Direct measurements of prosthesis stopping power maps using proton computed tomography

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[4] *TIFPA INFN Trento*

[5] *APSS Trento*

Motivation

Around 4% of radiotherapy patients [1] have metal implants (e.g.hip, spinal, dental, cochlear, breast) and this number is constantly increasing.

Challenges

- ❑ Metallic implants are responsible for the deterioration in the quality of the CT images used at each stage of the radiation therapy, during delineation, dosimetry and dose delivery.
- ❑ Dosimetry is calculated using CT images with Hounsfield units (HU) converted into electron / mass densities.
  - ♠ High density of metallic implants not correctly converted to HUs due to limited acquisition windows of standard CT scans (-1024; 3071).
- ❑ Artefacts due to projection errors, increased noise, dispersion and partial volume effect
  - ♠ drastical reduction of image quality → delineation uncertainties.
- ❑ HUs assigned to metallic implants saturate
  - ♠ identical regardless of implant composition.

Measuring SPRs of prostheses directly with proton Computed Tomography would solve these issues

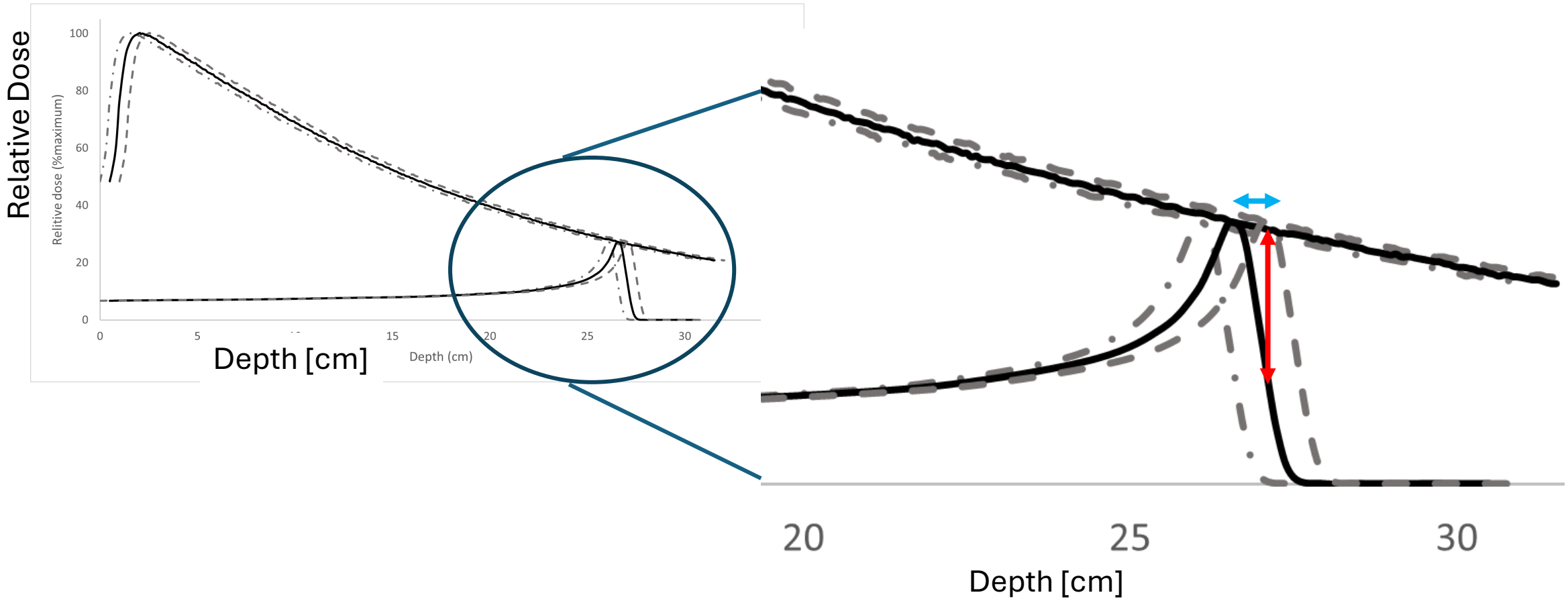
CT image of patient after spinal fusion surgery for scoliosis. Bright and dark streaks from Ti pedicle screws and Co-Cr rods obscure adjacent tissues **Katsura M. Published Online:** March 12, 2018 https://doi.org/10.1148/rg.2018170102

[1] Reft C et al. Dosimetric considerations for patients with HIP prostheses undergoing pelvic irradiation. Med Phys 2003;30:1162–82.

C. Le Fèvre et al. Management of metallic implants in radiotherapy Cancer/Radiothérapie 26 (2022) 411–416

Uncertainties in dose determination

Small errors on the Bragg peak position induce much higher error on the dose for protons than for X-rays



Mara Bruzzi, Direct measurements of prosthesis stopping power maps using proton computed tomography , Ion beam Imaging workshop, Oct.22, 2024

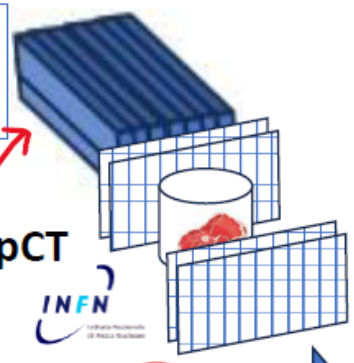
THE pRad PROJECT

INFN
Istituto Nazionale di Fisica Nucleare
CSN5

2024-2026

p-Rad system in treatment room

- ✓ **New Calorimeter**
  - pencil beam
  - reduced pile-up
  - cost effective
- ✓ **Range verification for stabilized bio-phantom**



See talk of C. Civinini

1

GOAL:
Increased accuracy in TPS

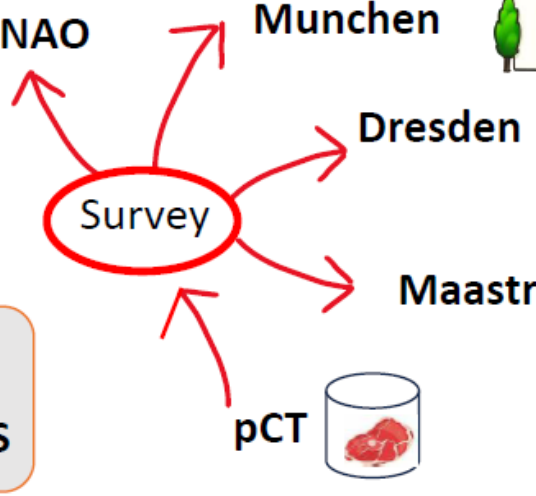
2

SPR direct measurement of metal implants

this talk

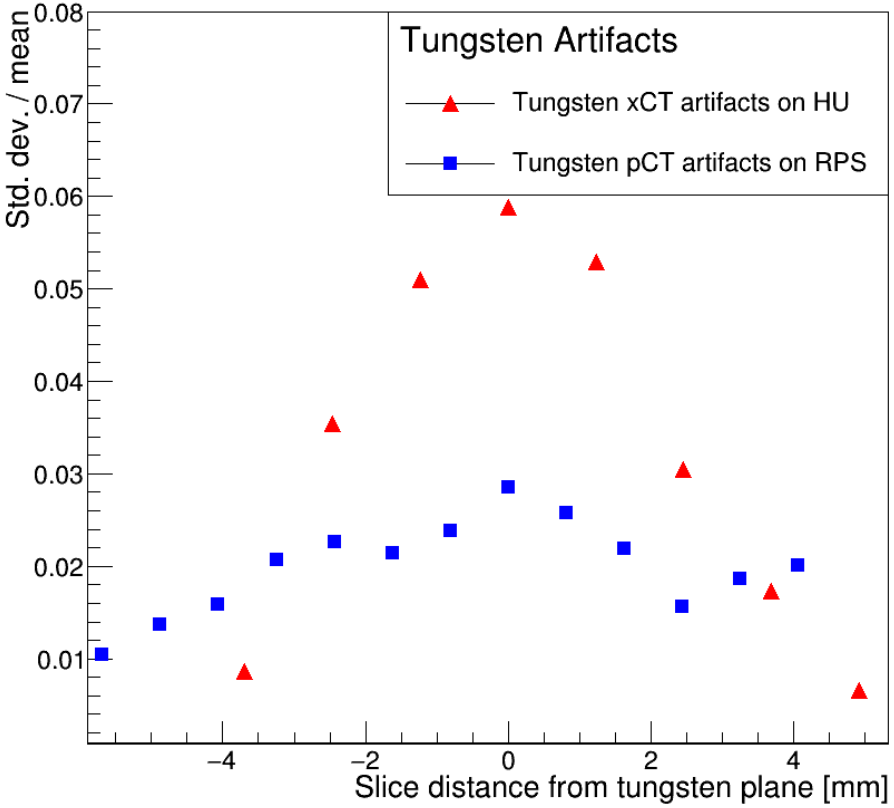
3

Reliability Test with four Institutes/Hospital in Europe

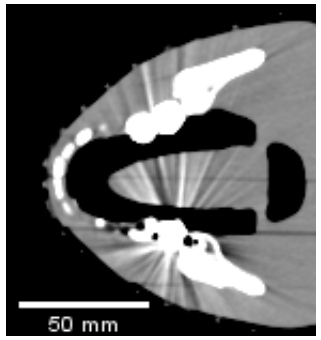


See talk of C. Civinini

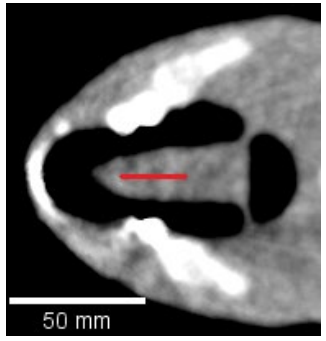
Early Studies with pCT on image artifacts with an anthropomorphic head phantom due to metal implants



