Deep Learning for Medical Image Analysis

COMP5423

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Introduction to Medical Image Analysis

- Background of MIA
- Medical Imaging Modalities
  - X-ray Imaging
  - Magnetic Resonance Imaging (MRI)
  - Nuclear Imaging
  - Ultrasound Imaging
  - Microscopy Imaging
  - Other Imaging Modalities
- Trends and Challenges

Slides Credit: Prof. Linda Shapiro and Klaus D. Guide to medical image analysis, 2017.

Introduction to Medical Image Analysis

- Background of Medical Image Analysis
- Medical Imaging Modalities

Why Medical Image Analysis?

>10K

Human Diseases

[IDC-11, 2020]

>90%

Imaging

[EMC research from IDC]

12,878

Symptoms

[Radiology Gamuts Ontology]

4,662

Diseases

[RadioGraphics, 2014]

Medical Image Analysis

Imaging is an essential aspect of medical sciences for

- visualization of anatomical structures
- functional or metabolic information of the human body

Structural and functional imaging of human body is important for understanding

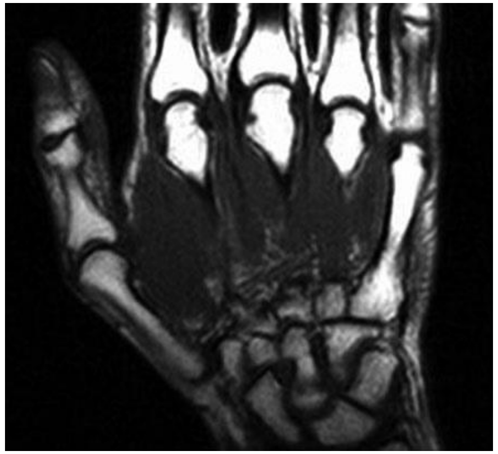
- human body anatomy
- physiological processes
- function of organs
- behavior of whole or a part of organ under the influence of abnormal physiological conditions or a disease

Medical Image Analysis

- **Medical images are different from other pictures**
  - Distributions of various physical features measured from the human body.
  - Different imaging techniques produce mappings of physical attributes in various ways for inspection.

Natural Image

One of the first radiographs showing wrist and part of the hand



Single slice through similar region by a magnetic resonance image (MRI)

Klaus D. Guide to medical image analysis, 2017.

Medical Image Analysis

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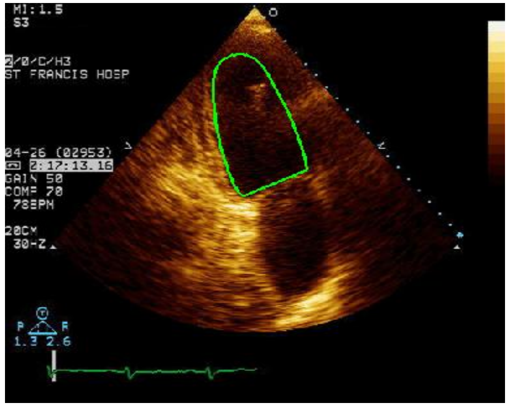
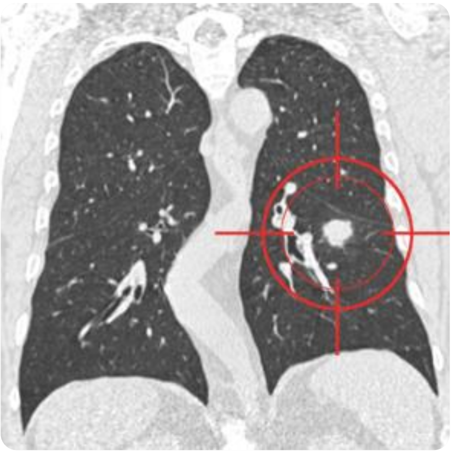
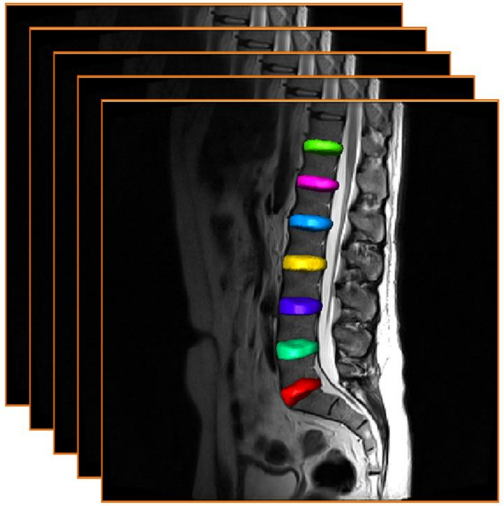
  - Computer-assisted analysis of medical images aims to support doctors in clinical decision making.



