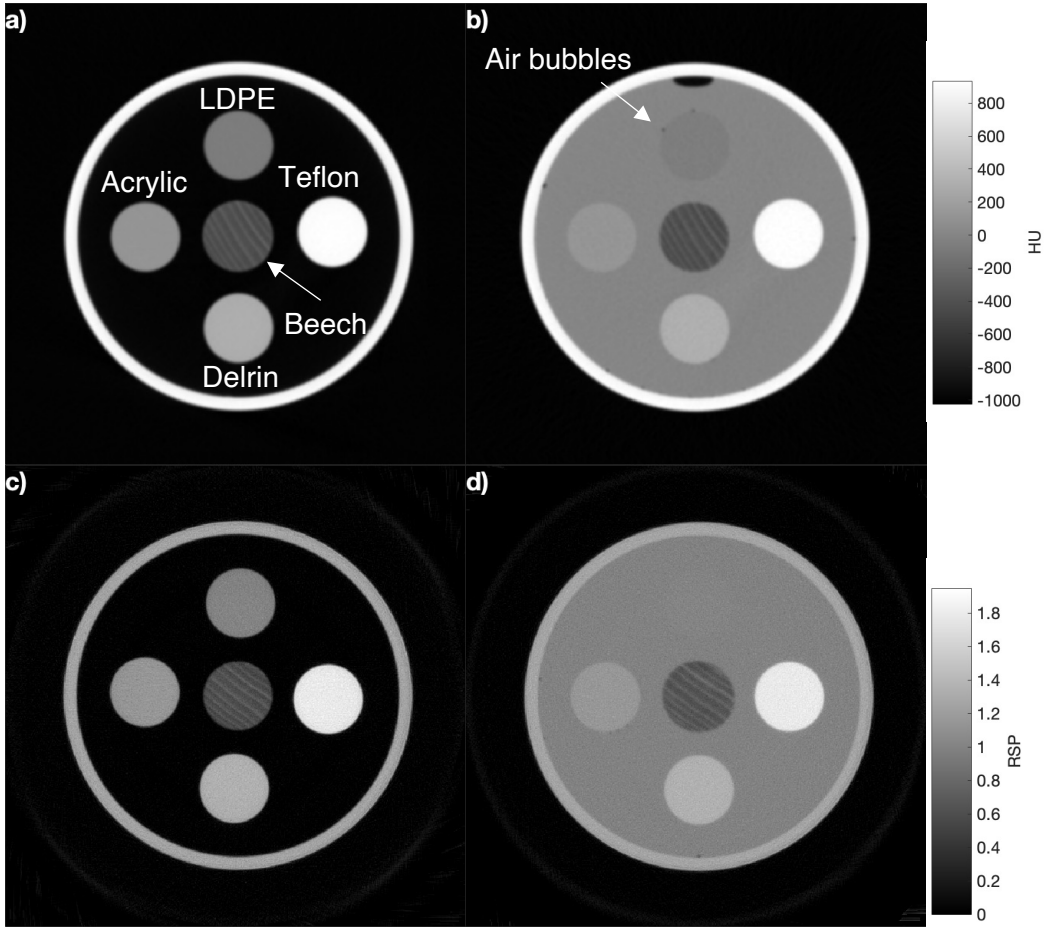


Air background

Water background

Clinical xCT

INFN pCT



Fogazzi E et al., *Phys. Med. Biol.* (2023)

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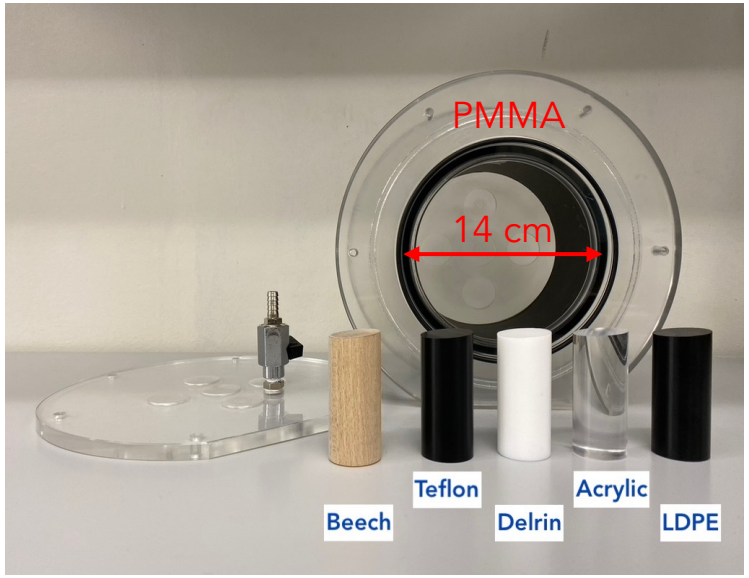

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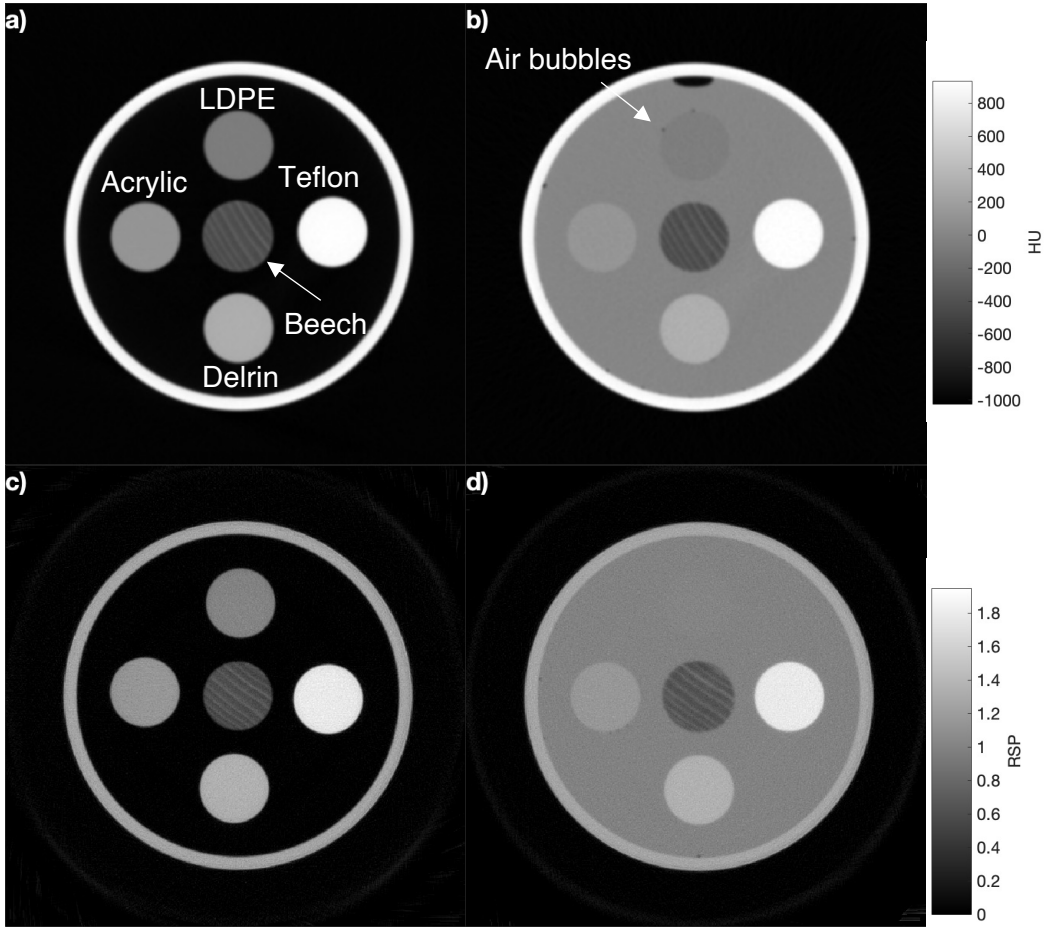

Fogazzi E et al., *Phys. Med. Biol.* (2023)

→ Good qualitative performances

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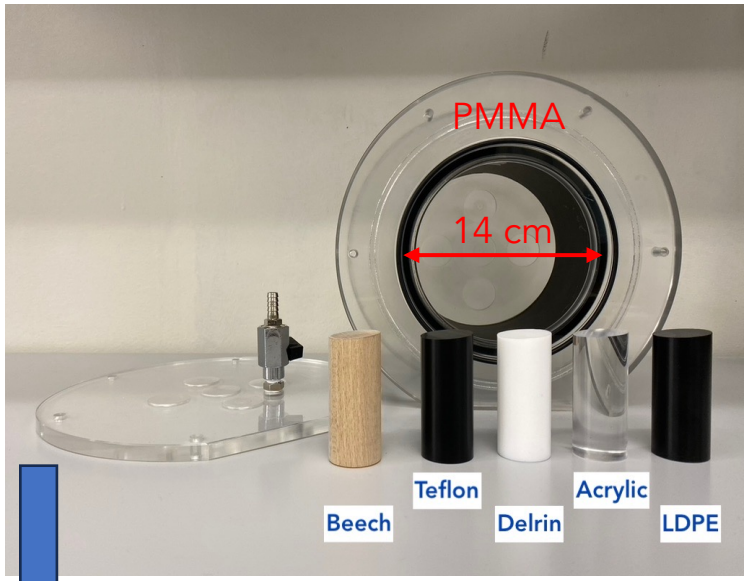

