Anthropomorphic Phantoms for Medical Imaging based on 3D printing: The role of Micro-CT Imaging for Manufacturing Quality Control

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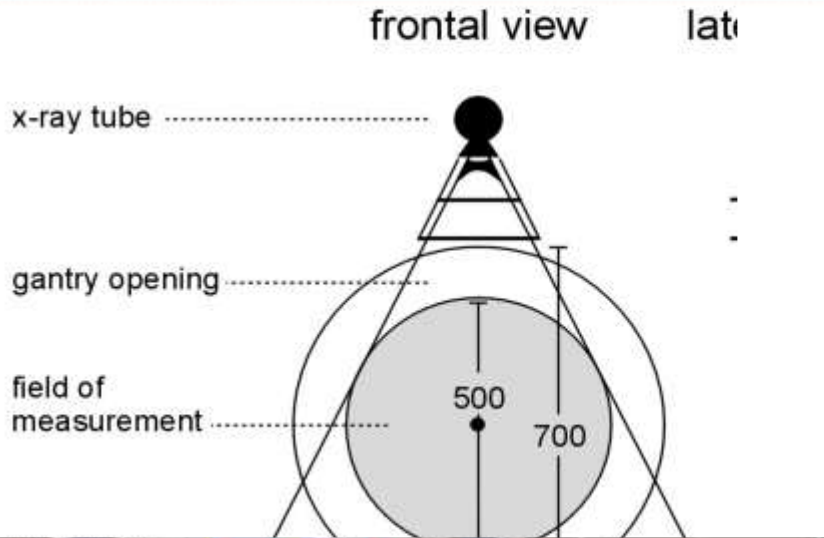
Content

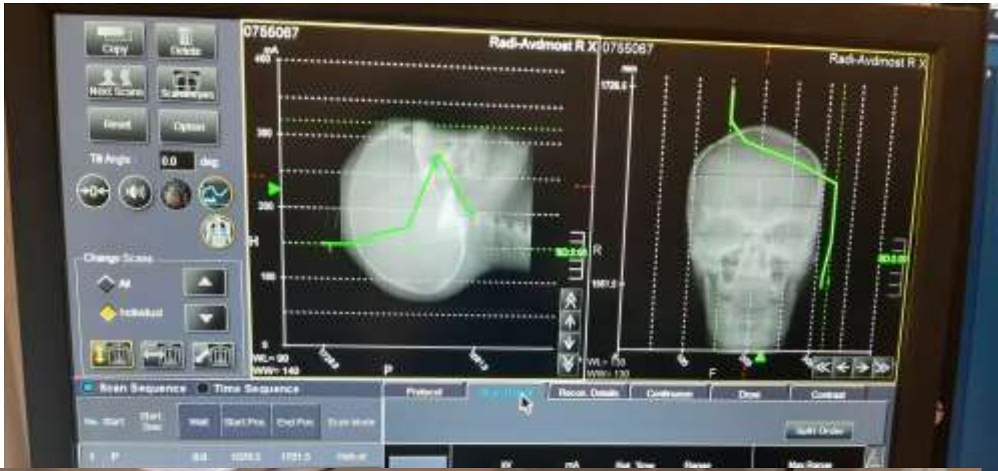
- Basic introduction to CT imaging
- Main differences between medical CT and micro-CT imaging
- Image quality (IQ) assessment from Physics point of view
- Diagnostic image quality
- Evolution of test objects or phantoms: from geometric to anthropomorphic
- Task-based image quality metrics: lesion detection, vessel detection and quantification
- Workflow to design and manufacture lung vessel anthropomorphic phantoms based on 3D printing
- Micro-CT imaging for QC of phantoms

Abstract

The performance evaluation of medical imaging devices has traditionally been done with test objects (phantoms) based on simple geometries (such as cylinders, for instance) cast on materials mimicking to some extent the patient overall X-ray attenuation. Such geometric phantoms contain different patterns for image quality assessment, like noise, uniformity, linearity of materials attenuation, modulation transfer function…[1] State of the art medical imaging devices, are intrinsically tailored to the human body characteristics, for instance with automatic exposure control systems calibrated for patients' morphometry or iterative and AI-based image reconstruction algorithms which make assumptions about the patient's characteristics or are trained with patient data. There is a need for expanding the medical image quality assessment framework, including anthropomorphic test objects, mimicking to some extent the overall patient attenuation, shape and morphometry, tissue texture and attenuation and others to some extent. The use of 3D printing plays a significant role in this regard, allowing for manufacturing customized patient anatomical models tailored to specific body parts or medical indications[2,3]. There is an interest in the medical physics community for these anthropomorphic phantoms with applications for X-ray imaging modalities, for instance Computed Tomography, and for others without the use of ionizing radiation (such as ultrasound or MRI). The accuracy, reproducibility and robustness of the 3d printing process is an expanding field, as there are several manufacturing providers, models, printing techniques, and a wide range of materials available. Micro-CT imaging can play an important role to assess the quality and characteristics of the developed anthropomorphic phantoms, generating ground truths of the objects that can be compared to the original models that were intended to be printed. Some case studies will be presented, ranging from simple 3D printed objects to more complex vessel-like structures, the latter intended to be an anthropomorphic phantom for image quality assessment of Computed Tomography systems[4].

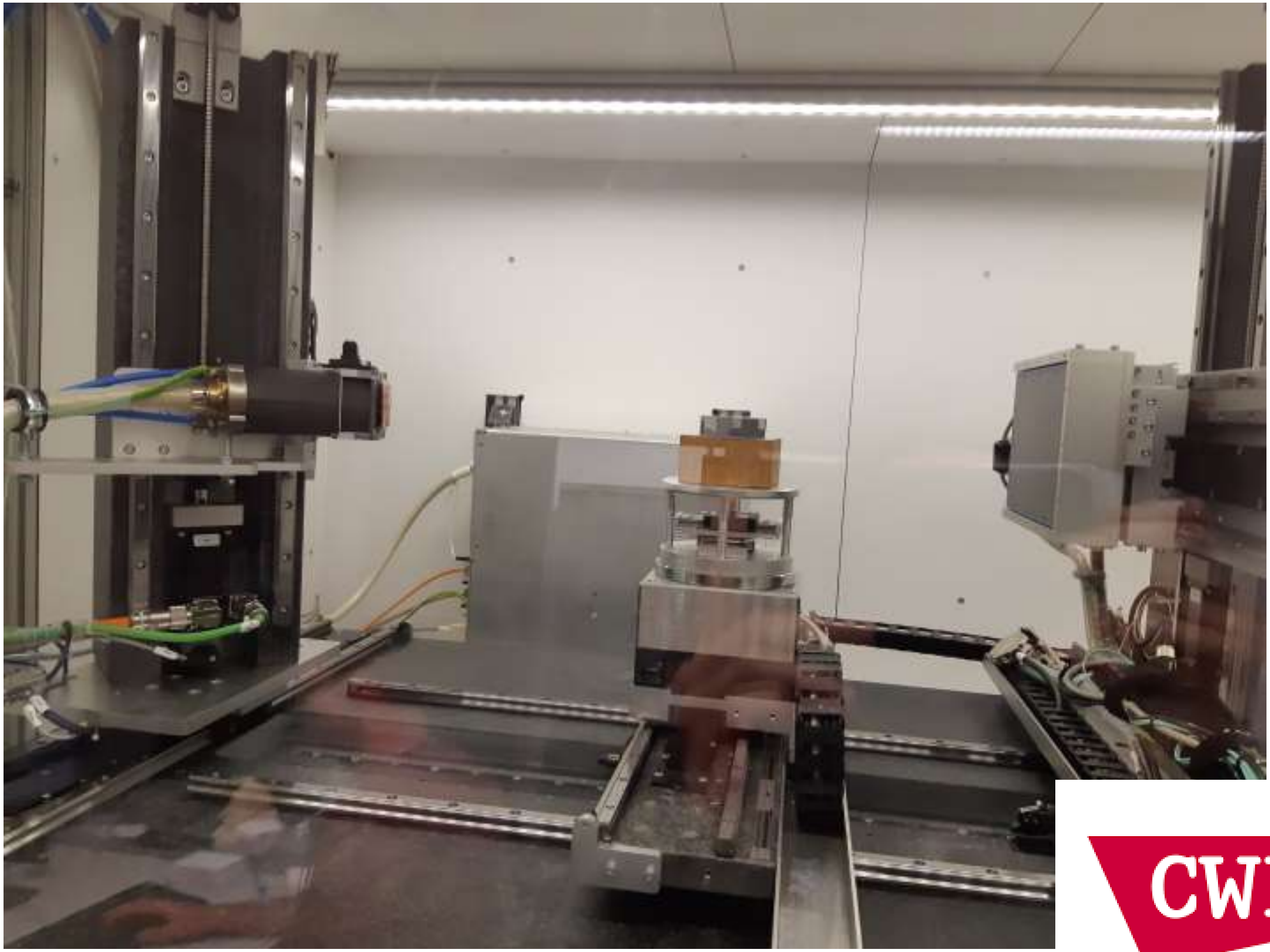
CT imaging (Radiology)





“Computed Tomography: Fundamentals, system technology, image quality and applications”, W. A. Kalender 2011

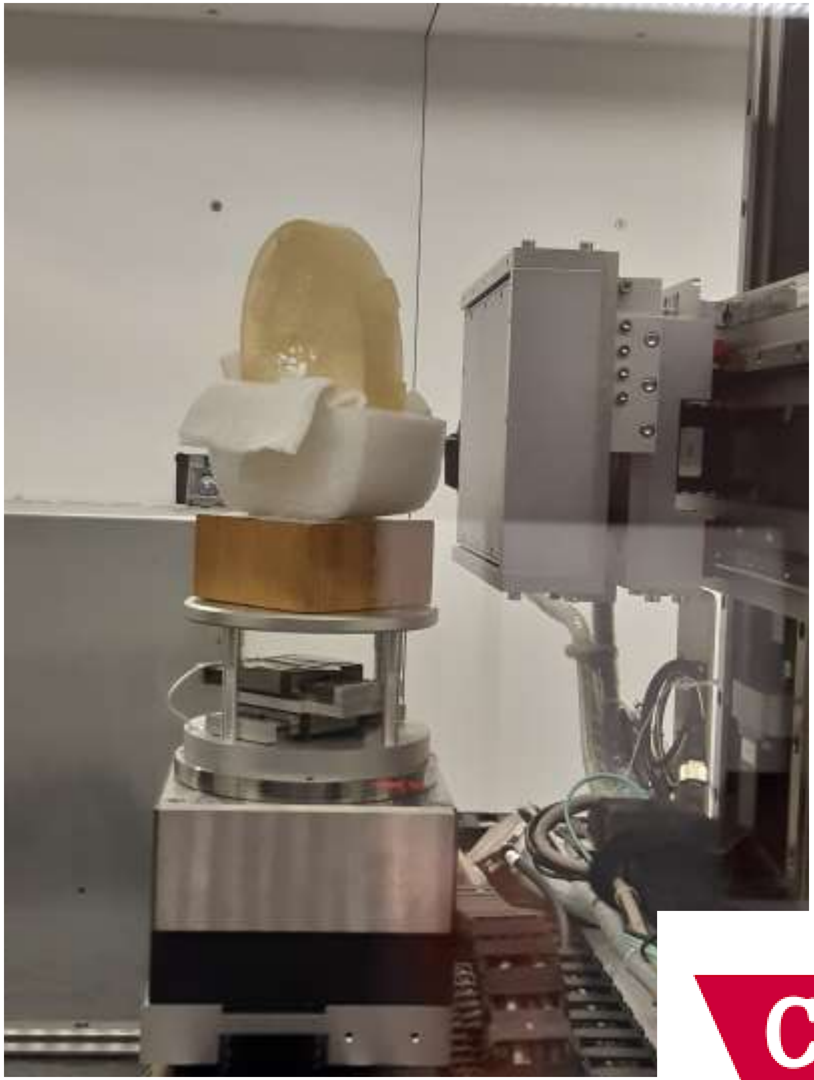
Micro-CT imaging



Flex Ray Lab

CWI
Centrum Wiskunde & Informatica

Micro-CT imaging



Flex Ray Lab

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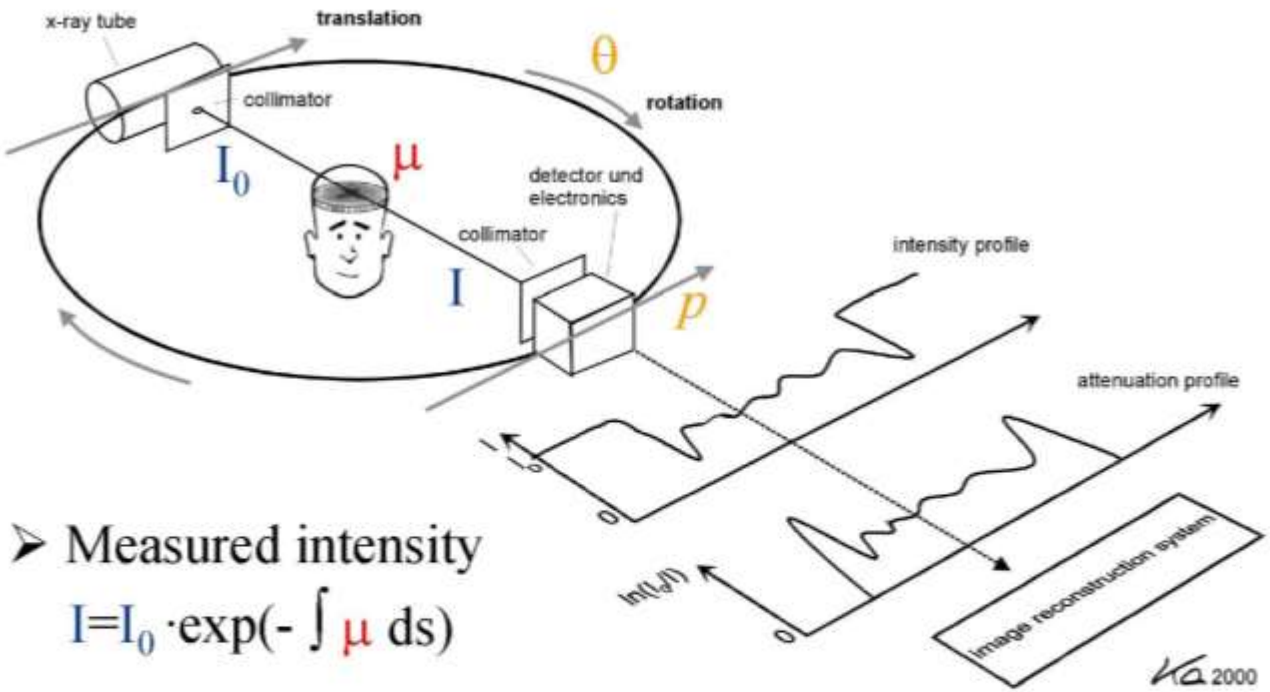


