X-ray microtomography

David Haberthür

September 27, 2023 | 485018-HS2023-0: Advanced Course II Ultraprecision Engineering

UNIVERSITÄT BERN

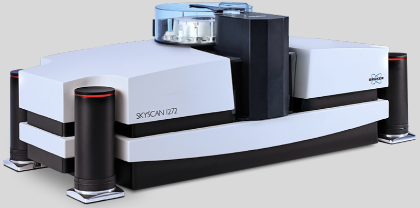
Grüessech mitenang!

- 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.

Grüessech from the µCT-group

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, 11]



bruker.com/skyscan1272

UNIVERSITÄT BERN

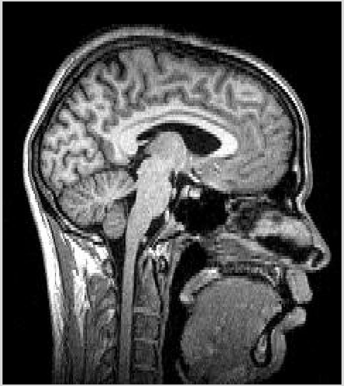
Contents

µCT

- 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. Correlative imaging pipelines, museum/ collection material)

Biomedical imaging

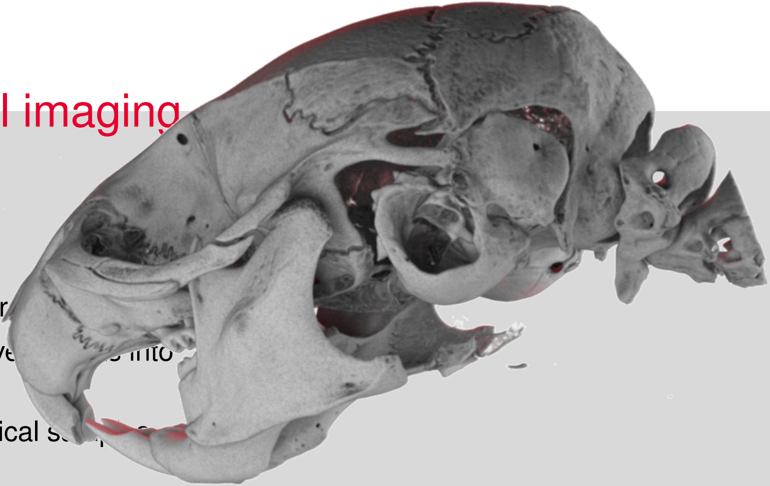
- Medical research
- Non-destructive insights into the samples
- (Small) Biological samples



w.wiki/7g4 ⓒⓘⓢ

UNIVERSITÄT BERN

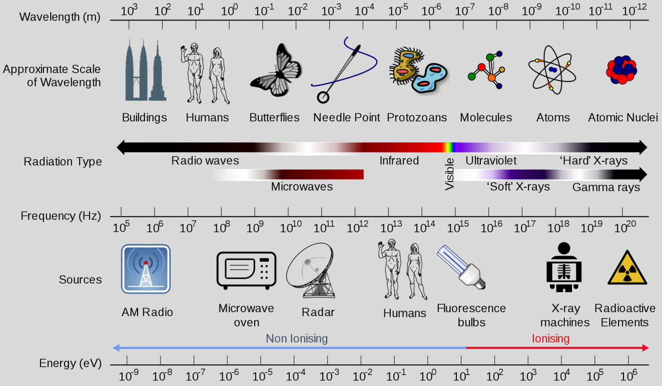
Biomedical imaging



- Medical resear
- Non-destructive … into the samples
- (Small) Biological s

UNIVERSITÄT BERN

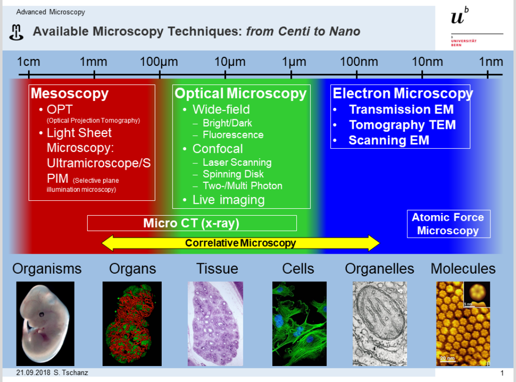
Wavelength & Scale



w.wiki/7fz

UNIVERSITÄT
BERN

Wavelength & Scale



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

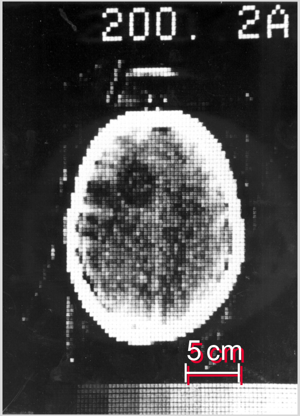
CT-Scanner

youtu.be/2CWpZKuy-NE

UNIVERSITÄT BERN

CT History

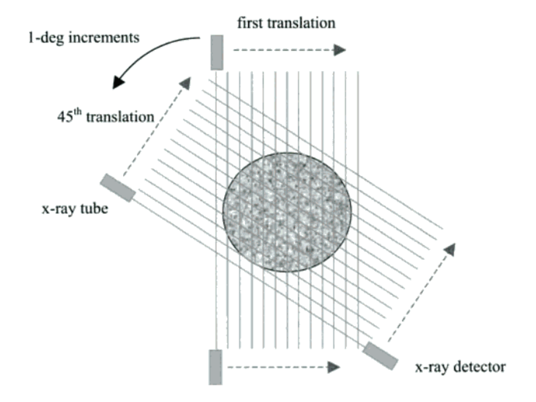
- Long history
  - 1963: Cormack used a collimated ^{60}Co source and a Geiger counter as a detector [12]
  - 1976: Hounsfield worked on first clinical scanner [13]
  - Nice overview by Hsieh [14]



From [**Beckmann2006**], Figure 5

CT History

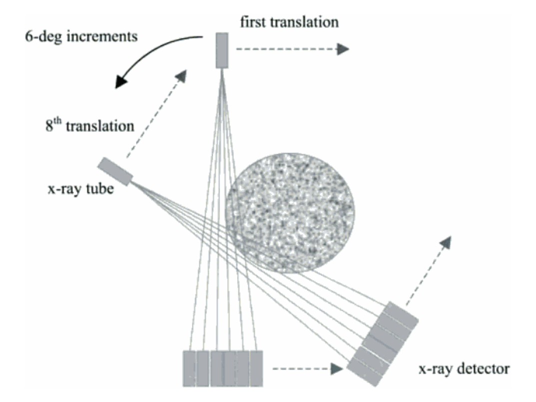
- Long history
  - 1963: Cormack used a collimated ^{60}Co source and a Geiger counter as a detector [12]
  - 1976: Hounsfield worked on first clinical scanner [13]
  - Nice overview by Hsieh [14]
- CT scanner generations: First



