Lecture 3:

Biomedical Imaging Technologies

From Molecules to Organs
Clinical Impact Through Imaging Science

Introduction to Biomedical Datascience

Imaging across scales visualization

Lecture Contents

Part 1/3:

Microscopy

- Resolution limits
- Contrast mechanisms
- Live vs fixed imaging
- 3D reconstruction

Light Microscopy Principles

Köhler illumination

Uniform field illumination technique

Numerical aperture

Light gathering power of objective

Abbe diffraction limit

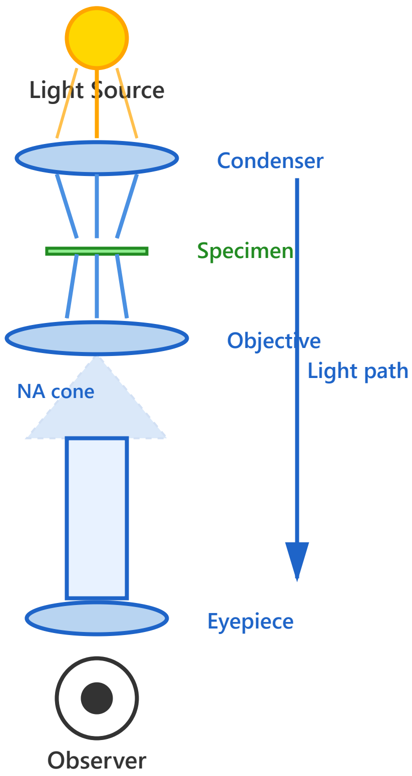
$d = \lambda/(2 \cdot NA) \approx 200$ nm

Point spread function

3D light distribution pattern

Optical aberrations

Spherical, chromatic distortions



Resolution and Magnification

Rayleigh criterion

Minimum resolvable distance

Empty magnification

Magnifying beyond resolution limit

Nyquist sampling

2× sampling above highest frequency

Digital resolution

Pixel size vs optical resolution

Super-resolution preview

Breaking diffraction barrier

Fluorescence Microscopy

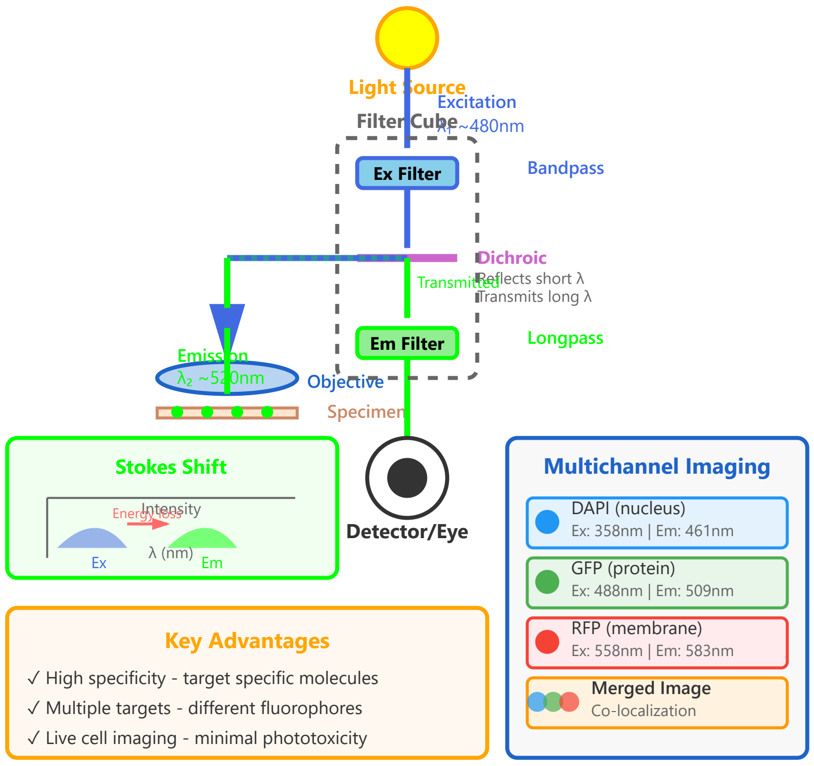
Filter cube design
Excitation, dichroic, emission filters

Multichannel imaging
Multiple fluorophores simultaneously

Autofluorescence
Background from endogenous molecules

Phototoxicity
Cell damage from light exposure

Live cell considerations
Environmental control requirements



Confocal Microscopy

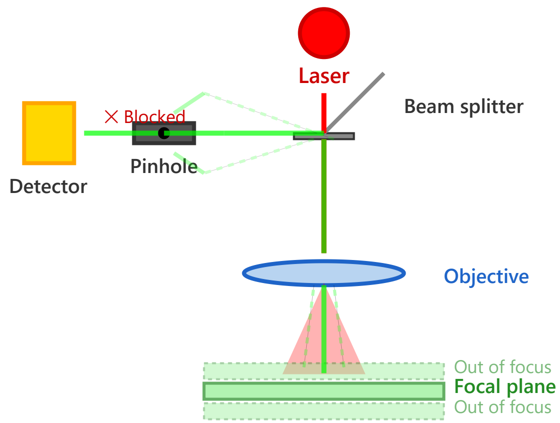
Pinhole principle
Rejection of out-of-focus light