- Measured intensity

  $I = I_0 \cdot \exp(-\int \mu \, ds)$

- Total attenuation (line integral)

$$f_\theta(p) = \int \mu \, ds = -\ln(I / I_0)$$

Attenuation coefficient, CT value

"Computed Tomography: Fundamentals, system technology, image quality and applications", W. A. Kalender 2011

What do the pixel values in CT represent?

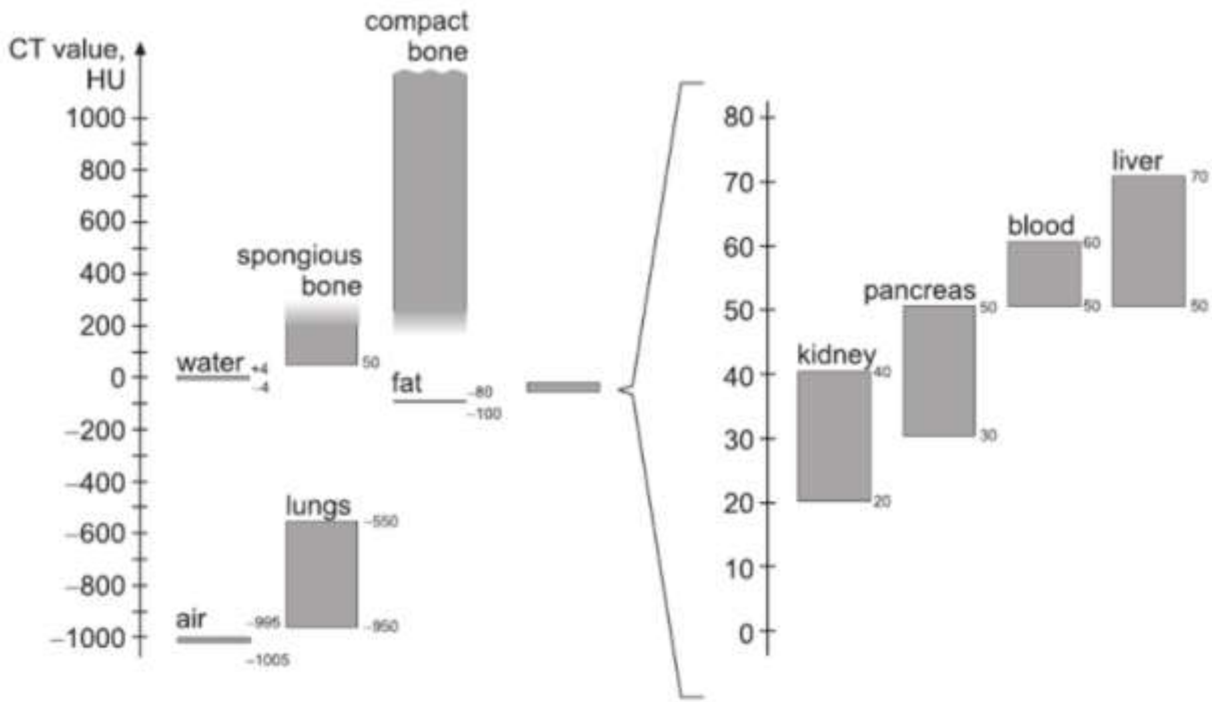
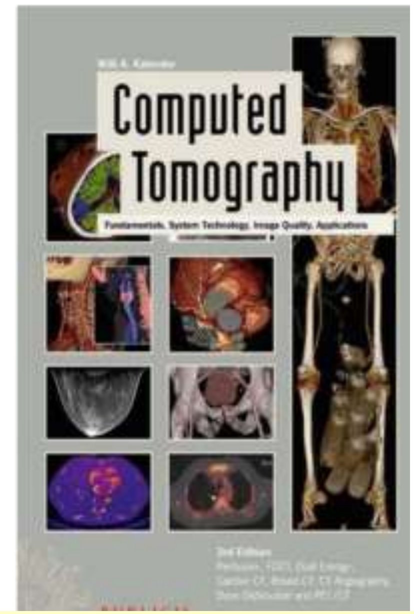


Figure 1.9
The Hounsfield scale. CT values characterize the linear attenuation coefficient of the tissue in each volume element relative to the μ-val
of different tissues are therefore defined to be relativel
independent of the x-ray spectrum.

"Computed Tomography: Fundamentals, sy
W. A. Kalender 2011



CT values of the same material depend on X-ray spectrum energy → kV dependence

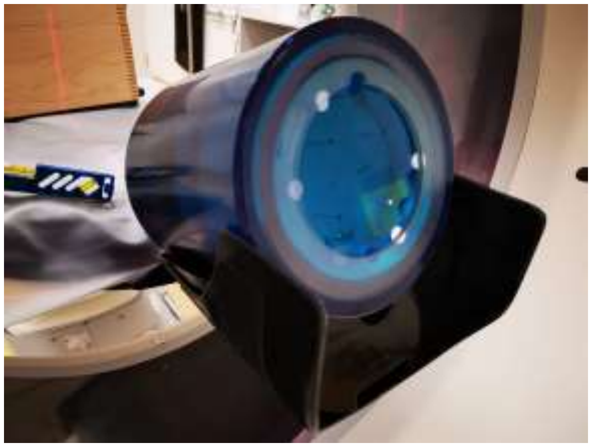
Some differences between medical CT and micro-CT

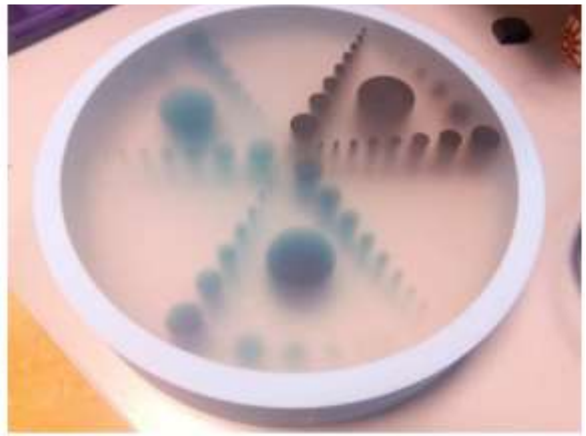
- The main target in medical CT is imaging human body. The system is calibrated for a range of materials attenuations (in general between air (low attenuation) and high dense bone (high attenuation).
- FOV can be adapated to patient size and scanned body part
- kV range between 80-140 kV
- Existing inherent filtration (bow tie filter or shape filters), depending on the target body part
- Tube current varies depending of indication but it is at least of the order of tens mAs (Ex. 200mAs)
- Table moves at the same time as X-ray tube rotates (in general)
- Different resolution in XY and Z. Z direction resolution threshold around detector element size (around 0.5mm or 0.25 mm for UHR systems)

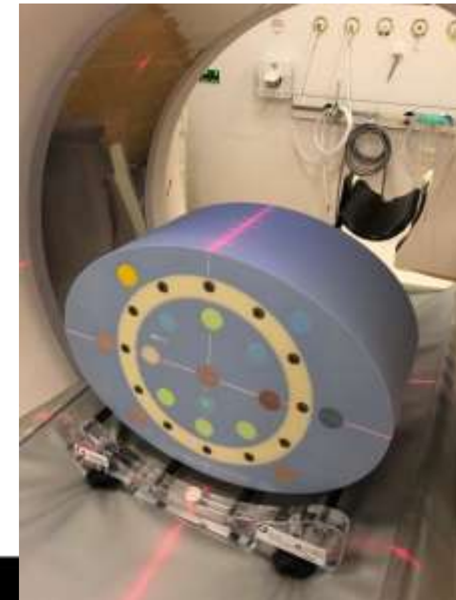
- Micro-CT imaging can have targets of all sorts and compositions: insects, minerals, tissue simples, industrial applications…
- In general for small objects or need for image stitching
- kV rangebetween 20kV up to 100kV) 50kV is usual)
- Usually no filtration, though it can be added, to absorb low energy photons that increase noise
- Tube current in the order of 500-1000μA
- Only X-ray tube rotates around sample
- Resolution of order of μm (0.001 mm)

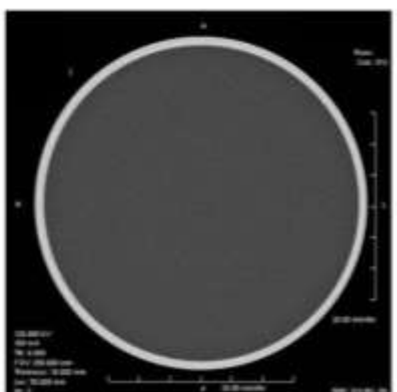
IQ assessment in Radiology (Physics)

Geometric phantoms

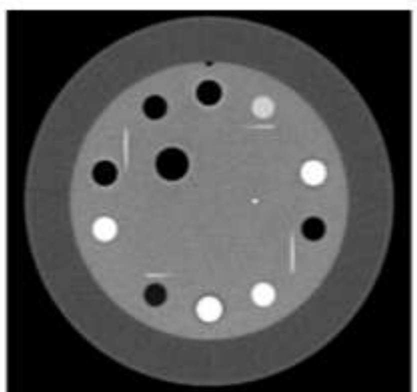




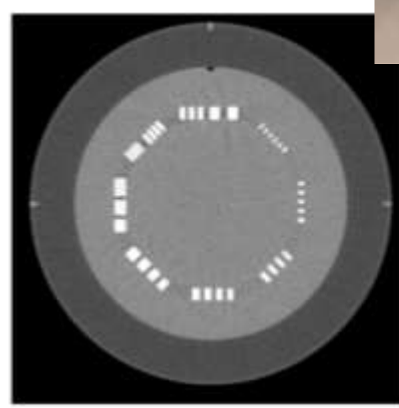




Noise



CT numbers consistency: Hounsfield Units (HU)

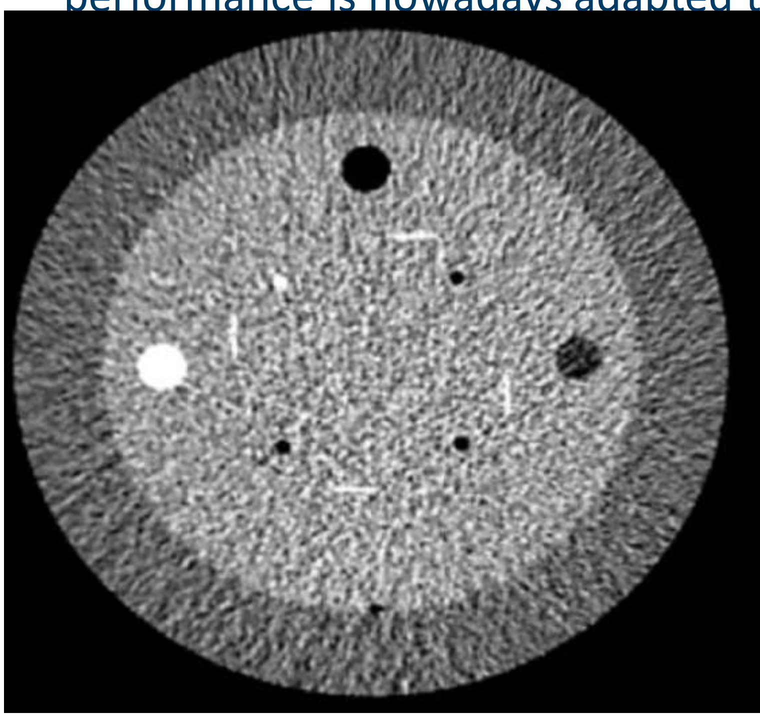


Spatial resolution: Line-pairs pattern

Geometric phantoms for IQ assessment in Radiology: limitations

- The most used phantoms to assess image quality, do not reproduce the shape nor the anatomy of the patient
- Most of this phantoms are meant to analyze aspects of image quality in 2D but lesions or anatomy is in 3D.

