X-ray microtomography

David Haberthür

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Grüessech!

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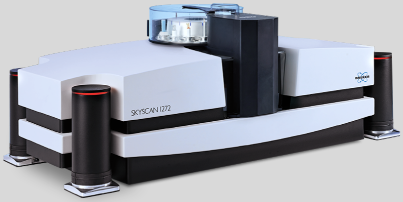
- David Haberthür
  - Physicist by trade
  - PhD in high resolution imaging of the lung, Institute of Anatomy, University of Bern, Switzerland
  - Post-Doc I: Tomographic imaging at TOMCAT, Swiss Light Source, Paul Scherrer Institute, Switzerland and working on the detector of the GlobalDiagnostiX project
  - Post-Doc II & currently: Tomographic imaging in the µCT group, Institute of Anatomy, University of Bern, Switzerland

µCT-group

- microangioCT [1]
  - Angiogenesis: heart, musculature [2] and bones
  - Vasculature: (mouse) brain [3], (human) nerve scaffolds [4], (human) skin flaps [5] and tumors
- Zebrafish musculature and gills [6]
- (Lung) tumor detection and metastasis classification [7]
- Collaborations with museums [8] and scientist at UniBe [9] to scan a wide range of specimens
- Automate *all* the things! [10]



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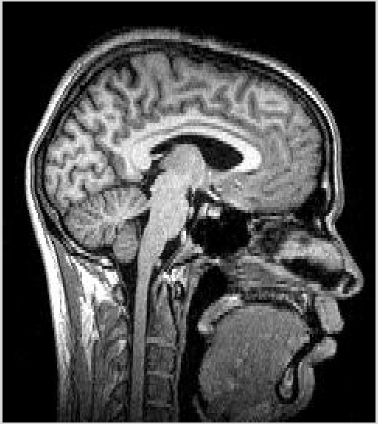
Contents

Biomedical imaging

- Medical research
- Non-destructive insights into the samples
- (Small) biological samples



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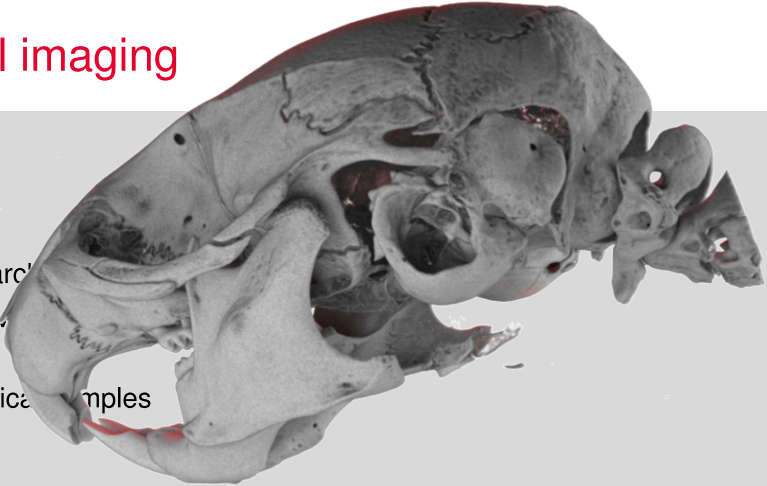
Biomedical imaging



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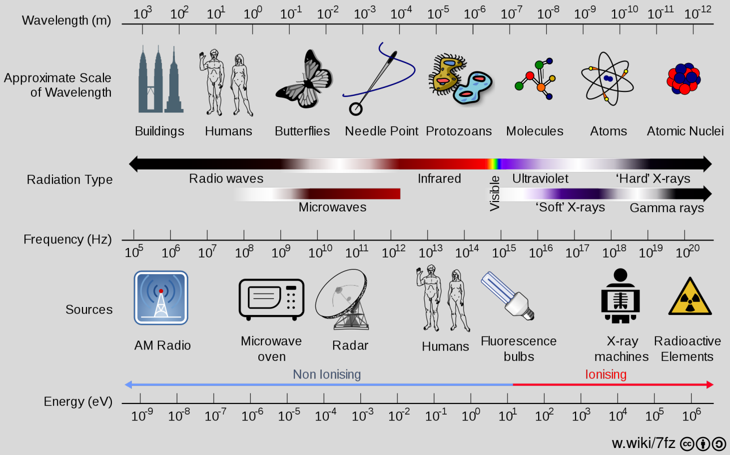
- (Small) biologica mples

Wavelength and scales



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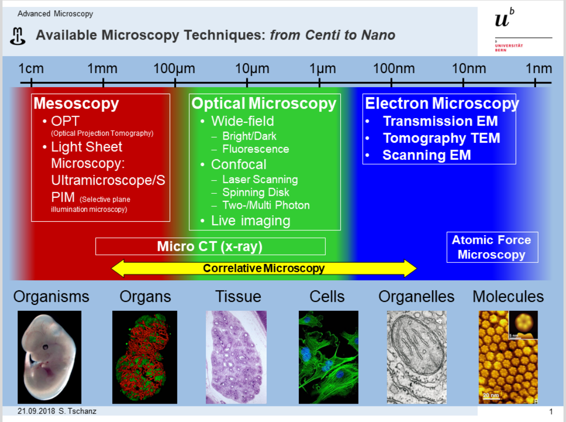


