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**UNIVERSITY
OF BERN**

u^b X-ray microtomography

485018-HS2024-0: Advanced Course II
Ultraprecision Engineering

David Haberthür

Institute of Anatomy, September 25, 2024

u^b Grüessech mitenang!

- David Haberthür
 - Physicist by trade
 - PhD in high resolution imaging of the lung, Institute of Anatomy, University of Bern, Switzerland
 - Post-Doc I: TOMCAT, Swiss Light Source, Paul Scherrer Institute, Switzerland
 - Post-Doc II: µCT group, Institute of Anatomy, University of Bern, Switzerland.

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Grüessech from the µCT group



David.Haberthuer@unibe.ch



Ruslan.Hlushchuk@unibe.ch

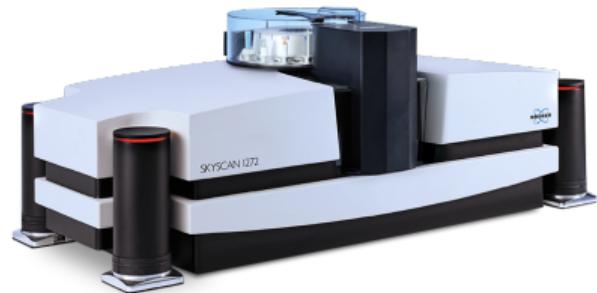


Oleksiy.Khoma@unibe.ch

μ

μ CT-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], [11]



bruker.com/skyscan1272

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Contents

Overview & Imaging methods

Tomography

Tomography

Interaction of x-rays with matter

Tomography today

A scan, from *getting started* to *nice image*

Examples

A study about teeth

Overview

Materials & Methods

Results

Metal foam analysis

A study on fish

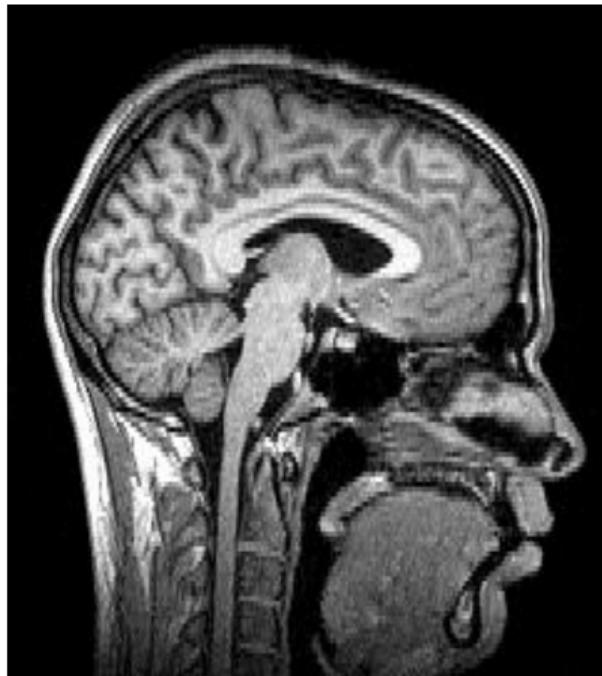
μ CT^b

- Dense and/or non-transparent samples
- Calibrated & isotropic 3D images at micron resolutions
- Covers a very large range of sample sizes
- Gives information at different length scales
- Nondestructive imaging, thus compatible with routine sample preparation.
Enables correlative imaging pipelines, scanning of museum & collection material

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Biomedical imaging

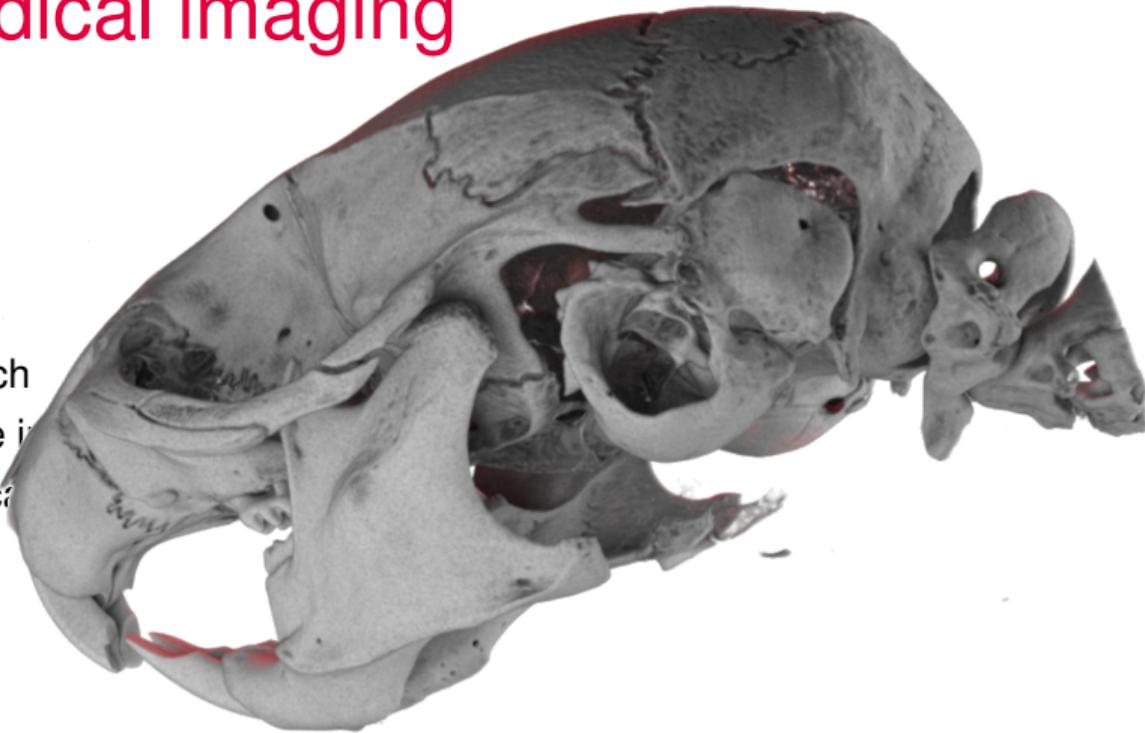
- Medical research
- Non-destructive insights into the samples
- (Small) Biological samples



w.wiki/7g4 CC BY-NC-SA

Biomedical imaging

- Medical research
- Non-destructive i
- (Small) Biological



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Biomedical imaging

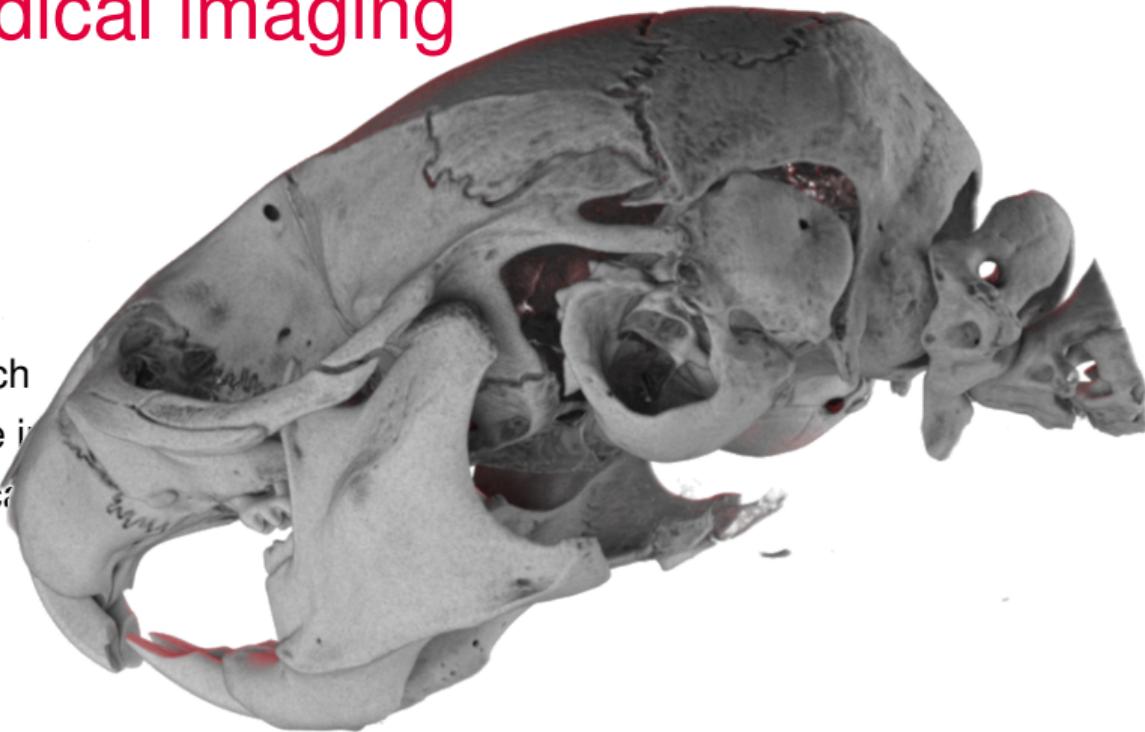
- Medical research
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- (Small) Biological samples



