



Up-grade on prostheses materials and devices SPR evaluation by proton computed tomography

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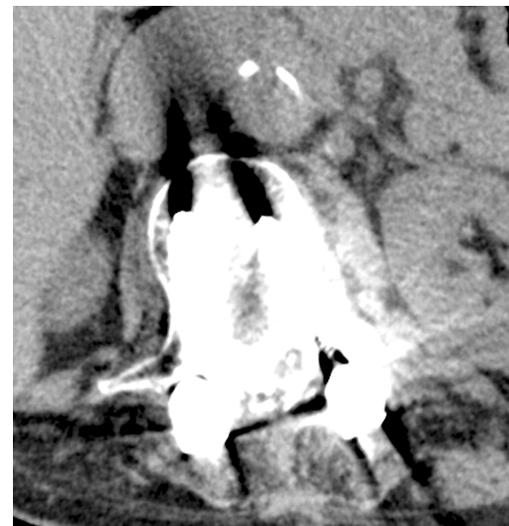
Motivation

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

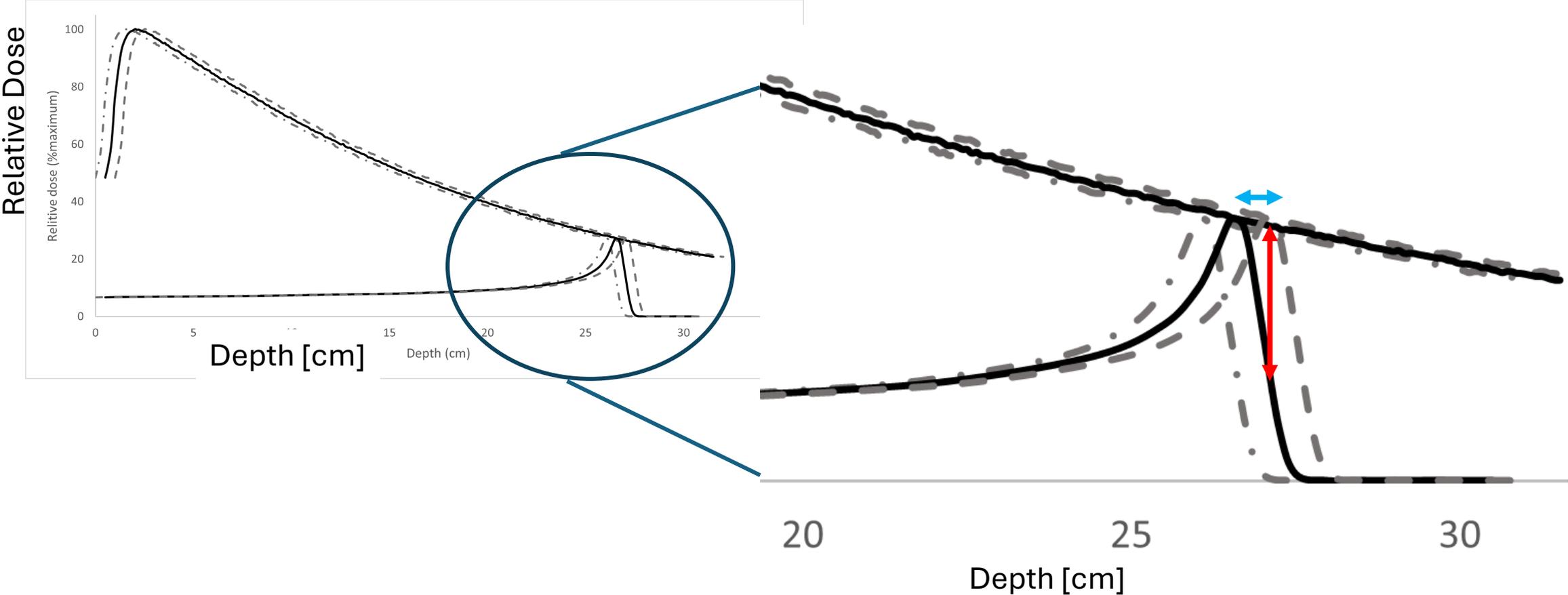
Katsura M. Published Online: March 12, 2018
<https://doi.org/10.1148/rq.2018170102>

[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

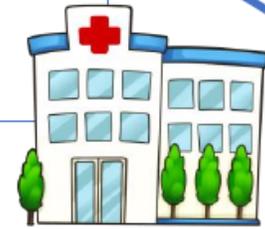


THE pRad PROJECT



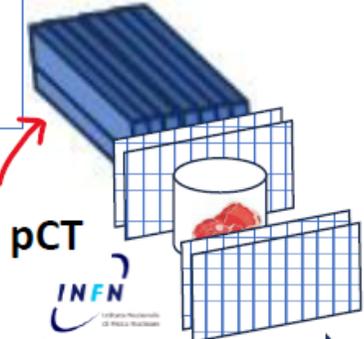
2024-2026

Reliability Test with four
Institutes/Hospital in Europe



p-Rad system in
treatment room

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



1

 **GOAL:**
Increased accuracy in TPS

3

CNAO

Munchen

Dresden

Maastro

Survey

pCT



2

SPR direct measurement
of metal implants

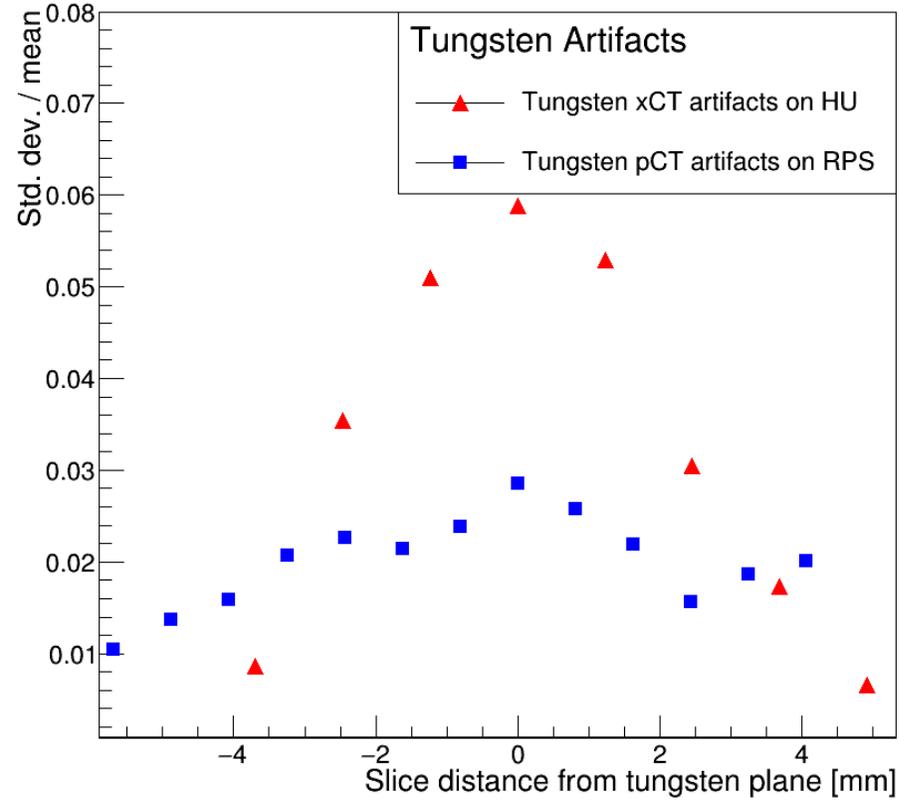
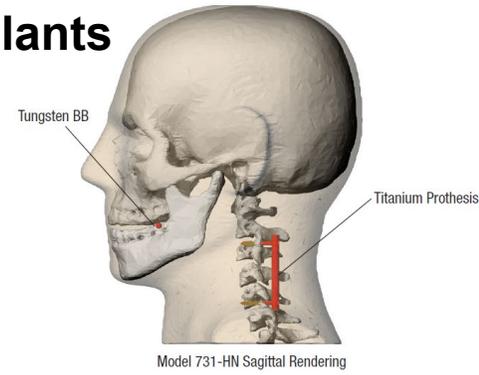