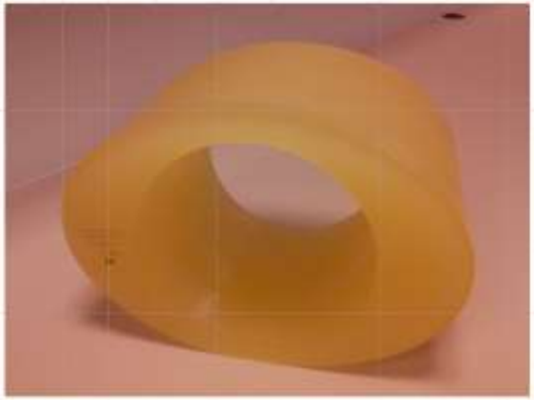
- Medical imaging systems become progressively more complicated and their performance is nowadays adapted to having in the scanner a human
  → X-ray tube out
  etry of the object
  and specially DL-
  ient data) are des



- to analyze the pe
  if they are within
  lity metrics. BUT.

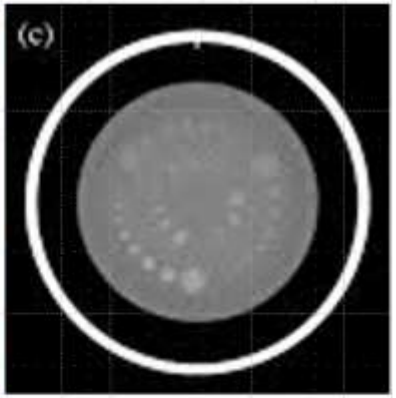
Anthropomorphic phantoms: accesories for geometric phantoms

- To mimic the shape and attenuation of the head and body of the patient, some phantoms have rings (sold separately).



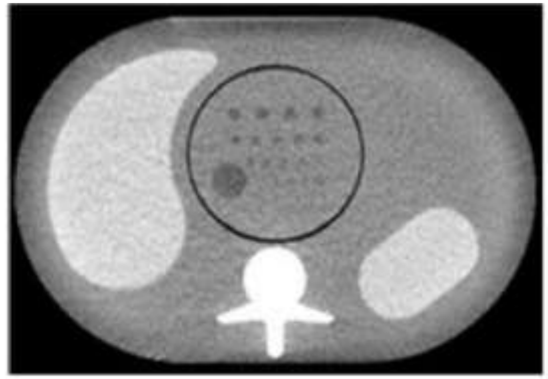
Thorax-shaped ring

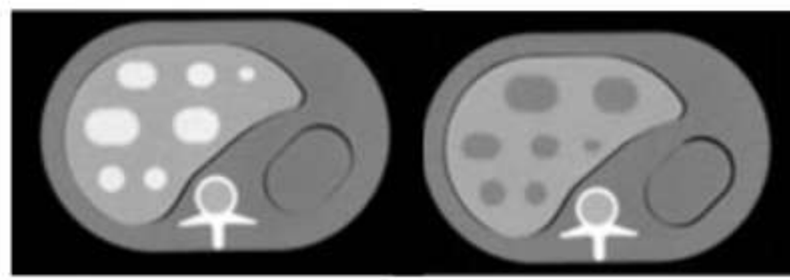
Abdominal rings



Teflon ring
(skull attenuation)

Anthropomorphic phantoms: accesories for geometric phantoms



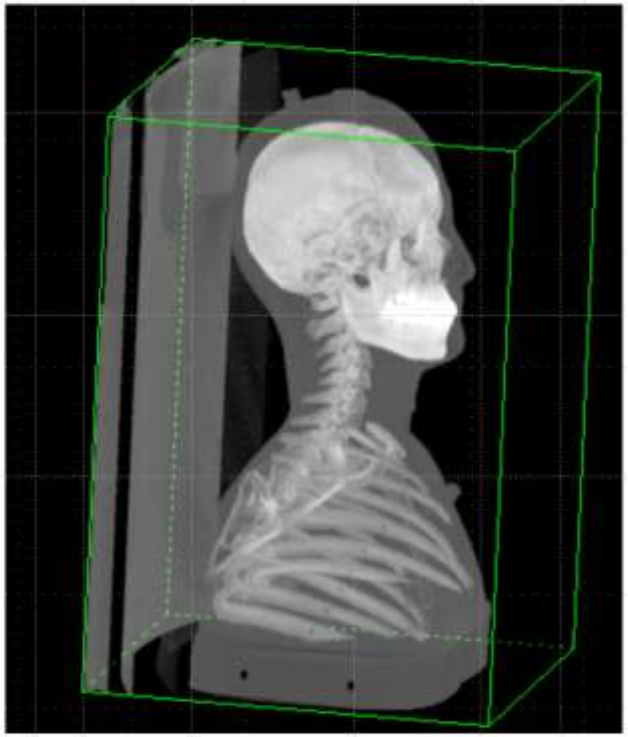


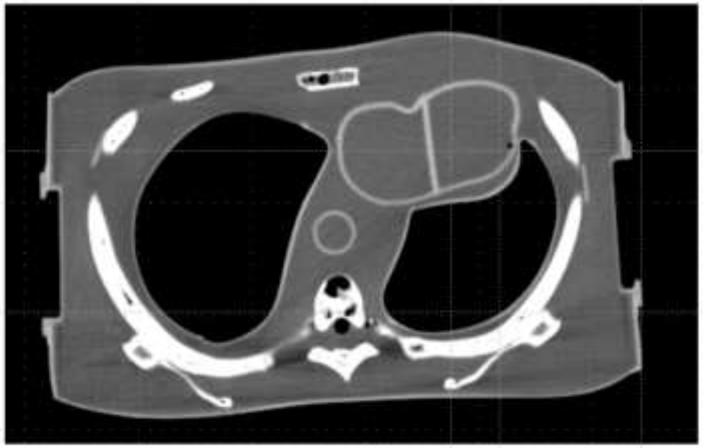
http://www.qrm.de/content/pdf/QRM-3DLC.pdf

http://www.qrm.de/content/products/anthropomorphic/extension_rings.htm

http://www.qrm.de/content/products/anthropomorphic/liver_phantom.htm

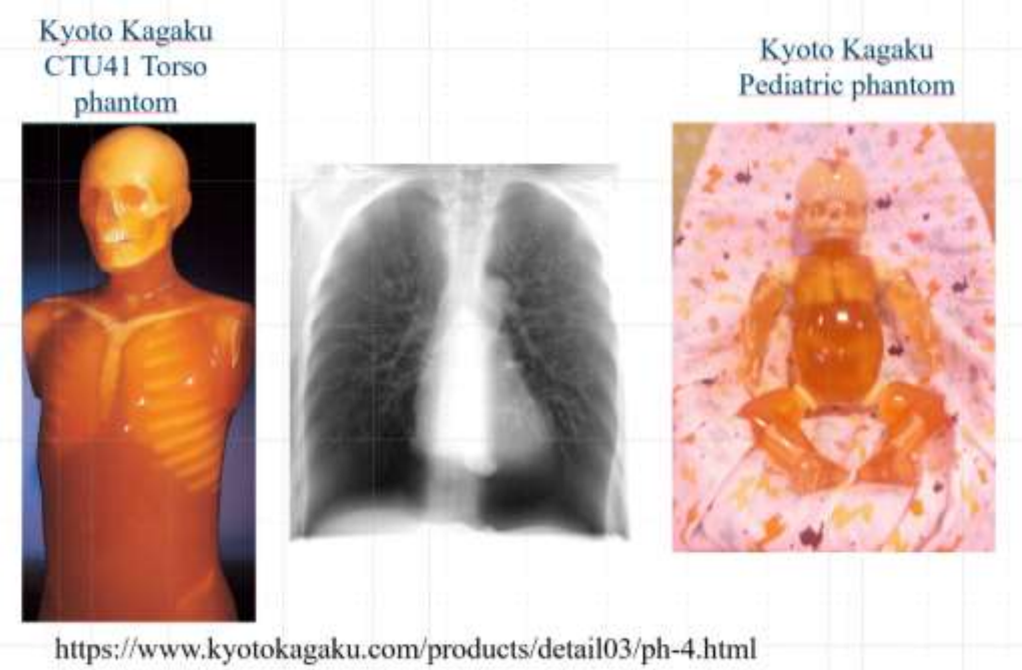
Anthropomorphic phantoms

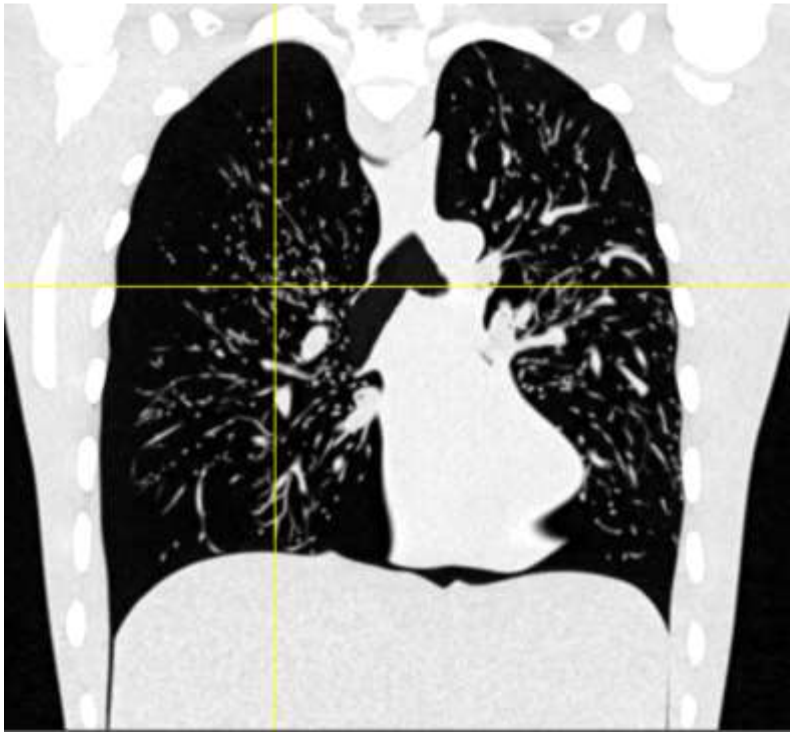




Usually organs are cast on one material each, and no tissue texture or complexity

Anthropomorphic phantoms



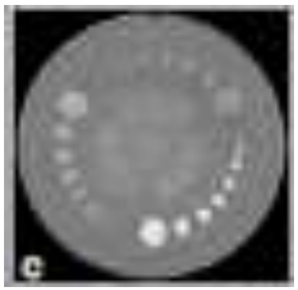


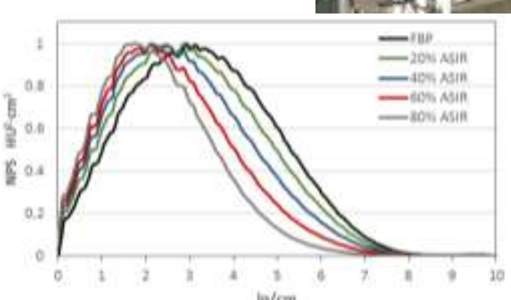
CT images courtesy of Dr. Marcel Greuter