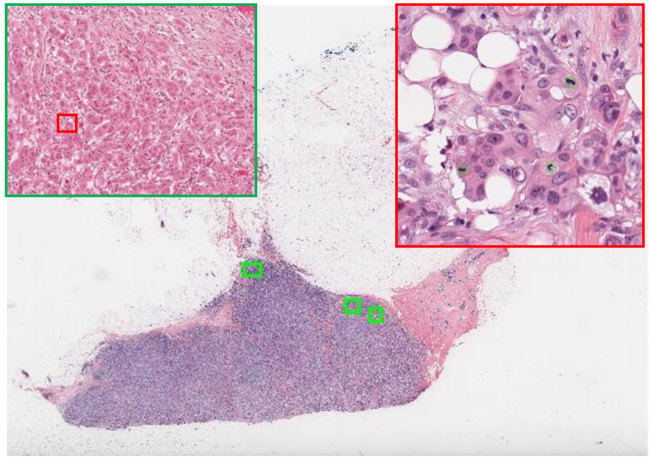
US



CT



MRI



Histology

Medical Image Analysis

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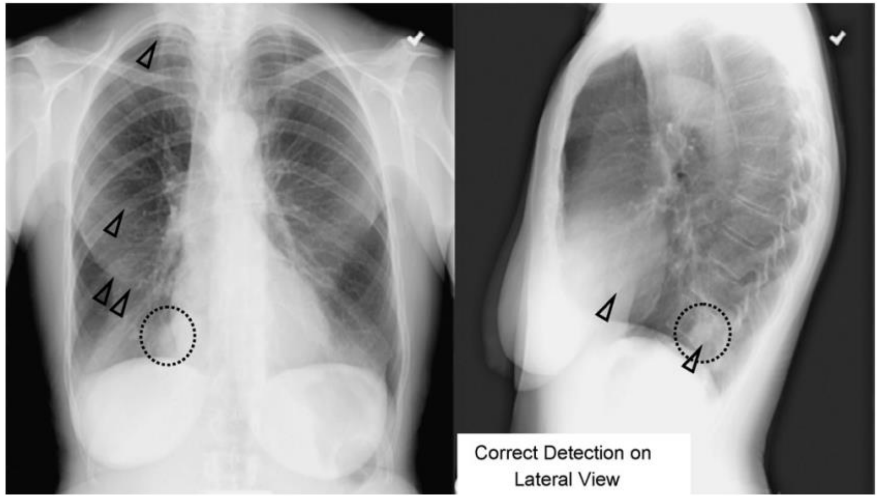
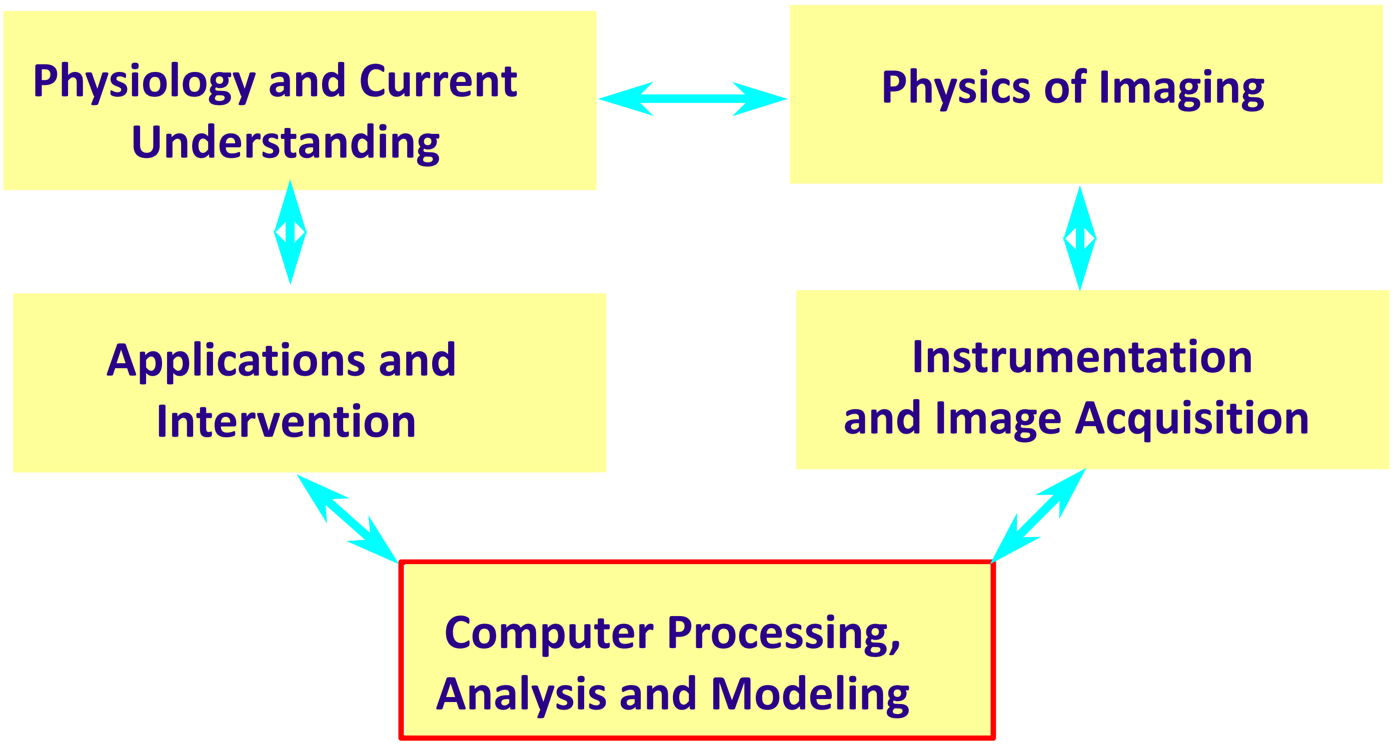


Computerized analysis of medical images in 1960s; CADe/CADx dated back to 1980s

[Kunio, CIMG, 2007]

Medical Image Analysis

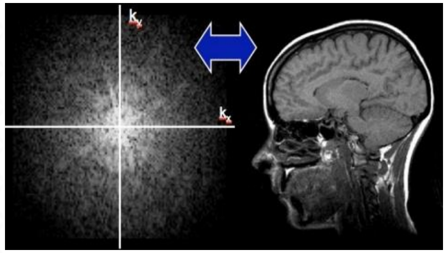
- A multidisciplinary paradigm

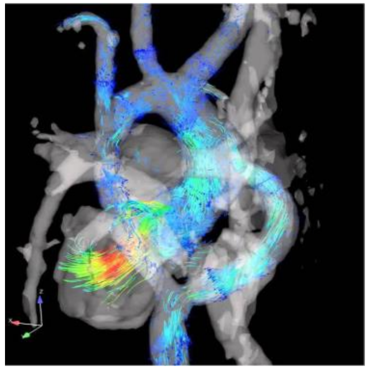


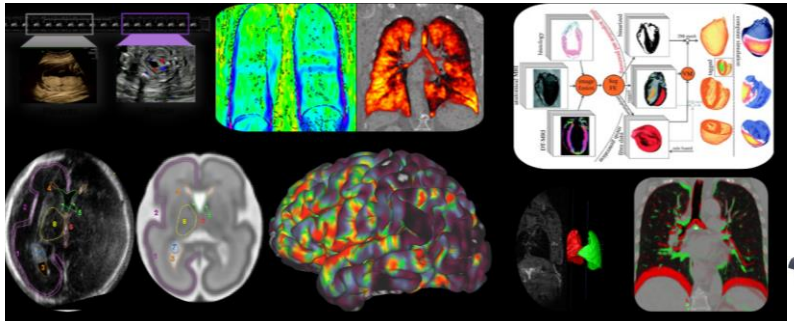
Medical Image Analysis

- **Including but not limited to**

Reconstruction, Enhancement, AR/VR Visualization, Registration, Lesion Detection & Segmentation, Diagnosis & Prognosis, Treatment Response, etc.