Optical sectioning
Thin optical slices through sample

Laser scanning
Point-by-point image acquisition

Z-stack acquisition
Series of optical sections

3D rendering
Volumetric visualization from stacks



Pinhole Principle

✓ In-focus light passes through pinhole

× Out-of-focus light blocked by pinhole

→ High axial resolution (~500 nm)

Two-Photon Microscopy

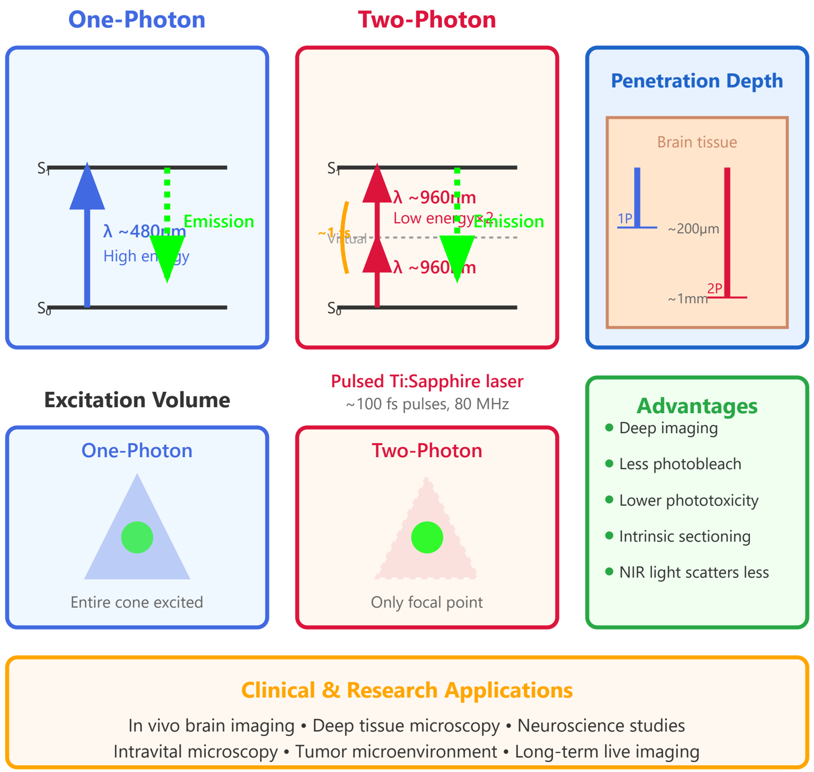
Nonlinear excitation
Two photons absorbed simultaneously

Deeper penetration
Up to 1mm in tissue

Reduced photobleaching
Excitation only at focal point

In vivo imaging
Live animal brain imaging

SHG imaging
Second harmonic generation for collagen



Super-Resolution Techniques

STORM/PALM principles
Single molecule localization (20-30 nm)

STED microscopy
Stimulated emission depletion (~50 nm)

SIM principles
Structured illumination (~100 nm)

Resolution comparisons
10× improvement over diffraction limit

Sample requirements
Special fluorophores and preparation

Electron Microscopy (SEM/TEM)

Electron sources

Wavelength ~0.004 nm vs light ~500 nm

Sample preparation

Fixation, dehydration, coating

Contrast mechanisms

Electron density differences

Cryo-EM revolution

Near-atomic resolution of proteins

Correlative microscopy

Combining light and electron microscopy

Part 2

Medical Imaging

- Clinical modalities overview
- Contrast agents
- Radiation considerations
- Multi-modal imaging

X-ray Physics and Imaging

X-ray production
High energy electrons hit metal target

Attenuation principles
Absorption varies with tissue density

Digital detectors
CR and DR systems replace film

Dose considerations
ALARA principle (As Low As Reasonably Achievable)

