Development and usage of 3D-phantom for AI-based dose verification in radiotherapy

Rossana Lanzillotta

Goal:

Create new 3D printed phantoms to

1) train AI models
2) to develop ALERT system

Outline

01

Phantom design

02

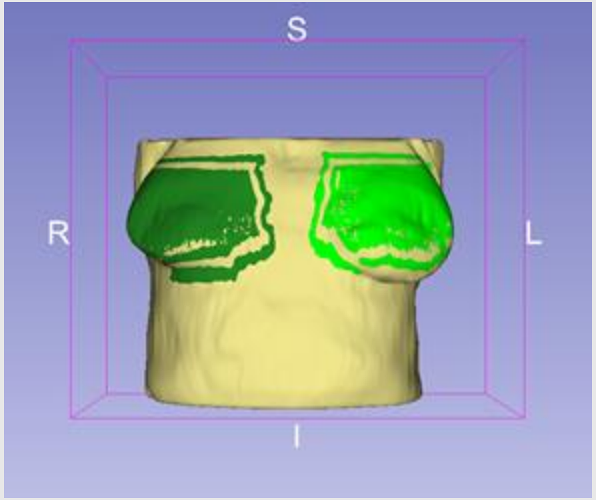
Material selection

03

3D printing

Phantom design

Inventor Autodesk



3D Slicer

Select suitable tissue equivalent material

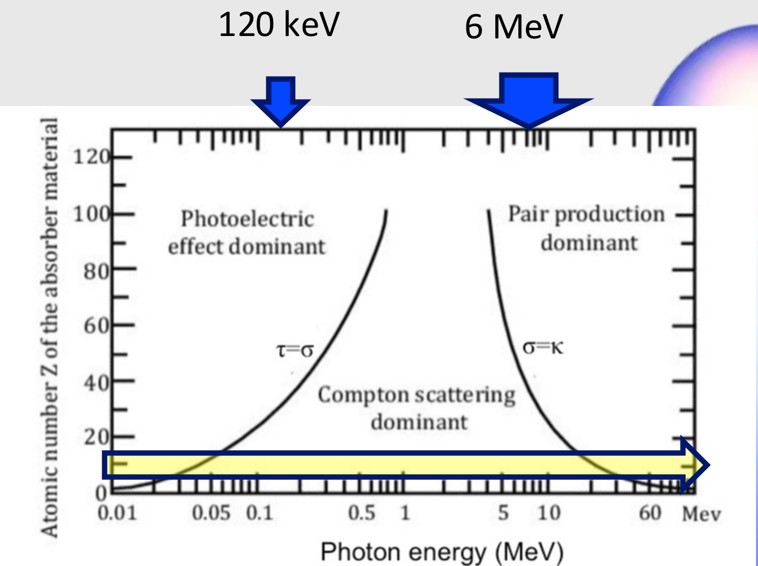
In TPSs, dose algorithms can model energy deposition from RT X-ray (from MeV linear accelerator) in patient tissues, that are characterized by the electron density derived from computed tomography (CT) imaging of patients (~80-180 keV).

Requisites for 3D printing material for radiotherapy phantoms:

- Materials must closely match the volume, density and chemical composition characteristics of the represented tissue for a proper radiological response at the energy of interest.
- The materials must be commercially available, simple to print, stable, and cheap
- Resolution of printing technique small

Goal: find 3D printed material that matches human tissue in terms of attenuation characteristics at MegaVoltage X-rays (RT X-rays) as well as CT X-rays

- Not easy! No direct relationship between linear attenuation coefficient from CT, and dose from MeV X-rays…
- What we know: Compton scattering dominates both for CT x-rays (120 keV) as for radiotherapy energies (MeV) (Z=low)



02: Select suitable tissue equivalent material

Much literature about 3D printing materials and characterization:

Tino R, Yeo A, Leary M, Brandt M, Kron T. A Systematic Review on 3D-Printed Imaging and Dosimetry Phantoms in Radiation Therapy. Technol Cancer Res Treat. 2019 J

- Interesting review citing many other papers and types of measurements (radiotherapy)
- Table 2 gives a good overview to citations to studies about 3D printing, including dosimetric ones

RELEVANT

Yuliang Liao 1, Linjing Wang 2, Xiangdong Xu 3, Haibin Chen 1, Jiawei Chen 1, Guoqian Zhang 2, Huaiyu Lei 2, Ruihao Wang 2, Shuxu Zhang 2, Xuejun Gu 4, Xin Zhen 1, Linghong Zhou 1 Med Phys. 2017 Jun;44(6):2369-2378. doi: 10.1002/mp.12229. Epub 2017 Apr 22. An anthropomorphic abdominal phantom for deformable image registration accuracy validation in adaptive radiation therapy

- Use CT in TPS to predict dose, compare with measurements (ionization chambers)
- Relevant for radiotherapy: CT X-rays and MeV X-rays

RELEVANT

Joseph Madamesila, Philip McGeachy, J. Eduardo Villarreal Barajas, Rao Khan, Characterizing 3D printing in the fabrication of variable density phantoms for quality assurance of radiotherapy, Physica Medica, Volume 32, Issue 1, 2016 Pages 242-247 (TECHNICAL NOTE)

- Relevant for radiotherapy: dosimetry with films and HU with CT
- Cannot access paper
- Low density material

RELEVANT

02: Select suitable tissue equivalent material

Much literature about 3D printing materials and characterization:

Mayer, Peter Liacouras, Andrew Thomas, Minglei Kang, Liyong Lin, Charles B. Simone; 3D printer generated thorax phantom with mobile tumor for radiation dosimetry. Rev. Sci. Instrum. 1 July 2015; 86 (7): 074301. https://doi.org/10.1063/1.4923294

- Relevant for radiotherapy but unaccessile
- Hus with CT→ put in TPS to obtain dose prediction
- Dose measured in a sagittal plane in phantom is compared to the calculated plan

RELEVANT

Yea JW, Park JW, Kim SK, Kim DY, Kim JG, Seo CY, Jeong WH, Jeong MY, Oh SA. Feasibility of a 3D-printed anthropomorphic patient-specific head phantom for patient-specific quality assurance of intensity-modulated radiotherapy. PLoS One. 2017 Jul 20;12(7):e0181560. doi: 10.1371/journal.pone.0181560. PMID: 28727787;

- Relevant for radiotherapy
- CT→ Comparisons of TPS prediction with measurements (I'mRTMatrixx and Films, in plane) ,

RELEVANT

Jeong et al, Preliminary study of the Dosimetric Characteristics of 3D printed Materials with Megavoltage Photons, Journal of the Korean Physical Society, Vol 67, No 1, July 2015, pp 189-194

- Relevant: CT X-rays and MeV X-rays
- They measure HU of 3 filling percentages
- For 6 MeV photon beam, they measure dose behind 5 cm thick phantom with Gafchromics EBT3 films and Matrixx detector

RELEVANT

Select suitable tissue equivalent material

Much literature about 3D printing materials and characterization:

Dancewicz, Orrie & Sylvander, Steven & Markwell, Tim & Crowe, Scott & Trapp, J.V.. (2017). Radiological properties of 3D printed materials in kilovoltage and megavoltage photon beams. Physica Medica. 38. 111-118. 10.1016/j.ejmp.2017.05.051. (engineering and chemistry department)

RELEVANT

- Very relevant: CT numbers 120 keV for lung and soft tissue + Radiotherapy X-rays
- Fusion Deposition Modelling and Stereolithography techniques (FDM, SLA), 100% infill density
- Compare with official Gammex tissue equivalent tissues (water, solid water, lung-300, lung450, adipose, breast, liver, varioust types of bone
- CT imaging of all materials
- Dose downstream the slab measured, «narrow field is desired [ref]» with 3D ionization chamber PTW