Acquisition Reconstruction Visualization Analysis Treatment & Prognosis

Safer, Faster, Better See the unseeable, Accurate, Quantitative Decision support, Minimize risk

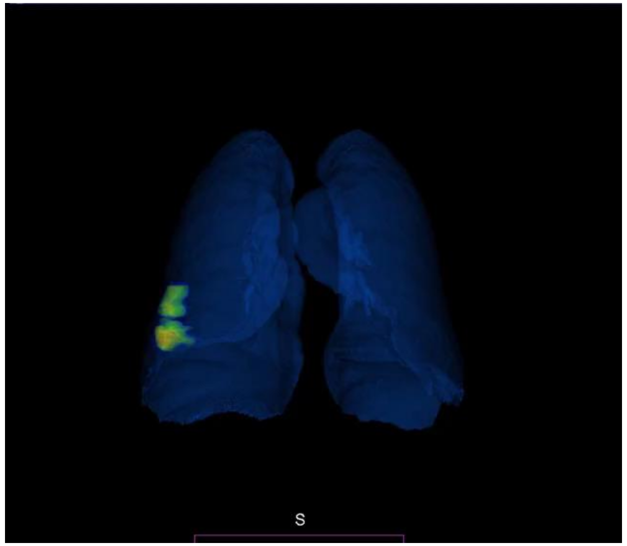
Medical Image Analysis

- **Applications**

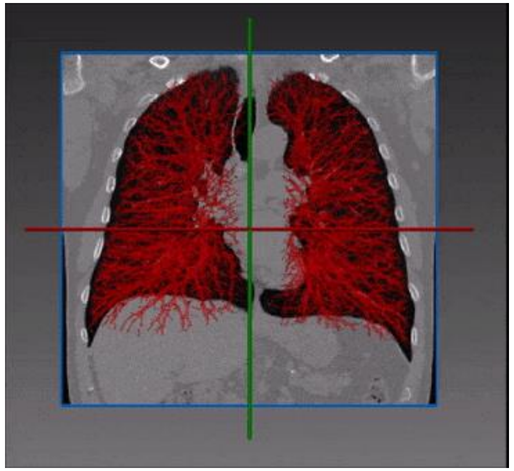
Disease screening and triaging;

Surgical planning and treatment;

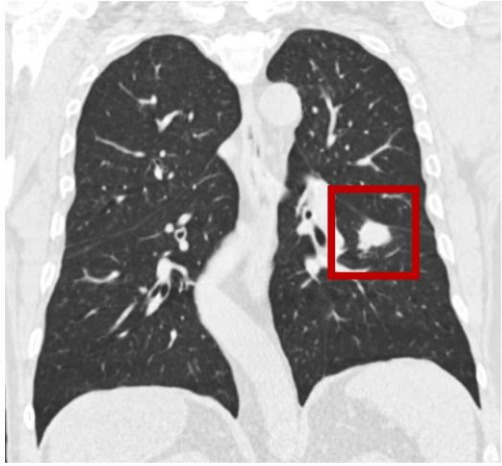
Measurements & visualization, etc.



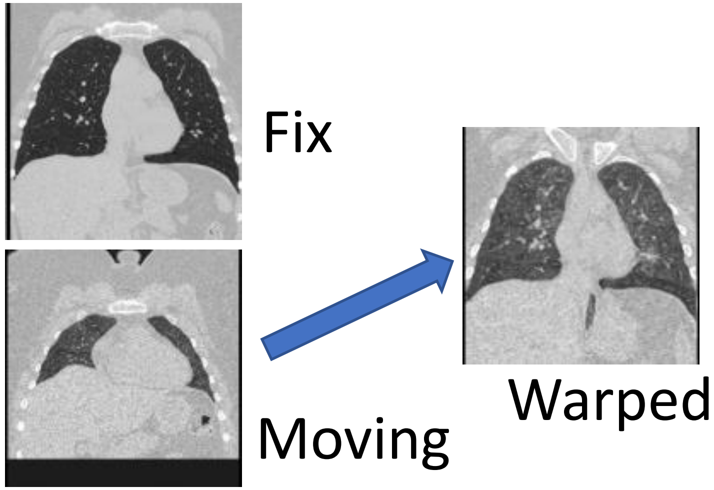
Longitudinal monitoring of Covid-19 patient



Vessel segmentation



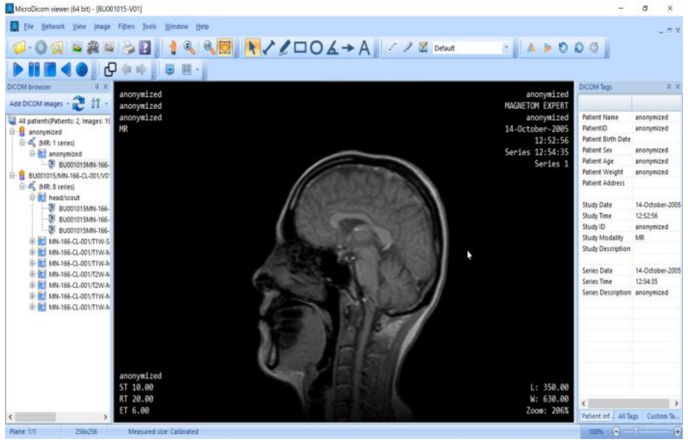
Lung nodule detection



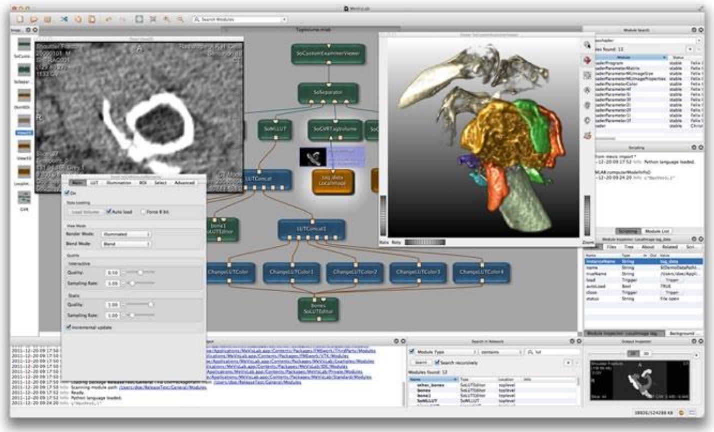
Lung registration

Medical Image Analysis Tools

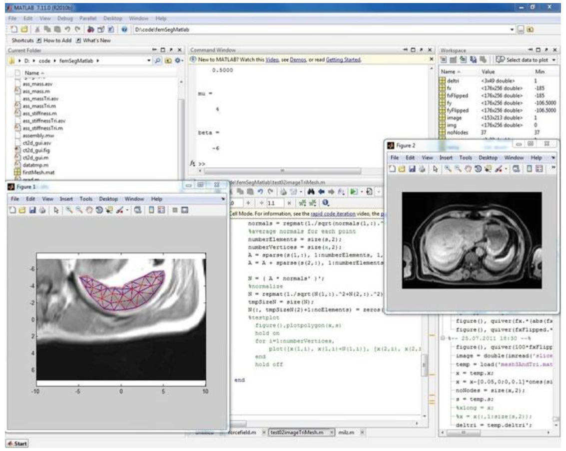
- **Different types of software greatly support speedy development**
  - Viewer software, e.g., MicroDicom viewer, ITK-SNAP.
  - Analysis software, e.g., MevisLab, 3D Slicer.
  - Rapid prototyping software , e.g., MATLAB, IDL.
  - Software libraries , e.g., OpenCV, ITK.
  - Deep learning libraries, e.g., Pytorch, Tensorflow.