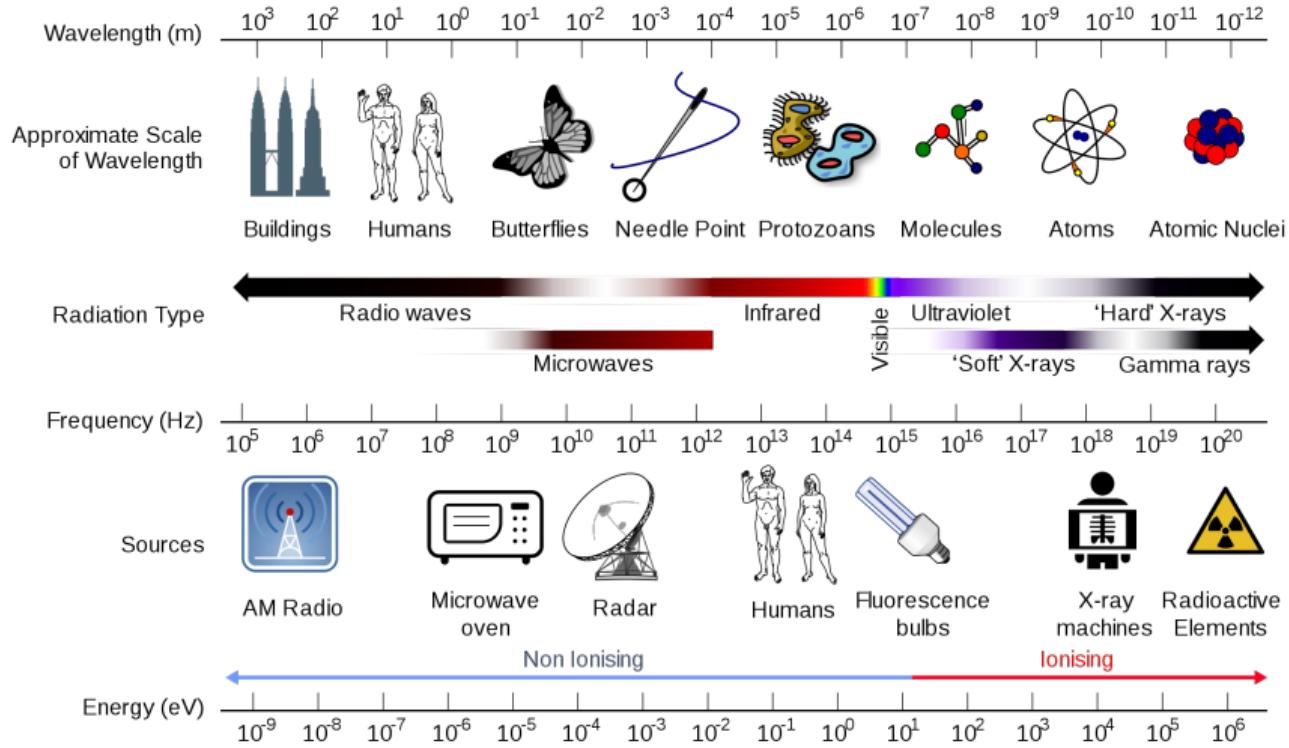
w.wiki/7g4 CC BY-NC-SA

Biomedical imaging

- Medical research
- Non-destructive i
- (Small) Biological

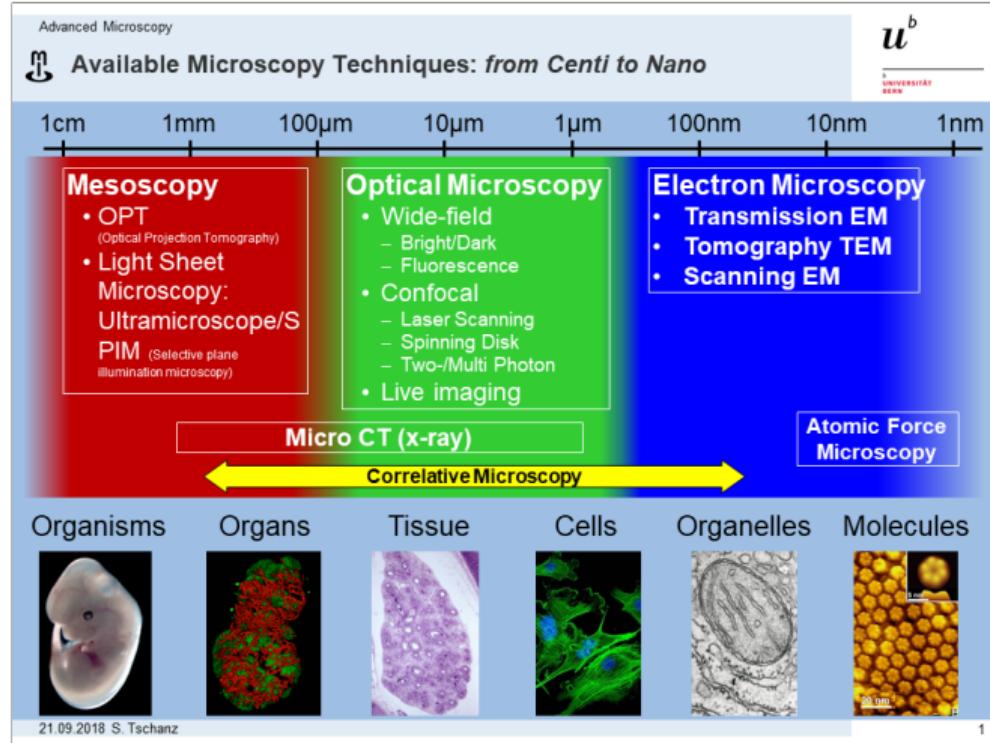


u^b Wavelengths & Scales



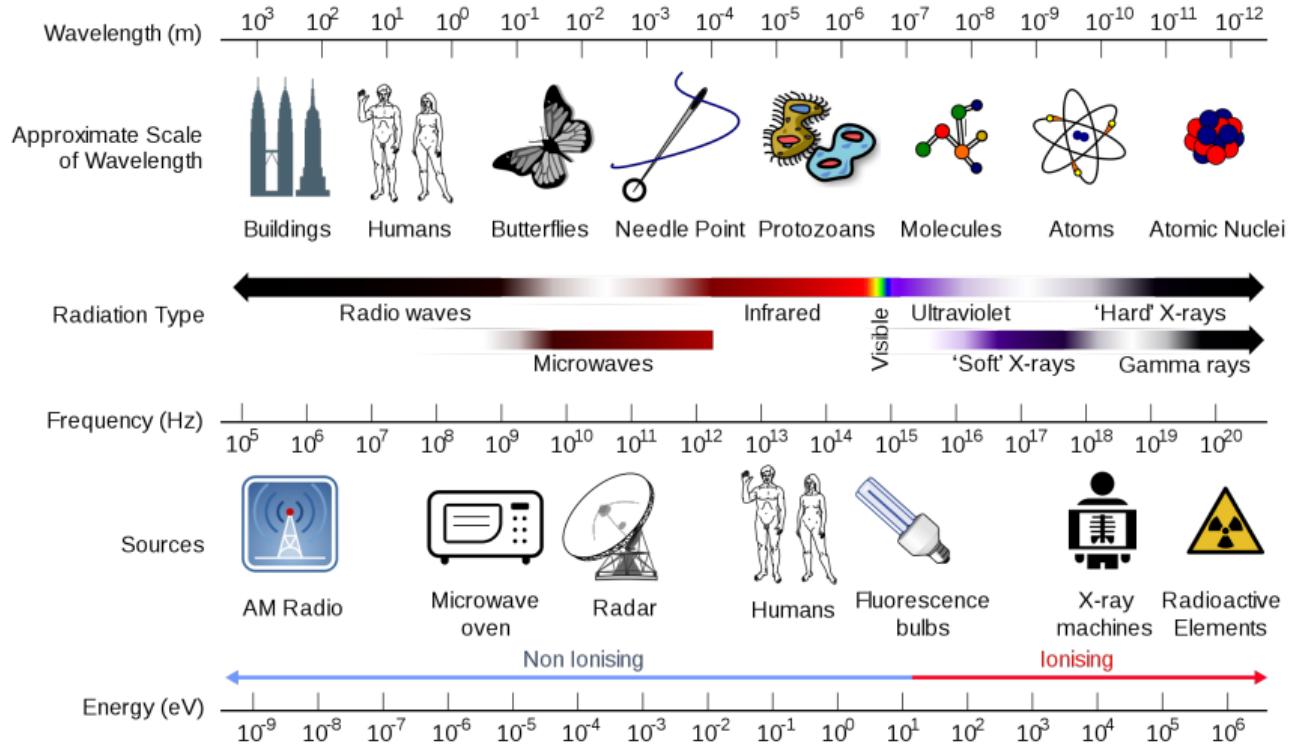
w.wiki/7fz @①②

u^b Wavelengths & Scales



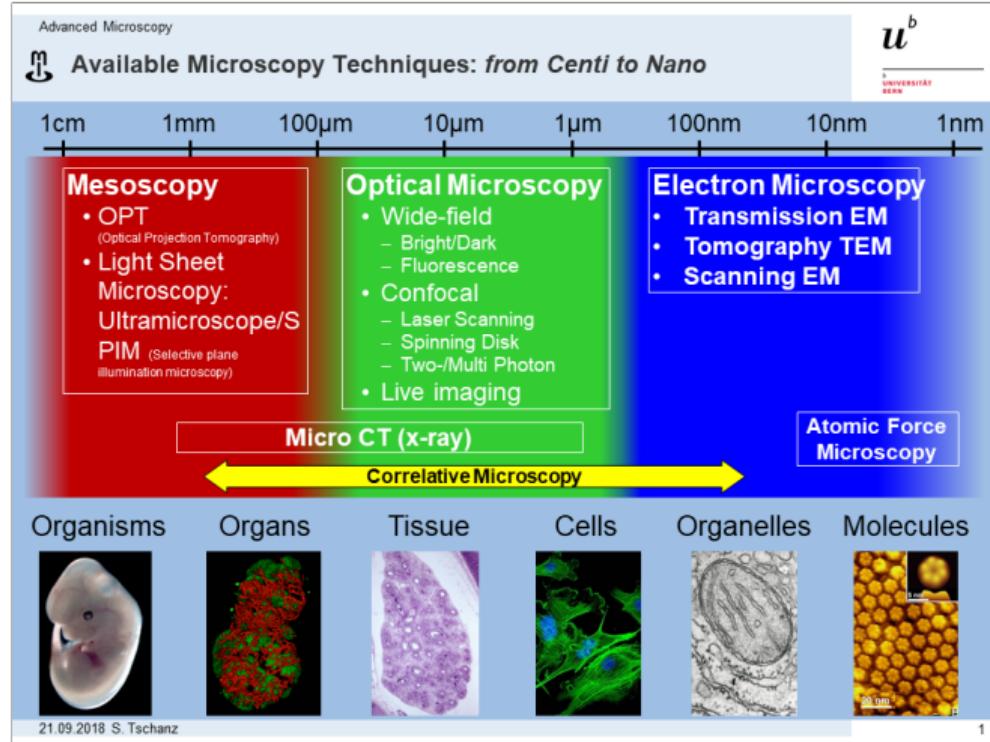
Stefan Tschanz, with permission

u^b Wavelengths & Scales



w.wiki/7fz @①②

u^b Wavelengths & Scales



Stefan Tschanz, with permission

Imaging methods

- Light (sheet) microscopy: see lecture of Nadia Mercader Huber
- X-ray imaging
- Electron microscopy
 - *Analytical electron microscopy* by Dimitri
 - *SEM Grundlagen* by Sabine Kässmeyer and Ivana Jaric
 - *Cryoelectron Microscopy & Serial Block Face SEM* by Ioan

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CT-Scanner



youtu.be/2CWpZKuy-NE

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CT-Scanner



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CT History

- 1895: Wilhelm Conrad Röntgen discovers X-rays

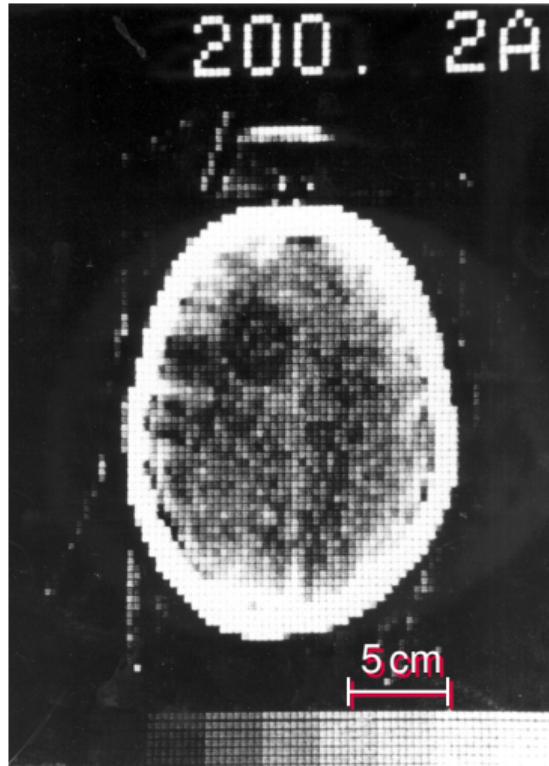


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CT History

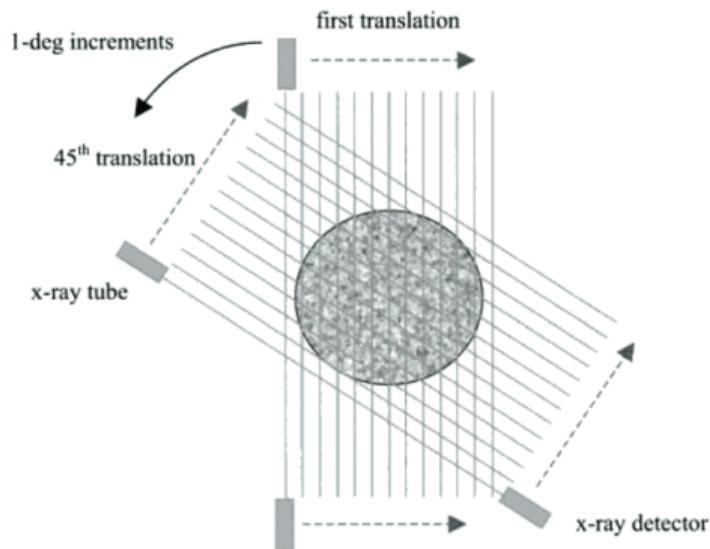
- 1895: Wilhelm Conrad Röntgen discovers X-rays
- 1963: Cormack used a collimated ^{60}Co source and a Geiger counter as a detector [12]
- 1976: Hounsfield worked on first clinical scanner [13]



From [14], Figure 5

CT History

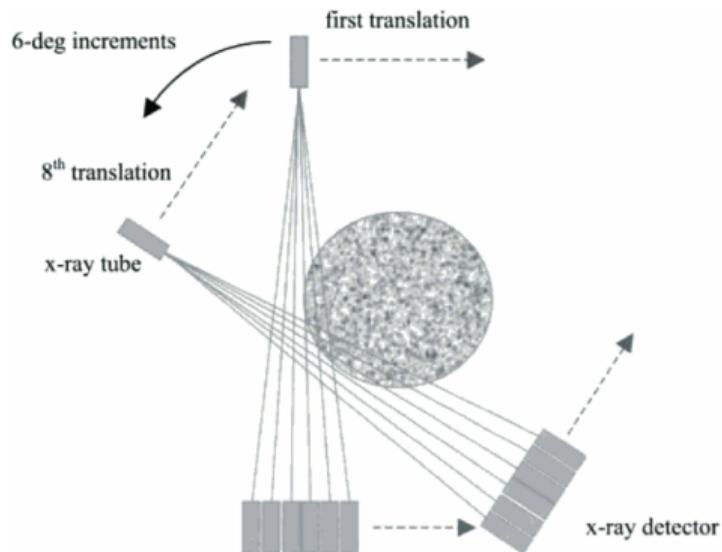
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- CT scanner generations
 - First generation



From [15], Figure 1.12

CT History

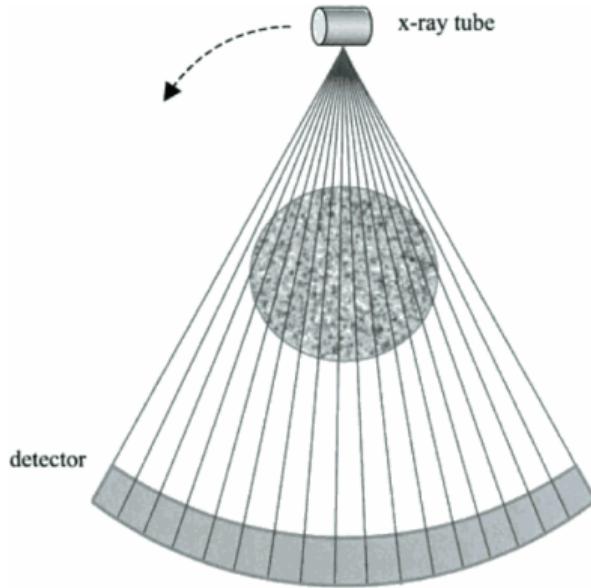
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- CT scanner generations
 - First generation
 - Second generation



From [15], Figure 1.13

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- 1976: Hounsfield worked on first clinical scanner [13]
- CT scanner generations
 - First generation
 - Second generation
 - Third generation