Stefan Tschanz, with permission

Imaging methods

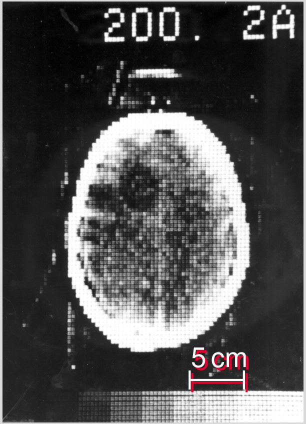
- Light (sheet) microscopy: see lecture of Myra Chavez
- X-ray imaging
- Electron microscopy: see lectures *Transmission Electron Microscopy* by Dimitri Vanhecke, *Scanning Electron Microscopy* by Sabine Kässmeyer & Ivana Jaric and *Cryoelectron Microscopy & Serial Block Face SEM* by Ioan Iacovache.

CT-Scanner

youtu.be/2CWpZKuy-NE

History

- Long history
  - 1963: Cormack used a collimated ^{60}Co source and a Geiger counter as a detector [11]
  - 1976: Hounsfield worked on first clinical scanner [12]
  - Nice overview by Hsieh [13]



From [14], Figure 5

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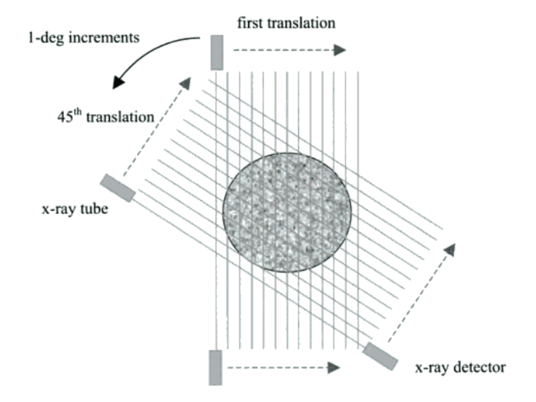
- CT scanner generations: First



From [13], Figure 1.12

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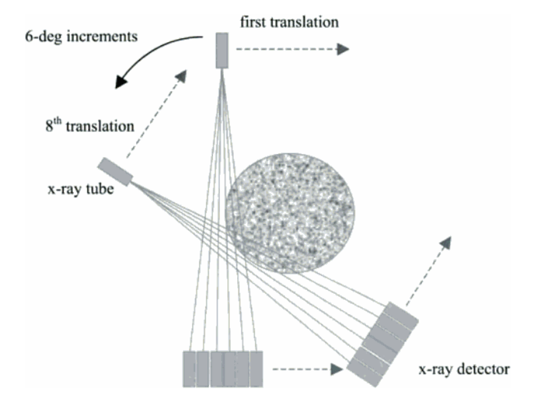
- CT scanner generations: First, second



From [13], Figure 1.13

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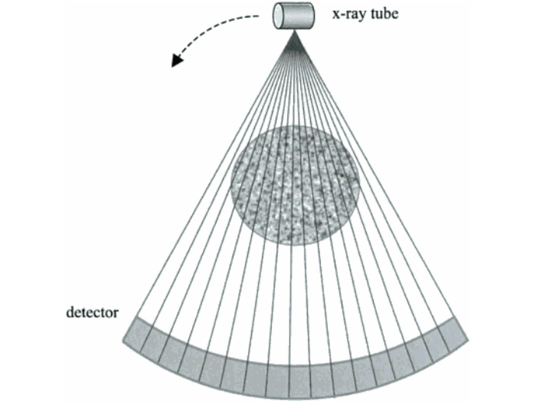
- CT scanner generations: First, second and third



From [13], Figure 1.14

X-ray interaction

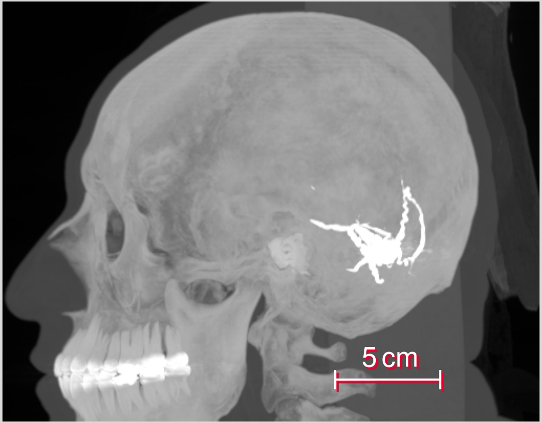
- "X-rays interact with tissue in 2 main ways: photoelectric effect and Compton scatter. To a first approximation, the photoelectric effect contributes to contrast while the Compton effect contributes to noise. Both contribute to dose." ([15])
  - Photoelectric absorption (τ) is strongly dependent on the atomic number Z of the absorbing material: $\tau \propto \frac{Z^4}{E^{3.5}}$
  - Compton scattering is one of the principle forms of photon interaction and is directly proportional to the electron density and physical density of the material. Compton scattering does *not* depend on the atomic number: $\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$
- Lowering X-ray energy increases contrast
- X-ray penetration decreases exponentially with sample thickness ([16, i. e. Beer-Lamberts law] $I(t) = I_0 e^{-\alpha z}$

