Bone Imaging

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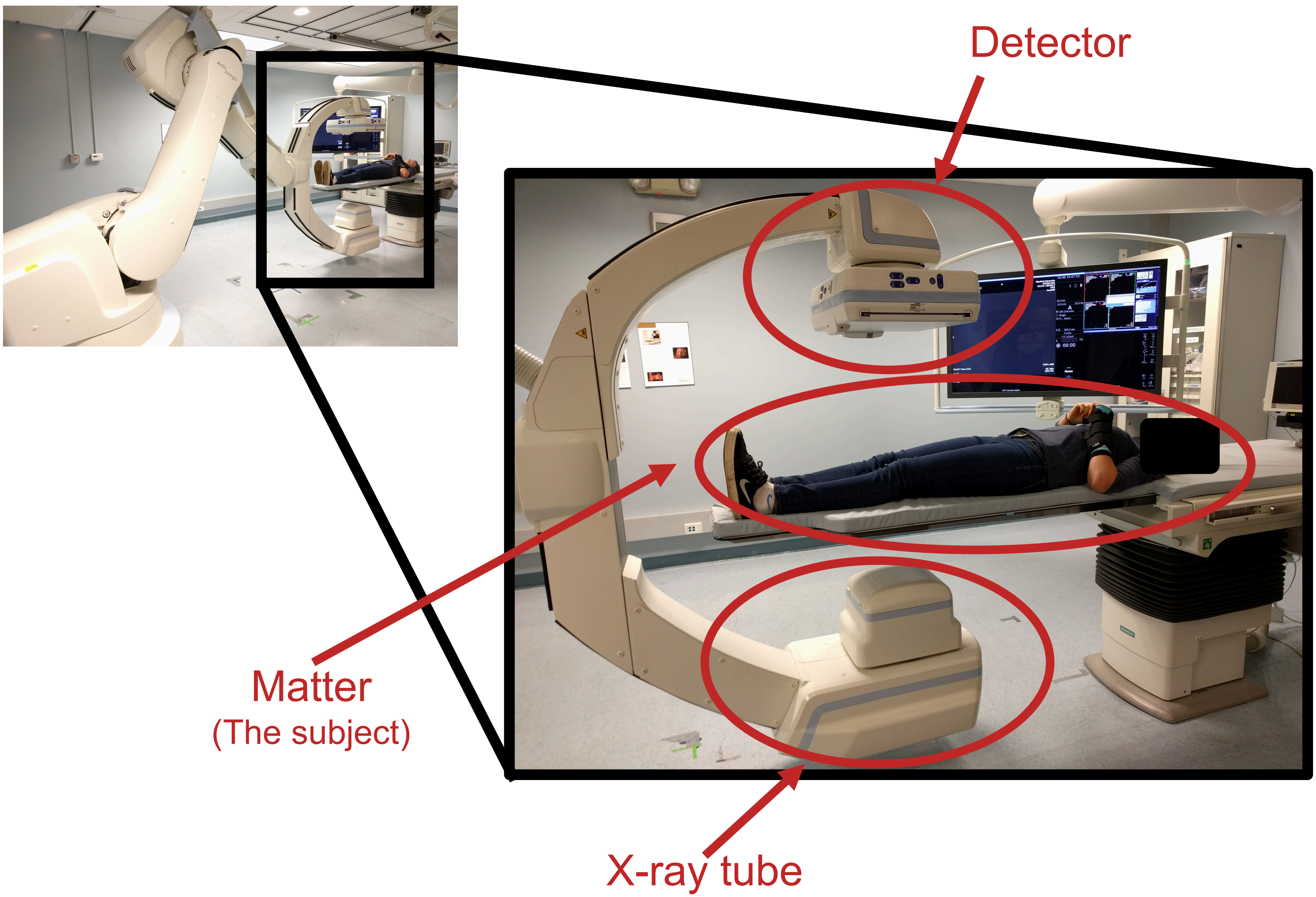
The imaging system: X-ray Tube, Subject and Detector



X-ray discovery

- 1895: Wilhelm Conrad Röntgen discovers X-rays

Early usage of X-rays

- Beyond being used for medical applications, X-rays triggered unprecedented euphoria

MAGIC THEATER

Affiche de spectacle au Théâtre Robert-Houdin
(source : revue *Contrastes* de Guerbet, 1995)

http://adammunich.com/a-brief-history-of-the-x-ray/

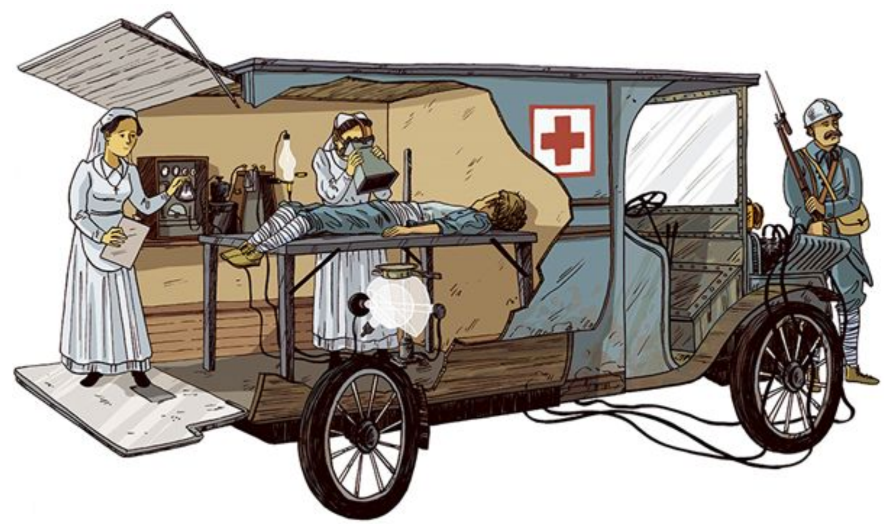
COIN OPERATED X-RAY MACHINES

http://www.underthepier.com/17_novelty_machines.htm

Early usage of X-rays

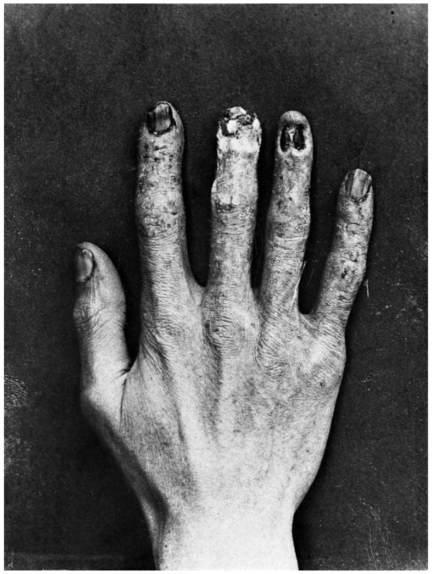
- 1914-1918 (World War I): Marie Curie created mobile X-ray vehicles to assist battlefield surgeons

https://en.wikipedia.org/wiki/Marie_Curie#World_War_I



http://www.carestream.com/blog/2014/11/13/radiology-first-world-war/

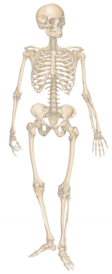
X-ray Safety



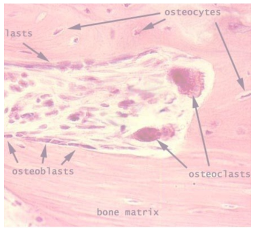
Multi-Scale Approach to Bone Study

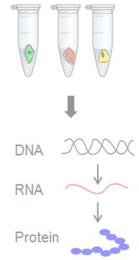
BODY LEVEL | ORGAN LEVEL | TISSUE LEVEL | CELLULAR LEVEL | MOLECULAR LEVEL

Biology


[m - cm]


[cm - mm]

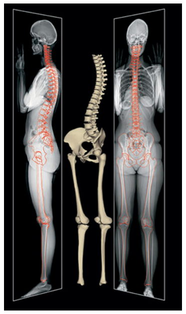


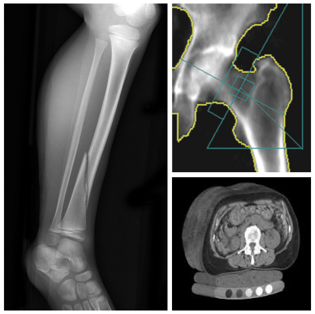


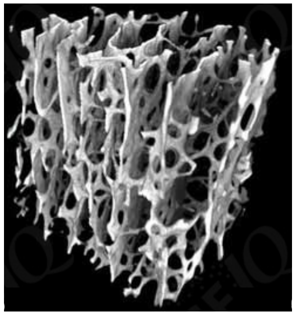
Biomechanics

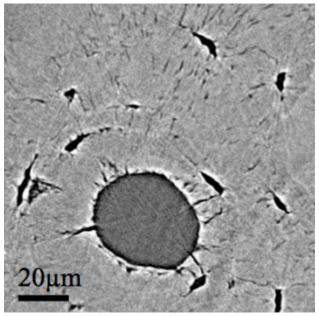
Rigid Object Models | Deformable Continuum Models | Statistical Models