From [14], Figure 1.12

CT History

- Long history
  - 1963: Cormack used a collimated ^{60}Co source and a Geiger counter as a detector [12]
  - 1976: Hounsfield worked on first clinical scanner [13]
  - Nice overview by Hsieh [14]
- CT scanner generations: First, second

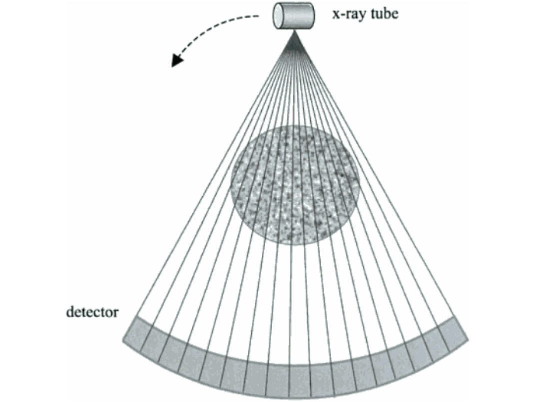


From [14], Figure 1.13

UNIVERSITÄT BERN

CT History

- Long history
  - 1963: Cormack used a collimated ^{60}Co source and a Geiger counter as a detector [12]
  - 1976: Hounsfield worked on first clinical scanner [13]
  - Nice overview by Hsieh [14]
- CT scanner generations: First, second and third



From [14], Figure 1.14

UNIVERSITÄT BERN

µCT History I

- X-ray computed tomography began to replace analog focal plane tomography in the early 1970s [**Lin2019**]
- µCT was first reported in the 1980s, for scanning gemstones
- Lee Feldkamp [**Feldkamp1984**] developed one of the early laboratory microCT systems by assembling a microfocus cone beam x-ray source, specimen holder and stagers, and an image intensifier at Ford Motor Company's Scientific Research Laboratory to nondestructively detect damage in ceramic manufactured automobile parts

µCT History II

- Met with scientists at Henry Ford Hospital and University of Michigan interested in understanding the relationship between the microstructure and biomechanical function of trabecular bone to study osteoporotic fractures [**Feldkamp1983**]
- CT scanners in medical diagnostics, beginning in the early 1970s
- Non-medical use in the late 1970s, for detection of internal defects in fabricated parts and equipment
- Today: Nondestructive imaging for 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

µCT History III

- Since the 1990s, µCT includes imaging of soft tissues and vasculature using radio-opaque contrast agents
- $\approx$2500 µCT systems are in use worldwide with over 1000 publications annually

UNIVERSITÄT BERN

X-ray interaction

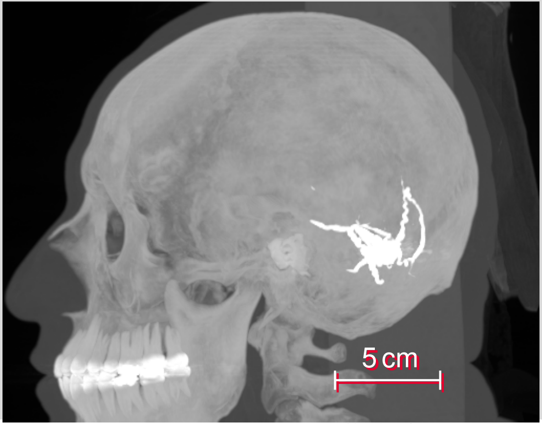
- “X-rays interact with tissue in 2 main ways: photoelectric effect and Compton scatter. To a first approximation, the photoelectric effect contributes to contrast while the Compton effect contributes to noise. Both contribute to dose.” ([15])
  - Photoelectric absorption (τ) is strongly dependent on 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 & physical) density of the material. It 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

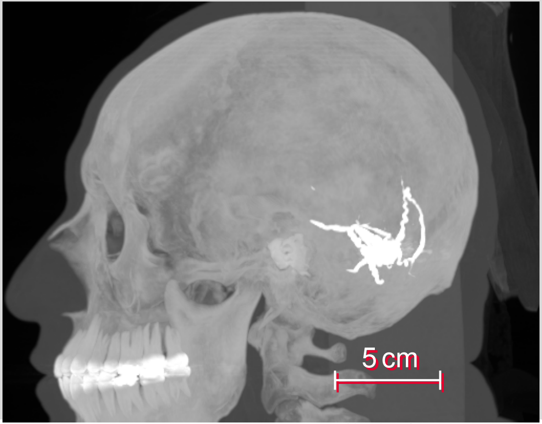
Why µCT?



From [17], Subject *C3L-02465*

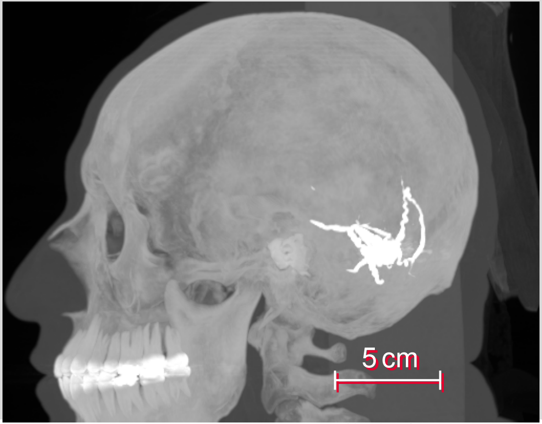
UNIVERSITÄT BERN

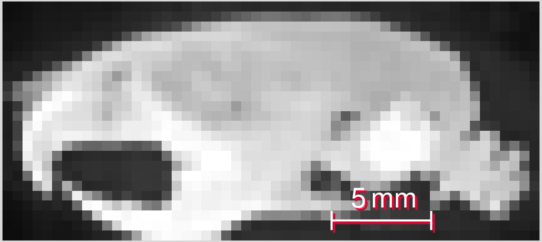
Why µCT?



From [17], Subject *C3L-02465*

Why µCT?