this talk

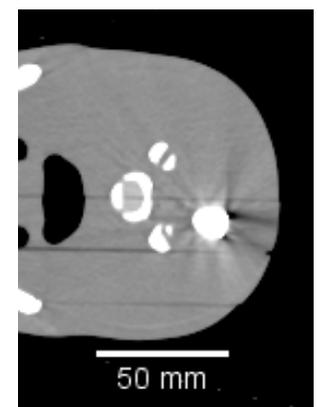
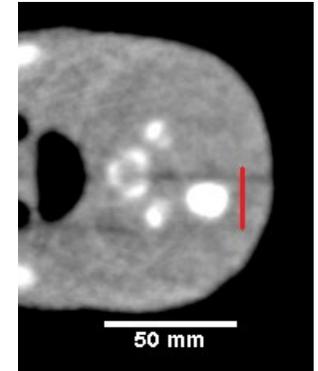
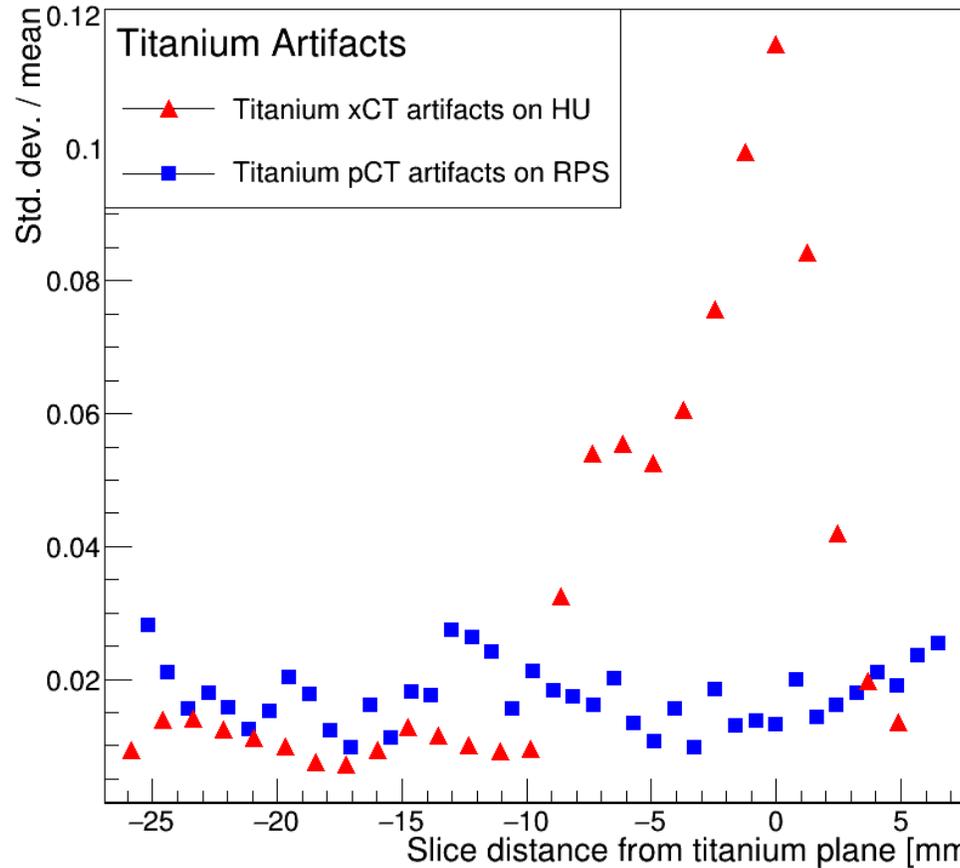
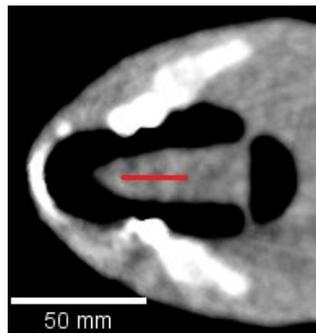
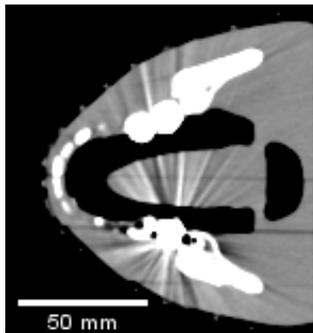


Early Studies with pCT on image artifacts with an anthropomorphic head phantom due to metal implants

Comparison of RSP and HU standard deviation , calculated within the ROIs close to metal prosthesys
 → **evidence of reduction with pCT**



calculated within the ROIs close to the tungsten dental filling

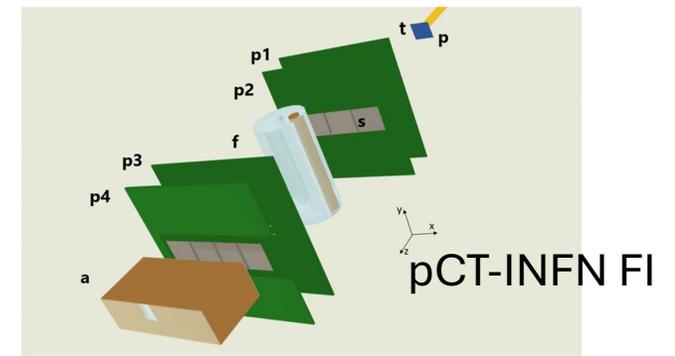
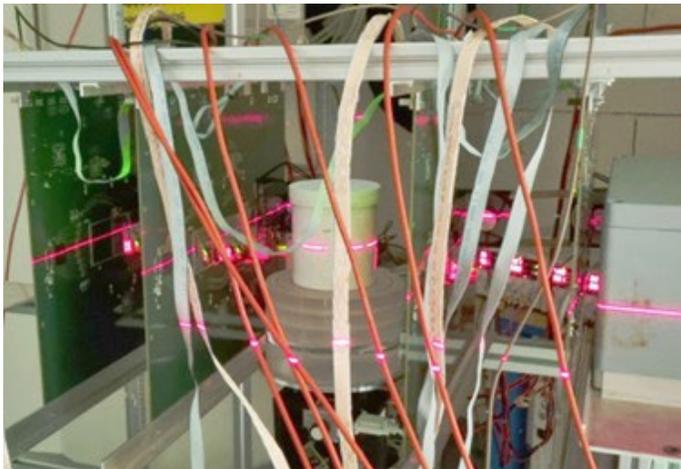


C. Civinini et al. Relative stopping power measurements and prosthesis artifacts reduction in proton CT, PHYSICS IN MEDICINE AND BIOLOGY 65 22 225012, 2020

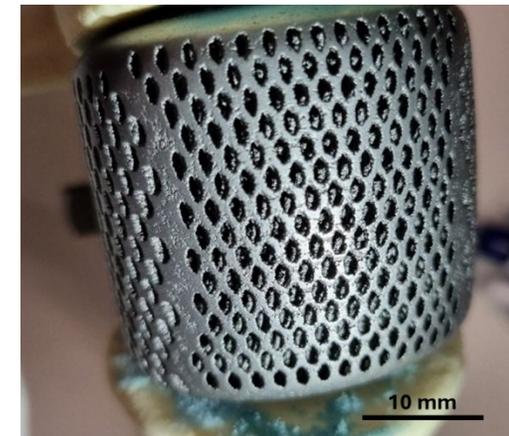
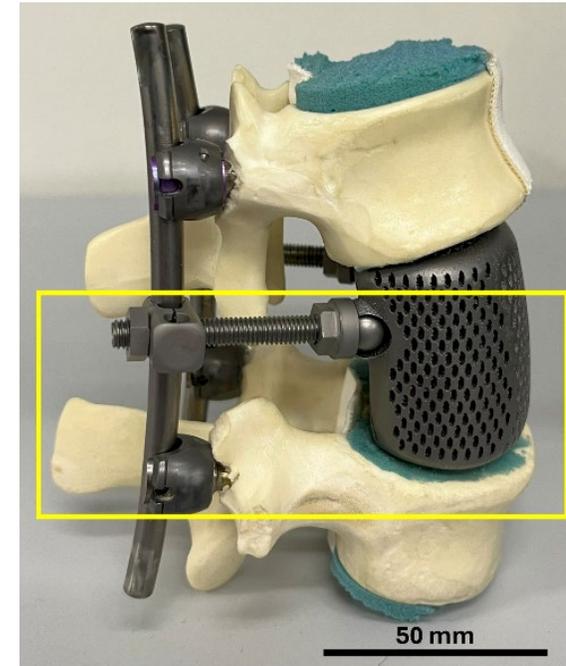
Implant Devices investigated by pCT technique

- 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.

Samples immersed into demineralized water within a plastic cylindrical container



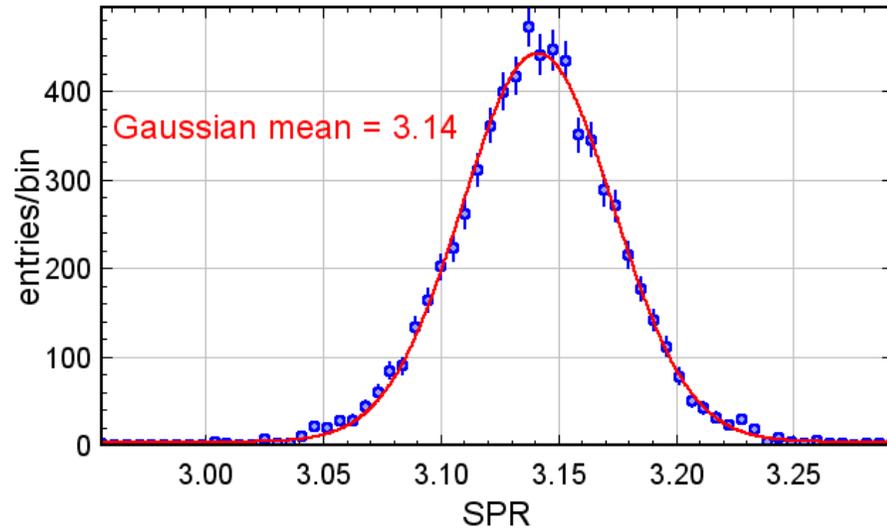
- p 211 MeV
- 1.3×10^9 trigger
- 18mGy



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.