Imaging





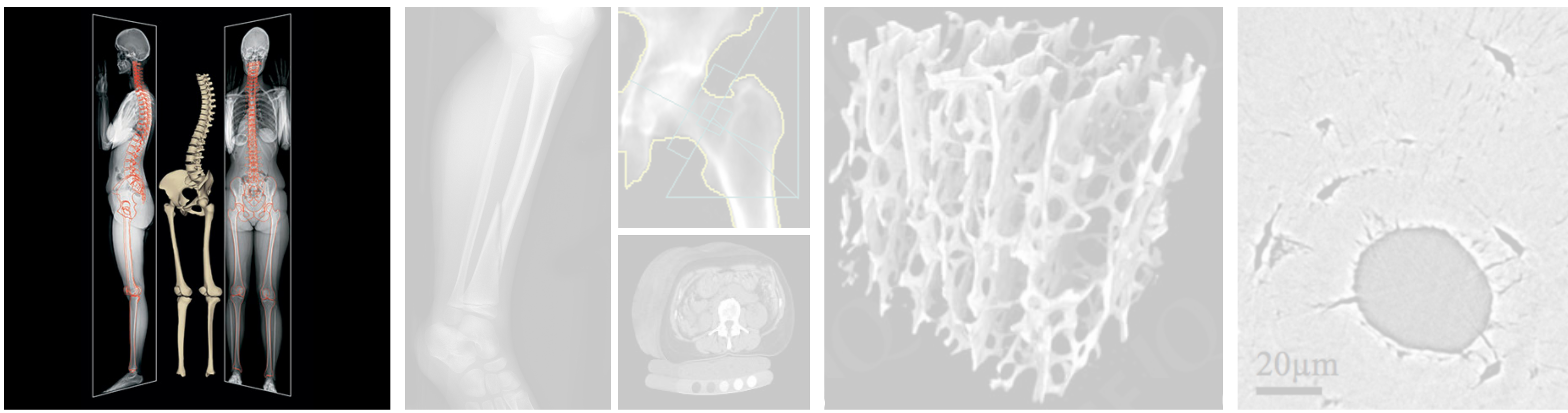




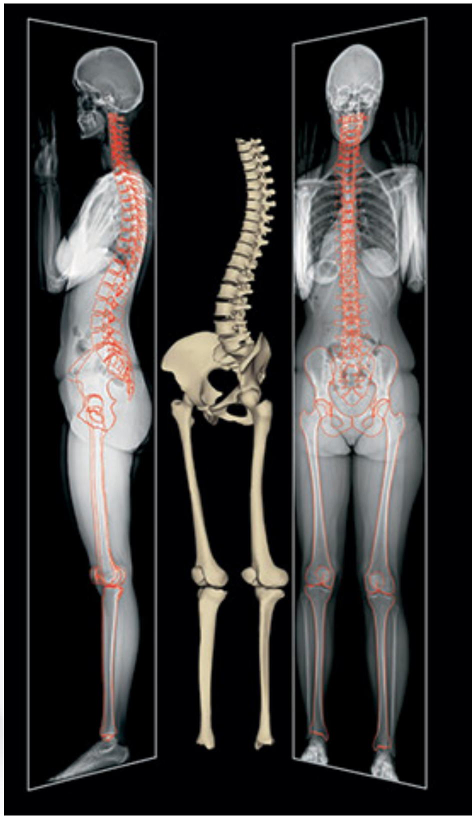
The Body Level

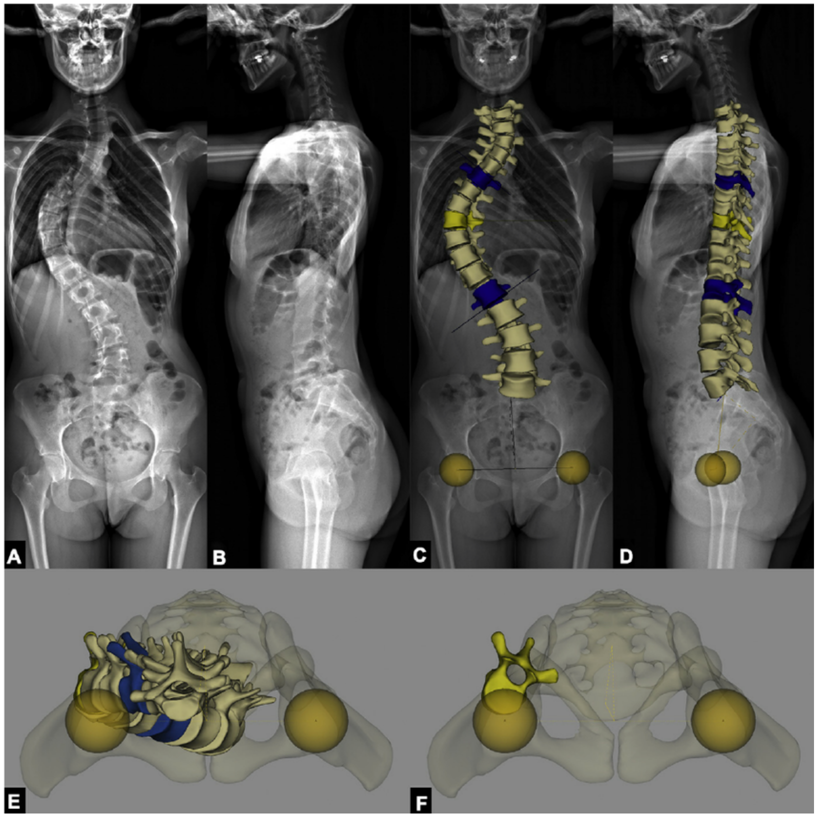
BODY LEVEL | ORGAN LEVEL | TISSUE LEVEL | CELLULAR LEVEL

Imaging



Whole-Body Imaging





The Organ Level

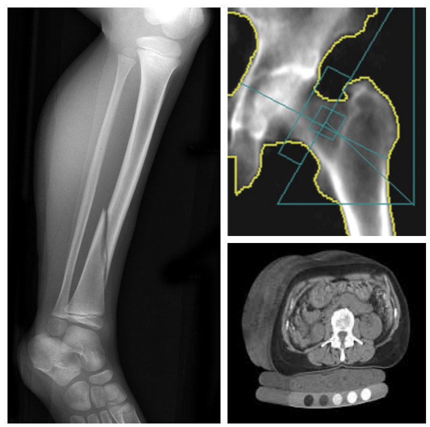
BODY LEVEL

ORGAN LEVEL

TISSUE LEVEL

CELLULAR LEVEL

Imaging

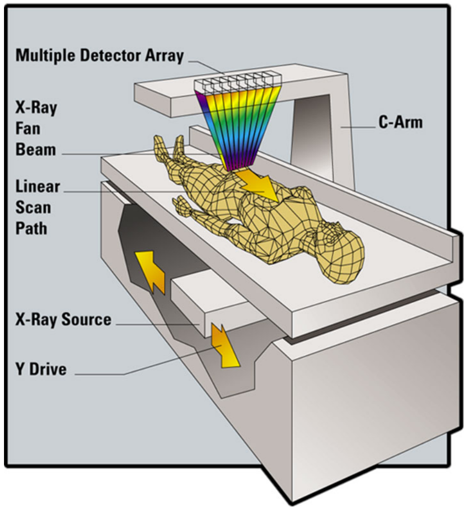


Radiography

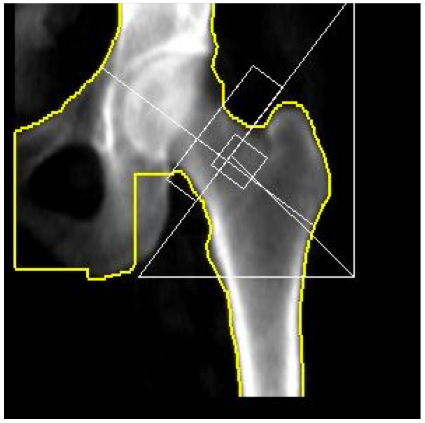
- Oldest medical application of X-rays

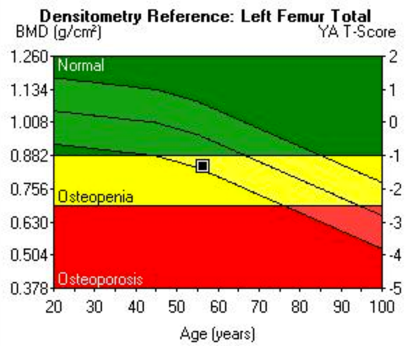
- Used mainly to diagnose fractures and to assess surgical outcome

DXA: Dual Energy X-ray Absorptiometry



- Introduced to clinical routine in 1987
- Standard technique to define osteoporosis
- It measures areal bone mineral density (aBMD) in vivo
- Low radiation dose
- Indicated for women > 65yo
- Recommended for men > 70yo



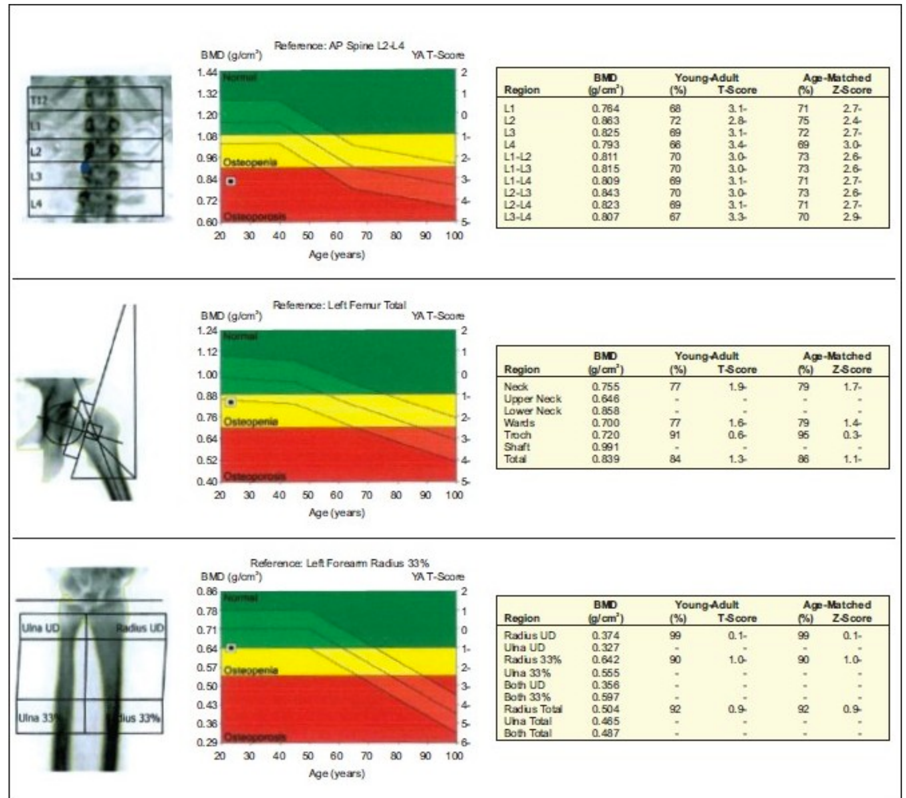


DXA: The Clinical Exam

https://www.youtube.com/watch?v=2h4EB-ZPNv8&spfreload=10

DXA: Measurements

- Measurement sites:
  - Spine: L1-L4
  - Hip: Total proximal femur, femoral neck, throchanter
  - Forearm: 1/3 radius
  - Whole body
- Acquisition time:
  - Spine, hip, forearm: ~1min
  - Whole body: 3-6min
- Radiation dose:
  - 10-15 µSv
    - Chest X-ray: 0.1 mSv
    - Cross country flight: ~0.05 mSv
    - Annual background radiation: ~3.6 mSv

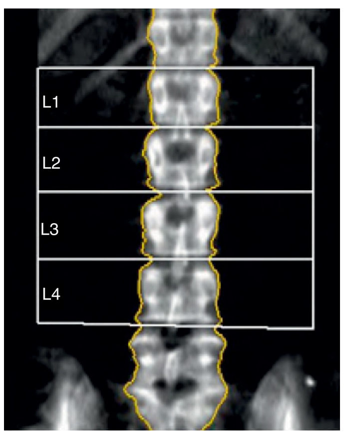


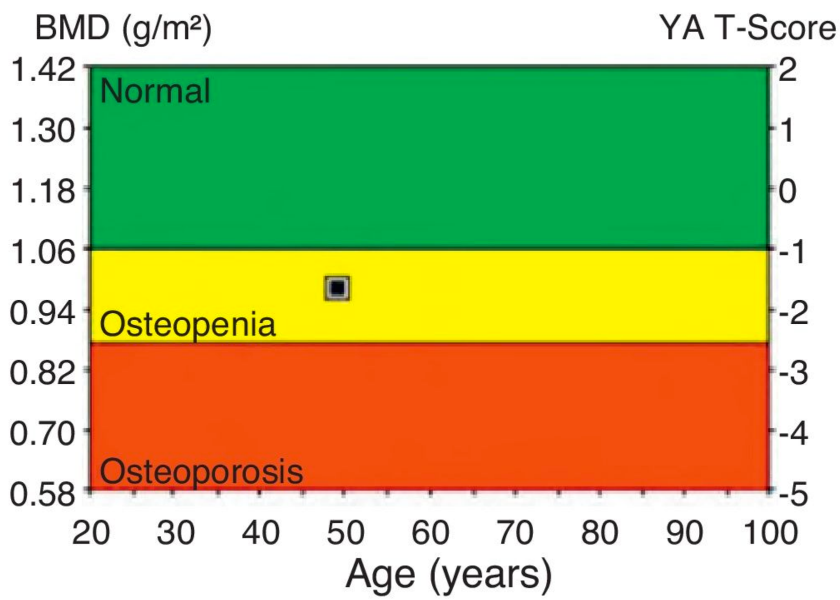
Adapted from G. Kazakia

DXA: T-score

- The T-score is used to classify and define aBMD measurements
- The T-score is the standard deviation of the aBMD of an individual patient compared with a young, healthy reference population, matched for sex and ethnicity

$$\text{T-score} = \frac{\text{Subject's BMD} - \text{Young-Adult Mean BMD}}{\text{1SD of Young-Adult Mean BMD}} \quad \text{Ex. T-score} = \frac{0.7\text{g/cm}^2 - 1.0\text{g/cm}^2}{0.1\text{g/cm}^2} = -3.0\text{g/cm}^2$$





T-score > -1 Normal → Normal

T-score < - 1 and > -2.5 → Osteopenia

T-score < -2.5 → Osteoporosis

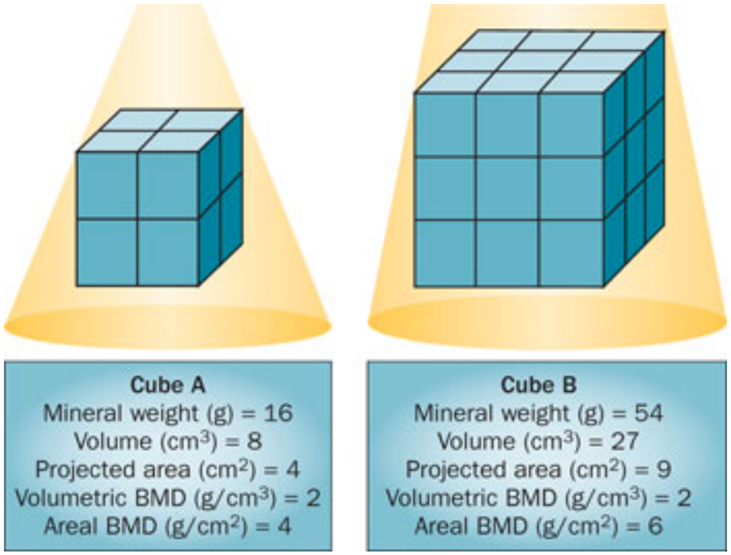
- The Z-score: comparison with age-matched population