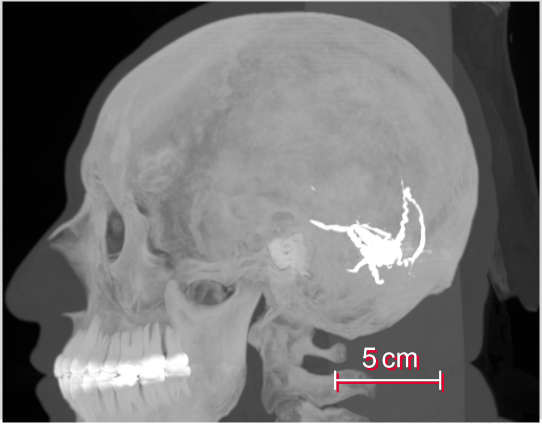




From [17]. Subject C3L-02465

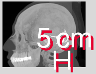
UNIVERSITÄT BERN

Why µCT?



From [17], Subject *C3L-02465*

Why µCT?



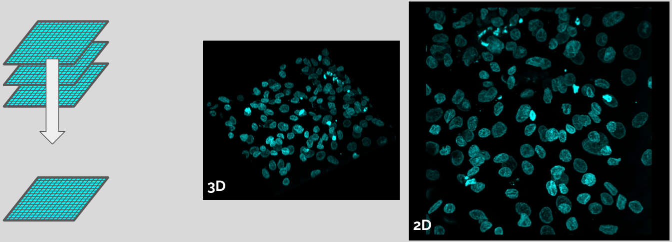
From [17], Subject *C3L-02465*

Maximum intensity projection

Projections

UNIVERSITÄT
BERN

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.



UNIVERSITÄT BERN

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

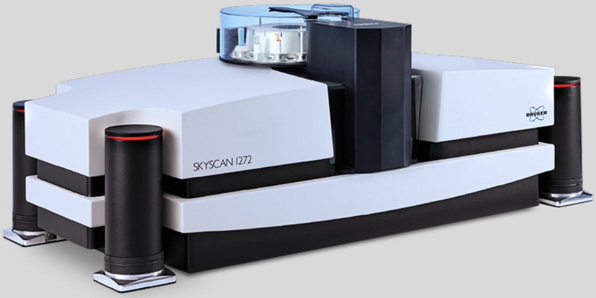
Machinery

- 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/fpTrGu

Machinery

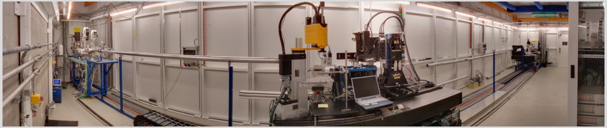
- Hospital CT
  - Voxel size around 0.5 mm
- Lab/Desktop CT
  - Voxel size around 7 µm (*in vivo*) or 0.5 µm (*ex vivo*)
- Synchrotron CT
  - Voxel size down to 160 nm



bruker.com/skyscan1272

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



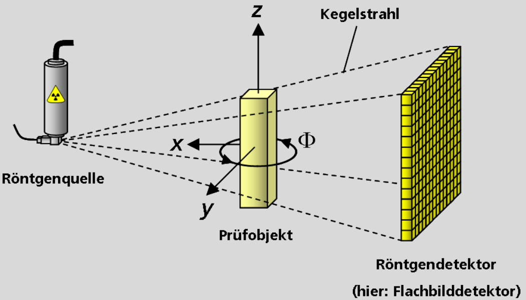
flic.kr/p/7Xhk2Y

UNIVERSITÄT BERN

What is happening?

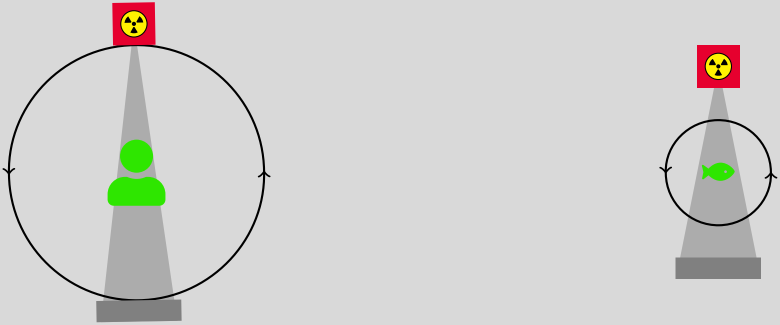
No matter what kind of machine, the basic principle is always the same