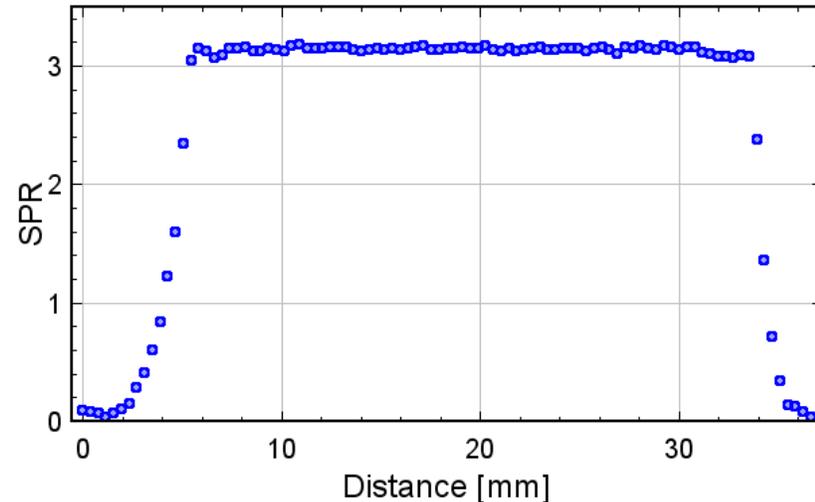
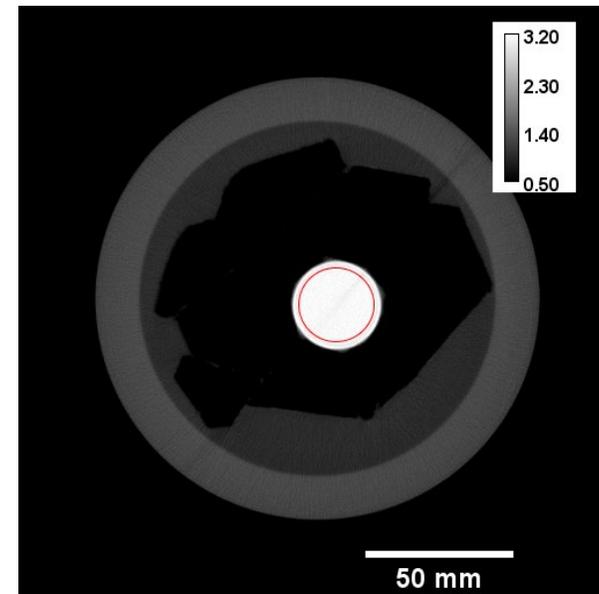


$$\text{SPR(pCT)} = 3.1365 \pm 0.02$$

SPR of the Ti6Al4V independently determined with an MLIC Giraffe in a 180 MeV proton beam :

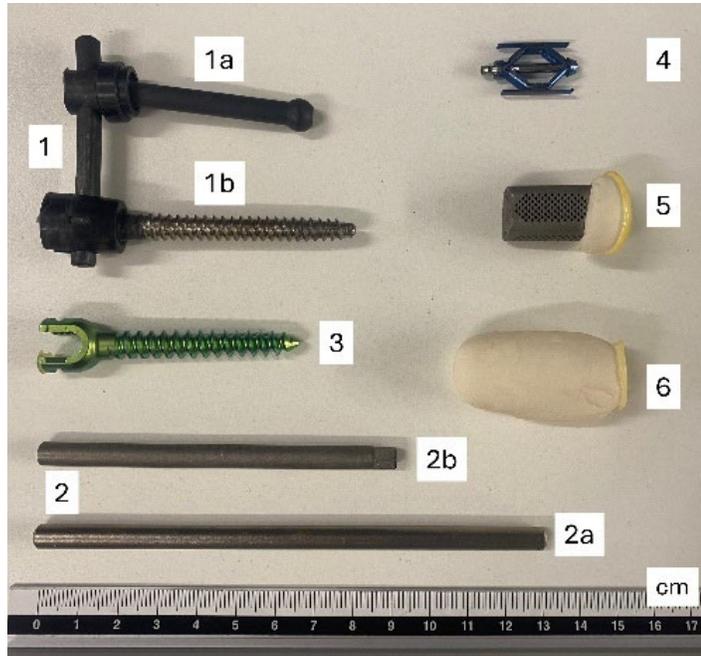
$$\text{SPR (MLIC)} = 3.17 \pm 0.02.$$

Dose 13mGy

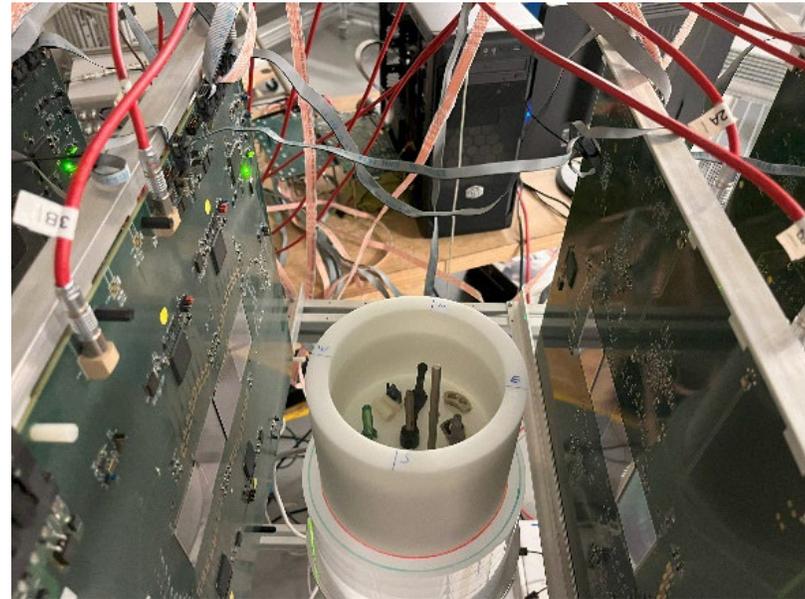


SPR profile measured along the diameter of the Titanium alloy sample phantom.

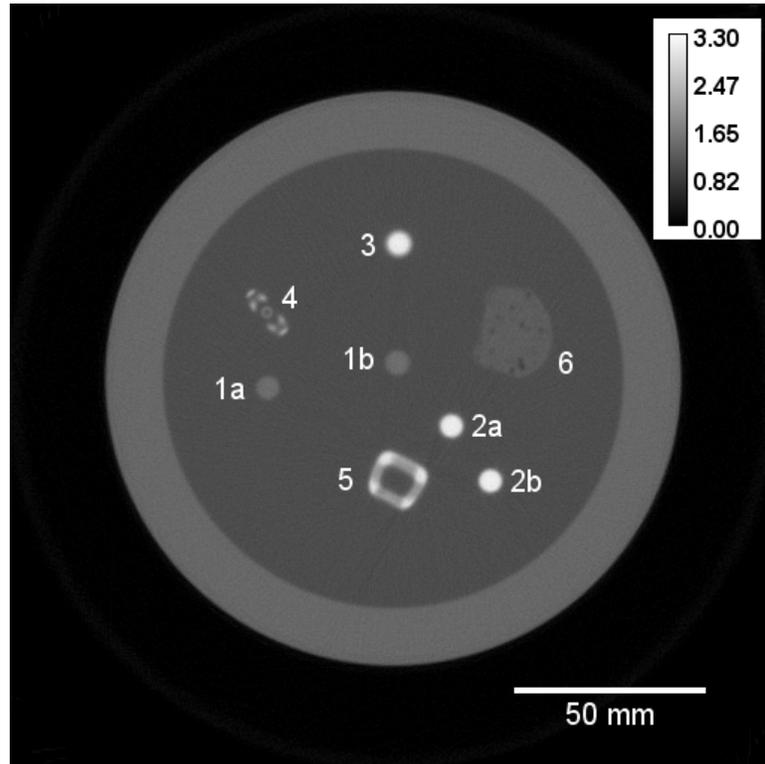
Set of implant devices inspected by pCT



#	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



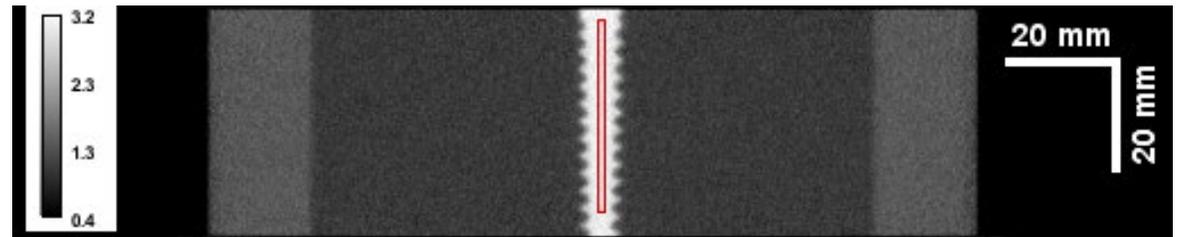
Dose 20mGy

#	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

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

Reconstruction:

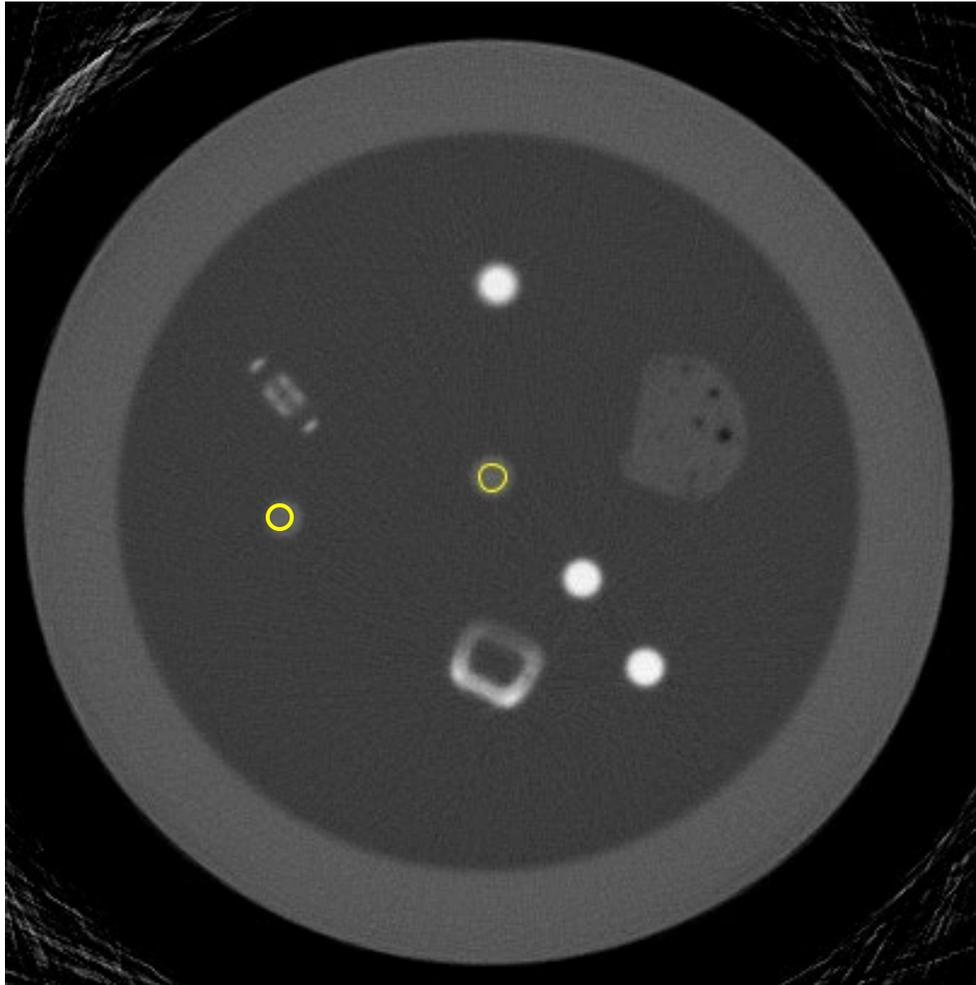
- FDK-like modified for MLP
- S. Rit et al., Med. Phys. 40 (3), March 2013
- No filter



Coronal view of the self-tapping screw #3, showing the 3 mm pitch screw threads. Red ROI used to determine SPR. Reconstruction pixel size is **390µm x 390µm x 390µm**.



1-Carbon bar and screw



The SPR

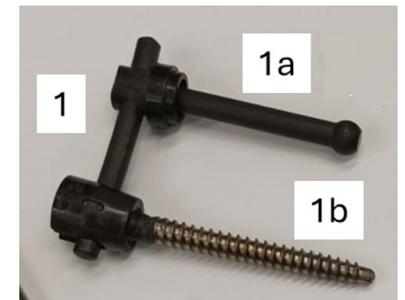
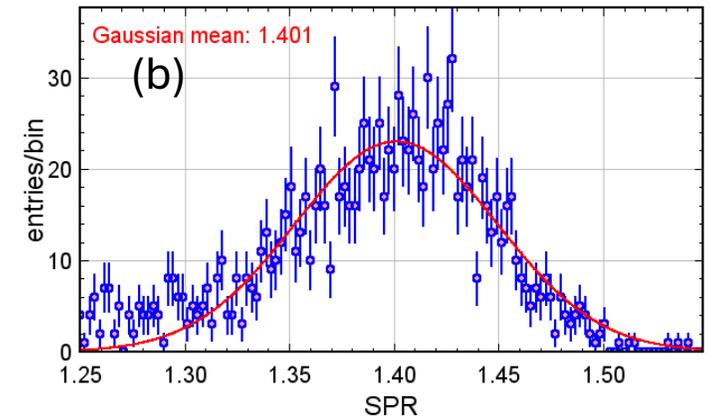
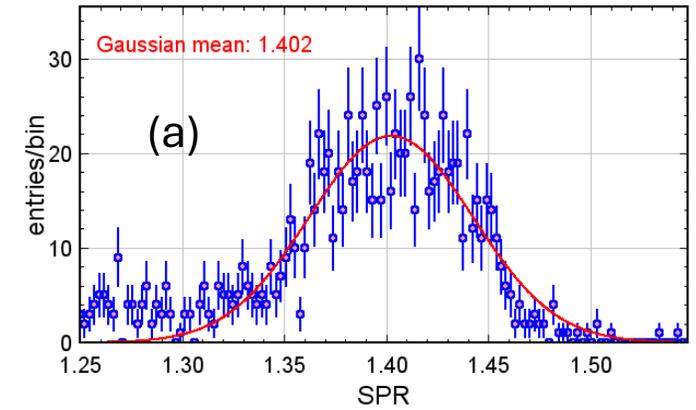
#1a 1.402 ± 0.009

#1b 1.401 ± 0.009

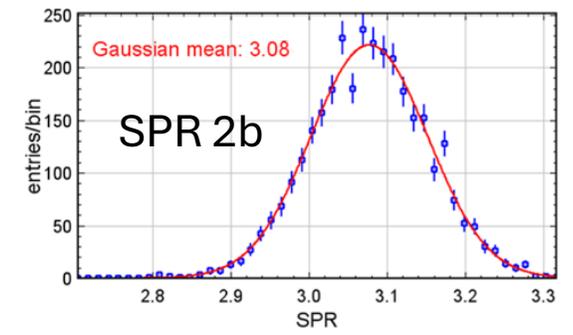
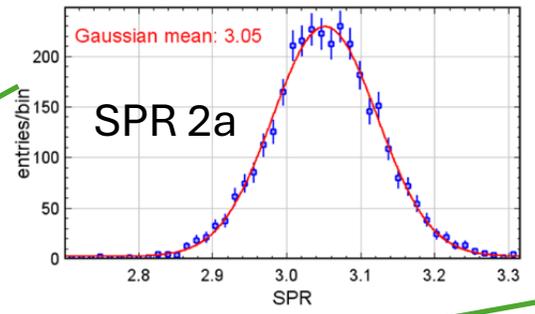
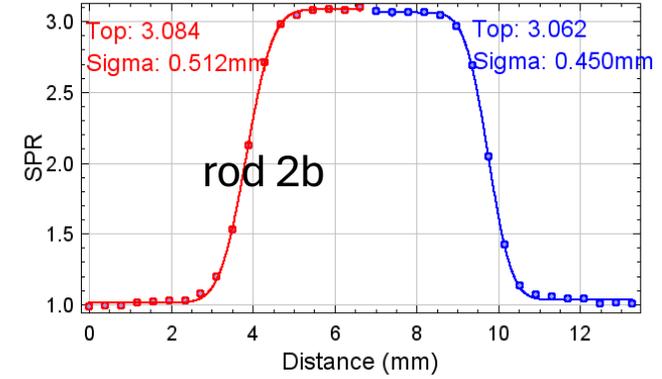
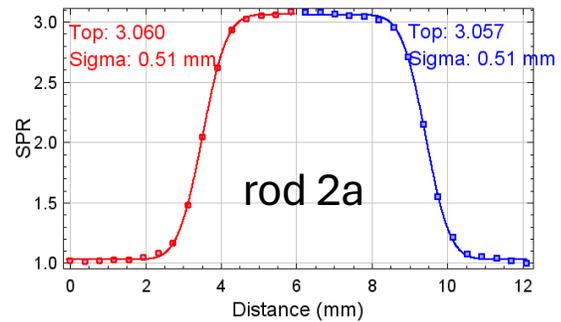
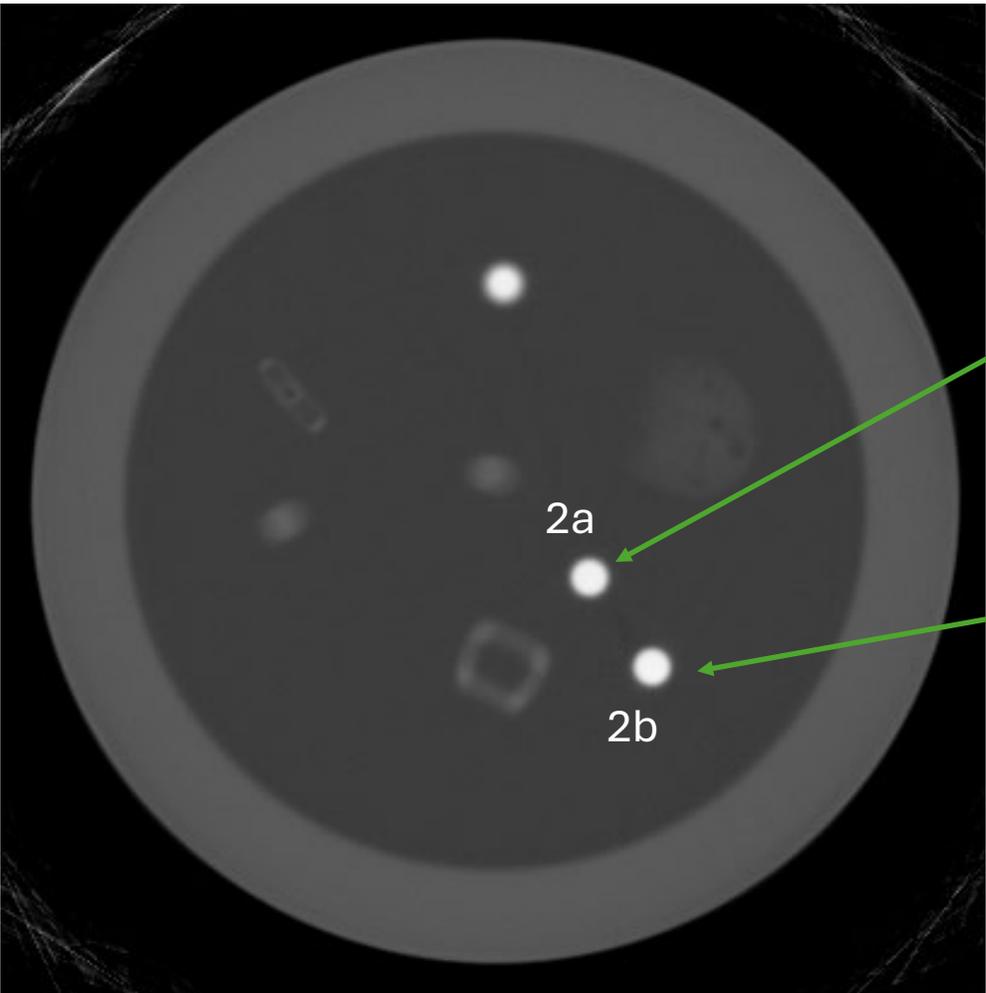
1b : Ti shield