DXA: Limitations

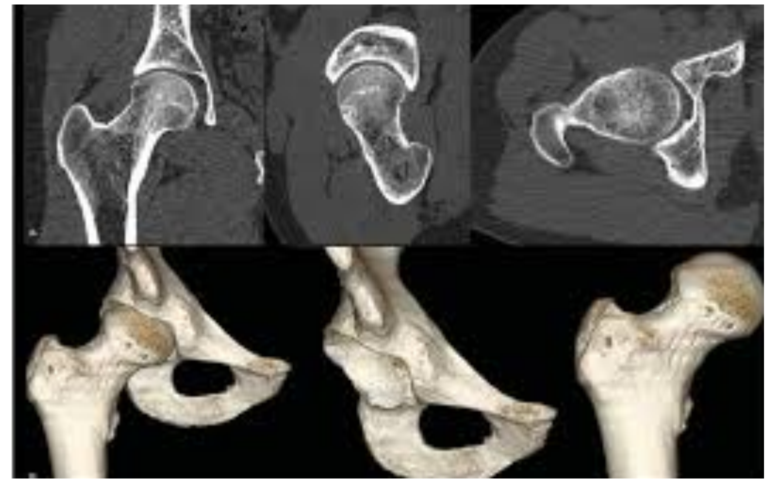
- DXA is 2D and measures *areal* BMD

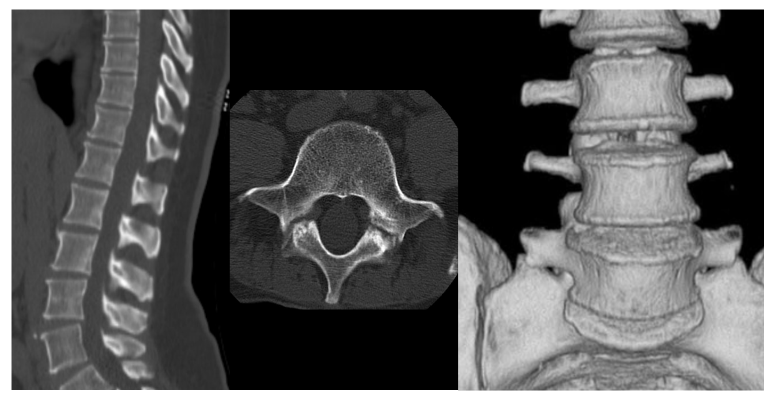
- Susceptibility to body size: overestimation of fracture risk for small individuals

- DXA cannot separate cortical and trabecular bone



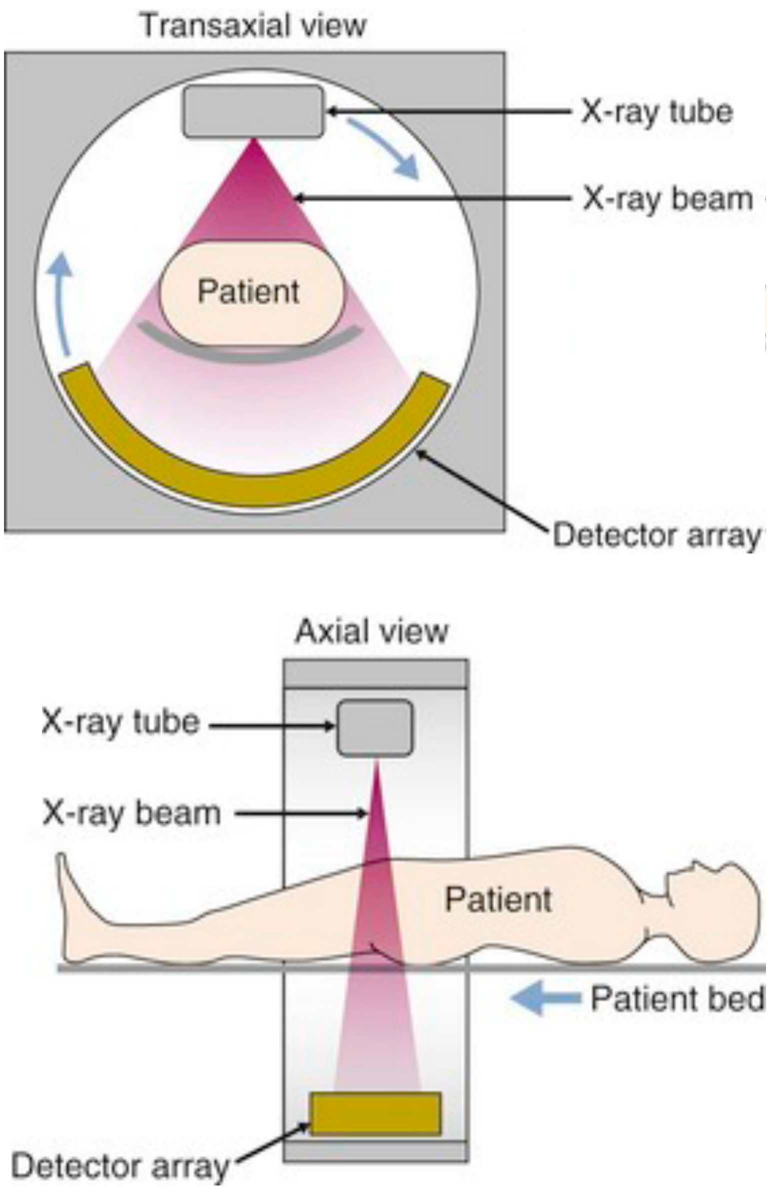
CT: Computed Tomography

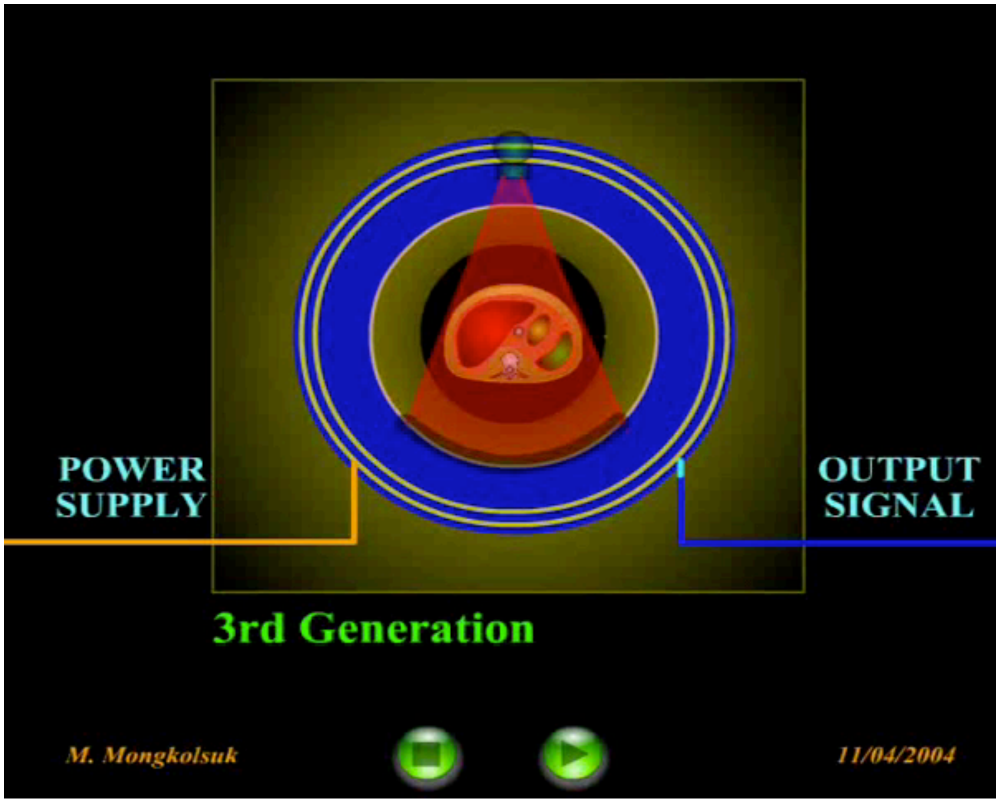




- 3D acquisitions
- Pixel → Voxel

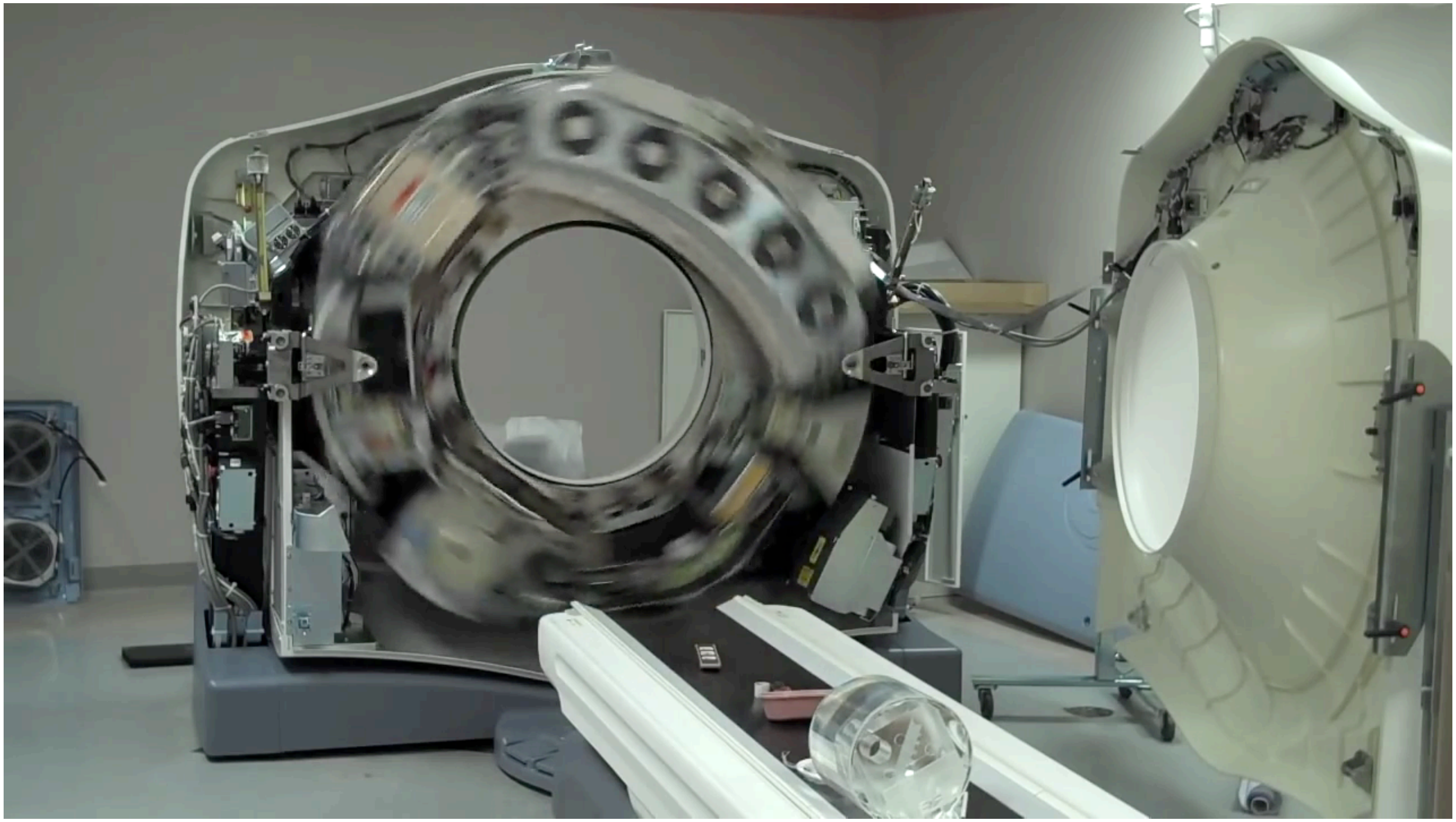
CT: Acquisition





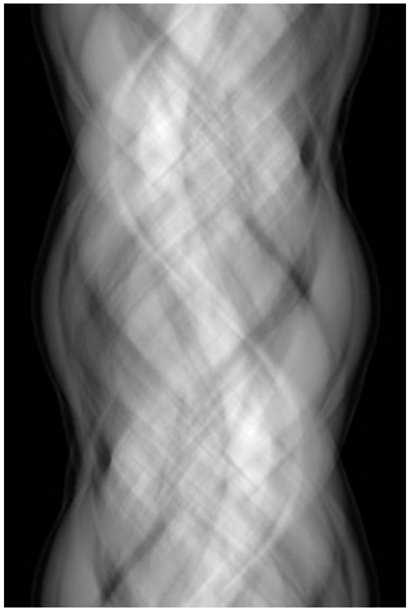
https://www.youtube.com/watch?v=bdf0kXn5Eeg&index=3&list=PL1RWXS1RBx2rtghGz7e7TF5UwkVdzMhcf