MicroDicom viewer



MevisLab



MATLAB

http://www.idoimaging.com www.microdicom.com/

Examples

- **Deep learning in medical image analysis**


ORIGINAL RESEARCH • NEURORADIOLOGY

A Deep Learning Model to Pr
of Alzheimer Disease by Usin
the Brain

JAMA | Original Investigation

Diagnostic Assessment of
for Detection of Lymph N
in Women With Breast Ca

ARTICLES
https://doi.org/10.1038/s41591-018-0107-6

Clinically applicable dee
and referral in retinal di

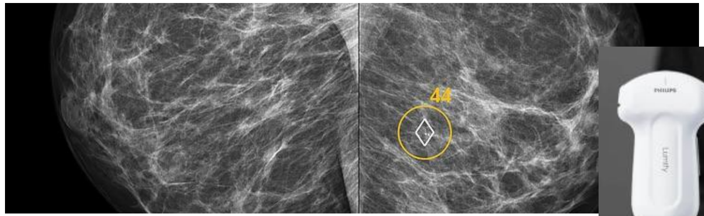
nature medicine

ARTICLES
https://doi.org/10.1038/s41591-019-0508-1

Clinical-grade computational pathology using weakly supervised deep learning on whole slide images

- **FDA approved DL-based products**

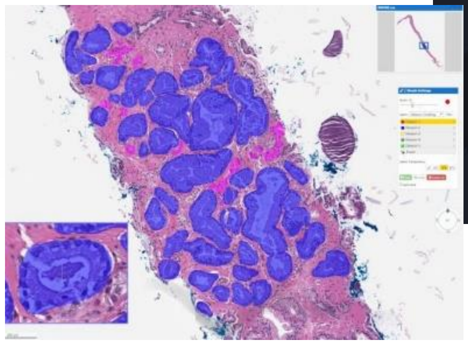
ScreenPoint Medical



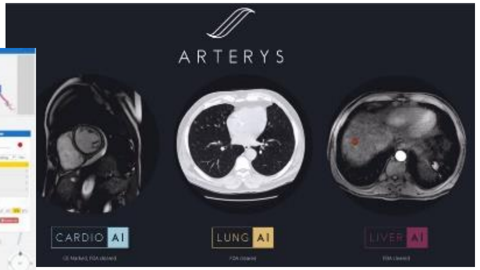
Mammogram

Ultrasound

Fundus



Pathology



CT & MRI

Introduction to Medical Image Analysis

- Background of Medical Image Analysis
- Medical Imaging Modalities

Medical Imaging

- **Anatomical**
  - X-Ray Radiography
  - X-Ray CT
  - MRI
  - Ultrasound
  - Optical
  - 3D Mesh from Stereo
  - Etc.

- **Functional/Metabolic**
  - SPECT
  - PET
  - fMRI, pMRI
  - Ultrasound
  - Optical Fluorescence
  - Electrical Impedance
  - Etc.

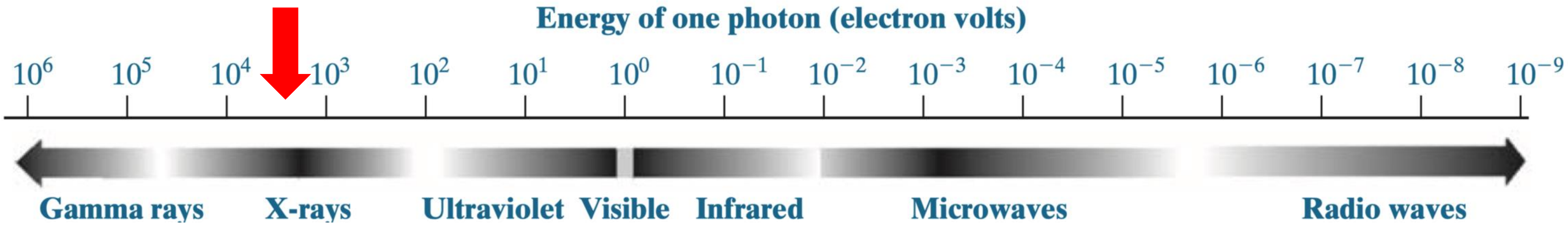
Medical Imaging

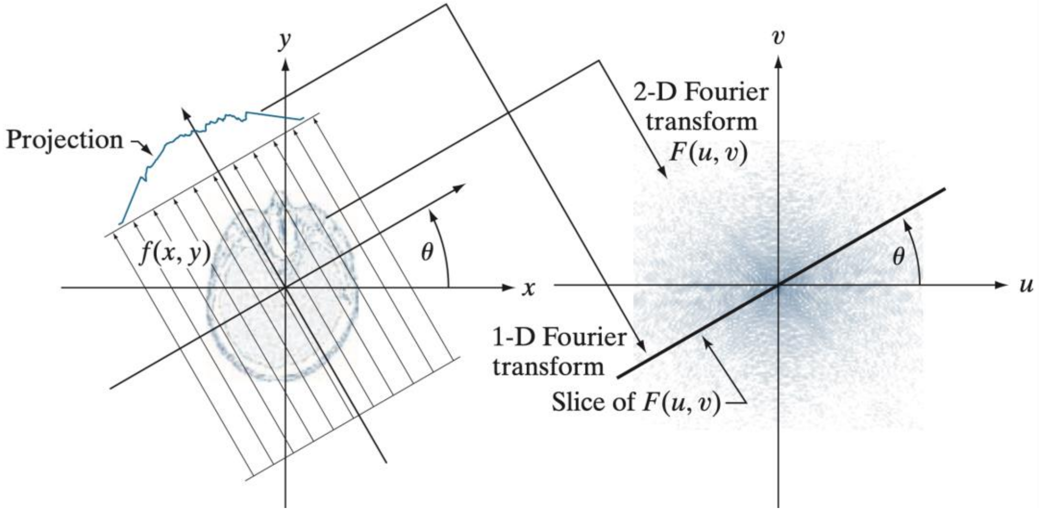
- **Major techniques**
  - **X-ray imaging** measures absorption of short-wave electromagnetic waves, which is known to vary among different tissues.
  - **Magnetic resonance imaging** measures density and molecular binding of selected atoms (most notably hydrogen which is abundant in the human body), which varies with tissue type, molecular composition, and functional status.
  - **Ultrasound imaging** captures reflections at boundaries between and within tissues with different acoustic impedance.
  - **Nuclear imaging** measures the distribution of radioactive tracer material administered to the subject through the blood flow. It measures function in the human body.

