Technology Transition Workshop| *Mohamed R. Mahfouz, Ph.D.*

History and Application of Computed Tomography (CT) Images

Outline

- Why 3D?
- CT Principles
- Calibration
- Modeling
- Applications

Technology
Transition Workshop

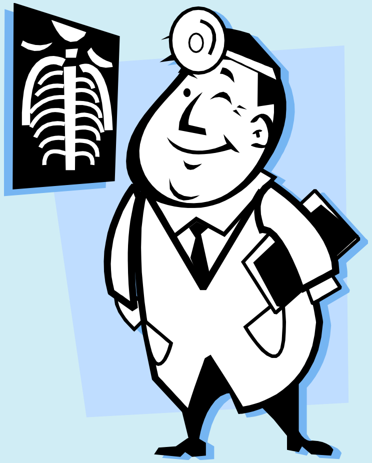
NIJ National Institute of Justice

Why 3D?

Technology
Transition Workshop
NIJ
National Institute of Justice

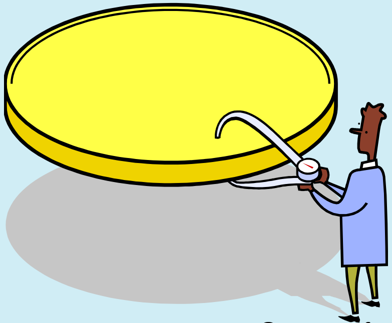
Conventional Methods

- X-Ray



© Microsoft

- Calipers

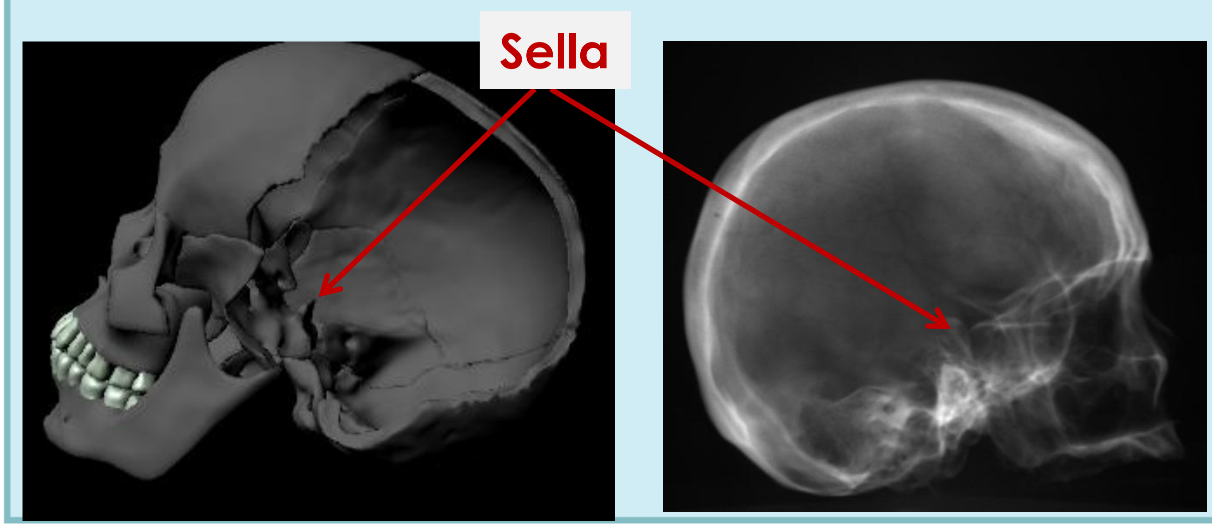


© Microsoft

Technology
Transition Workshop

X-Ray

- **2D Projection of 3D Anatomy**
  - **Dense object can shadow structure behind it**
  - **No depth perception**
  - **Projection change by rotating object relative to imaging plane**
  - **Limited soft tissue information**



Technology
Transition Workshop

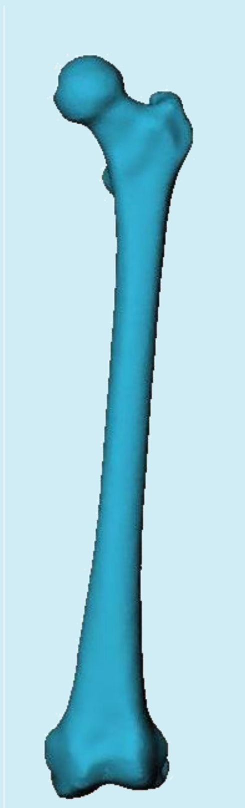
National Institute of Justice

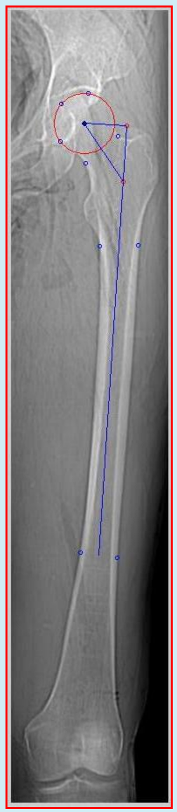
X-Ray Accuracy

Female Case

X-Ray Proximal Angle = 142.78

True 3D proximal angle = 130.84

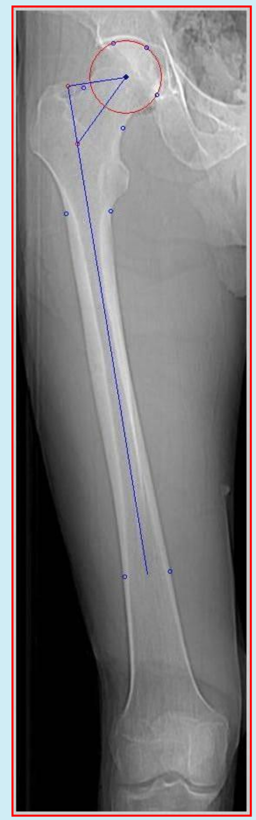


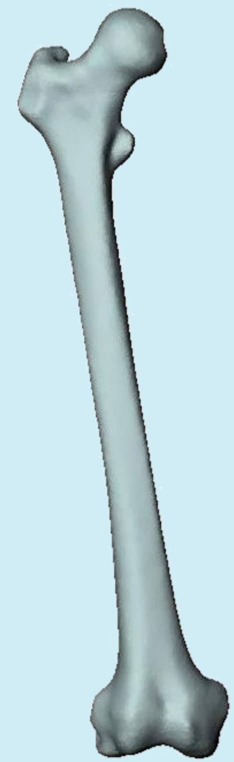


Male Case

X-Ray Proximal Angle = 140.16

True 3D proximal angle = 127.62



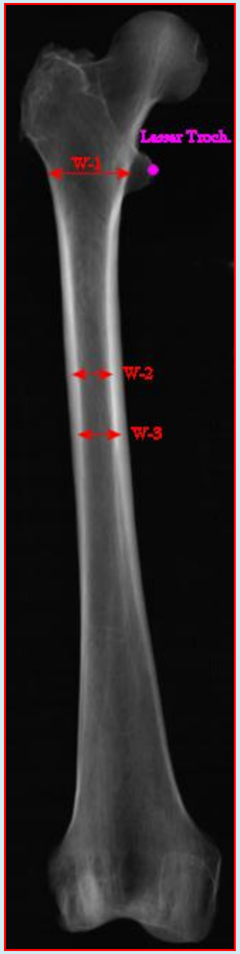


Technology Transition Workshop

Effect Of Rotation on X-Ray

Technology
Transition Workshop

Effect Of Rotation on X-Ray



2-D Measurements

	W-1	W-2	W-3
μ	7.90%	4.62%	2.25%
σ	5.90%	3.01%	2.51%

Percentage Error in 2-D Measurements
Due to 12˚ External Rotation

	W-1	W-2	W-3
μ	5.84%	3.83%	1.41%
σ	6.23%	1.73%	1.75%

Percentage Error in 2-D Measurements
Due to 10˚ Internal Rotation

Technology
Transition Workshop

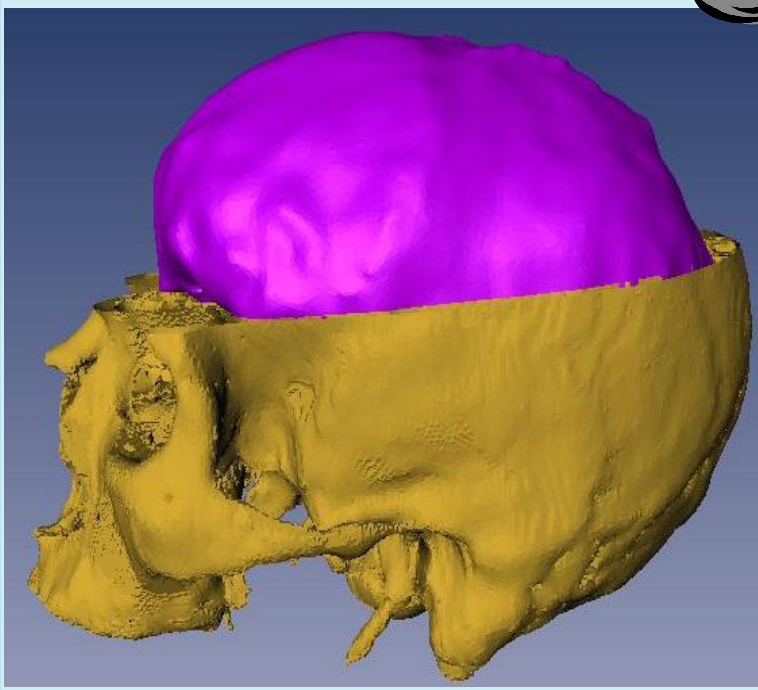
NIJ National Institute of Justice

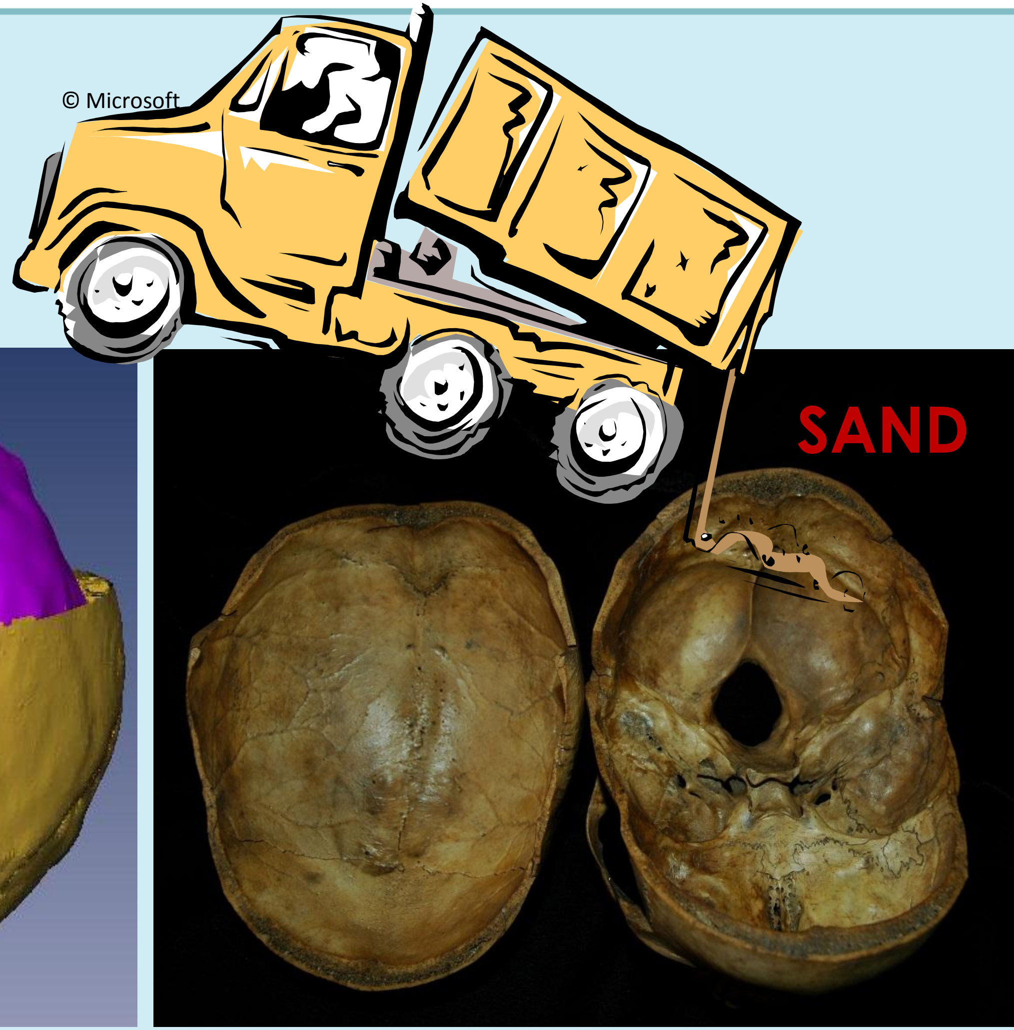
Calipers

- **Intra- and inter-observer error**
- **Can be only used for geodesic measurements**
- **Limited access to anatomical features**
  - **Finding internal landmarks (autopsy)**
  - **Limited number of landmarks**
- **Time consuming**

Technology
Transition Workshop

Calipers





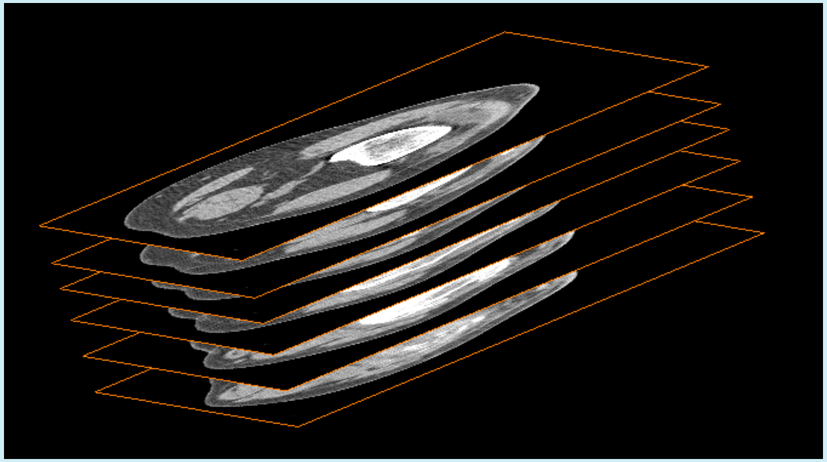
How To Measure Volume???