Composition of biological tissues

Tissue: content by mass percentage

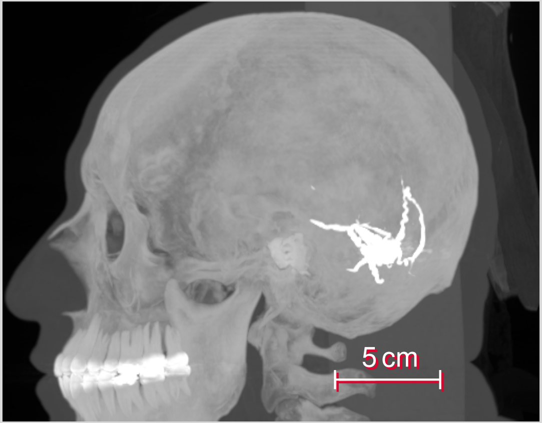
Element	H	C	N	O	Na	P	S	Cl	K	Ca
Atomic number	1	6	7	8	11	15	16	17	19	20
Fat	11.4	59.8	0.7	27.8	0.1		0.1	0.1		
Water	11.2			88.8						
Blood	10.2	11	3.3	74.5	0.1	0.1	0.2	0.3	0.2	
Liver	10.2	13.9	3	71.6	0.3	0.2	0.3	0.2	0.3	
Brain	10.7	14.5	2.2	71.2	0.2	0.4	0.2	0.3	0.3	
Bone	3.4	15.5	4.2	43.5	0.1	10.3	0.3			22.5

Why µCT?



From [17], Subject *C3L-02465*

Why µCT?



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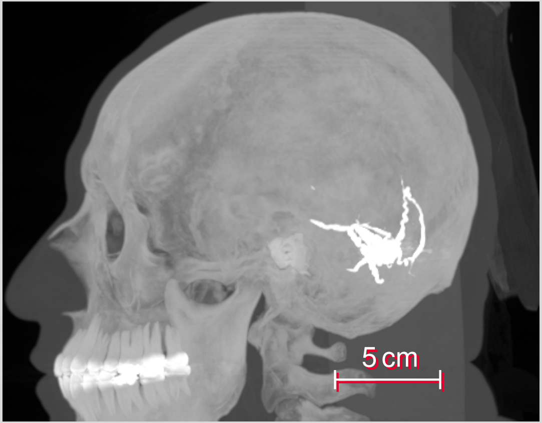

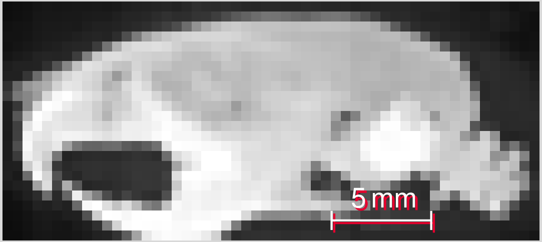

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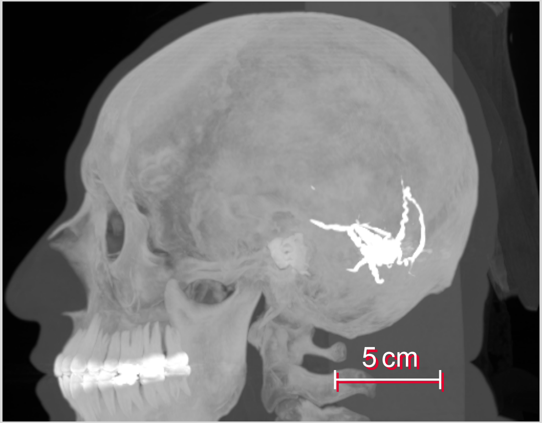

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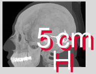

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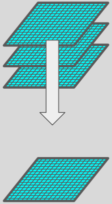
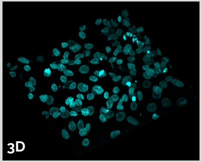
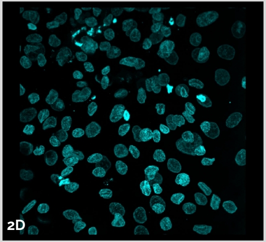
Maximum intensity projection

Projections

Reducing the dimensions of a dataset. For example projecting a volume (3D) to a surface by taking the maximum value across planes for each pixel.