CT: Acquisition

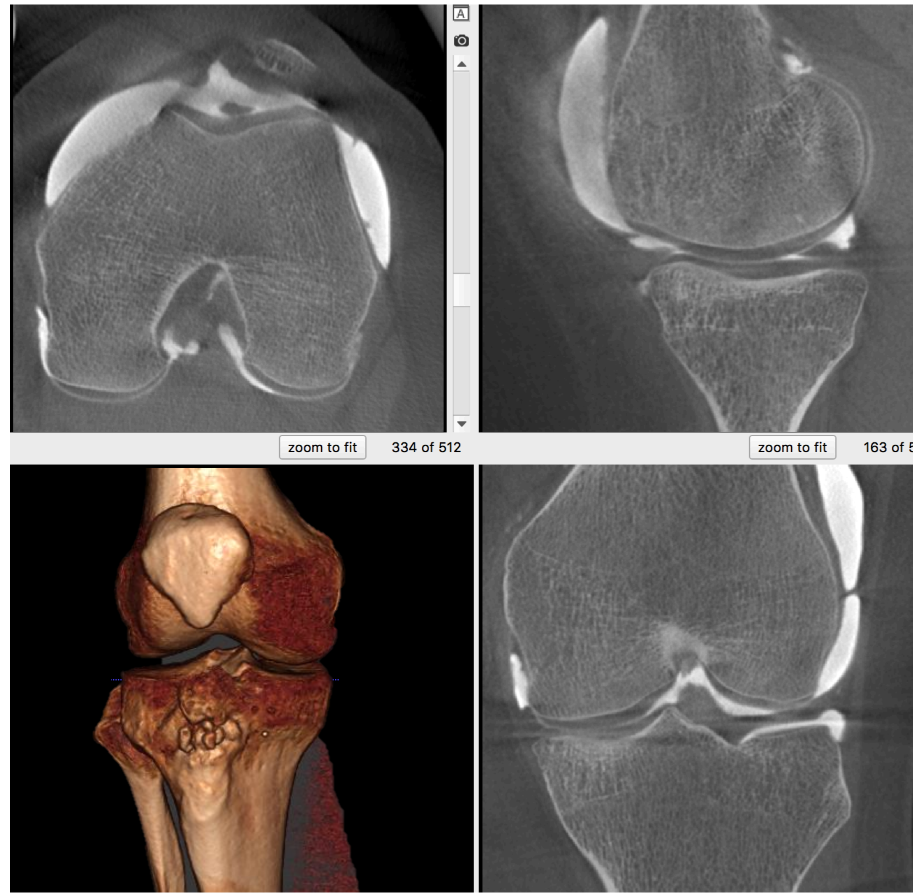


https://www.youtube.com/watch?v=bg0iNhw2ARw

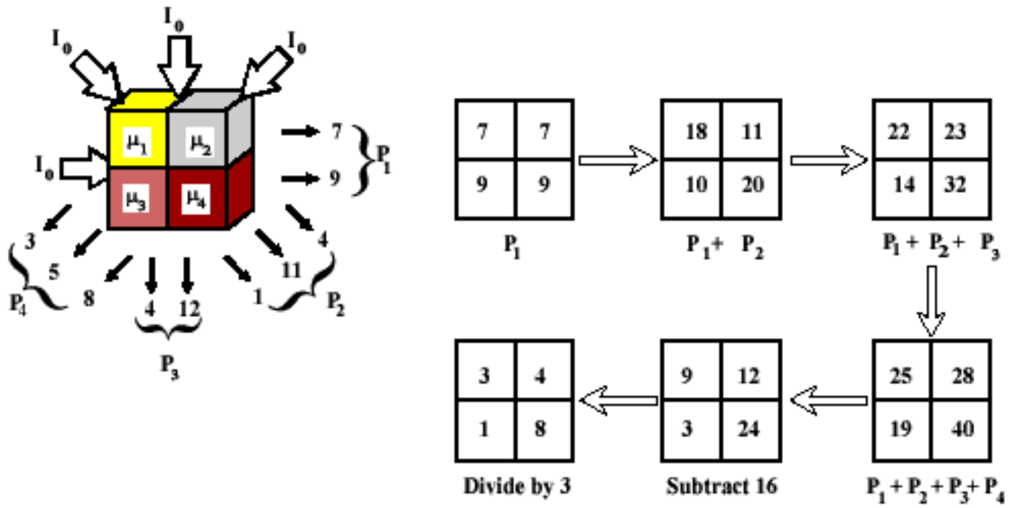
CT: Image Creation

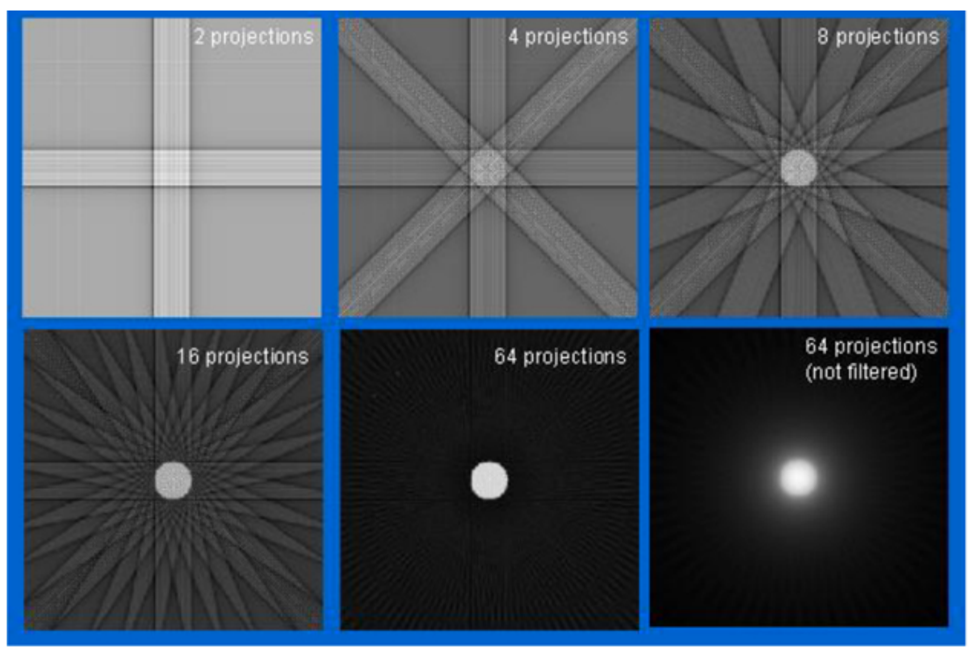


Filtered Back-Projection



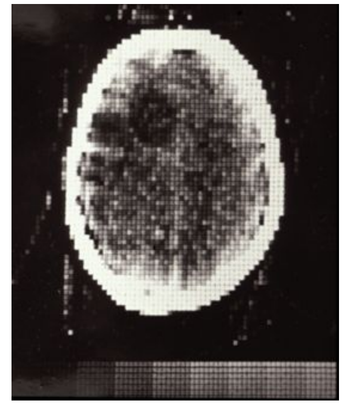
CT: Filtered Back-Projection



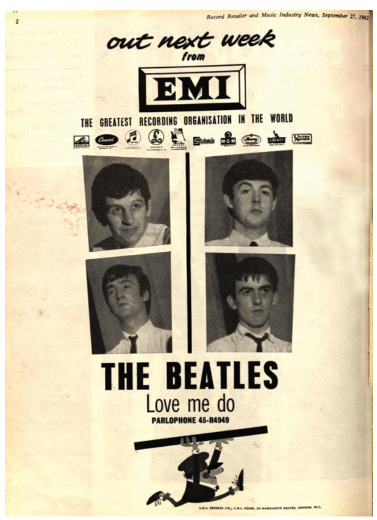


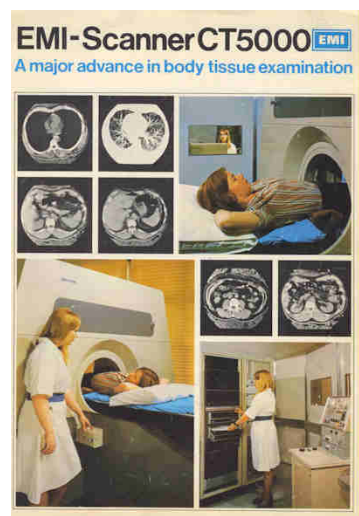
CT: Invention

- 1979: Godfrey Newbold Hounsfield invented Computed Tomography

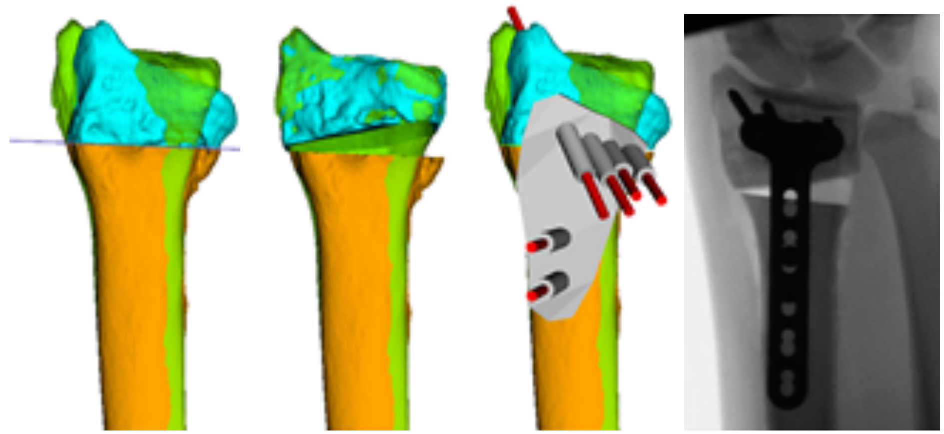


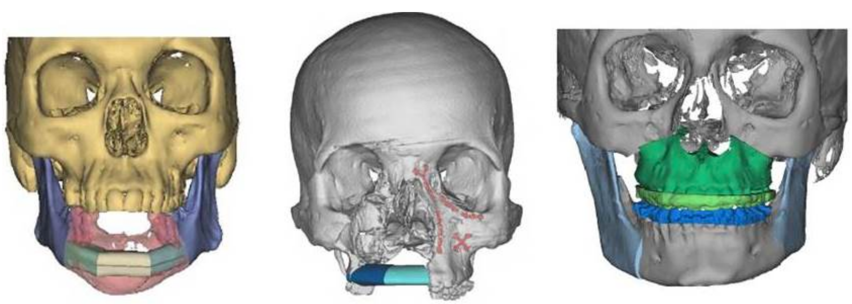
- CT scanner was “the greatest legacy” of the Beatles: the massive profits from their record sales enabled EMI to fund scientific research