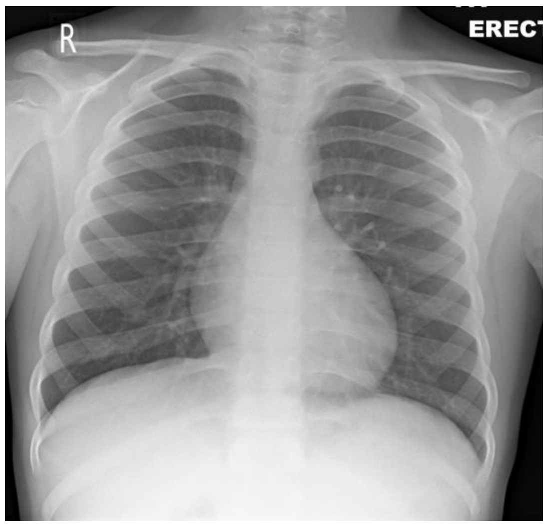
  …

X-ray Imaging

- Imaging of X-rays



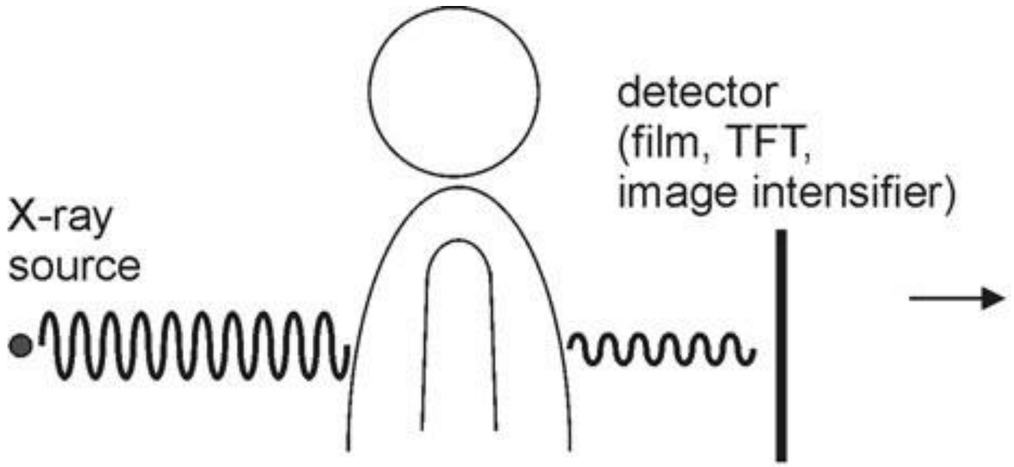


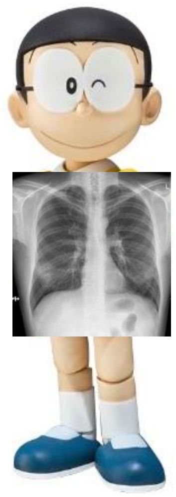


Digital Image Processing, by Gonzalez and Woods, Pearson, 2018.

X-ray Imaging

- X-rays have been discovered in 1895 by Wilhelm Röntgen (1901 Nobel Prize).
- A material-specific amount of the energy of an X-ray is attenuated when penetrating a material.

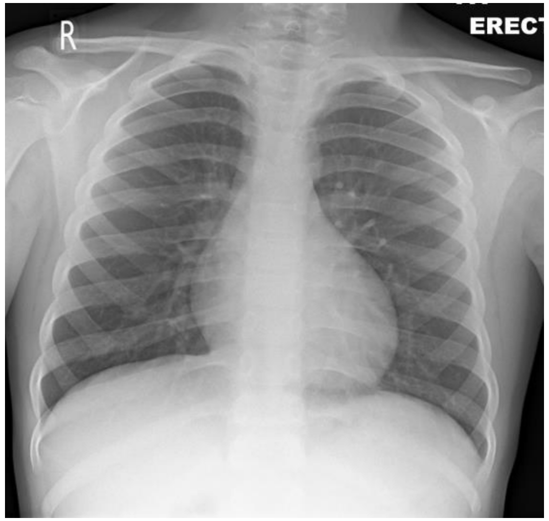




X-rays penetrate the human body and produce an image that shows the integral of tissue-specific absorption along a path from the X-ray source to a detector.

X-ray Imaging

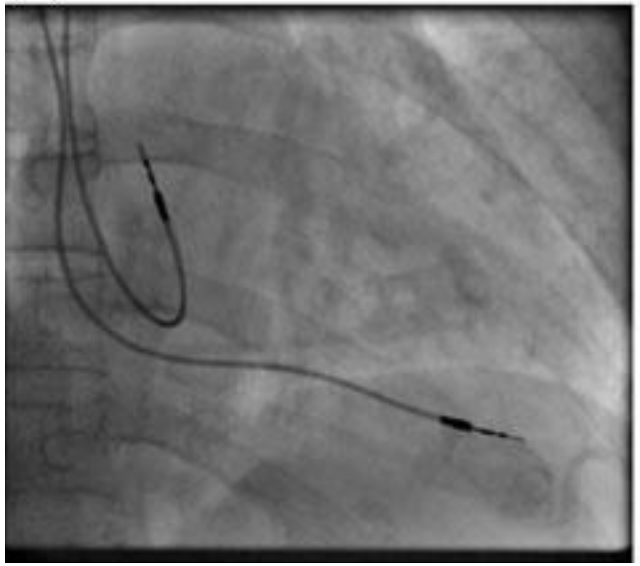
- X-ray radiographs are the simplest form of medical imaging via the transmission of X-rays through the body which are then collected on a film.
- The attenuation or absorption of X-rays is described by the photoelectric and Compton effects providing more attenuation through bones than soft tissues or air.



Fluoroscopy and Angiography

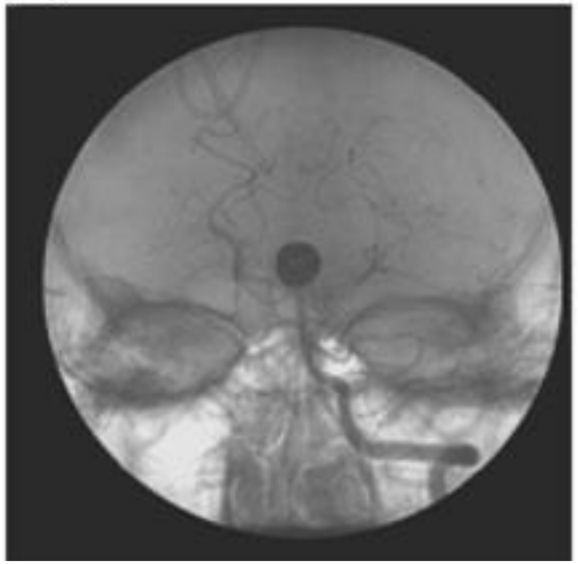
- Fluoroscopy is a specific kind of X-ray imaging to visualize moving or changing objects in the human body.