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

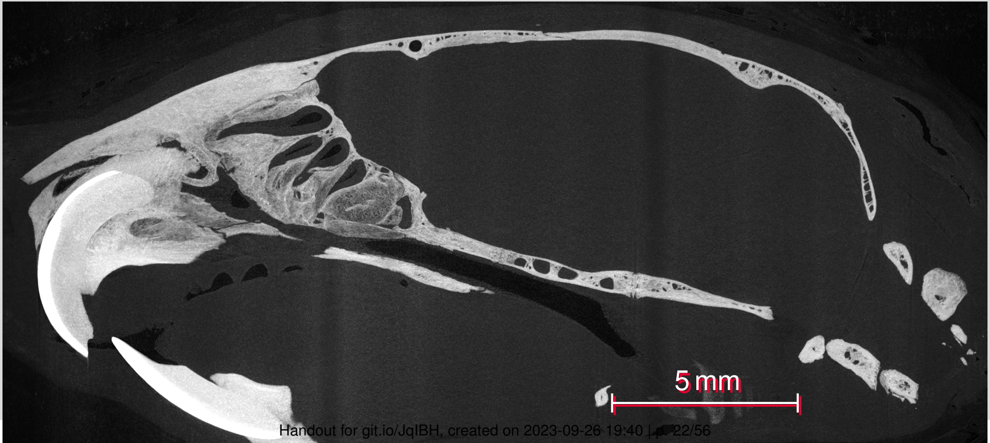


w.wiki/7g3

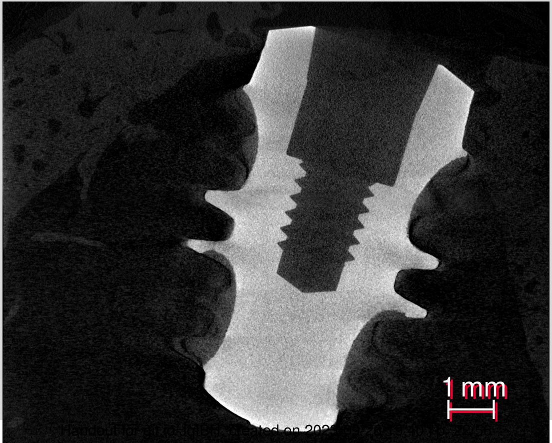
Machinery



Examples

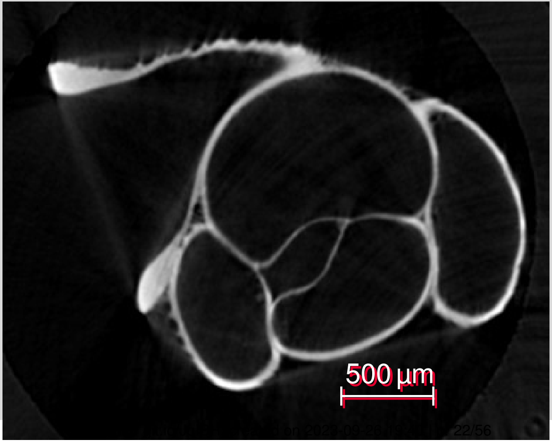


Examples

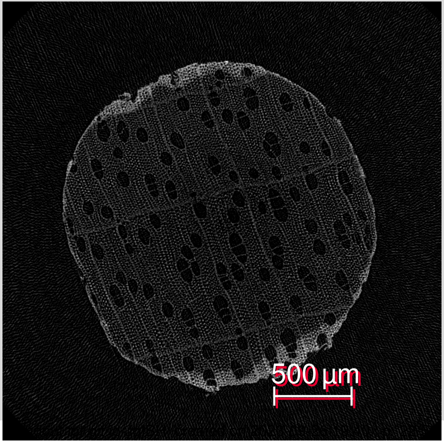


UNIVERSITÄT BERN

Examples



Examples



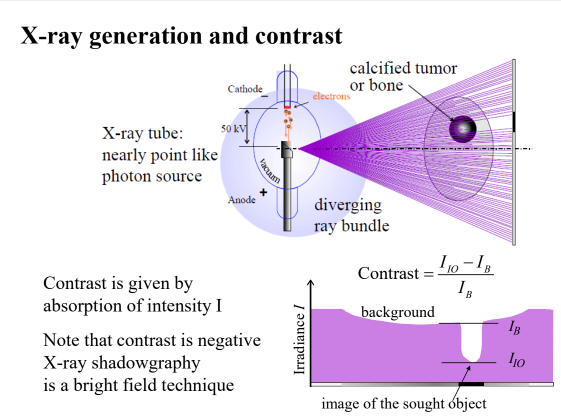
Examples

Preparation

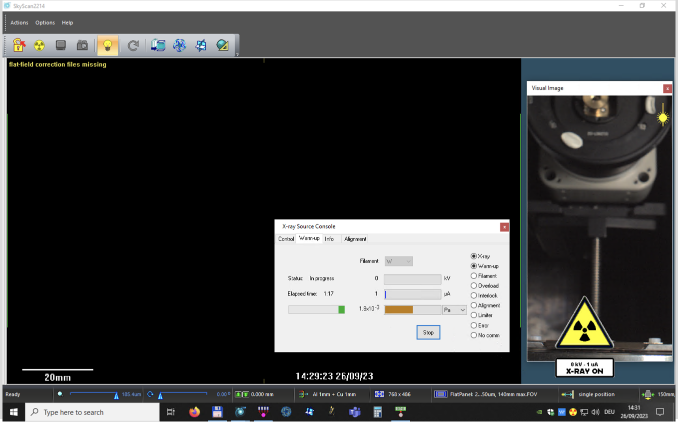
- Study design
- Sample preparation

UNIVERSITÄT BERN

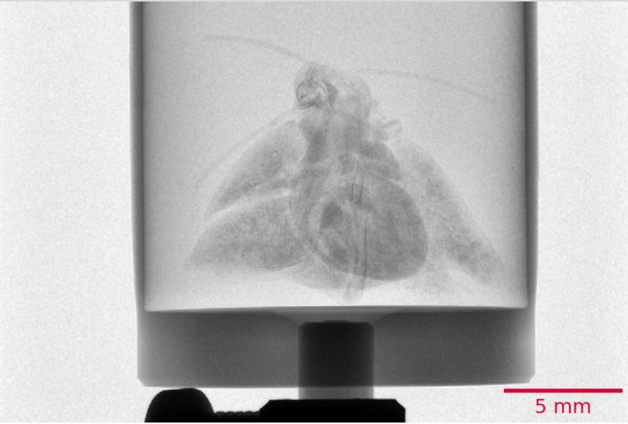
Projections



Projection acquisition



Projections



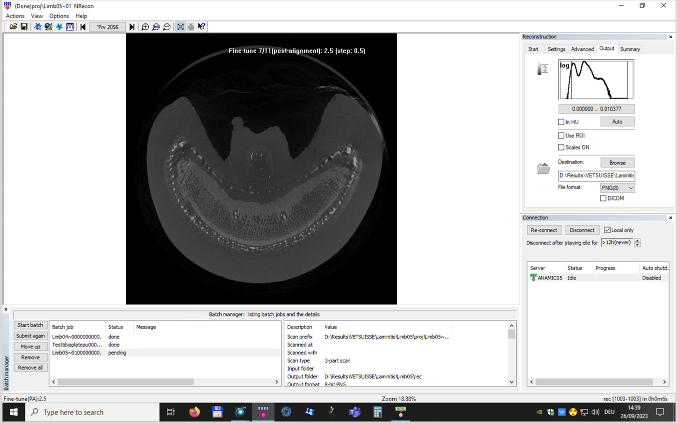
Projections

- 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

u^b

b UNIVERSITÄT BERN

Reconstructions



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

UNIVERSITÄT BERN

Visualization

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

UNIVERSITÄT BERN

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!

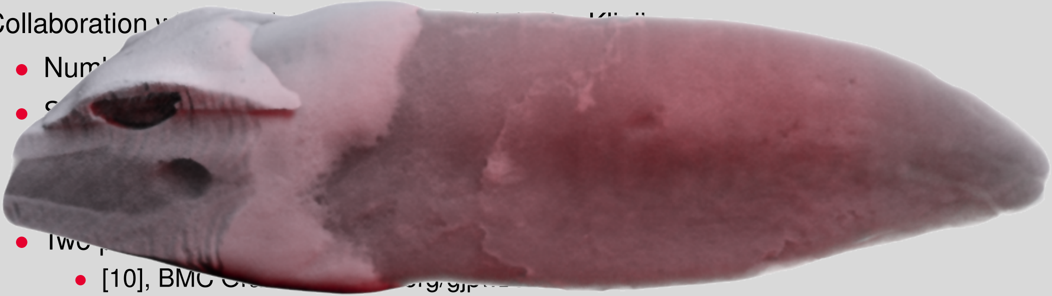
Quantitative data

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

Internal morphology of human teeth

Collaboration w

- Num
- S
- Two p
  - [10], BMC
  - [20], Scientific Reports, doi.org/g7r8



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

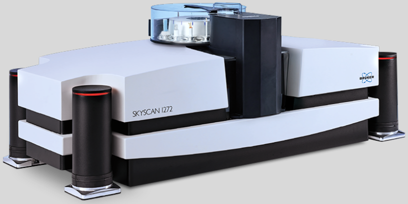
UNIVERSITÄT BERN

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!