Technology
Transition Workshop

NIJ
National
Institute
of Justice

CT

- **What's a CT?**
  - **X-Ray device capable of imaging cross sections of object**
  - **Create stack of images; each represents slice from object**
  - **Images stacks can be arranged in 3D to create volume**

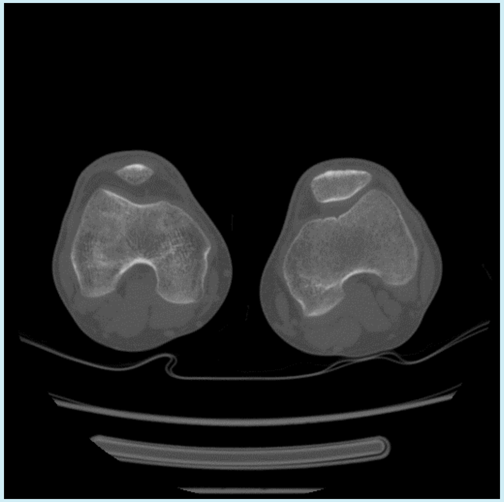


Technology Transition Workshop

National Institute of Justice

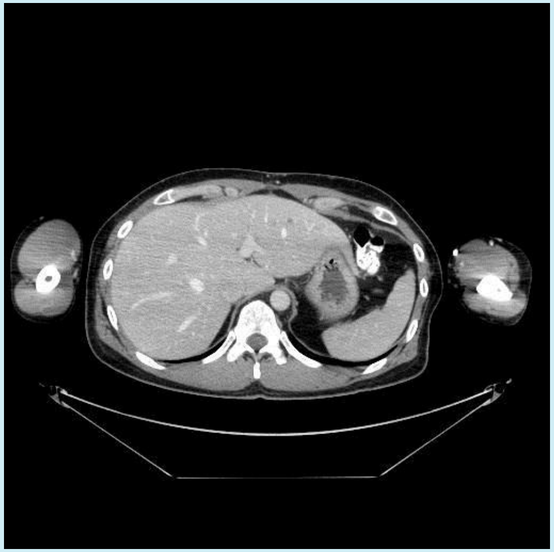
CT Applications

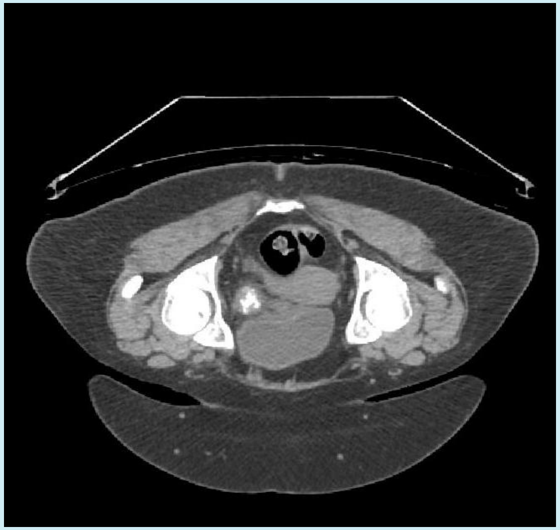
- **Wide range of applications in both soft tissue and bones**



Knee

Lumbar



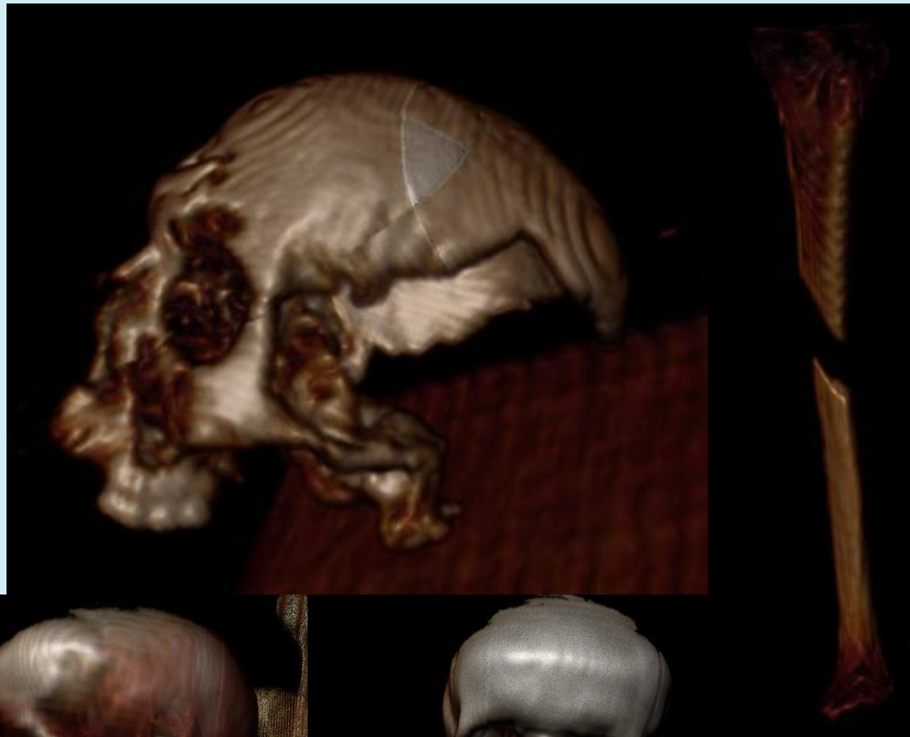


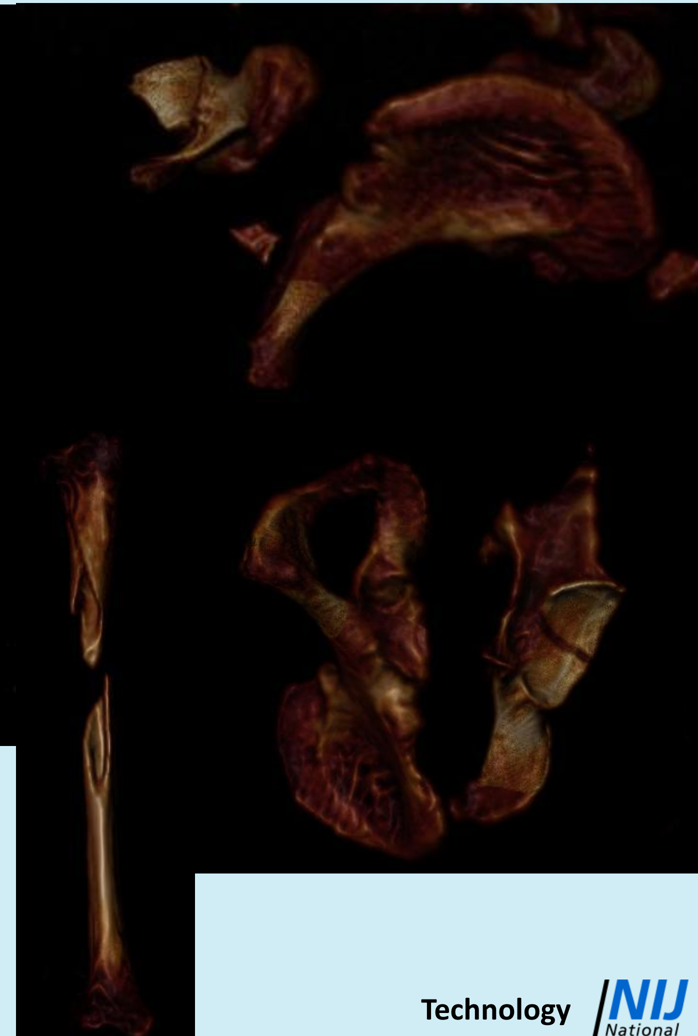
Hip

Technology Transition Workshop

NIJ National Institute of Justice

CT Applications





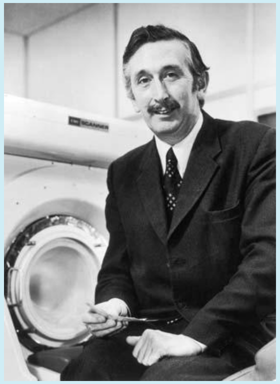
Technology
Transition Workshop

NIJ National Institute of Justice

CT History

- Computed tomography (CT) became the historically first tomographic modality entirely based on digital reconstruction of images
- Medical image reconstruction refers to the reconstruction of cross sectional or volume data from the projection data at various angles
- Introduced by Hounsfield and Cormack
- Nobel Price 1979 (Physiology or Medicine)

Sir Godfrey Newbold Hounsfield
1919-2004
Nobel Price for Medicine : 1979



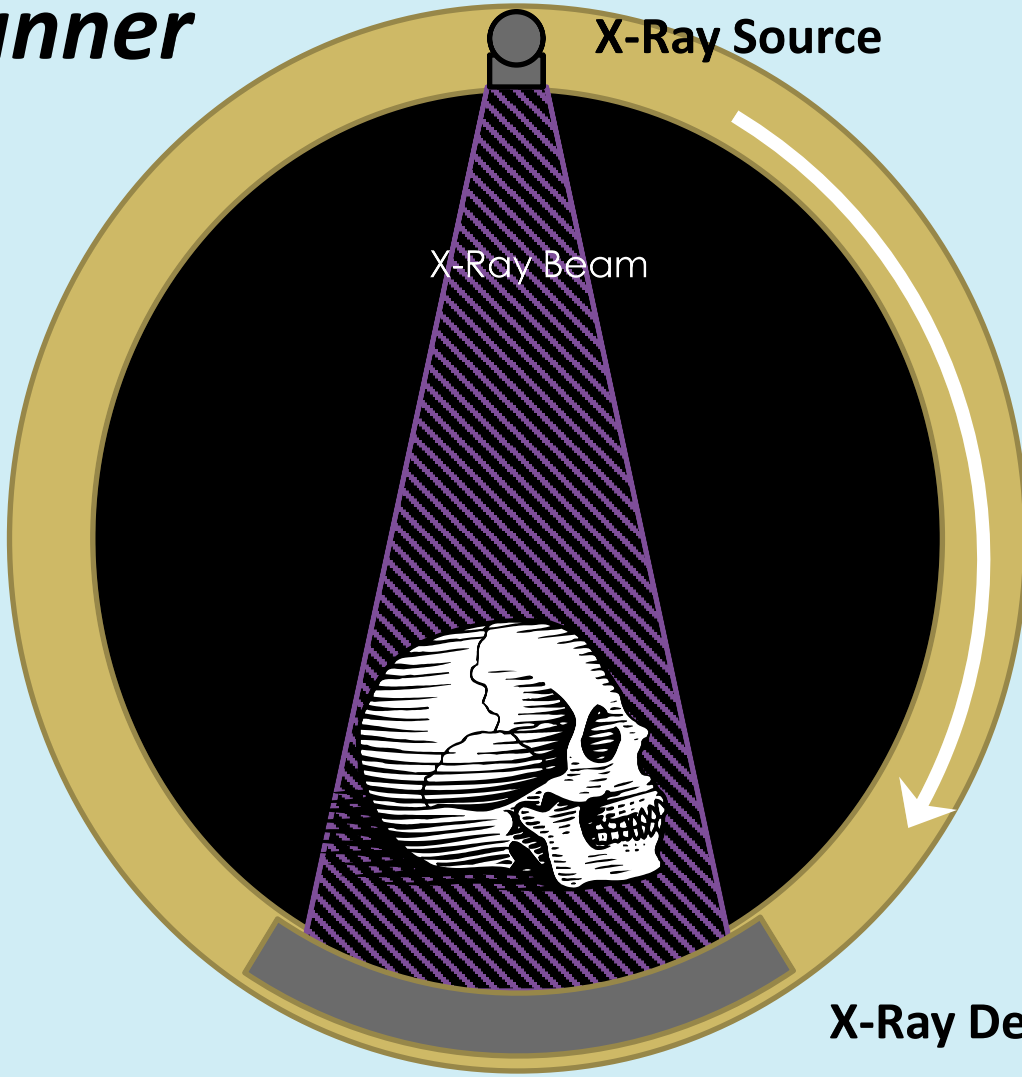
Prof. Allan McLeod Cormack
1924-1998
Nobel Price for Medicine : 1979