Fundamentals of Digital Image Processing (2022) by Guillaume Witz, Slide 23

Machinery

- Hospital CT
  - Voxel size around 0.5 mm
- Lab/Desktop CT
  - Voxel size around 7 µm (*in vivo*) or 0.5 µm (*ex vivo*)
- Synchrotron CT
  - Voxel size down to 160 nm

flic.kr/p/D4rbom

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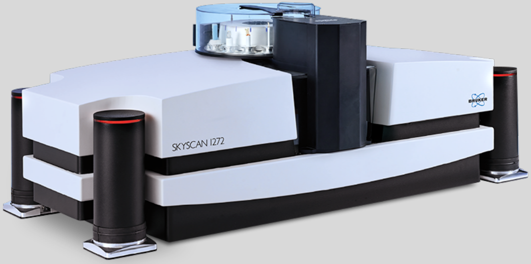

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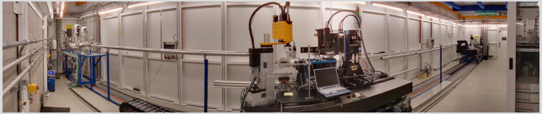

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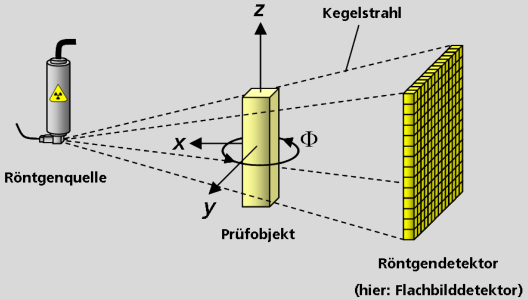
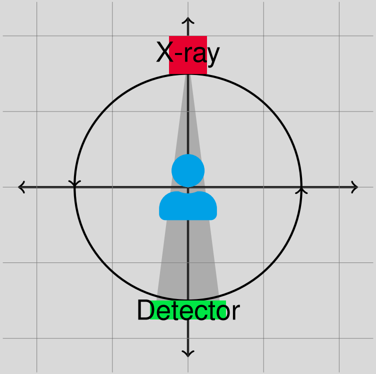
What is happening?

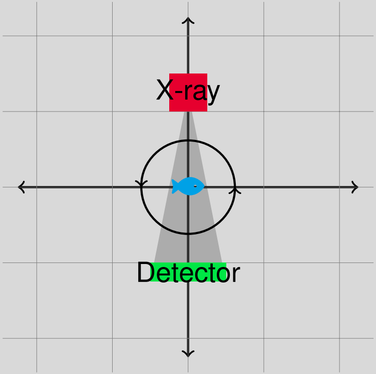
The basic components of a computer tomography device are always

- an X-ray source
- something to image
- a detector

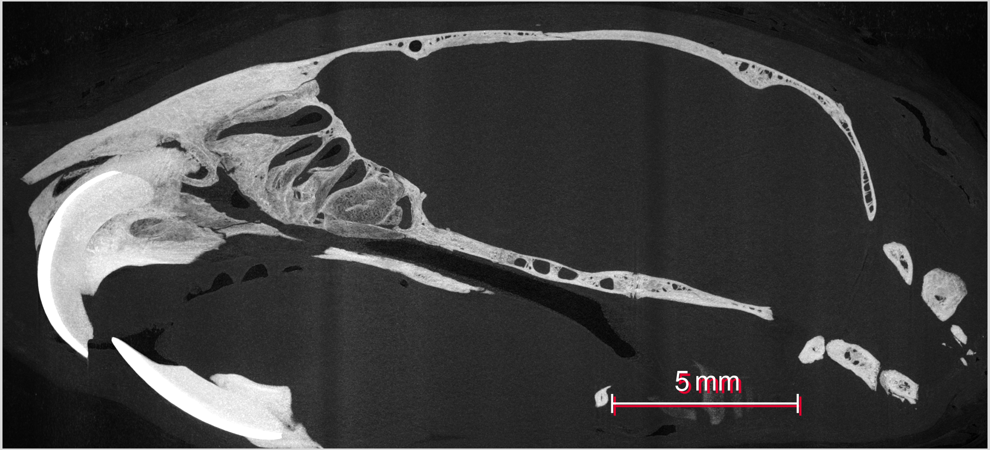


Machinery





Examples



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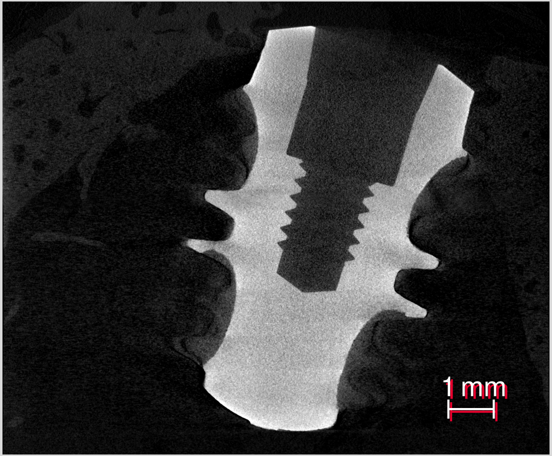

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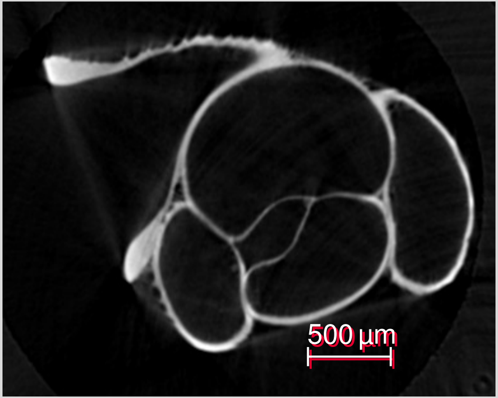