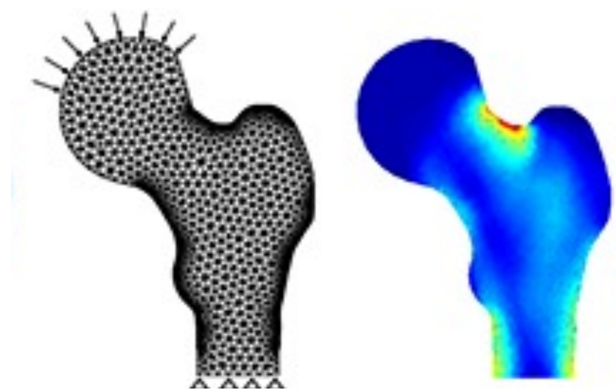




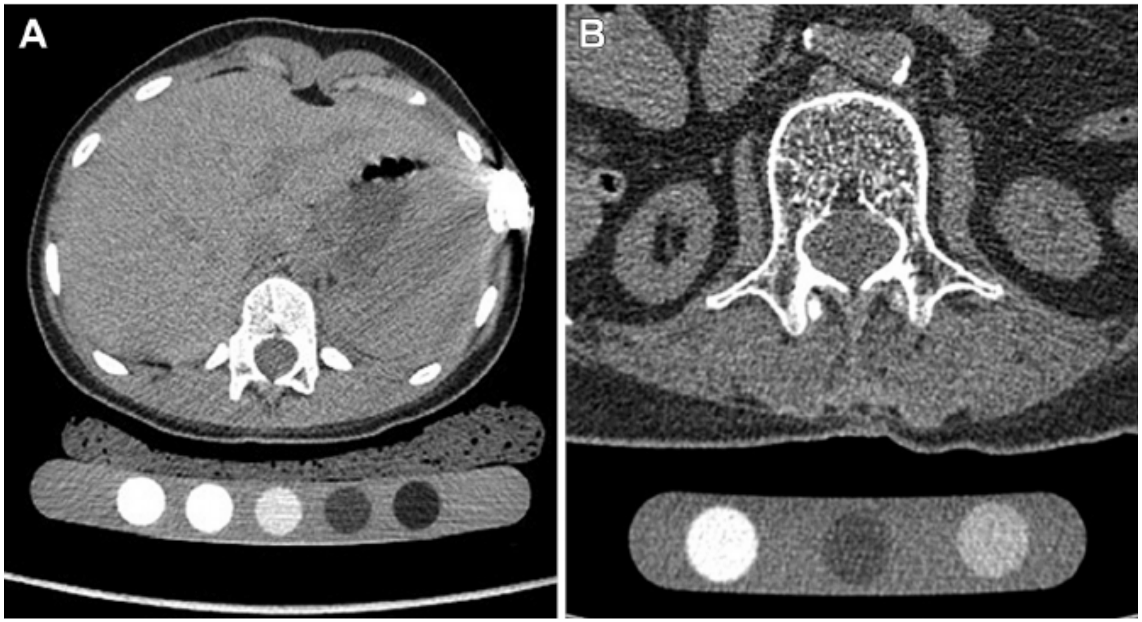
CT: Use in Bone







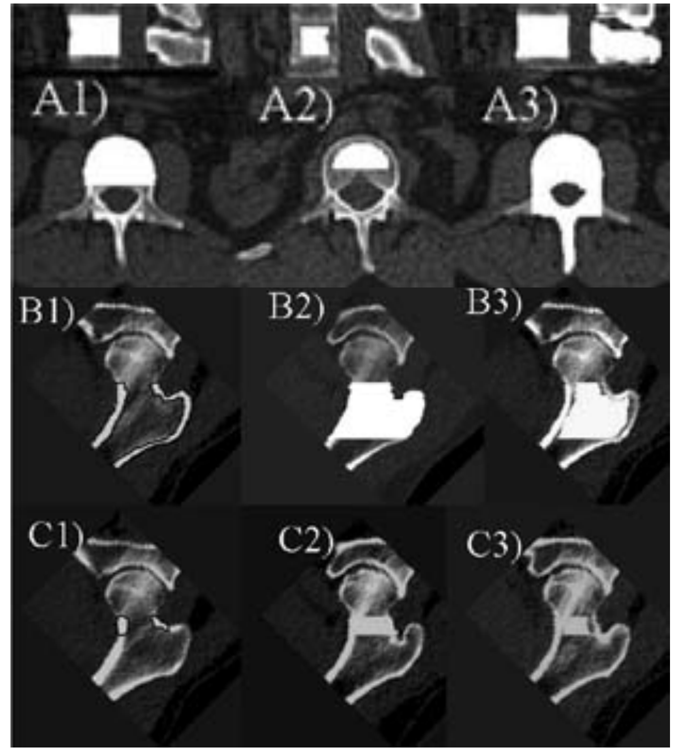
QCT: Quantitative Computed Tomography



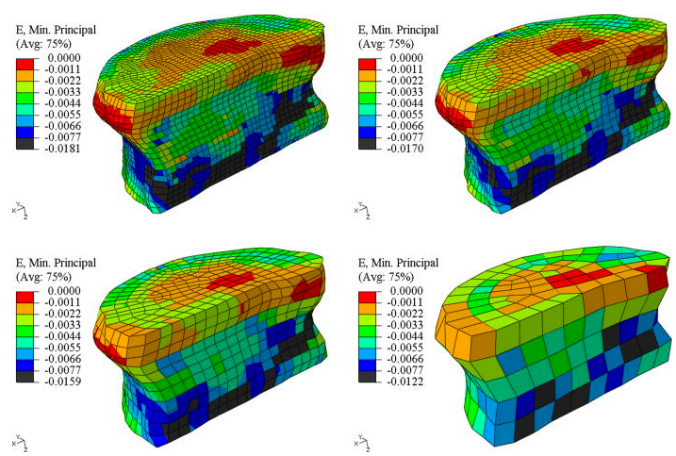
Hounsfield Units → Maps of Bone Mineral Density (BMD)

QCT: Pros and Cons

- QCT provides *volumetric* BMD of spine and femur
- QCT provides separate measurements of cortical and trabecular bone
- QCT provides geometry and Young's modulus for mechanical simulations (FEM)