Courtesy of Freebase.com

Technology Transition Workshop

NIJ National Institute of Justice

CT Scanner



Technology
Transition Workshop

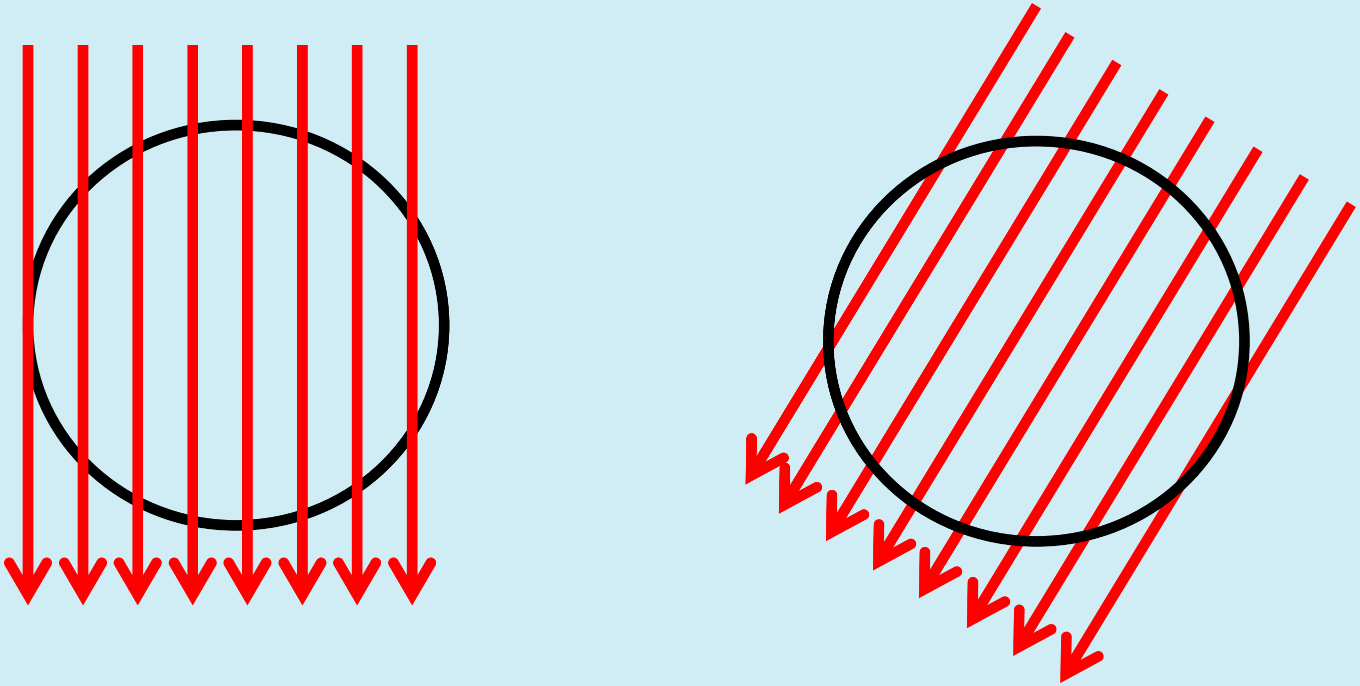
Basic Idea

- **2D views (projections) at all angles around the patient**
  - **Rotating source and detector**
  - **Sample attenuation at each detector for each angle**
  - **Generate projections**
  - **Different beam geometry**
    - **Parallel**
    - **Fan**
    - **Cone**

Technology Transition Workshop

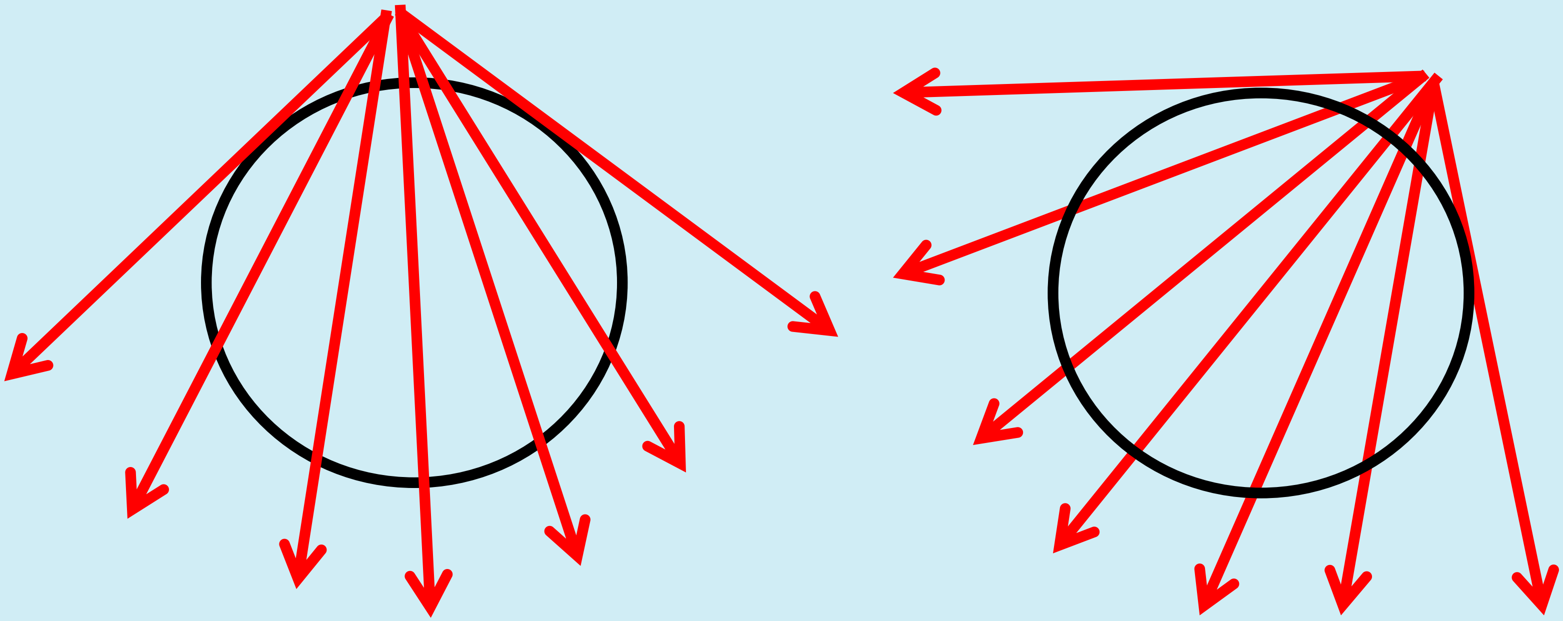
NIJ National Institute of Justice

Parallel Beam



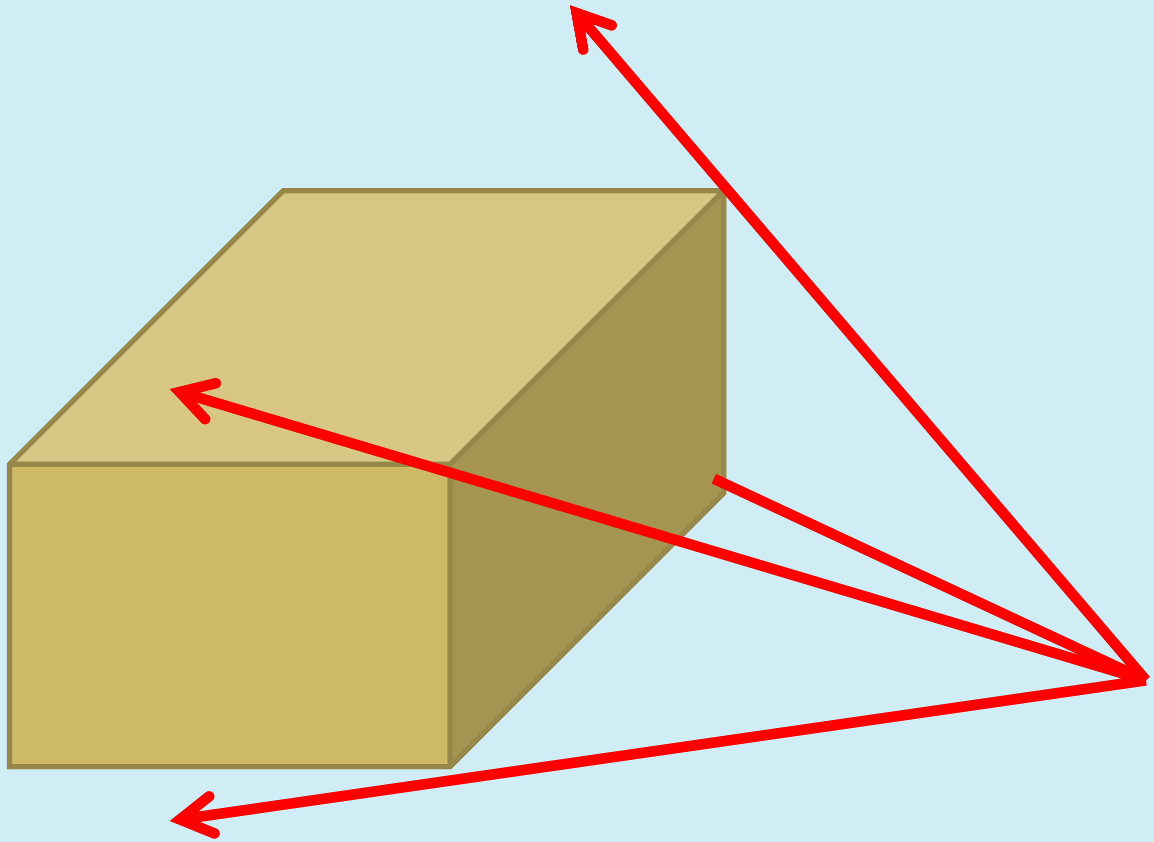
Technology
Transition Workshop

Fan Beam



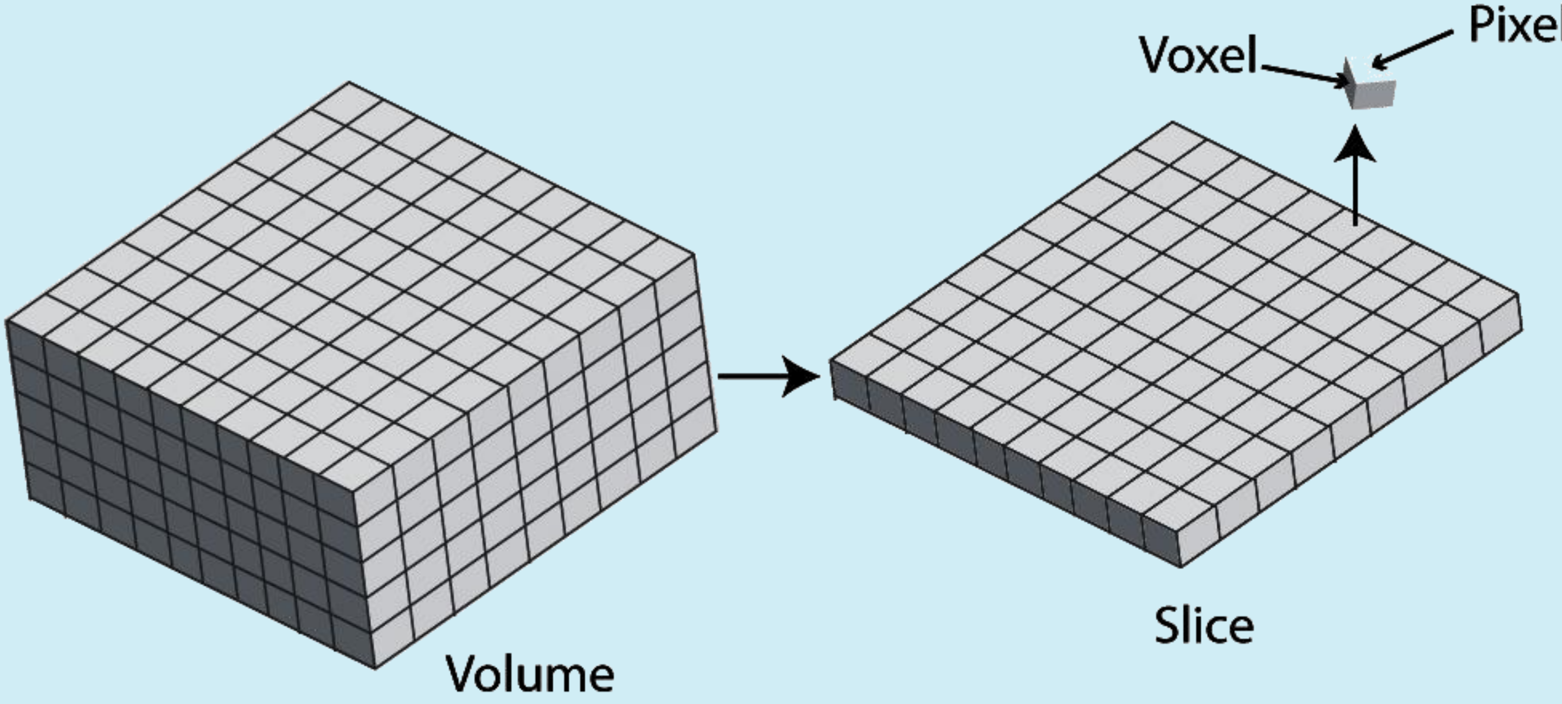
Technology
Transition Workshop

Cone Beam



Technology
Transition Workshop

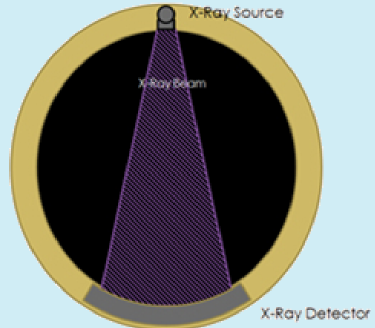
Pixel vs Voxel



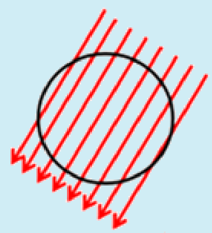
Technology
Transition Workshop

NIJ National Institute of Justice

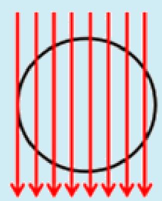
CT Reconstruction

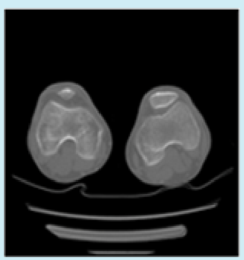


Attenuation Data from rotating source and detector around object

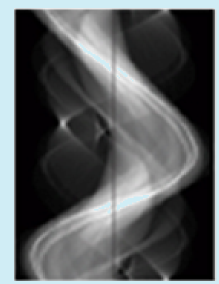


Reconstuction Routine





Reconstructed Image



Sinogram: a line for every angle

Technology Transition Workshop

CT Number

- **Images:**
  - **Size generally 512*512**
  - **Linear attenuation coefficient measured between tube and detector**
    - **Attenuation coefficient measure: how x-ray absorbed with material**
    - **Values in Hounsfield Units (HU)**