From [8], *Diancta phoenīx*

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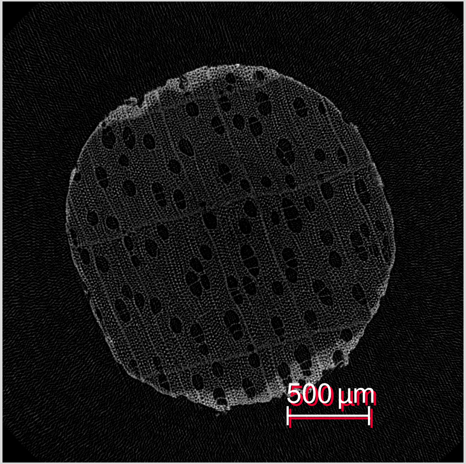

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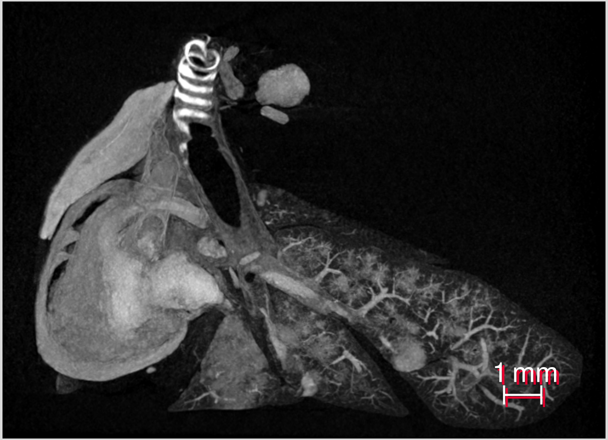
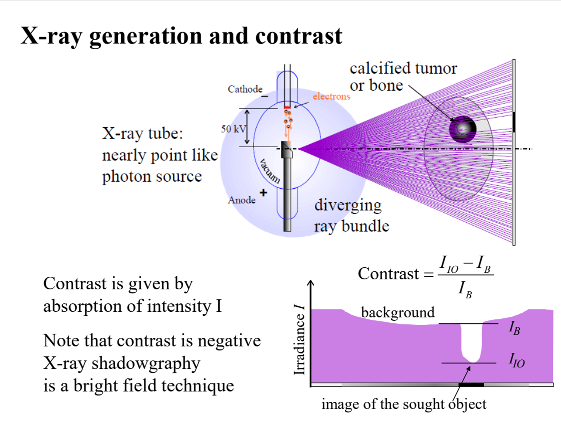


Preparation

- Study design
- Sample preparation

Projections



Contrast, Magnification and Resolution—Laws of Physics for Microscopists (1, 2022) by Martin Frenz, Slide 21

Projections

Projections

- A (micro-focus) X-ray source illuminates the object
- The X-rays penetrate the sample and are attenuated
- A scintillator converts the X-rays to visible light
- A (planar) X-ray detector collects (magnified) projection images.
- The projections are recorded on disk

Reconstructions

Reconstructions

- Based on hundreds of angular views acquired while the object rotates, a computer synthesizes a stack of virtual cross section slices through the object.
- Radon Transformation
- Filtered back projection
- Fan beam reconstruction
- Corrections (beam hardening, etc.)
- Writing to stack

Visualization

Visualization

- Based on the reconstructions, a computer synthesizes a three-dimensional view of the scanned sample

What to use?

- ImageJ/Fiji [18]
- Also see *Fundamentals of Digital Image Processing* by Guillaume Witz
- Reproducible research
  - in Jupyter [19]
  - git
  - Script all your things!
  - Data repositories; i. e. sharing is caring!

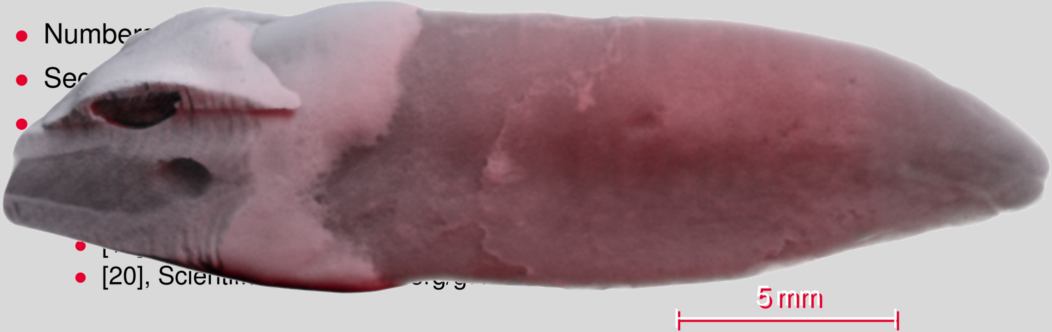
Quantitative data

- Pretty images are nice, but we need quantitative numbers
- Segmentation
- Characterization

Internal morphology of human teeth

Collaboration with zmk bern – Zahnmedizinische Kliniken

- Numbe
- Se
-
  -
  - [20], Scienti



Internal morphology of human teeth

Collaboration with zmk bern – Zahnmedizinische Kliniken

- Numbers instead of just pretty images
- Segmentation of teeth and root canal
- (Unbiased) Characterization
- Reproducible and automated image analysis (in Jupyter [19])
- Two publications:
  - [10], BMC Oral Health, doi.org/gjpw2d
  - [20], Scientific Reports, doi.org/g7r8

How?