1a: no Ti shield

No difference in SPR
due to Ti shield



2-Titanium alloy bars

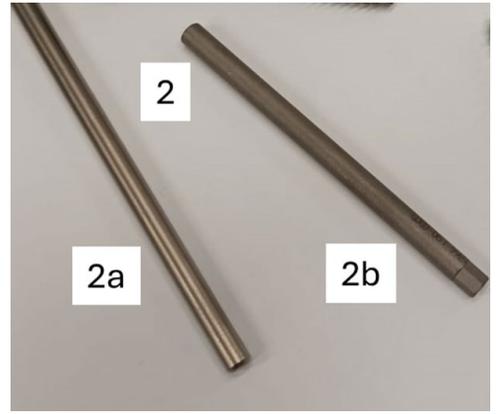


(mean of histogram)

$$SPR_{2a} = 3.05 \pm 0.02$$

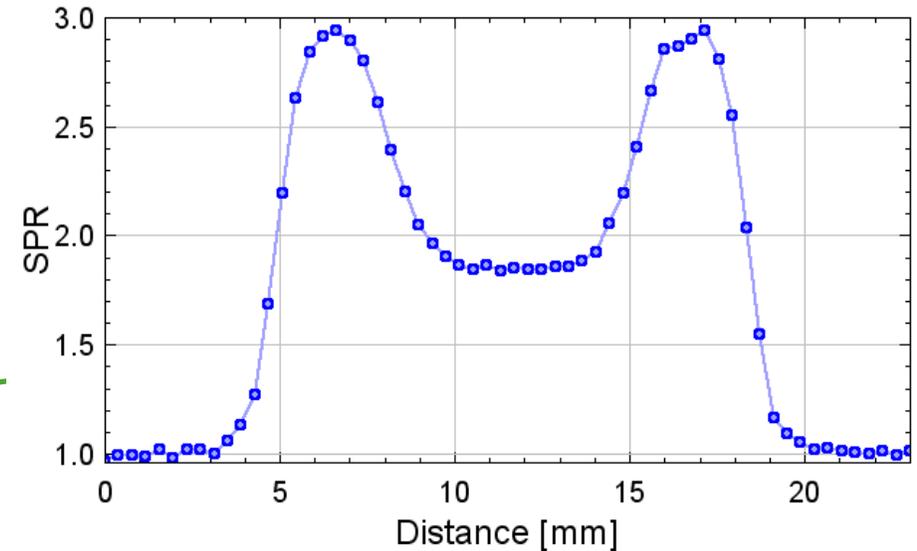
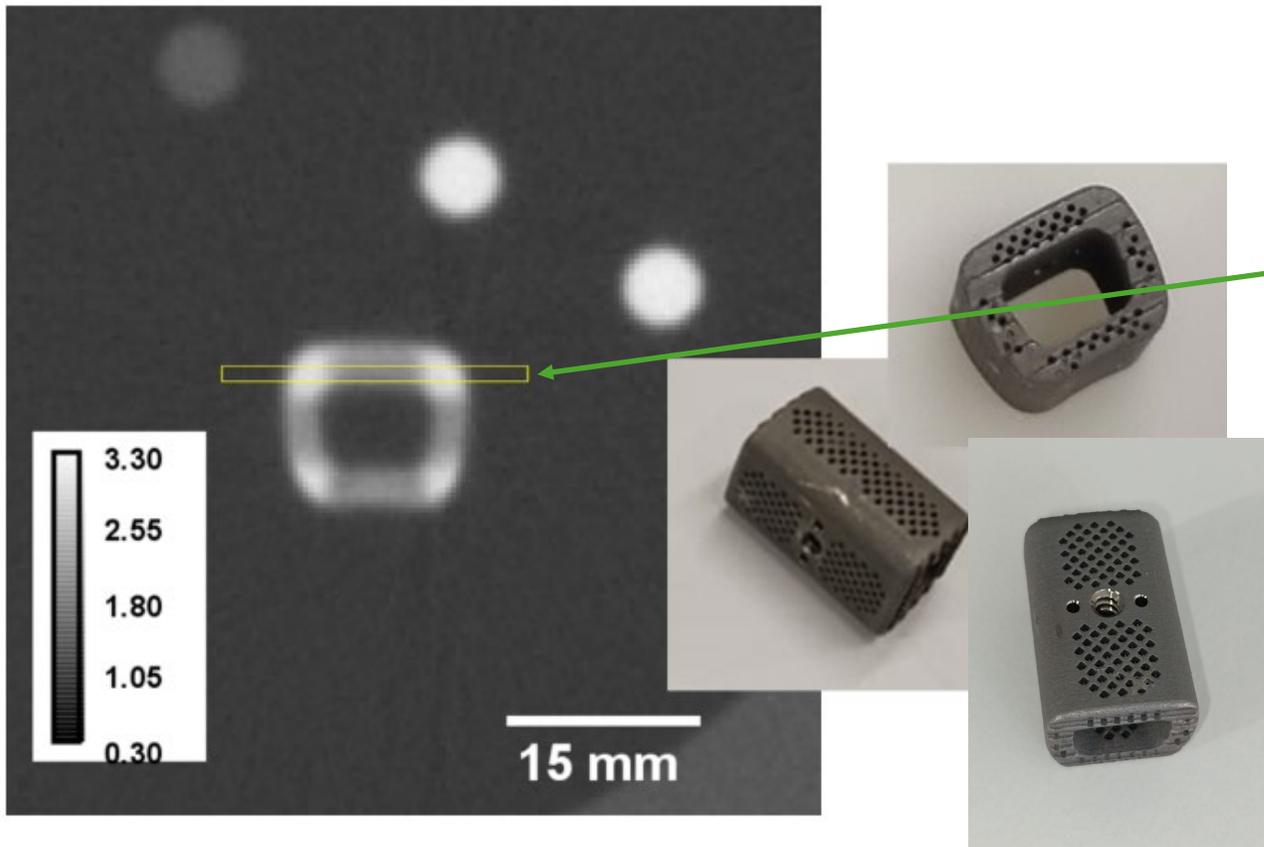
$$SPR_2 = 3.08 \pm 0.02$$

Different materials?