From [15], Figure 1.14

μ CT History I

- X-ray computed tomography began to replace analog focal plane tomography in the early 1970s [16]
- In the early 1980s, Lee Feldkamp [17] developed one of the early laboratory microCT systems by assembling a micro-focus cone beam x-ray source, specimen holder and stages, and an image intensifier at Ford Motor Company's Scientific Research Laboratory to nondestructively detect damage in ceramic manufactured automobile parts
- Met with scientists at Henry Ford Hospital and University of Michigan interested in understanding bone microstructure [18] and osteoarthritis [19]
- 1987: The first commercially available μ CT scanner was developed by SkyScan (now Bruker)

μ CT History II

- Today: μ CT is widely used in various fields for non-destructive imaging
 - quantifying the microstructure of organic materials, particularly mineralized bone tissue and the relationships between the mechanical behavior of bone to its structural and compositional properties
 - Material Science: internal structure of composites, foams, and other materials. Understand the relationship between structure and properties.
 - Biomedical Research: microarchitecture of bone tissue, dental research, and small animal imaging. Since the 1990s, μ CT includes imaging of soft tissues and vasculature using radio-opaque contrast agents
 - Paleontology and Archaeology: study of fossils and archaeological artifacts
- \approx 2500 μ CT systems are in use worldwide with over 1000 publications annually

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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.” ([20])
 - 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 & physical) density of the material. It does *not* depend on the atomic number: $\lambda' - \lambda = \frac{\hbar}{m_e c} (1 - \cos \theta)$
- Lowering x-ray energy increases contrast
- X-ray penetration decreases exponentially with sample thickness [21, i.e. Beer-Lambers law]: $I(t) = I_0 e^{-\alpha z}$

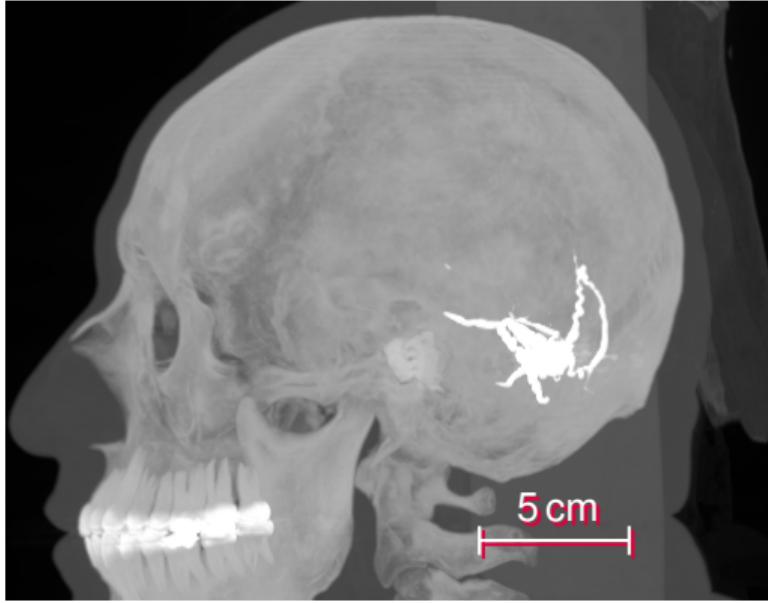
Composition of biological tissues

Tissue: content by mass percentage

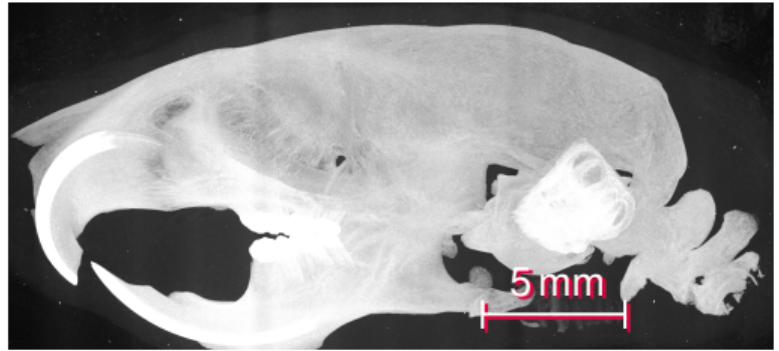
Element Atomic number	H 1	C 6	N 7	O 8	Na 11	P 15	S 16	Cl 17	K 19	Ca 20
Fat	11.4	59.8	0.7	27.8	0.1		0.1	0.1		
Water	11.2			88.8						
Blood	10.2	11	3.3	74.5	0.1	0.1	0.2	0.3	0.2	
Liver	10.2	13.9	3	71.6	0.3	0.2	0.3	0.2	0.3	
Brain	10.7	14.5	2.2	71.2	0.2	0.4	0.2	0.3	0.3	
Bone	3.4	15.5	4.2	43.5	0.1	10.3	0.3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

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Why μ CT?

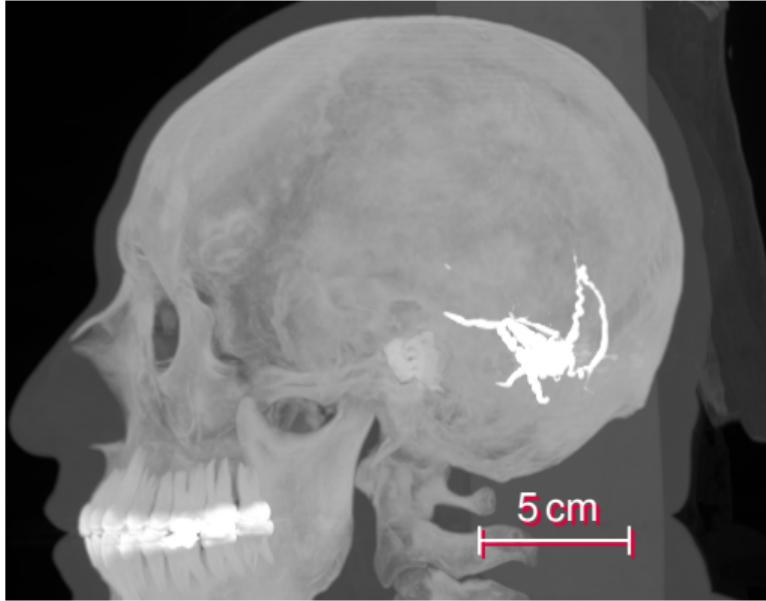


From [22], Subject C3L-02465



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Why μ CT?

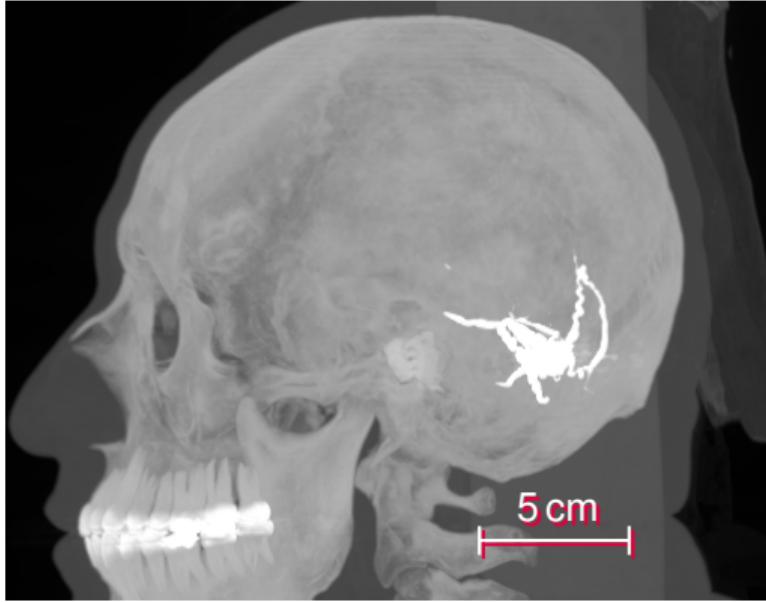


From [22], Subject C3L-02465

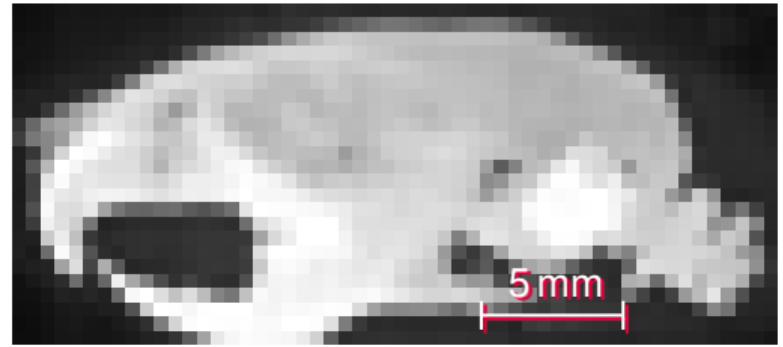


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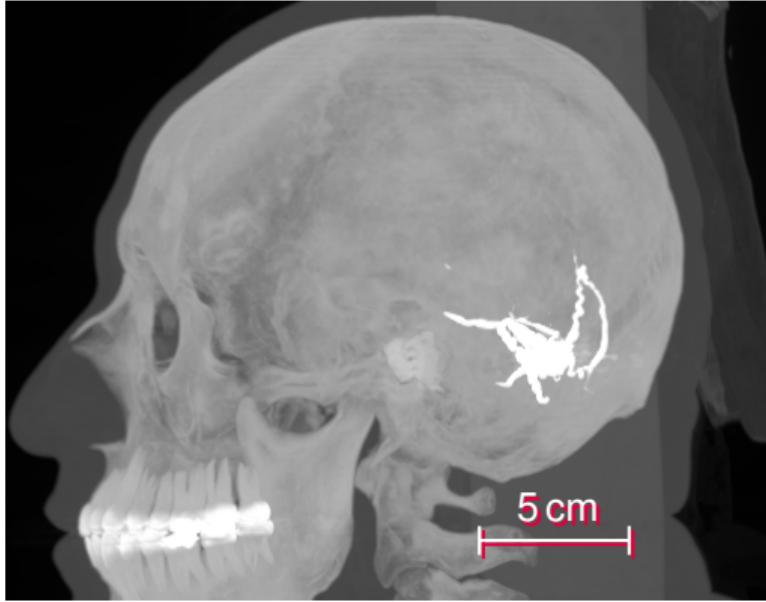


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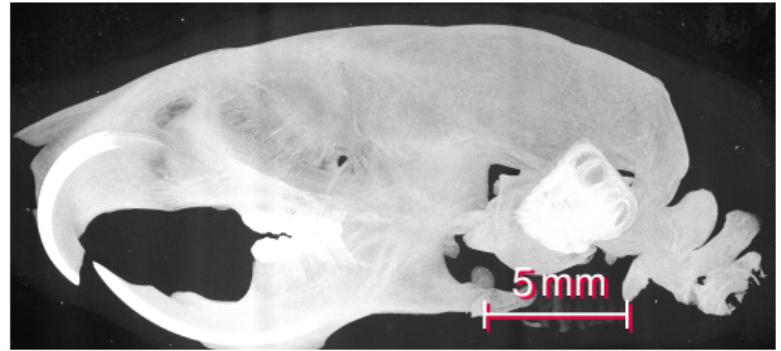


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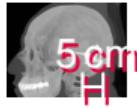


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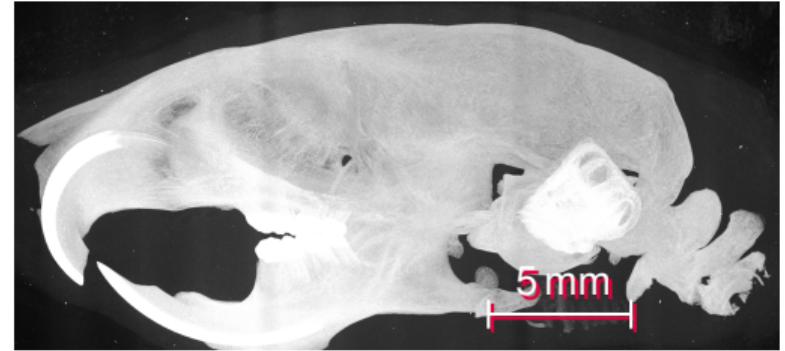


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Why μ CT?



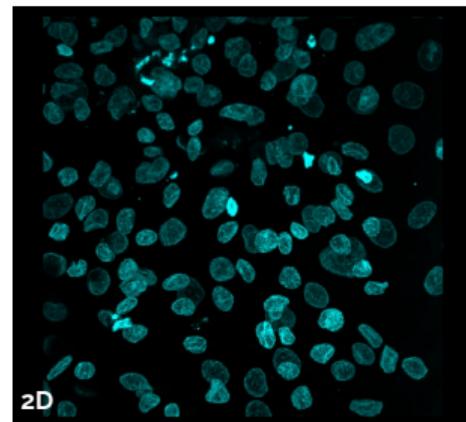
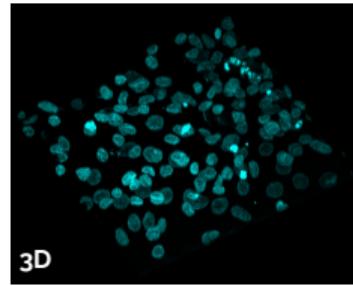
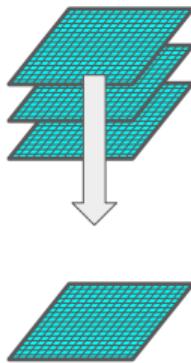
From [22], Subject C3L-02465



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.