- 104 extracted human permanent mandibular canines
- µCT imaging
- Root canal configuration, according to Briseño-Marroquín et al. [21]
- *Reproducible* analysis [22], e. g. you can click a button to double-check or recalculate the results yourself!

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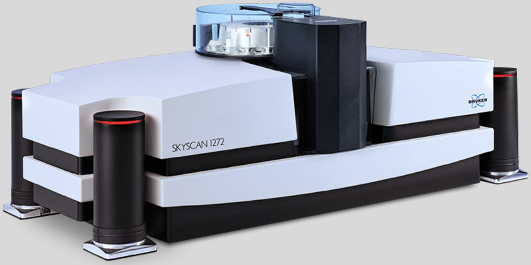

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```
Scanner=SkyScan1272
Instrument S/N=15G09089-B
Software Version=1.1.19
Filename Prefix=Tooth045~00
Number Of Files=  482
Number Of Rows= 1092
Number Of Columns= 1632
Source Voltage (kV)=  80
Source Current (uA)= 125
Image Pixel Size (um)=9.999986
Exposure (ms)=950
Rotation Step (deg)=0.400
Frame Averaging=ON (3)
Filter=Al 1mm
Study Date and Time=02 Jul 2020  08h:23m:34s
Scan duration=0h:39m:51s
```

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Sample changer on the SkyScan 1272

In total:

- 13 days of *continuous* µCT scanning
- 819 GB of raw data
  230 648 TIFF projections
- 326 GB data as input for analysis