(a)



Fluoroscopy guiding pacemaker implanting

(b)



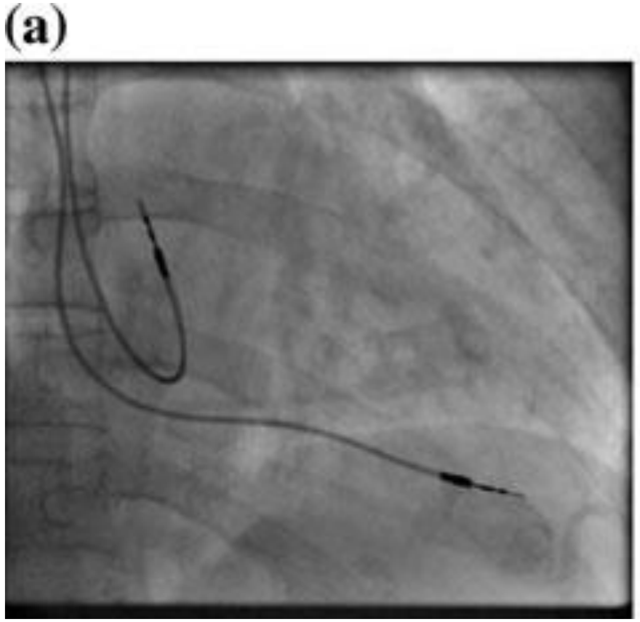
Angiogram of cranial vessels

(c)

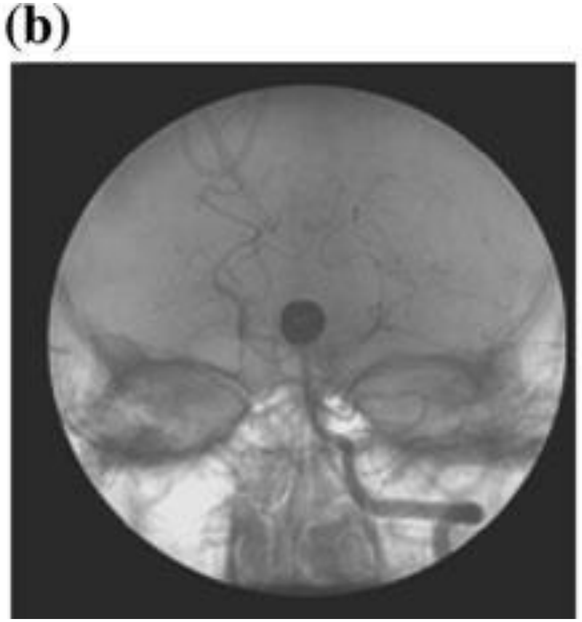
Digital subtraction Angiogram of (b)

Fluoroscopy and Angiography

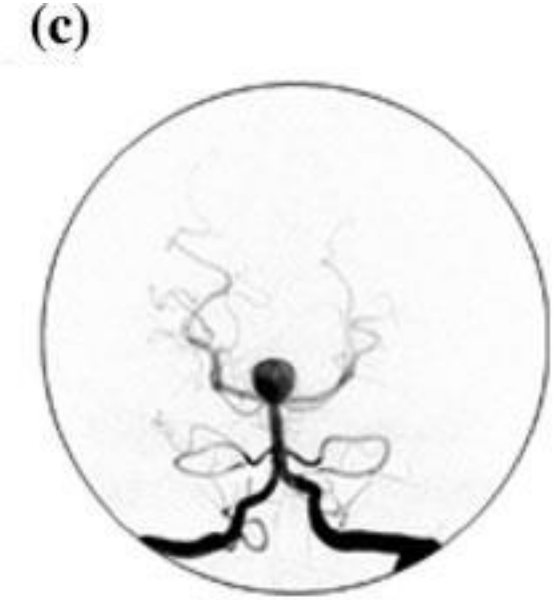
- Fluoroscopic imaging of the vascular system using a contrast agent is called angiography.



Fluoroscopy guiding pacemaker implanting



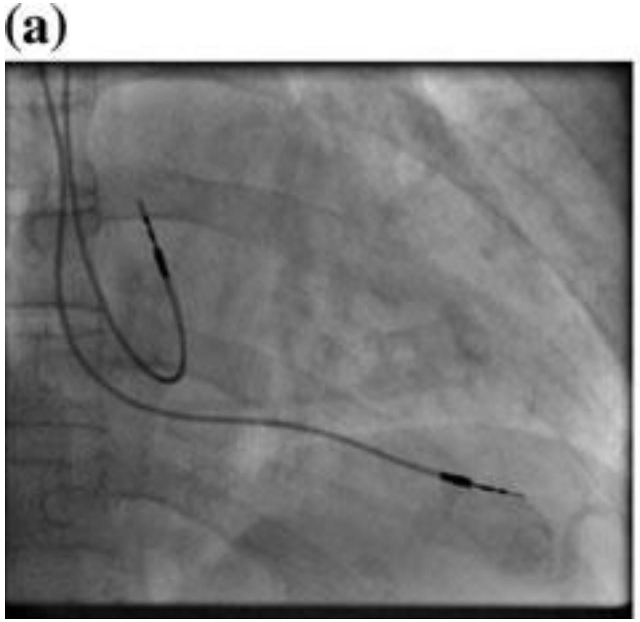
Angiogram of cranial vessels



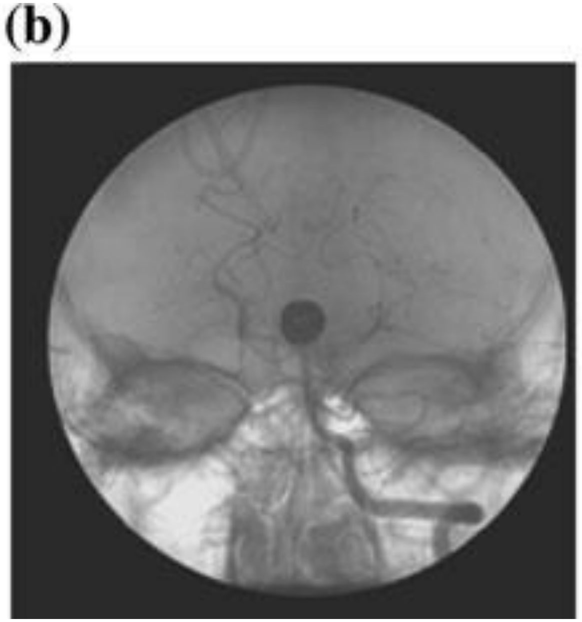
Digital subtraction Angiogram of (b)

Fluoroscopy and Angiography

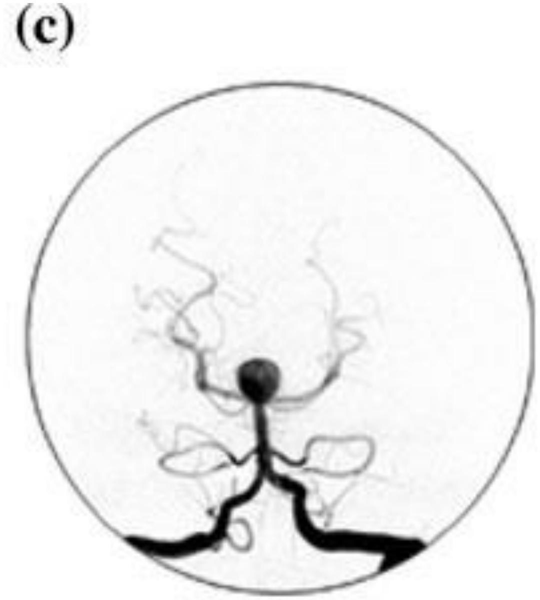
- Digital subtraction angiography (DSA) is a technique that anatomic information from all other structures can be removed.