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!



bruker.com/skyscan1272

UNIVERSITÄT BERN

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!

```
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
```

UNIVERSITÄT BERN

How?

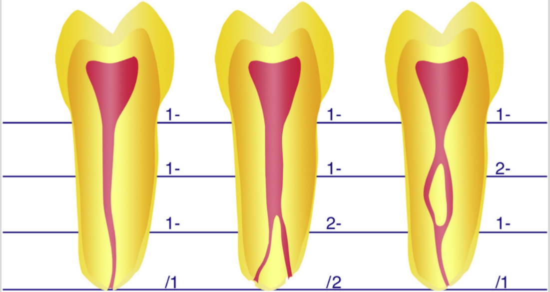
- 104 extracted human permanent mandibular canines
- µCT imaging
- Root canal configuration, according to Briseño-Marroquín et al. [21]
- *Reproducible* analysis [22], e. g. you can click a button to double-check or recalculate the results yourself!

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

How?

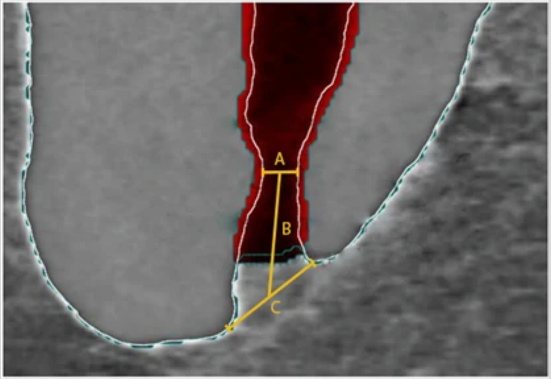
- 104 extracted human permanent mandibular canines
- µCT imaging
- Root canal configuration, according to Briseño-Marroquín et al. [21]
- *Reproducible* analysis [22], e. g. you can click a button to double-check or recalculate the results yourself!



From [21], Fig. 2

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!



From [23], Fig. 1

How?

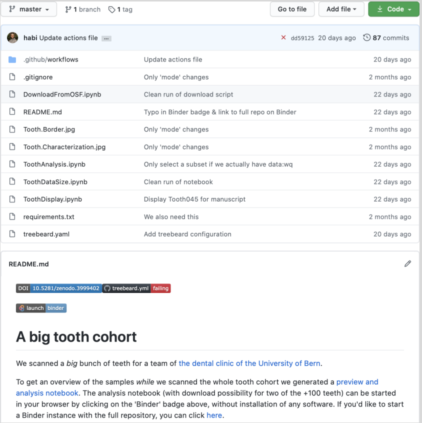
- 104 extracted human permanent mandibular canines
- µCT imaging
- Root canal configuration, according to Briseño-Marroquín et al. [21]
- *Reproducible* analysis [22], e. g. you can click a button to double-check or recalculate the results yourself!

gph.is/2nqkple

UNIVERSITÄT BERN

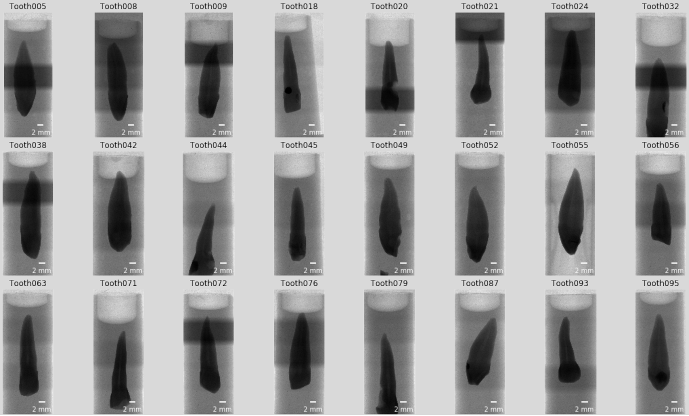
How?

- 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!