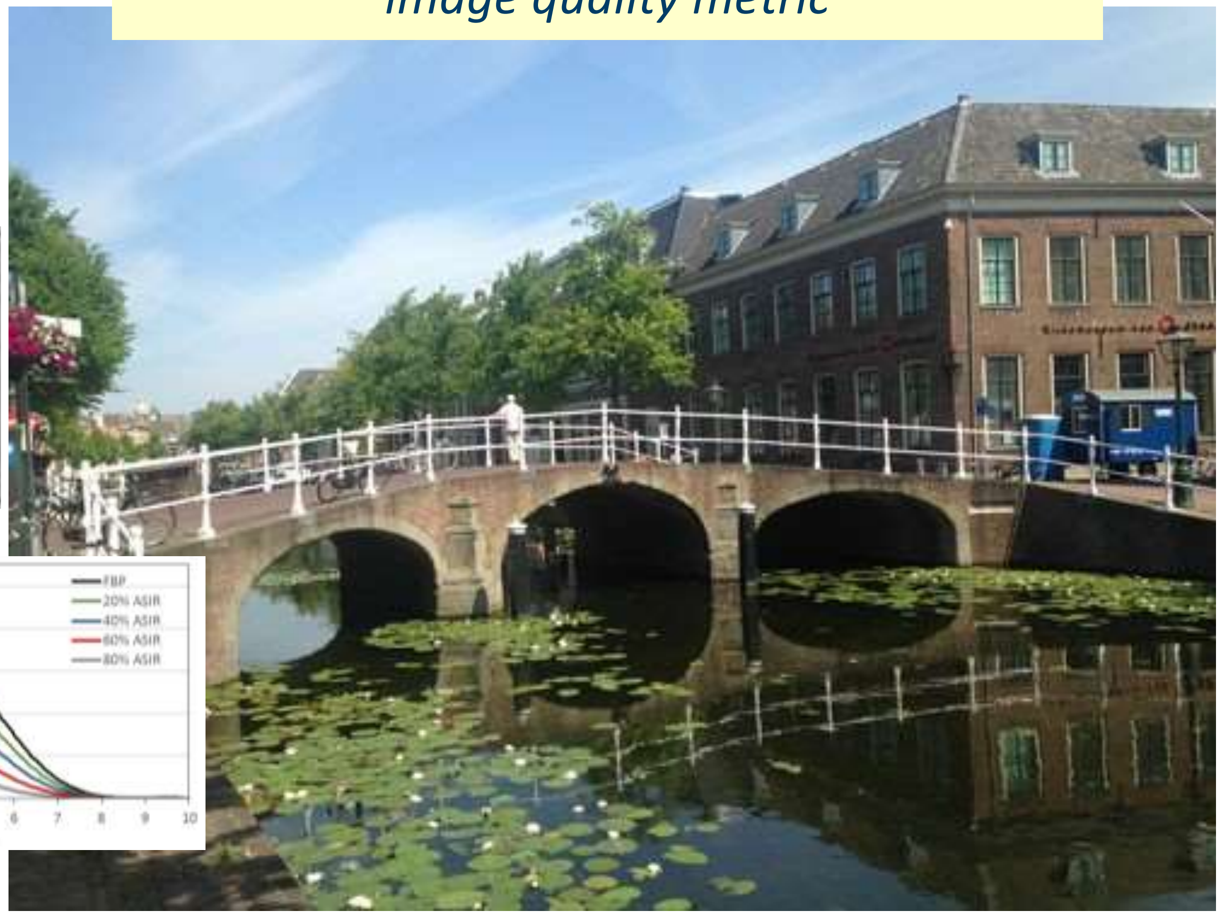
TASK-BASED

We need to define:
Clinically relevant tasks that can be translated into an objective measurment/ image quality metric

Physicists







Radiologists

CAD/AI

We need anthropomorphic phantoms that mimic tissue attenuation, anatomical distribution and patient total attenuation and shape, containing relevant lesion surrogates.

3D PRINTING

3D printing origins

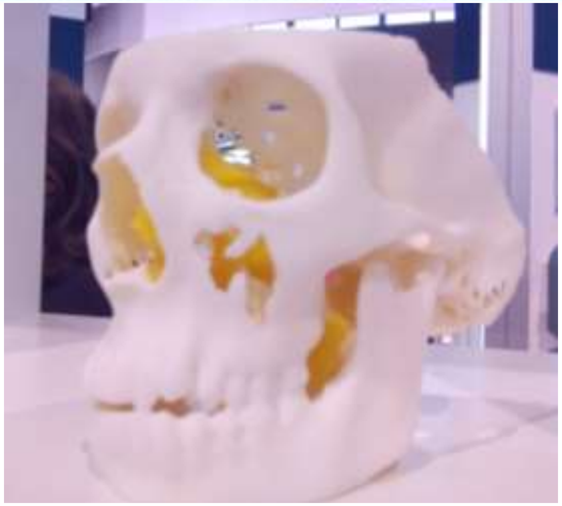
Charles Hull
Inventor of Stereolithoragphy (SLA)~ 1980s
Co-founder of 3D systems

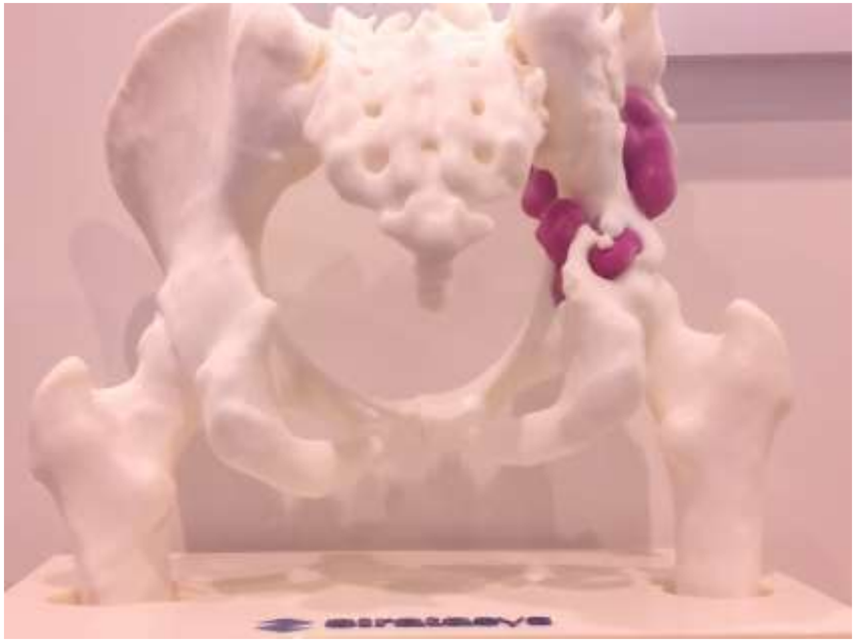
- Problem: How to prototype plastic parts to be used for injection molds? Tedious, manual process, errors in the molds…
- He also worked in a company that gave UV-cured plastic coatings to materials (furniture) layer by layer
- If you can put many of these plastic layers together, you can create a pure plastic part!
  → Stereolithography (SLA)

Video with Chuck Hull
https://www.youtube.com/watch?v=yQMJAg45gFE

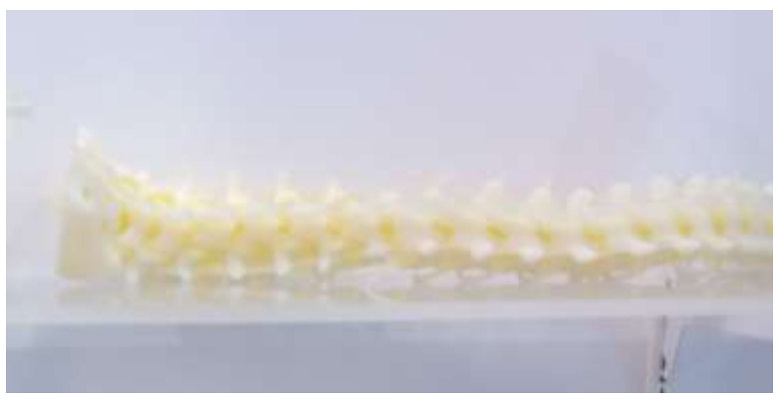
Photo from:
https://www.epo.org/learning-events/european-inventor/finalists/2014/hull.html

3D printing in Medicine: State of the art
Surgery/Treatment planning





3D printing in Medicine: State of the art
Training/demo of normal/pathological anatomy



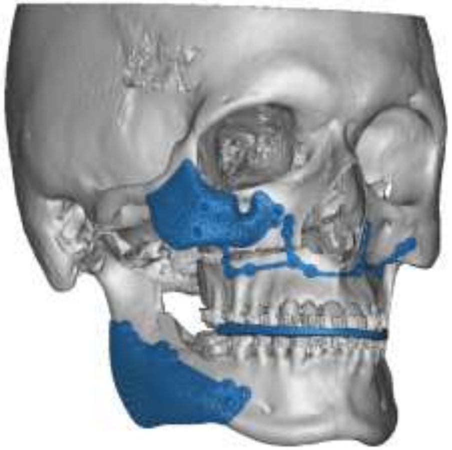
3D printing in Medicine: State of the art
Prosthesis/medical devices

ISO 13485:2016

Preview

Medical devices -- Quality management systems -- Requirements for regulatory purposes

ISO 13485:2016 specifies requirements for a quality management system where an organization needs to demonstrate its ability to provide medical devices and related services that consistently meet customer and applicable regulatory requirements. Such organizations can be involved in one or more stages of the life-cycle, including design and development, production, storage and distribution, installation, or servicing of a medical device and design and development or provision of associated activities (e.g. technical



nature > scientific reports > articles > article

SCIENTIFIC REPORTS

Article | OPEN | Published: 27 November 2014

Fabrication of low cost soft tissue prostheses with the desktop 3D printer

Yong He, Guang-huai Xue & Jian-zhong Fu

Scientific Reports **4**, Article number: 6973 (2014) | Download Citation

https://www.materialise.com/en/blog/from-superhero-mask-to-new-face-and-new-life-thanks-to-3d-printed-cmf-implants

https://www.iso.org/standard/59752.html

3D printing in Medicine: State of the art
Prosthesis/medical devices

https://www.oceanz.eu/en/about/business-cases/medisch-3d-printen-een-prothesekoker

http://enablingthefuture.org/

3D printing has a great potential in applications for prosthesis for children/adults due to the relative low cost and customization options:

- Enables to replace prosthesis as the child grows
- Increasing access to prosthesis in developing or in conflict countries

3D printing in Medical imaging
Phantoms for image quality

- **Based on patient CT images**
- **Based on models reproducing patient anatomical structures**

Solomon et al 2014
printed lung phantom
containing nodules

Phantom sample courtesy of
Paul Jahnke (PhantomX,
https://phantomx.de/)

Solomon J, Samei E. Quantum nois ... red backgrounds across
reconstruction algorithms: FBP anc

Phantoms based on 3D printing for medical imaging applications

MEDICAL PHYSICS
The International Journal of Medical Physics Research and Practice

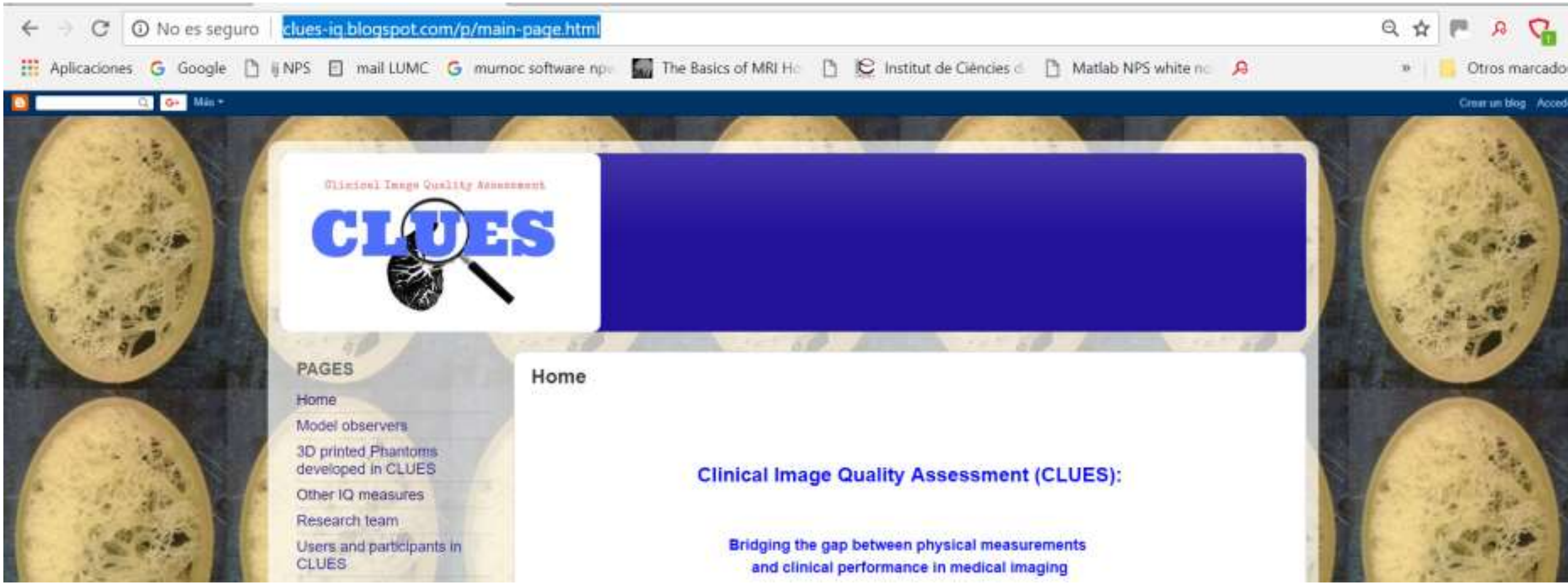
Review Article | Open Access

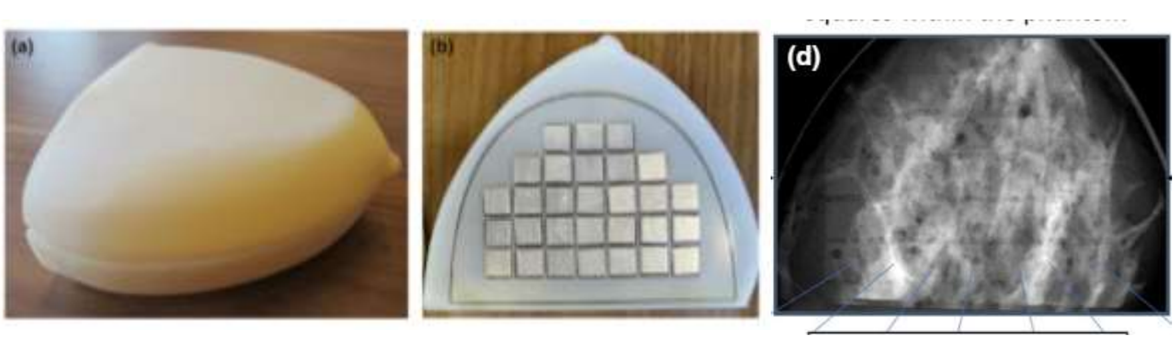
Recent advances on the development of phantoms using 3D printing for imaging with CT, MRI, PET, SPECT, and ultrasound