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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



trim=<left> <lower> <right> <upper>

flic.kr/p/D4rbom @①\$②

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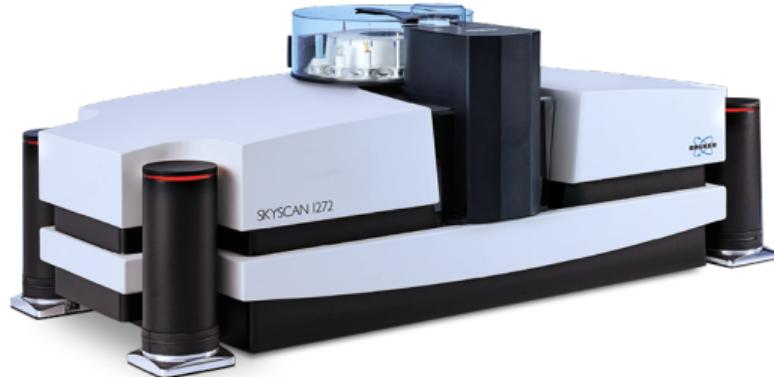


flic.kr/p/fpTrGu

trim=<left> <lower> <right> <upper>
v. (None)

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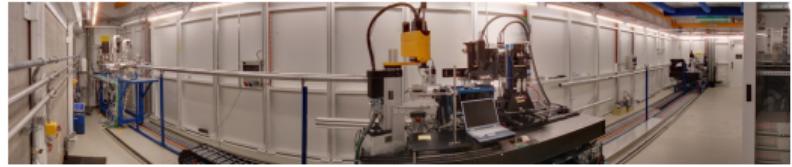
trim=<left> <lower> <right> <upper>

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trim=<left> <lower> <right> <upper>

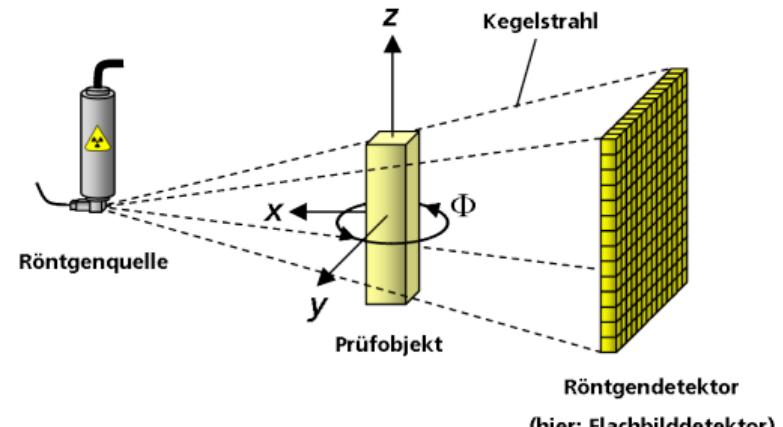
flic.kr/p/7Xhk2Y

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What is happening?

No matter what kind of machine, the basic principle is always the same

- an x-ray source
- a sample
- a detector



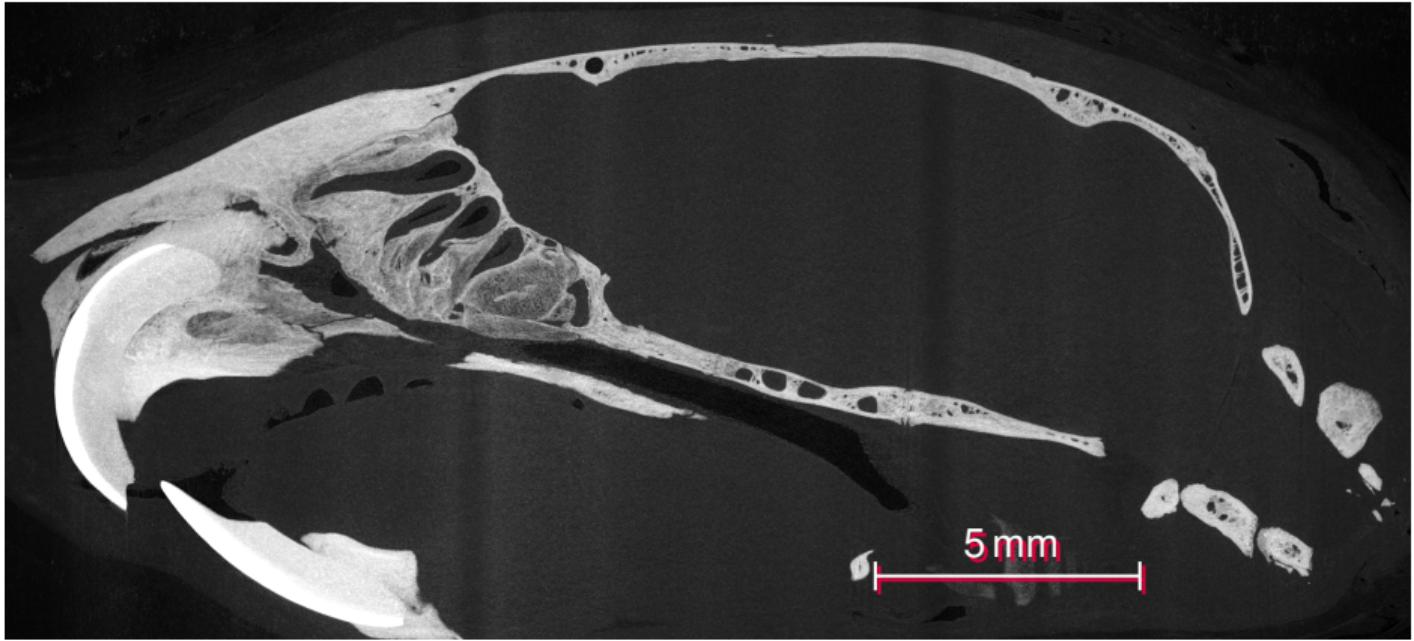
w.wiki/7g3 @①②

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Machinery

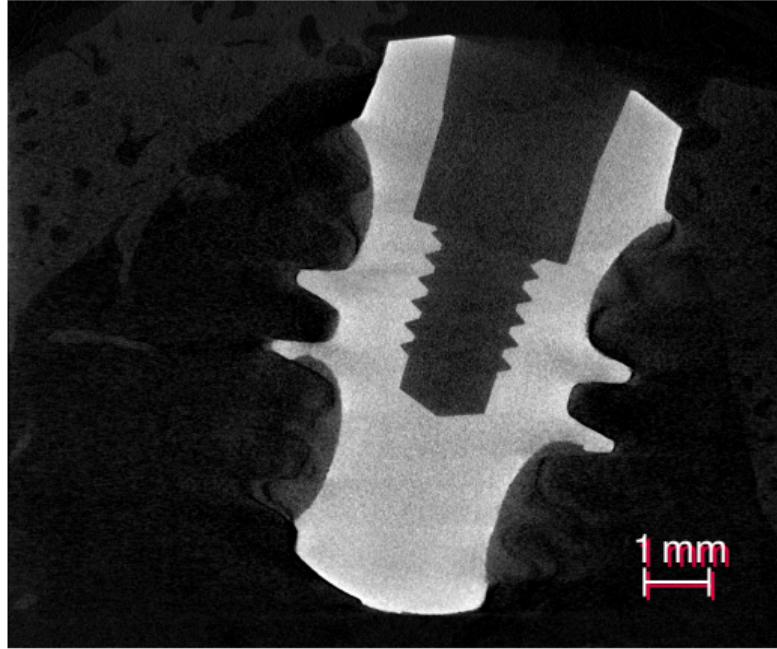
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Examples



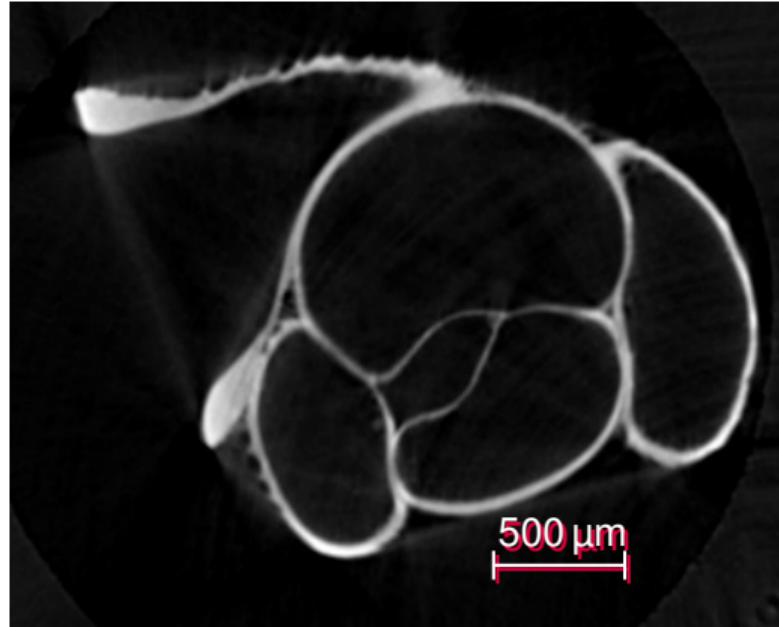
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Examples



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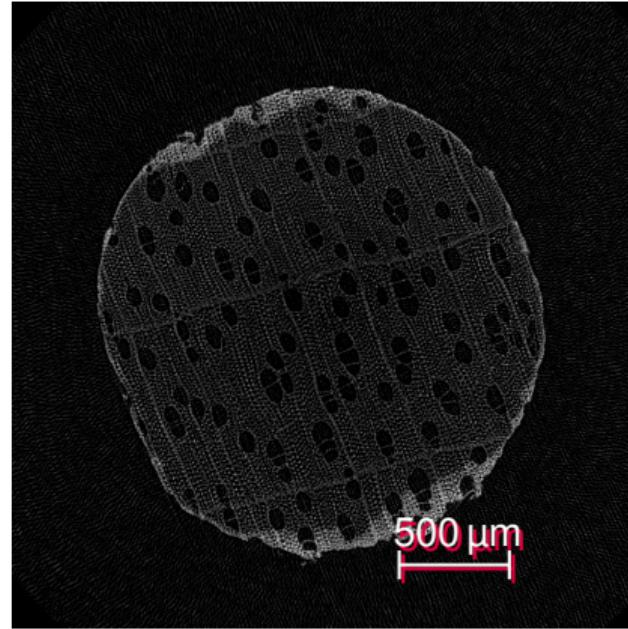
Examples



From [8], *Diancta phoenix*

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Examples



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Examples



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Preparation

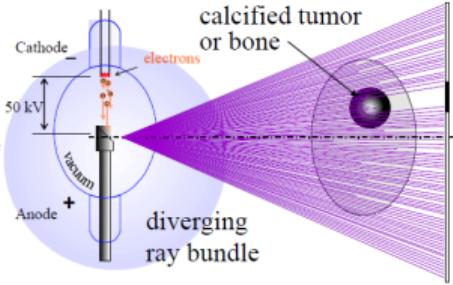
- Study design
- Sample preparation

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Projections

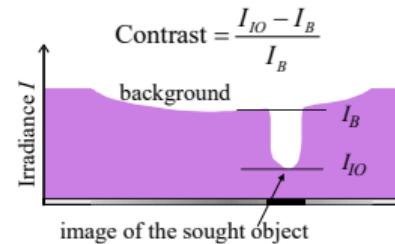
X-ray generation and contrast

X-ray tube:
nearly point like
photon source



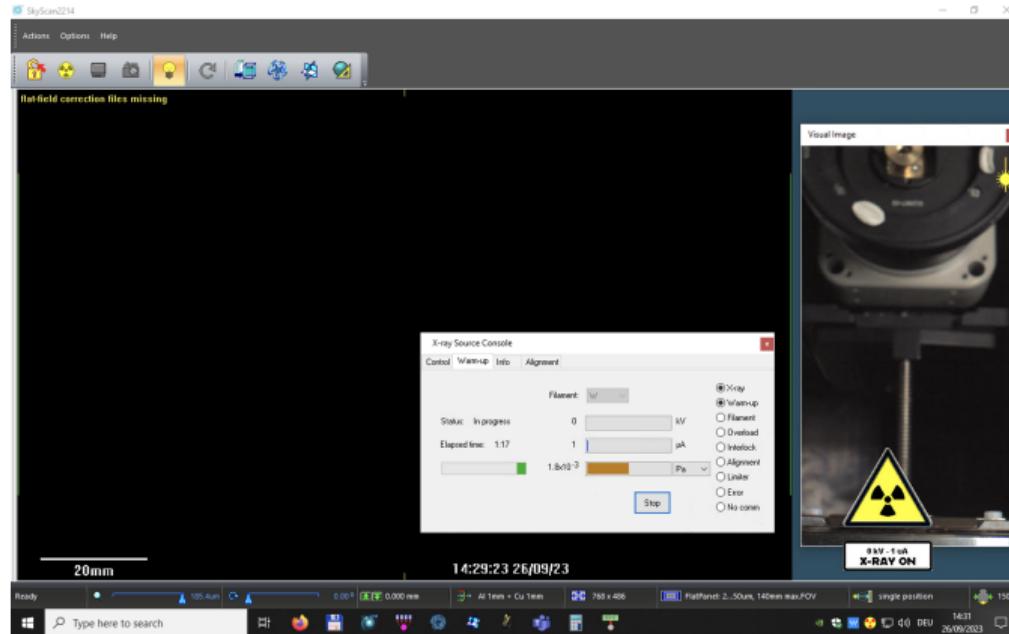
Contrast is given by
absorption of intensity I