calculated within the ROIs close to the tungsten dental filling



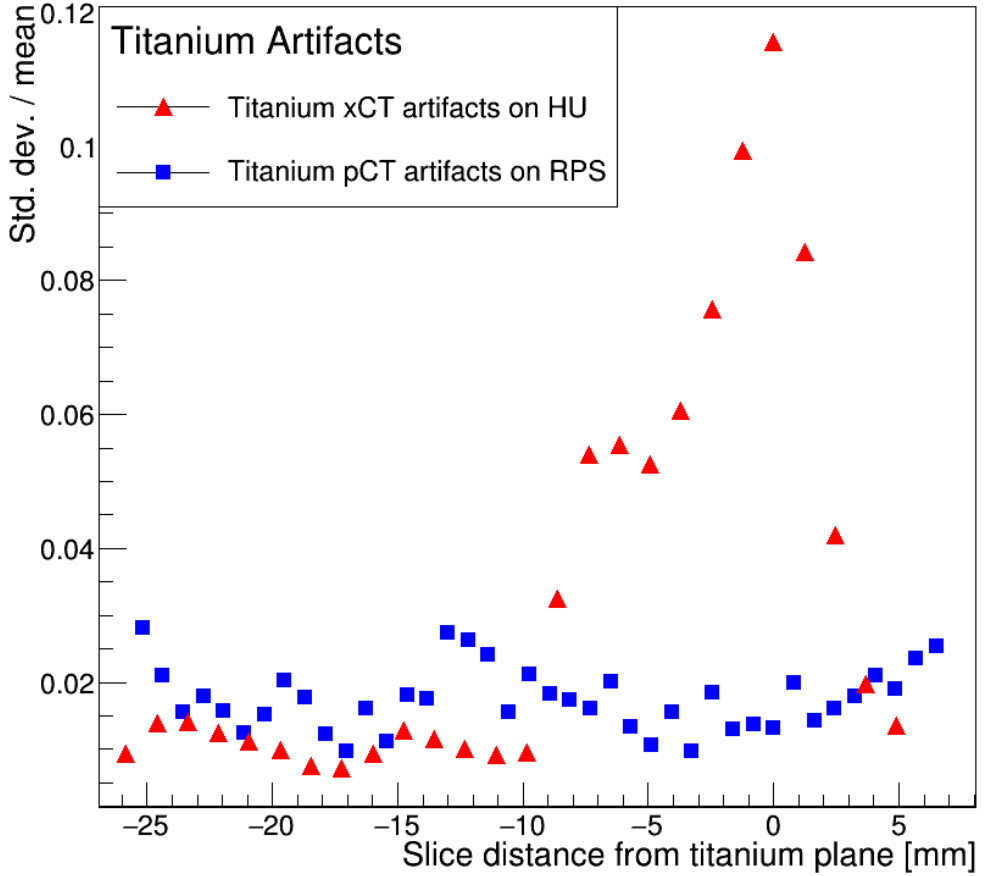
xCT

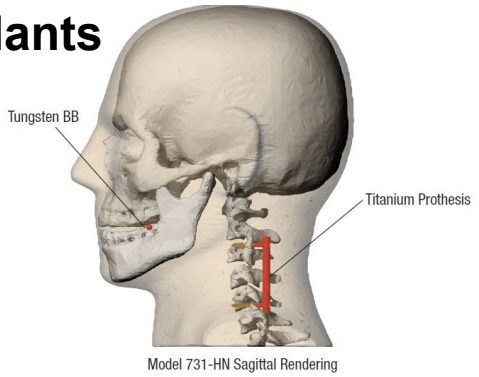


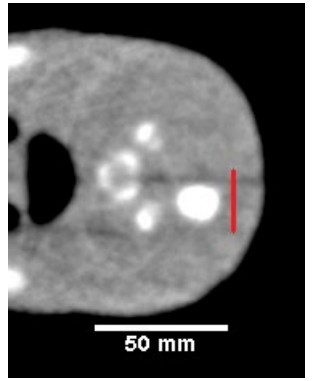
pCT

Comparison of RSP and HU standard deviation , calculated within the ROIs close to metal prosthesys

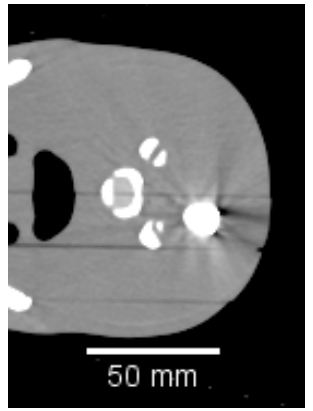
→ ***evidence of reduction with pCT***







pCT



xCT

C. Civinini et al. Relative stopping power measurements and prosthesis artifacts reduction in proton CT, PHYSICS IN MEDICINE AND BIOLOGY 65 22 225012, 2020

Metal alloys employed in implants

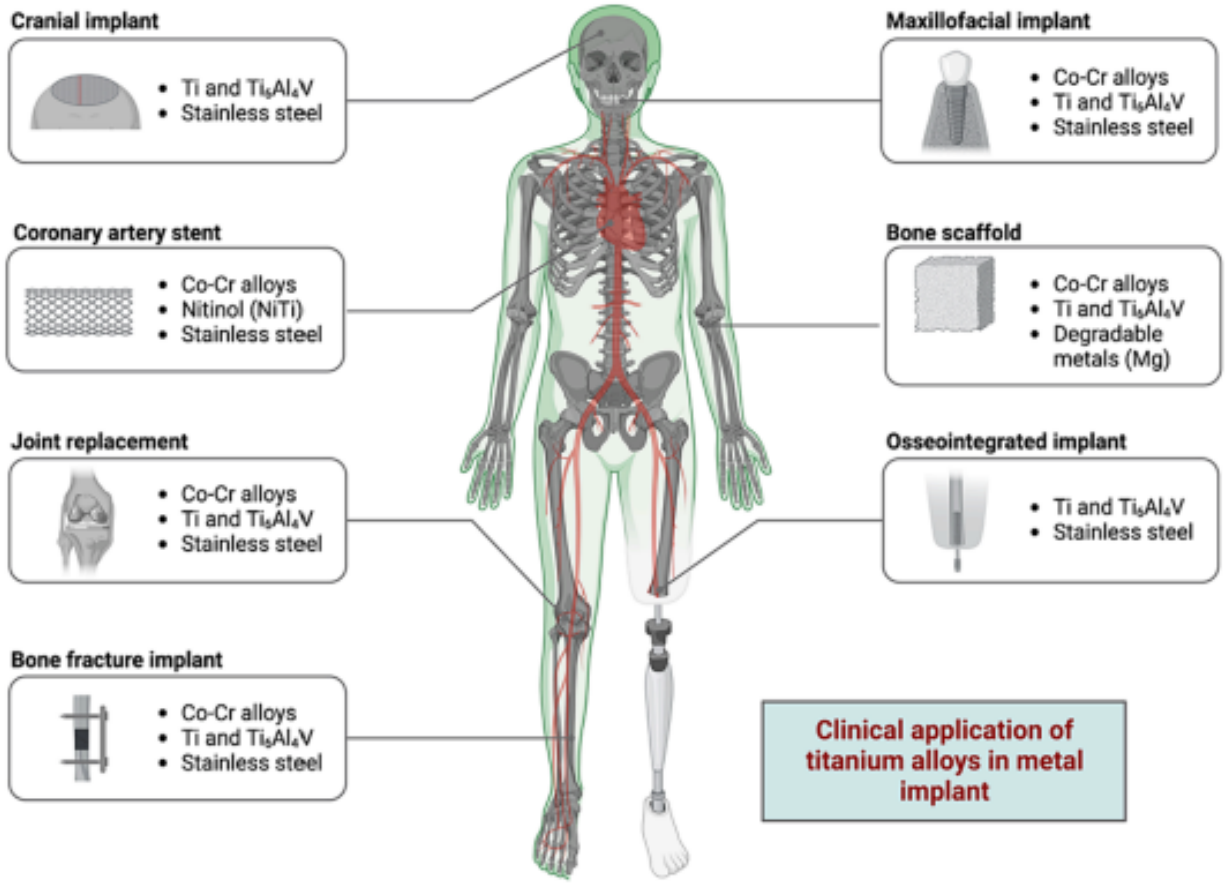


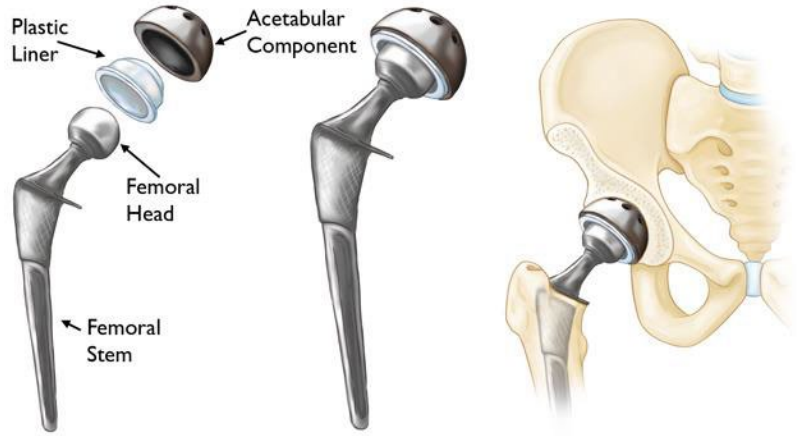
Fig. 2. Metal implant in the human body, highlighting the clinical applications of Ti alloys in cranial, maxillofacial, orthopedic, and cardiovascular devices; Created by BioRender.

Challenges

♠ Complex geometry: difficult to measure each material e.g. by MLIC;

♠ Often actual composition of an implant unknown due to industrial secrecy

☺ **pCT can determine SPRs for all materials in one single image.**



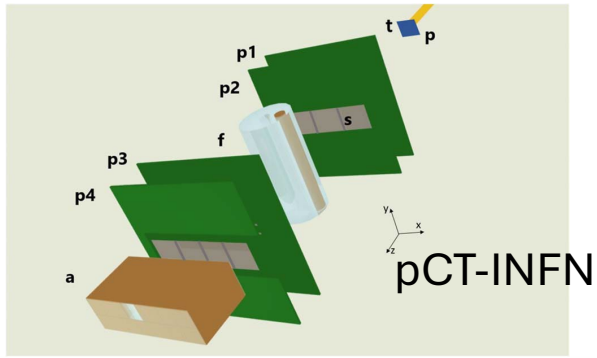
☺ New materials with electron density 1.7 - 1.9 g/cm^3 as carbon fiber, alternative to conventional implants.

Implant Devices investigated by pCT technique

1) A homogeneous cylindrical (3 cm diameter, 1 cm height) Ti alloy sample (Ti6Al4V grade 5).

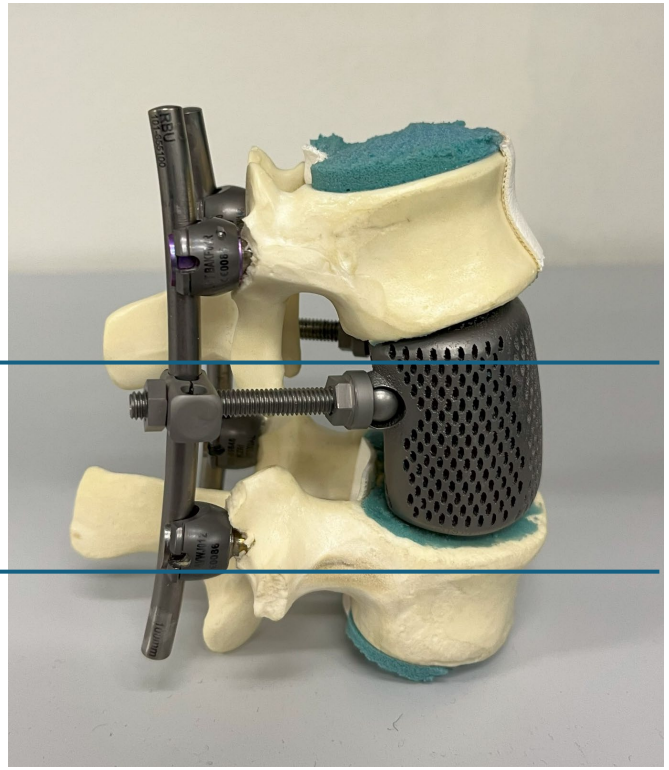
2) A set of devices used for prostheses, (see next slides)

3) An intra-vertebral titanium alloy implant system made of various components: a 3D meshed cage, support rods, screws and plastic structures simulating vertebrae.