$$\text{CT number (HU)} = \frac{\mu - \mu_{H2o}}{\mu_{H2o}} * 1000$$

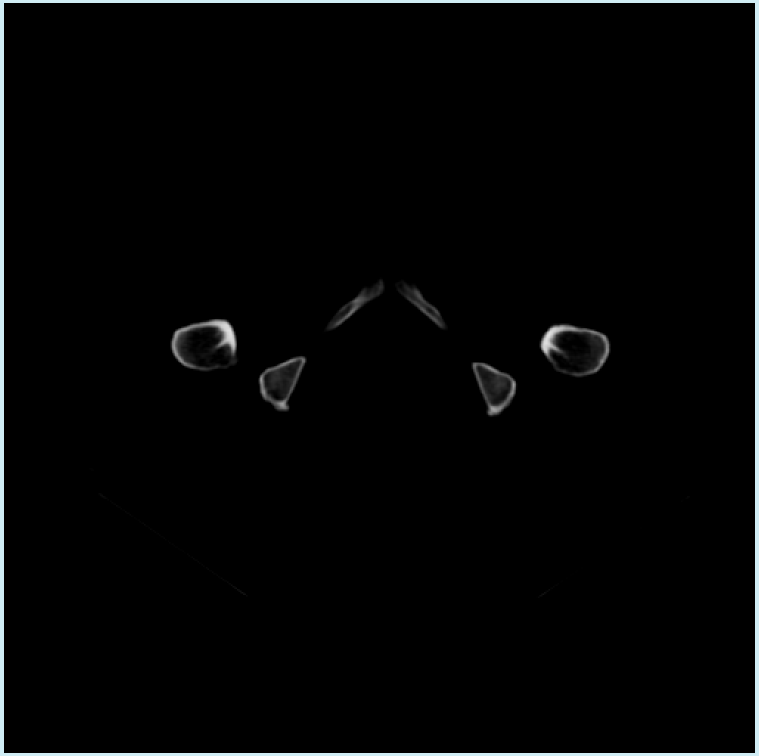
Technology
Transition Workshop
NIJ National Institute of Justice

CT Number Window

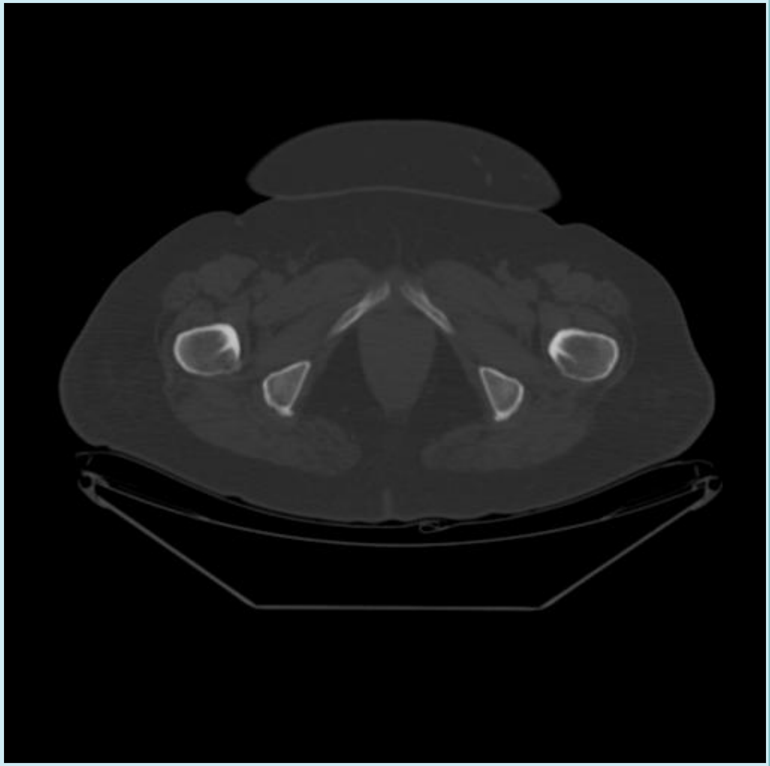
- Due to large dynamic range, windowing is used to view images
- The windowing affects both brightness and contrast
- Window is defined by Window Level (WL) and Window Width (WW)
  - WL is CT number of the mid gray
  - WW is number of HU from black to white

Technology
Transition Workshop

CT Number Window



WL: 752
WW: 2639



WL: 899
WW: 1531

Technology
Transition Workshop

CT Parameters

- **Acquisition parameters**
  - **Determine production of scan data set**
- **Reconstruction parameters**
  - **Determine presentation of the data**

Technology
Transition Workshop

Acquisition Parameters

- **Tube potential**
  - **Voltage between cathode and anode**
  - **Measured in KeV**
  - **Higher potential accelerates electrons and thus increase x-ray energy**
- **Tube current**
  - **Current flowing through cathode**
  - **Measured in mA**
  - **Larger current increases number of electrons and thus increases beam intensity**

Technology Transition Workshop

NIJ National Institute of Justice

Acquisition Parameters (Continued)

- **Scan time**
  - **Time taken for tube and detectors to perform complete rotation**
  - **Longer scan time increases total x-ray count**
- **Collimation\slice thickness**
  - **Width of CT slice along z-axis**
- **Beam filtration**
  - **Different beam shaping filter, optimized for different examinations**

Technology Transition Workshop

Reconstruction Parameters

- **Field of view**
  - **Size of image in X and Y directions**
- **Reconstruction matrix**
  - **Usually 512*512**
- **Reconstruction filter**
  - **Different filters available from smooth (soft tissue) to sharp (bone)**

Technology
Transition Workshop

CT Generations

- 1St generation
  - Single detector
  - Translate – rotate acquisition
    - Translate across patient
    - Rotates around patient
  - Very Slow
    - Minutes per slice

Technology
Transition Workshop
NIJ National Institute of Justice

CT Generations (Continued)

- **2nd Generation**
  - **Narrow fan beam (10 degree)**
  - **Multiple detectors**
  - **Rotation and translation**
  - **Slow**
    - **20 seconds per slice**

Technology
Transition Workshop

CT Generations (Continued)

- 3rd Generation
  - Wide fan beam
  - Multiple detectors (500-1000)
  - Rotation only
  - Multiple angle acquisition at each position
  - Faster
    - 0.5 second per rotation

Technology
Transition Workshop
NIJ National Institute of Justice

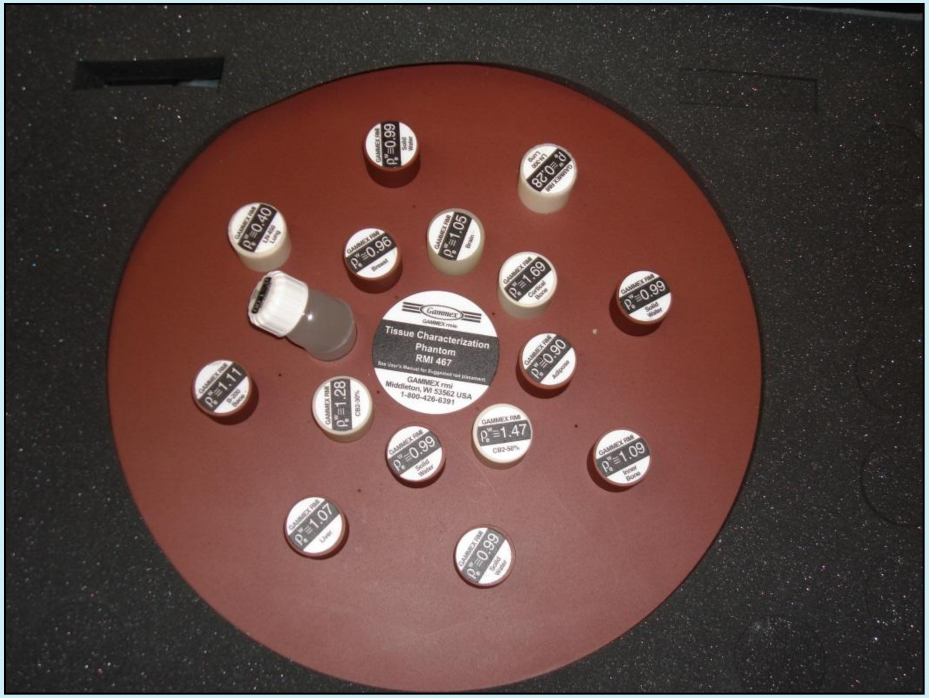
CT Generations (Continued)

- **4th Generation**
  - **Fan beam**
  - **Static detectors all around gantry**
  - **Only tube rotates**

Technology
Transition Workshop

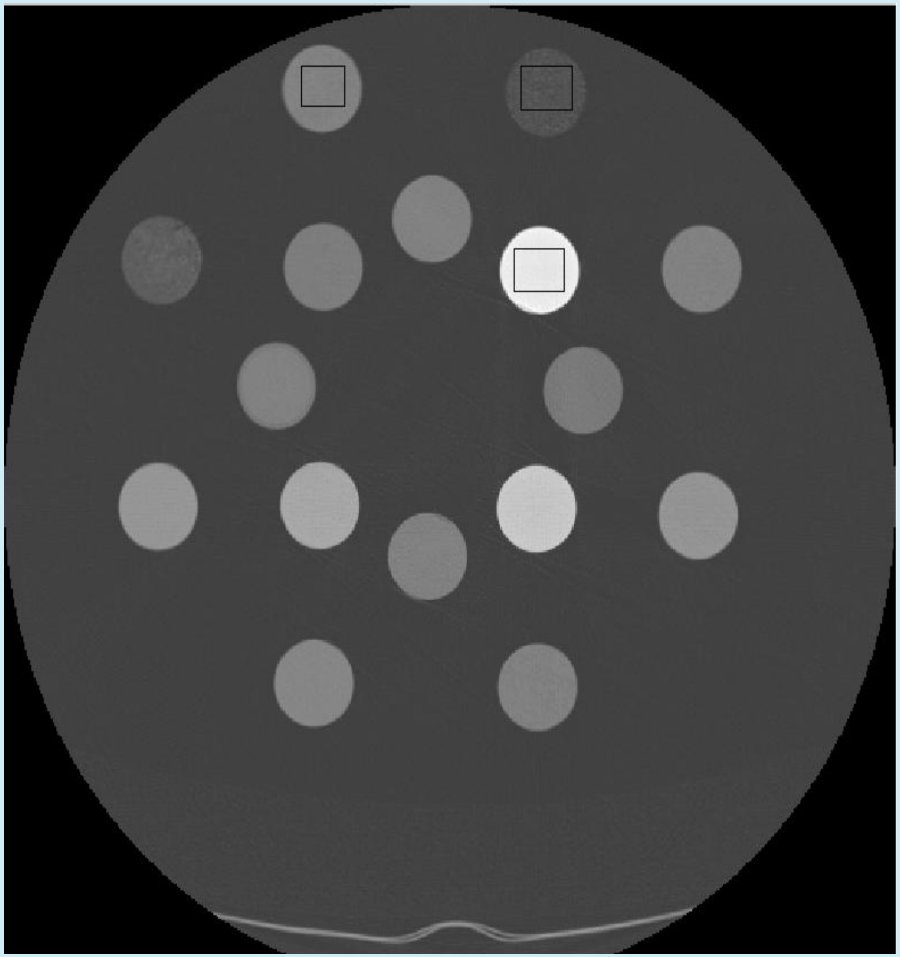
Calibration Phantom

- **Has similar properties to human tissue**
- **Used in procedures for measurement of absorption of radiation**
- **Used for calculating bone density**