Air background

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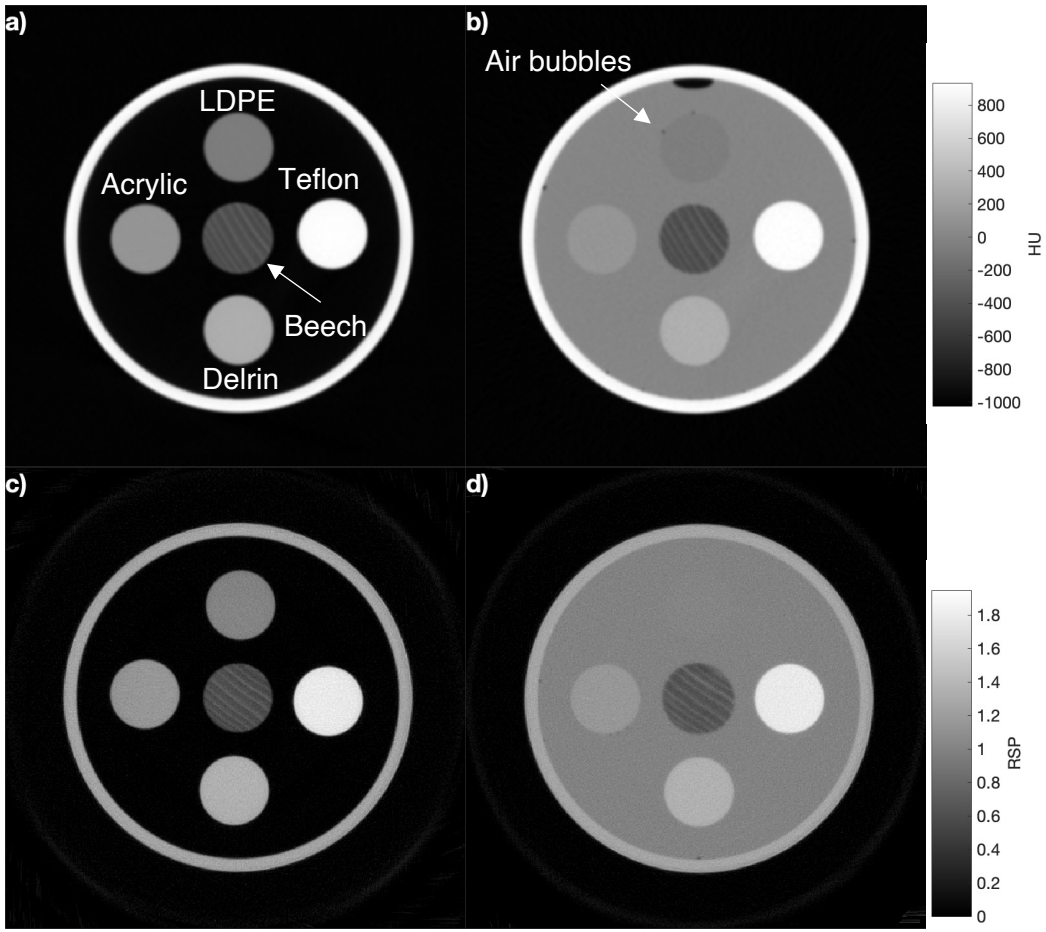

Fogazzi E et al., *Phys. Med. Biol.* (2023)

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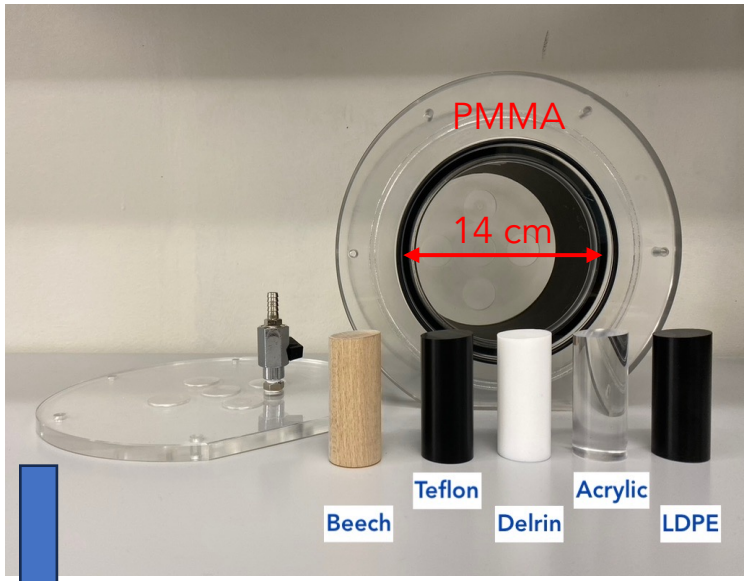


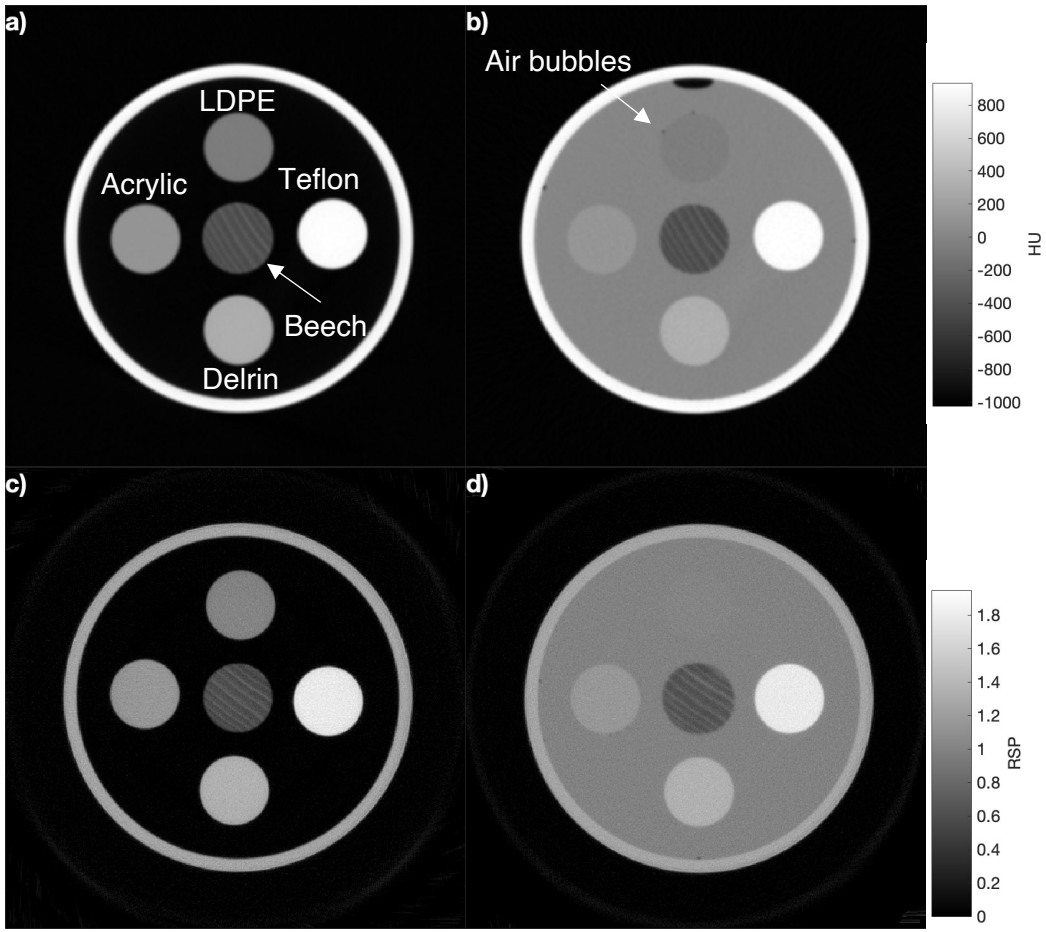
At the same dose level (11.6 mGy) and with the same voxel size ((0.39,0.39,1.5) mm^3):

- Spatial resolution → comparable with clinical xCT (~0.54 lp/mm)
- Noise power spectrum → lower than clinical xCT
- RSP accuracy → < 1%

Air background | Water background

Clinical xCT

INFN pCT



Fogazzi E et al., *Phys. Med. Biol.* (2023)

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How to implement pCT in clinics?

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pCT imaging of the patient?

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not feasible at the moment
(low acquisition rate,
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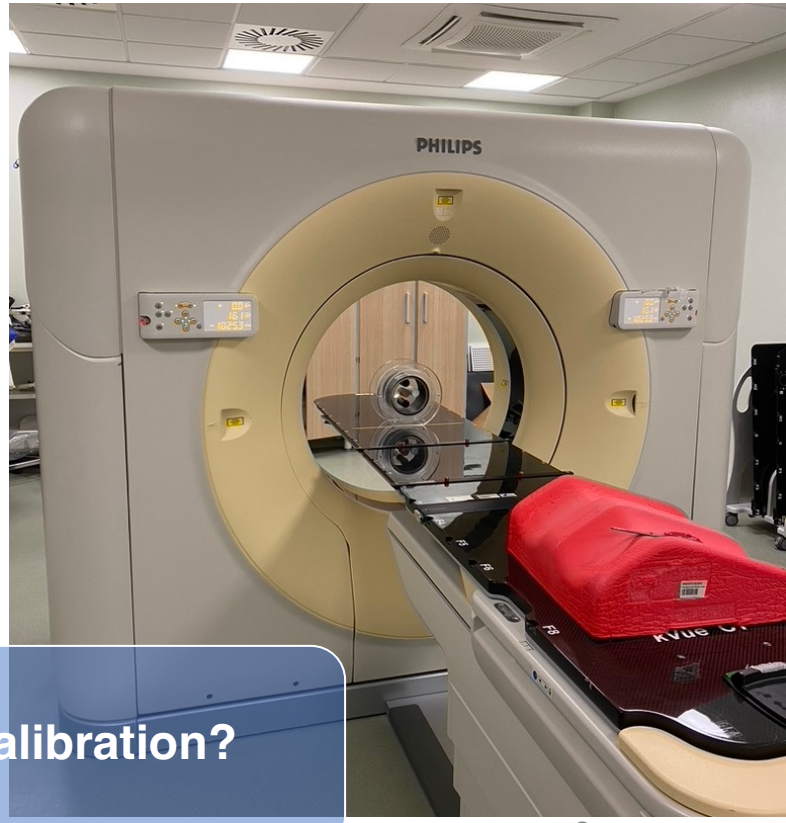

pCT for xCT calibration?