Fluoroscopy guiding pacemaker implanting



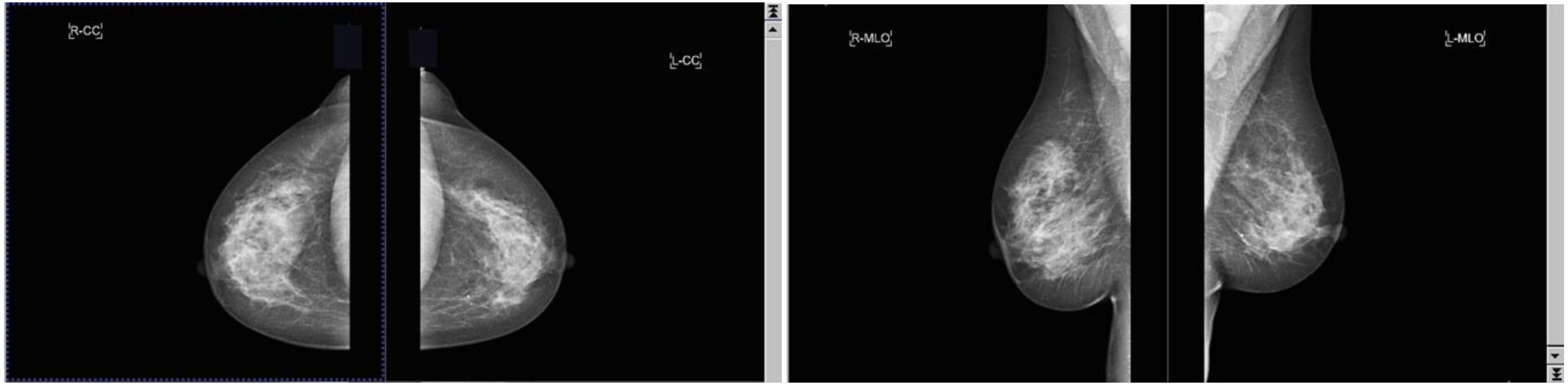
Angiogram of cranial vessels



Digital subtraction angiogram of (b)

Mammography

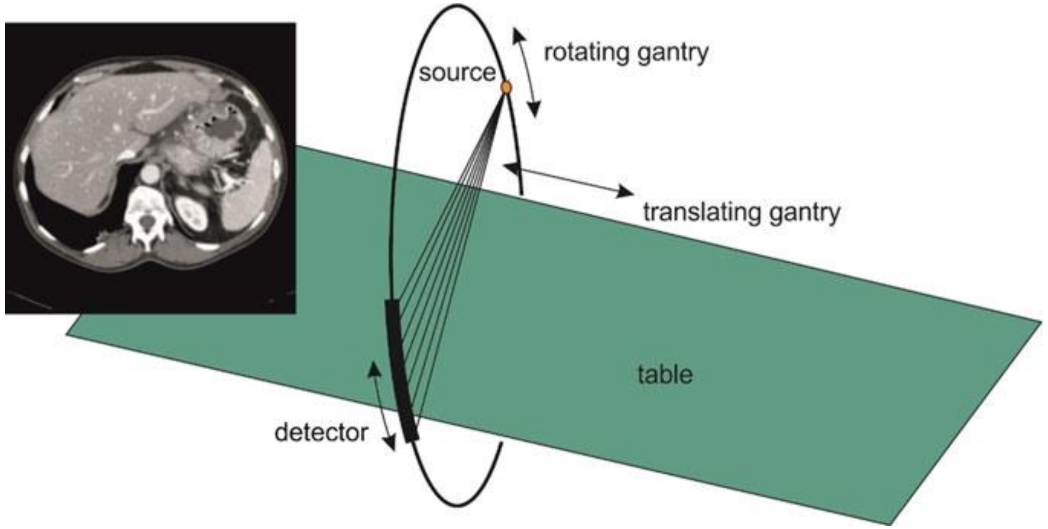
- The purpose of mammography is to detect small non-palpable lesions in the breast.
- This requires a much higher image quality than normal X-ray imaging with respect to contrast and spatial resolution.



Computed Tomography

- Radiography, in which a three-dimensional image of a body structure is reconstructed by computer from a series of plane cross-sectional images made along an axis, is also called computed axial tomography, or **computed tomography**.

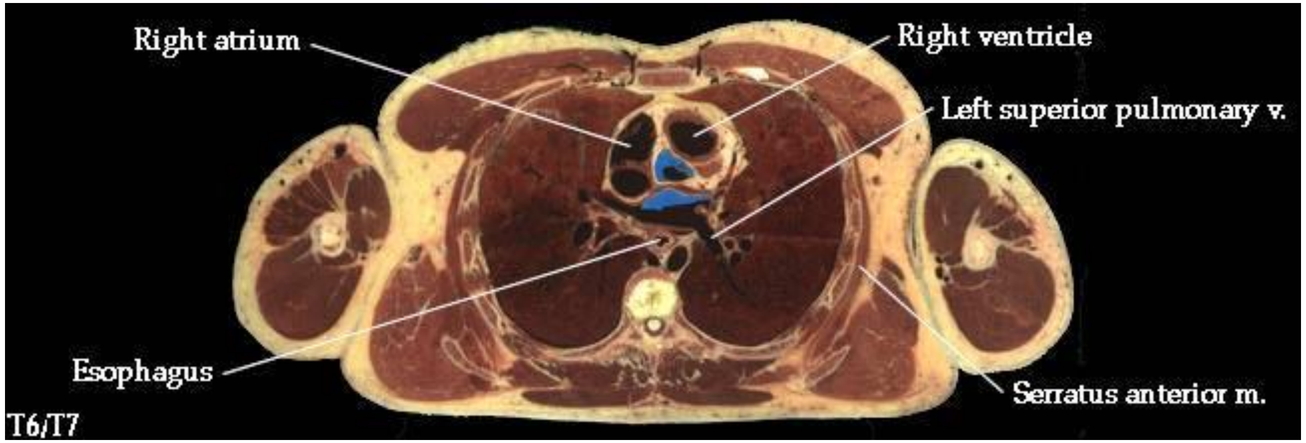
An X-ray CT scanner



Schematic view of CT image generation.