Valeria Filippou, Charalampos Tsoumpas

First published: 22 June 2018 | https://doi.org/10.1002/mp.13058 | Citations: 105

CLUES Project (2015-2019)





Balta et al. A model observer study using acquired mammographic images of an anthropomorphic breast phantom Med Phys 2018;45(2):655-665

http://clues-iq.blogspot.com/p/main-page.html

NWO- Veni Talent Scheme Programa Project (Jan 2020-Jan 2023):

Through the eyes of AI:

safe and optimal integration of artificial intelligence in radiology

Radiologists

Develpment of anthropomorphic test objects as patient surrogates, with a known ground truth to evaluate the effect of acquisition and reconstruction parameters on CAD/AI performance in CT

CAD/AI

Goal

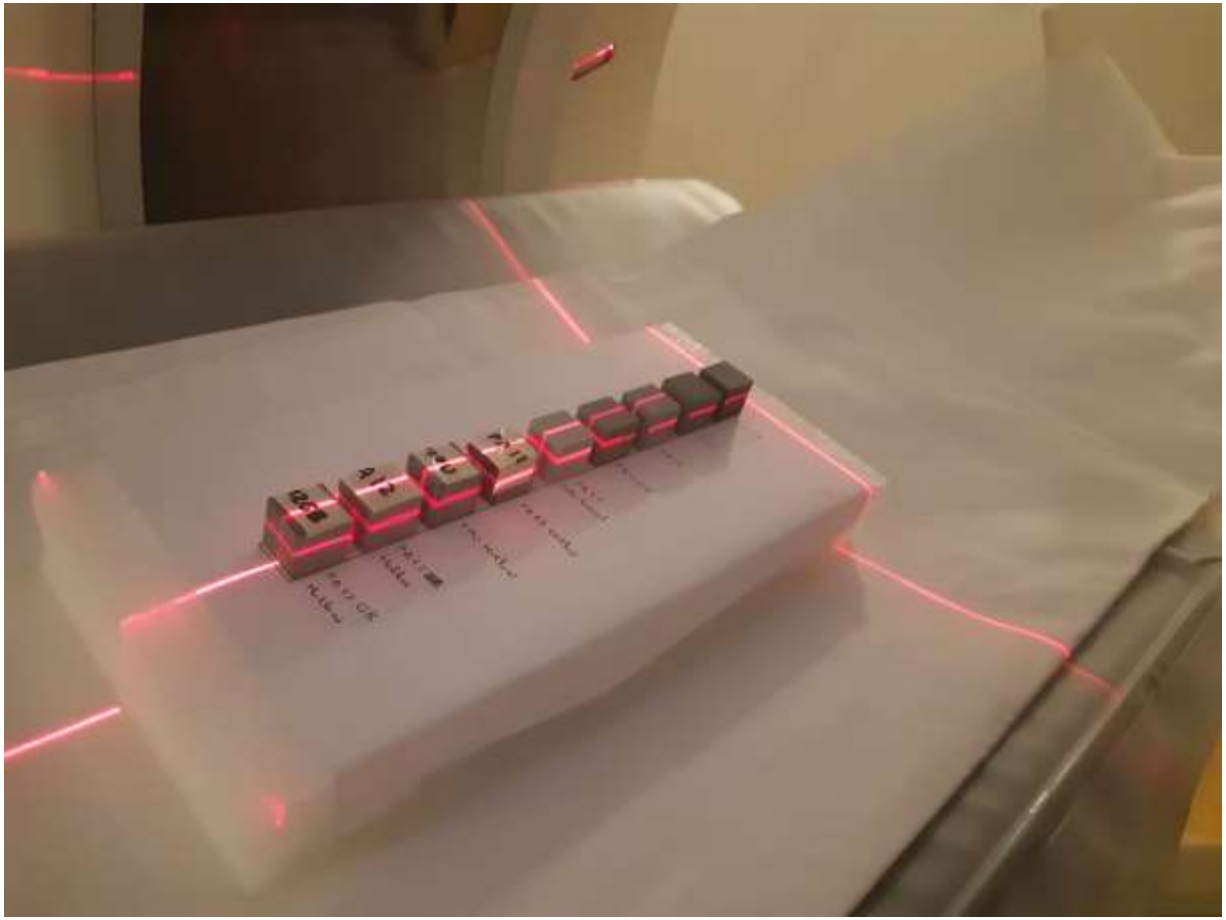
- We wanted an anthropomorphic phantom for CT image quality assessment that was portable and designed for specific diagnostic tasks.
- We looked into CT thorax imaging
- Lung vessel detection and quantification is used to determine patient diagnosis and disease stage and evolution
- These diagnostic tasks are performed by humans (segmenting CT images by hand) or with automatic algorithms
- Having a test object where the ground truth is known (custom model) can help to determine the influence of different acquisition and reconstruction parameters in image quality, in particular their effect in vessel quantification.
- Such phantom can be used for QA of CT systems, comparison and benchmark of CT protocols and systems…
- Such a phantom could be combined with inserted lesions as surrogates for lung nodules

3D printed anthropomorphic phantoms for CT

Checklist and things to think about:

- The materials need to mimic to some extend the X-ray attenuation of the target tissues
- Metals are usually forbidden (unless in small quantity and in powder form, to increase attenuation and not produce artifacts or to test metal artifact influence on IQ)
- Multimaterial printing still needs development
- Image quality phantoms is very niche in 3D printing, usually regular providers do not know about it. Problems with finishing methods, for instance can arise
- 3d printing materials are plastic based, the same commercial name for a plastic does not neccesarily mean that the HU in CT will be the expected

Evaluation of attenuation of 3D printing materials in CT imaging



Measure pixel value in ROIs over several images, averaged between several scans, for each material. Try to match, HU values in tissues to potential 3D printing materials candidates

Initiatives for libraries of materials and 3D printing providers

ORIGINAL RESEARCH article

Front. Bioeng. Biotechnol., 29 November 2021 | https://doi.org/10.3389/fbioe.2021.763960

Check for updates

Classification of X-Ray Attenuation Properties of Additive Manufacturing and 3D Printing Materials Using Computed Tomography From 70 to 140 kVp

es

Xiangjie Ma[1], Martin Buschmann[2], Ewald Unger[1] and Peter Homolka[1]*

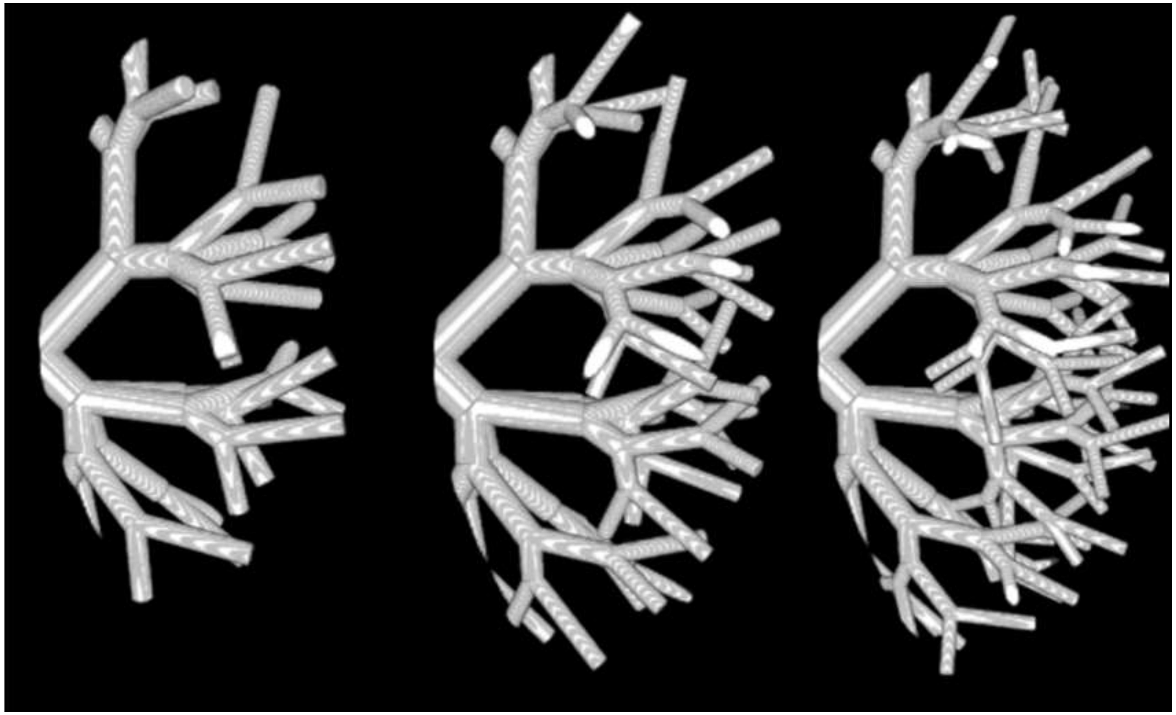
[1]Center for Medical Physics and Biomedical Engineering, Medical University of Vienna, Vienna, Austria

[2]Division of Medical Radiation Physics, Department of Radiation Oncology, Medical University of Vienna, Vienna, Austria

Some companies provide sample material kits that you can scan to find out potential tissue equivalents. Otherwise, create a simple and small model (cube 2x2x2cm) as test.

https://www.frontiersin.org/articles/10.3389/fbioe.2021.763960/full

Lung vessel model



14 generations of vessels, diameters down to 0.2 mm, ~20000 vessels

Weibel ER. What makes a good lung? Swiss Med Wkl 2009;139 (27–28):375–386

Weibel ER, Gomez DM. Architecture of the human lung. Use of quantitative methods establishes fundamental relations between size and number of lung structures. Science 1962;137(3530):577-85.

From model to 3D printed phantom

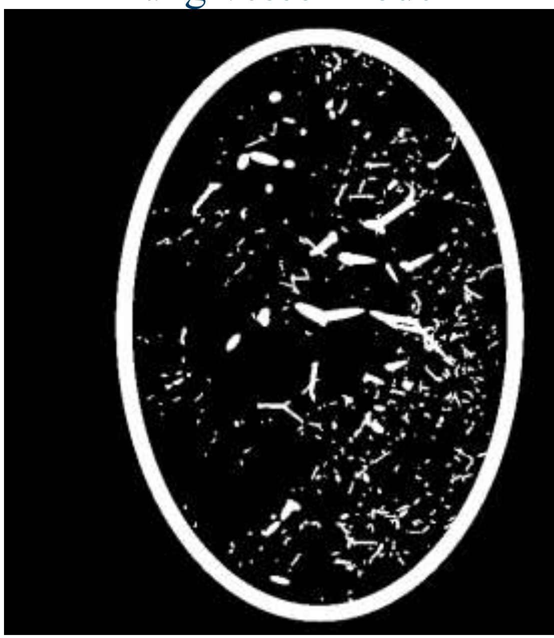
3d printer

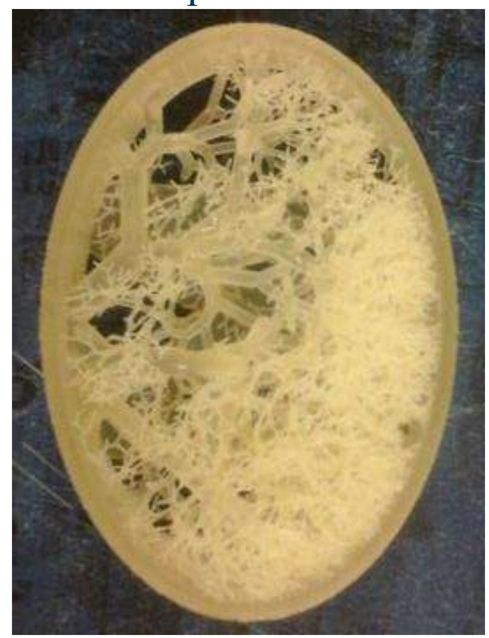
ProJet HD 3000
MJM technique (UHD)
32µm layer thickness
Resolution 656x656x800 DPI