They seem to conclude that, apart from metals, **when materials match CT values, also ok for «MVCT» images**

,

Halloran, Andrew & Newhauser, Wayne & Chu, Connel & Donahue, William. (2021). Personalized 3D-printed anthropomorphic phantoms for dosimetry in charged particle fields. Physics in Medicine & Biology. 66. 10.1088/1361-6560/ac3047

RELEVANT

- Electron beams

Select suitable tissue equivalent material

Much literature about 3D printing materials and characterization:

Peter Homolka, Michael Figl, Andreas Wartak, Mathias Glanzer, Martina Dünkelmeyer, Azadeh Hojreh and Johann Hummel, Design of a head phantom produced on a 3D rapid prototyping printer and comparison with a RANDO and 3M lucite head phantom in eye dosimetry applications Phys. Med. Biol. 62 3158

- Radiotherapy, but dose but on 3 mm depth
- No CT characterization

NO RT

Sepideh Hatamikia et at, 3D printed patient-specific thorax phantom with realistic heterogenous bone radiopacity using filament printer technology, Volume 32, Issue 4, November 2022, Pages 438-452 Zeitschrift für Medizinische Physik

- Torax phantom withh bone
- Focus on HU in relation with in-fill density
- No radiotherapy

NO RT

Alssabbagh, Moayyad & Tajuddin, Abd & Abdul Manap, Mahayuddin & Zainon, Rafidah. (2017). Evaluation of nine 3D printing materials as tissue equivalent materials in terms of mass attenuation coefficient and mass density. International Journal of ADVANCED AND APPLIED SCIENCES. 4. 168-173.

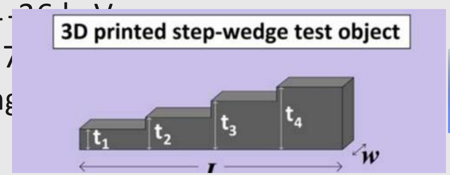
- Evaluate mass attenuation coefficients of 9 materials
- No radiotherapy

NO RT

Select suitable tissue equivalent material

Much literature about 3D printing materials and characterization:

G. Mettiviere, … P. Russo (Napoli), Attenuation coefficient in the energy range 14-
of 3D printing materials for physical breast phantom, Phys. Med Bio 67 (2022), 17



- Develop breast phantom for testing imaging devices and QA in breast imaging
- Applications: digital mamography, digital breast tomosynthesis, breast CT
- Make step-wedge test object, no radiotherapy

NO RT

ADAM: A breathing phantom for lung SBRT QA, Phys. Med. 2017
- HU of materials tested and material selected for lung phantom
- Radiotherapy but for focused on motion

NO RT

Hatamikia, et al (Austria), Realistic 3D printed CT imaging tumor phantoms for validation of image processing algorithms, Phys. Med. 105 (2023) 102512
- Test HU of various imahing systems (-217 to 226)
- Application: for development and validation of imaging algorithms, No radiotherapy S

NO RT

Mei K, Geagan M, Roshkovan L, et al. Three-dimensional printing of patient-specific lung phantoms for CT imaging: emulating lung tissue with accurate attenuation profiles and textures. Med Phys. 2022; 49: 825–835.
- Test 3D printing system to create realistic lung phantoms in texture and density
- Application: CT research, No radiotherapy

NO RT

Select suitable tissue equivalent material

Too much literature, much research involved → not easy to do quickly

Good news!

- From Dancewitz et al, it seems that when HU is equivalent, also the dose measurements with MeV photons match (to be read more carefully!)
- Other papers about RT dosimetry and 3D filament printing seem to confirm this. Usual procedure is:
  - CT of 3D printed material
  - Make a treatment plan with TPS, base on this CT
  - Check dose somewhere inside or behind material, using films or ionization chambers
  - Quote a Gamma Passing Rate (it always matches OK, apart from metals).

Solution for us:

- Try different materials (24 in total: 10 Bio3DModel, 9 LNGS and 5 INFN Pisa)
- Make selection based on HU for realistic material (focus on soft tissue)
- Cross-check the MeV X-ray response by taking EPID images and compare with solid water

Material selection

- CT scans and EPID images of 24 material cubes of varying compositions and 3 cm solid water slabs.
- 120 keV X-rays (see next): Calculation of the Hounsfield Unit (HU) value for each material cube using DICOM metadata:

```
slope = float(ds.RescaleSlope)
intercept = float(ds.RescaleIntercept)
hu_array = pixel_array * slope + intercept
```

- 6 MeV X-rays (see slide X): Determination of the difference between EPID images (cubes vs. water).

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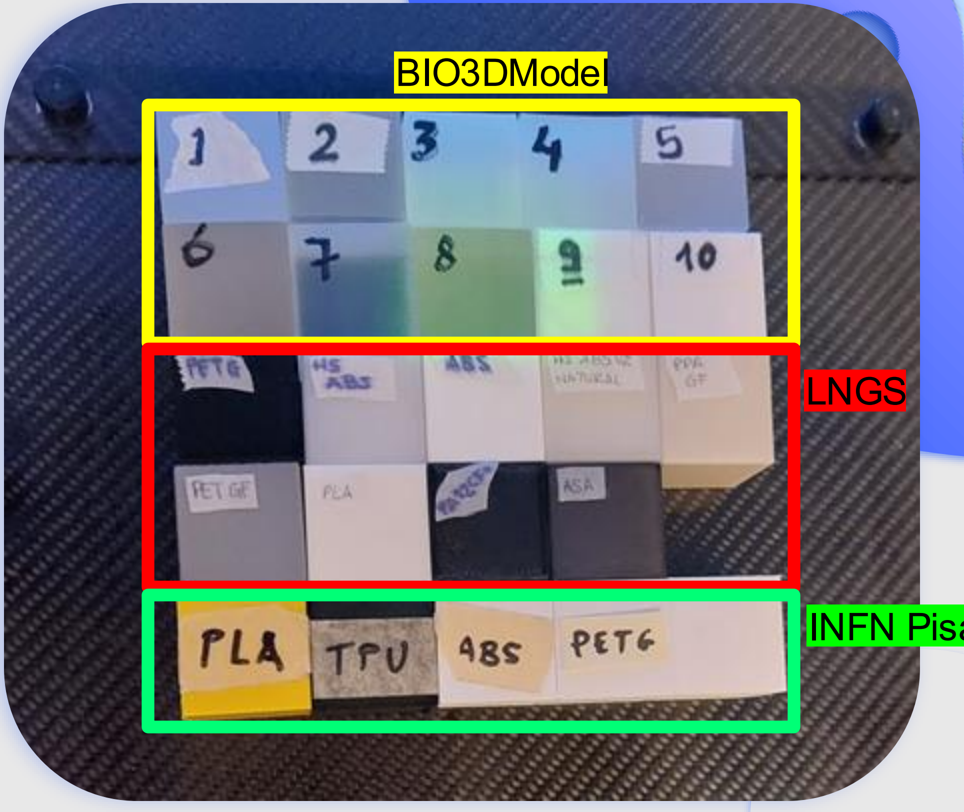