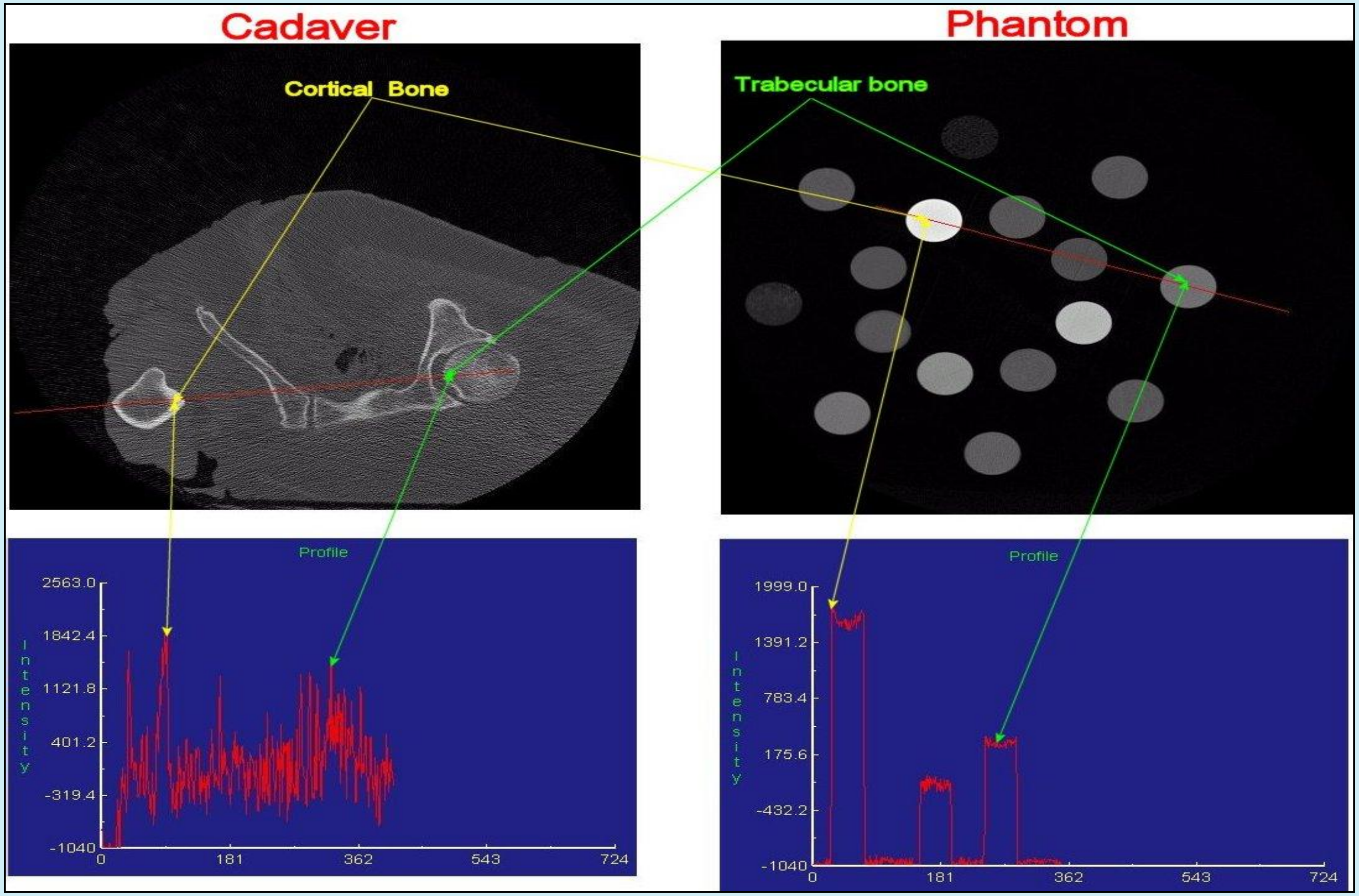
Technology Transition Workshop

CT Image of Phantom



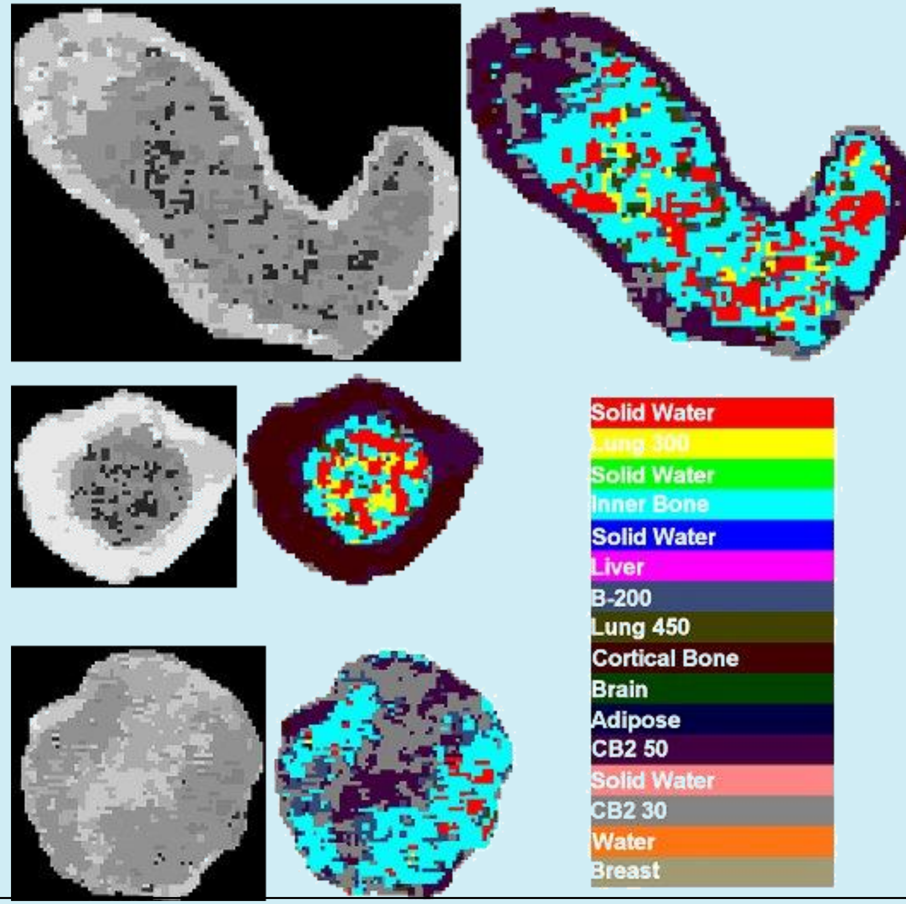
Technology
Transition Workshop

Density Mapping



Technology
Transition Workshop

Density Mapping



Density and Color Map for Different Parts in Proximal Femur

From Moore, Mahfouz, Abdel Fatah and Badawi (2006).

Technology Transition Workshop

NIJ National Institute of Justice

Modeling

Two Methods:

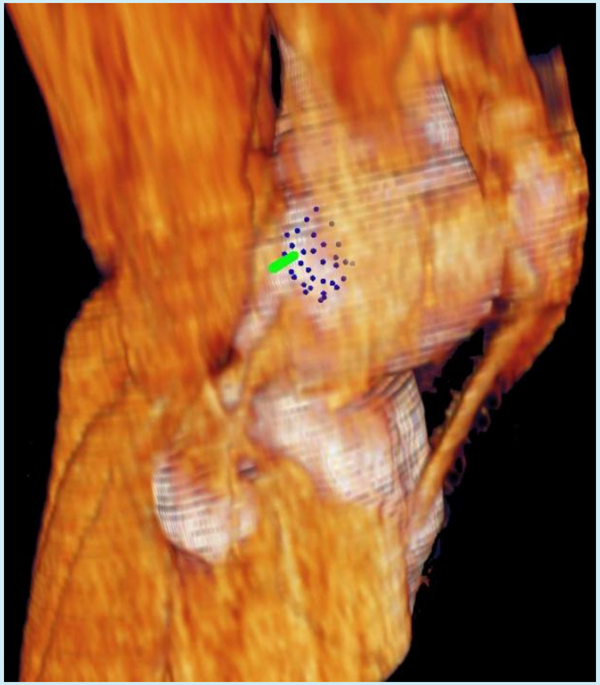
1. Directly find landmarks or perform measurements on CT slices
2. Generation of 3D surface model by segmenting object of interest, then perform measurements on the segmented model

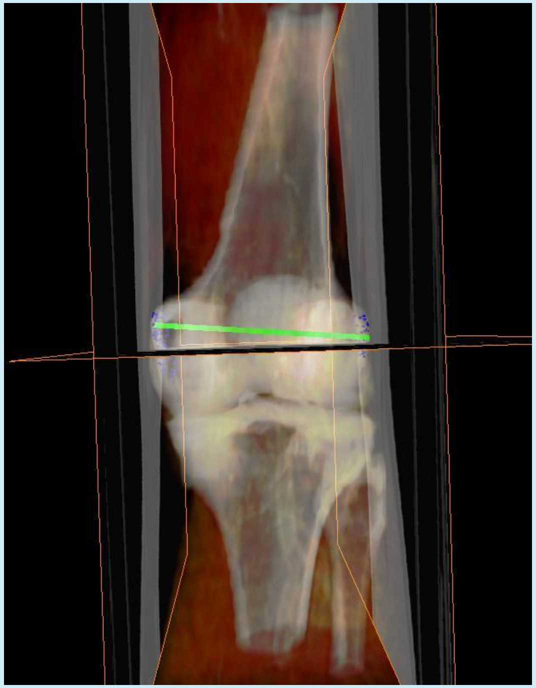
Technology
Transition Workshop

NIJ National Institute of Justice

Modeling Directly from CT Slices

- **Features can fall between slices**





Example: Epicondyler Axis in Femur

Technology Transition Workshop

NIJ National Institute of Justice

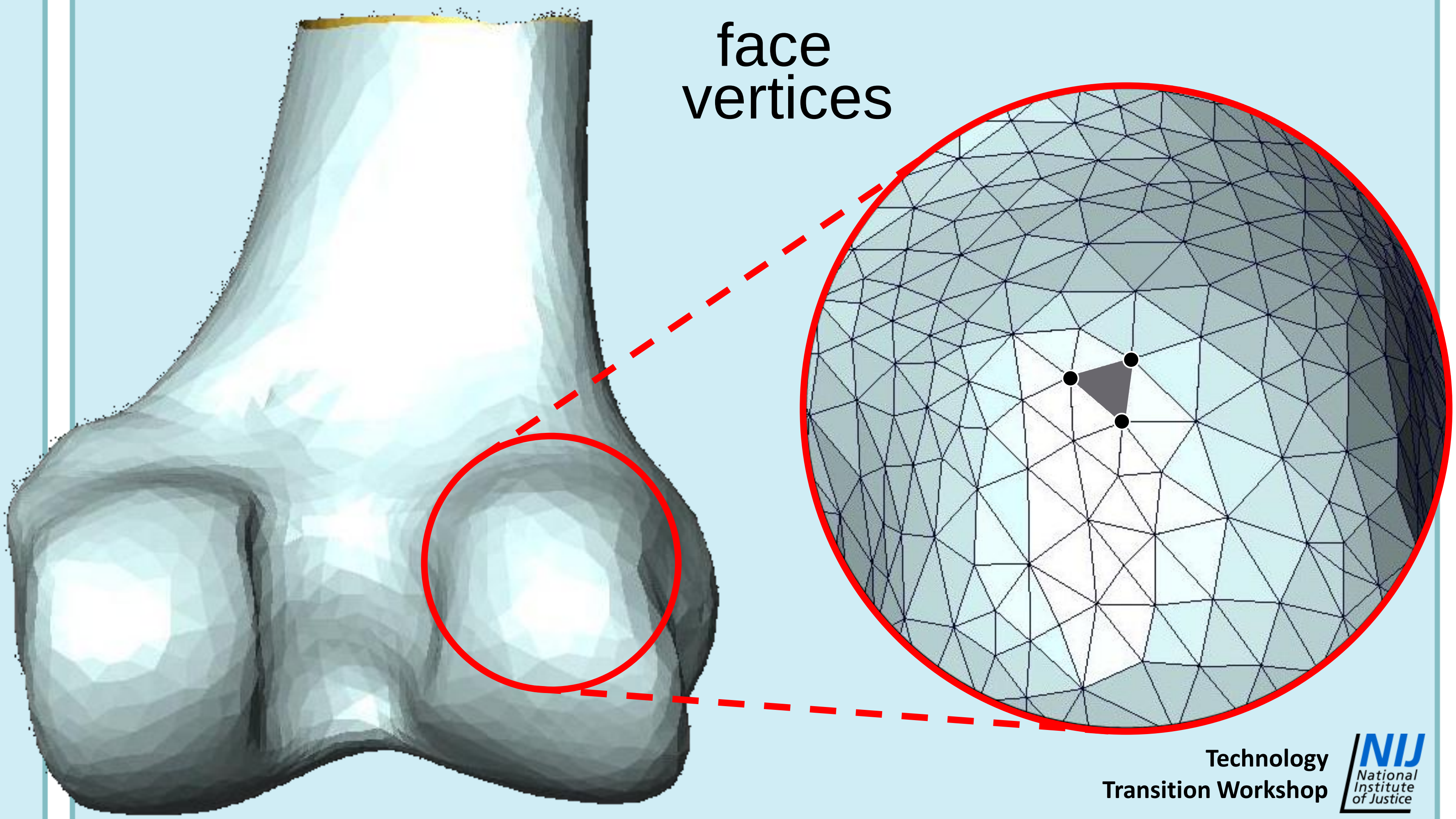
Modeling Using 3D Models

- **Segmentation**
- **Statistical atlases**
- **Reconstructing missing data**
- **Measurements and landmarking**
- **Statistical analysis**