Axial slice mean from 3 to 25

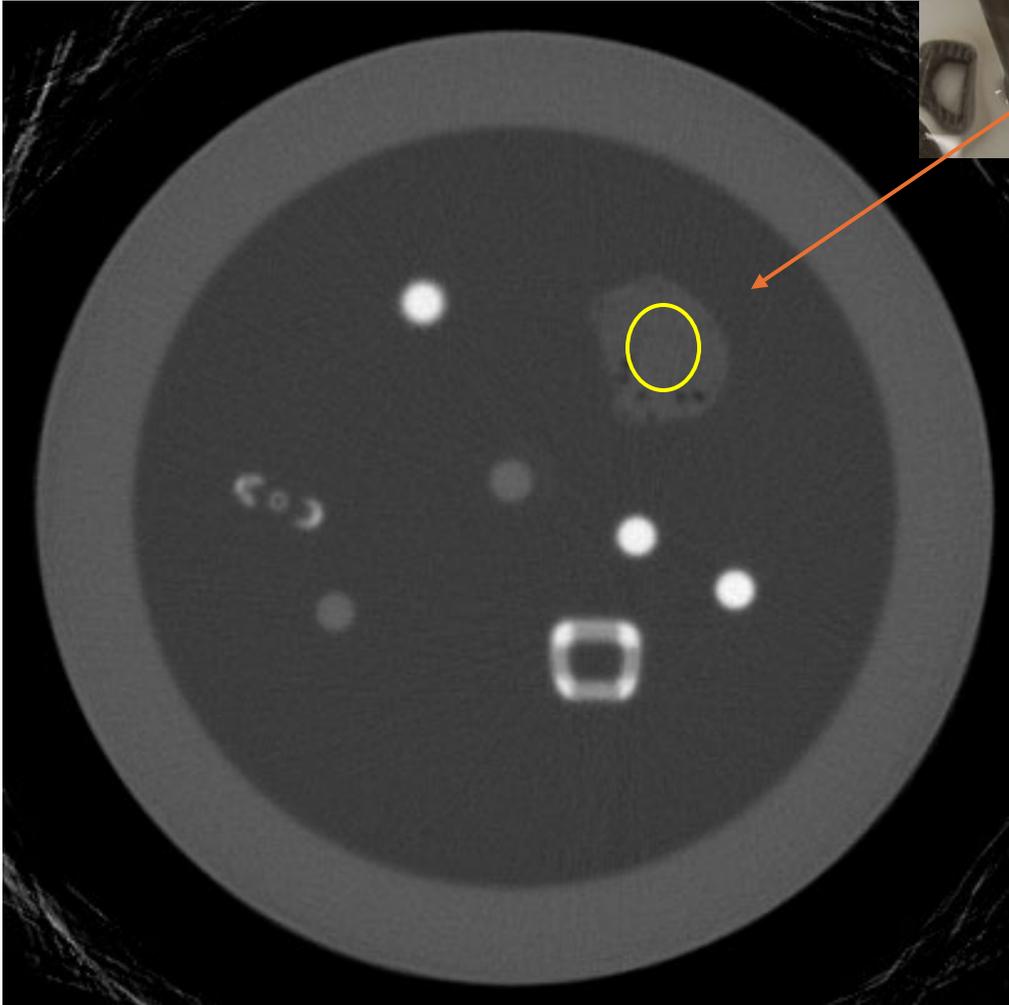
5-Titanium cage – axial slice



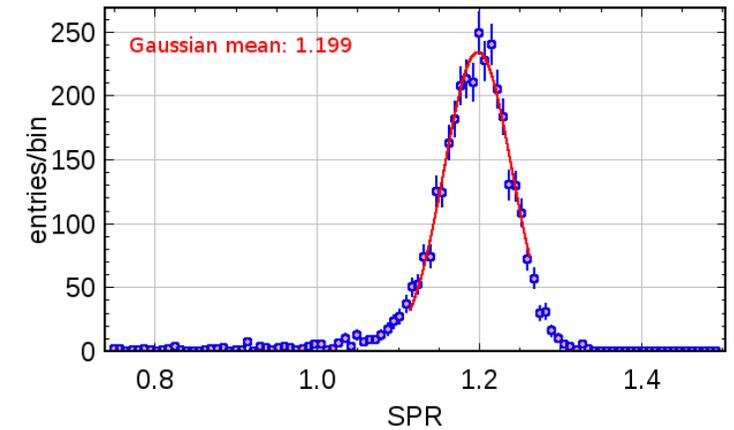
SPR profile along the ROI shown in yellow

significant partial volume effect in drilled regions. Effective SPR value ≈ 1.8 due to contributions of Ti and water in holes.

6- bone cement



SPR distribution for ROI2
fitted in 1.1 - 1.3.

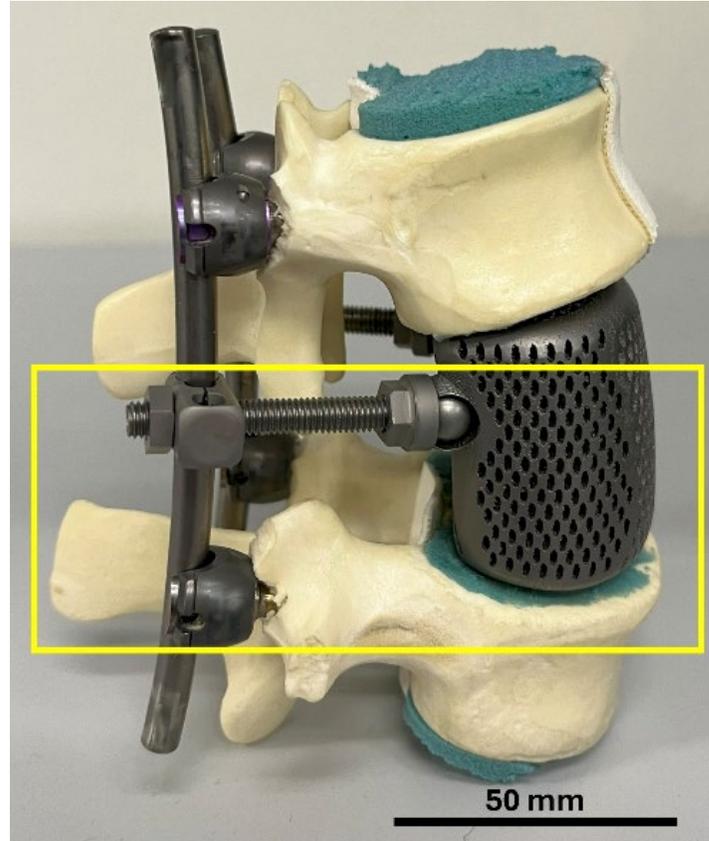


Influence of air inclusion and the irregular shape of the cement sample studied with 3 ROIs with different (x,y,z) voxels:

- ROI1 20x30x18
- ROI2 10x20x15 Average SPR 1.198 ± 0.003 .
- ROI3 6x16x15 core of cement
- Total error of the measurement: 0.009.

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
 $\rightarrow 18mGy$ dose



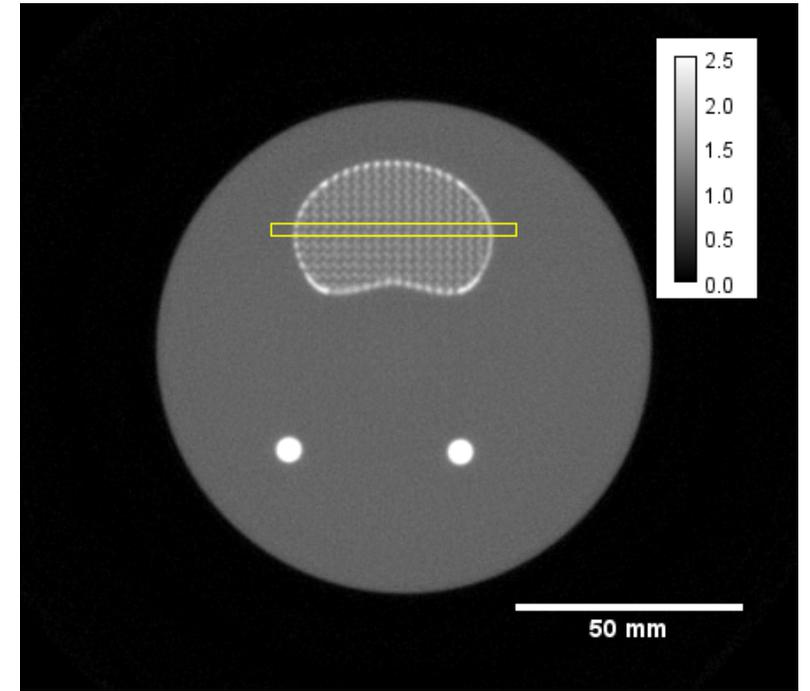
Next slide
Section

SPR in grid region

- Voxel size: $0.39 \times 0.39 \times 0.39 \text{ mm}^3$
- FDK-like modified for MLP
 - S. Rit et al., Med. Phys. 40 (3), March 2013
- No smoothing filter
- Diam 115 mm

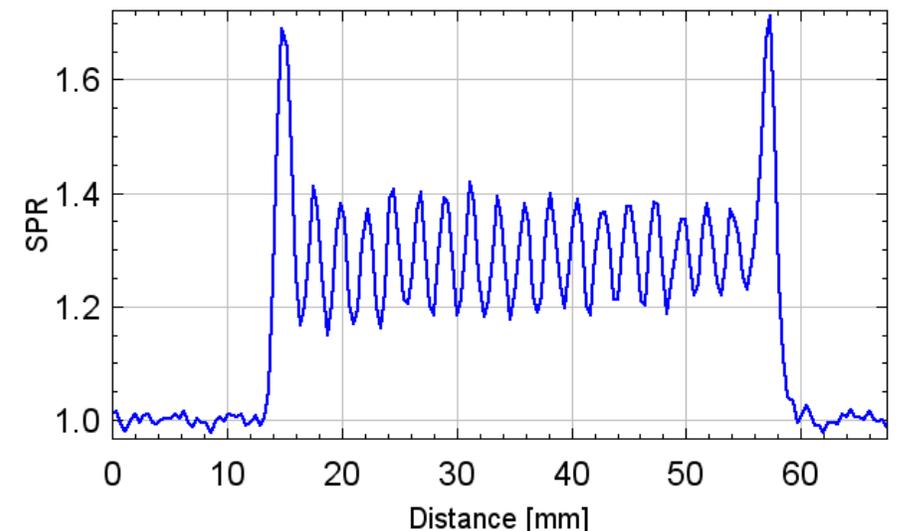
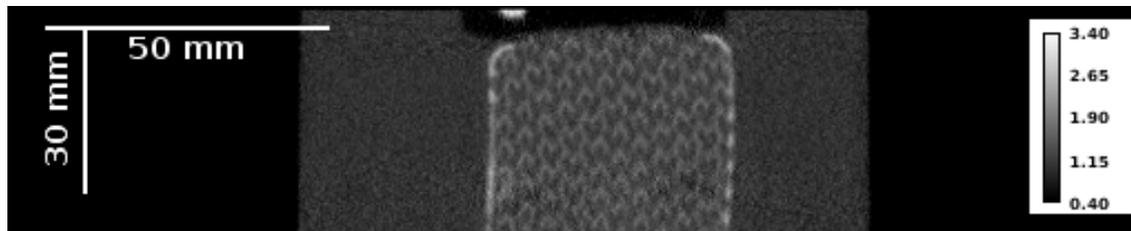