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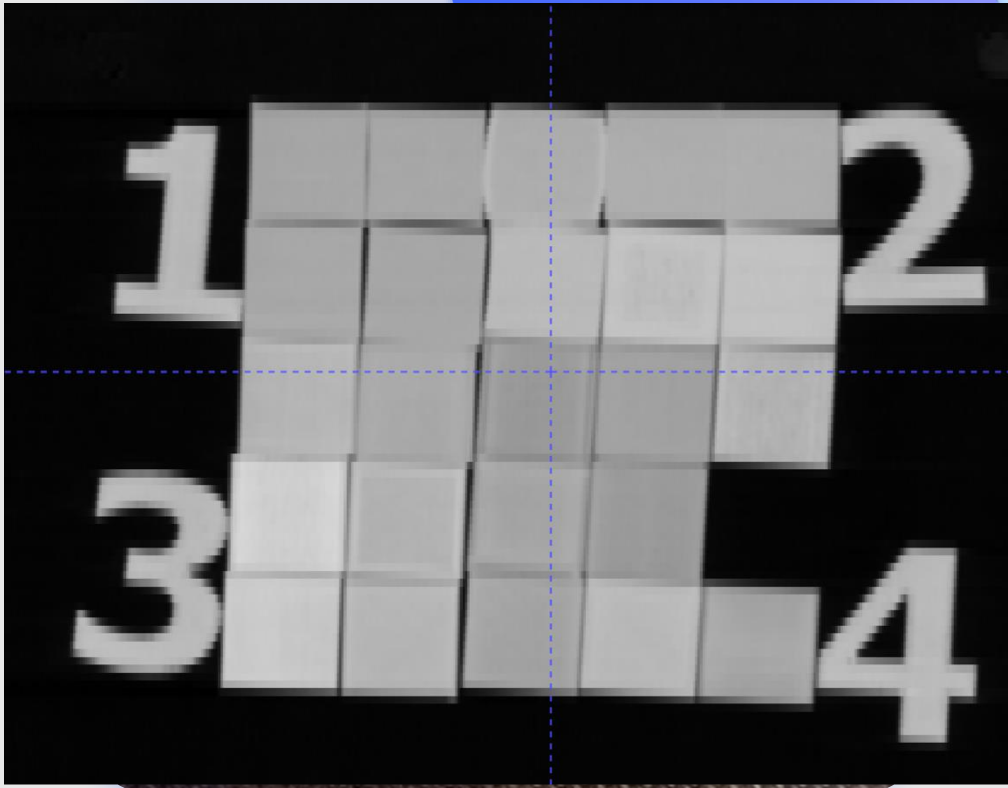
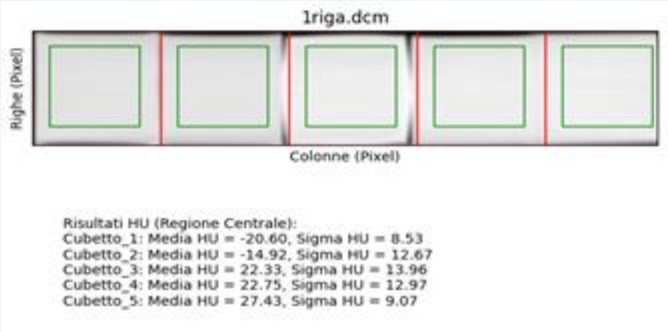
ITK-SNAP