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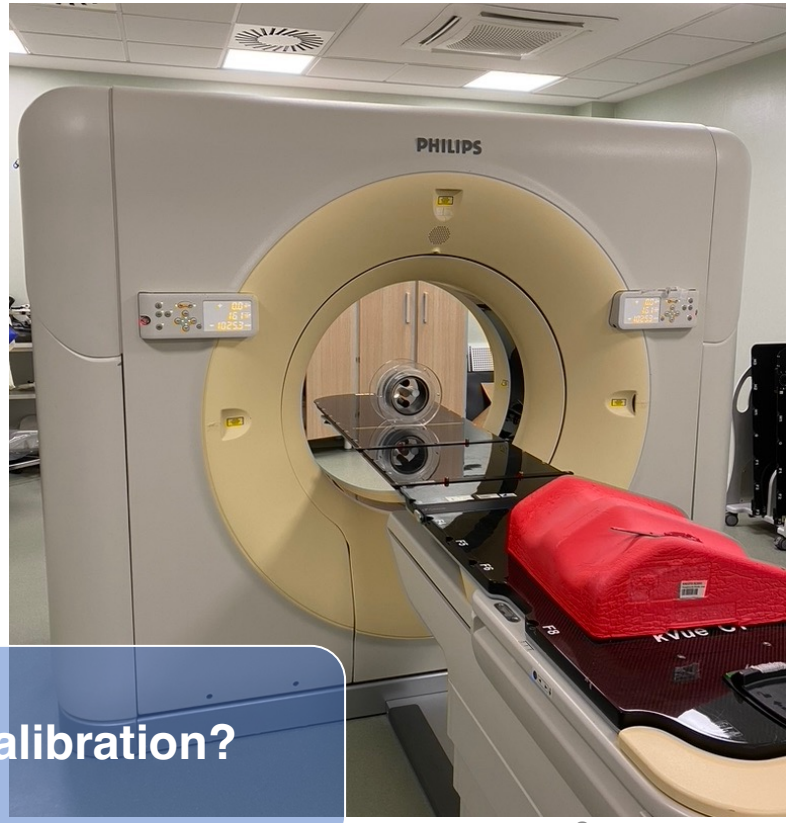
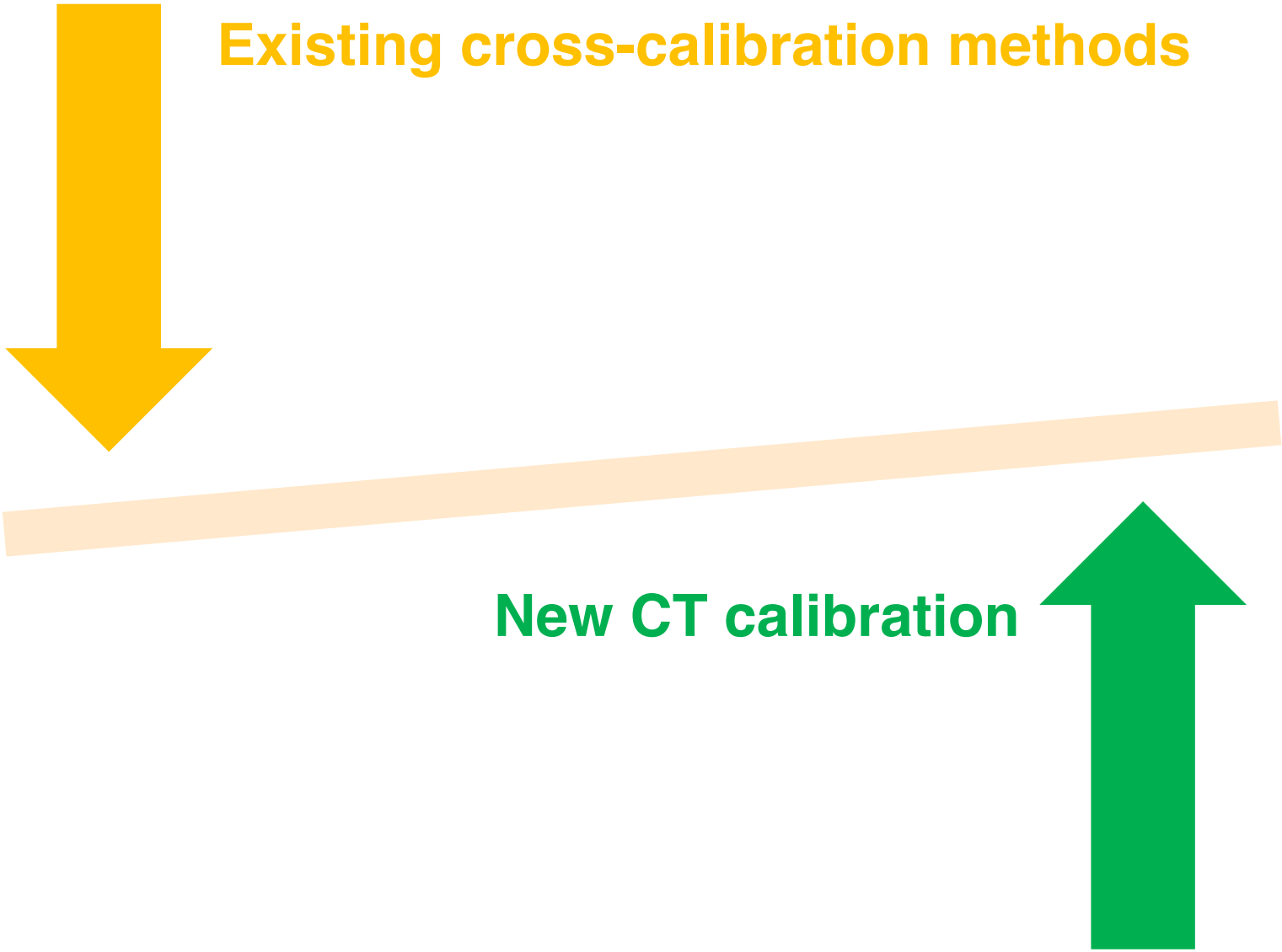
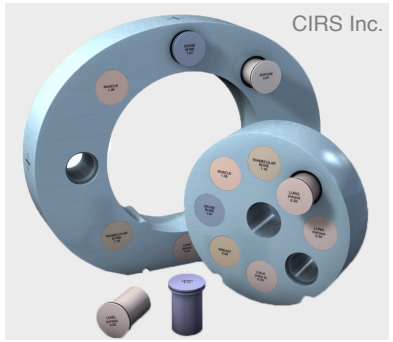


✓ **pCT for xCT calibration?**


Existing cross-calibration methods
New CT calibration



Existing cross-calibration methods

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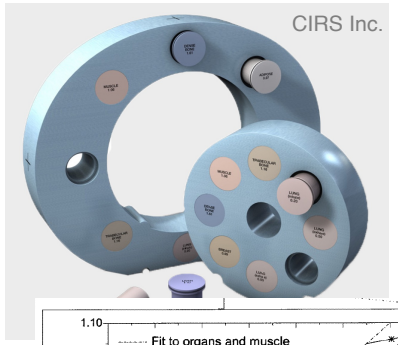

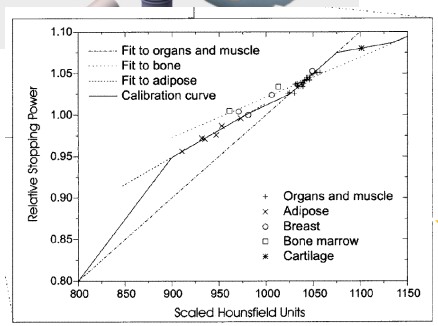

Schaffner B. and Pedroni E., Phys. Med. Biol. (1998)

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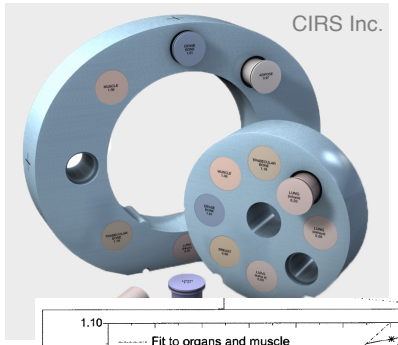

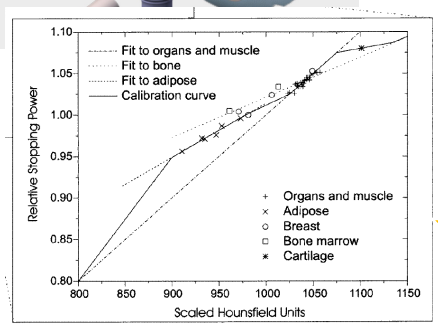

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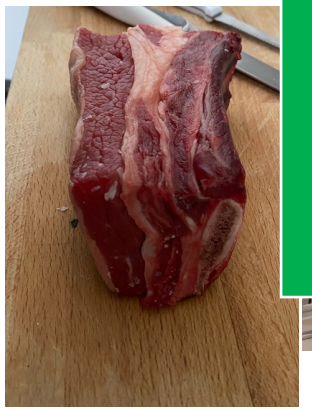
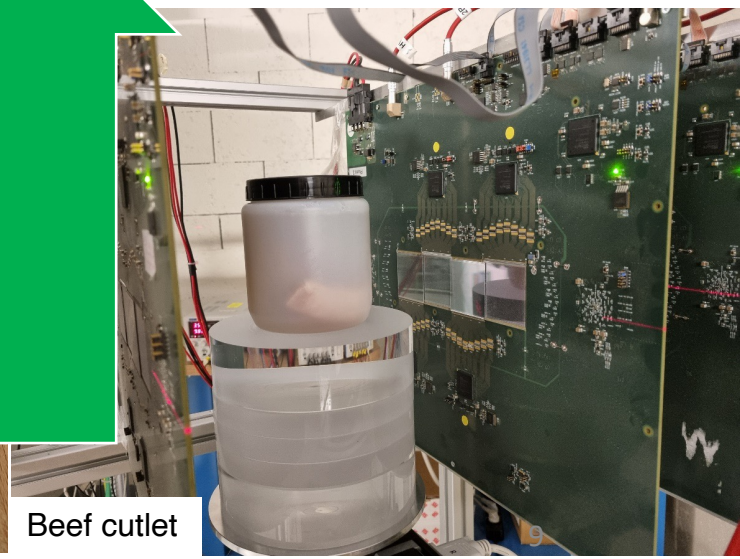
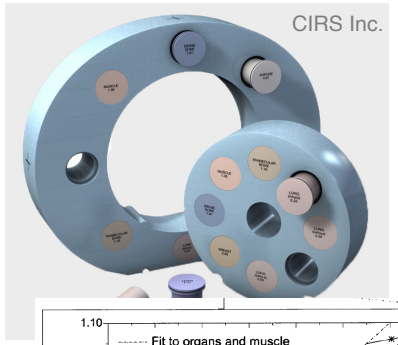
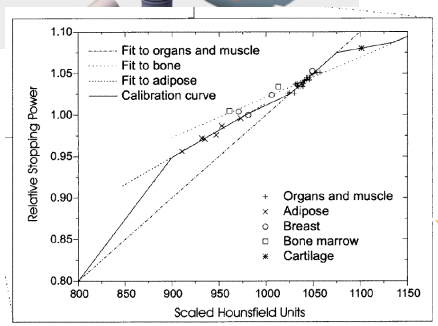