Pitch 2.2mm

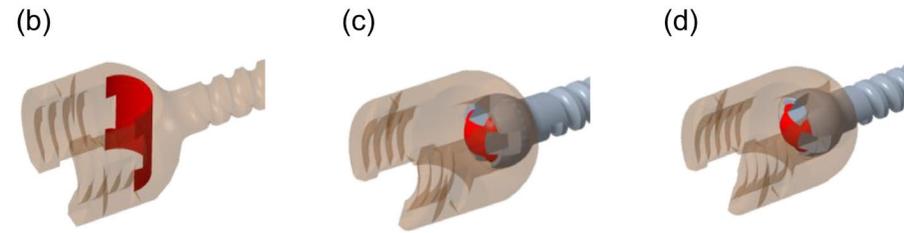
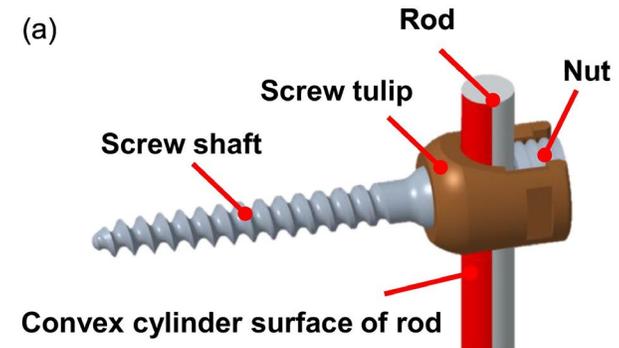
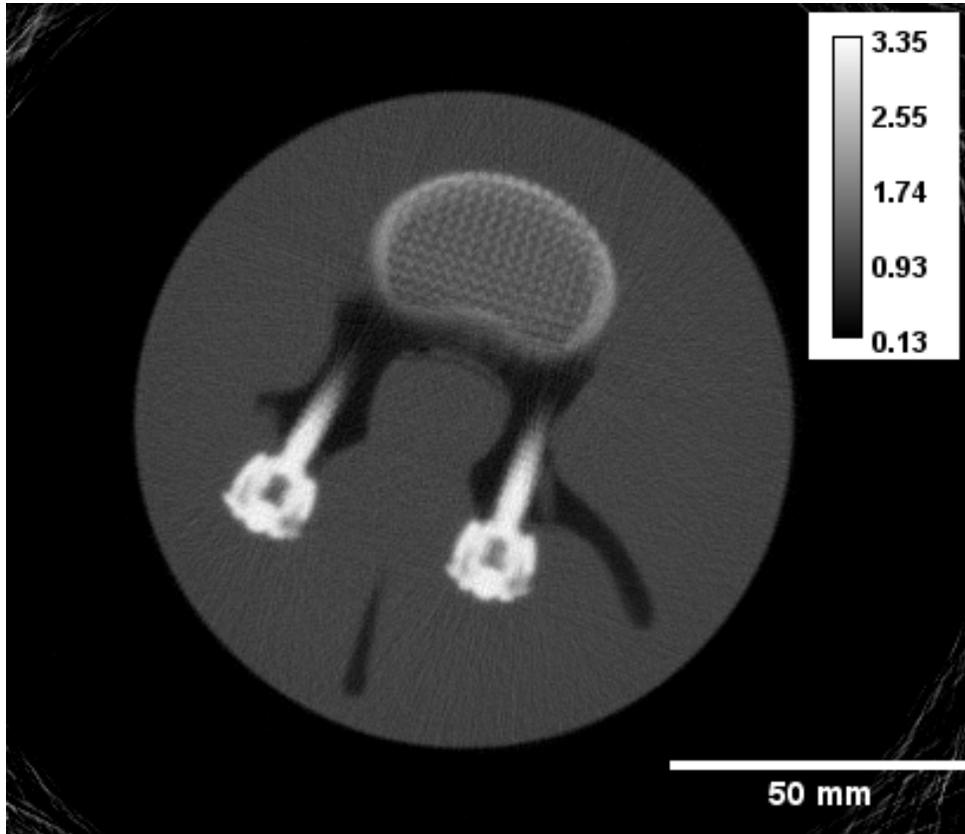


- Internal structure of the grid clearly visible
- SPR distribution affected by partial volume effects

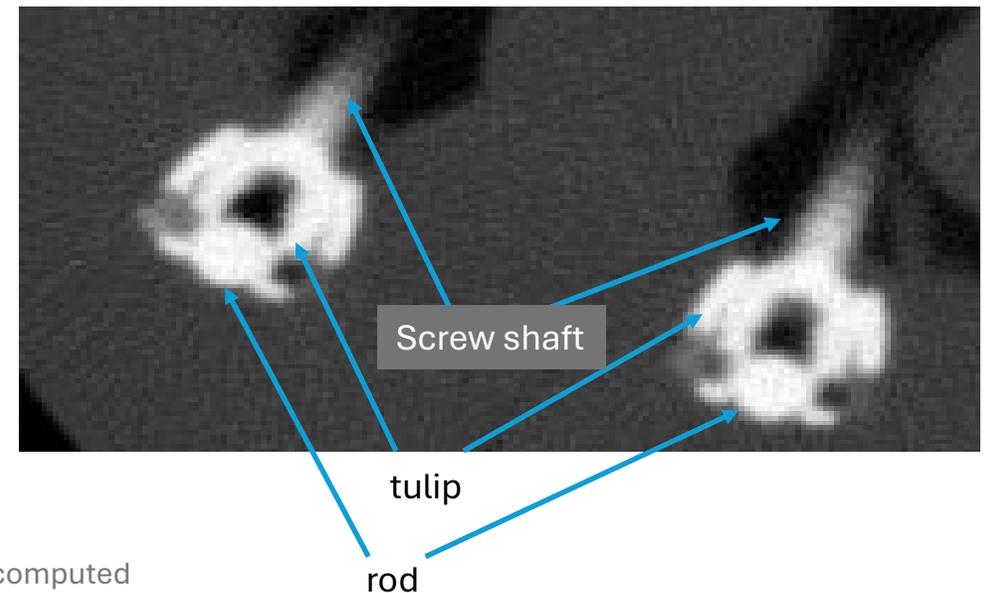
coronal section of 3D vertebral Ti



SPR in tulip-rods



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



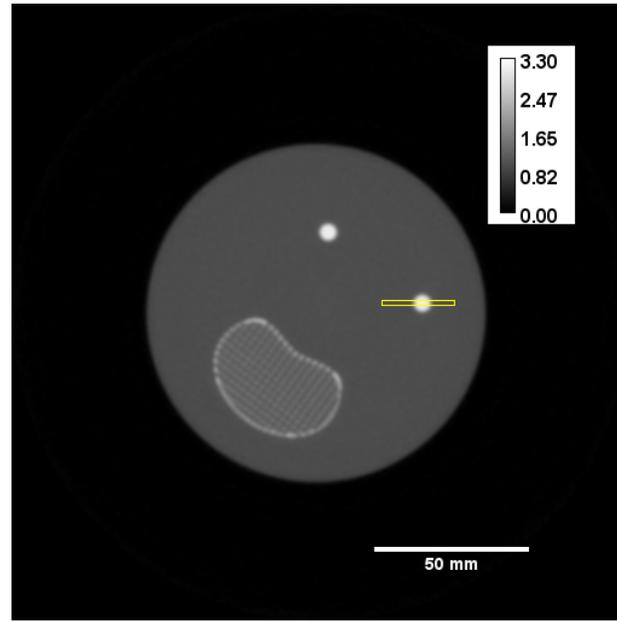
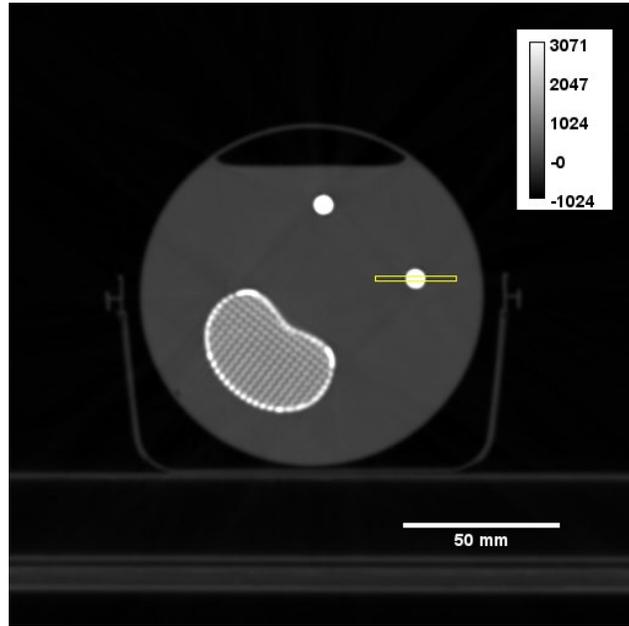
Summary of SPR measurements - estimation for different materials

	pCT measurement
Demineralized water	$0.997 \pm 0.007^*$
Titanium alloy (Ti6Al4V)	$3.14 \pm 0.02^{**}$
Rod (#2a)	3.05 ± 0.02
Rod (#2b)	3.08 ± 0.02
Screw (#3)	3.04 ± 0.02
Carbon rod (#1a)	1.402 ± 0.009
Carbon screw (#1b)	1.401 ± 0.009
Bone Cement (PMMA + Ba)	1.198 ± 0.009