- p 211 MeV
- 1.3x10^9 trigger
- 20mGy

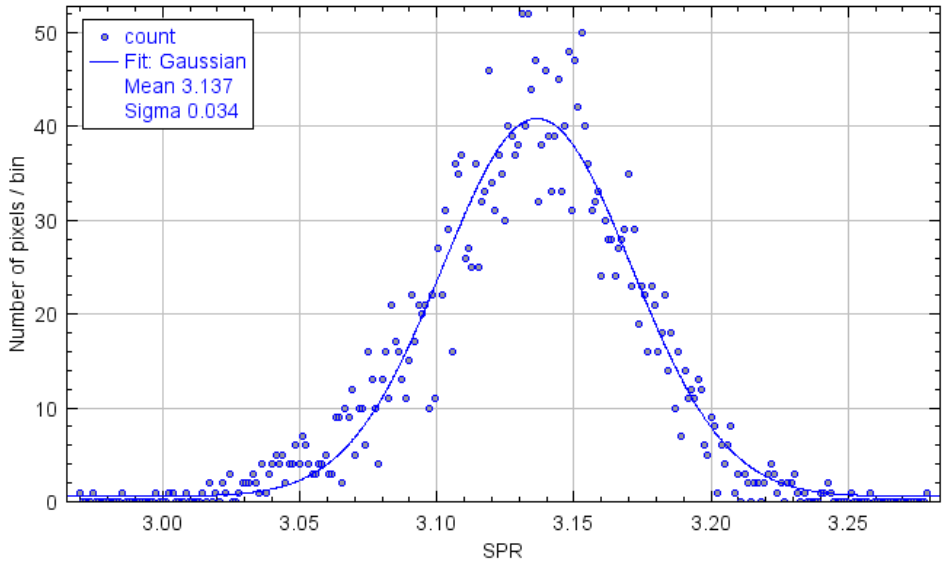
Samples immersed into demineralized water within a plastic cylindrical container



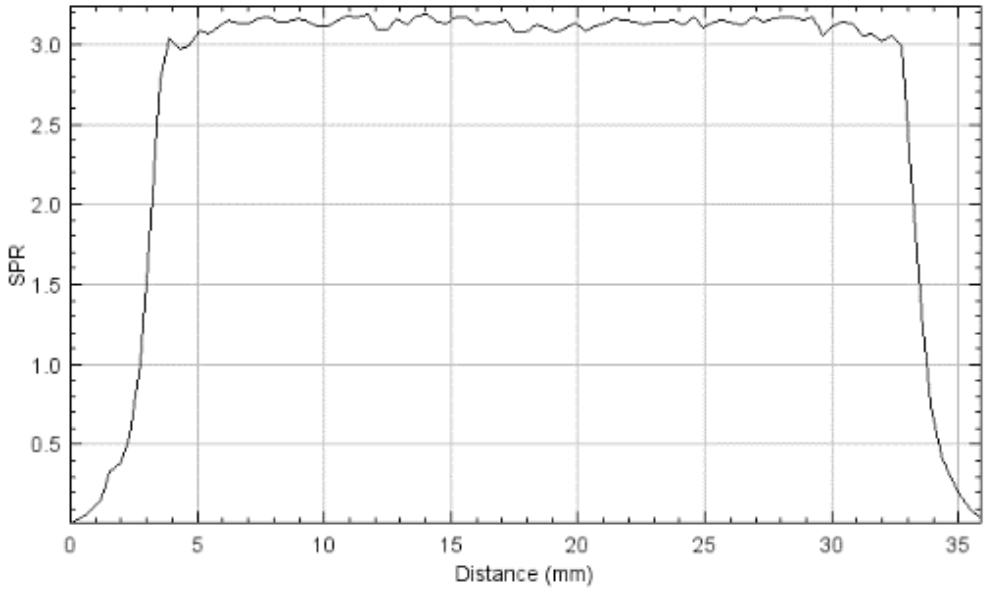
pCT measurements performed at experimental beam line of Trento Proton Therapy Centre (Azienda Provinciale per i Servizi Sanitari—APSS, Trento, Italy (APSS).

Homogeneous Ti6Al4V alloy sample: Results

SPR distribution within the 2.5 cm diameter, 6 mm height cylindrical ROI coaxial to the specimen.

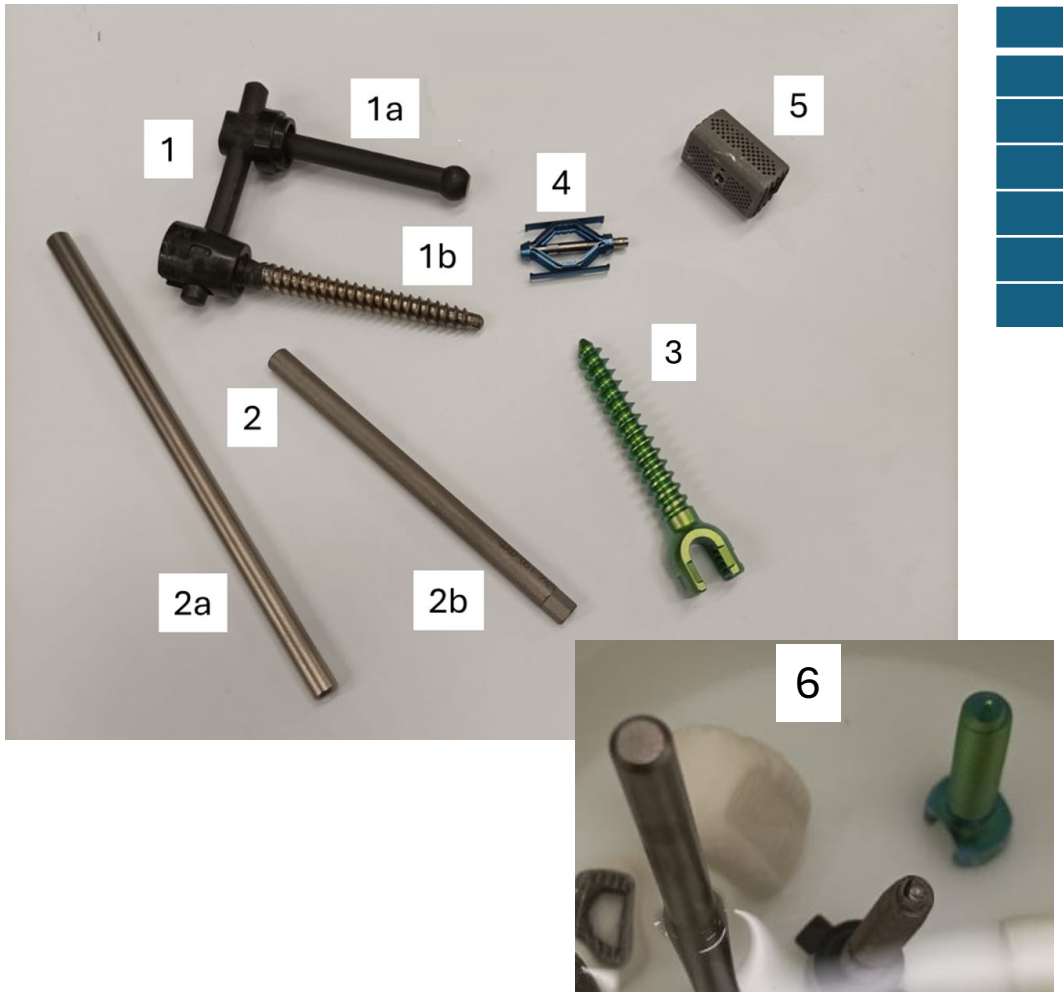


SPR profile measured along the diameter of the Titanium alloy sample phantom.

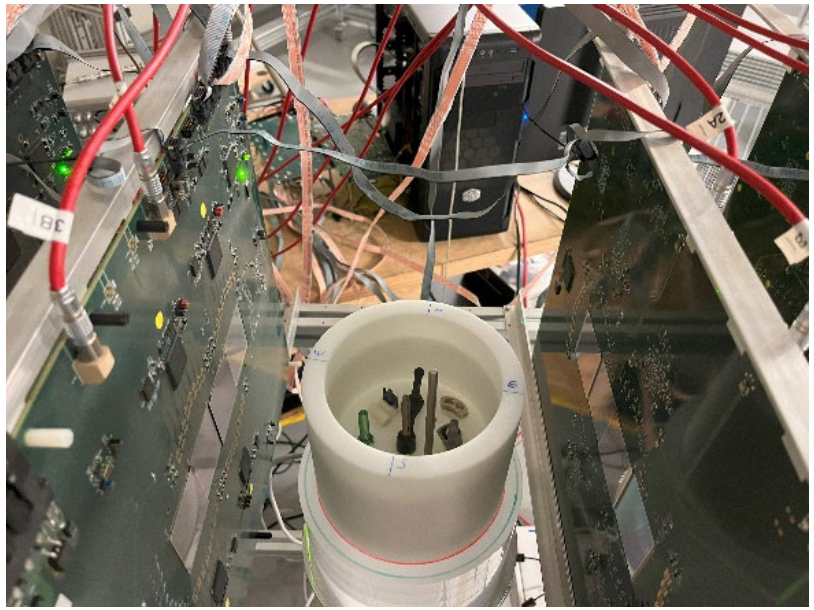


$$\mathrm{SPR} = 3.1365 \pm 0.0006\ (stat) \pm 0.016\ (syst)\ .$$

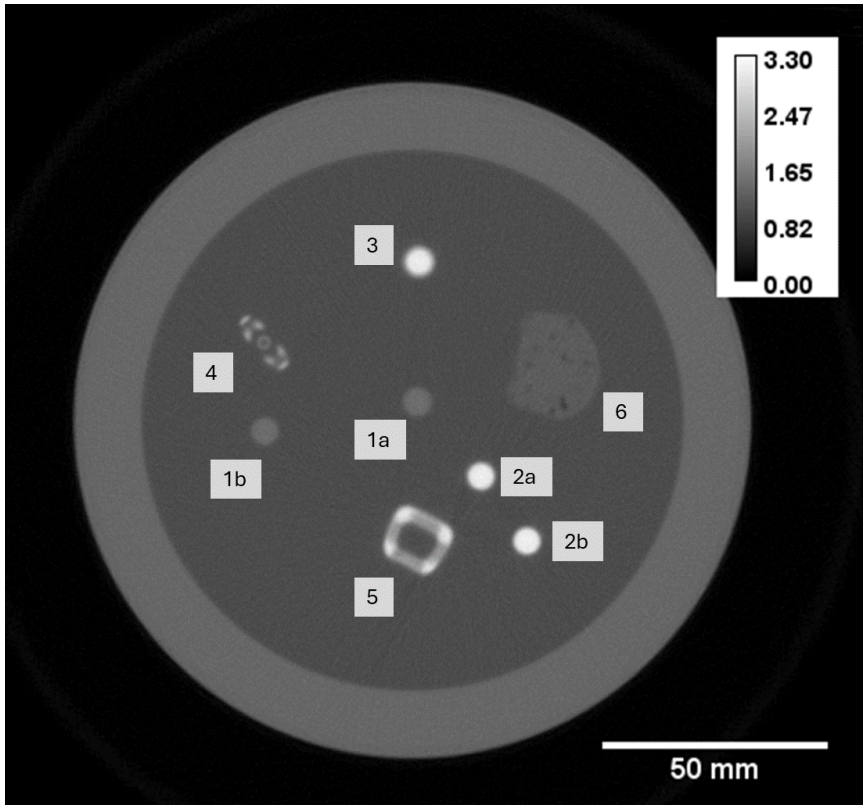
Set of implant devices inspected by pCT



#	Description
1	Carbon rods with a titanium-coated screw
2	Titanium rods (6mm diameter)
3	Titanium screw
4	Titanium vertebral thickness regulator
5	Titanium drilled cage
6	Bone cement