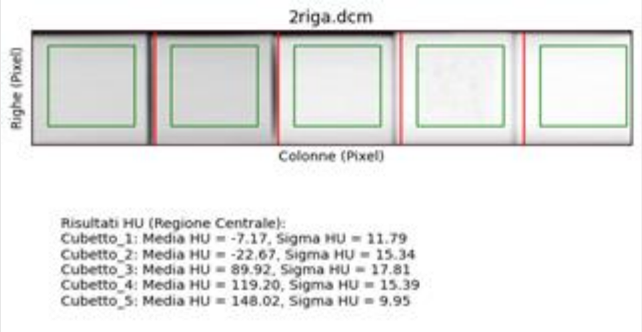
120 keV CT scan

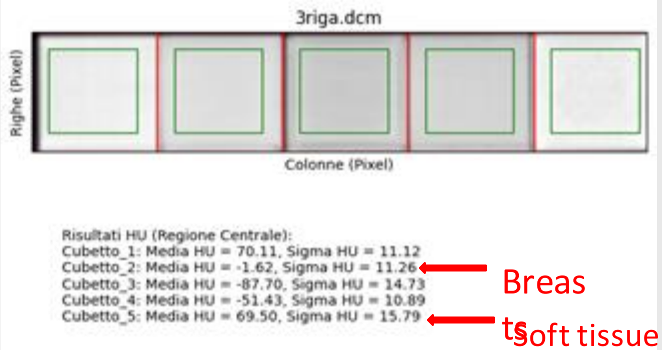


Material selection: HU

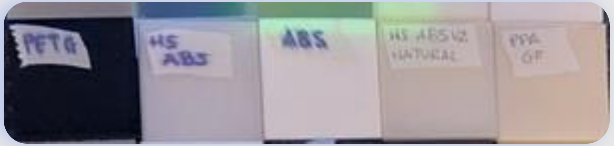
1riga
2riga
3riga
4riga
5riga



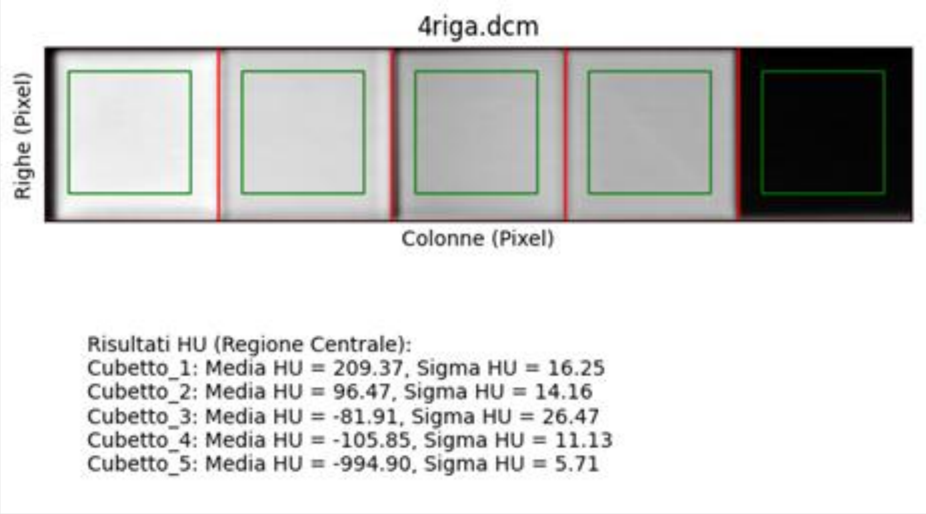


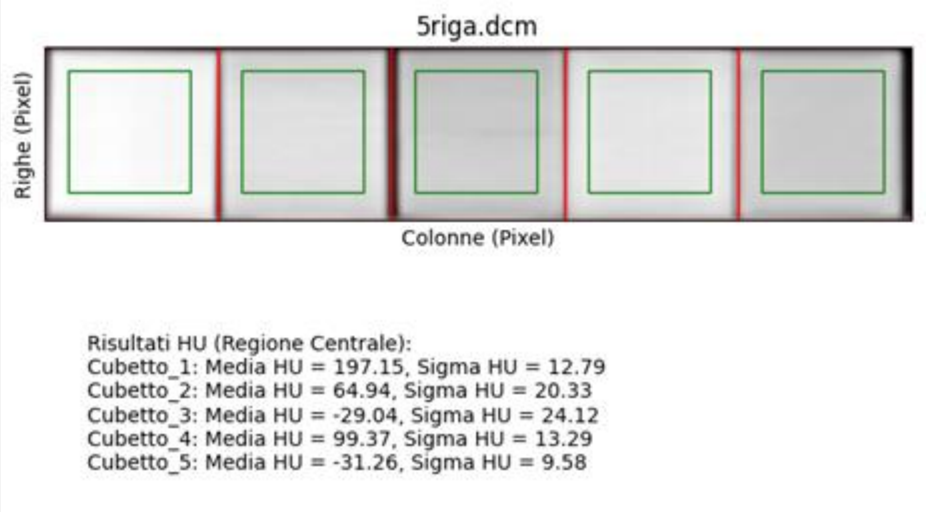


Breas
ts
Soft tissue



Material selection : HU



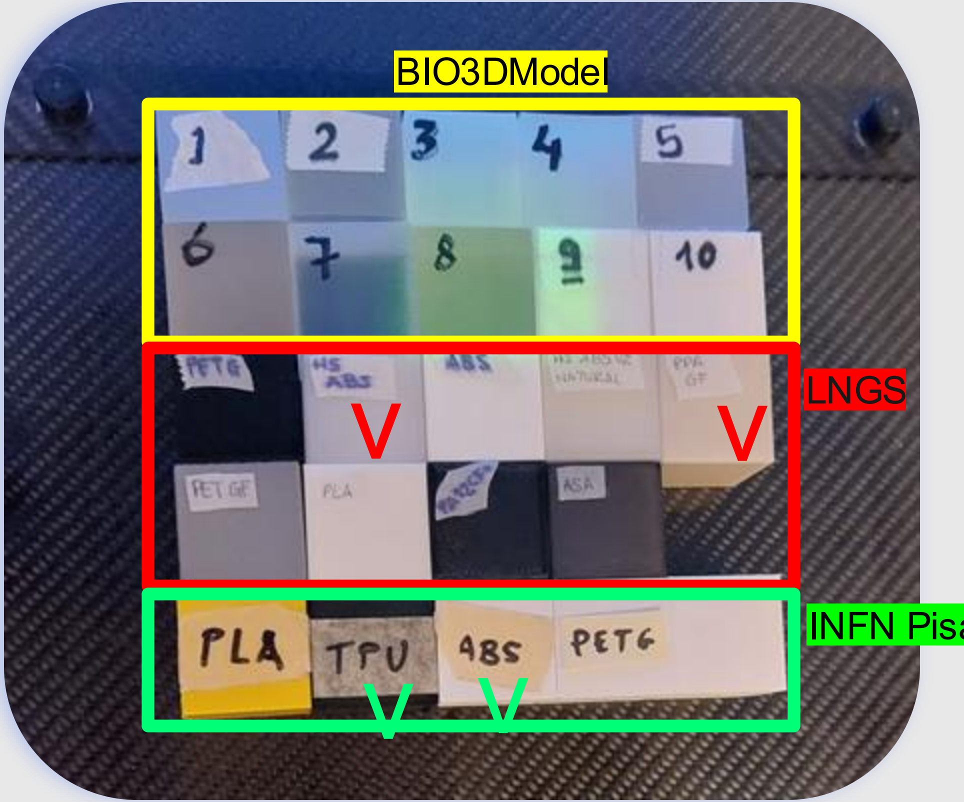


Material selection : HU

CT scans

After discussion with Stefania

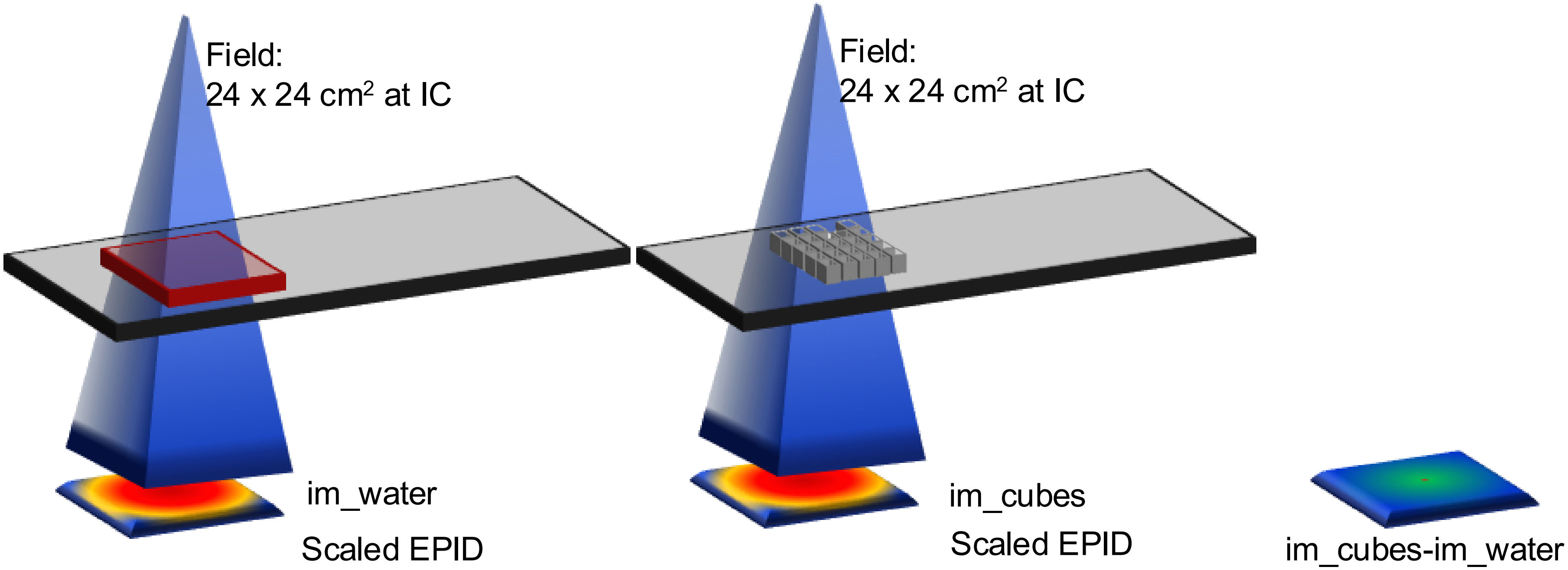
- Combination LNGS:
  - ✓ Breast =-1.62
  - ✓ Soft Tissue 69.70
- Combination INFN Pisa:
  - ✓ Breast -29.0
  - ✓ Soft Tissue: 64.94