  282 062 PNG reconstructions

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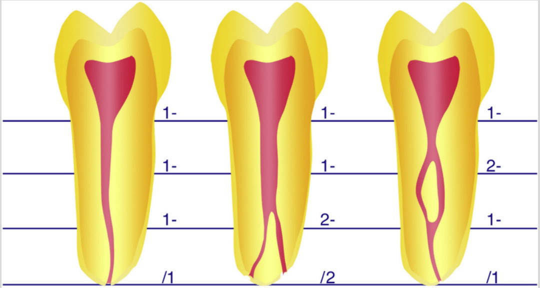

From [21], Fig. 2

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gph.is/2nqkple

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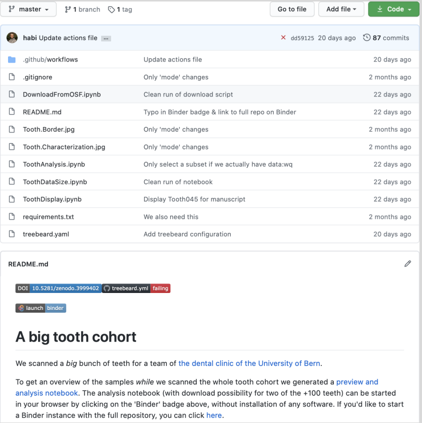
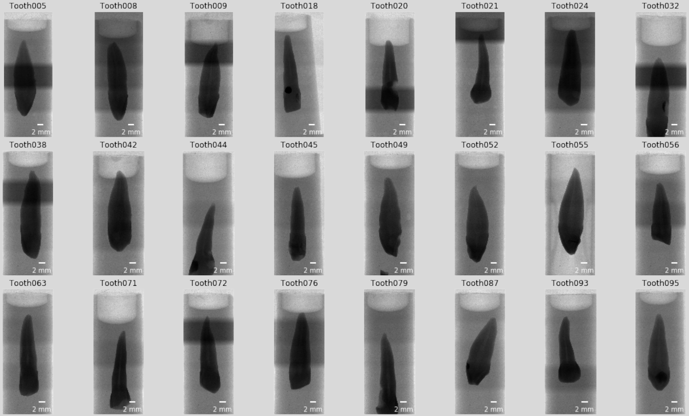


µCT imaging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Tooth052
Tooth055
Tooth056
Tooth063
Tooth071
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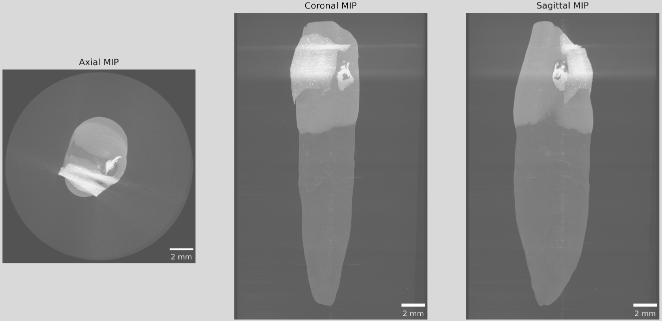
Tooth087
Tooth093
Tooth095
2 mm

Dataset cropping

- Full datasets: 326 GB
- Cropped datasets: 115 GB



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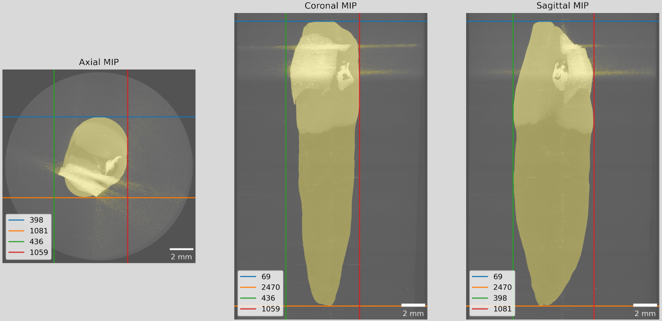
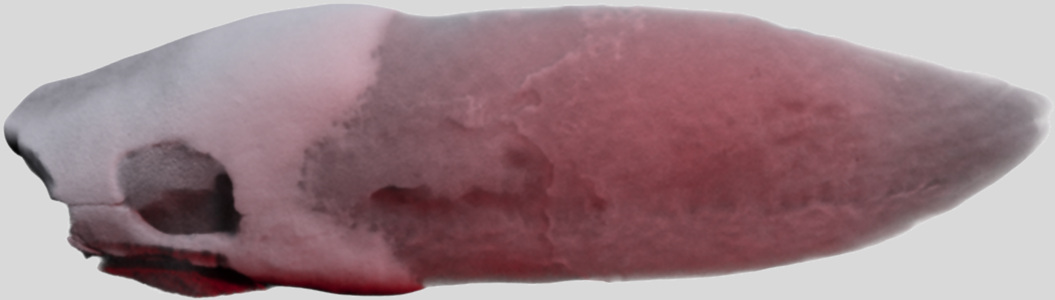


Tooth morphology



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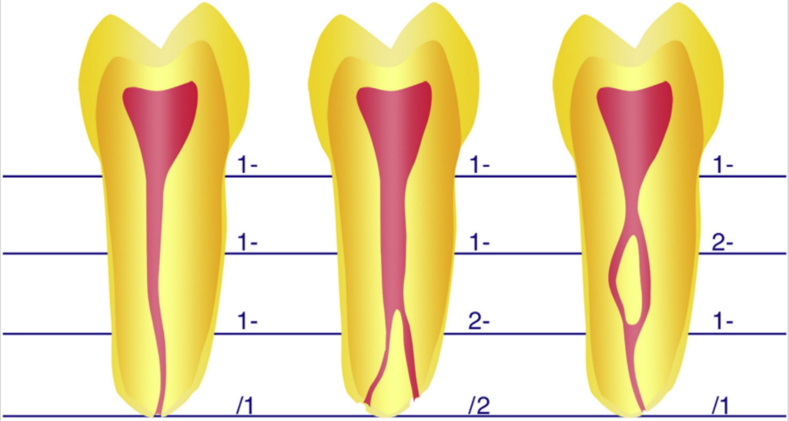
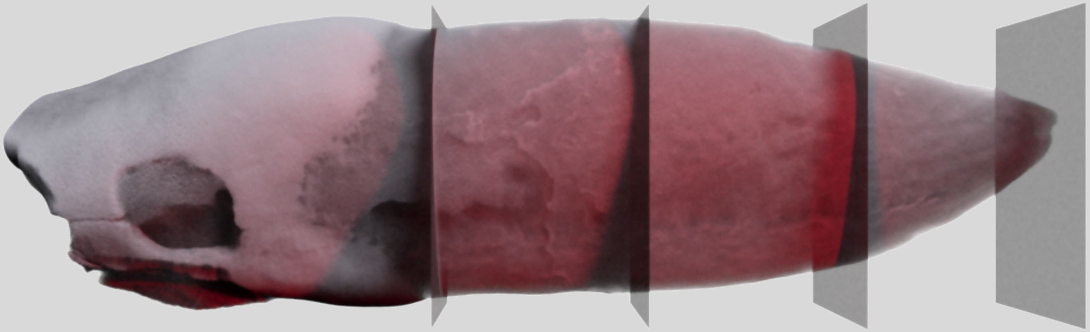
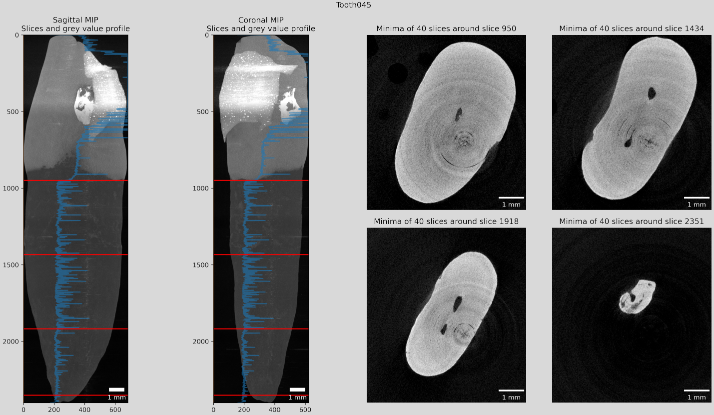


From [21], Fig. 2