Image quality metrics
Contrast, resolution, noise tradeoffs

CT Scan Principles

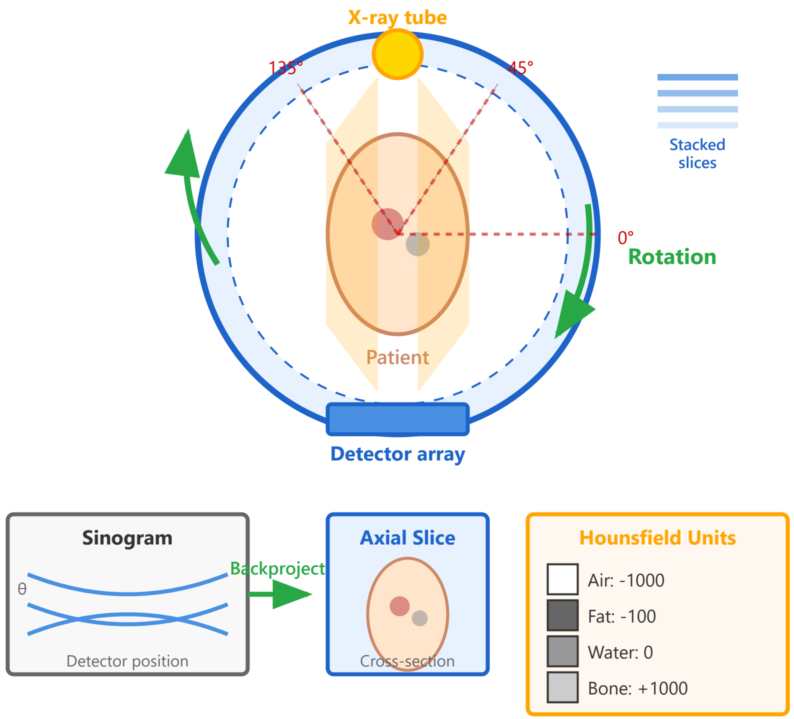
Tomographic reconstruction
Multiple X-ray projections create 3D volume

Hounsfield units
Standardized tissue density scale

Spiral/helical CT
Continuous rotation and table movement

Dose reduction strategies
Iterative reconstruction, tube modulation

Contrast protocols
IV contrast timing for specific applications



MRI Physics Basics

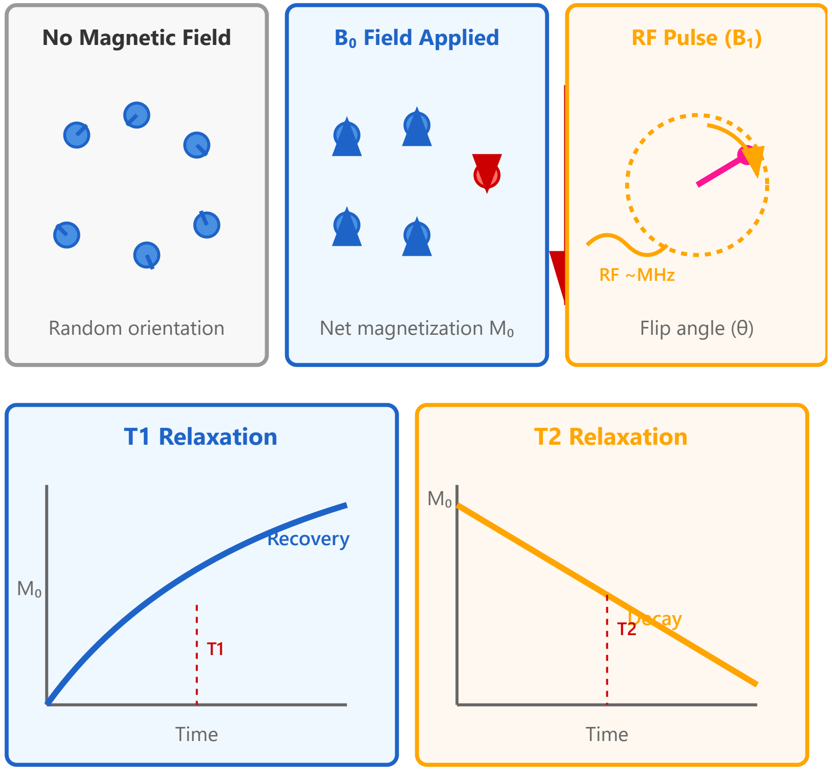
Nuclear magnetic resonance
Hydrogen protons align in magnetic field

Gradient fields
Spatial encoding of signal

K-space
Frequency domain data representation

Relaxation times (T1, T2)
Tissue-specific signal recovery

Signal equation
S ∝ ρ·(1-e^(-TR/T1))·e^(-TE/T2)



MRI Sequences and Contrast

Spin echo

180° refocusing pulse, high SNR

Gradient echo

Faster acquisition, T2* weighting

T1/T2/PD weighting

Tissue contrast manipulation

DWI/DTI

Diffusion imaging for stroke and white matter

Functional MRI basics

BOLD signal reflects brain activity

Ultrasound Imaging

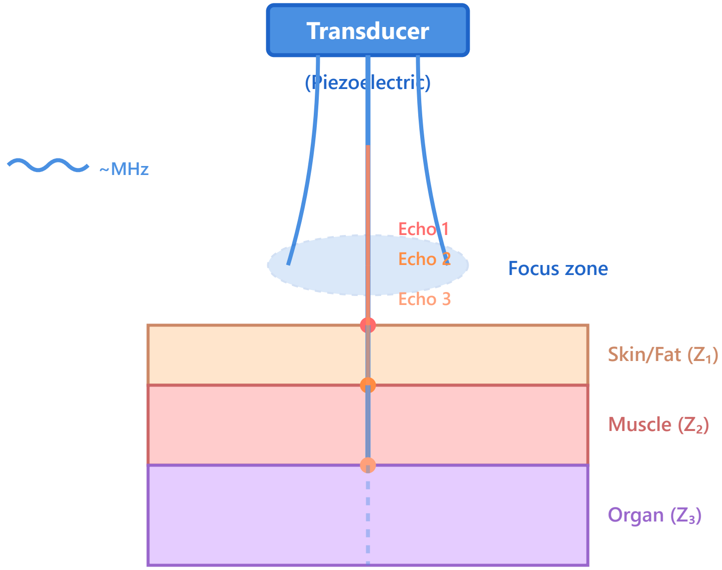
Piezoelectric transducers
Convert electrical to acoustic energy