Material selection : MeV X-rays

6 MeV «images» of Elekta Versa HD, i.e., EPID images

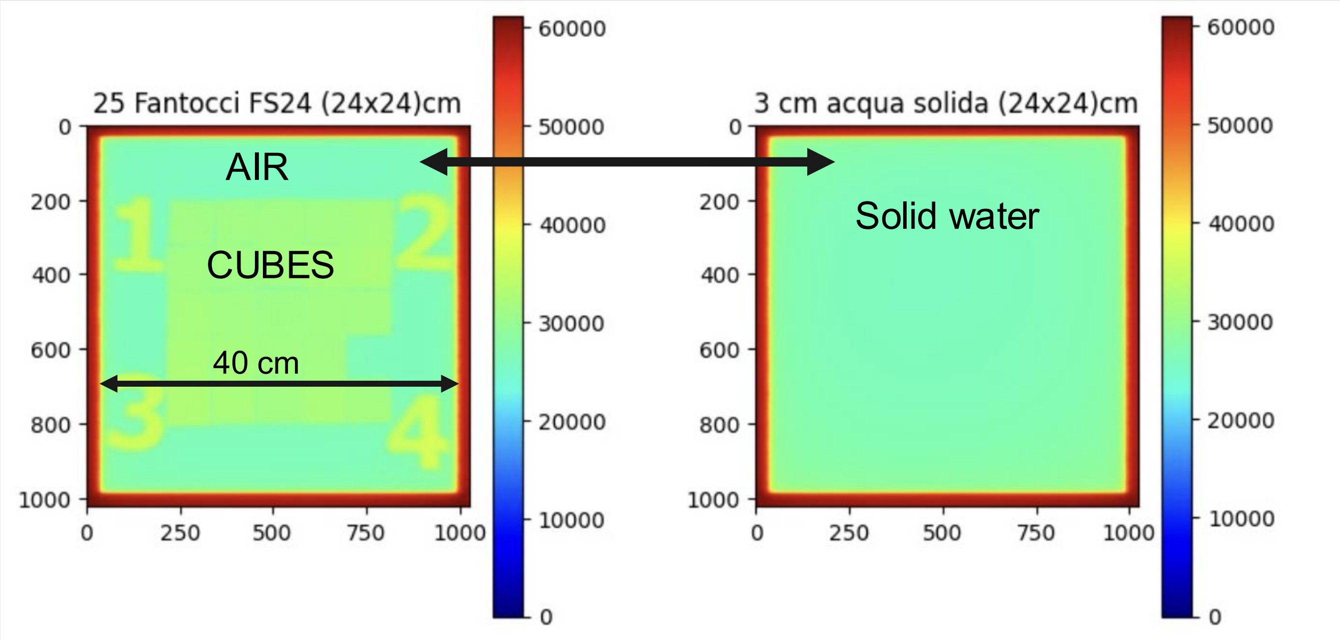
- Compare them with a reference (solid water) : regions with the same composition/density should have a signal difference between them ~ 0
- Solid water also has HU close to 0
- Should be inverted with scale factor (65535-pixelvalue)/PSF to obtain images to scale



Material selection : MeV x-rays

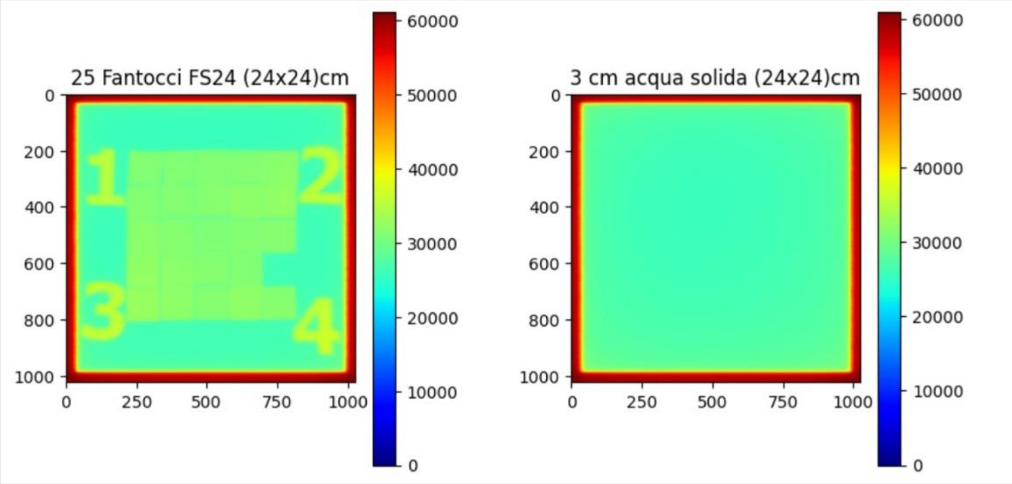
Data raw

- EPID images from 24 x 24 cm2 acquisition
- Results in ~40 x 40 cm2 at EPID plane
- Scale from 0 to 65535
- Clear that scale has no quantative meaning! (air has signal quite similar to solid water…)



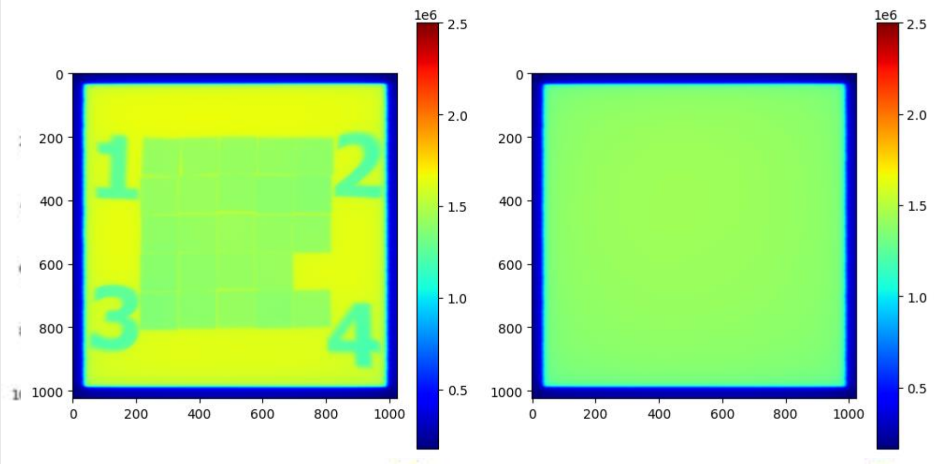
Material selection : MeV x-rays

Data raw



Color bar 0 to 60000

EPIDs inverted



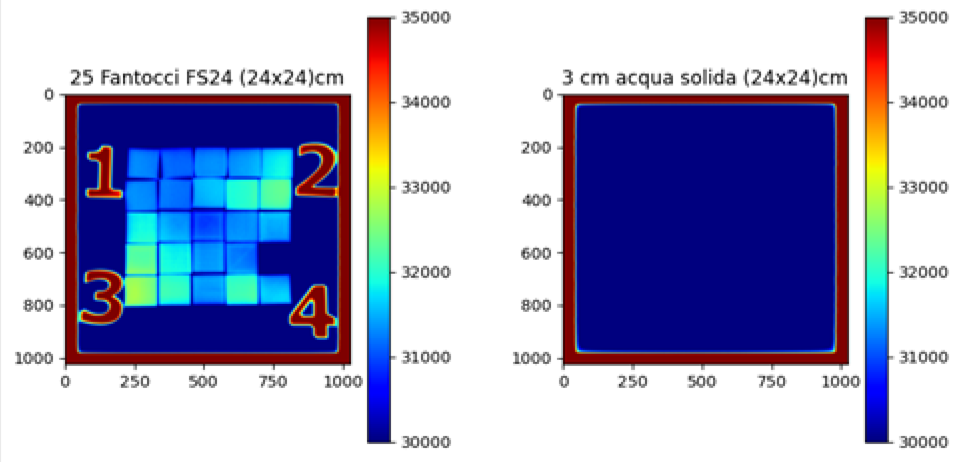
Each pixel: scale factor (65535-pixelvalue)/PSF