Lung vessel model

STL file

3D printer





Material:
Visijet EX200
Density: 1.1 g·cm^{-3}
~105 HU@ 120 kV

Smallest vessels:
0.2 mm diameter

Phantom dimensions:
150x103x26 mm

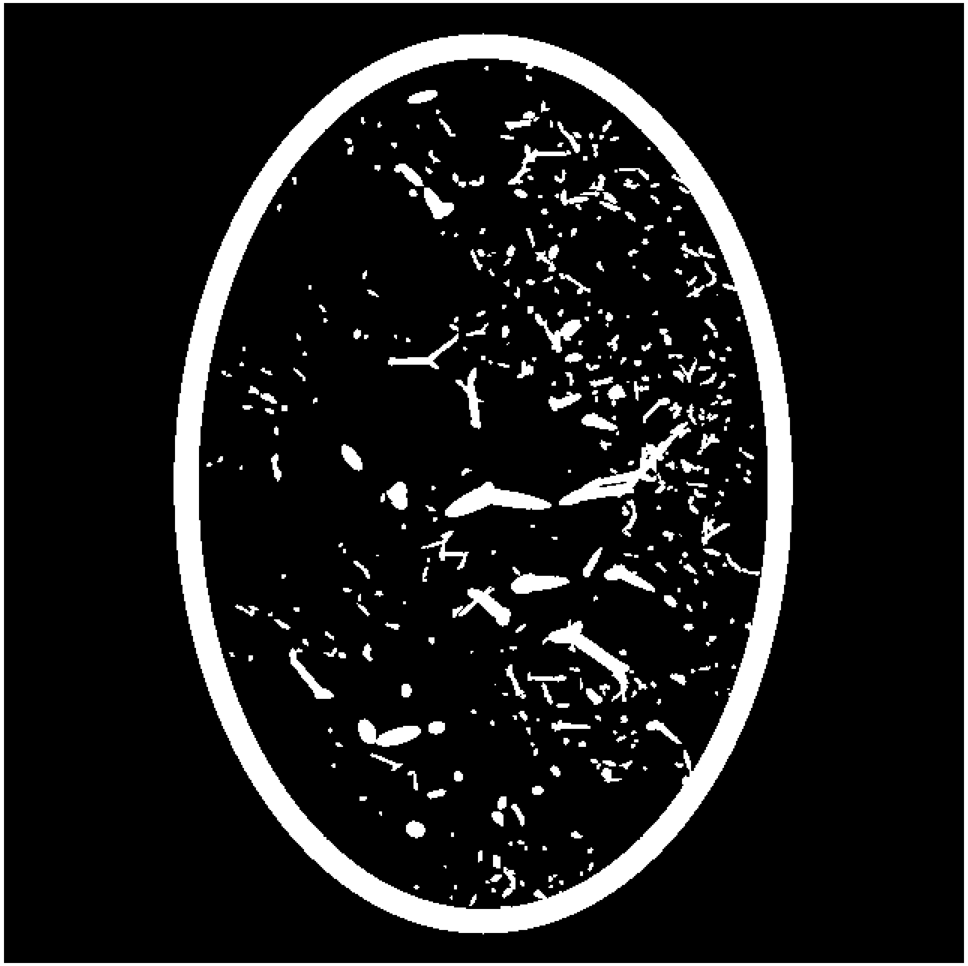
Weibel ER. What makes a good lung? Swiss Med Wkl 2009;139 (27–28):375–386

Weibel ER, Gomez DM. Architecture of the human lung. Use of quantitative methods establishes fundamental relations between size and number of lung structures. Science 1962;137(3530):577-85.

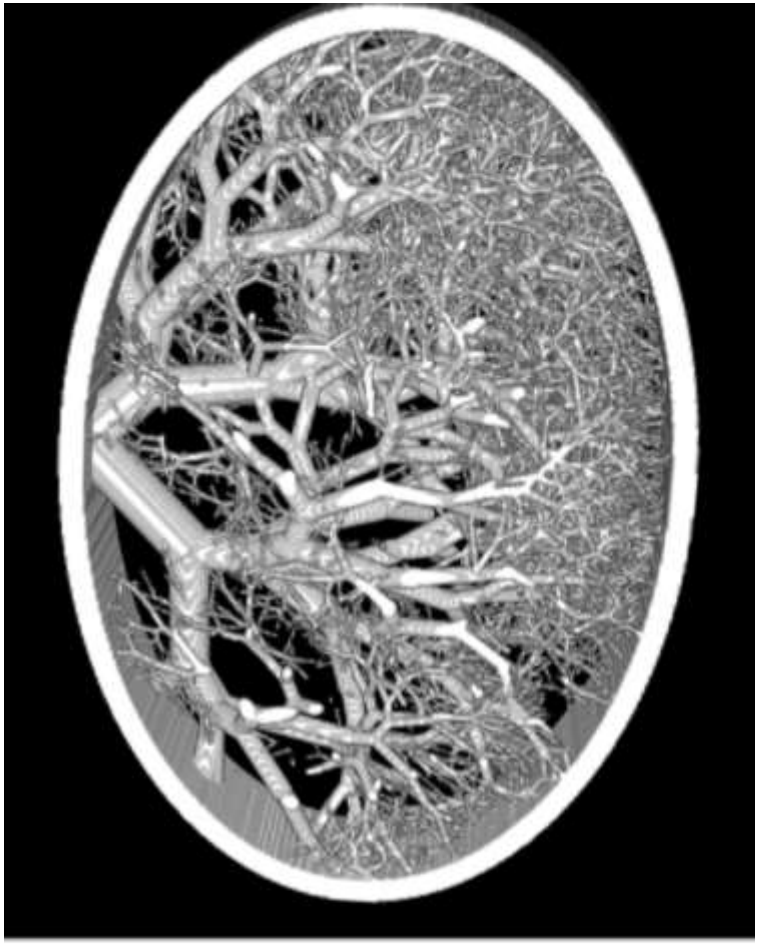
Initial lung vessel model software design by Dr. Chiel den Harder