Tooth morphology



Detection of enamel-dentin border



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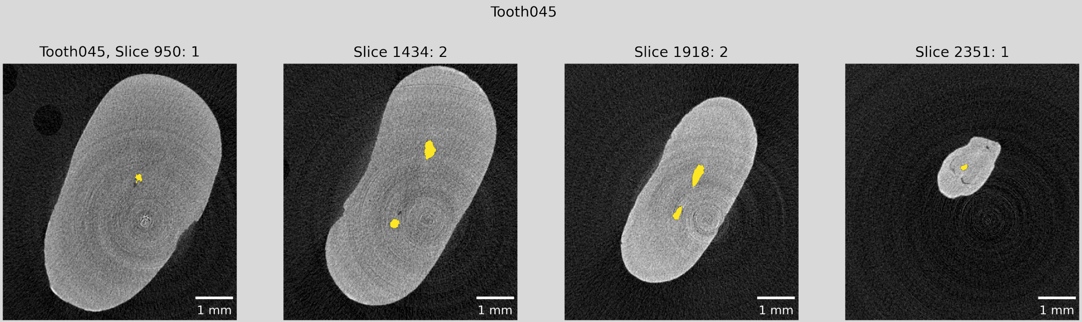
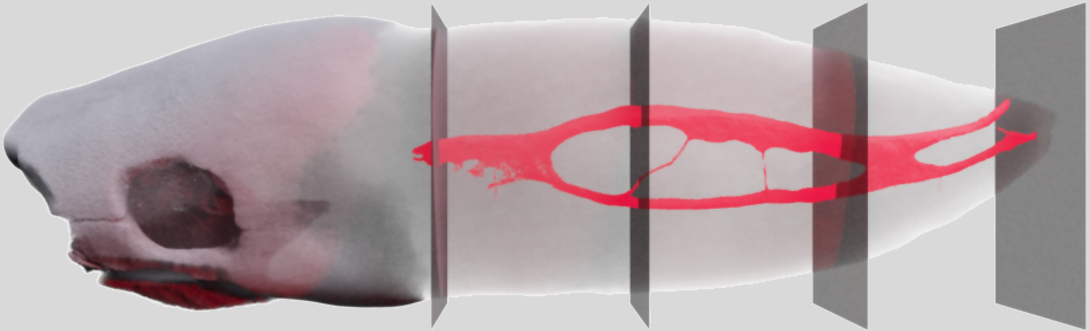


Extraction of root canal space



Results of root canal space extraction

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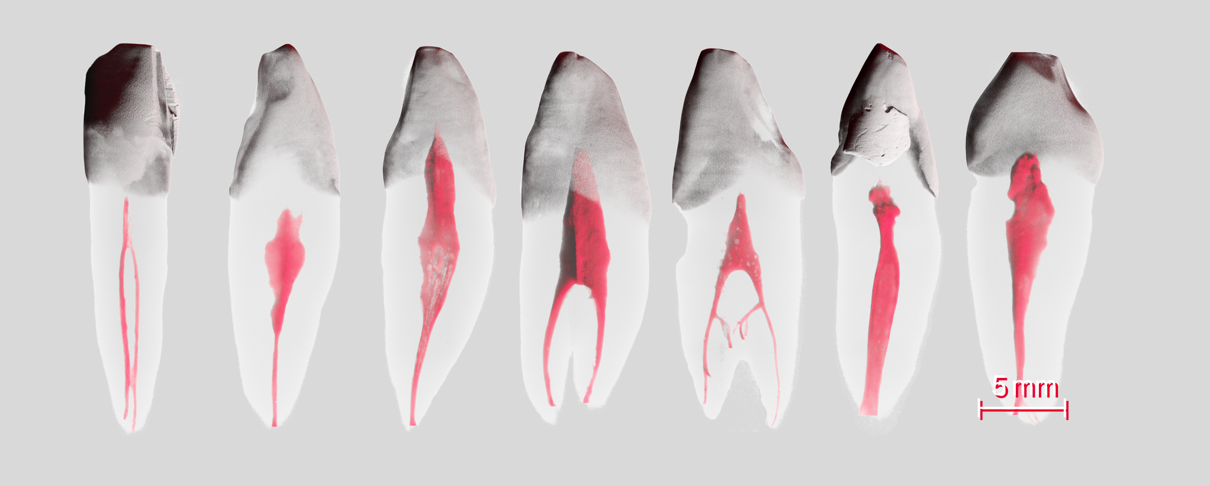

Conclusion

- Efficient use of time, e. g. more teeth does not mean more (human) work
- Reproducible analysis with *free and open-source* software, usable by *anyone*
- Objective analysis, e. g. no operator bias

Thanks!

- Thanks for listening to me!
- What questions do you have for me?

References I

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Colophon

- This BEAMER presentation was crafted in LaTeX with the (slightly adapted) template from *Corporate Design und Vorlagen* of the University of Bern.
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[1] Details on how this works are specified in a small test repository here: git.io/JeOOj