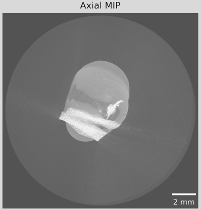
b
UNIVERSITÄT
BERN

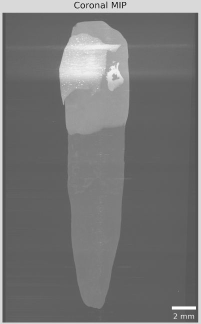
µCT imaging

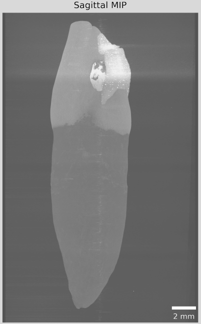


Dataset cropping

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

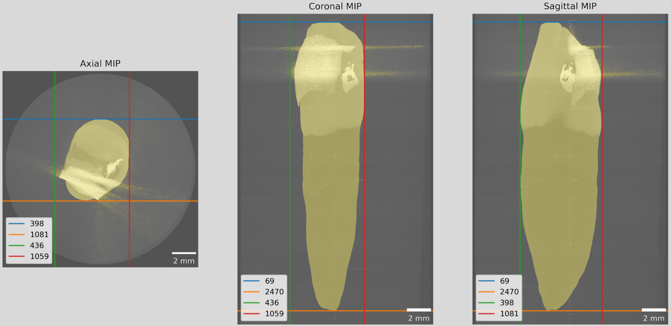




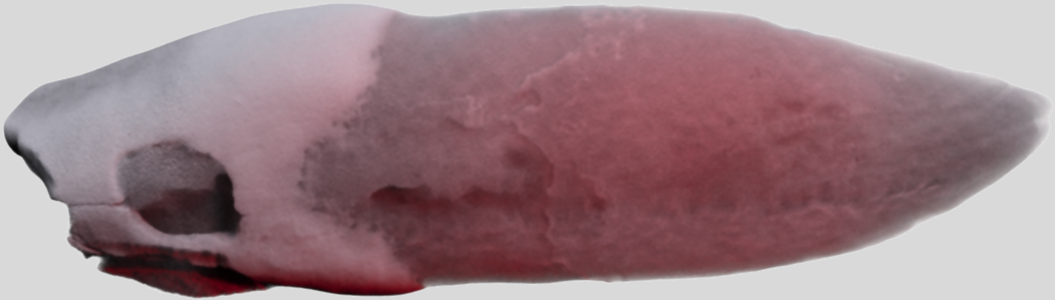


Dataset cropping

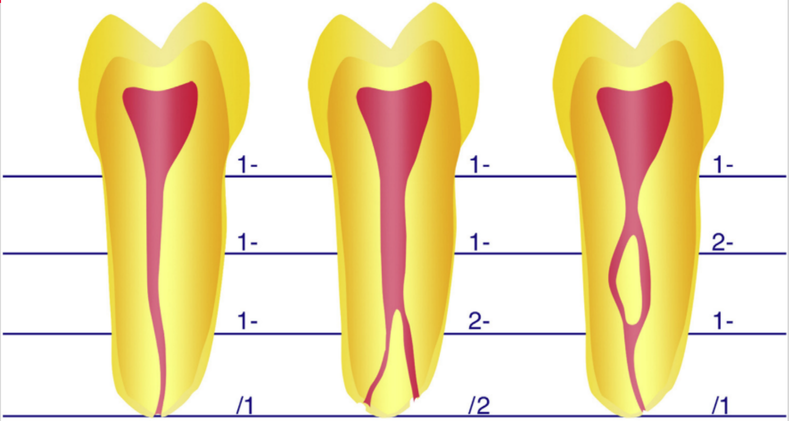
- Full datasets: 326 GB
- Cropped datasets: 115 GB