Mathematical lung vessel model

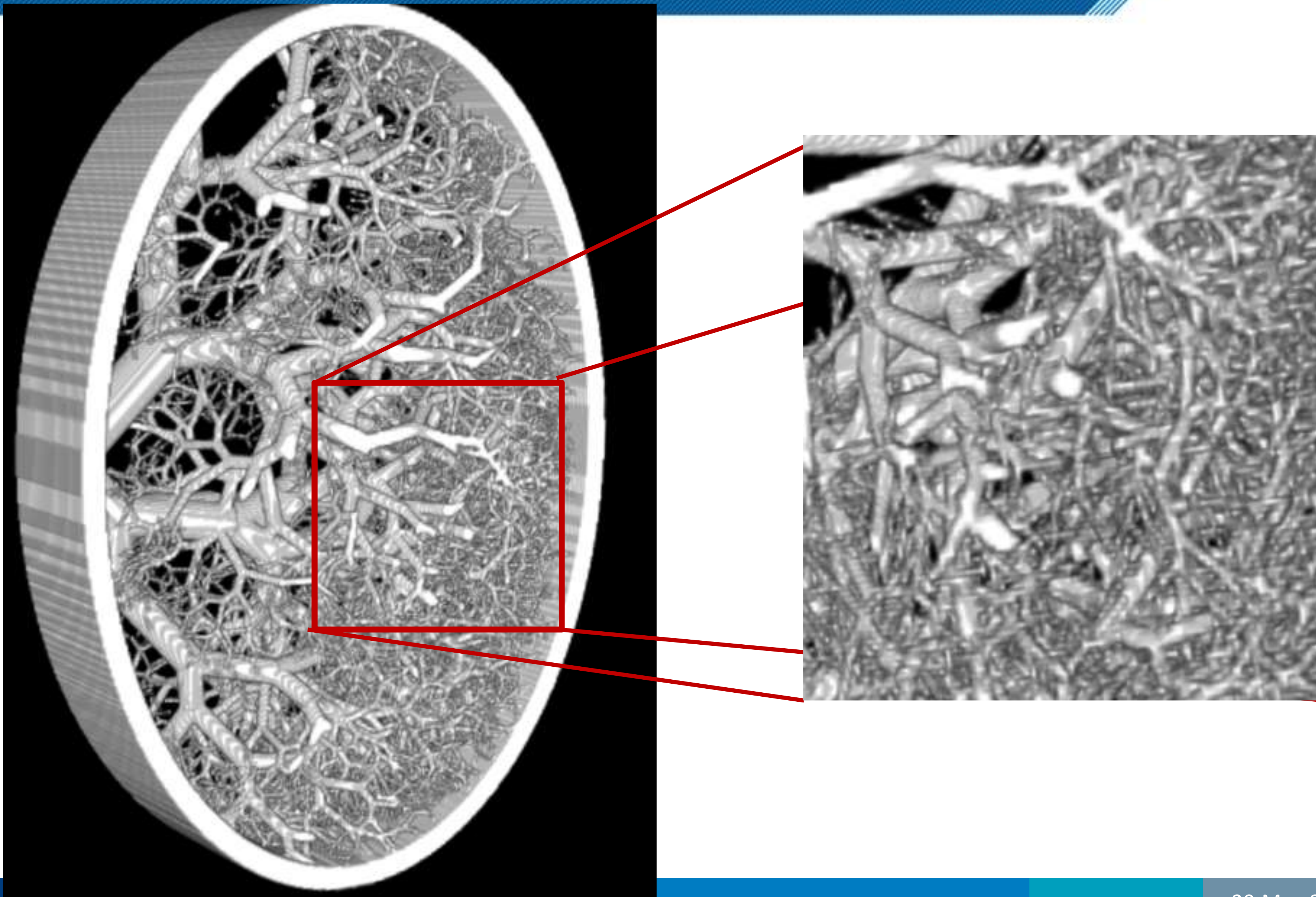
Mathematical model output

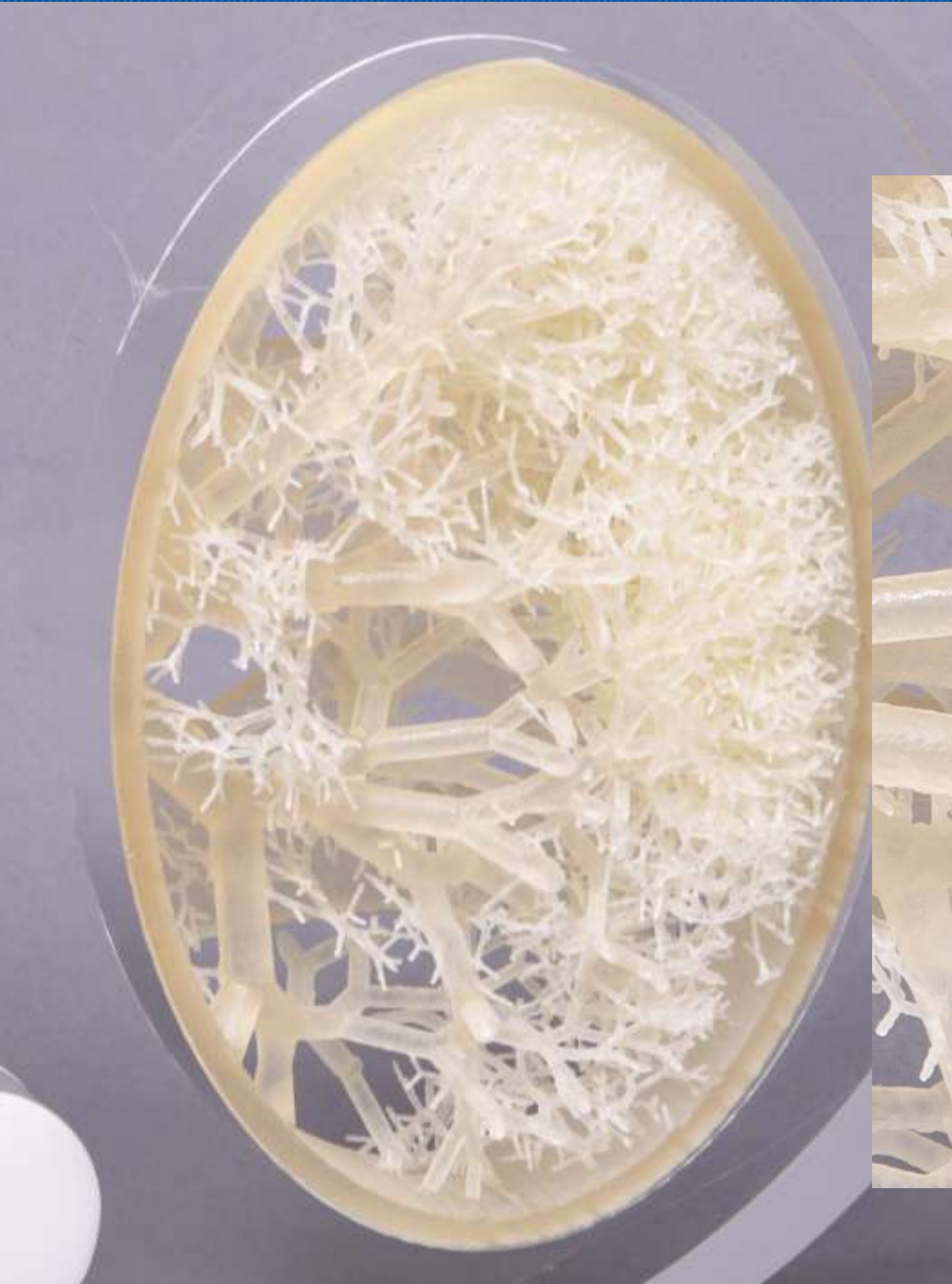


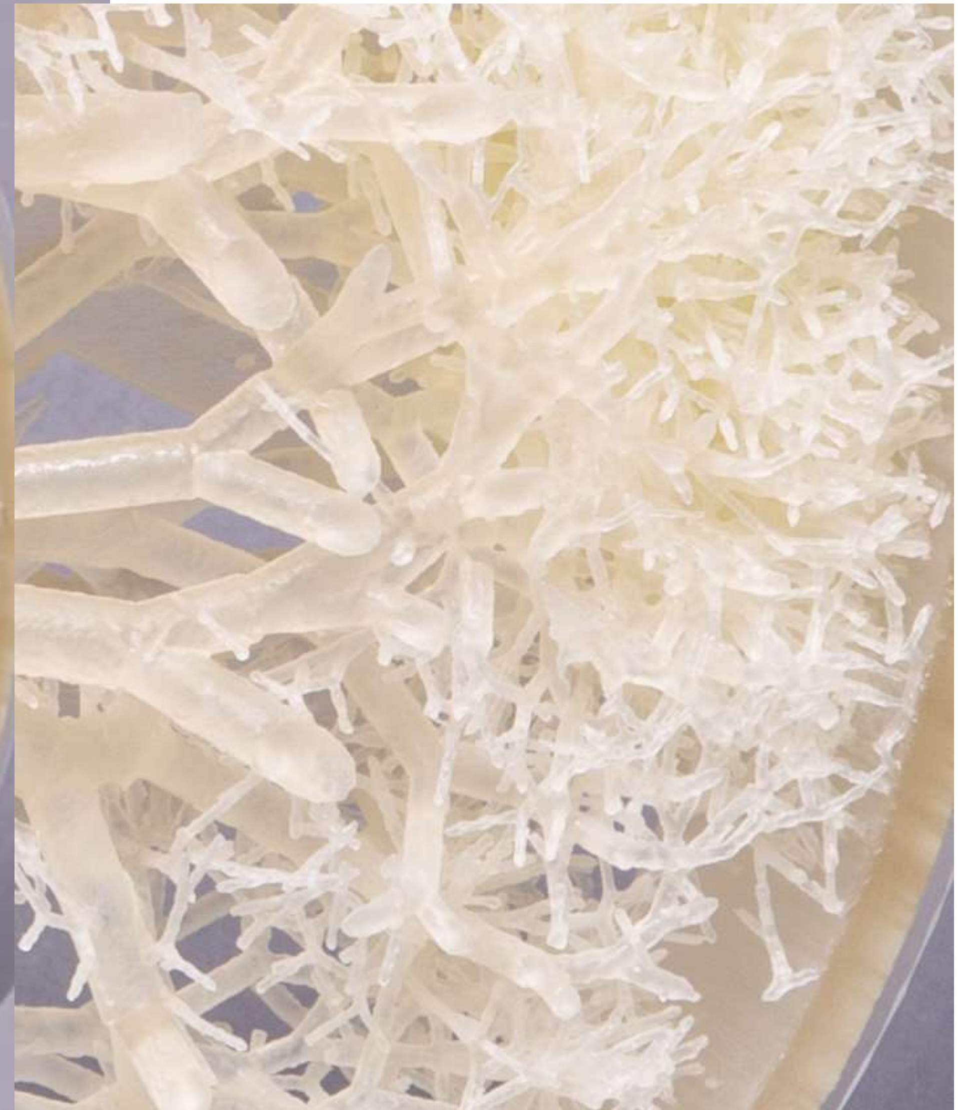
3D rendering



Mathematical lung vessel model







3D printed lung vessel phantom

Thorax-shaped holder

30x20x2.5 cm

10x15x2.5 cm

Physica Medica 57 (2019) 47–57

Contents lists available at ScienceDirect

Physica Medica

journal homepage: www.elsevier.com/locate/ejmp

ELSEVIER

Original paper

Development of a 3D printed anthropomorphic lung phantom for image quality assessment in CT

Check for updates

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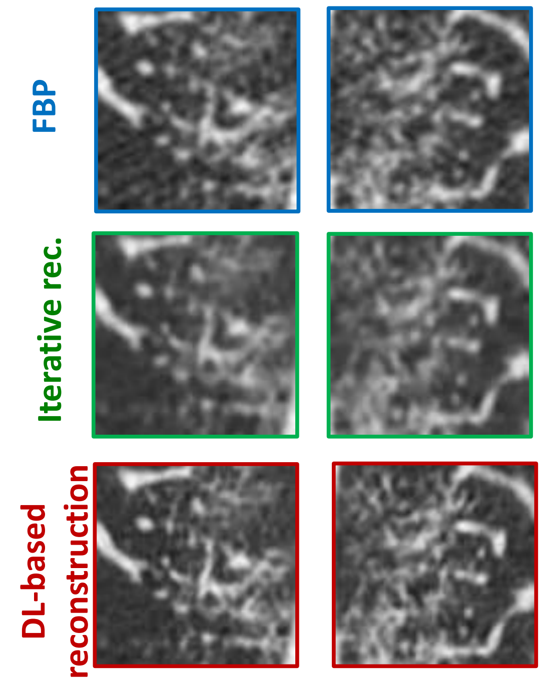
[b] *Academic Medical Center (AMC), Amsterdam, The Netherlands*

Simulation of printing process different materials, same printer

Strength test material 1

Strength test material 2

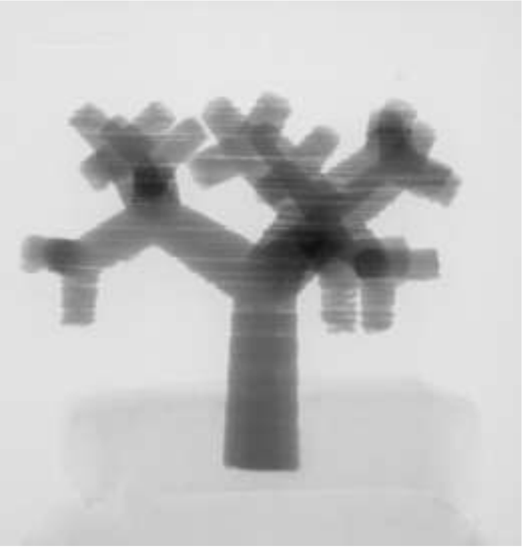
Visual inspection: CT images



What is our phantom gold standard? Our design file? What changes can have happened between desing till printing?

3D printing pilot and micro-CT

Small fractal vessel tree, BCN stratos printer, PLA, 150 micros layers



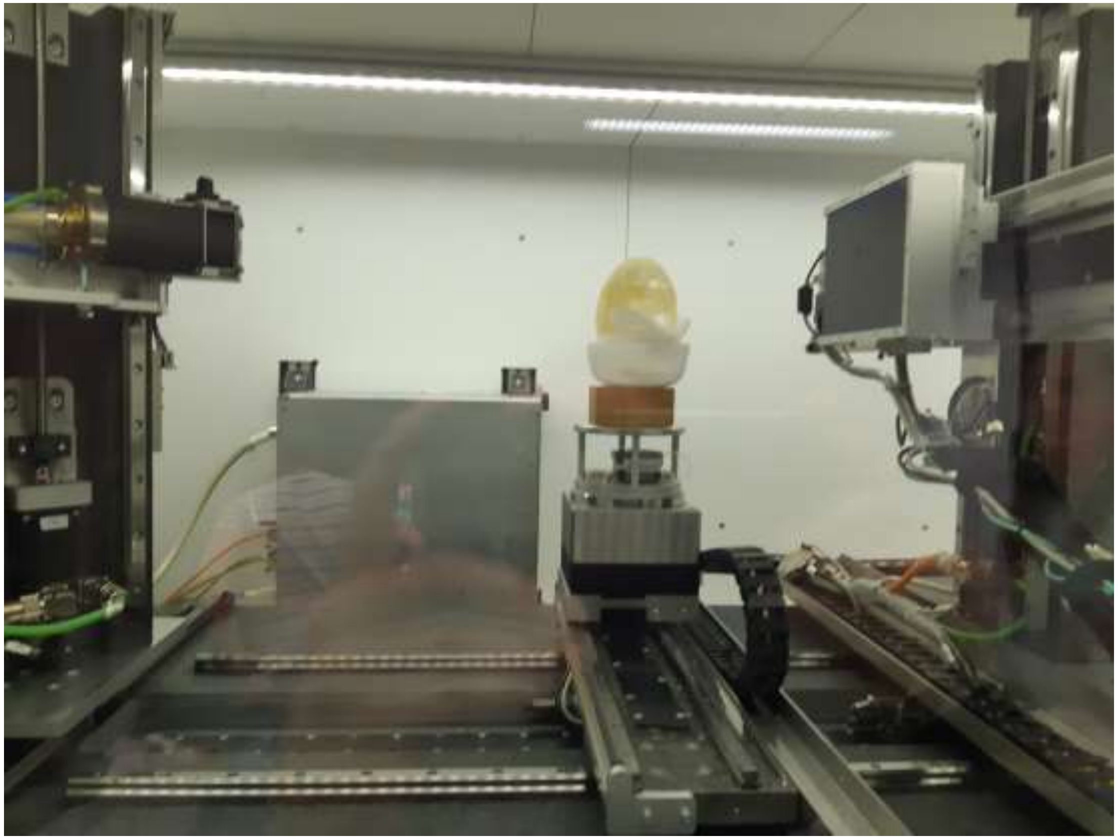
Micro-CT projections 50kV, 100µA, 1s, 2000 projections

3D rendering based on micro-CT images

Cooperation with Dr. Chevalier, MsC Belarra and MsC student Sara de Scals, Universidad Complutense de Madrid (UCM)

Mathematical model (segmented by thresholding)

Micro-CT imaging: Obtaining a gold standard for 3D printed object



Flex Ray Lab

CWI

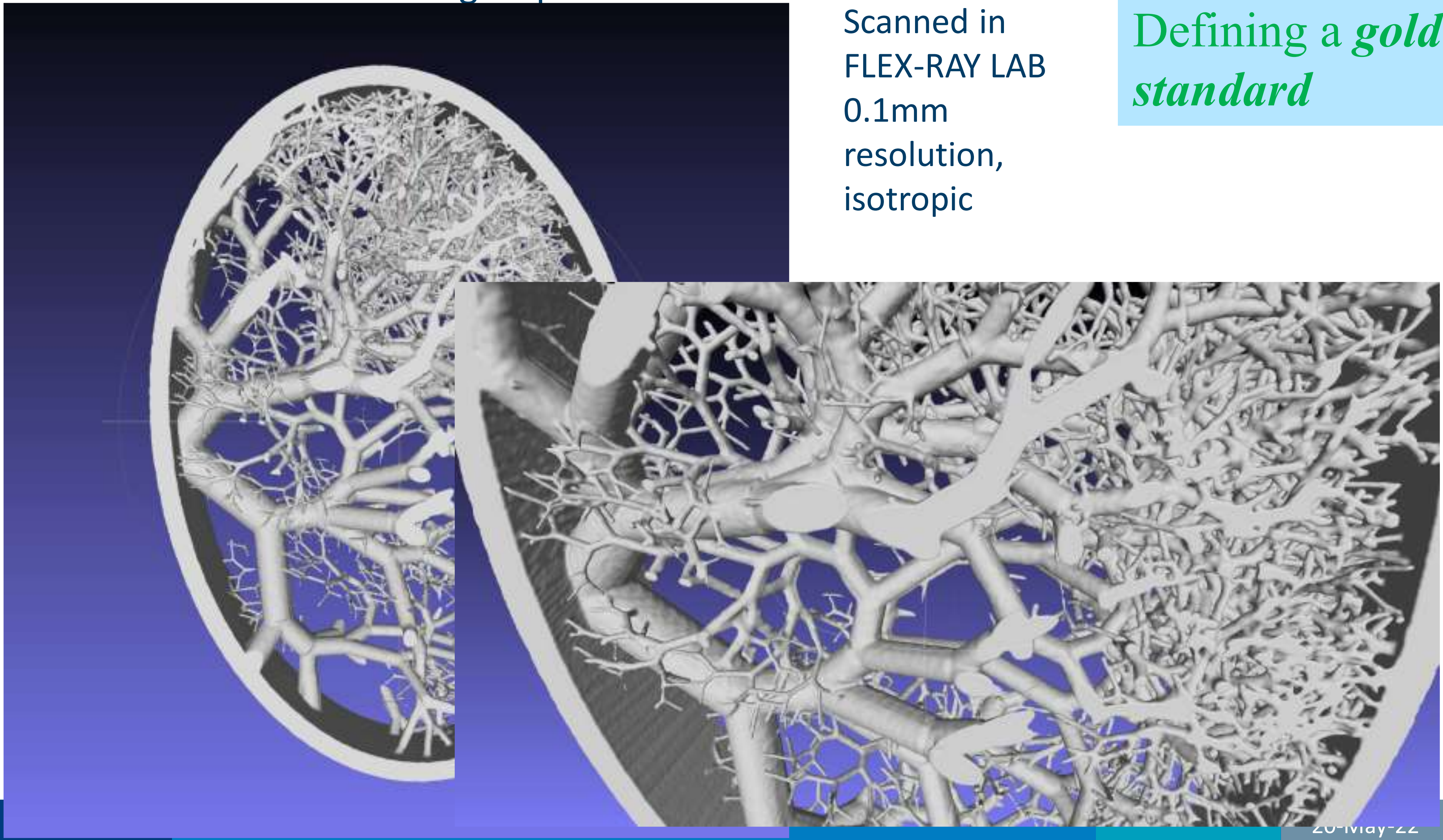
Centrum Wiskunde & Informatica

Micro-CT (CWI)