Technology
Transition Workshop

NIJ National Institute of Justice

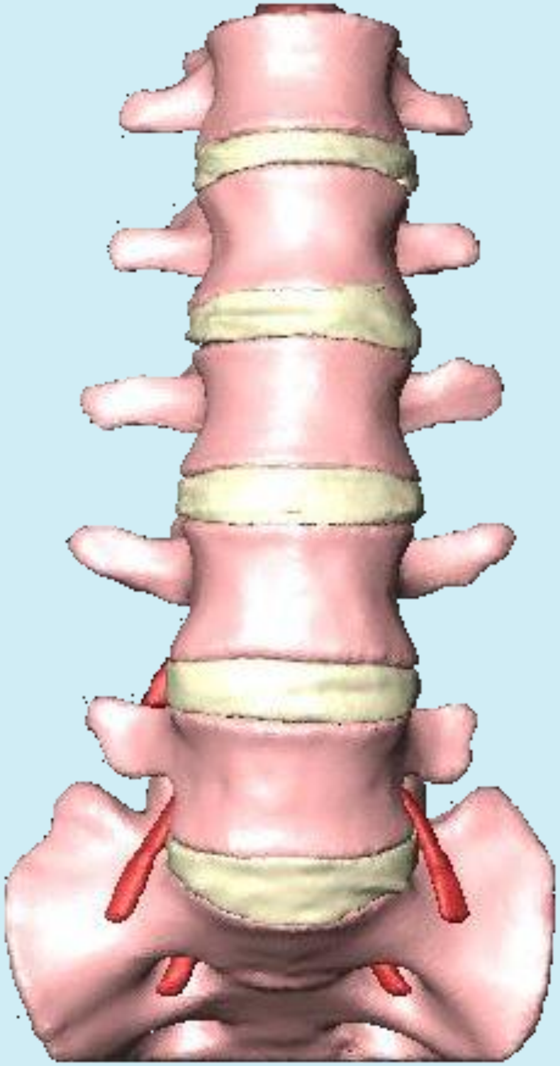
What is a 3D Model?

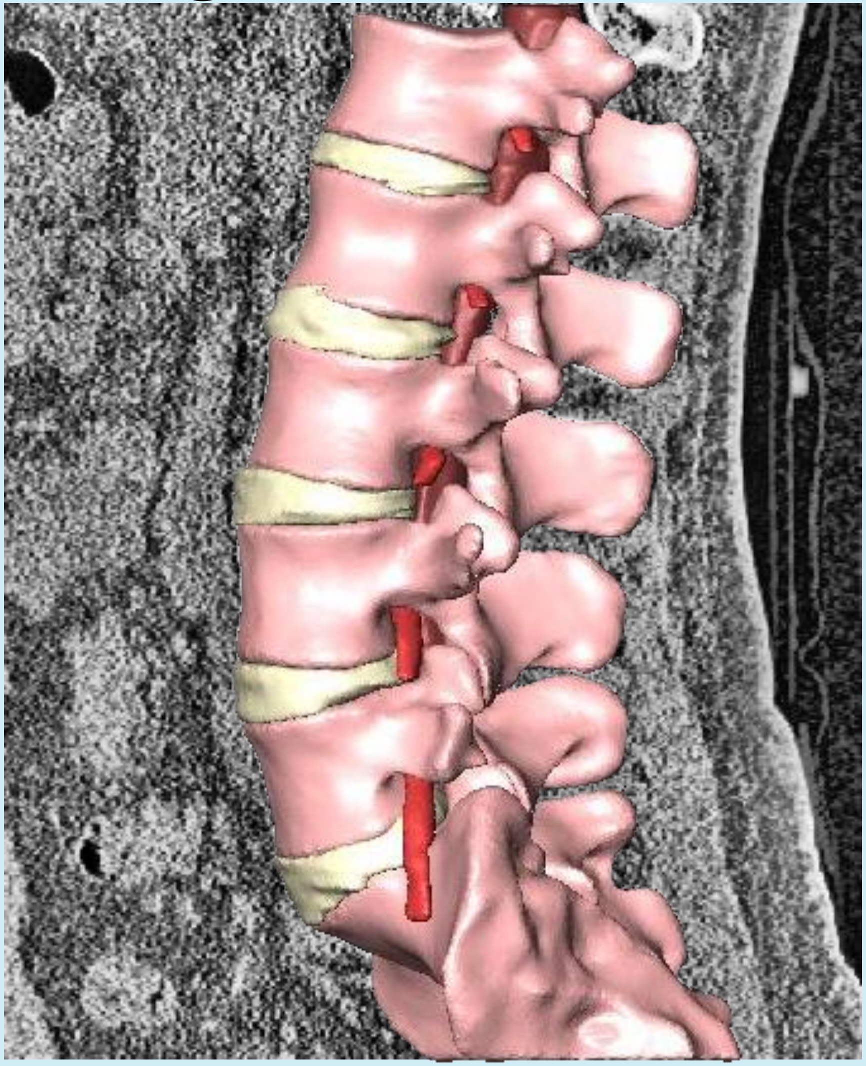


Technology
Transition Workshop

NIJ National Institute of Justice

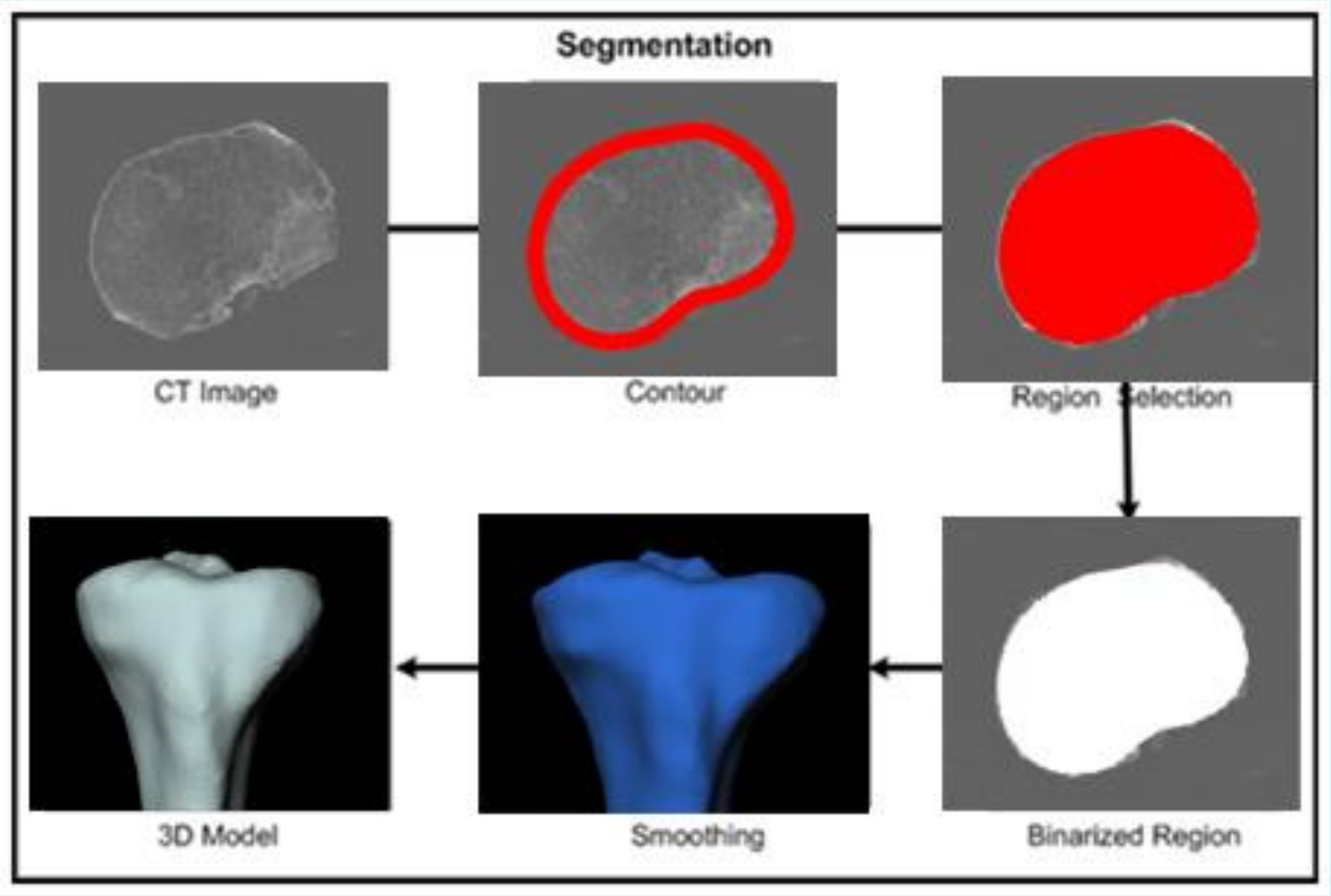
3D Models vs 2D Images





NIJ National Institute of Justice

Model Segmentation



Technology
Transition Workshop

Model Segmentation

Technology
Transition Workshop

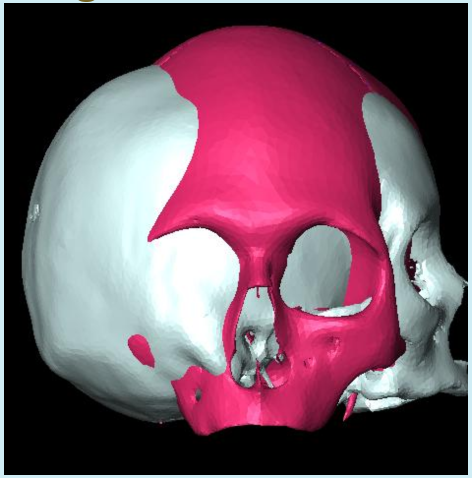
Statistical Bone Atlas

- Generate surface mesh models built from computed tomography data
  - New models are converted to a normalized mesh
  - Models then represented with principal components that govern bone shape
- Statistical variation of morphology can be computed for a population of bones
- "Average" bone model computed from bones in the atlas

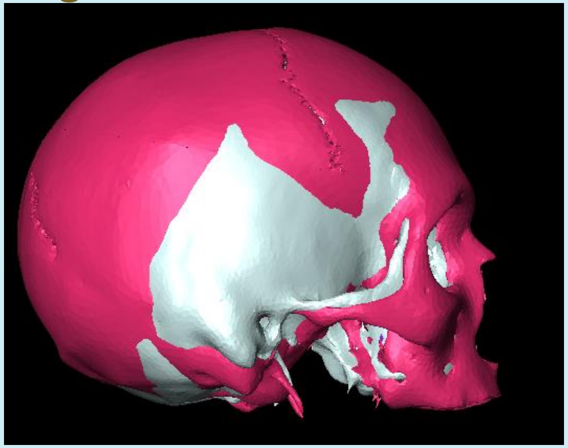
Technology
Transition Workshop

Statistical Atlas

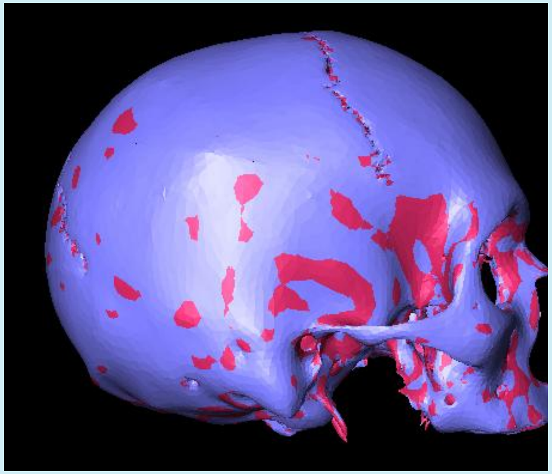
Align bone centroids



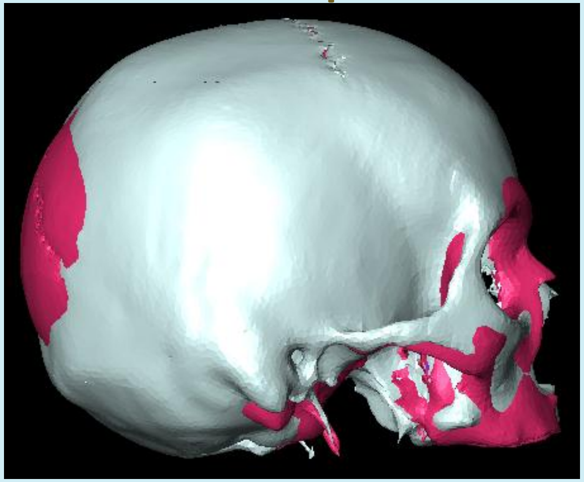
Perform Rigid Iterative Closest Point (ICP)