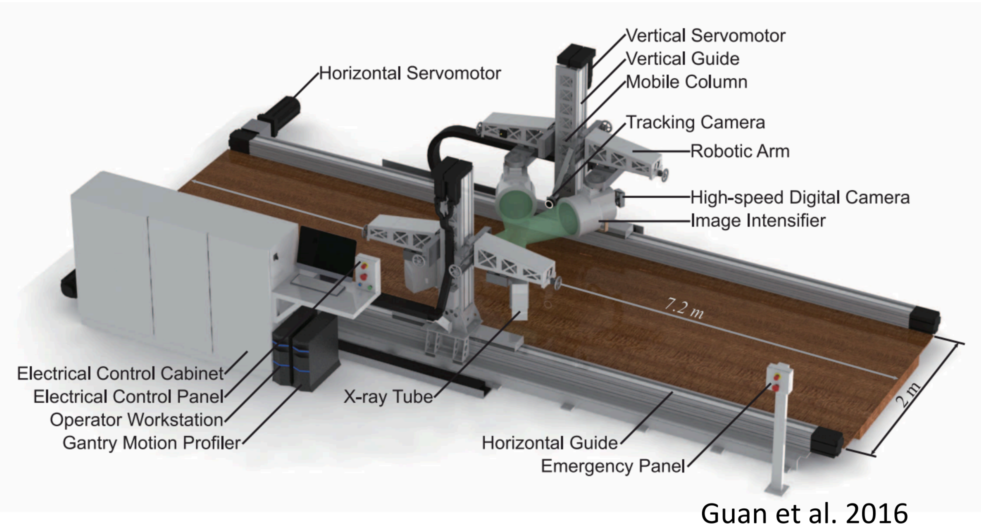


- Higher radiation dose
- Scanner cross-calibration is an issue

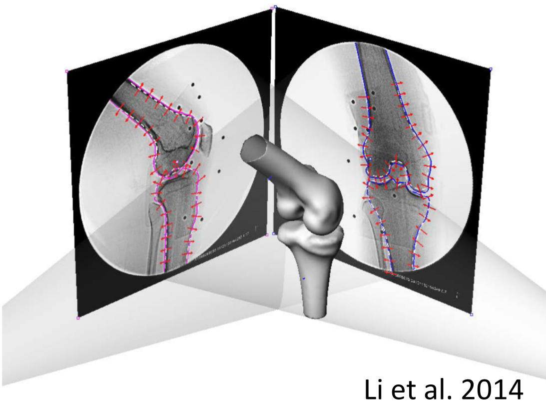


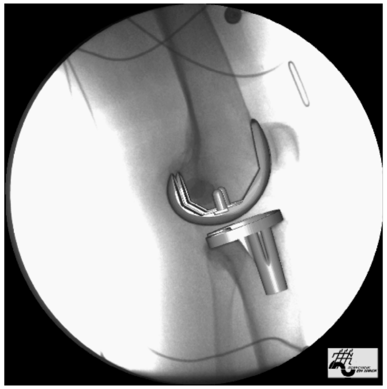
Fluoroscopy

- Single plane and bi-plane fluoroscopy
- Used to study joint kinematics

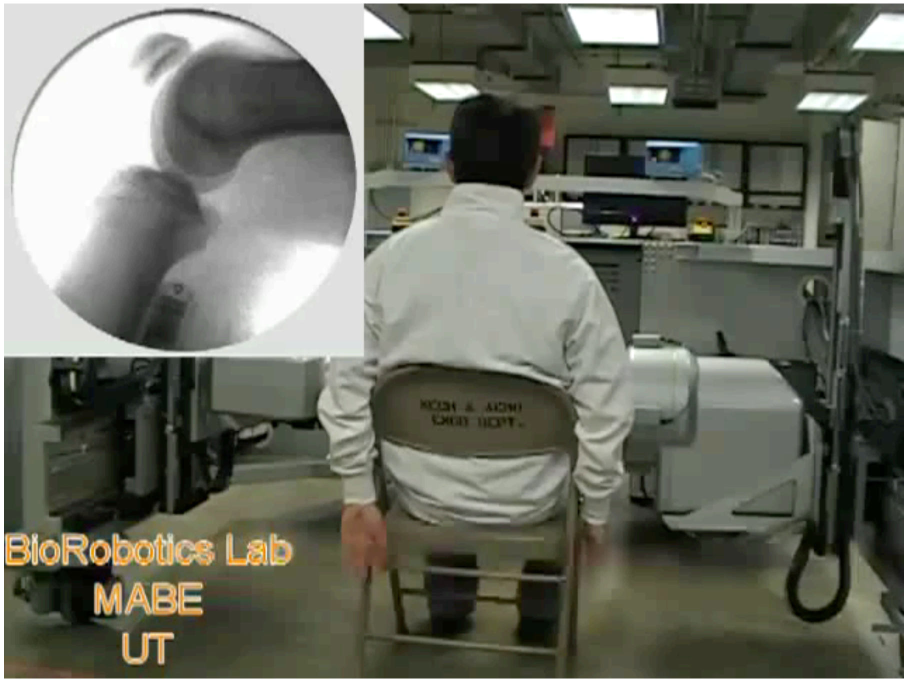


Guan et al. 2016



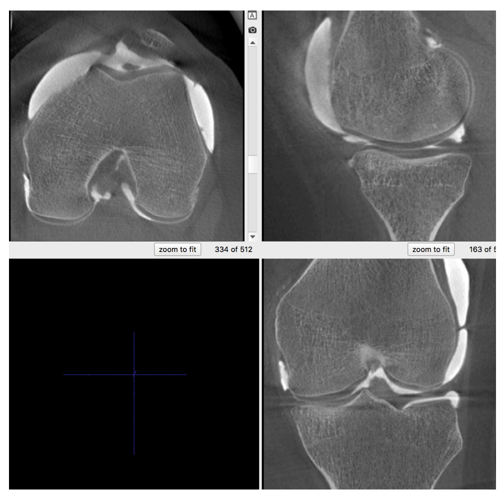


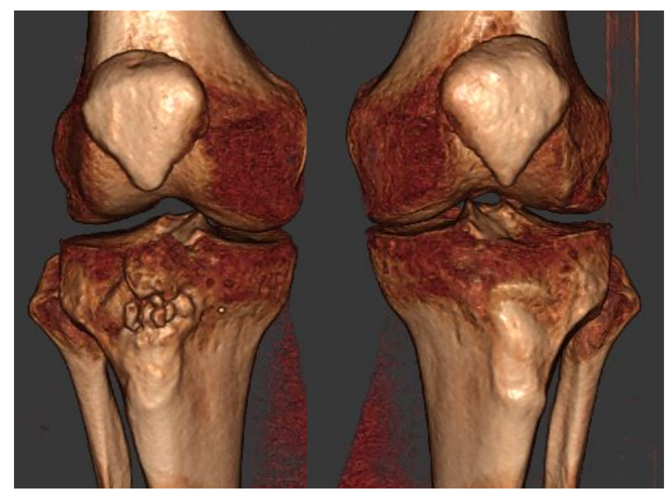
Li et al. 2014



https://www.youtube.com/watch?v=nwnOSuFL0ps

Weight-bearing Imaging

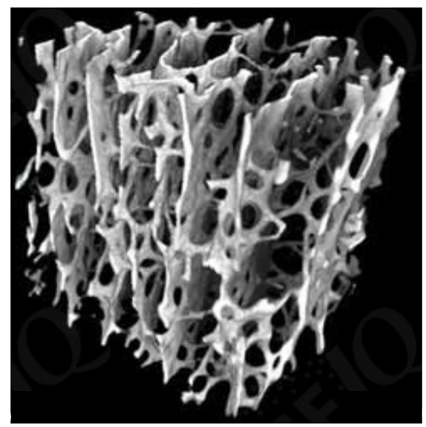




The Tissue Level

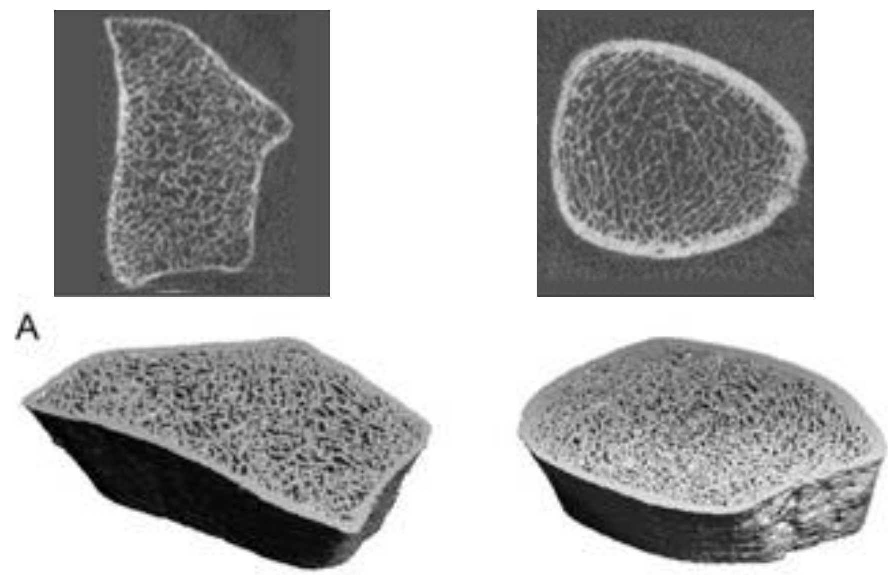
BODY LEVEL	ORGAN LEVEL	TISSUE LEVEL	CELLULAR LEVEL

Imaging

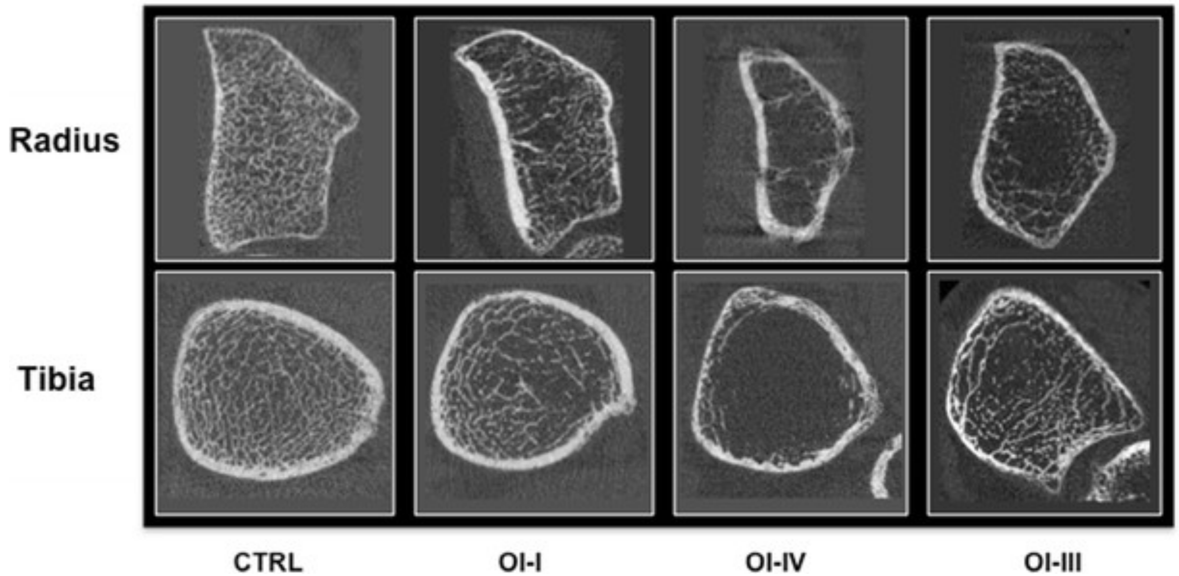


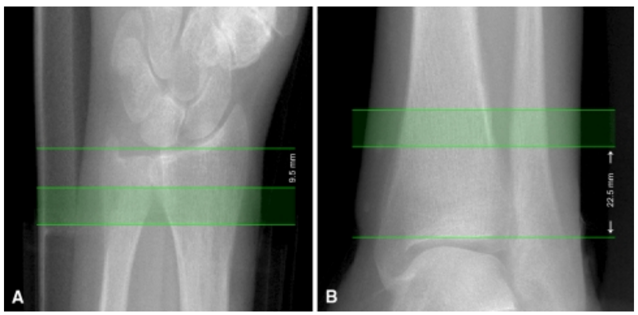
HR-pQCT: High-Resolution peripheral Quantitative Computed Tomography

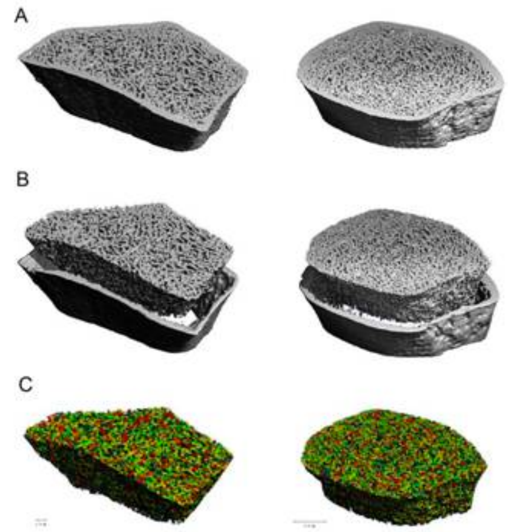
- Introduced in the 1990s
- Imaging of peripheral radius and tibia
- Low radiation dose



HR-pQCT: Acquisition and Images

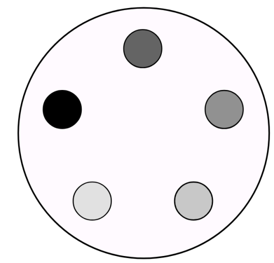




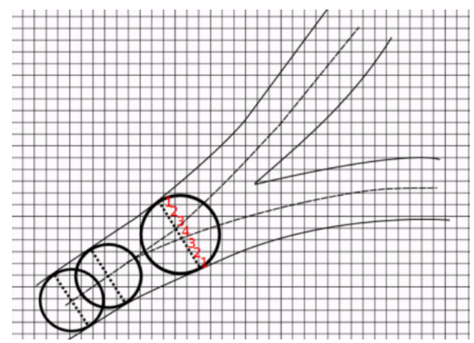


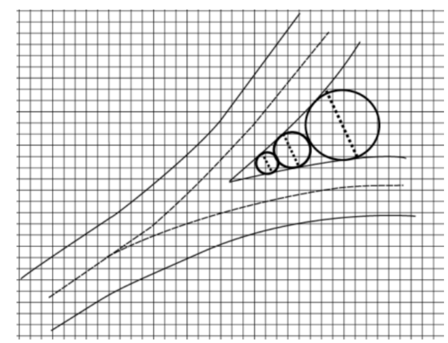
HR-pQCT: Measurements

- Densitometric measurements
  - Total, cortical and trabecular BMD

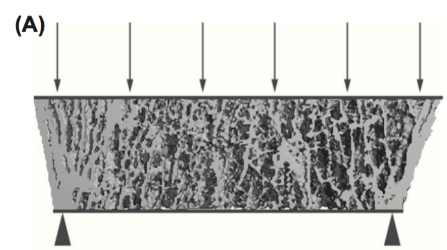


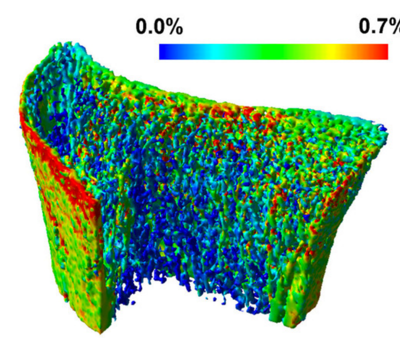
- Morphologic measurements
  - Cortical area, thickness
  - Trabecular number, thickness, heterogeneity





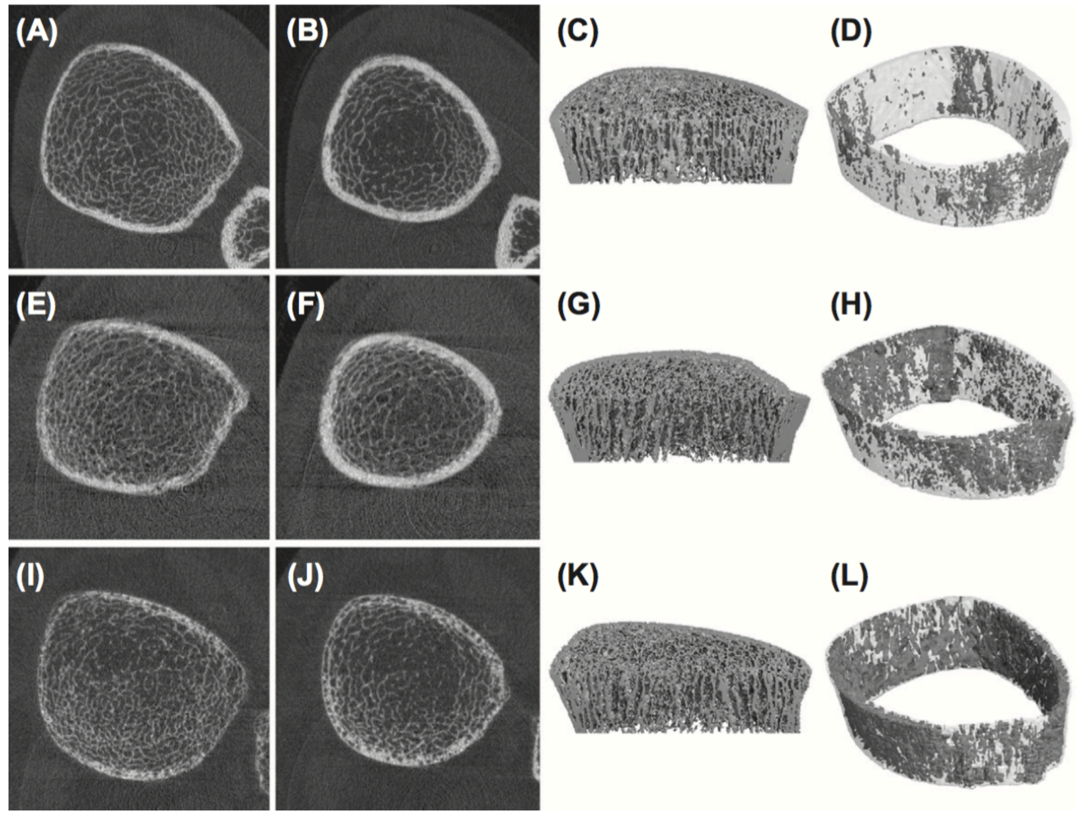
- Mechanical response
  - FEM with axial loading