Acoustic impedance
Tissue resistance to sound propagation

Reflection and refraction
Interface properties determine echoes

Beamforming
Focusing and steering ultrasound beam

Harmonic imaging
Higher frequencies improve resolution



Acoustic Impedance

$Z = \rho \times c$

ρ = density, c = sound speed

Reflection Coefficient

$R = (Z_2 - Z_1)^2 / (Z_2 + Z_1)^2$

Larger ΔZ → Stronger echo

Doppler Ultrasound

Doppler shift principle

Frequency change with moving blood

Color flow mapping

Direction and velocity visualization

Power Doppler

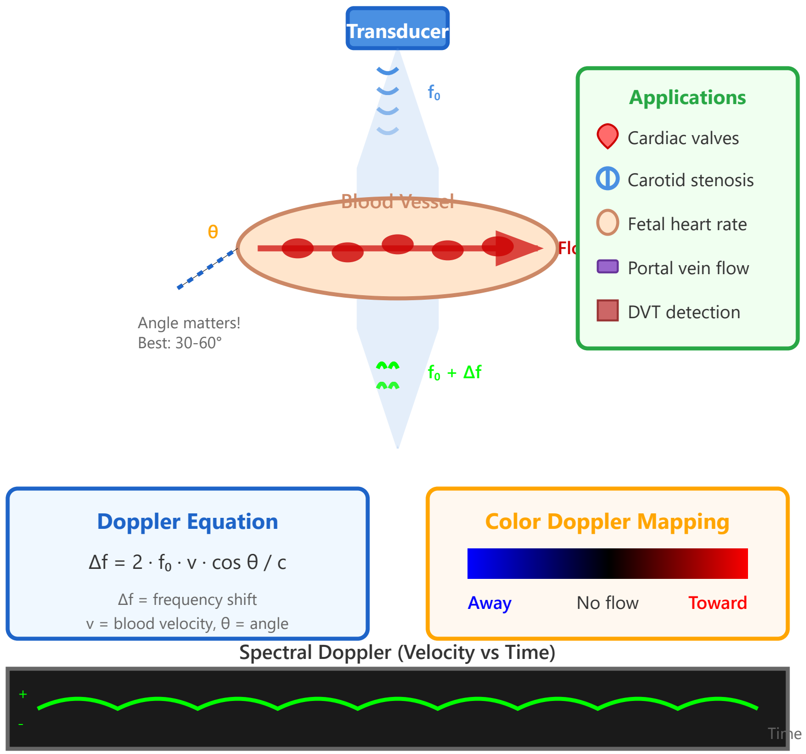
More sensitive to low flow

Spectral analysis

Velocity vs time waveforms

Clinical applications

Vascular, cardiac, obstetric imaging



PET Imaging

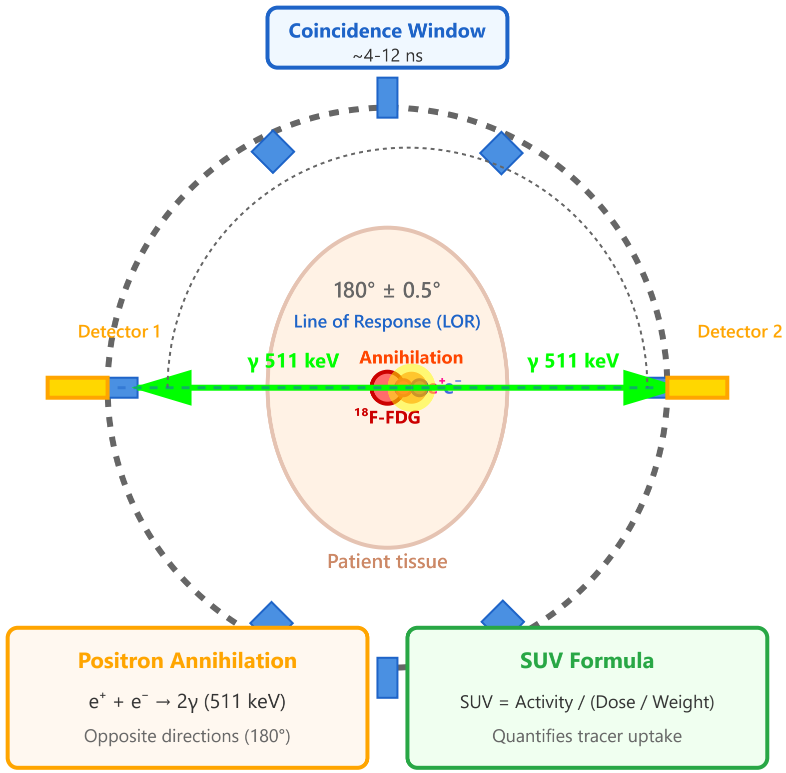
Positron annihilation
511 keV photons in opposite directions