Free Form Transformation

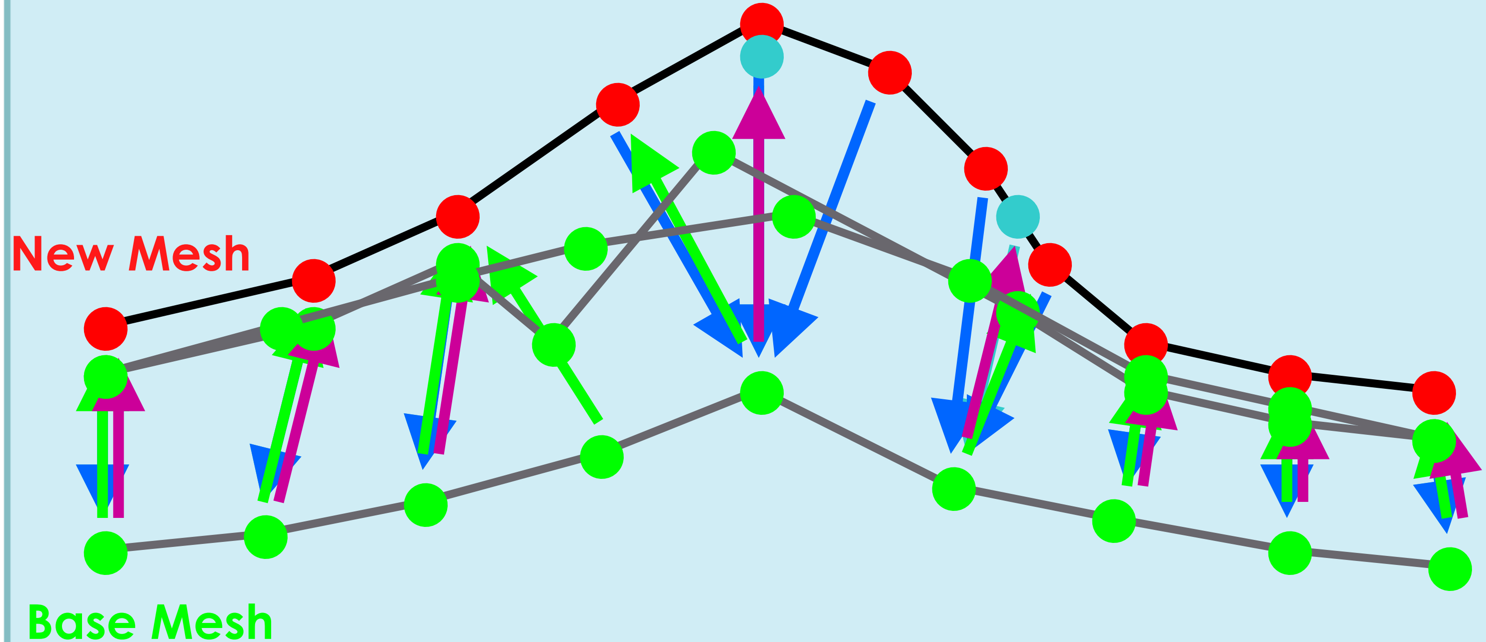


Surface Correspondence



NIJ National Institute of Justice

Surface Correspondence



Move base points along weighted combination of vectors

Technology
Transition Workshop

NIJ National Institute of Justice

Feature Extraction Techniques

Statistical Shape Model	*Specific Landmarks*
Principal Components (PCA)	**Measurements**
(Global)	***(Local)***

Technology
Transition Workshop

NIJ National Institute of Justice

Statistical Representation

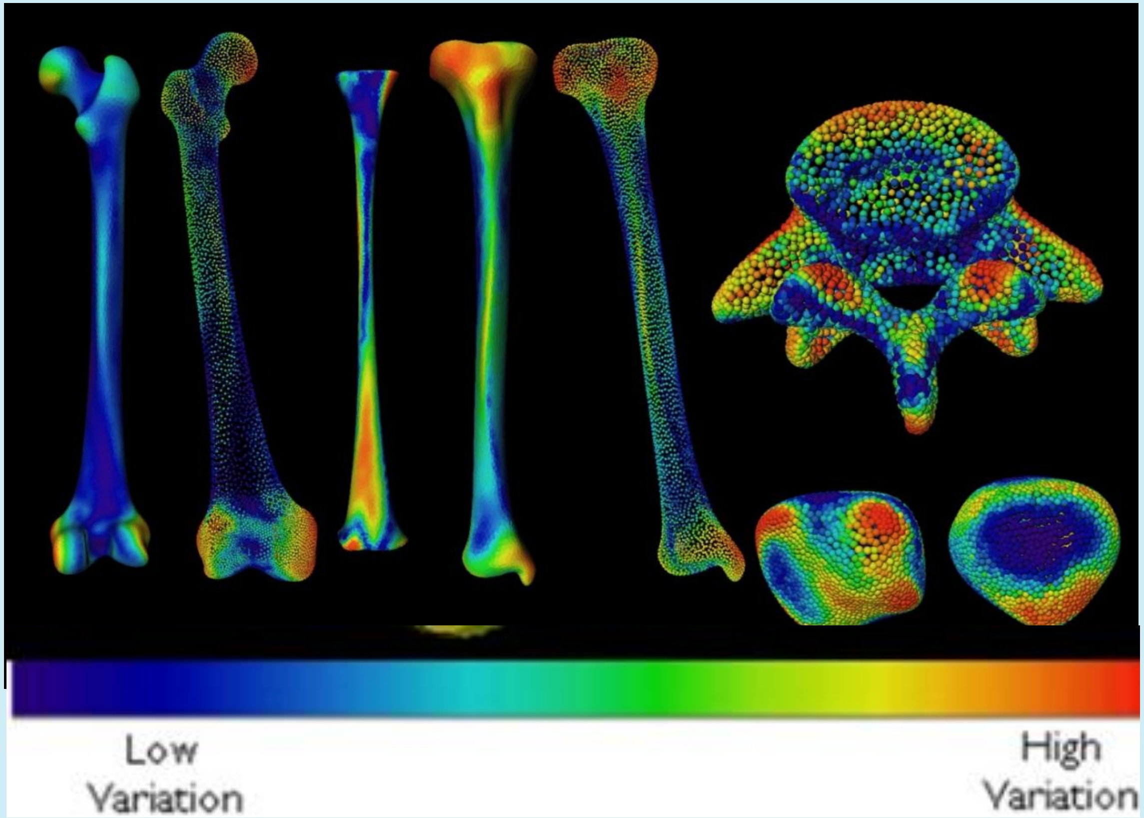
- Landmark-Based
  - Disadvantage: manually defined landmarks
  - Disadvantage: time-consuming
  - Disadvantage: high intraobserver error
  - *Only capture local statistics*

- Surface-Based
  - Advantage: performed on entire bone surface after establishing correspondence
  - Advantage: quick and convenient method
  - Advantage: eliminates subjectivity and only done once
  - *Capture both global and local statistics*

Technology
Transition Workshop

Morphological Differences

- **Analysis of differences between gender, ethnicities and ages**



Technology Transition Workshop

NIJ National Institute of Justice

Extrapolating Missing Anatomy

- **Extrapolation of missing bone segments**

Technology
Transition Workshop

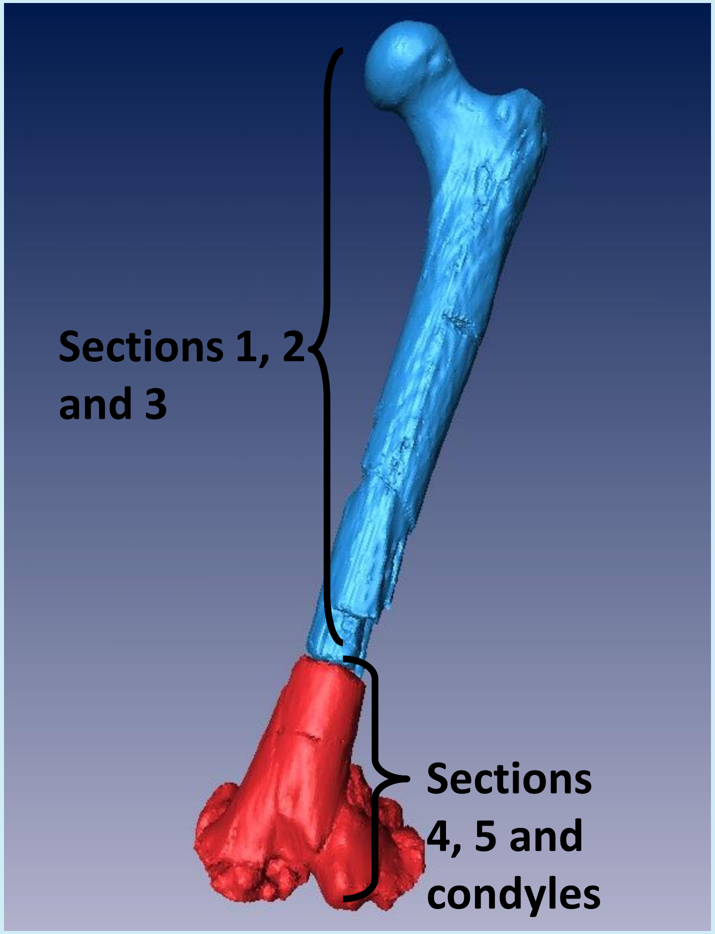
NIJ National Institute of Justice

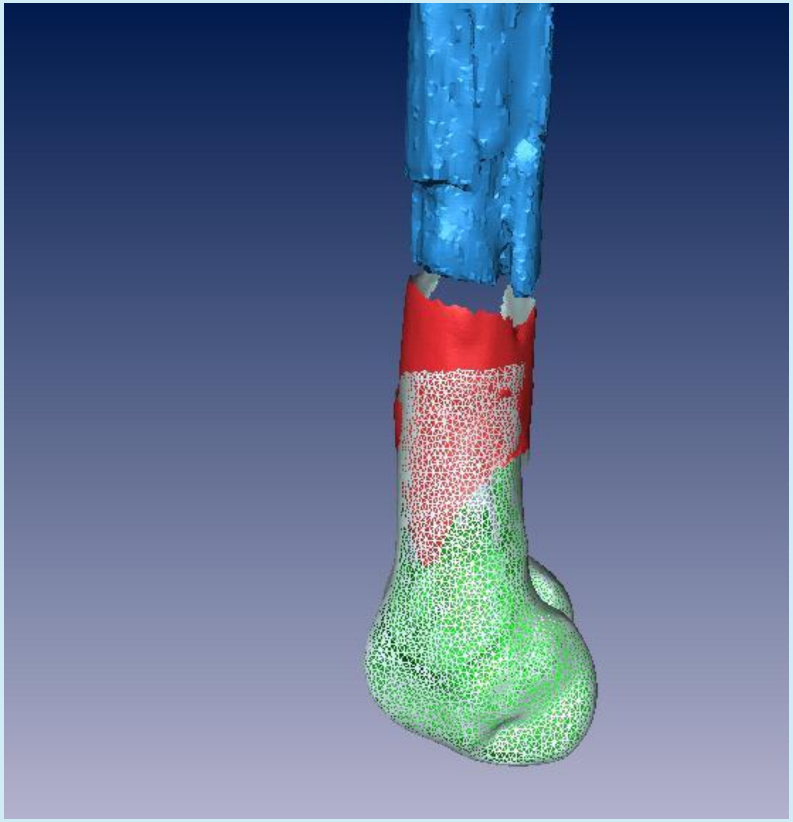
Fragmentary Bone Reconstruction (Traditional By Hand)