Color bar zoomed to relevant region

PSF not same!
0.0241384
0.0278235

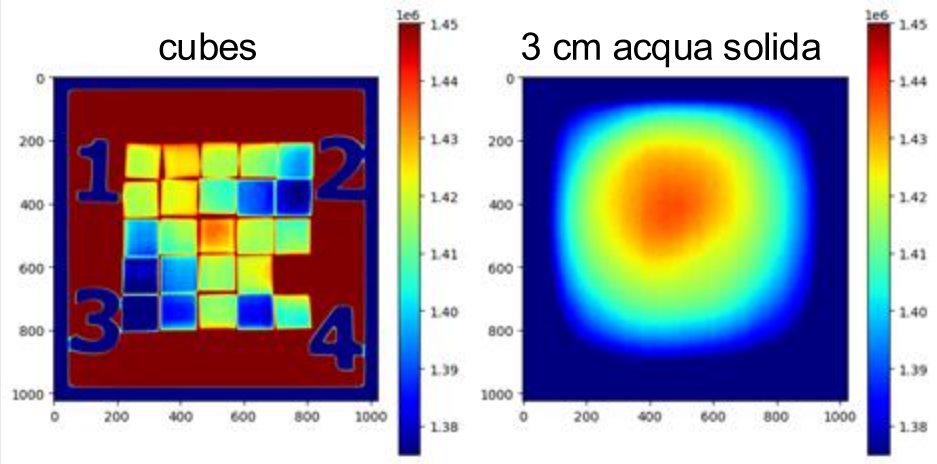
Material selection : MeV x-rays

Data raw



Color bar 30000 to 35000h

EPIDs inverted



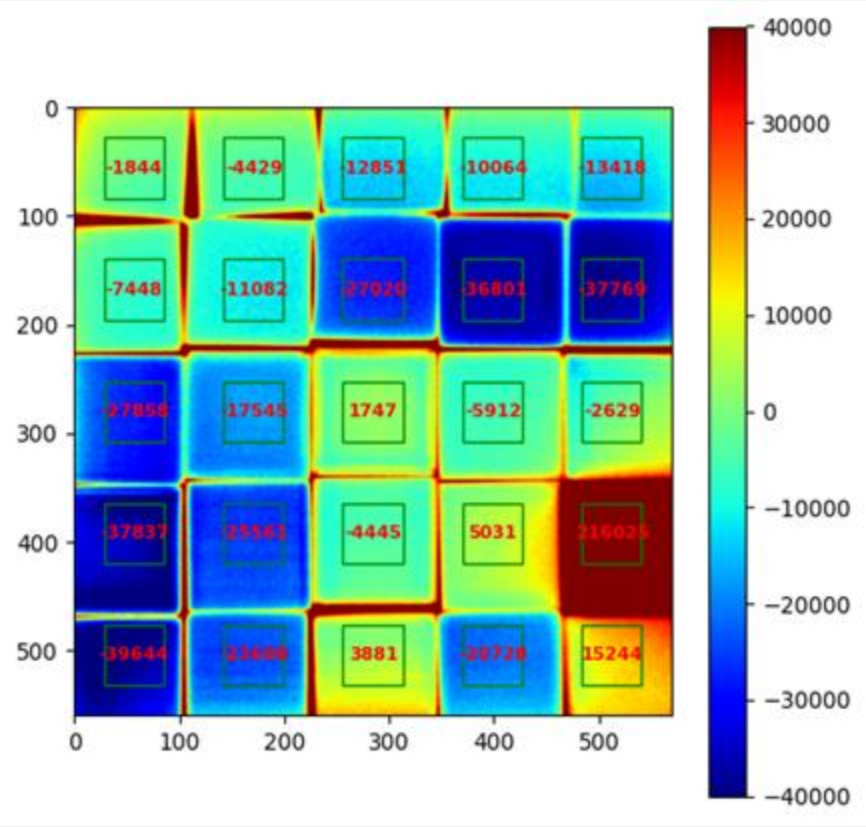
Each pixel: scale factor (65535-pixelvalue)/PSF

Color bar zoomed to relevant region

PSF not same!
0.0241384
0.0278235

Material selection : MeV x-rays

Difference (using 25% of cube's surface)



Difference=im_cubes-im_water

Remember that:

- Less attenuation means higher signal and vice versa
- Regions with:
  - Negative difference: material is more dense than water
  - Positive difference: material is less dense than water

Material selection : MeV x-rays

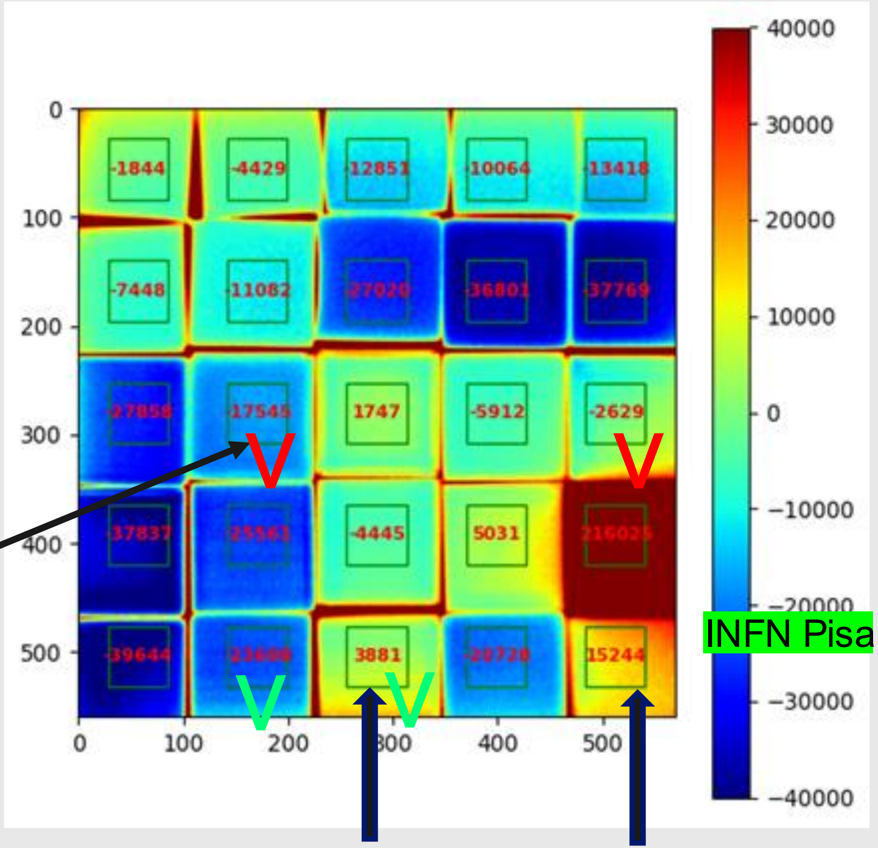
Difference (using 25% of cube's surface)

From CT's we had this selection

- Combination LNGS:
  - Breast HU =-1.62
  - Soft Tissue HU=69.70
- Combination INFN Pisa:
  - Breast -29.0
  - Soft Tissue: 64.94

Observations:

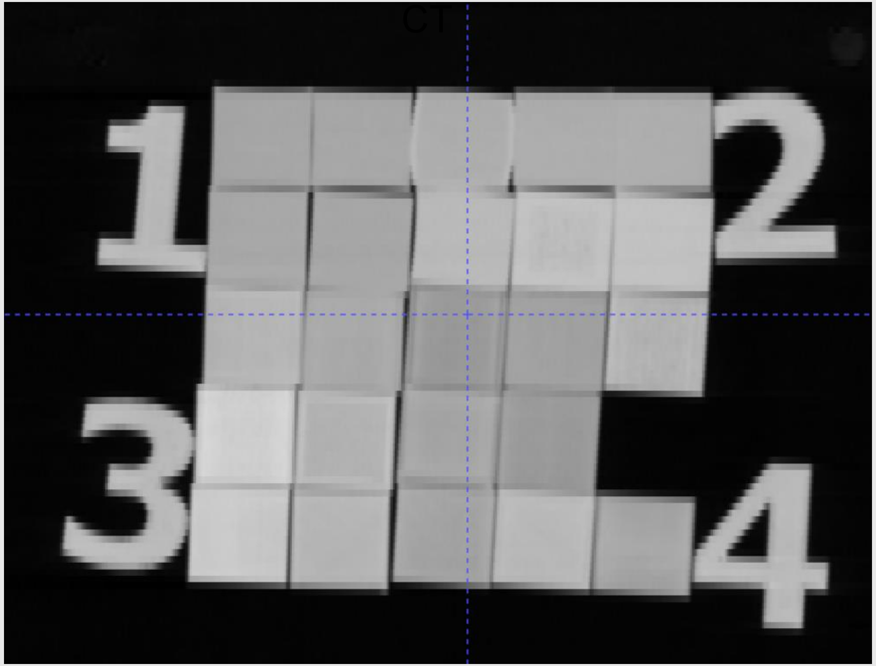
- HU=-1.62 should be very close to (solid) water. But EPID signal is quite different
- Same material (ABS) but response depends on region
  - Scattering?
- Some large differences, e.g. -39664: Remember that max of scaled EPID images (see slide 18) is around 1.5xE6, so it's actually relatively small