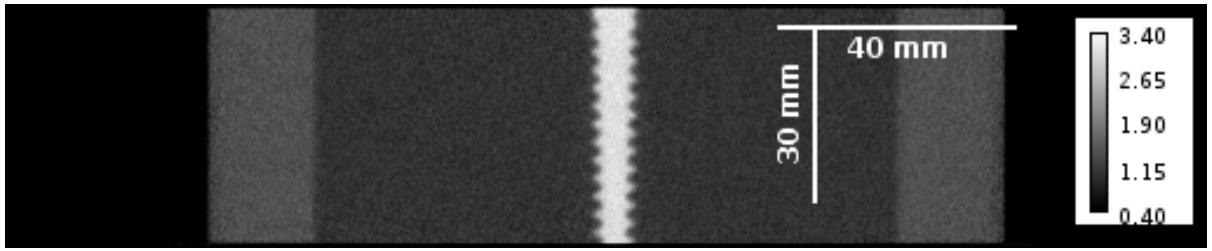


Set of implant devices inspected by pCT: Results



Axial slice of the prosthesis devices
Reconstruction pixel size: **0.39x0.39x1.5 mm³**

#	Description
1	Carbon rods with a titanium-coated screw
2	Titanium rods (6mm diameter)
3	Titanium screw
4	Titanium vertebral thickness regulator
5	Titanium drilled cage
6	bone cement



Coronal view of the self-tapping screw #3, showing the 3 mm pitch screw threads.
Reconstruction pixel size is **390µmx390µmx390µm.**

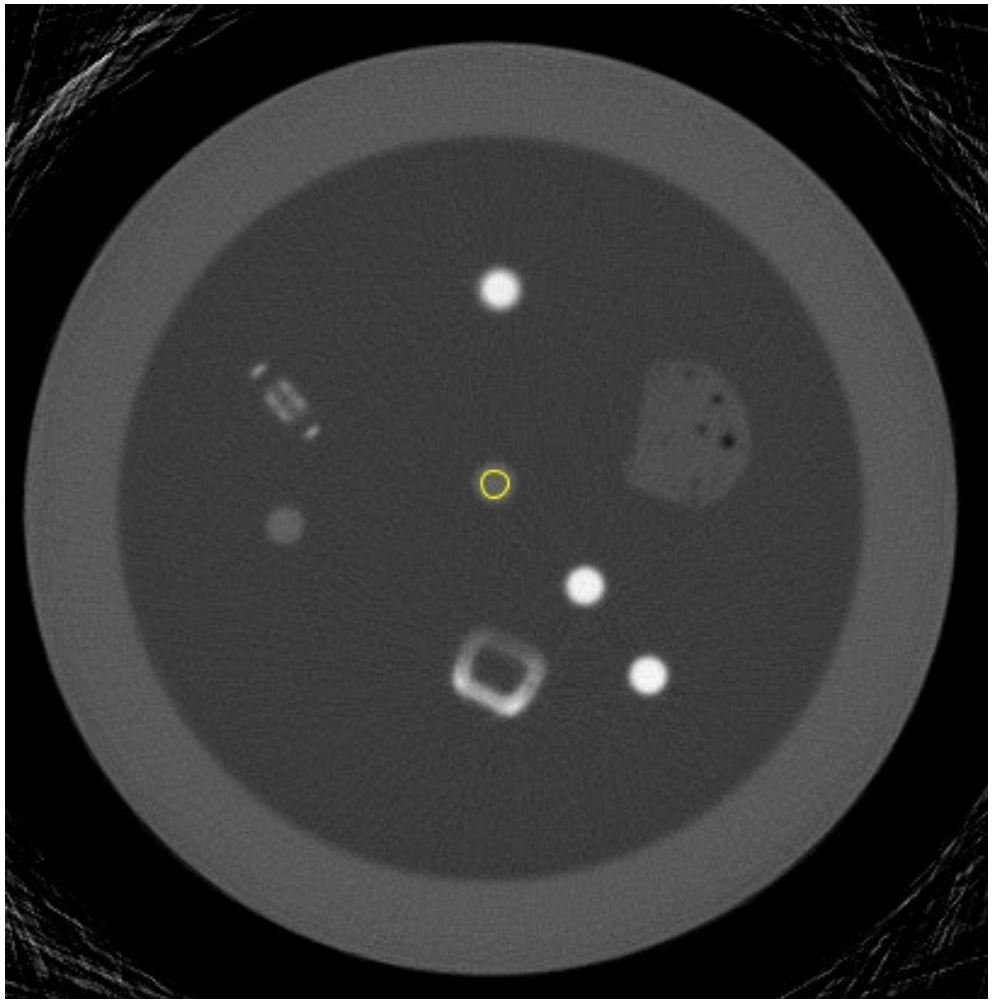
Reconstruction:

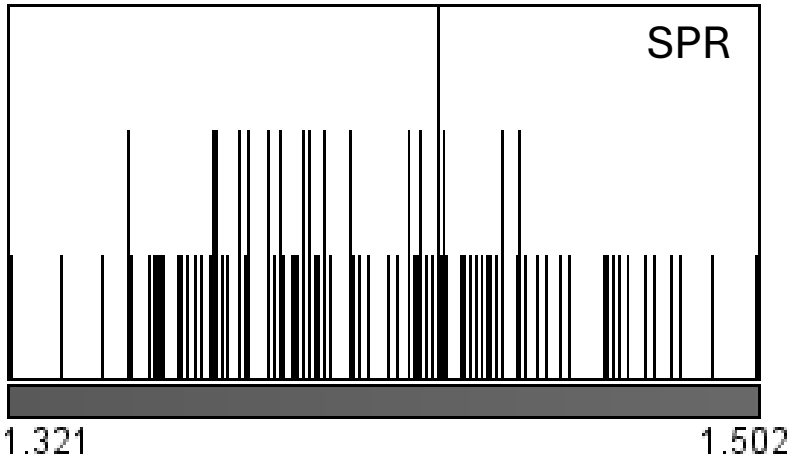
- FDK-like modified for MLP

S. Rit et al., Med. Phys. 40 (3), March 2013

- No filter

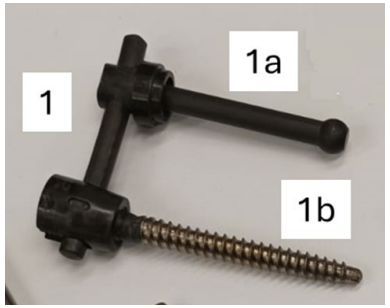
1-Carbon bar and screw



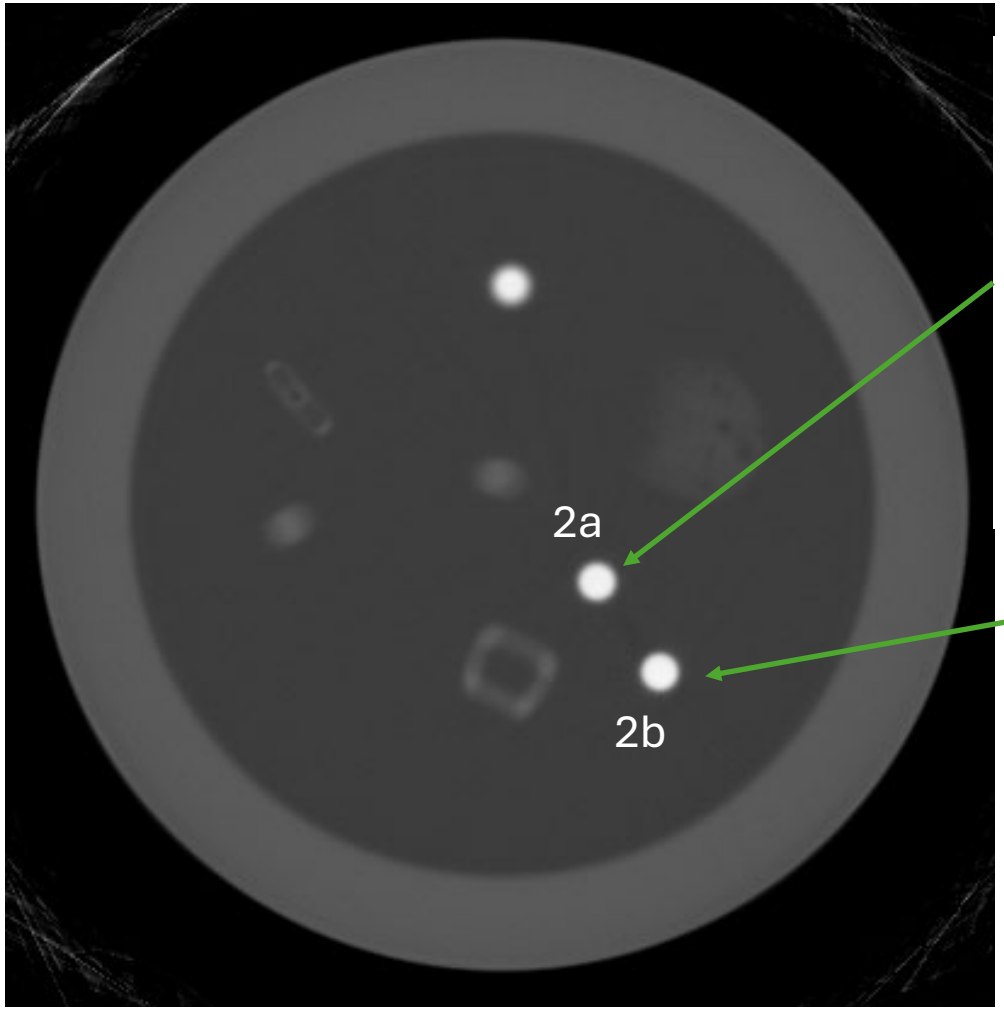


N: 97	Min: 1.321
Mean: 1.408	Max: 1.502
StdDev: 0.0392	Mode: 1.424 (3)
Bins: 256	Bin Width: 0.000705
Value: 1.452	Count: 0