Technology
Transition Workshop

NIJ
National Institute of Justice

Reconstruction : Conjoinable Pieces



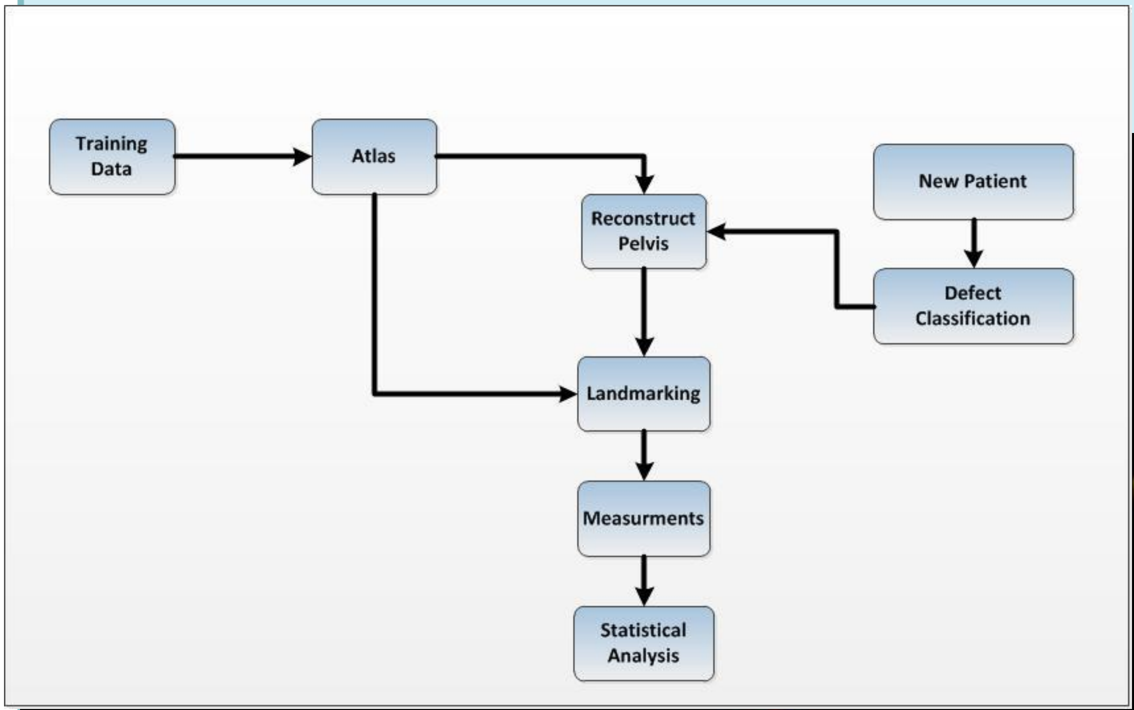


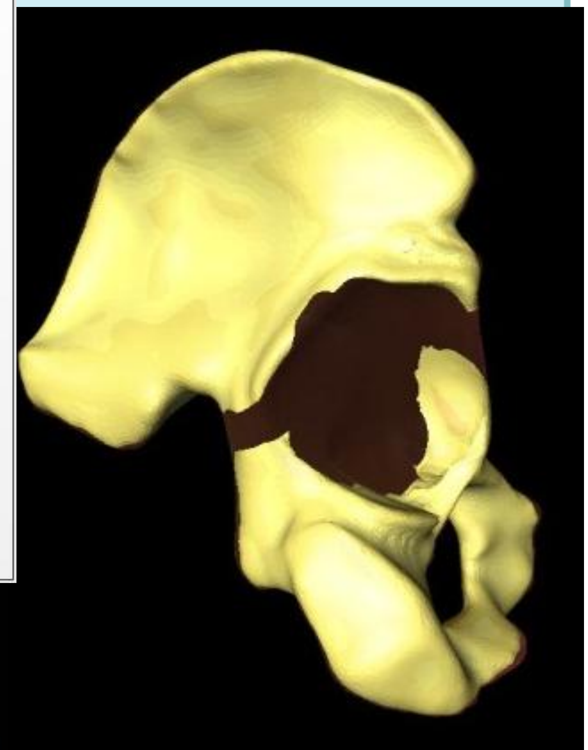
From Sylvester, Merkl and Mahfouz (2008).

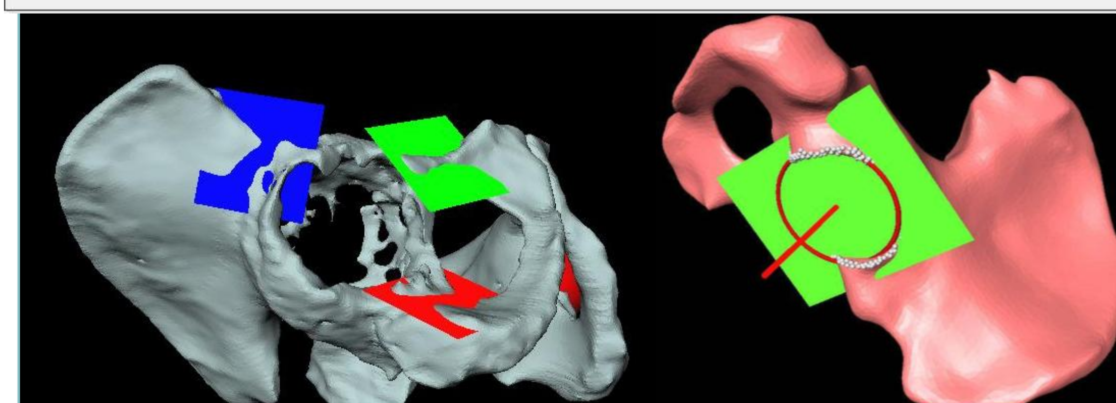
Technology Transition Workshop

NIJ National Institute of Justice

Pelvis Reconstruction



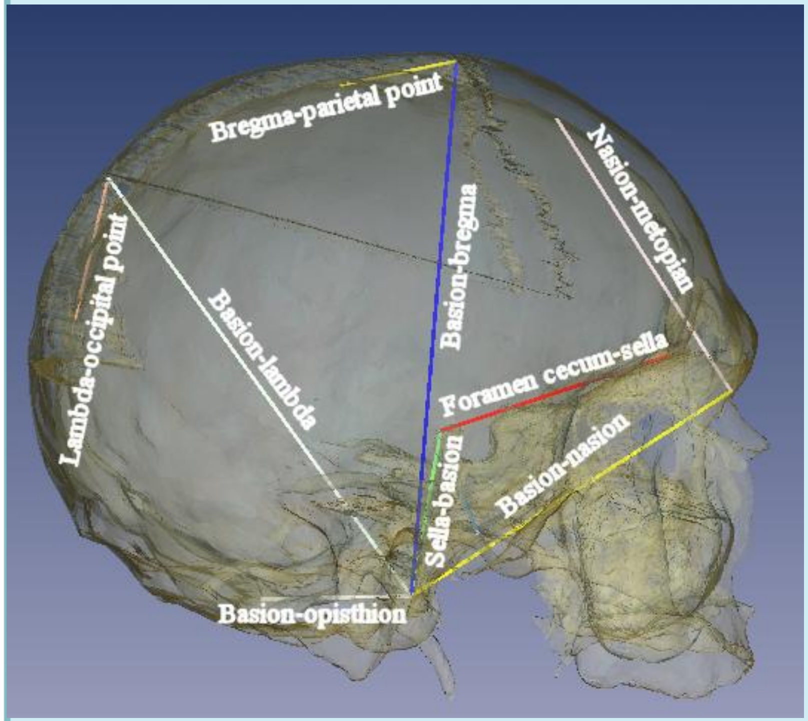


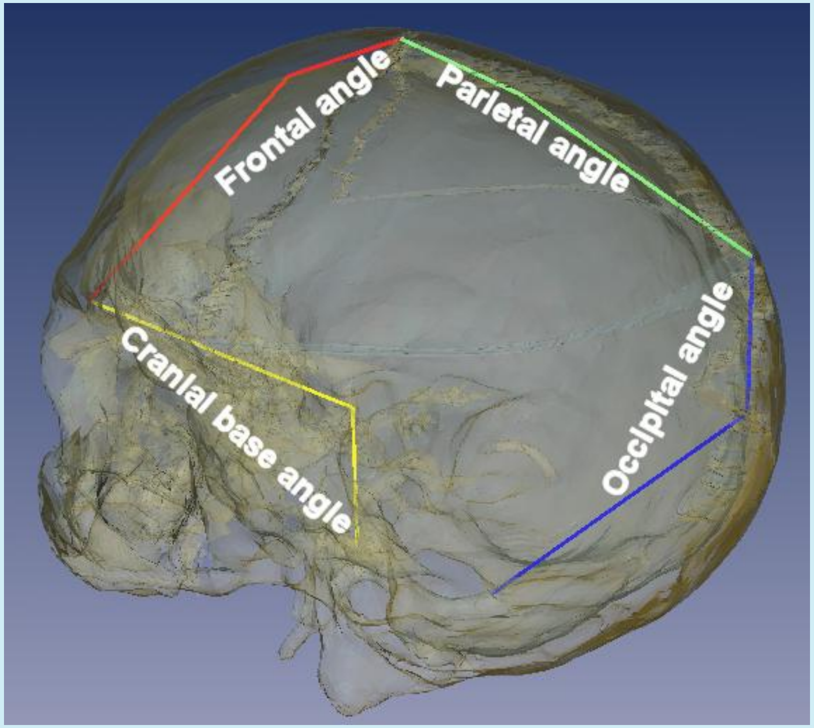


Technology Transition Workshop

NIJ National Institute of Justice

Automatic Measurements (Skull)





Skull Sexing 98% Using 11 Features

From Shirley, Abdel Fatah, Jantz and Mahfouz (2011).

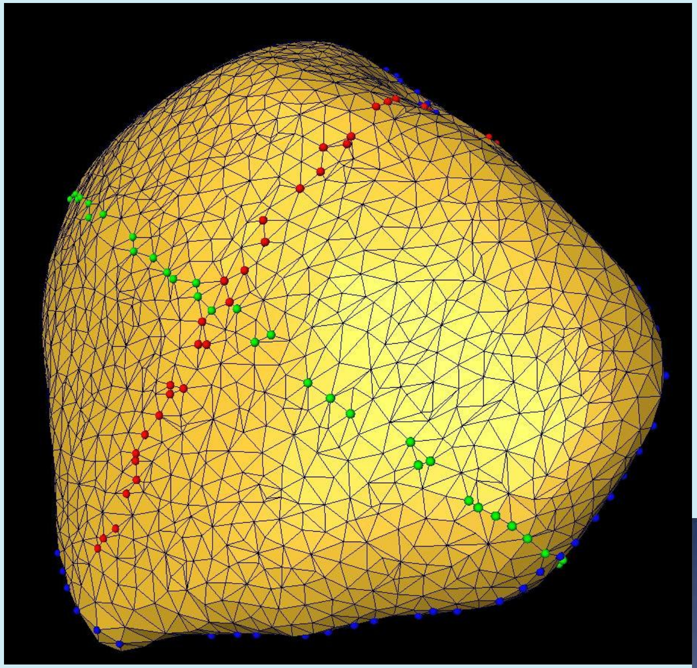
Technology Transition Workshop

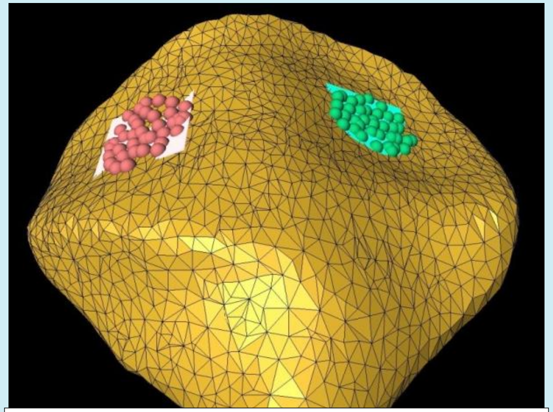
Thickness Measurements (Skull)

Technology
Transition Workshop

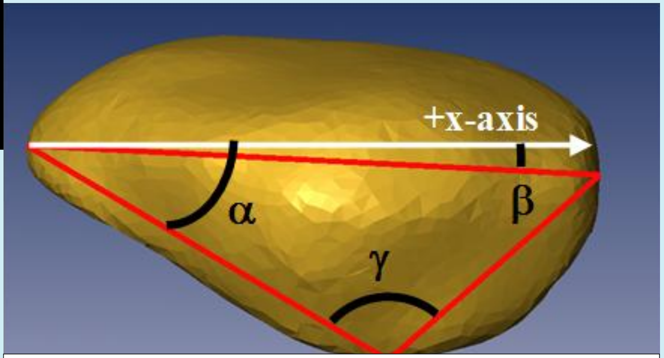
NIJ National Institute of Justice

Automated Measurements (Patella)





Posterior Facet Angle



Circumference Moment Measurements Around 3 Coordinate Axes

2D In-plane Measurements

Technology
Transition Workshop

NIJ National Institute of Justice

Patella Sexing

Testing results of confusion matrix using a neural network trained on the full 45 features (93.51% correctly classified)

Actual	Predicted		
	Females	Males	Total
Female	28	3	31
Male	2	44	46
Total	30	47	77

From Mahfouz, Badawi, Merkl, Abdel Fatah, Pritchard, Kesler, Moore, Jantz and Jantz (2007).

Technology Transition Workshop

Cited Scientific References

- Mahfouz, M.R.; Badawi, A.M.; Merkl, B.C.; Abdel Fatah, E.E.; Pritchard, E.; Kesler, K.; Moore, M.K.; Jantz, R.L.; Jantz, L.M. Patella Sex Determination by 3D Statistical Shape Models and Nonlinear Classifiers. *Forensic Science International* 2007, *173(2)*, 161-170.
- Moore, M.K.; Mahfouz, M.R.; Abdel Fatah, E.E.; Badawi, A.M. Comparison of Dry and In Vivo Bone Densities from CT Images using Fuzzy Logic and Neural Networks. *Computer Methods in Biomechanics and Biomedical Engineering, 7th International Symposium*, Cote De Azure, France, 2006.
- Shirley, N.R.; Abdel Fatah, E.E.; Jantz, R.L.; Mahfouz, M.R. Improving Sex Estimation from the Human Cranium Using 3D CT Scans. *American Academy of Forensic Sciences, 63rd Annual Scientific Meeting*, Chicago, IL, 2011.
- Sylvester, A.D.; Merkl, B.C.; Mahfouz, M.R. Reconstructing the AL 288-1 Femur Using Three-Dimensional Computer Models. *Journal of Human Evolution* 2008, *55*, 665-671.

Technology
Transition Workshop

NIJ National Institute of Justice

Questions?

Technology Transition Workshops are a project of NIJ's Forensic Technology Center of Excellence, operated by the National Forensic Science Technology Center (www.nfstc.org), funded through cooperative agreement #2010-DN-BX-K210.

Technology
Transition Workshop

NIJ National Institute of Justice

Contact Information

Mohamed R. Mahfouz, Ph.D.

307 Perkins Hall

University of Tennessee

Knoxville, TN, 37996

865-974-7668

mmahfouz@utk.edu

Note: All images are courtesy of Dr. Mohamed R. Mahfouz and the Center for Musculoskeletal Research at The University of Tennessee, unless otherwise indicated.

Technology Transition Workshop

NIJ National Institute of Justice