Note that contrast is negative
X-ray shadowgraphy
is a bright field technique



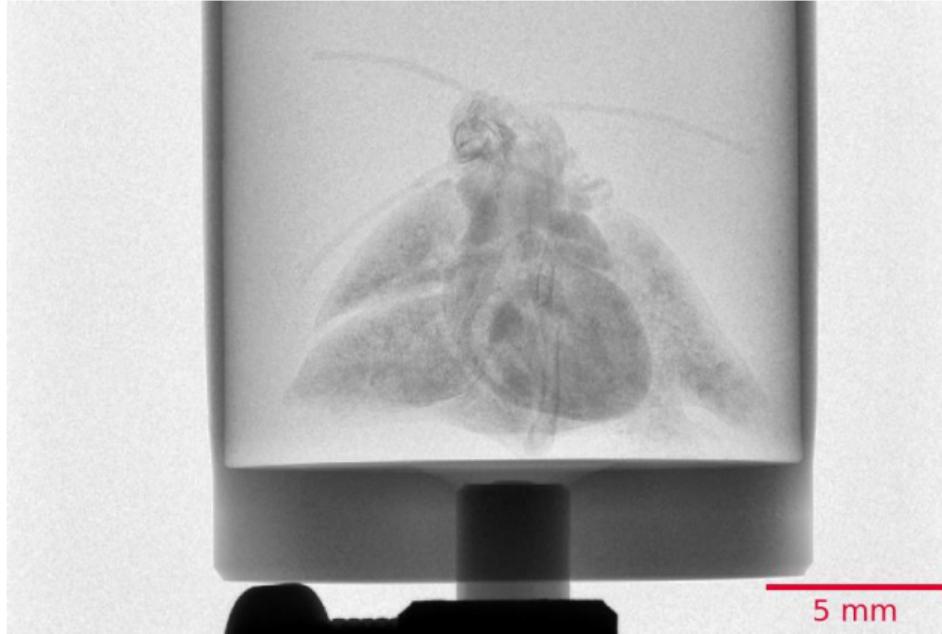
Contrast, Magnification and Resolution—Laws of Physics for Microscopists (1, 2022) by Martin Frenz, Slide 21

u^b Projection acquisition



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Projections

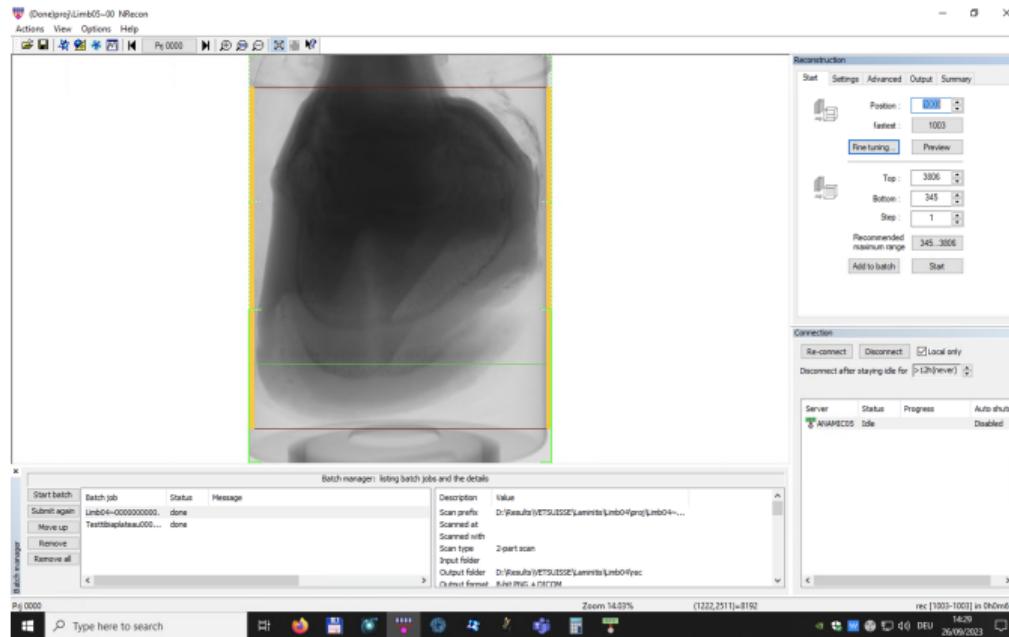


Projections

- 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

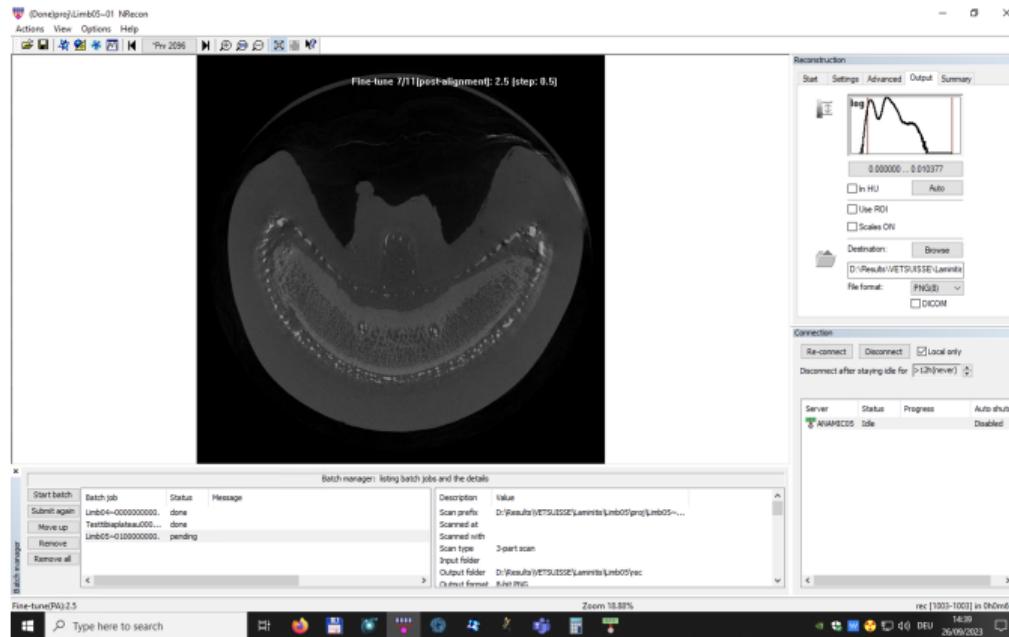
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Reconstructions



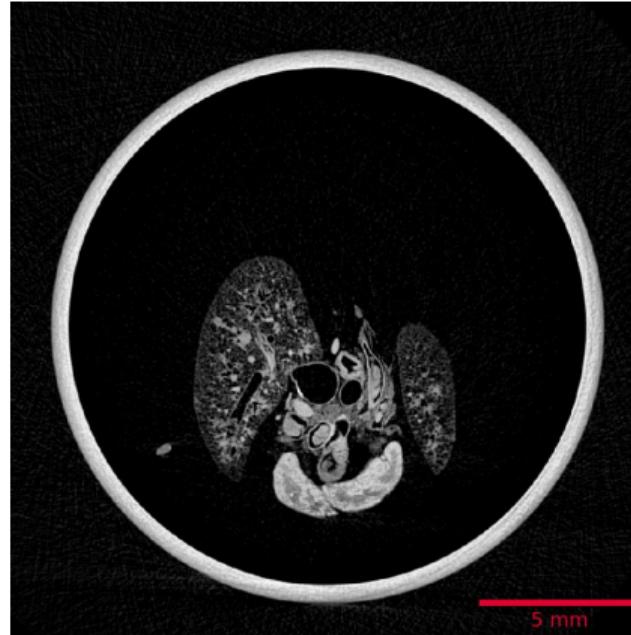
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Reconstructions



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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

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Visualization



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Visualization

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

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What to use?

- ImageJ/Fiji [23]
- Also see *Fundamentals of Digital Image Processing* by Guillaume Witz
- Reproducible research
 -  in Jupyter [24]
 - **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

- Numbers instead of just pretty images
- Segments
- (L)
-



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 [24])
- Two publications:
 - [10], BMC Oral Health, doi.org/gjpw2d
 - [25], Scientific Reports, doi.org/g7r8

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How?

- 104 extracted human permanent mandibular canines
- μ CT imaging
- Root canal configuration, according to Briseño-Marroquín *et al.* [26]
- *Reproducible* analysis [27], e. g. you can click a button to double-check or recalculate the results yourself!



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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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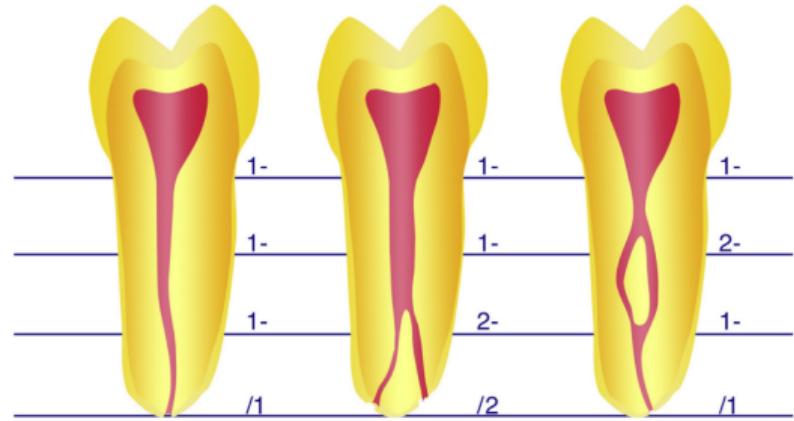
Sample changer on the SkyScan 1272
In total:

- 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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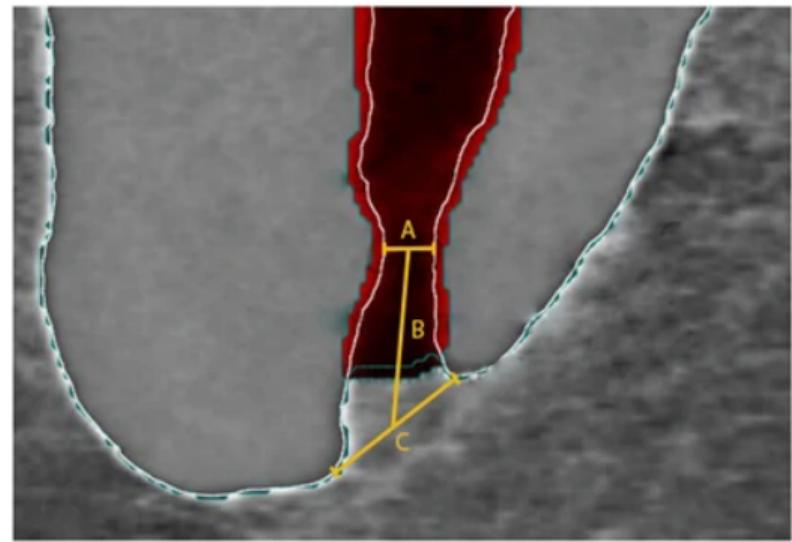
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From [26], Fig. 2

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From [28], Fig. 1

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gph.is/2nqkple

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The screenshot shows a GitHub repository interface. At the top, there are buttons for 'master' (with 1 branch), '1 tag', 'Go to file', 'Add file', and 'Code'. Below this is a list of files:

File	Description	Last Commit
.github/workflows	Update actions file	20 days ago
.gitignore	Only 'mode' changes	2 months ago
DownloadFromOSF.ipynb	Clean run of download script	22 days ago
README.md	Typo in Binder badge & link to full repo on Binder	22 days ago
Tooth.Border.jpg	Only 'mode' changes	2 months ago
Tooth.Characterization.jpg	Only 'mode' changes	2 months ago
ToothAnalysis.ipynb	Only select a subset if we actually have data.wq	22 days ago
ToothAxisSize.ipynb	Clean run of notebook	22 days ago
ToothDisplay.ipynb	Display Tooth045 for manuscript	22 days ago
requirements.txt	We also need this	2 months ago
treebeard.yaml	Add treebeard configuration	20 days ago

Below the file list is the 'README.md' page, which contains the following content:

READEME.md

(DOI: <https://doi.org/10.5281/zenodo.3999402>) treebeard.yaml failing

[launch Binder](#)

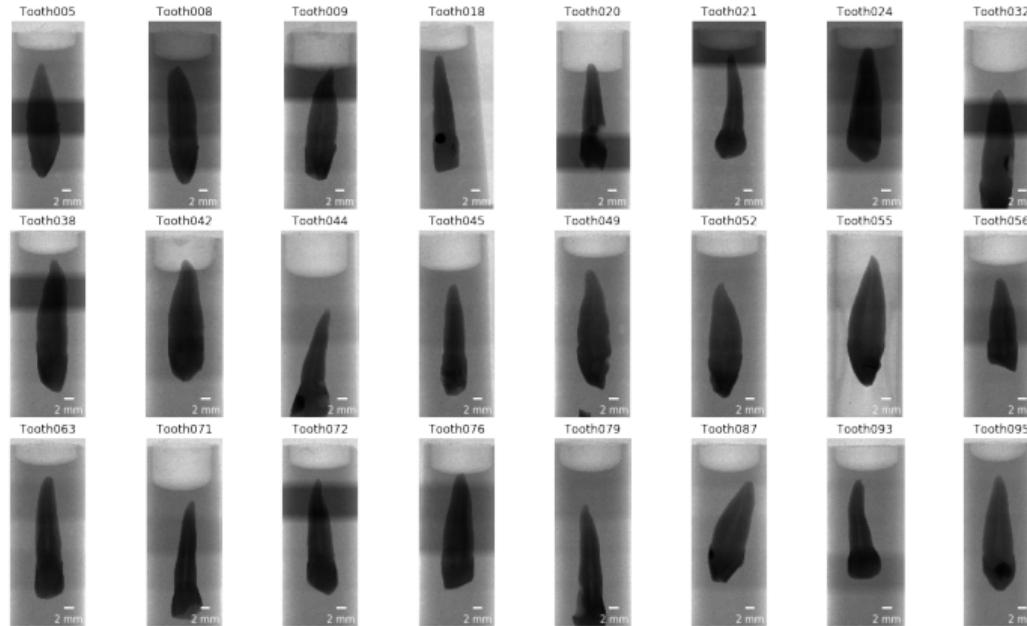
A big tooth cohort

We scanned a big bunch of teeth for a team of the dental clinic of the University of Bern.