Coincidence detection
Simultaneous detection localizes source

Radiotracers (FDG, etc.)
FDG shows glucose metabolism

SUV calculations
Standardized uptake value quantification

PET/CT integration
Functional and anatomical fusion



SPECT Imaging

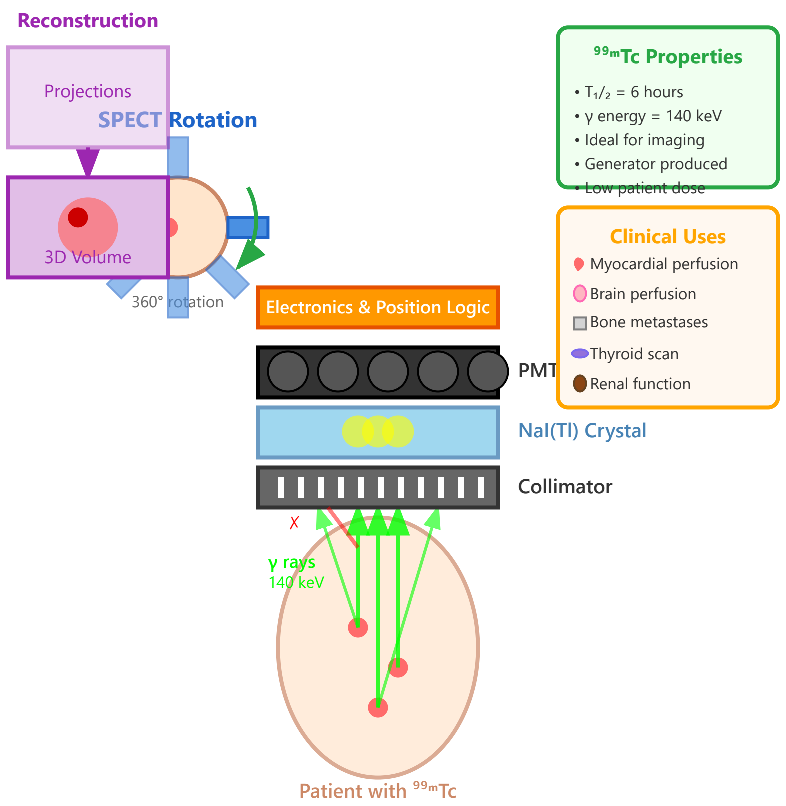
Gamma camera principles
Scintillation crystal detects photons

Collimator design
Determines sensitivity and resolution

SPECT tracers
Tc-99m most common radionuclide

Cardiac applications
Myocardial perfusion imaging

SPECT/CT
Attenuation correction and localization



Part 3

Image Analysis

- Digital image fundamentals
- Processing pipeline
- Quantification methods
- AI integration

Digital Image Basics

Pixel and voxel concepts
2D picture elements, 3D volume elements

Bit depth
8-bit (256 levels), 16-bit (65,536 levels)

File formats
TIFF, PNG (lossless), JPEG (lossy)