Beef cutlet





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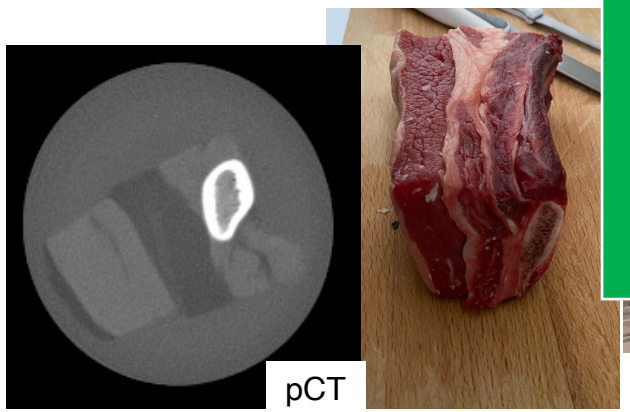
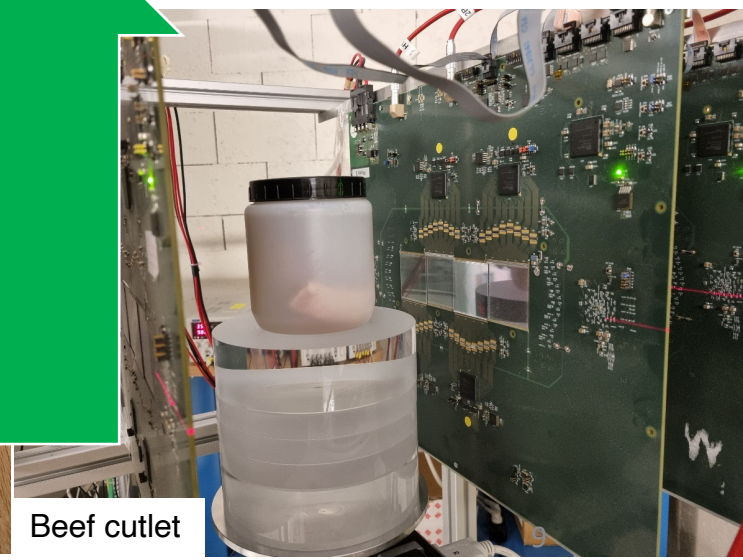
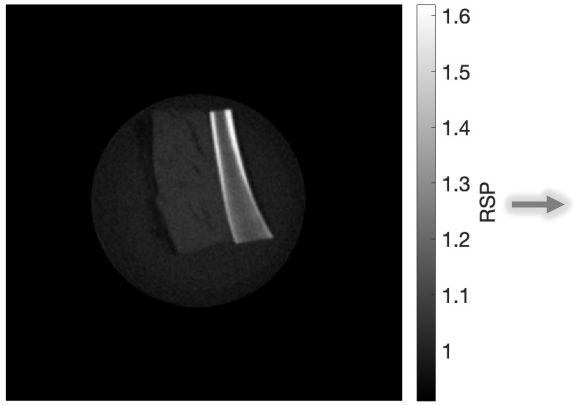
New CT calibration

- <u>Real biological phantoms</u>
  (histology stabilization by buffered formalin, fixation in 10% w/v Agar-Agar solution)
- 3D RSP map directly measured on the biological phantom

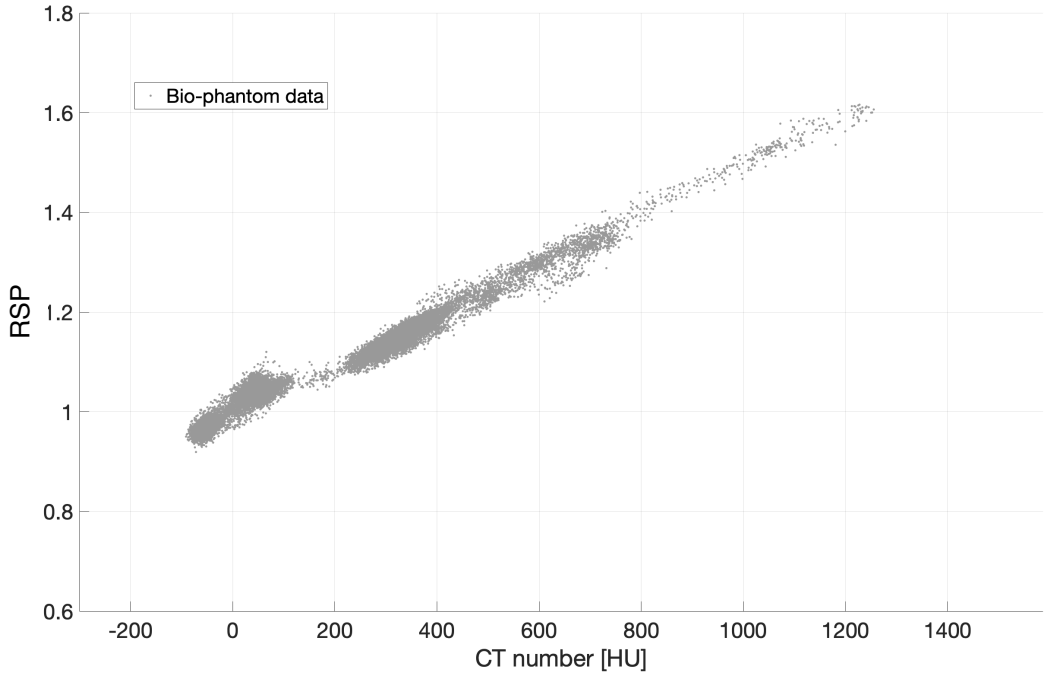




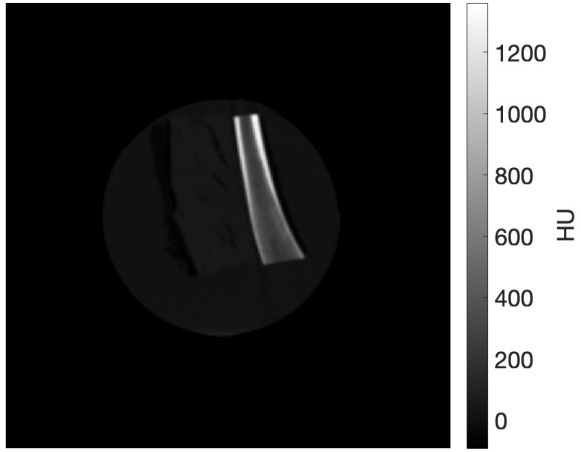
Adapted from Fogazzi E et al, submitted to *Phys Med Bio* (2024)



pCT



xCT



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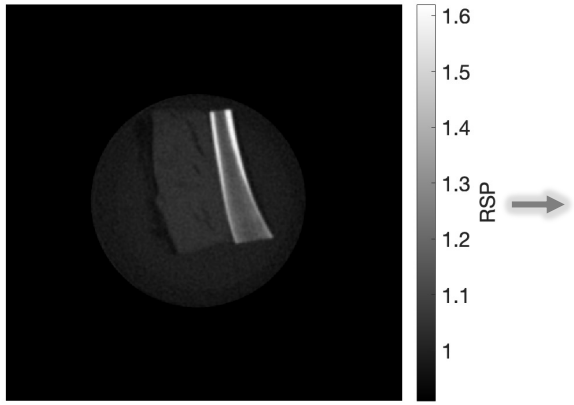

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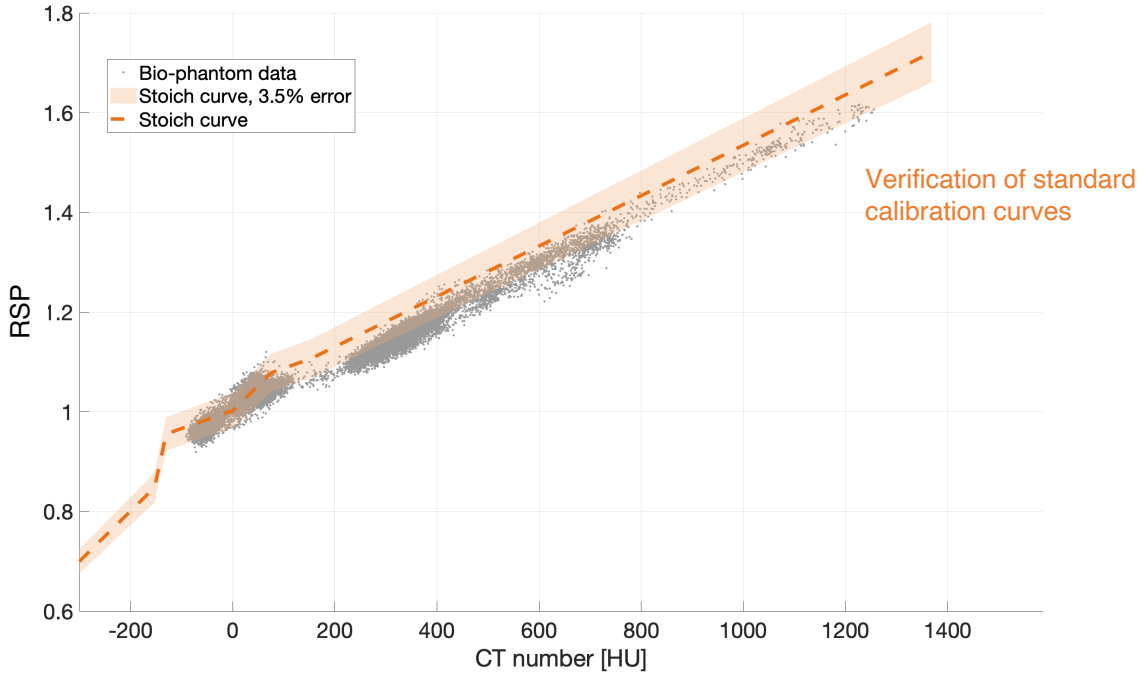
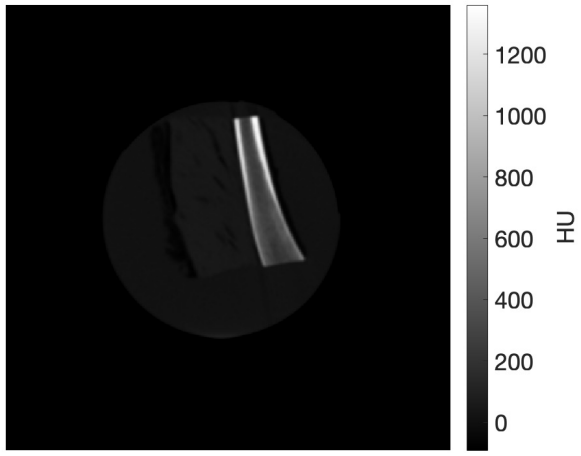