To get an overview of the samples while we scanned the whole tooth cohort we generated a [preview](#) and [analysis notebook](#). The analysis notebook (with download possibility for two of the >100 teeth) can be started in your browser by clicking on the 'Binder' badge above, without installation of any software. If you'd like to start a Binder instance with the full repository, you can click [here](#).

μ b

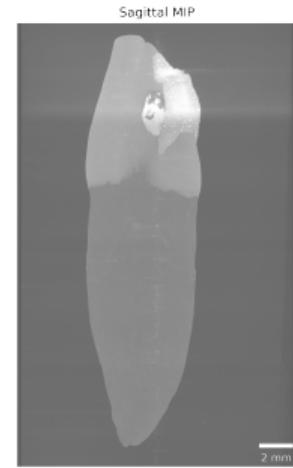
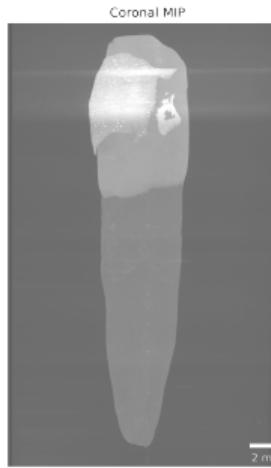
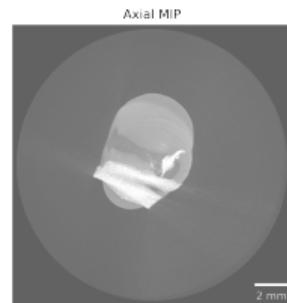
μ CT imaging



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Dataset cropping

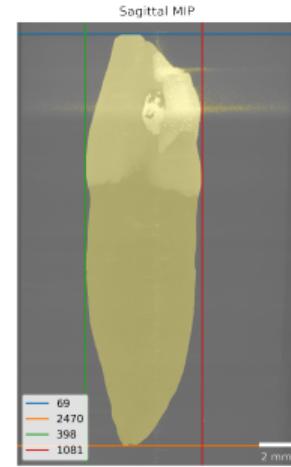
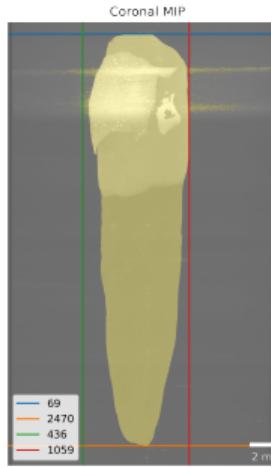
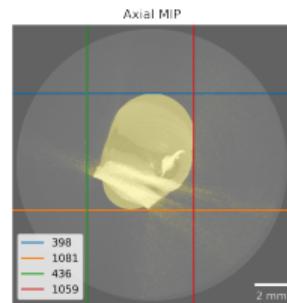
- Full datasets: 326 GB
- Cropped datasets: 115 GB



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Dataset cropping

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



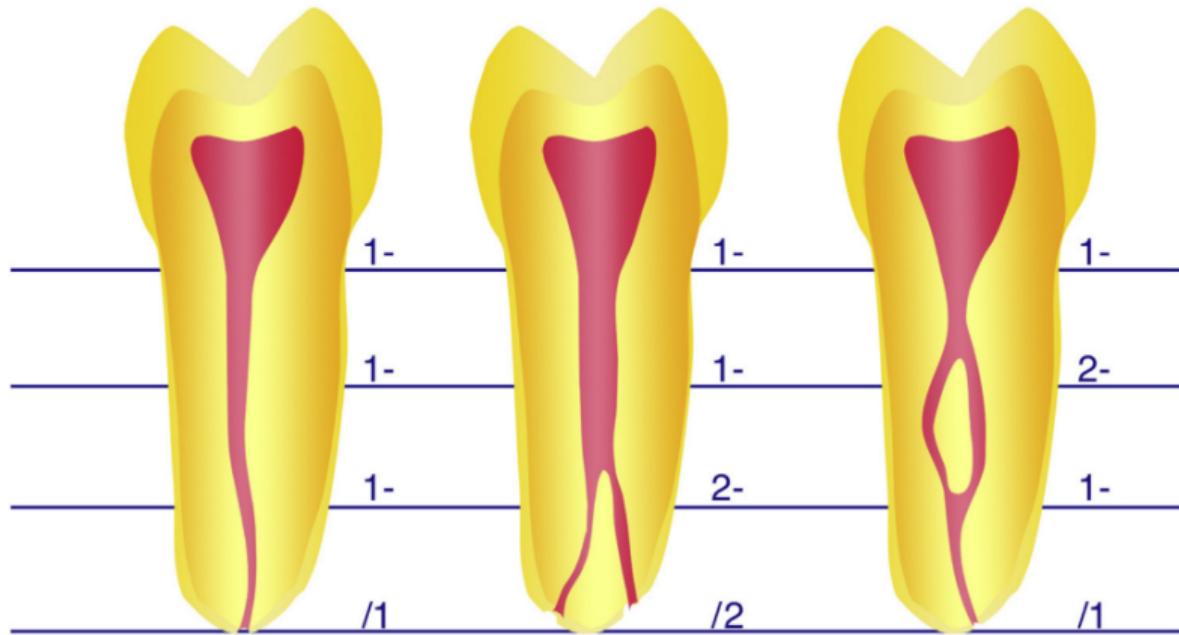
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Tooth morphology



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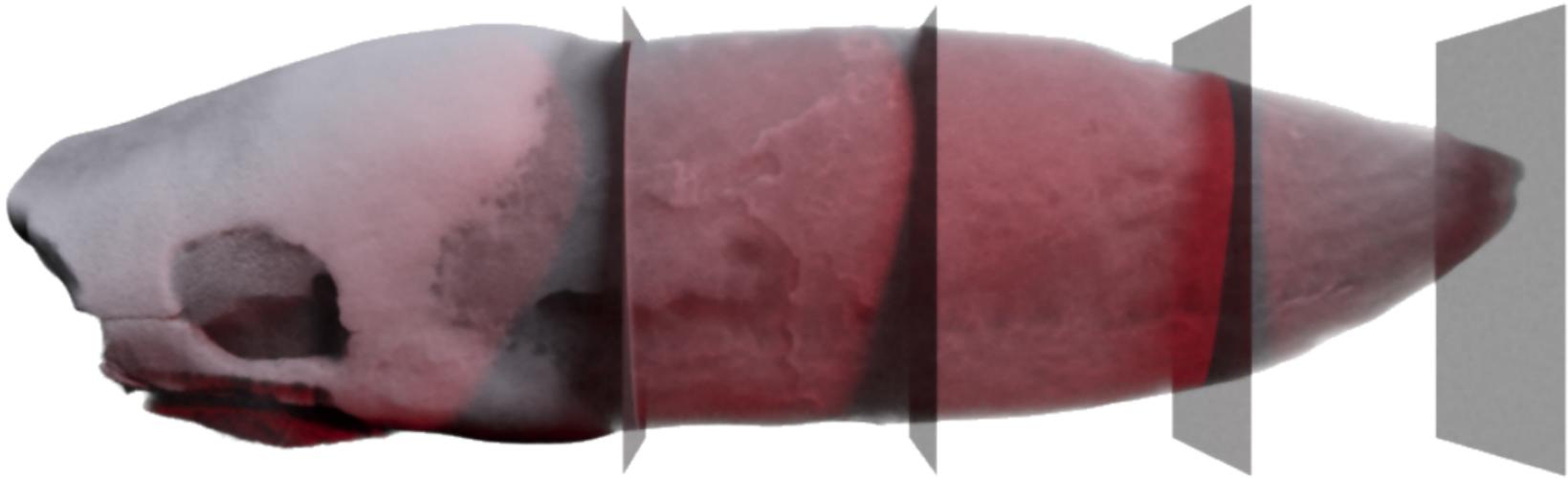
Tooth morphology



From [26], Fig. 2

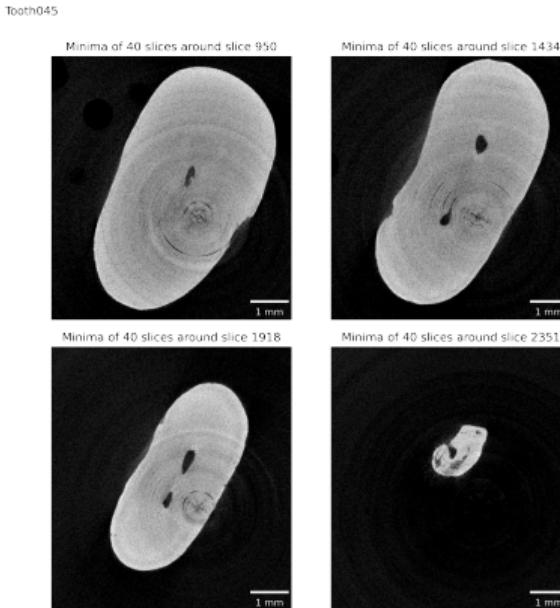
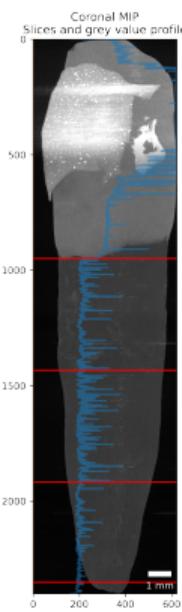
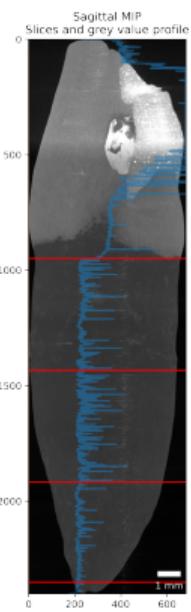
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Tooth morphology



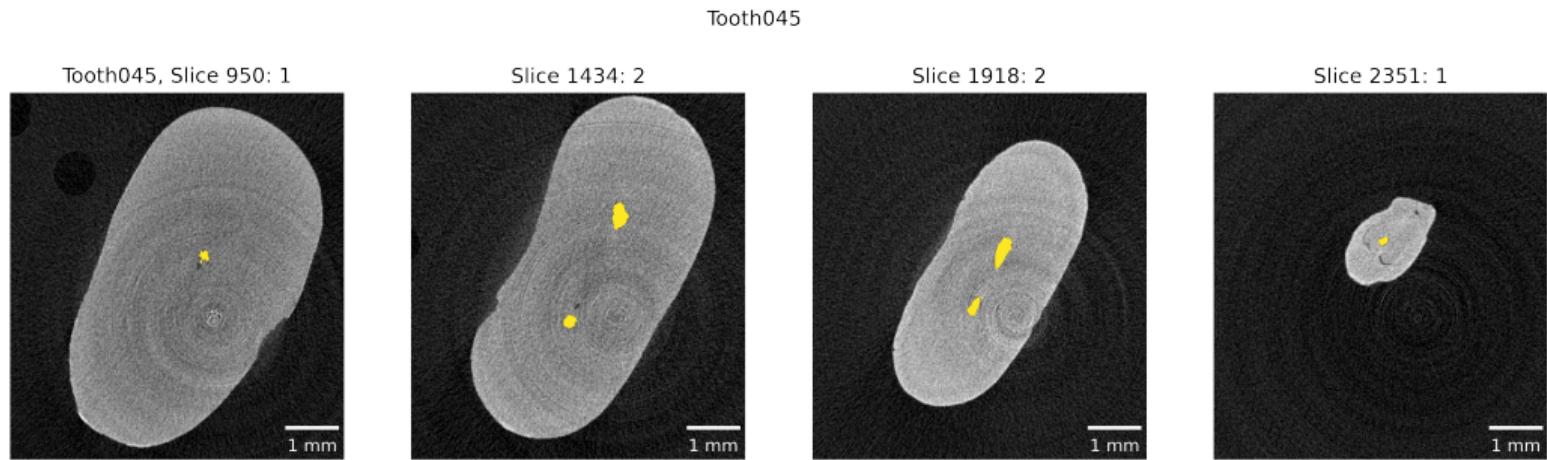
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Detection of enamel-dentin border



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Detection of enamel-dentin border