Tooth morphology

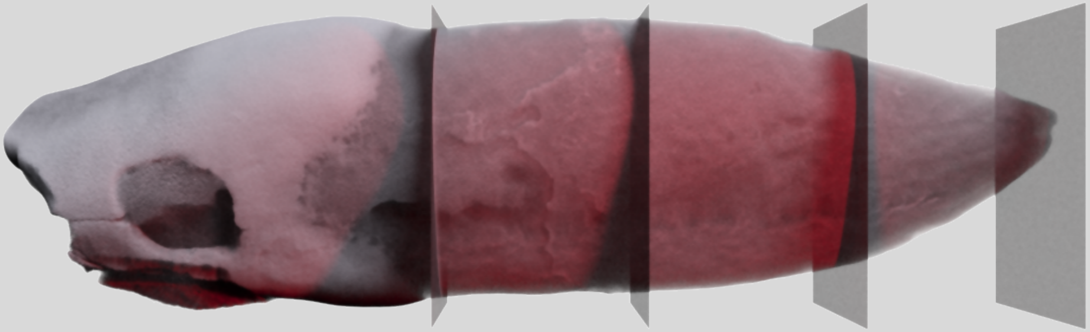


Tooth morphology



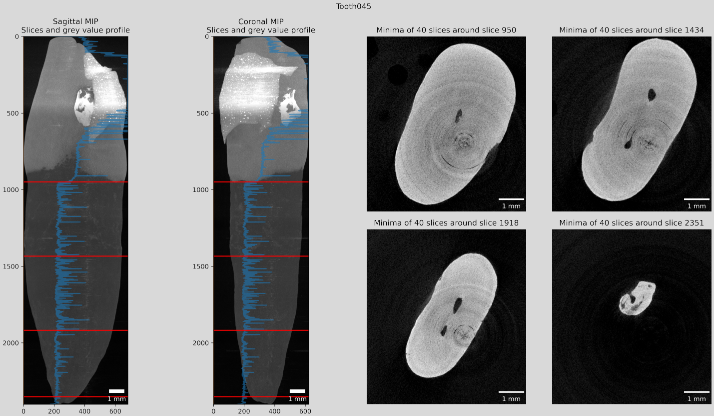
From [21], Fig. 2

Tooth morphology

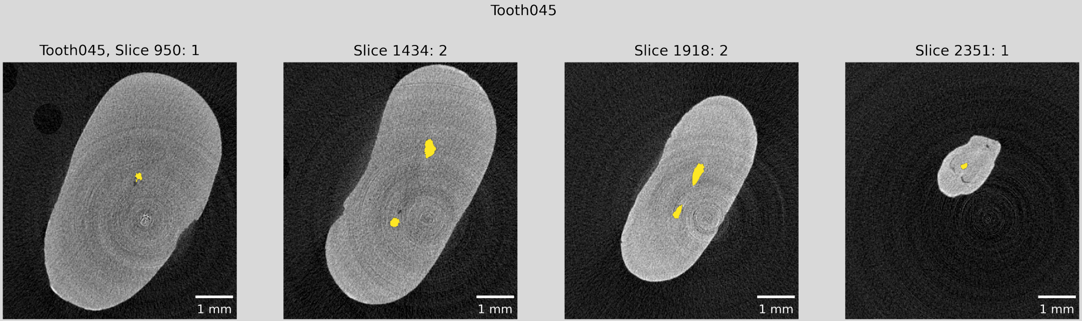


UNIVERSITÄT BERN

Detection of enamel-dentin border



Detection of enamel-dentin border

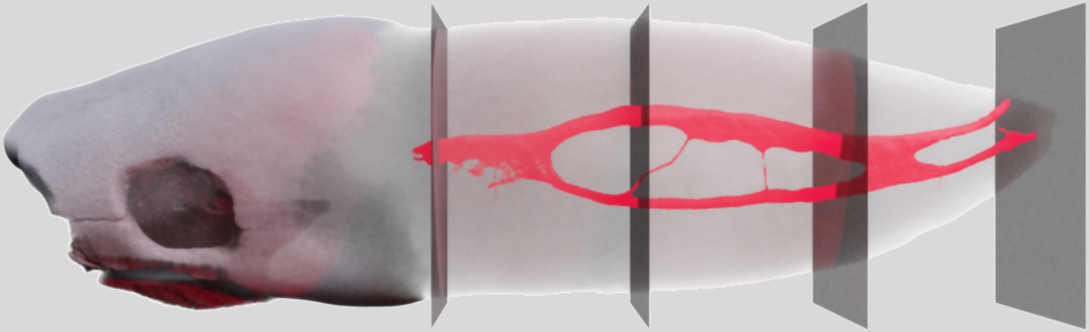


UNIVERSITÄT BERN

Outcome root canal configuration classification

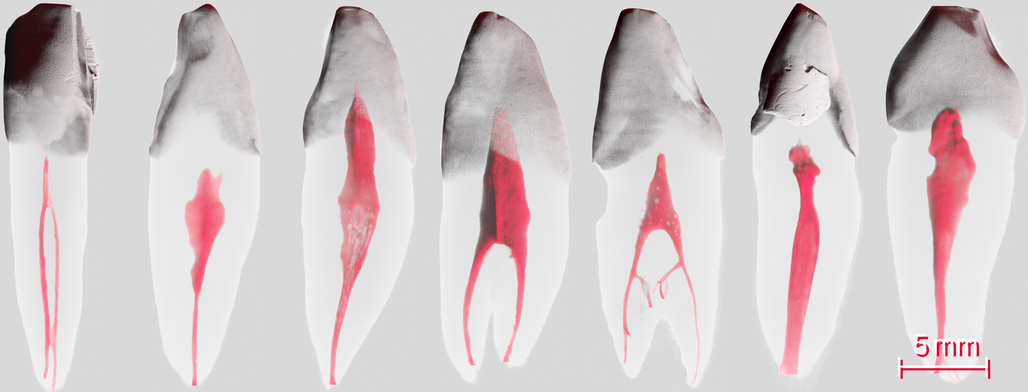
Roots		RCC	#	%
Single (N=98)		1-1-1/1	73	74.5
		1-1-1/2	14	14.3
		1-1-1/3	1	1.0
		1-1-1/4	2	2.1
		1-1-2/1	1	1.0
		1-2-1/1	4	4.1
		1-2-1/2	1	1.0
		1-2-2/2	1	1.0
		2-3-1/1	1	1.0
Double (N=3)	Buccal	1-1-1/1	2	66.6
		1-2-1/1	1	33.3
	Lingual	1-1-1/1	2	66.6
		1-1-1/2	1	33.3

Extraction of root canal space



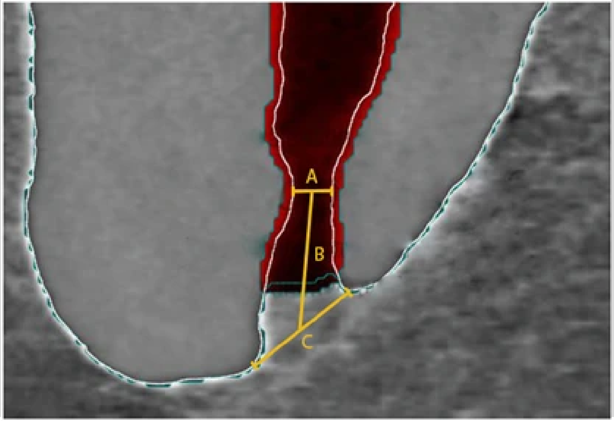
UNIVERSITÄT BERN

Results of root canal space extraction



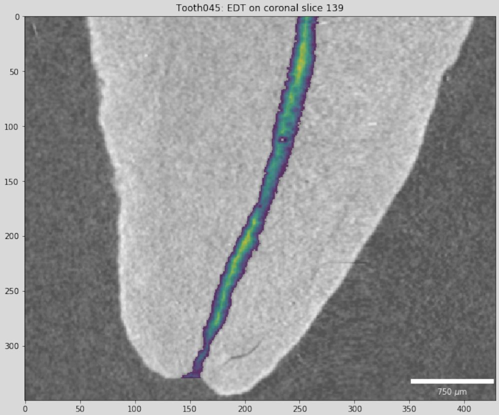
u^b UNIVERSITÄT BERN

Analysis of the physiological foramen geometry



From [23], Fig. 1

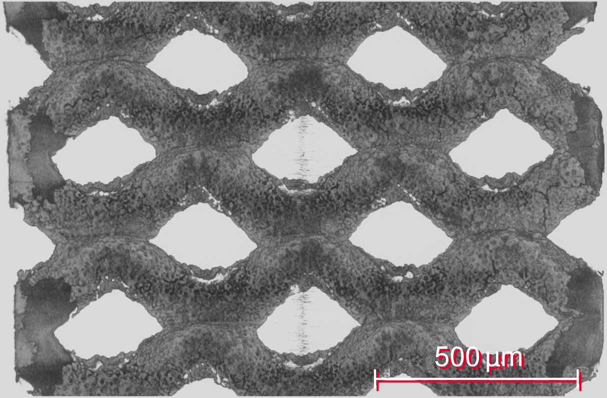
Analysis of the physiological foramen geometry



Conclusion ZMK

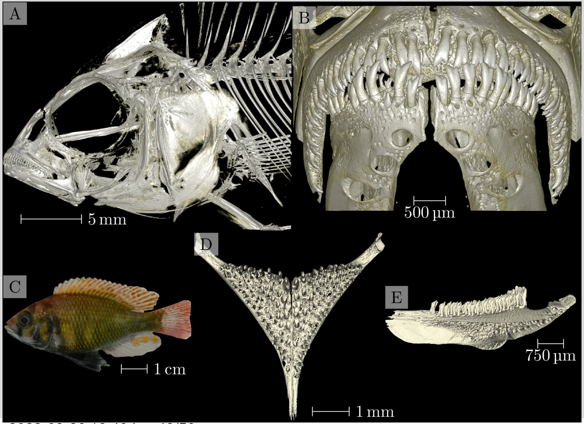
- Efficient use of time, e. g. more teeth does not mean more (human) work
- Reproducible analysis with *free and open-source* software, usable by *anyone*
- Objective analysis, e. g. no operator bias

Metal foam



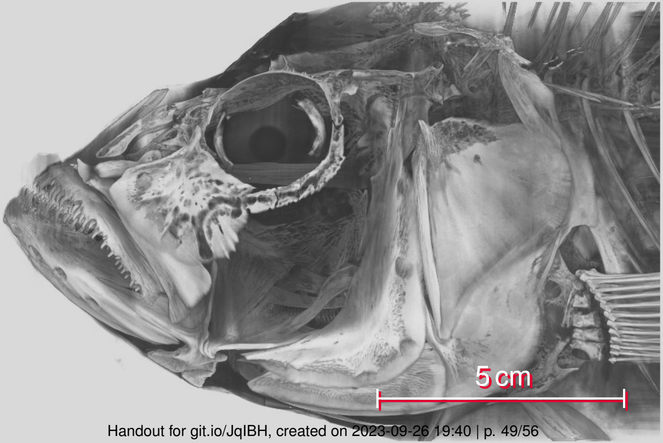
Data wrangling by example: Cichlids

- 372 tomographic scans of 133 different Cichlids, from 6–18 cm [a]
- 9.8 TB of projection images, 1.5 TB of reconstructions
- Reproducible and automated dataset