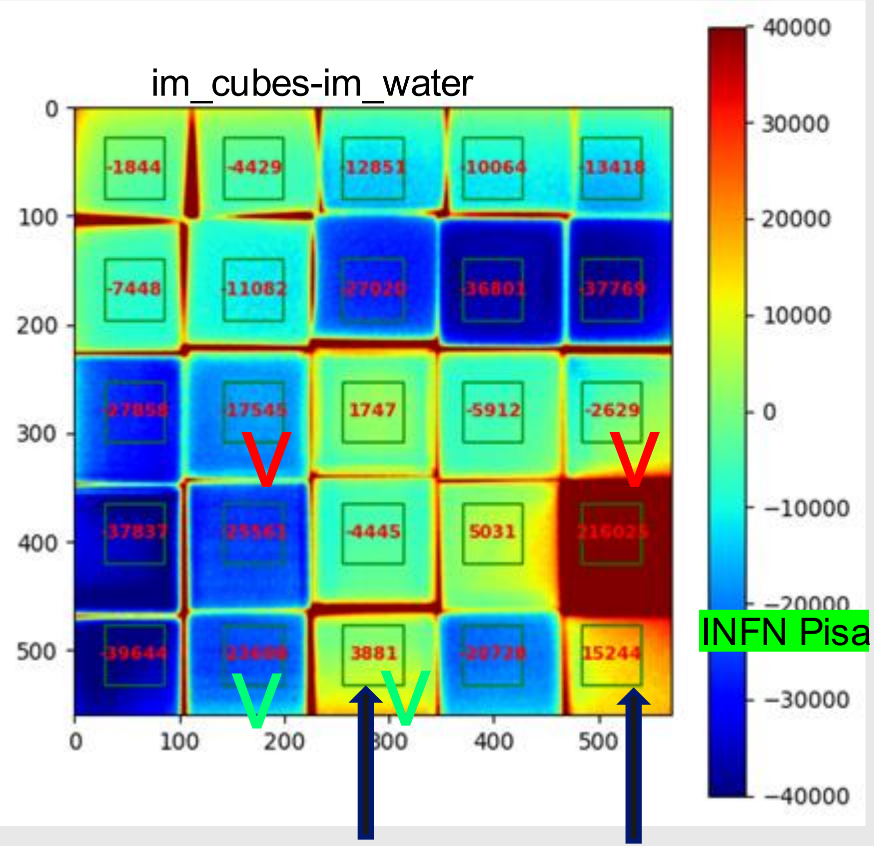


Same material, ABS

Material selection : MeV x-rays

CT

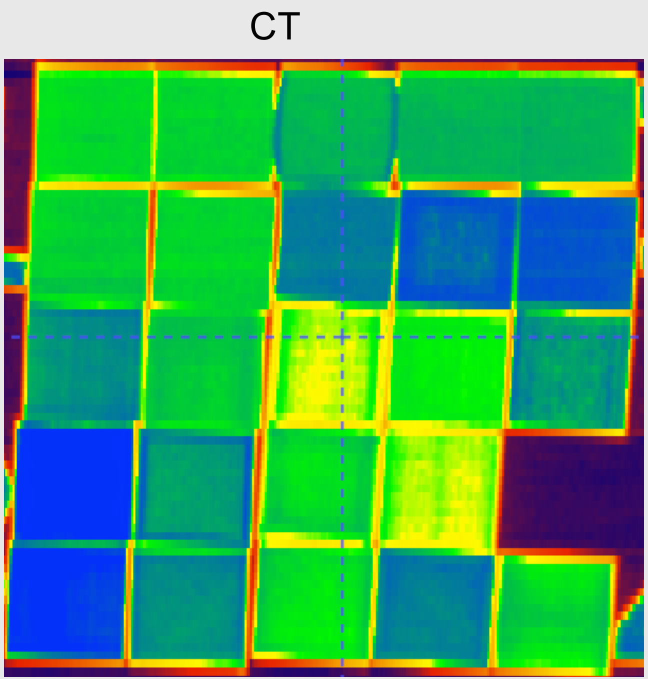


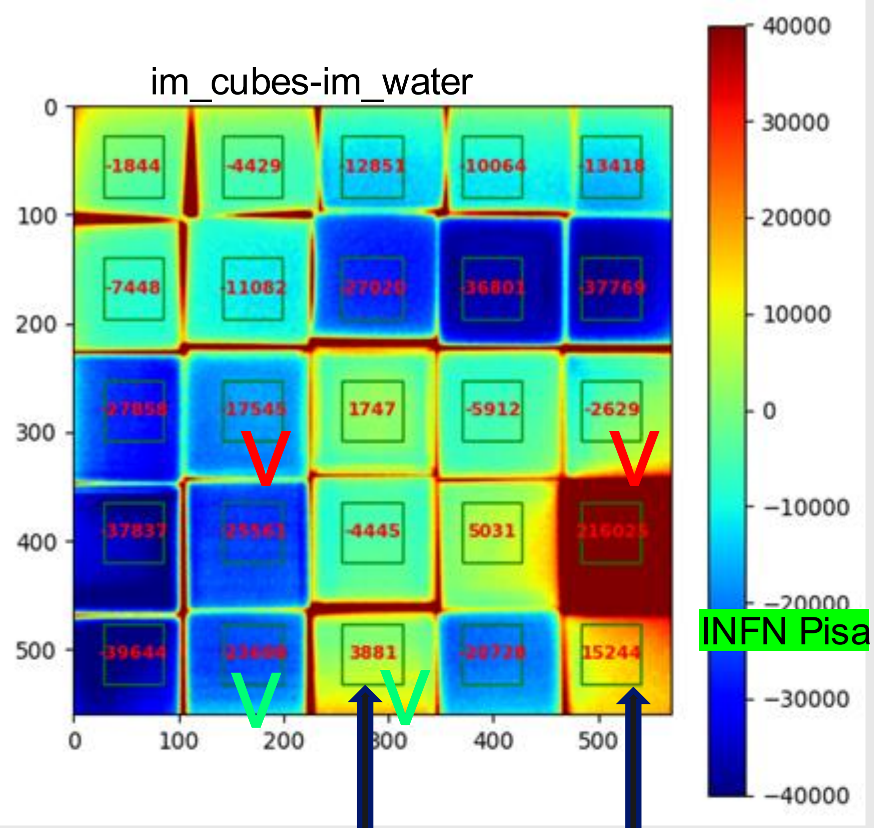


There is some correlation!