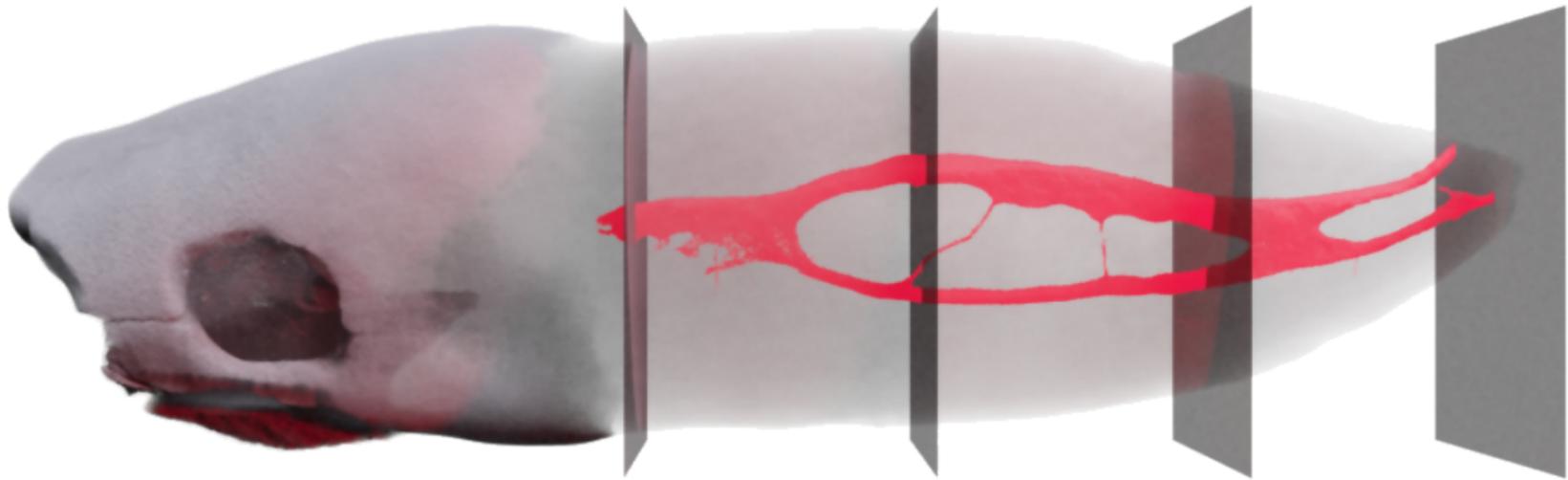
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Outcome root canal configuration classification

Roots	RCC	#	%	
Single (N=98)	1-1-1/1	73	74.5	
	1-1-1/2	14	14.3	
	1-1-1/3	1	1.0	
	1-1-1/4	2	2.1	
	1-1-2/1	1	1.0	
	1-2-1/1	4	4.1	
	1-2-1/2	1	1.0	
	1-2-2/2	1	1.0	
	2-3-1/1	1	1.0	
Double (N=3)	Buccal	1-1-1/1	2	66.6
		1-2-1/1	1	33.3
	Lingual	1-1-1/1	2	66.6
		1-1-1/2	1	33.3

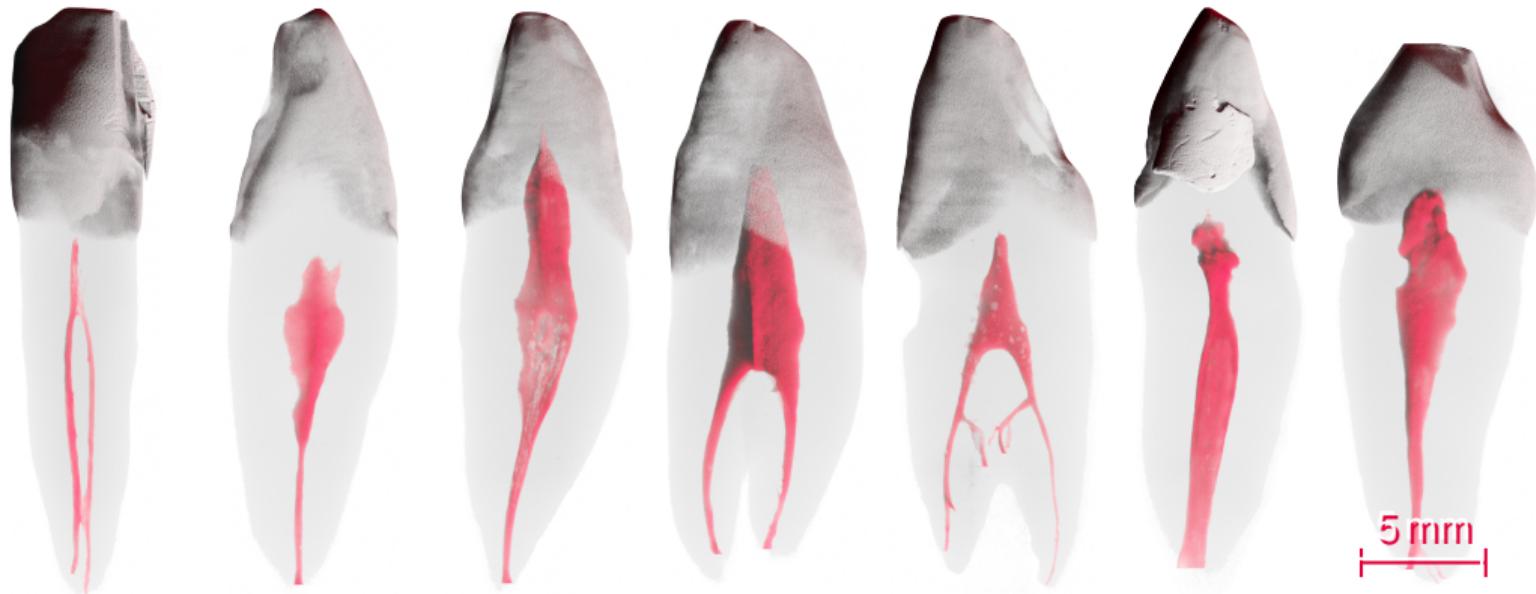
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Extraction of root canal space



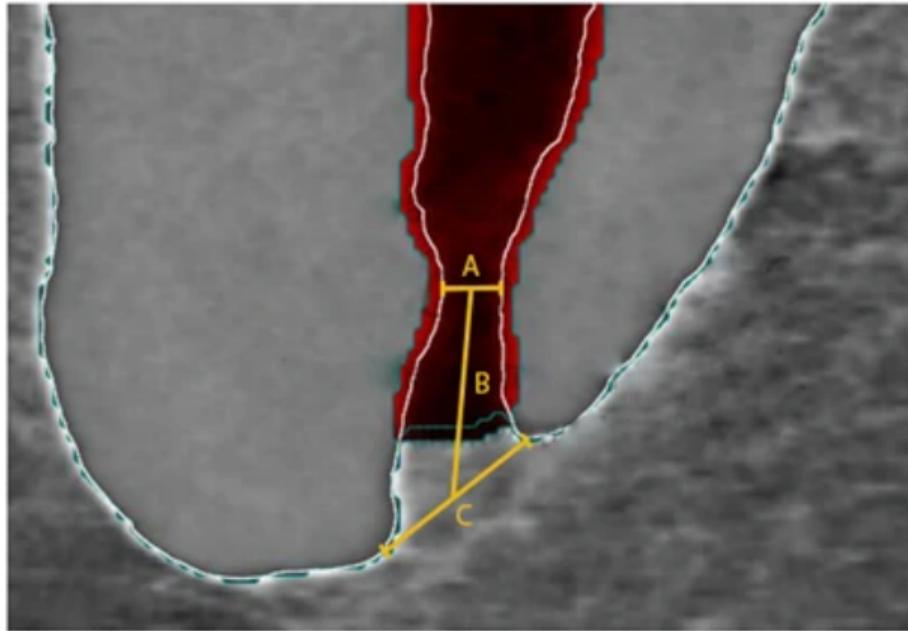
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Results of root canal space extraction



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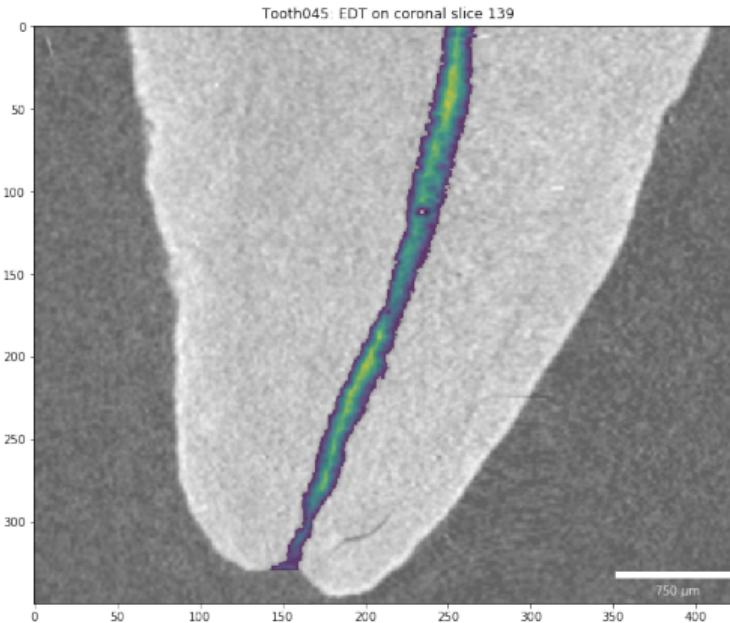
Analysis of the physiological foramen geometry



From [28], Fig. 1

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Analysis of the physiological foramen geometry

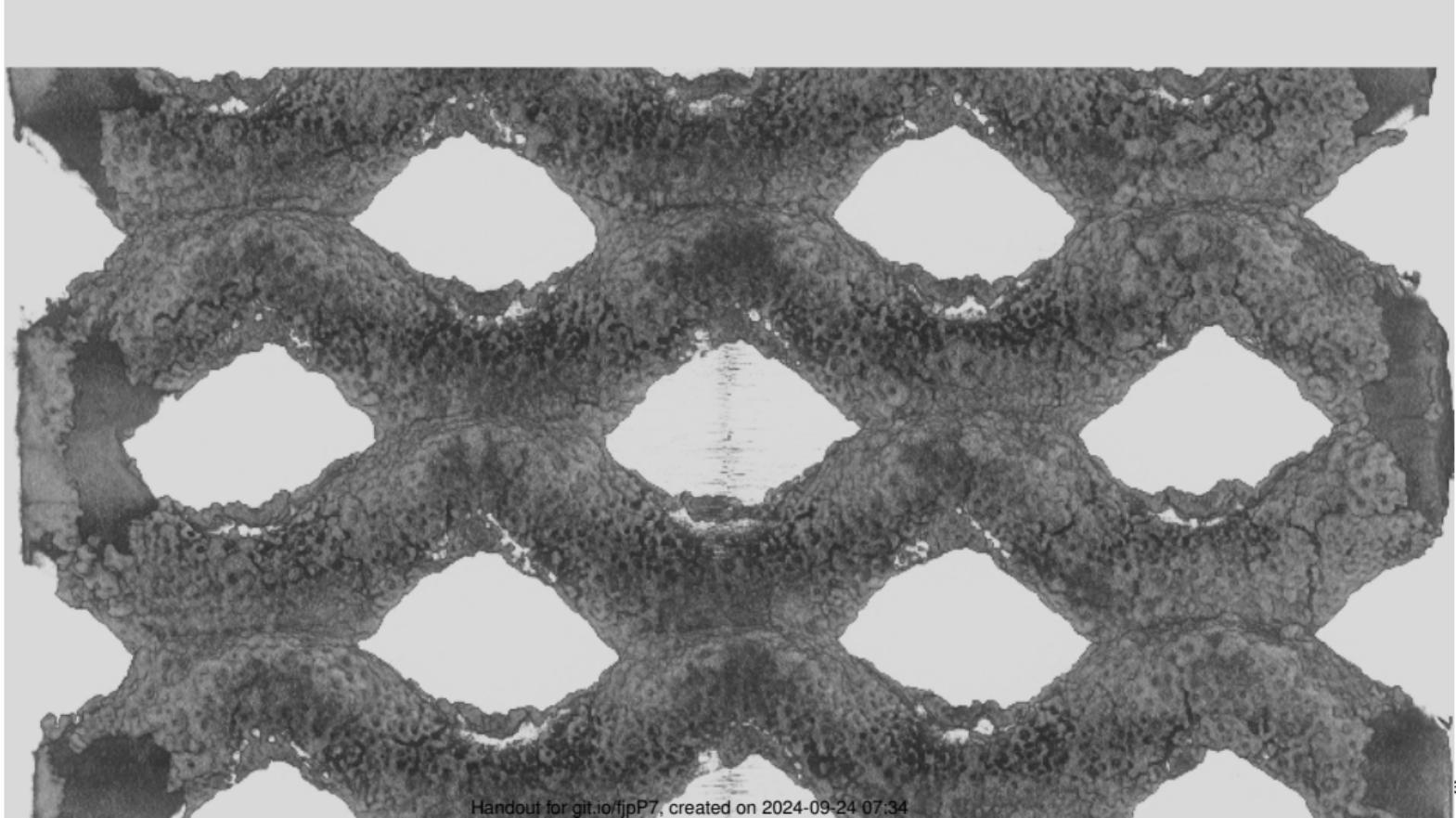


Conclusion ZMK

- 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

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Metal foam

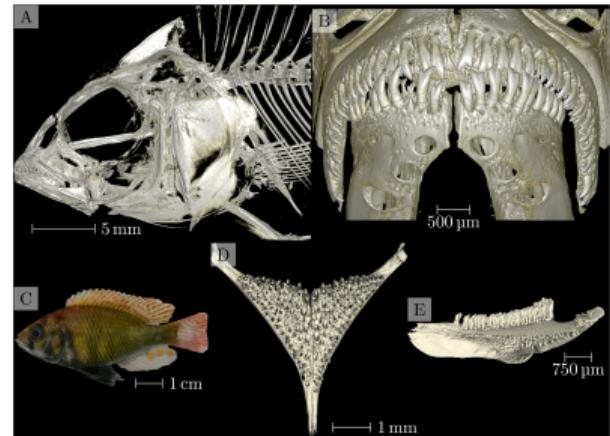


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Data wrangling by example: Cichlids