Compression methods
Lossless vs lossy tradeoffs

Metadata standards
EXIF, OME-TIFF for scientific imaging

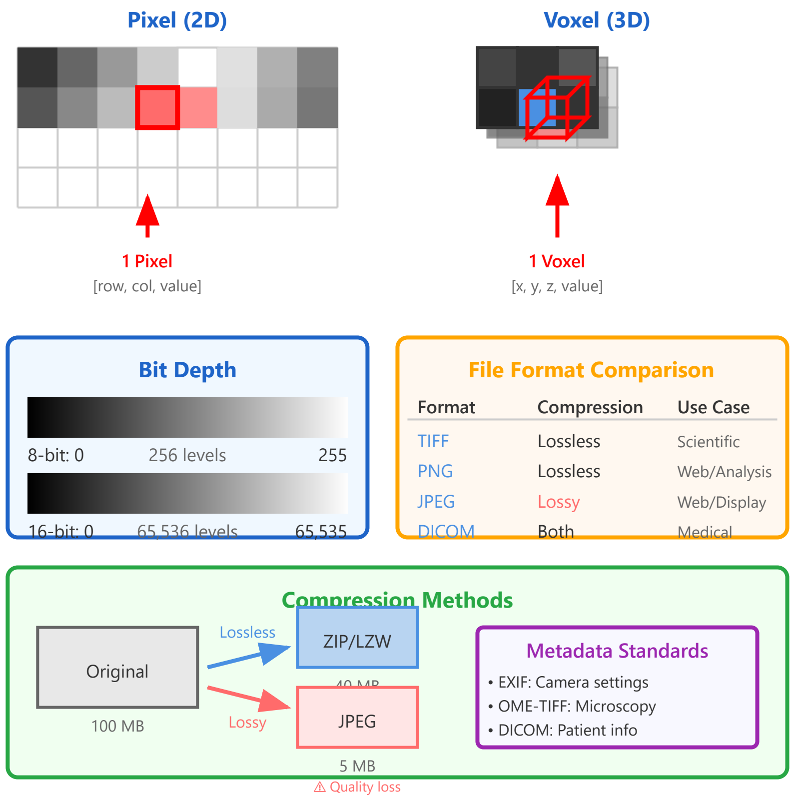


Image Preprocessing

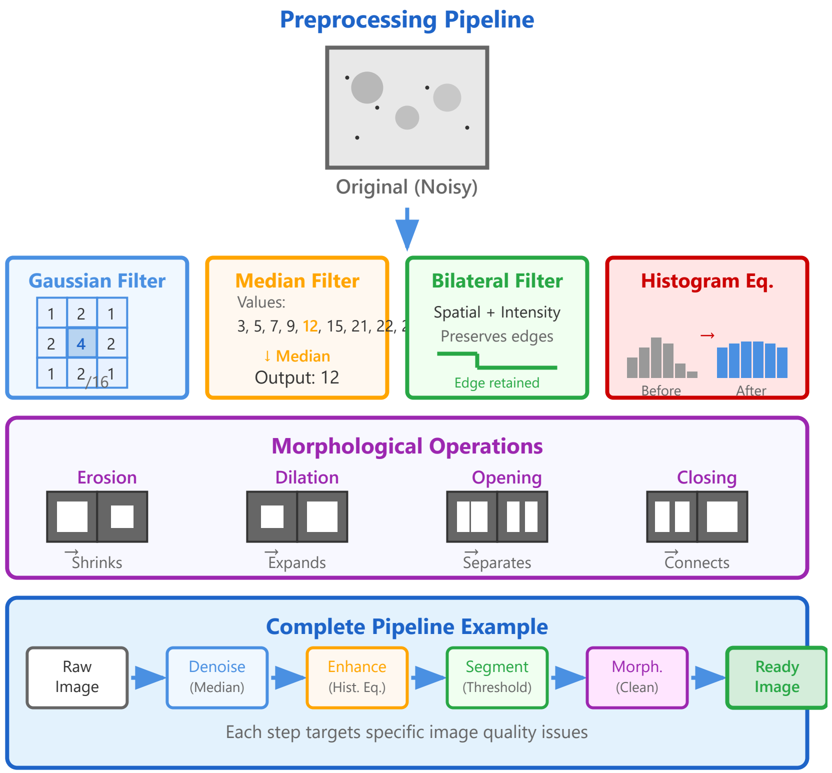
Noise reduction
Gaussian, median, bilateral filtering

Contrast enhancement
Stretching, adaptive methods

Histogram equalization
Uniform intensity distribution

Morphological operations
Erosion, dilation, opening, closing

Registration basics
Aligning multiple images



Segmentation Methods

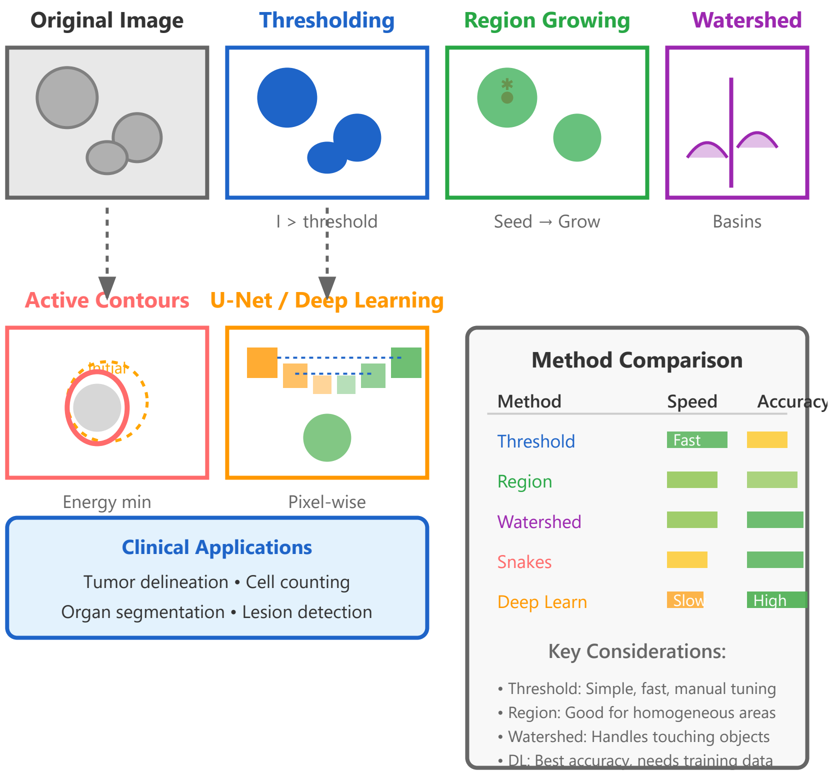
Thresholding techniques
Global, adaptive, Otsu's method