Same material, ABS

Material selection : MeV x-rays



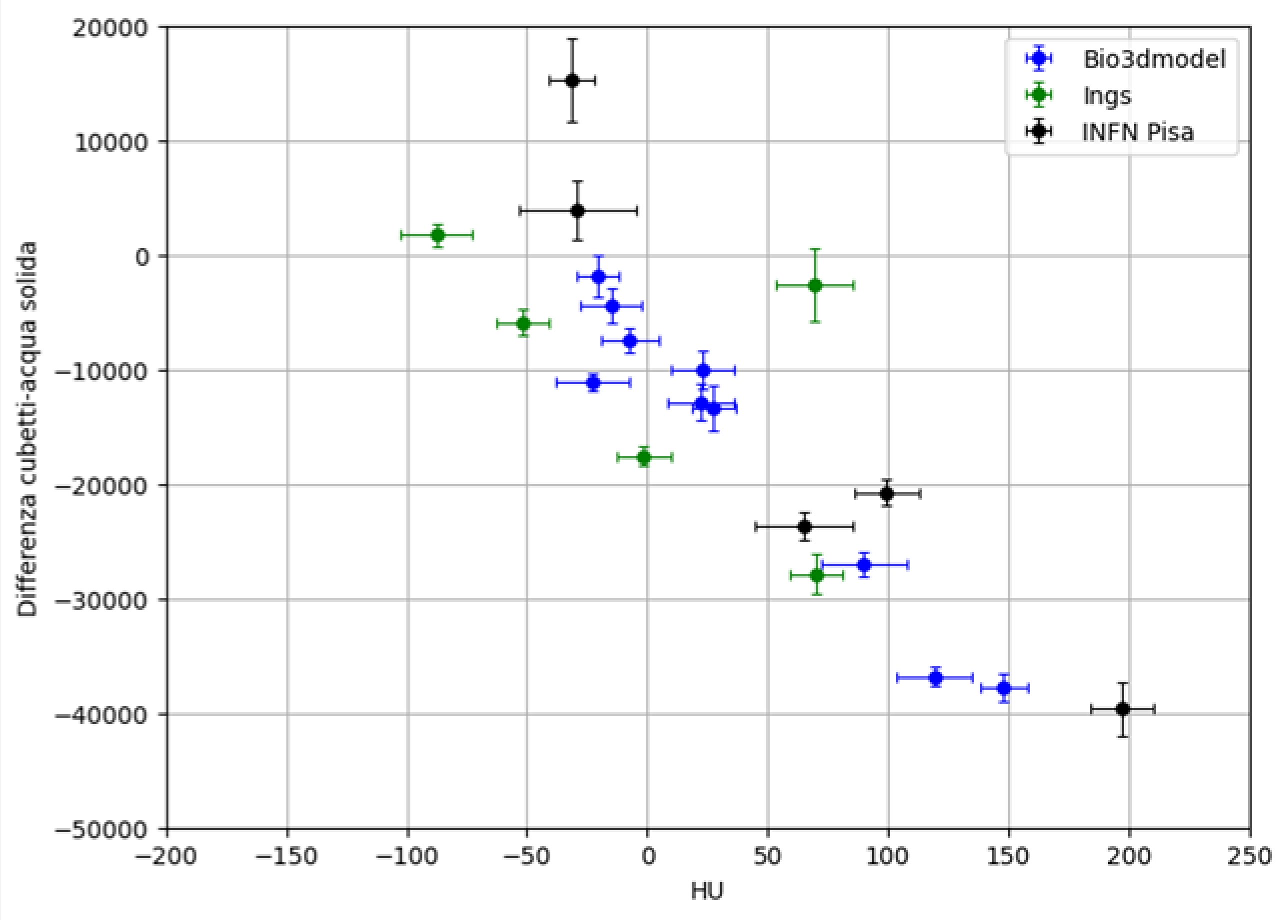


There is some correlation!

Same material, ABS

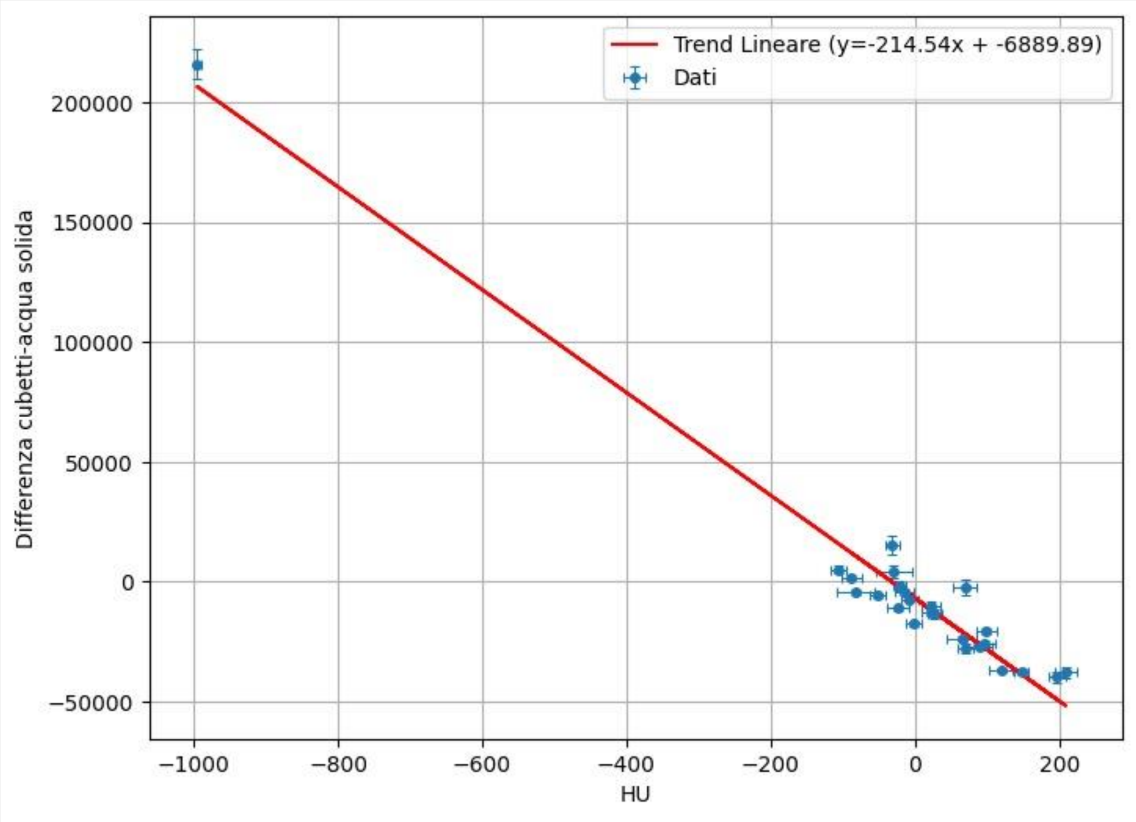
Correlation between both

Scatterplot difference vs HU



Correlation between both

Including air «cube»



Recent news

- Not possible to print ABS and PPA together at LNGS → 3DSlicer phantom can consist only of 1 material
- Now printing at INFN Pisa

Conclusions

- Selection of an appropriate material is difficult, active field of research!
- Based on literature, we will base the material choice on the CT for now: best match for breast and soft tissue
- Print 3D Inventor Autodesk phantom at INFN Pisa
- Print 3D slicer phantom in LNGS: 2 extrudors in parallel
- Determine density of 24 materials (plot HU as a function of density to check whether it follows the usual curve)
- For future:
  - Repeat measurements of materials for smaller fields (as suggested in literature), one at the time?
  - To perform dosimetry measurements. Rather than printing new cubes, how about measuring dose with GafChromics or ionization chamber in or behind the printed phantoms and compare with TPS predictions?