Collaboration with team of *Aquatic Ecology & Evolution*,
from the Institute of Ecology and Evolution [11]

- 133 Cichlids from Lake Victoria, East Africa
 - Functional anatomy of the skulls and jaws
 - 6–18 cm in size
- 375 scans in total
 - Voxelsizes from 3.5–50 µm
 - 46 days of scanning time
 - 9.8 TB of raw data
 - 1.5 TB/+1 000 000 reconstructions

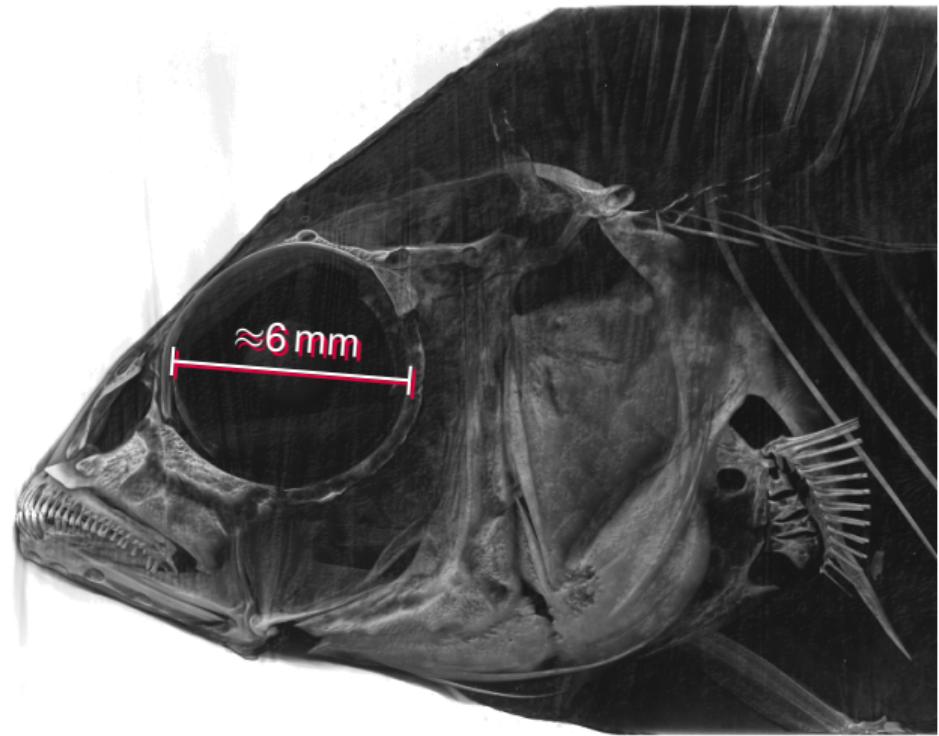


DOI:gsst8t, Fig. 1

[11] D. Haberthür *et al.*, Sep. 2023. DOI: gsst8t.

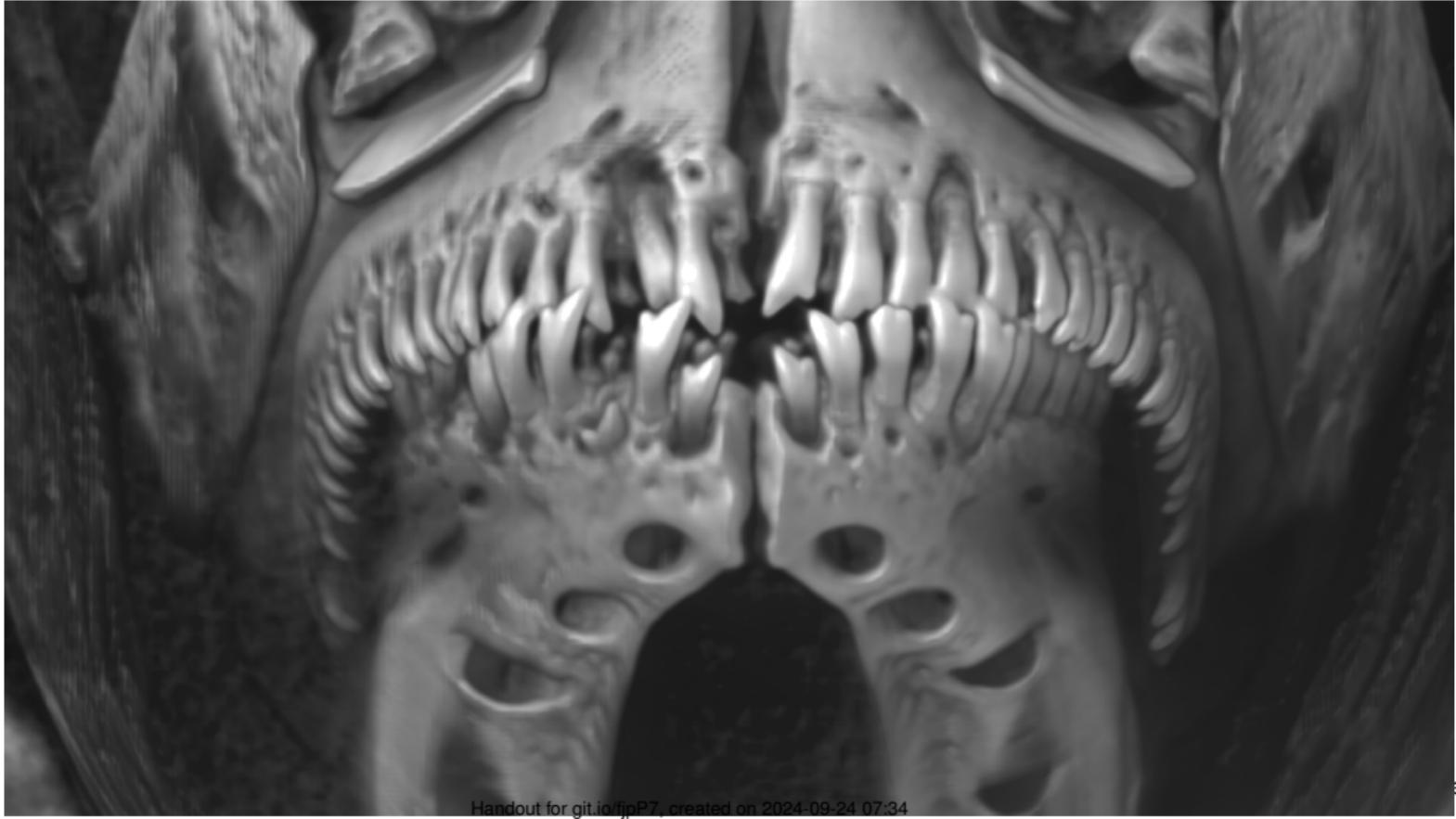
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Visualization of cichlid head



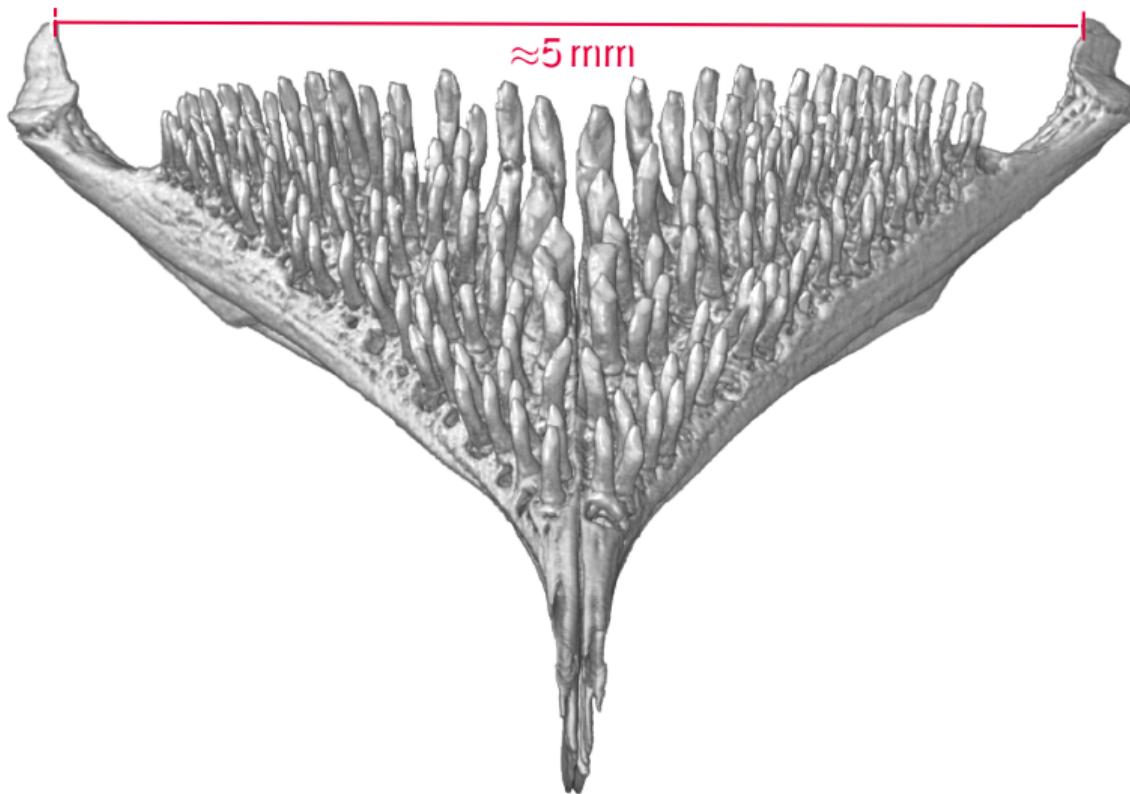
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Visualization of cichlid head



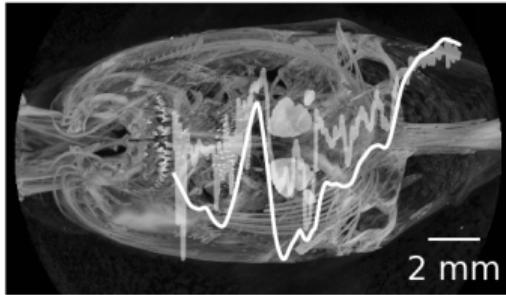
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Visualization of segmented pharyngeal jaw



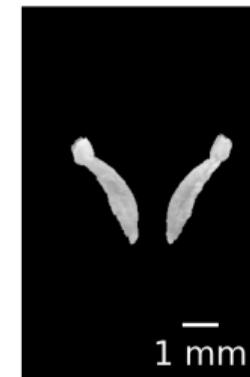
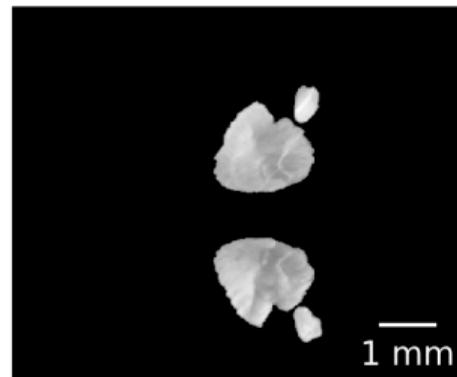
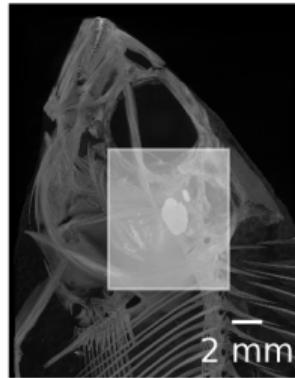
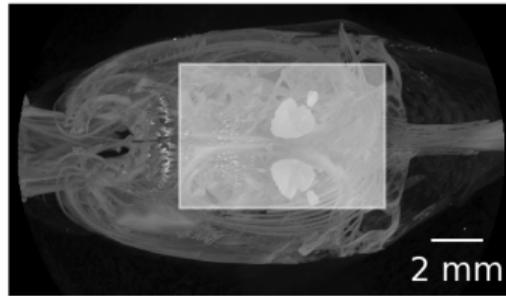
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Data wrangling by example: Cichlids



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Data wrangling by example: Cichlids



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Thanks!

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

Colophon

- This BEAMER presentation was crafted in \LaTeX with the (slightly adapted) template from *Corporate Design und Vorlagen* of the University of Bern.
 - Complete source code: git.io/fjpP7
 - The \LaTeX code is automatically compiled with a GitHub action to a (handout) PDF which you can access here: git.io/JeQxO
- Did you spot an error?
 - File an issue: git.io/fjpPb
 - Submit a pull request: git.io/fjpPN
 - Send me an email: david.haberthuer@unibe.ch

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