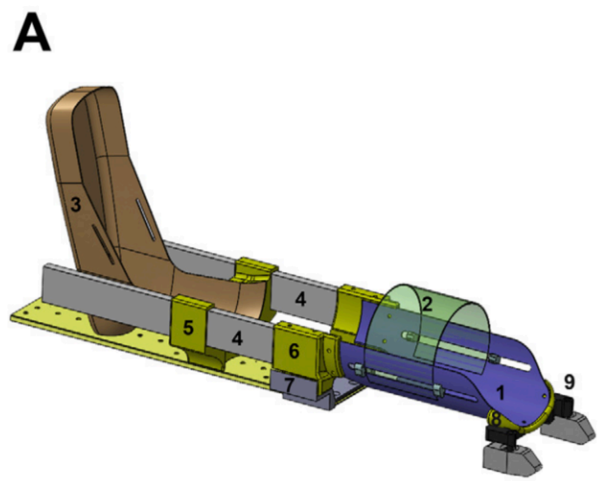
HR-pQCT: Applications

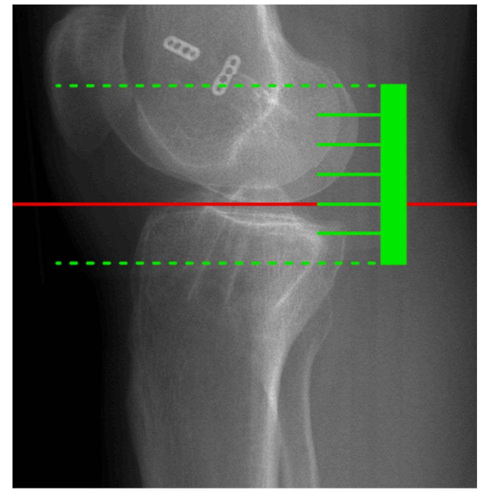
- Cross-sectional studies
  - Bone quality assessment
  - Changes in cortical porosity
  - Fracture risk assessment
- Longitudinal studies
  - Drug studies

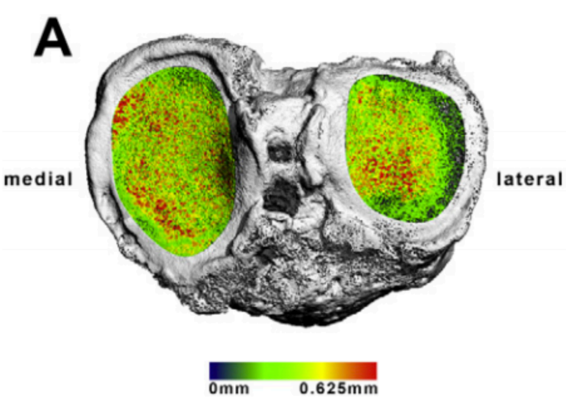


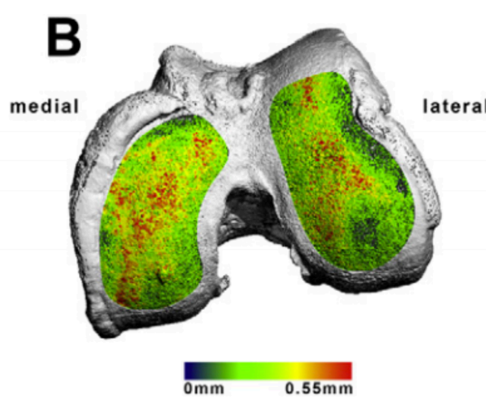
Burghardt et al. 2011

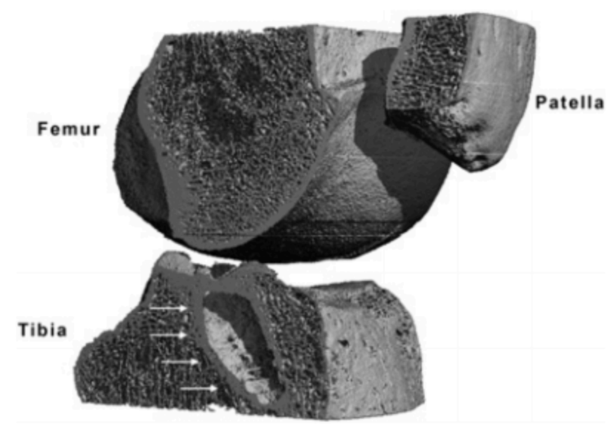
HR-pQCT: New Applications











Maps of Cortical Thickness

Kroker et al., 2017

HR-pQCT: Acquisition Standardization

UCSF University of California, San Francisco

UCSF Reference Line Training & Evaluation

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Launch Web App

http://webapps.radiology.ucsf.edu/refline/

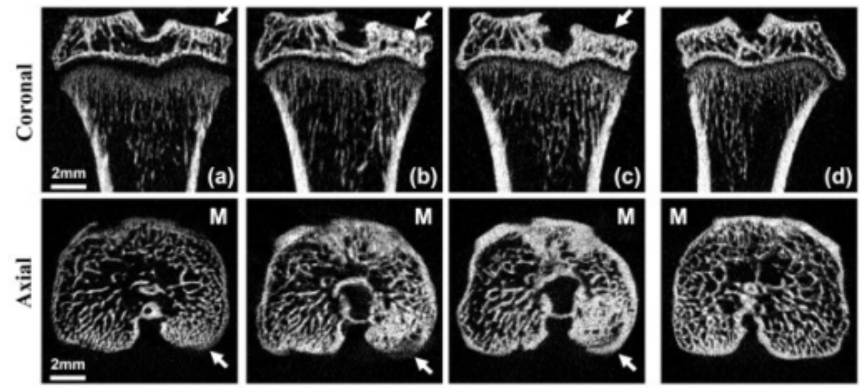
µCT: Micro Computed Tomography

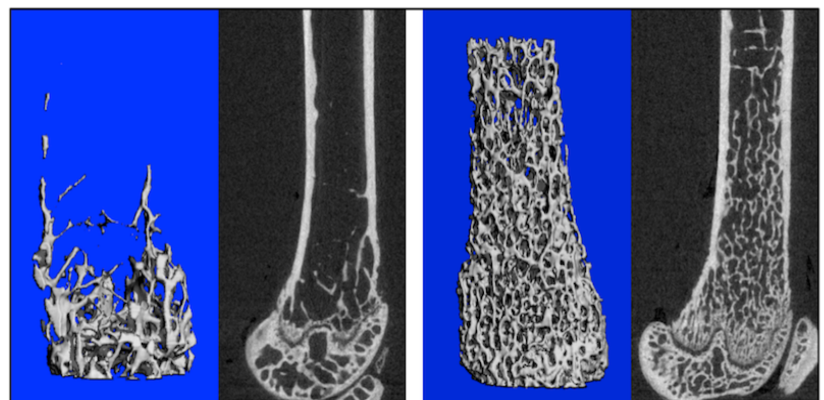
- Introduced in the 1980s as an alternative to histology (destructive and 2D)

- Gold standard for evaluation of bone morphology and microarchitecture in animal studies
    - E.g. mouse trabeculae [30-50µm]

µCT: Applications

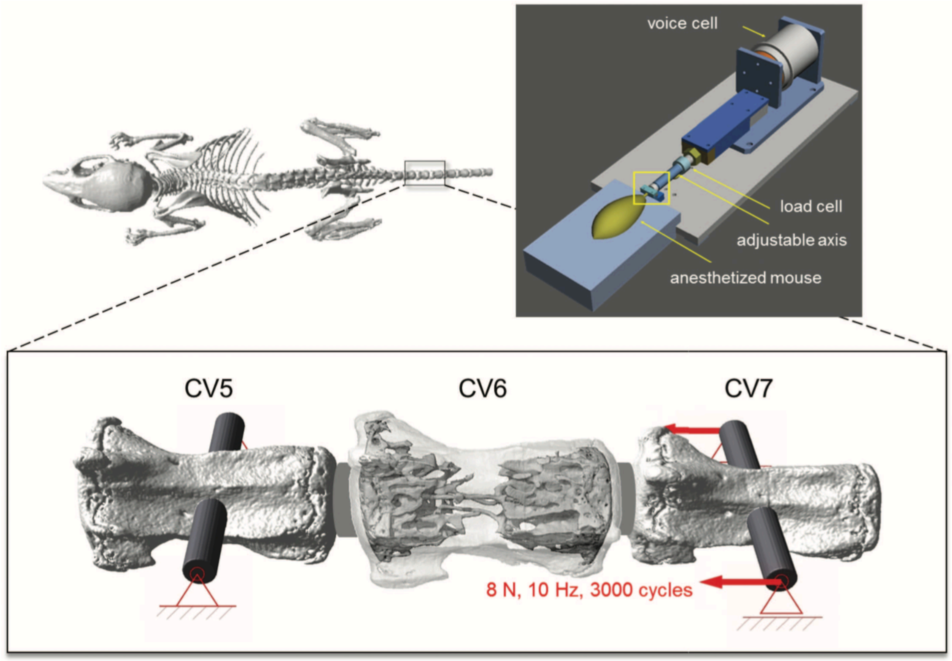
- Bone models to evaluate
  - Bone growth and development
  - Effects of pharmacological intervention
  - Effects of mechanical loading
  - Macrocracks in cortical bone
  - Fracture healing
  - 3D vascular architecture (with constrast agent)





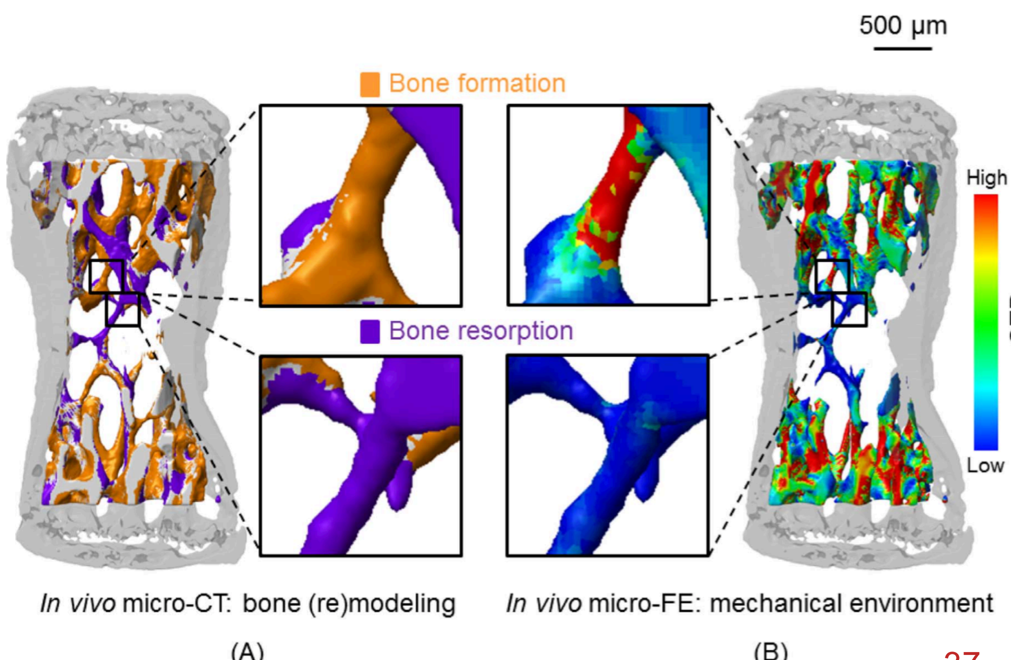
3D reconstructions and sagittal views of an untreated control (left images) and an antiresorptive drug treated mouse (right images).