Carbon core within a Ti shield
Mean SPR=1.408

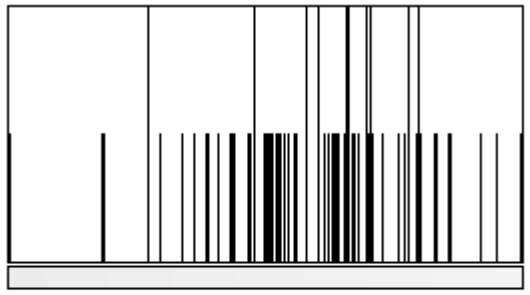


2-Titanium alloy bars

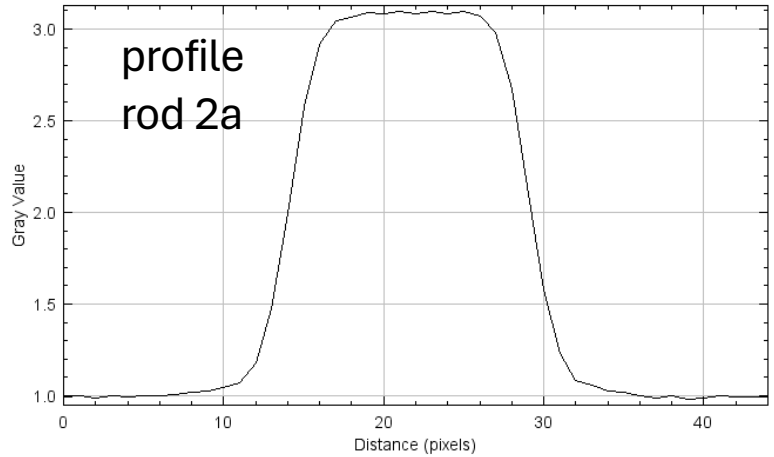


Axial slice mean from 3 to 25

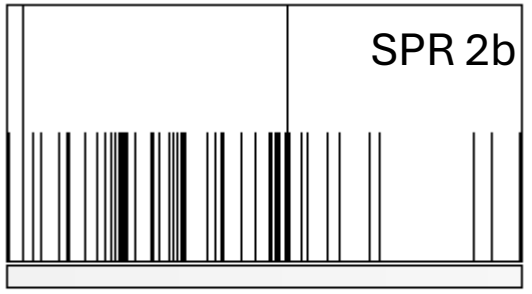
SPR 2a



N: 70	Min: 3.026
Mean: 3.081	Max: 3.118
StdDev: 0.0175	Mode: 3.051 (2)
Bins: 256	Bin Width: 0.000359
Value: 3.068	Count: 0



SPR 2b

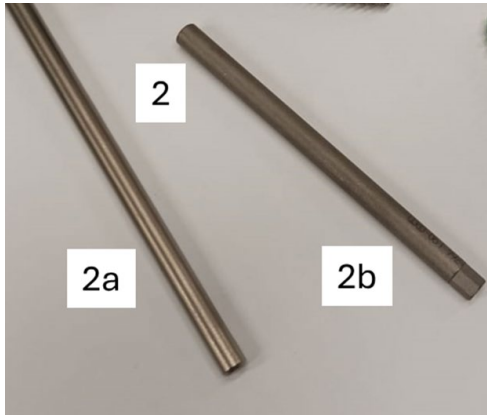


N: 52	Min: 3.094
Mean: 3.116	Max: 3.152
StdDev: 0.0135	Mode: 3.096 (2)
Bins: 256	Bin Width: 0.000224
Value: ---	Count: ---

(mean of histogram)

$$SPR_1 = 3.081 \pm 0.0021$$
$$SPR_2 = 3.116 \pm 0.0019$$

Different materials?



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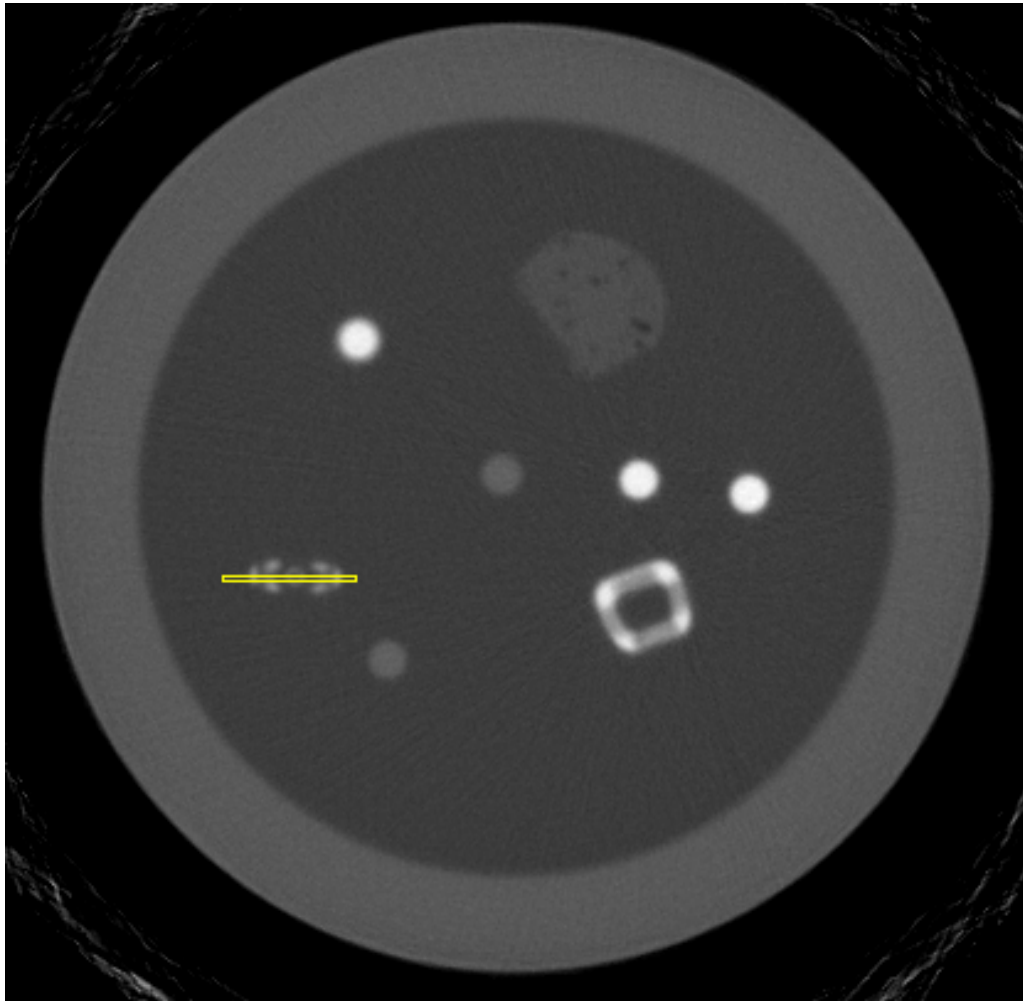
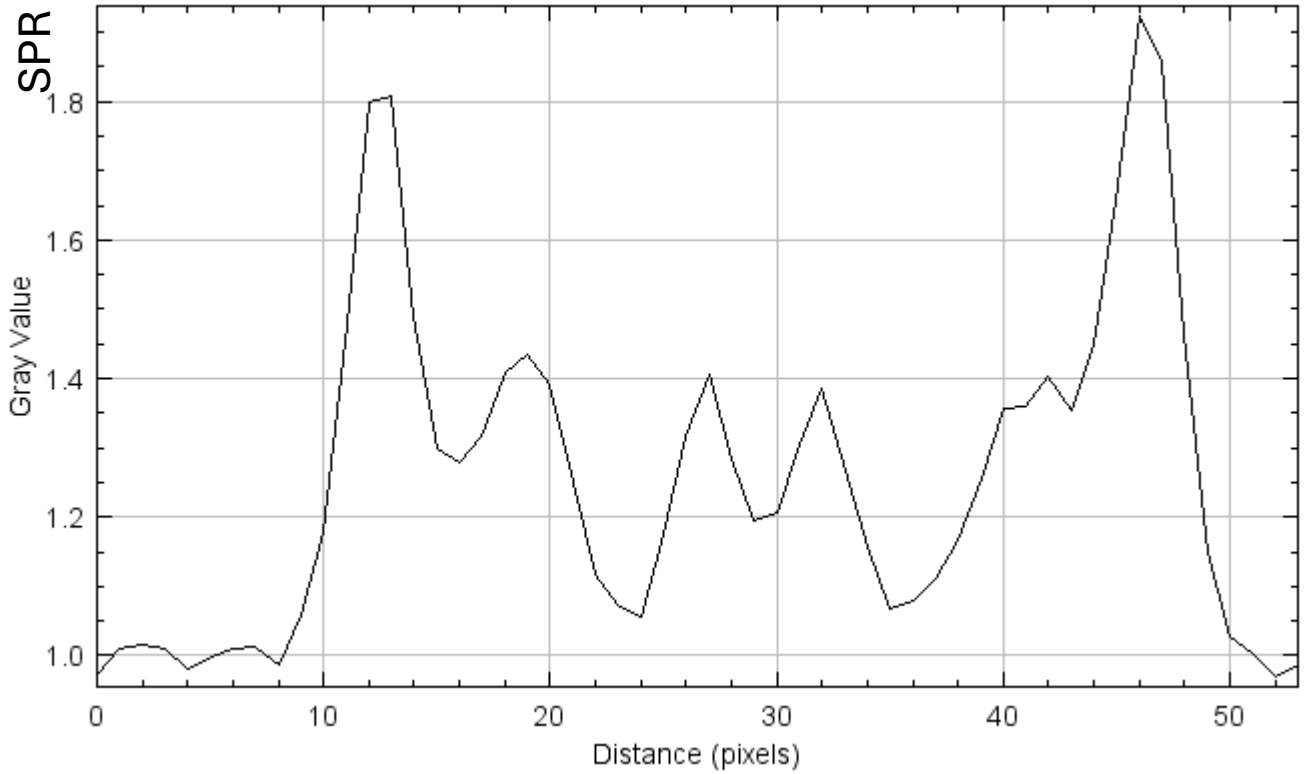
4-Titanium jack