Verification of standard calibration curves

xCT



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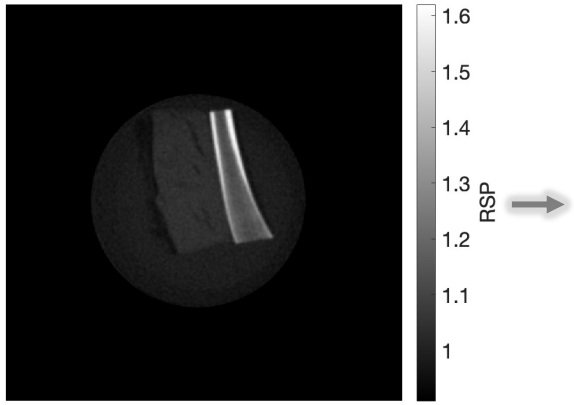

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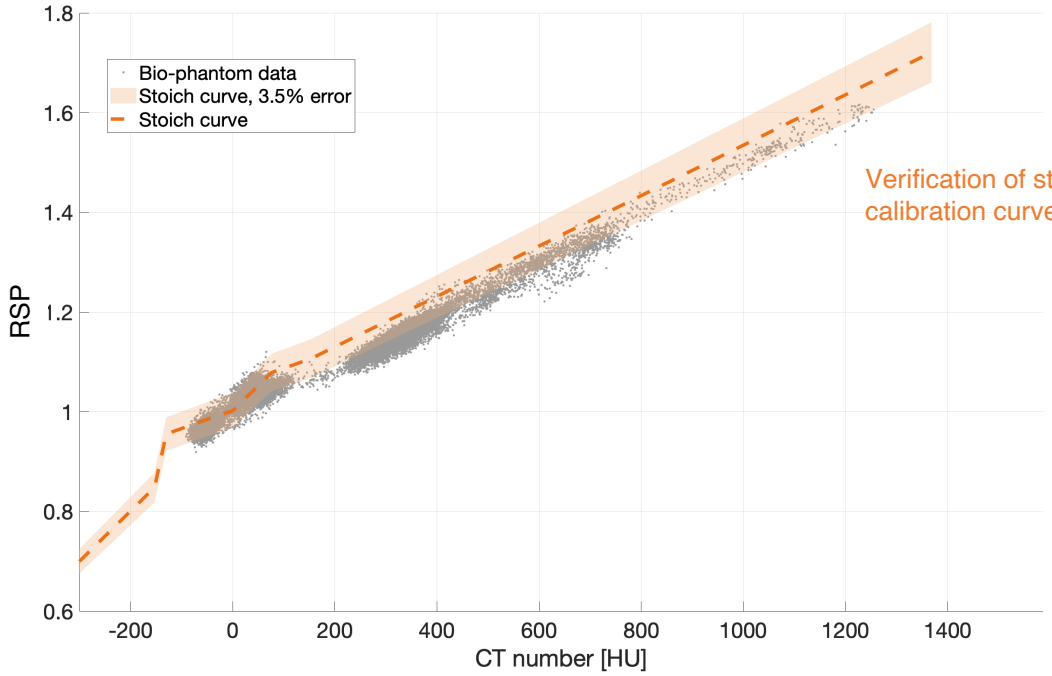

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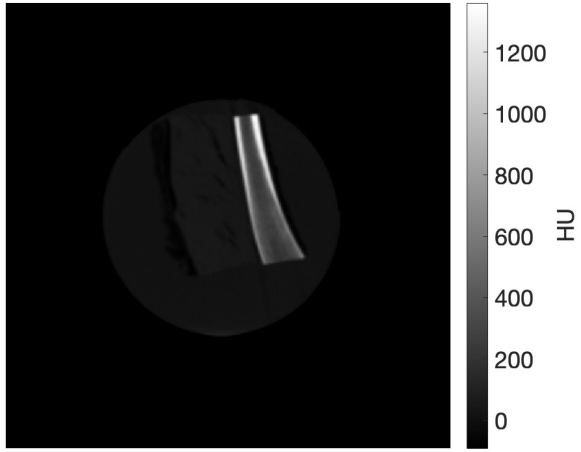
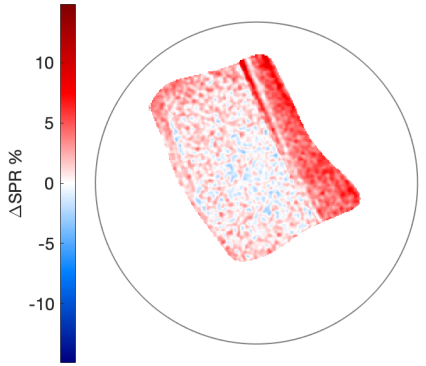
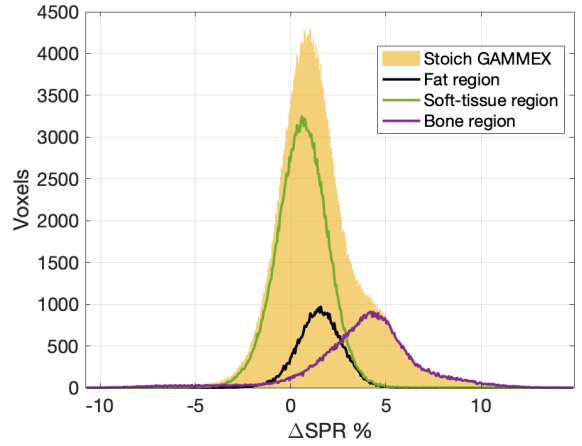


Calibrated xCT - pCT

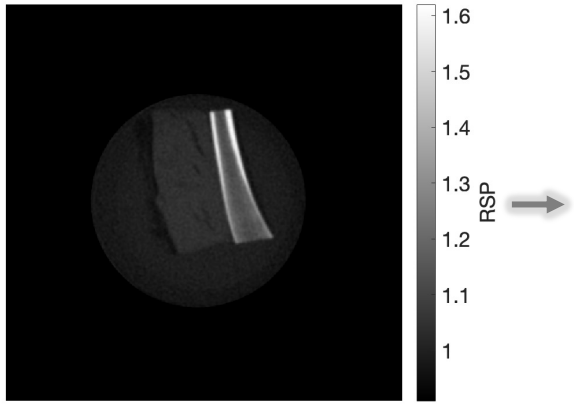




Fat region: -130 < HU < -26
Soft-tissue region: 0 < HU < 76
Bone region: HU > 53

* Peters N et al, Rad Oncol (2023)

Adapted from Fogazzi E et al, submitted to *Phys Med Bio* (2024)



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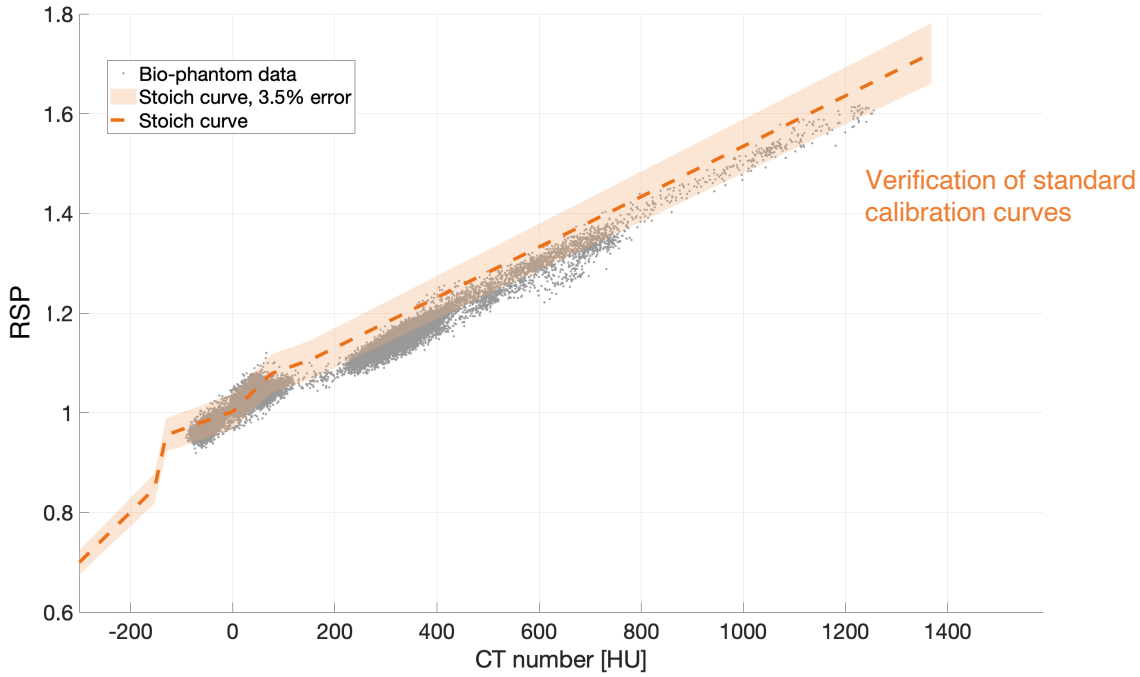