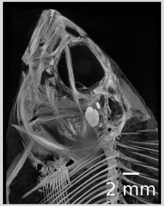
UNIVERSITÄT BERN

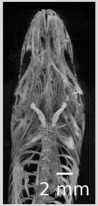
Cichlids



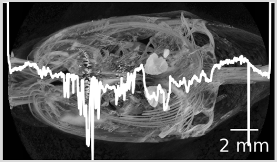
UNIVERSITÄT BERN

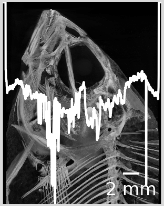
Data wrangling by example: Cichlids

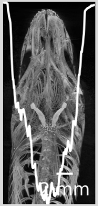




Data wrangling by example: Cichlids

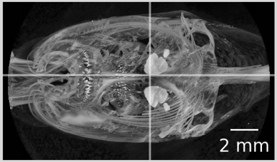


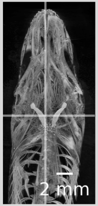




UNIVERSITÄT BERN

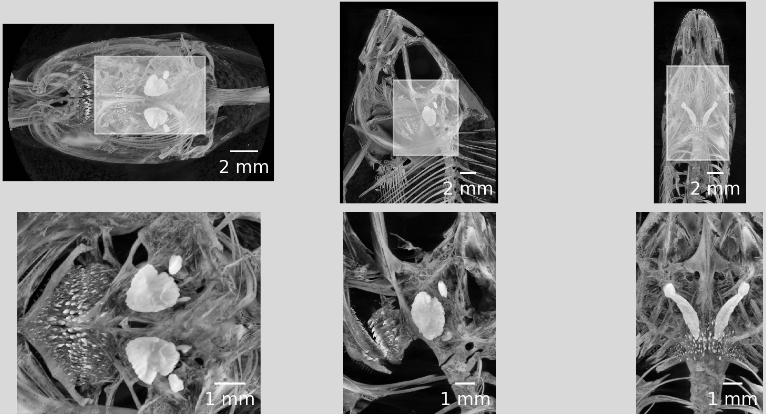
Data wrangling by example: Cichlids





UNIVERSITÄT BERN

Data wrangling by example: Cichlids



UNIVERSITÄT BERN

Thanks!

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

UNIVERSITÄT BERN

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 [1] 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: haberthuer@ana.unibe.ch

[1] Details on how this works are specified in a small test repository here: git.io/JeOOj

UNIVERSITÄT BERN

References I

[1] Ruslan Hlushchuk et al. “Ex Vivo microangioCT: Advances in Microvascular Imaging”. DOI: 10.1016/j.vph.2018.09.003.

[2] Henry Nording et al. “The C5a/C5a Receptor 1 Axis Controls Tissue Neovascularization through CXCL4 Release from Platelets”. DOI: 10.1038/s41467-021-23499-w.

[3] Ruslan Hlushchuk et al. “Innovative High-Resolution microCT Imaging of Animal Brain Vasculature”. DOI: 10.1007/s00429-020-02158-8.

[4] Tsering Wüthrich et al. “Development of Vascularized Nerve Scaffold Using Perfusion-Decellularization and Recellularization”. DOI: 10.1016/j.msec.2020.111311.

[5] Cédric Zubler et al. “The Anatomical Reliability of the Superficial Circumflex Iliac Artery Perforator (SCIP) Flap”. DOI: 10.1016/j.aanat.2020.151624.

[6] Matthias Messerli et al. “Adaptation Mechanism of the Adult Zebrafish Respiratory Organ to Endurance Training”. DOI: 10.1371/journal.pone.0228333.

UNIVERSITÄT BERN

References II

[7] Verdiana Trappetti et al. "Synchrotron Microbeam Radiotherapy for the Treatment of Lung Carcinoma: A Pre-Clinical Study". DOI: 10.1016/j.ijrobp.2021.07.1717.

[8] Estée Bochud et al. "A New Diancta Species of the Family Diplommatinidae (Cyclophoroidea) from Vanua Levu Island, Fiji". DOI: 10.3897/zookeys.1073.73241.

[9] Sebastian Halm et al. "Micro-CT Imaging of Thiel-embalmed and Iodine-Stained Human Temporal Bone for 3D Modeling". DOI: 10.1186/s40463-021-00522-0.

[10] David Haberthür et al. "Automated Segmentation and Description of the Internal Morphology of Human Permanent Teeth by Means of Micro-CT". DOI: gjpw2d.

[11] David Haberthür et al. *Microtomographic Investigation of a Large Corpus of Cichlids*. DOI: 10.1101/2023.03.30.534917.

[12] A. M. Cormack. "Representation of a Function by Its Line Integrals, with Some Radiological Applications". DOI: 10.1063/1.1729798.

UNIVERSITÄT BERN

References III

[13] Godfrey Newbold Hounsfield. “Historical Notes on Computerized Axial Tomography.”.

[14] J Hsieh. *Computed Tomography: Principles, Design, Artifacts, and Recent Advances*. Society of Photo Optical.

[15] Mark Hammer. *X-Ray Physics: X-Ray Interaction with Matter, X-Ray Contrast, and Dose*.

[16] Wikipedia contributors. *Beer–Lambert Law — Wikipedia, The Free Encyclopedia*.

[17] Kenneth Clark et al. “The Cancer Imaging Archive (TCIA): Maintaining and Operating a Public Information Repository”. DOI: 10.1007/s10278-013-9622-7.

[18] Johannes Schindelin et al. “Fiji: An Open-Source Platform for Biological-Image Analysis”. DOI: 10.1038/nmeth.2019.

[19] Thomas Kluyver et al. “Jupyter Notebooks – a Publishing Format for Reproducible Computational Workflows”. DOI: 10.3233/978-1-61499-649-1-87.

UNIVERSITÄT BERN

References IV

[20] Thomas Gerhard Wolf et al. “Internal Morphology of 101 Mandibular Canines of a Swiss-German Population by Means of Micro-CT: An Ex Vivo Study”. DOI: 10.1038/s41598-021-00758-w.

[21] Benjamín Briseño-Marroquín et al. “Root Canal Morphology and Configuration of 179 Maxillary First Molars by Means of Micro–Computed Tomography: An Ex Vivo Study”. DOI: 10.1016/j.joen.2015.09.007.

[22] David Haberthür. “Habi/Zmk-Tooth-Cohort: Used for Manuscript about Method”. DOI: 10.5281/ZENODO.3999402.

[23] Thomas Gerhard Wolf et al. “Three-Dimensional Analysis of the Physiological Foramen Geometry of Maxillary and Mandibular Molars by Means of Micro-CT”. DOI: 10.1038/ijos.2017.29.