Region growing
Seed-based similar pixel grouping

Watershed algorithm
Treating image as topographic surface

Active contours
Energy-minimizing snakes

Machine learning methods
U-Net, Mask R-CNN for segmentation



Feature Extraction

Texture analysis
GLCM, LBP patterns

Shape descriptors
Area, perimeter, circularity, moments

Intensity statistics
Mean, std, min/max, histogram metrics

Haralick features
14 texture features from GLCM

Radiomics
High-throughput feature extraction

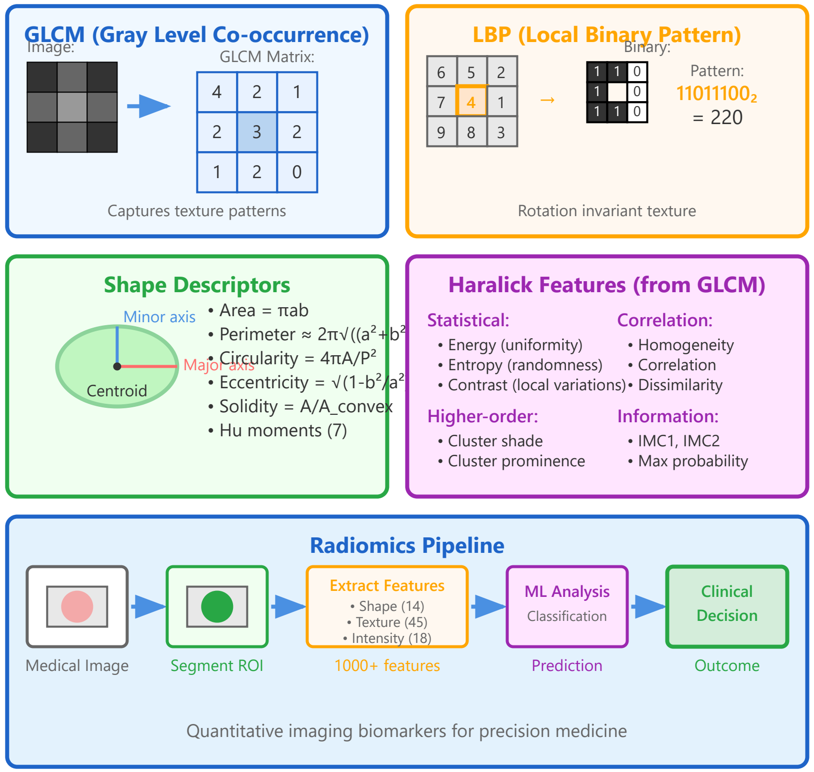


Image Registration

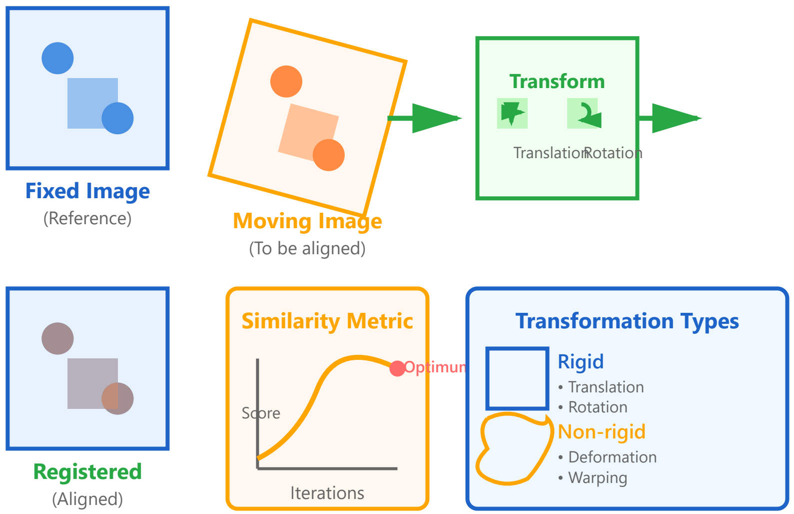
Rigid vs non-rigid
Translation/rotation vs deformation

Similarity metrics
Mutual information, correlation

Optimization methods
Gradient descent, genetic algorithms

Multi-modal registration
Aligning different imaging modalities

Validation approaches
Fiducial markers, Dice coefficient



Clinical Applications

- Multi-modal fusion (MRI + PET)
- Longitudinal analysis (tumor growth)
- Atlas-based segmentation
- Image-guided surgery planning