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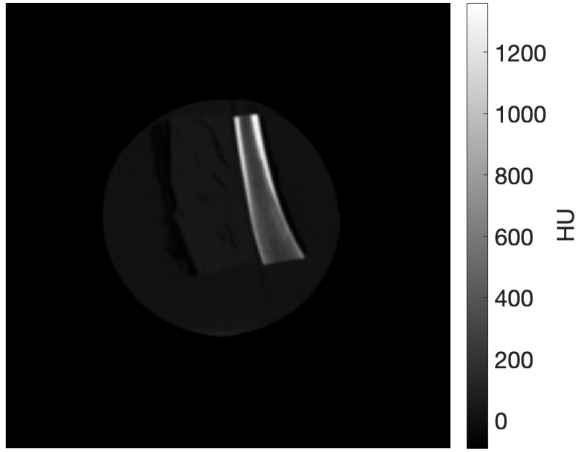

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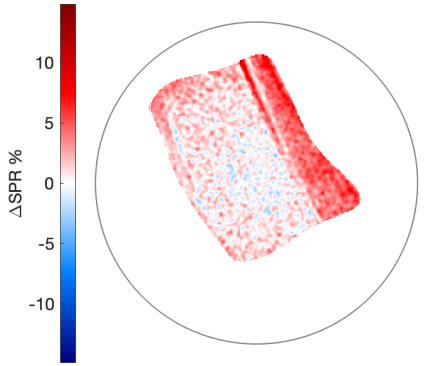

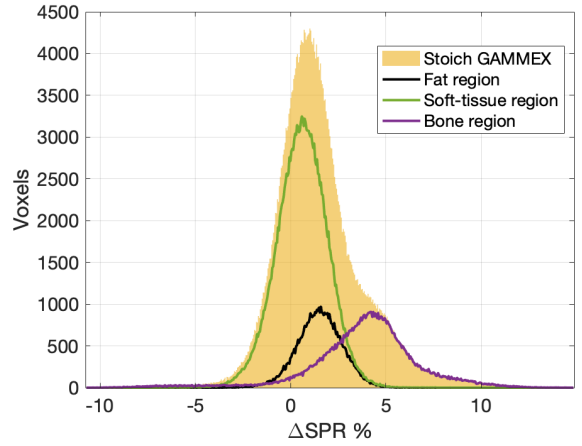

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→ Main discrepancy (~4%) in the bone region

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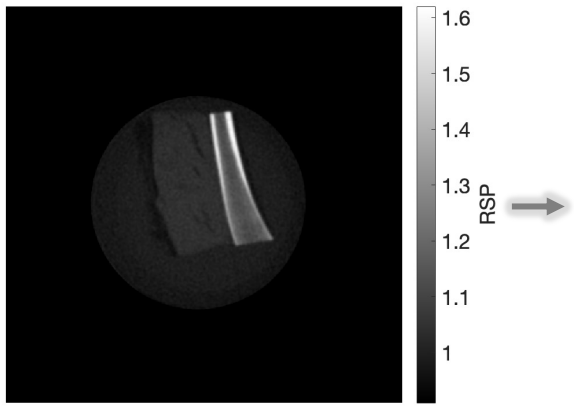

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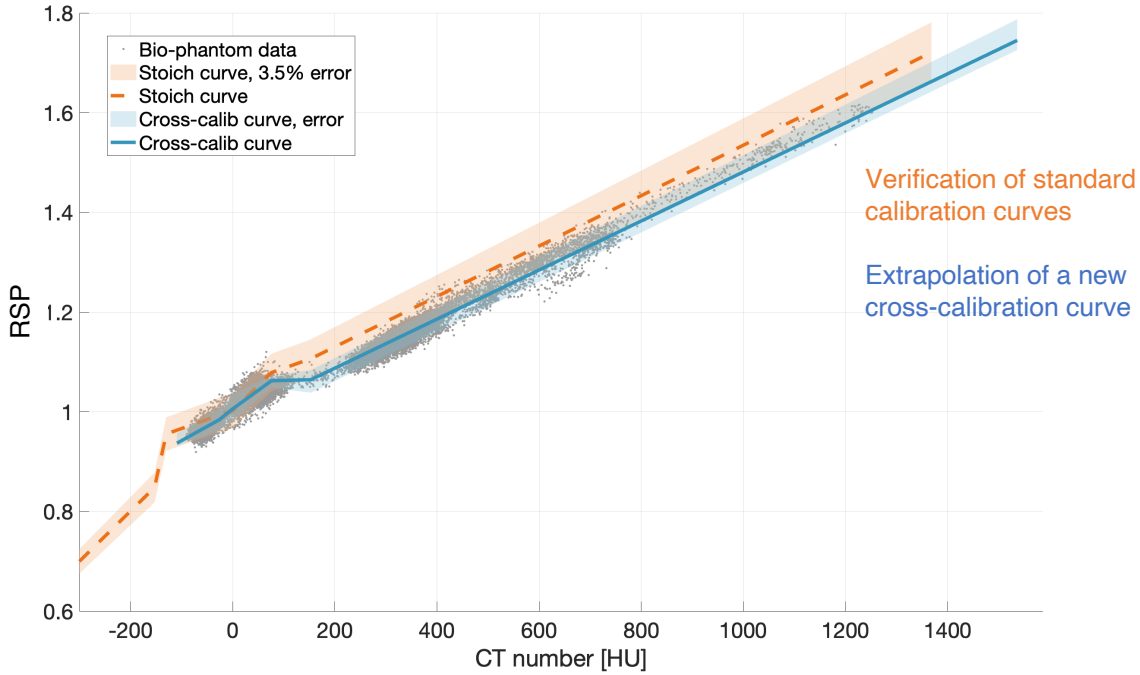
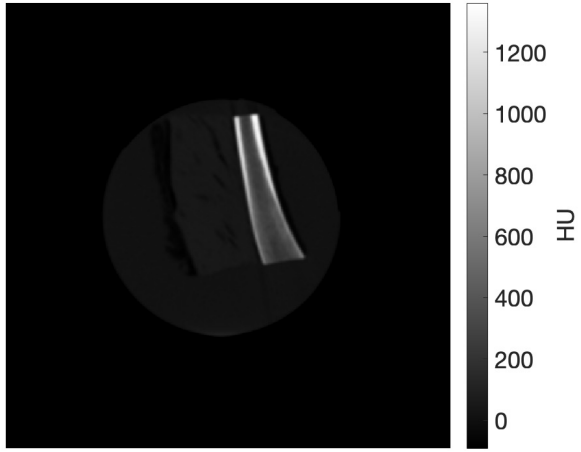


Verification of standard calibration curves

Extrapolation of a new cross-calibration curve

xCT



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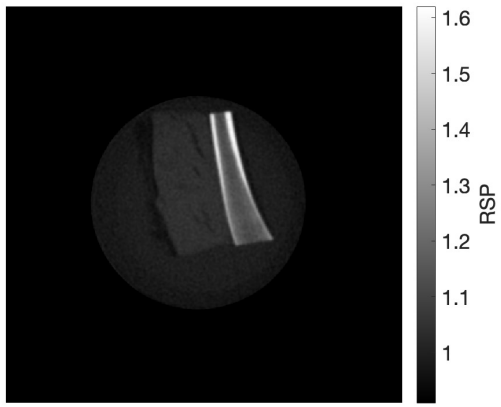

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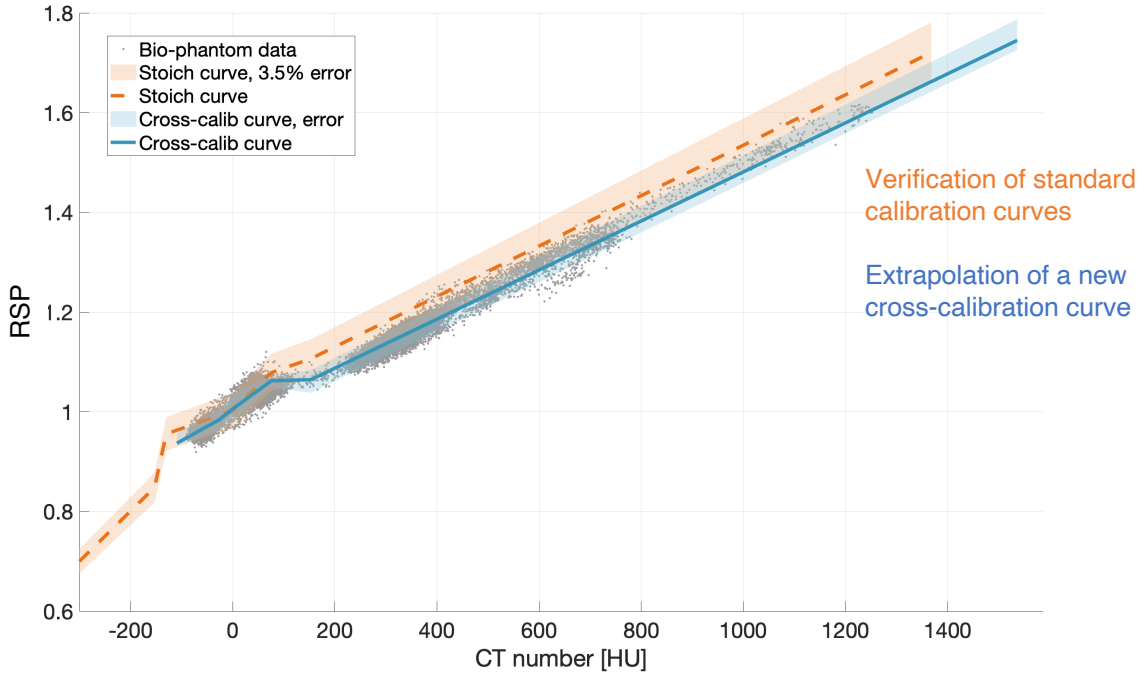