µCT: Bone Mechanical Response



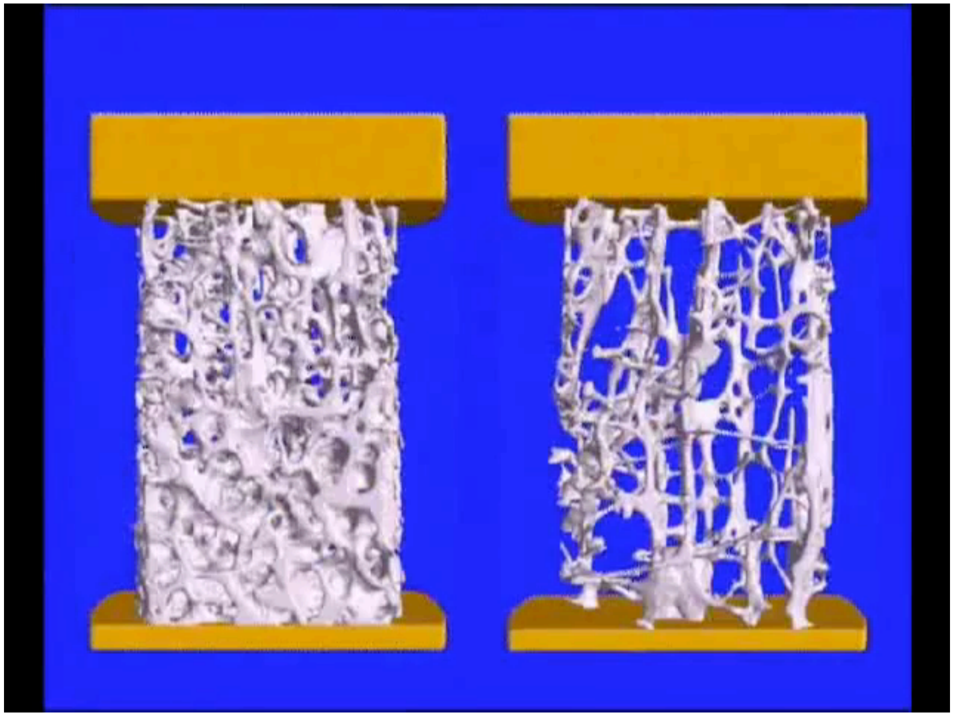
- The 6th caudal vertebra (CV6) is cyclically loaded
- Controlled force is obtained through two pins inserted in the adjacent vertebrae

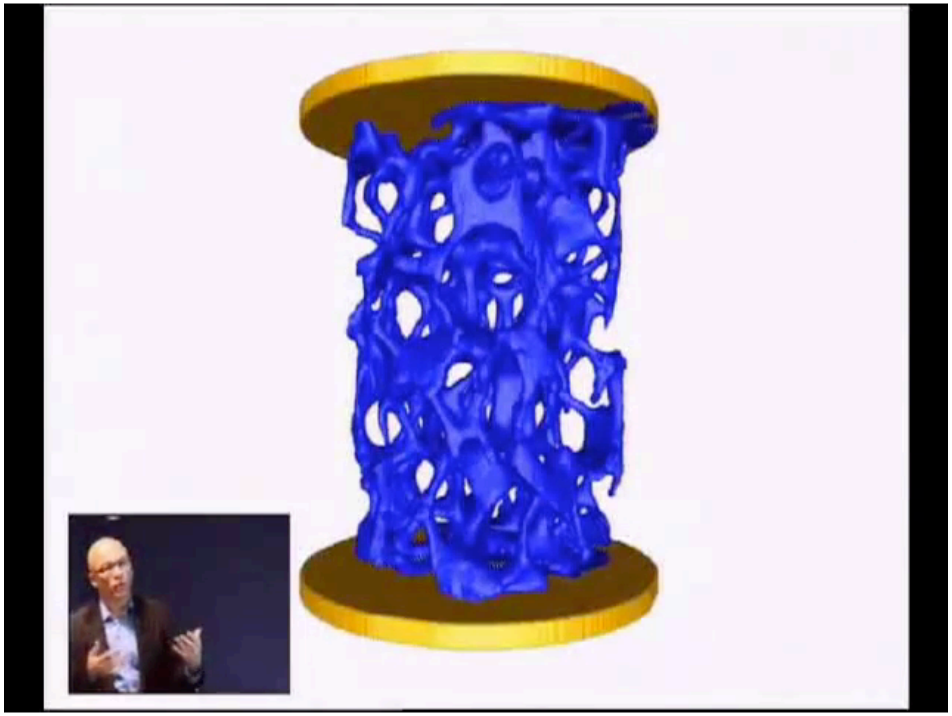
- Trabecular bone formation and resorption measured *in vivo* over 4 weeks
- High SED correspond to sites of bone formation, while low SED correspond to sites of bone resorption.



Schulte et al. 2010

µCT – Bone Mechanical Response





https://www.youtube.com/watch?v=1ubdRWjXTok

The Cellular Level

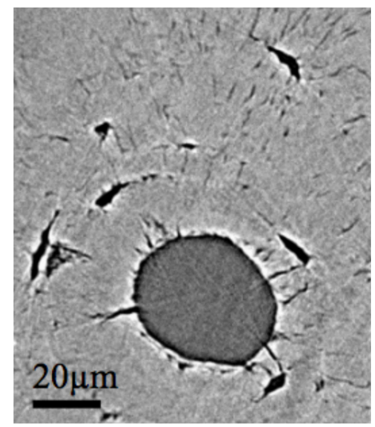
BODY LEVEL

ORGAN LEVEL

TISSUE LEVEL

CELLULAR LEVEL

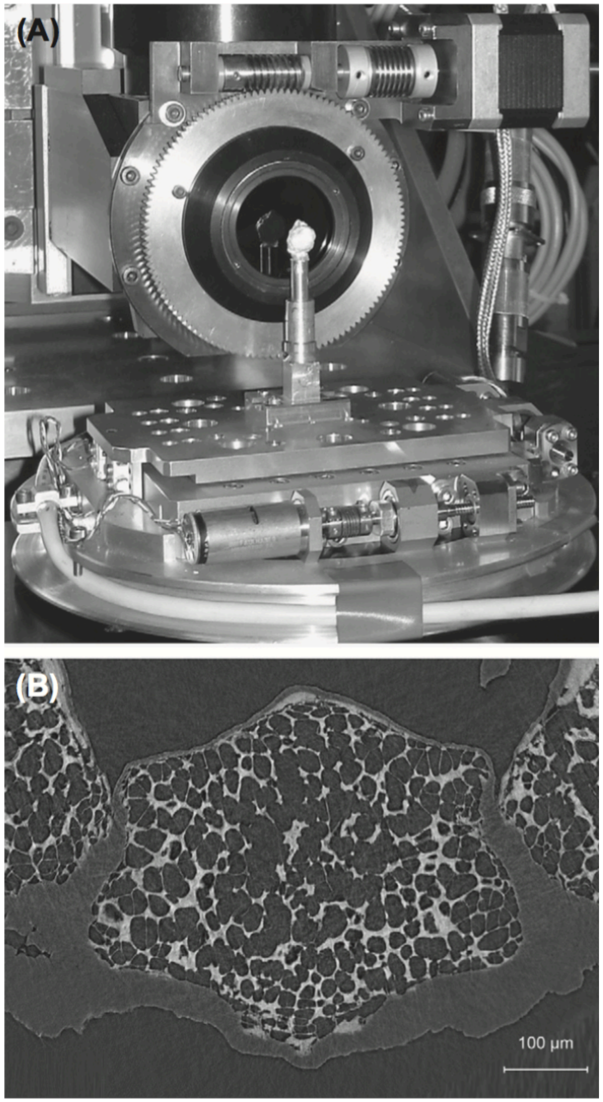
Imaging



Synchrotron radiation µCT

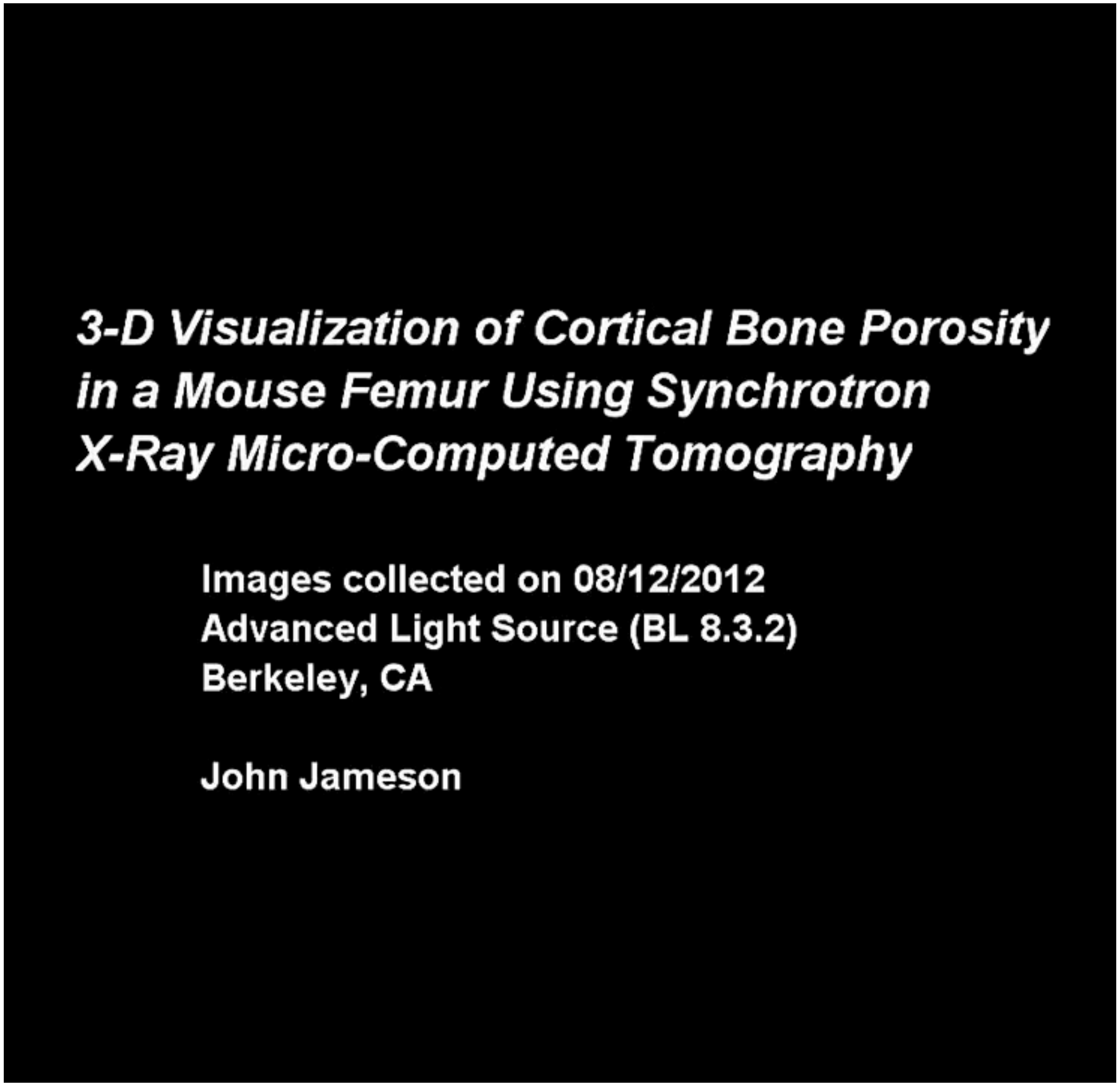
- Need a Synchrotron!
- Fast acquisition and high SNR
- Monocromatic beam

- *Ex-vivo* for morphological studies



Burghardt et al. 2011

Synchrotron radiation µCT



https://www.youtube.com/watch?v=3D6yG2apYiU