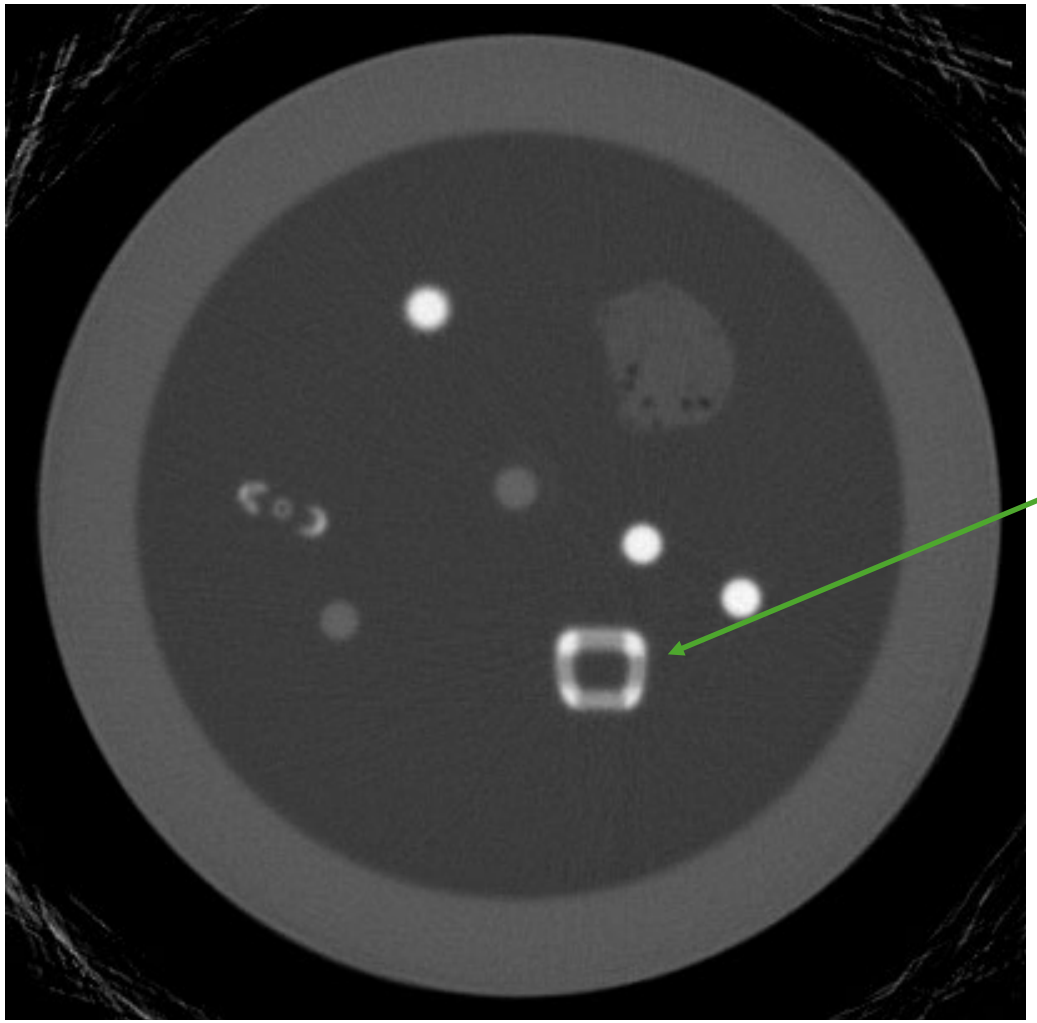




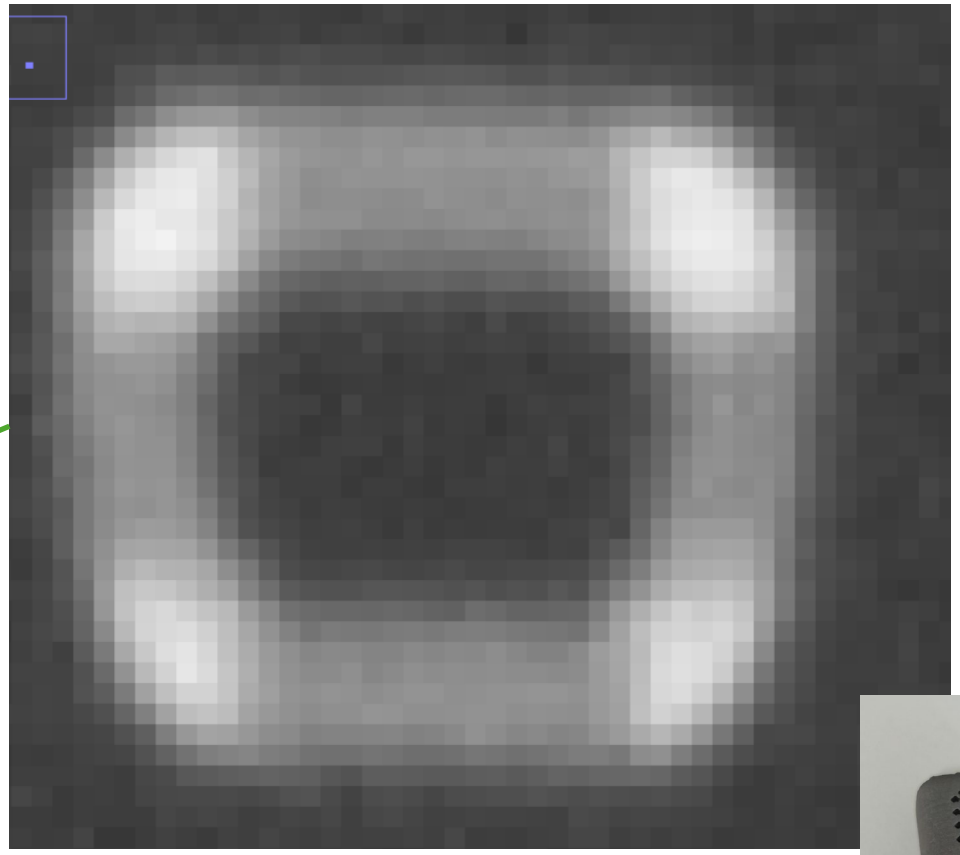
SPR profile along the jack;
SPR value affected by partial volume effects