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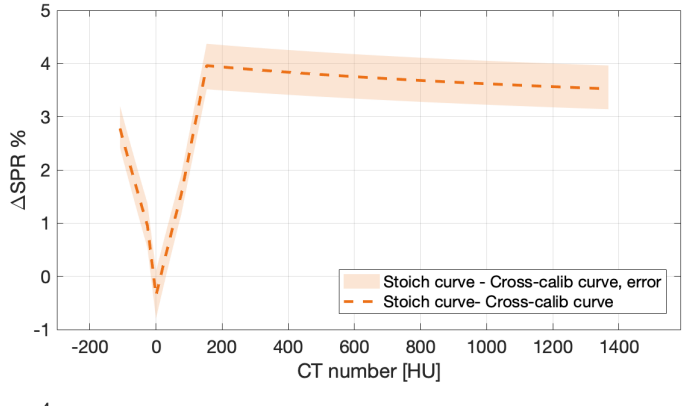

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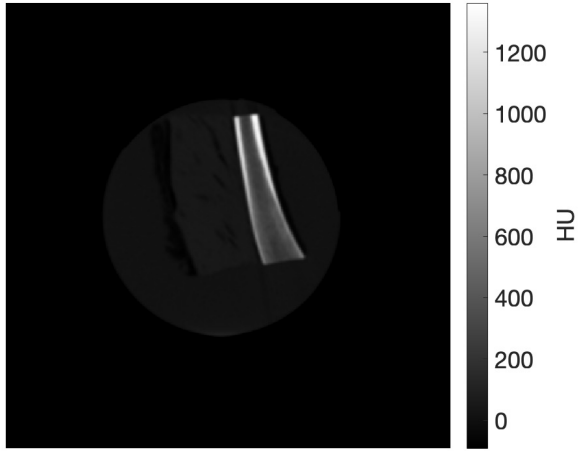
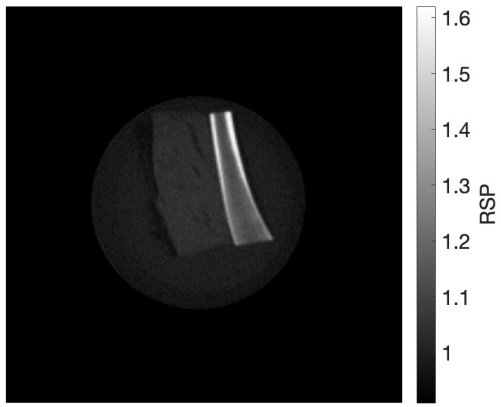
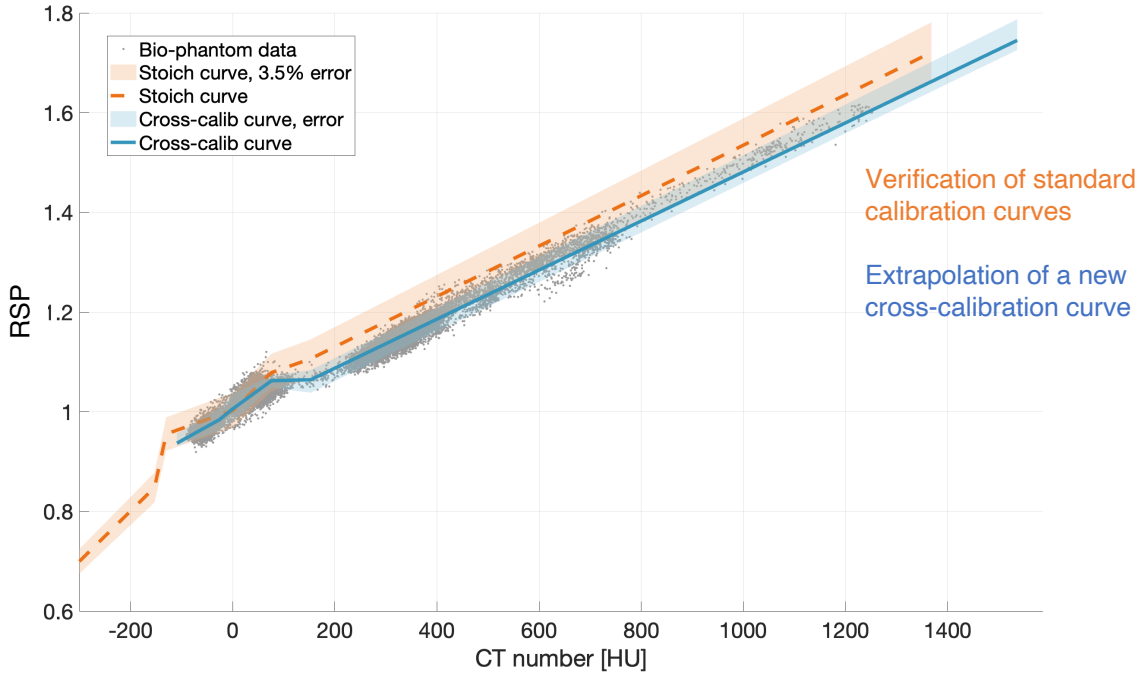
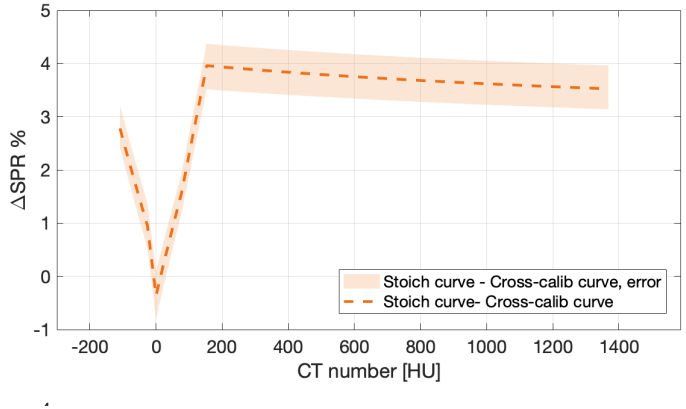


Adapted from Fogazzi E et al, submitted to *Phys Med Bio* (2024)



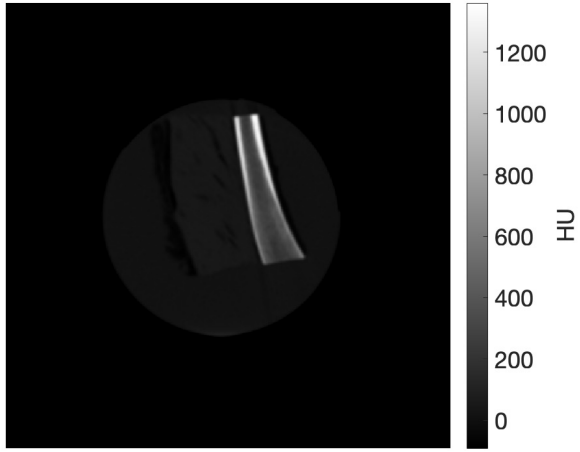
pCT





→ Potential higher accuracy

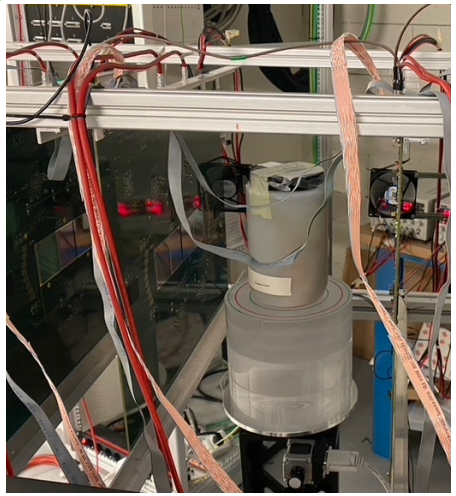
xCT



Comparison with advanced xCT scanners

Comparison with advanced xCT scanners

pCT



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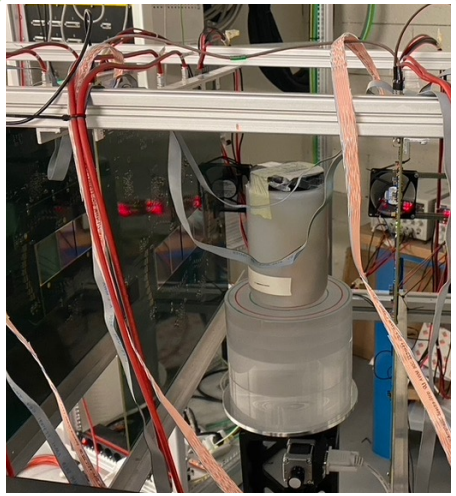
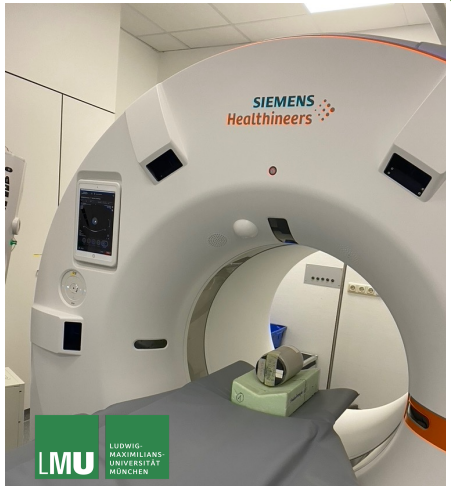


Dual-Energy CT

Photon-Counting CT



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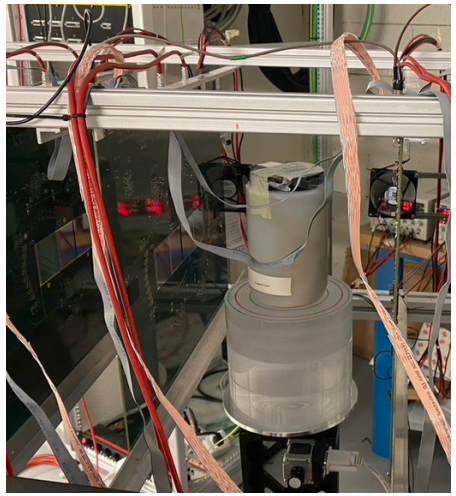