3D Reconstruction

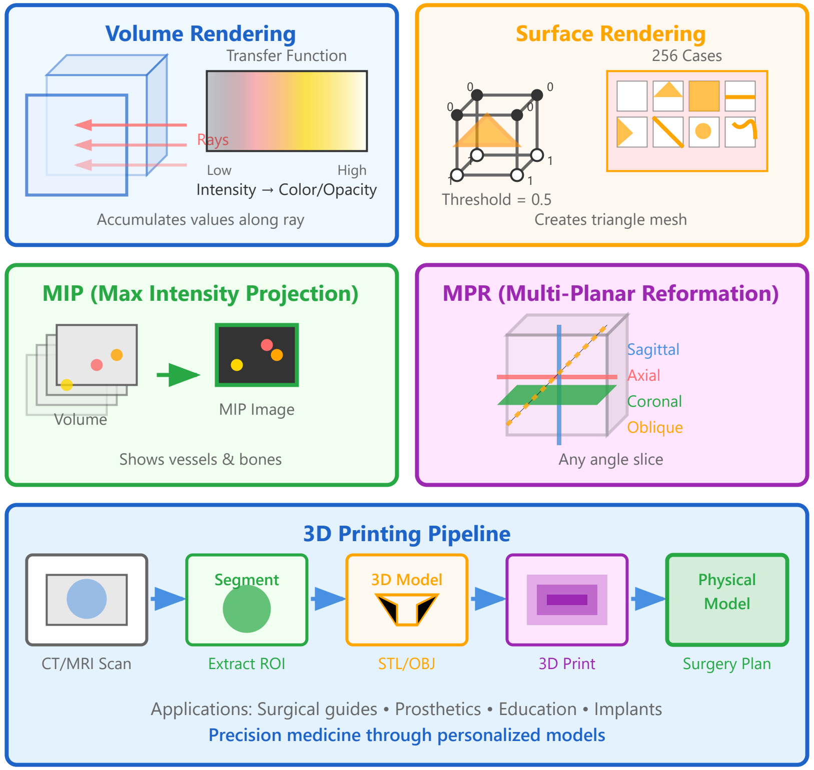
Volume rendering
Ray casting through 3D data

Surface rendering
Isosurface extraction (Marching Cubes)

Maximum intensity projection
MIP shows brightest voxels

Multi-planar reformation
MPR creates arbitrary slice planes

3D printing applications
Surgical planning, prosthetics



DICOM Format

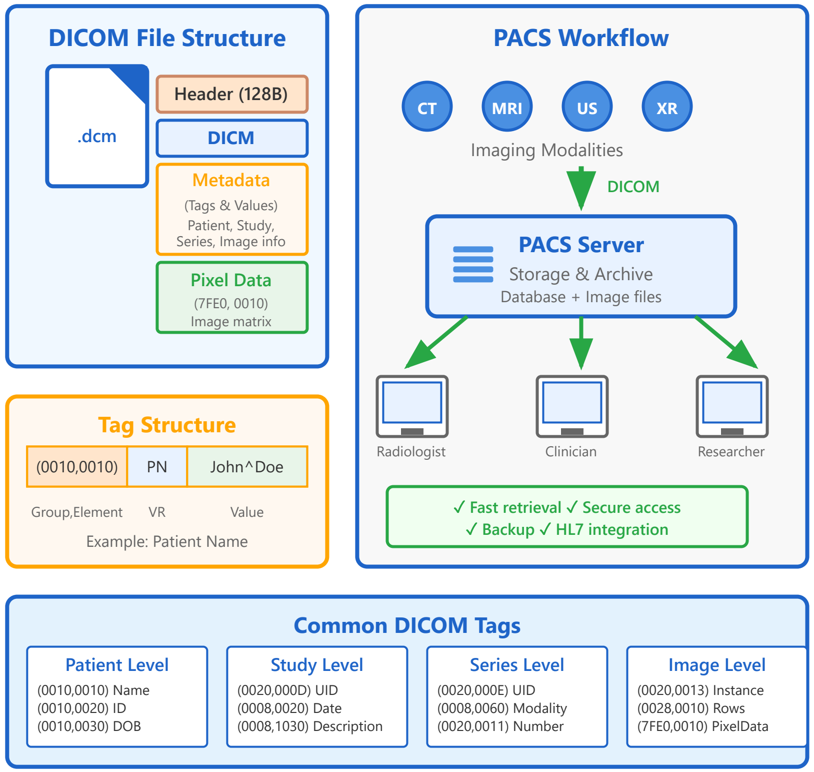
DICOM structure
Digital Imaging and Communications in Medicine

Tags and metadata
Patient info, acquisition parameters

PACS systems
Picture Archiving and Communication Systems

Anonymization
Removing protected health information

Viewer software
Horos, 3D Slicer, RadiAnt



💻 Hands-on: Medical Image Processing

SimpleITK tutorial

Python library for medical image analysis

Loading DICOM series

sitk.ReadImage() and GetArrayFromImage()

Basic operations

Filtering, thresholding, morphology

Segmentation example

Region growing and connected components

3D visualization

Integration with matplotlib and VTK

💻 Hands-on: ImageJ and Python Imaging

ImageJ macro basics
Automating repetitive tasks

Python with scikit-image
skimage for scientific imaging

Batch processing
Processing multiple images efficiently

Custom plugins
Extending ImageJ functionality

Analysis workflows
Cell counting, intensity measurements

Thank You!

Clinical Impact Through Imaging Science

✓ Imaging breakthroughs enabling precision medicine

✓ Super-resolution microscopy revealing molecular structures

✓ AI transforming medical image analysis

✓ Multi-modal imaging providing comprehensive diagnosis

Introduction to Biomedical Datascience