Axial slice 5/27

5-Titanium cage – axial slice

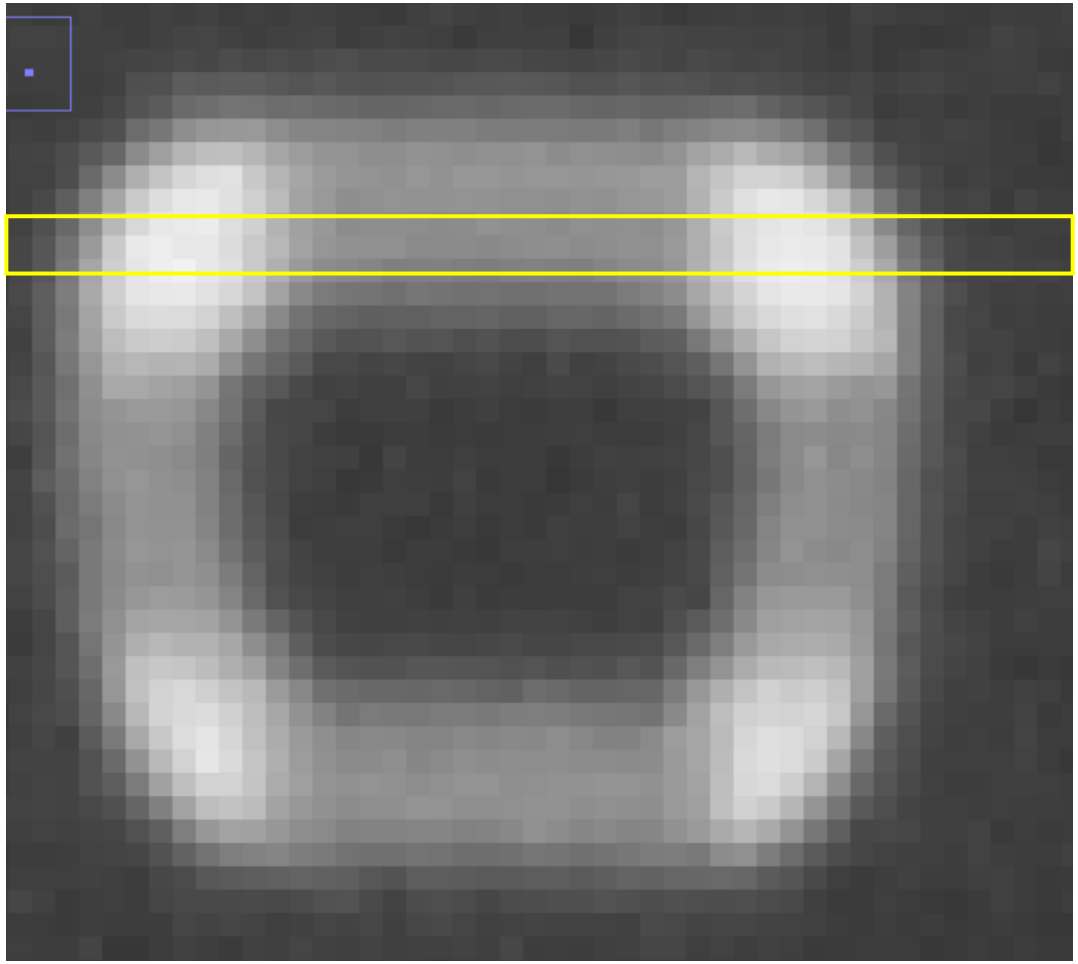


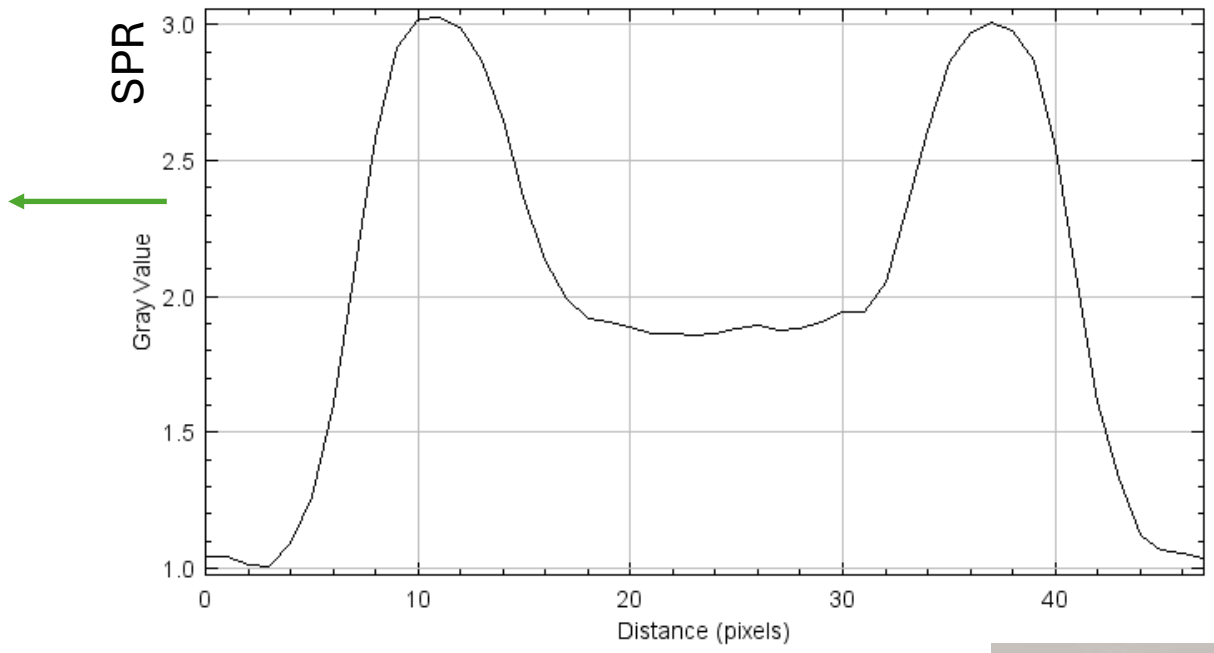
Axial slice 4/27



Zoom

5-Titanium cage – SPR profile

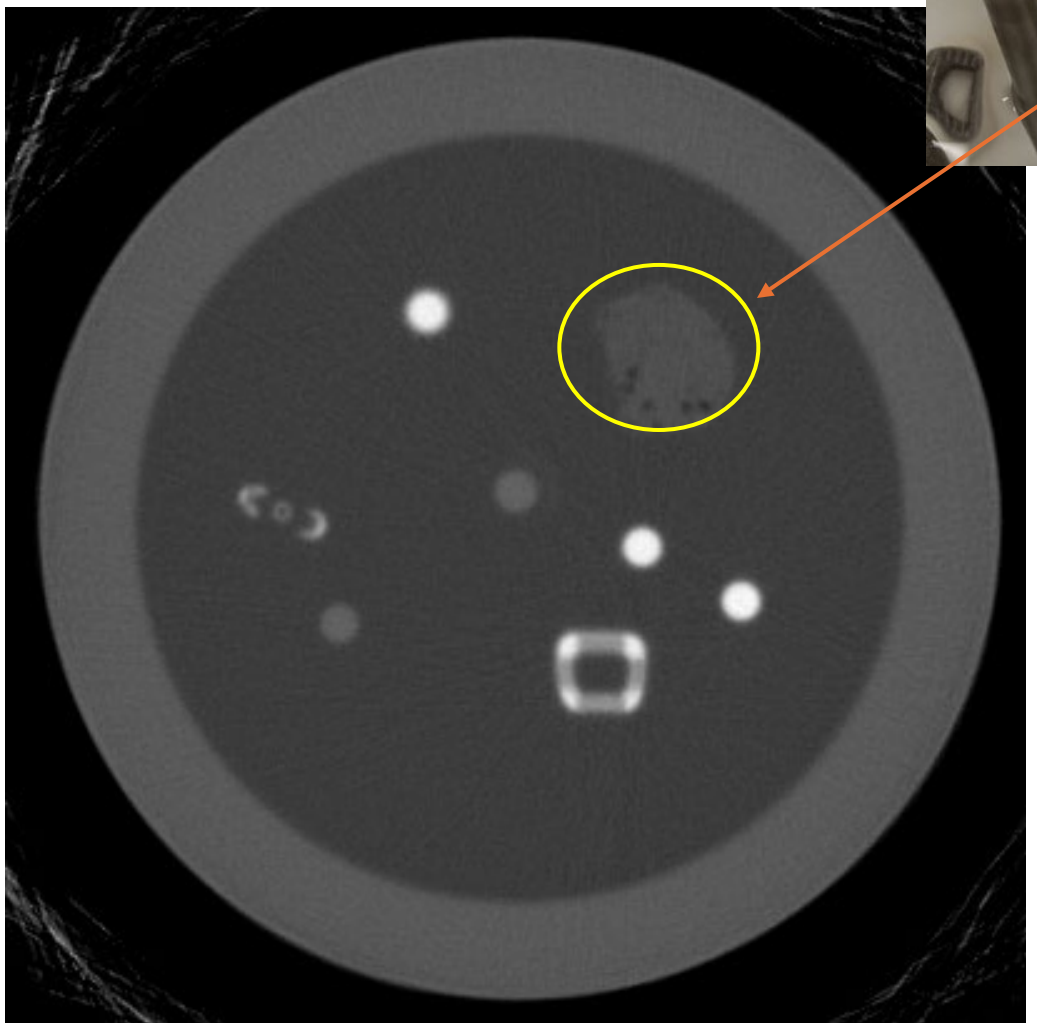


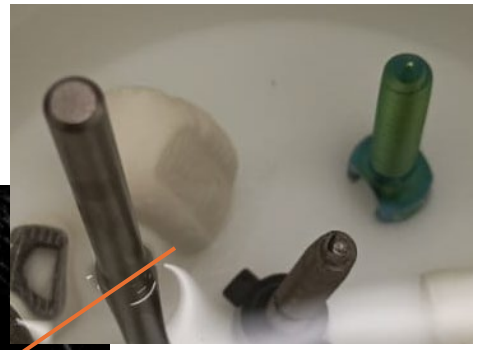


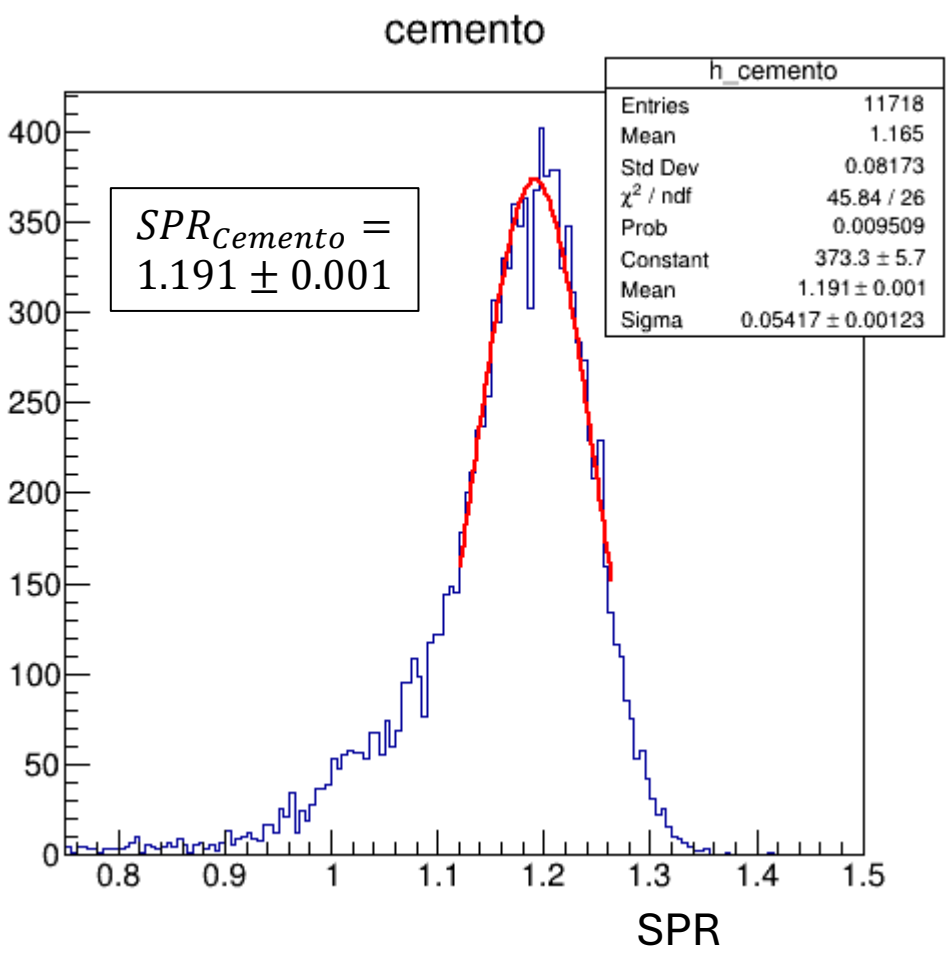
SPR profile along the jack;
affected by partial volume effects in the presence of holes

Axial slice 4/27

6- bone cement







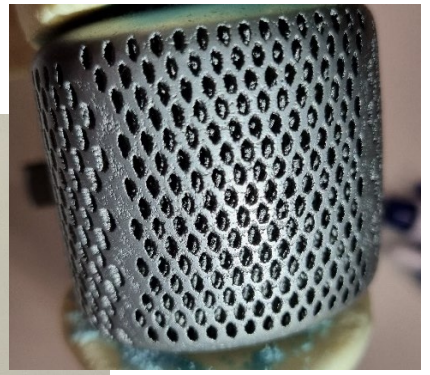
SPR in a ROI including bone cement

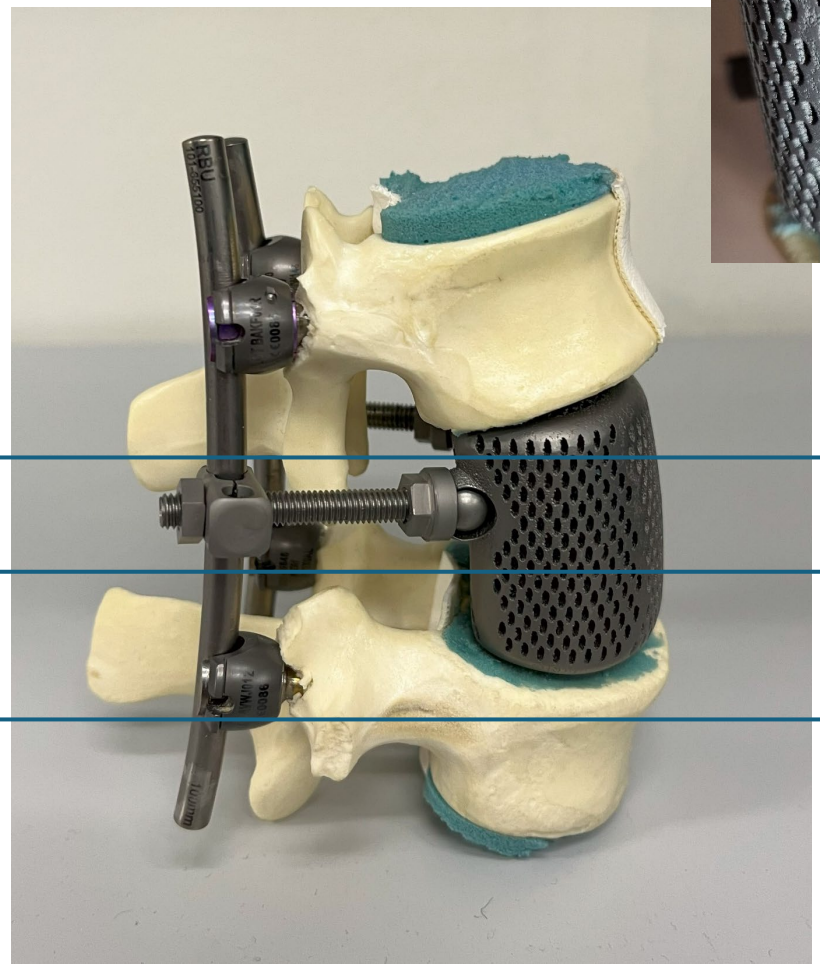
Distribution fitted with a gaussian for SPRs between 1.1 and 1.3 to avoid influence of the low-values tail.

pCT measurements of an intra-vertebral titanium (Ti6Al4V) implant system made of various components:
a meshed cage, spines…

$\sim 1.3 \times 10^9$ trigger

→$\sim 20 mGy$ dose



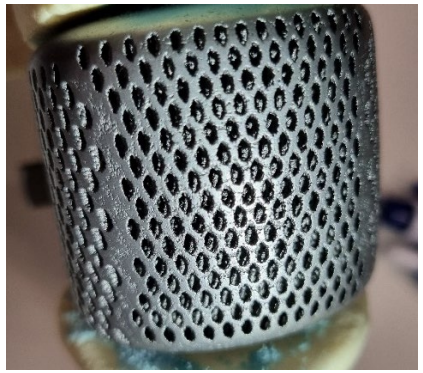


Field-of-view
$\sim 45\ mm$

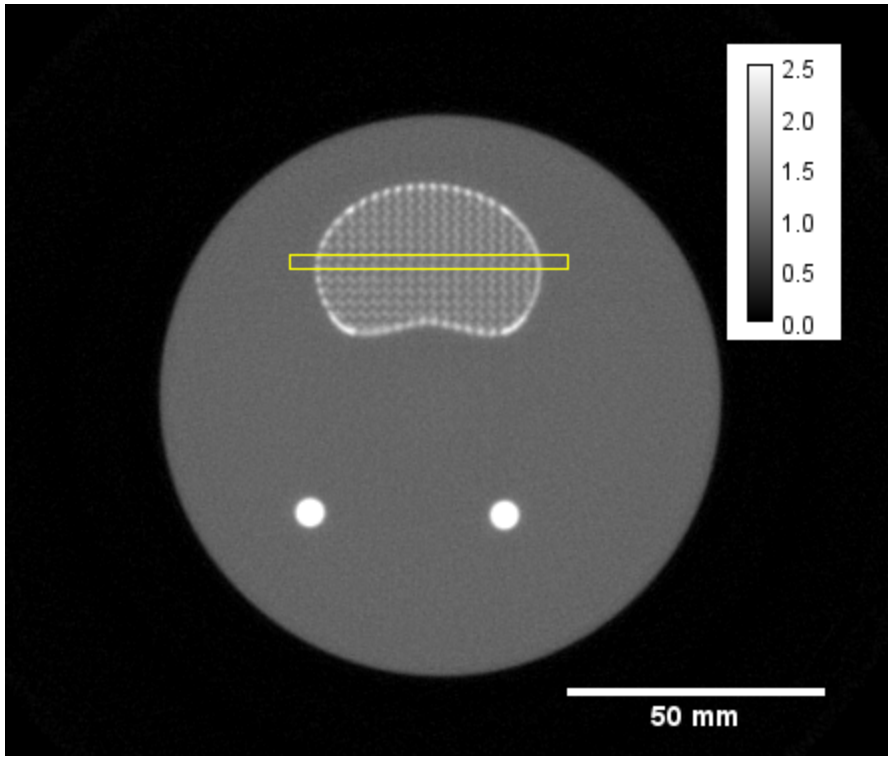
Next slide
Section

SPR in grid region

- Voxel size: 0.39x0.39x0.39 mm^3
- FDK-like modified for MLP
  - S. Rit et al., Med. Phys. 40 (3), March 2013
- No smoothing filter
- Diam 115 mm