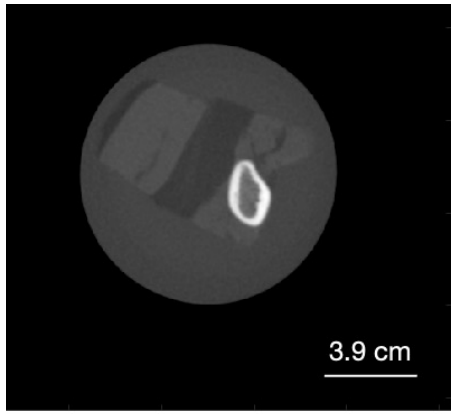

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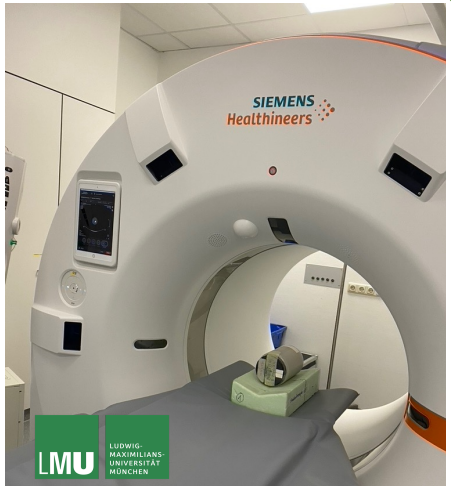

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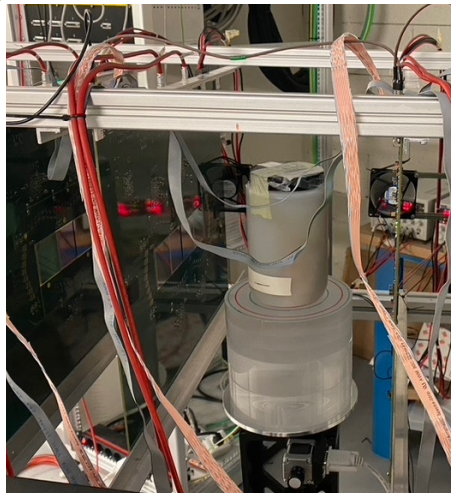

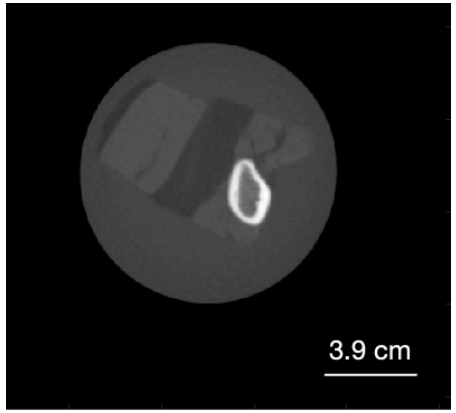

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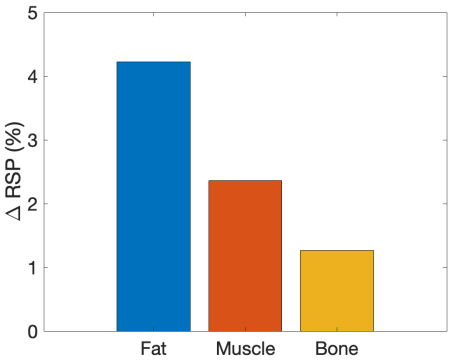
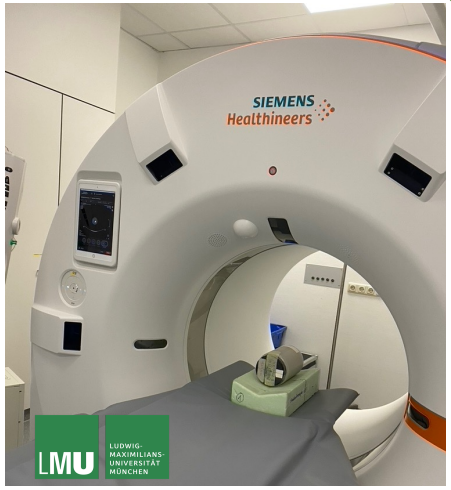
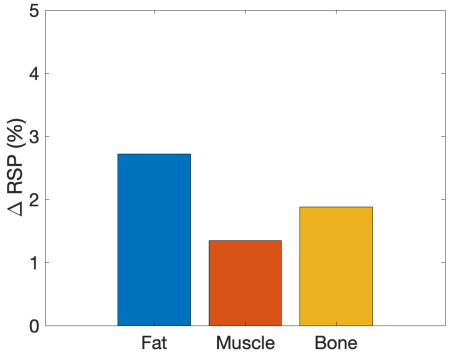


Dual-Energy CT - pCT

Photon-Counting CT





Photon-Counting CT - pCT

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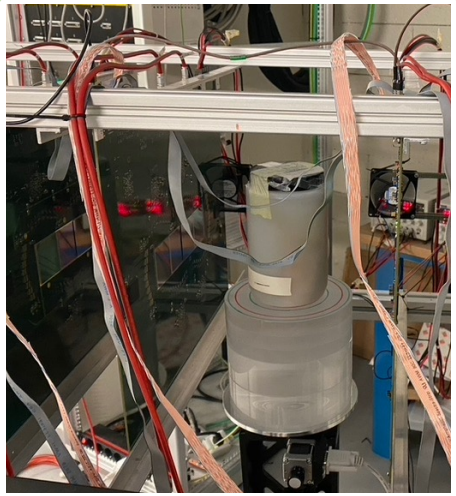
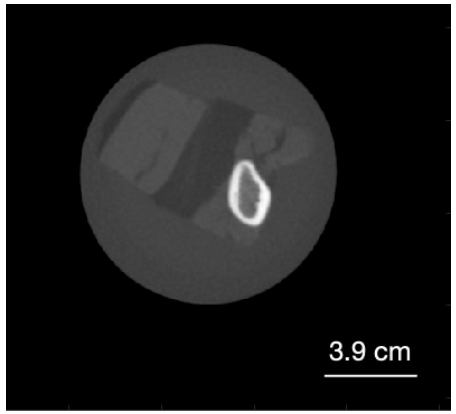
pCT





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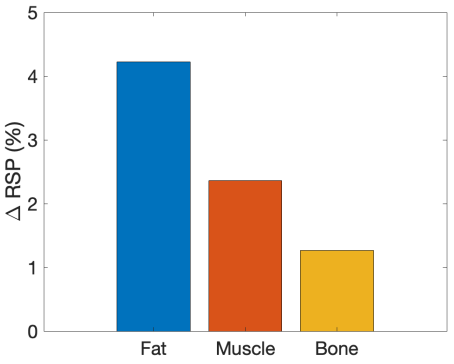

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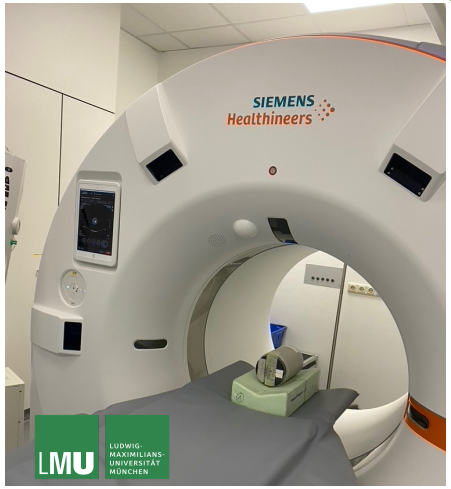
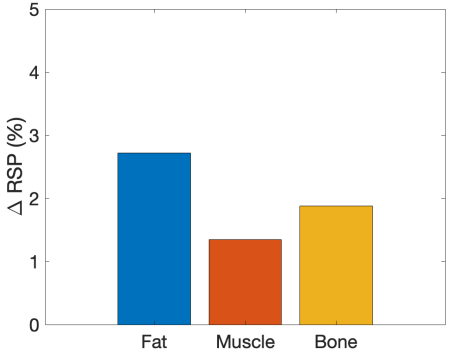
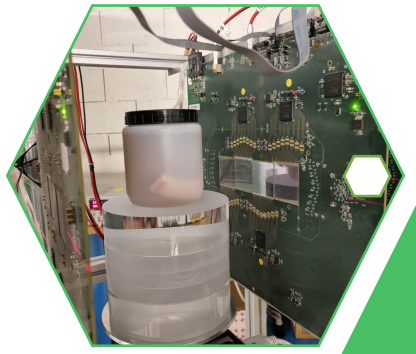
Photon-Counting CT





Photon-Counting CT - pCT

Conclusions and outlook



INFN pCT

Proton computed tomography system for proton treatment planning

Scaringella et al, *PMB* (2023)

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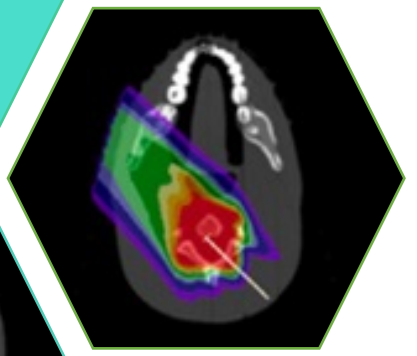

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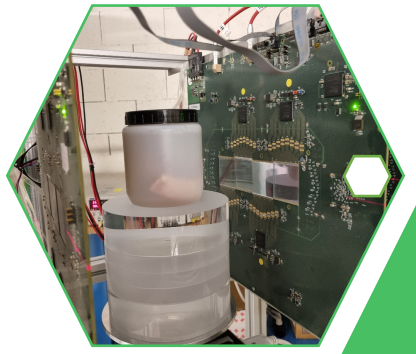

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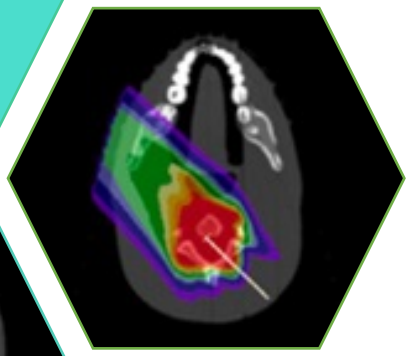

Elena Fogazzi, on behalf of the XpCalib collaboration
elena.fogazzi@unitn.it