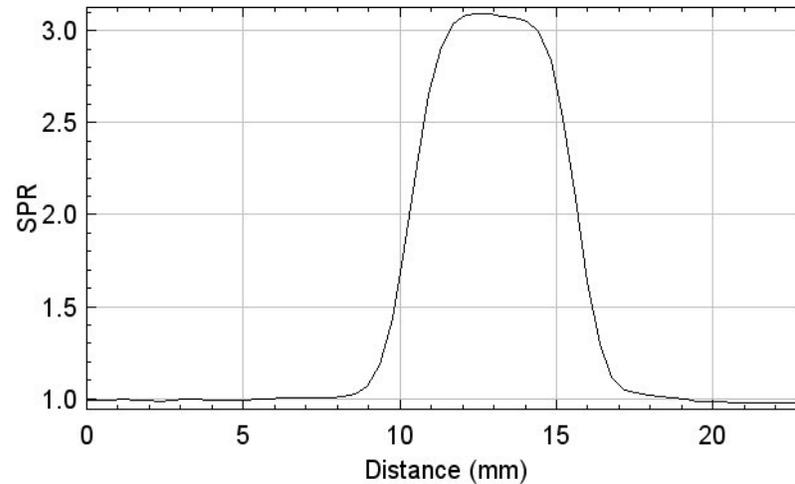
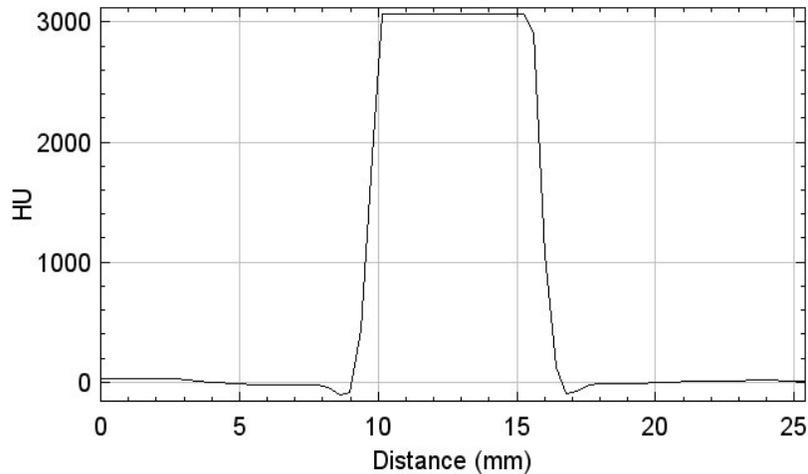
* Compares well with the expected demineralized water SPR at 21°C: 0.998.

**Titanium alloy (Ti6Al4V) SPR compares well with what measured by MLIC: 3.17 ± 0.02 .

Comparison xCT vs pCT : SPR evaluation



- 12-bit big bore **Brilliance CT scanner** (Philips Medical Systems, Cleveland, OH, USA) with an **O-MAR (Metal Artifact Reduction for Orthopedic Implants) filter**
- **same voxel dimensions** as in pCT.
- pCT image reconstructed with **Hann filter**, cut-off frequency 0.65 times Nyquist frequency.
- similar spatial resolution
- better contrast for xCT, as expected.
- Ti-bar profile in xCT saturated at 3071HU,
- SPR by pCT 3.07 ± 0.02 compatible with #2a,b #3

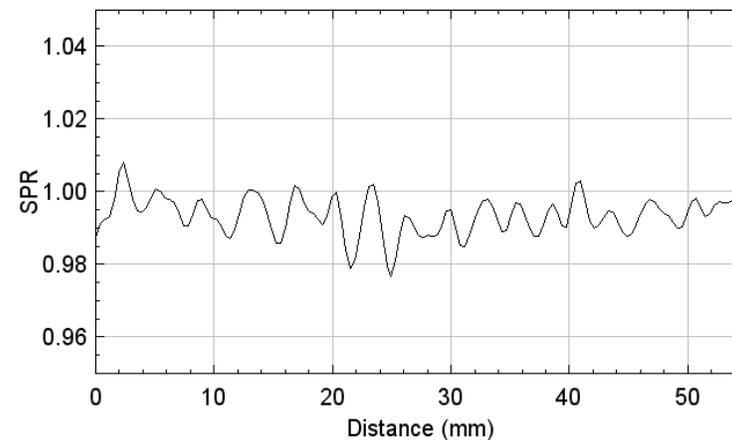
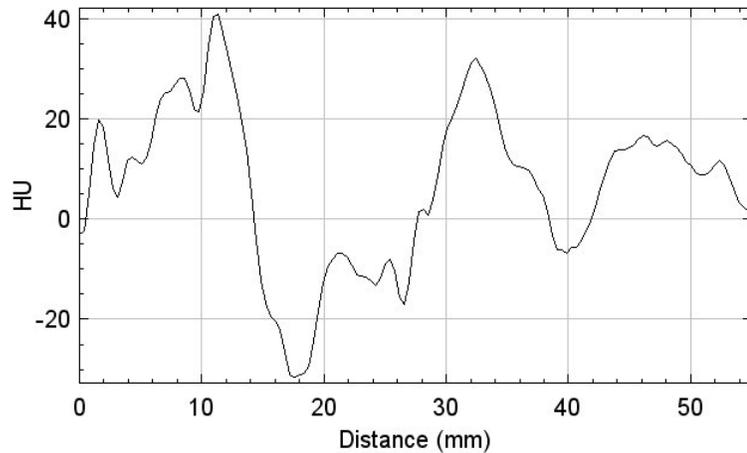
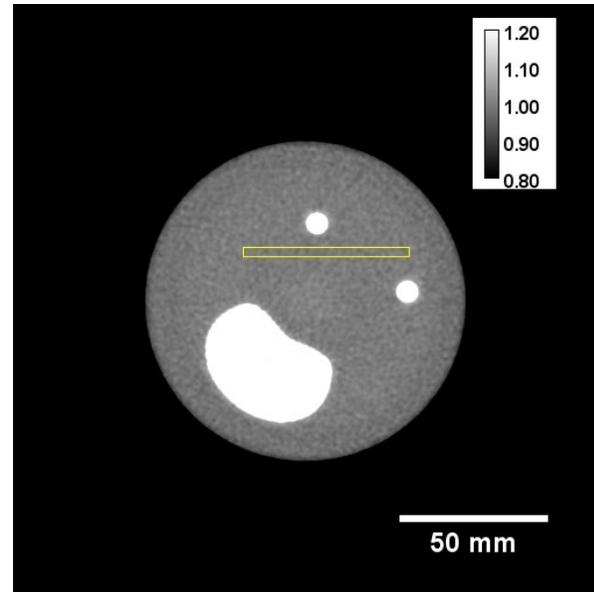
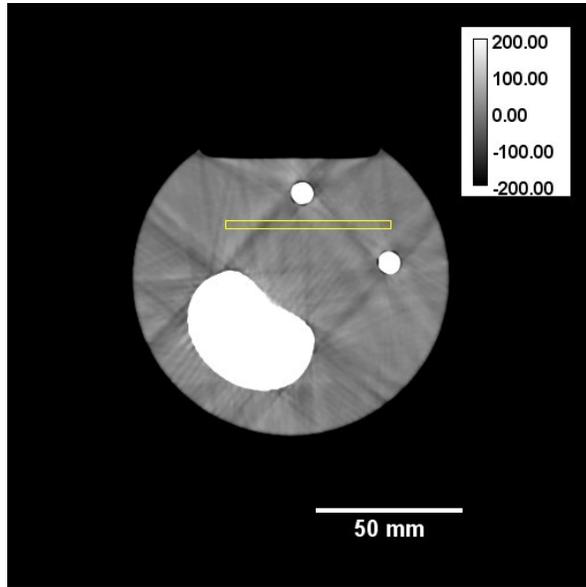


forthcoming work: comparison with a 16-bit xCT scanner

Comparison xCT vs pCT: Artifacts

xCT/pCT images in HU/SPR water values scale range $\pm 20\%$.

ROI 55mm long and 3mm wide (in yellow) in same position within the water region, to analyse the presence of artifacts.



artifacts in images and fluctuations in profiles of metal objects made with conventional x-CT can be significantly reduced when using pCT.

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.
- pCT avoid saturation observed with 12-bit xCT scanner.
- Forthcoming: compare with 16-bit xCT scanner.



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Mara Bruzzi, Up-grade on prostheses materials and devices SPR evaluation by proton computed tomography, Ion Imaging Workshop, Oct.20-21, 2025