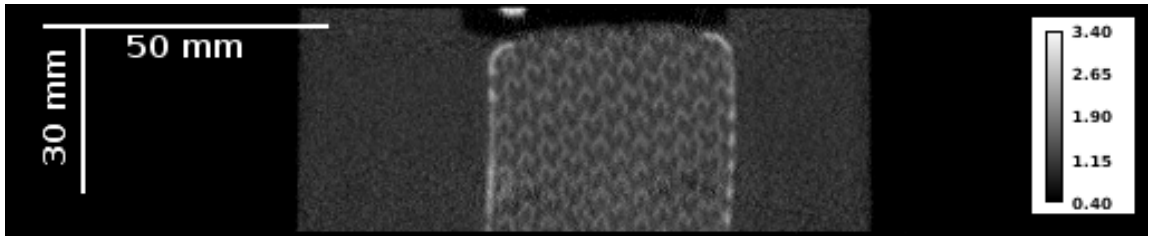


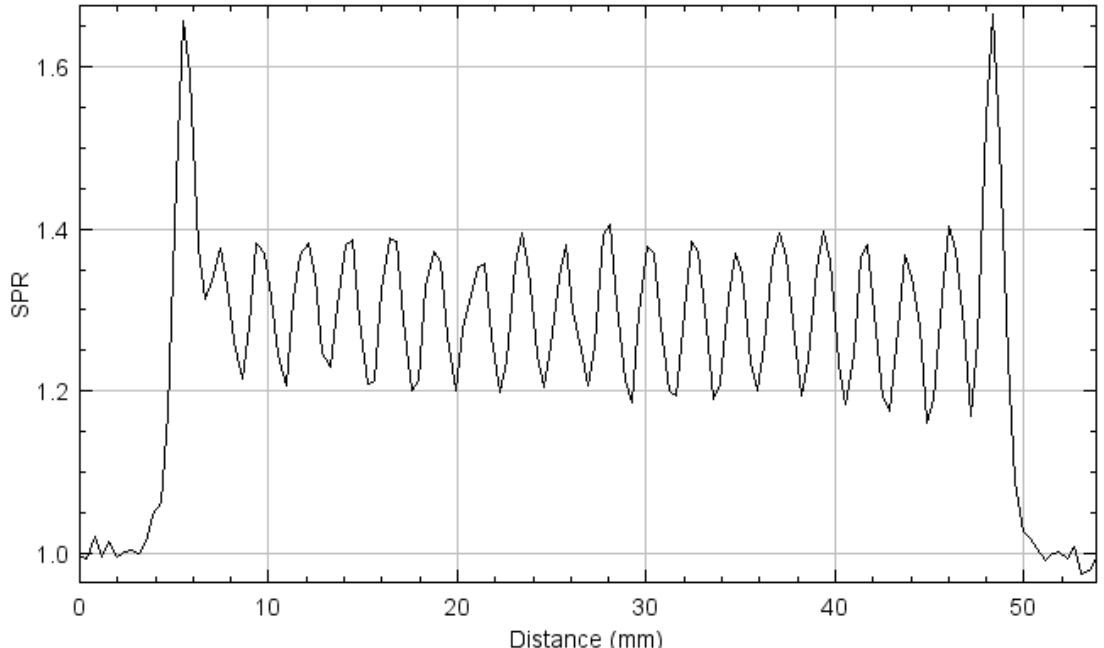
Pitch 2.2mm



- ❑ Internal structure of the grid clearly visible
- ❑ SPR distribution affected by partial volume effects

coronal section of 3D vertebral Ti





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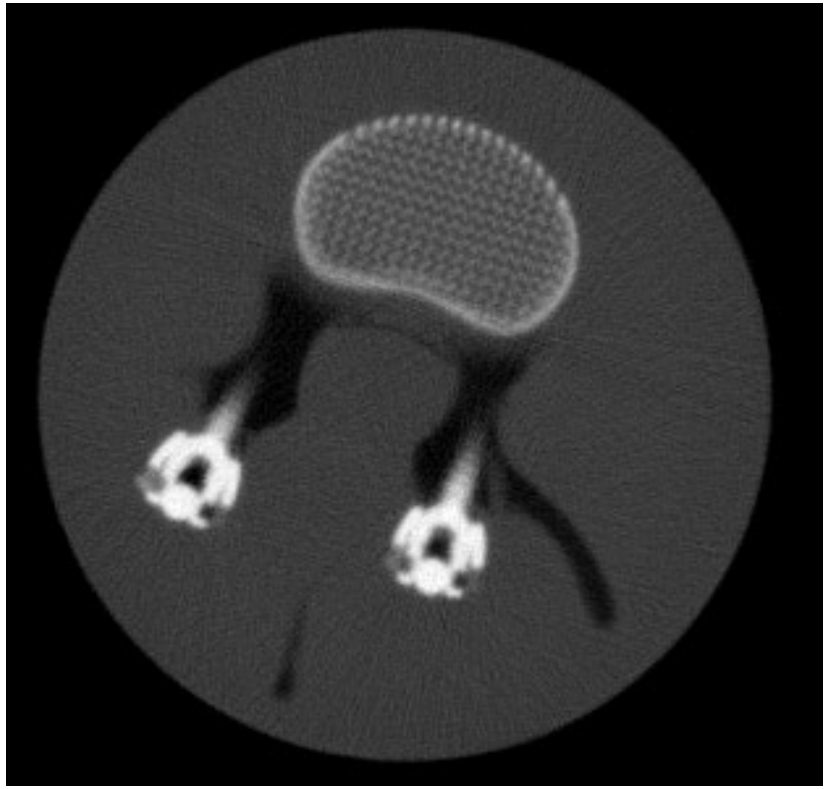
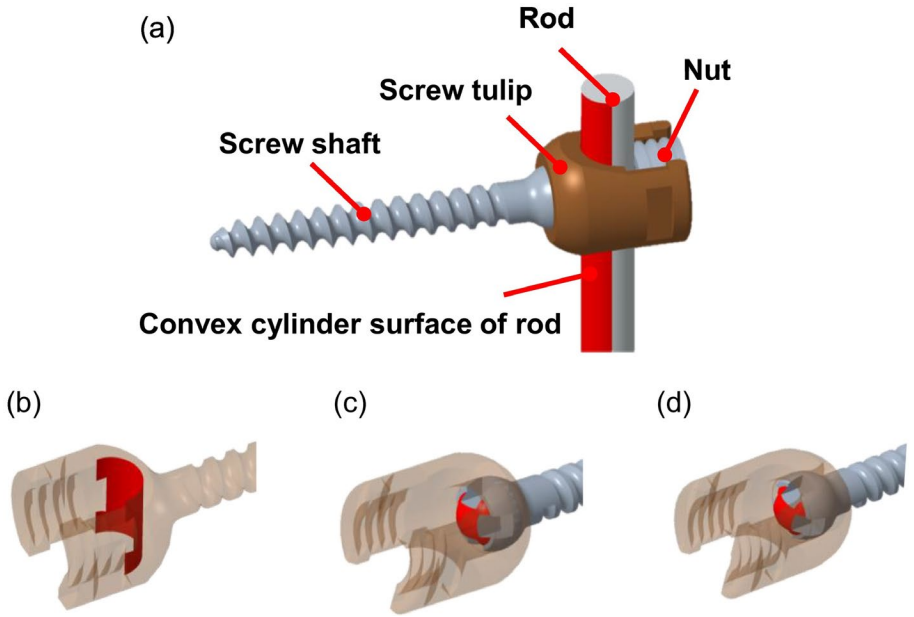
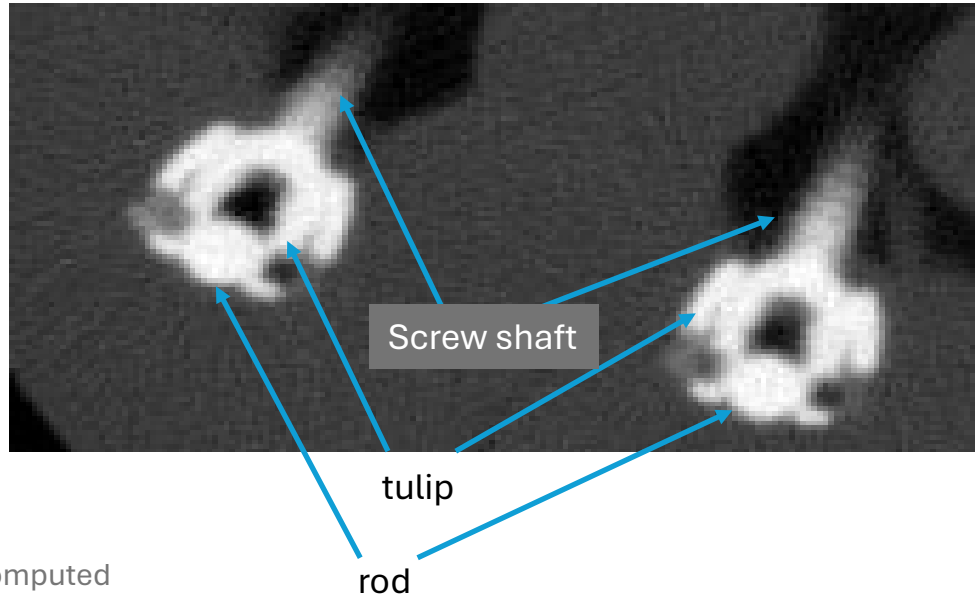
SPR in tulip-rods





https://doi.org/10.1016/j.clinbiomech.2019.06.003



Summary of SPR measurements - estimation for different materials

	pCT measurement	Estimation	notes
Demineralized water	0.997 ± 0.005	0.998	1
Titanium alloy (Ti6Al4V)	3.136 ± 0.016	3.17	2
Carbon fiber	1.399 ± 0.007	N.A.	3
Bone cement	1.191 ± 0.006	1.16	4

1) pCT measurements @ 21^oC; value expected for pure water scaled to corresponding density.
2) estimation done using Bragg's additivity rule for Ti6Al4V considering the NIST's stopping values of the three elements and the density of the alloy ($\rho_{Alloy}=4.43\ g/cm^3$)
3) SPR estimation of Carbon fiber material not available since exact composition unknown.
4) estimated value relative to pure PMMA, based on NIST database.

Conclusions

- pCT technique applied for the first time to directly determine SPRs of metallic implants
- Results are promising, both in terms of single elements and complex devices
- direct measurement of SPRs by pCT may be beneficial for metal artifact reduction in proton therapy.

Thank for your attention

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