Images courtesy of Jan Matula and Felix Lucka, cooperation with Tristan van Leeuwen’s group

Scanned in FLEX-RAY LAB 0.1mm resolution, isotropic

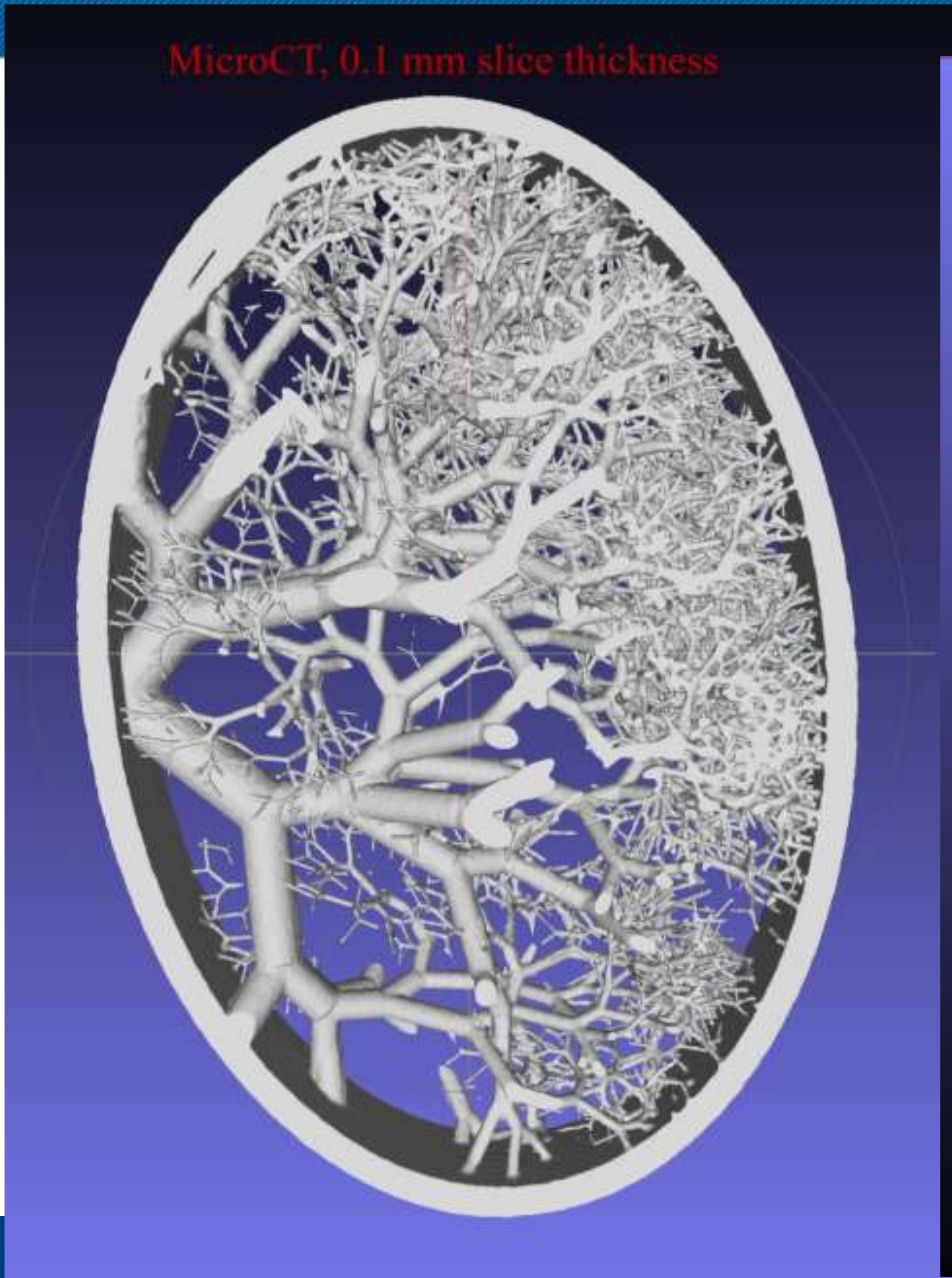
Defining a ***gold standard***

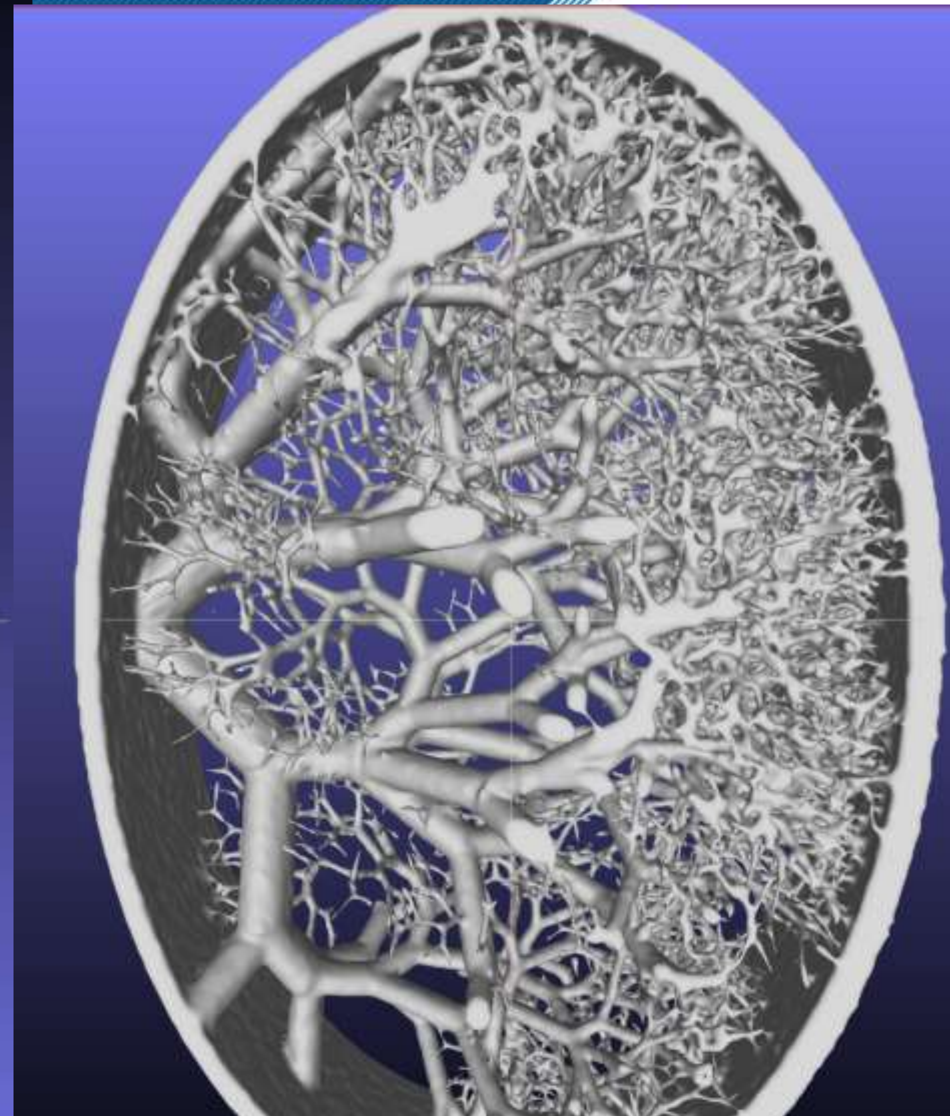


Mathematical model

MicroCT

PCCT, 0.2mm slice thicknes
0.3125mms/px

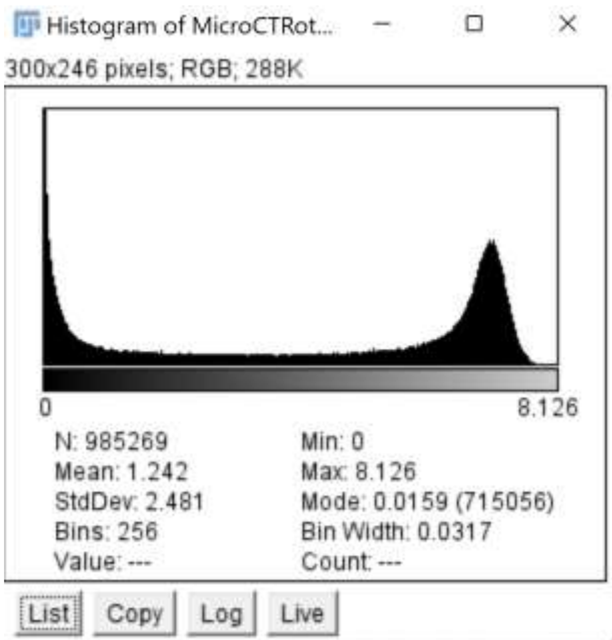




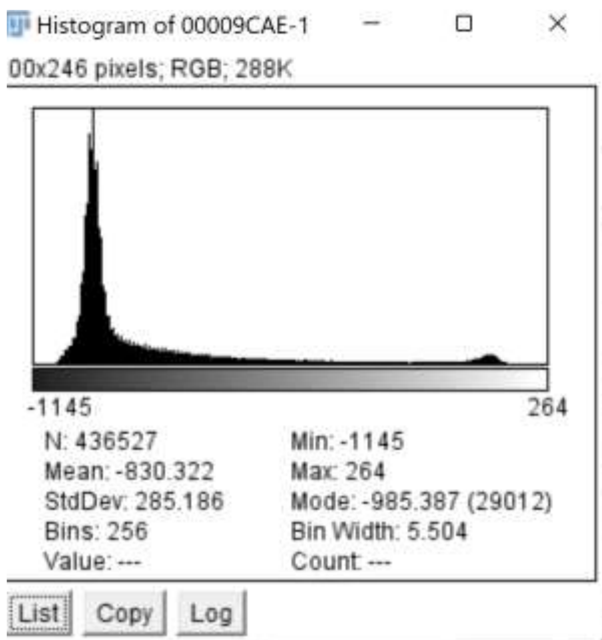
Cooperation with Erasmus MC, to be presented at ECR July 2022

Pixel value (attenuation) quantification

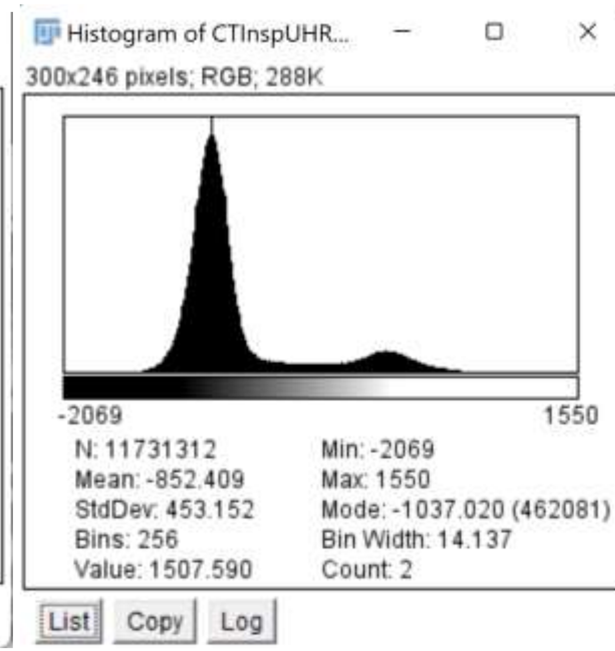
MicroCT



State of the art CT



Photon Counting CT



- Different system filtration, different kV → Different X-ray spectrum and photon penetration
- This affects the range of different contrast values that can be visualized simultaneously

Using micro-CT imaging for QC of 3d printed objects

ELSEVIER

MethodsX

Volume 5, 2018, Pages 1102-1110

Method Article

Standard method for microCT-based additive manufacturing quality control 1: Porosity analysis

Anton du Plessis [a], Philip Sperling [b], Andre Beerlink [b], Lerato Tshabalala [c], Shaik Hoosain [c], Ntombi Mathe [c], Stephan G. le Roux [a]

3D Printing and Additive Manufacturing > Vol. 5, No. 3 > Original Articles   Open Access

X-Ray Microcomputed Tomography in Additive Manufacturing: A Review of the Current Technology and Applications

Anton du Plessis, Igor Yadroitsev, Ina Yadroitsava, and Stephan G. Le Roux

Published Online: 13 Sep 2018 | https://doi.org/10.1089/3dp.2018.0060

Room for development for micro-CT imaging wrt phantoms characterization

- Making micro-CT a more quantitative imaging modality
- How to expand the [partially hidden] contrast resolution for different materials
- Stablishment of QC [partially hidden] tion of 3D printed objects (how many projectio[partially hidden] econstruction…)
- Methods to benchm[partially hidden] to micro-CT images (work in progress: image r[partially hidden] s SSIM, Haralick's texture parameters, SSIM…)
- Optimization of mic[partially hidden] en time and results, depending on intend[partially hidden]

Thank you, Bedankt, Gracias!