Computed Tomography

- CT Chest Images



Pathological image of a slice of the cardiac cavity of a cadaver.

X-ray CT image of the same slice.

Computed Tomography

- Hounsfield scale
  - Attenuation coefficients are normalized for making the result independent of imaging parameters such as beam energy. The scale is called Hounsfield scale. Normalization is based on the attenuation μ_{water} of water and μ_{air} of air:

$$\mathrm{HU}(\mu) = 1000 \times \frac{\mu - \mu_{\text{water}}}{\mu_{\text{water}} - \mu_{\text{air}}}$$

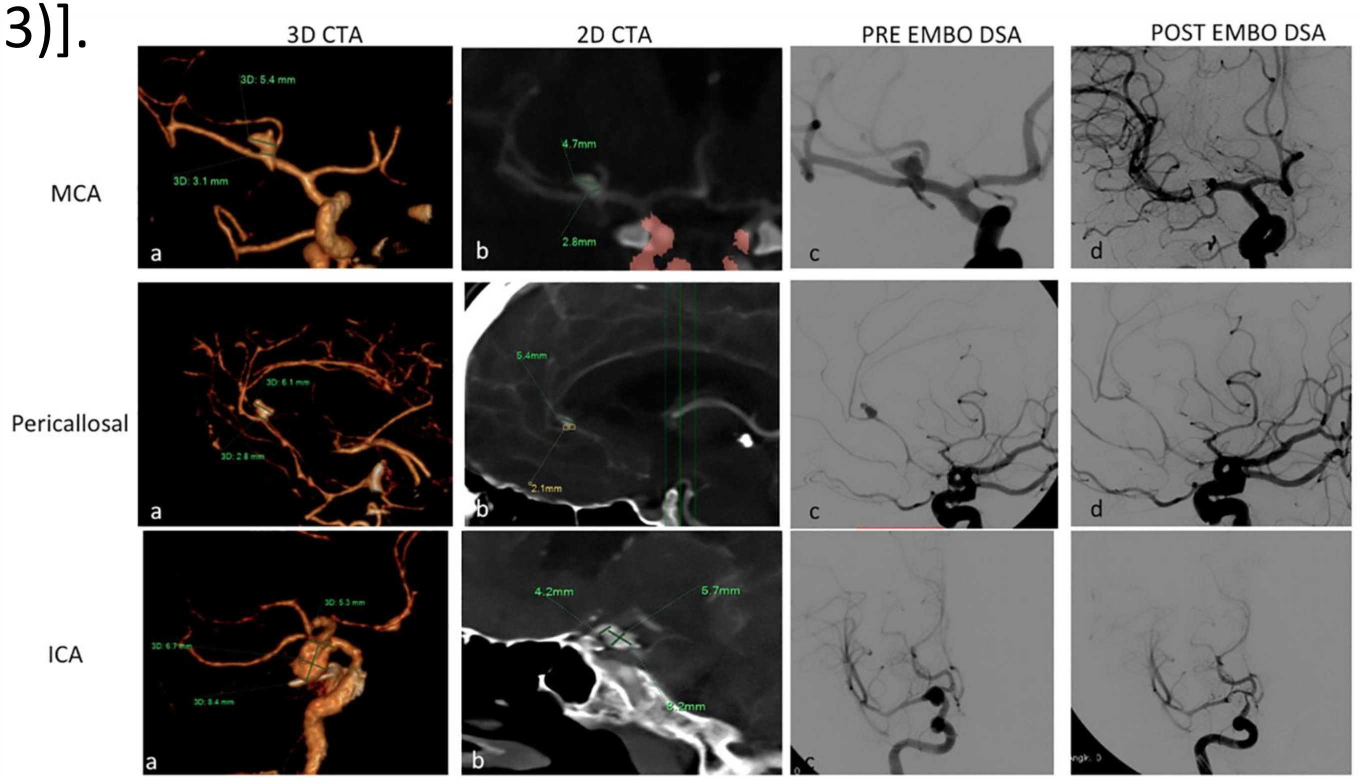
Hounsfield units of different tissues

Air	Fat	Water	Blood	Muscle	White matter	Gray matter	CSF	Bone
−1000	−100	0	30–45	40	20–30	37–45	15	>150

Note air, water, and bone are well differentiated, while contrast between different soft tissues is low

Computed Tomography

- Contrast Enhancement in X-ray Computed Tomography
  - A major application is the depiction of vessels [CT angiography or CTA, Dillon et al. (1993)].



Three different patients. 3D CTA (a), 2D CTA (b) reconstructions and DSA pre (c), and post (d) embolisation of a middle cerebral artery (MCA) bifurcation (1st row), pericallosal (2nd row) and ICA (3rd row) aneurysms.

Kapsalaki. Morphological characteristics of ruptured intracranial aneurysms: A comparative study between CTA and DSA. Hellenic Journal of Radiology, 2021.

Magnetic Resonance Imaging

- MRI is a non-invasive imaging technology that produces three dimensional detailed anatomical images.
- It is often used for disease detection, diagnosis, and treatment monitoring.
- It is based on sophisticated technology that excites and detects the change in the direction of the rotational axis of protons found in the water that makes up living tissues.

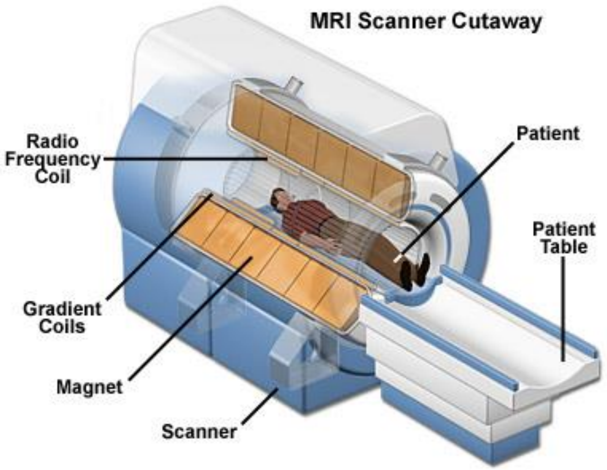
MRI scanner

MRI of a knee

https://www.nibib.nih.gov/science-education/science-topics/magnetic-resonance-imaging-mri

Magnetic Resonance Imaging

- The electromagnetic induction based RF signals are collected through nuclear magnetic resonance from the excited nuclei with magnetic moment and angular momentum present in the body. Most common is proton density imaging.

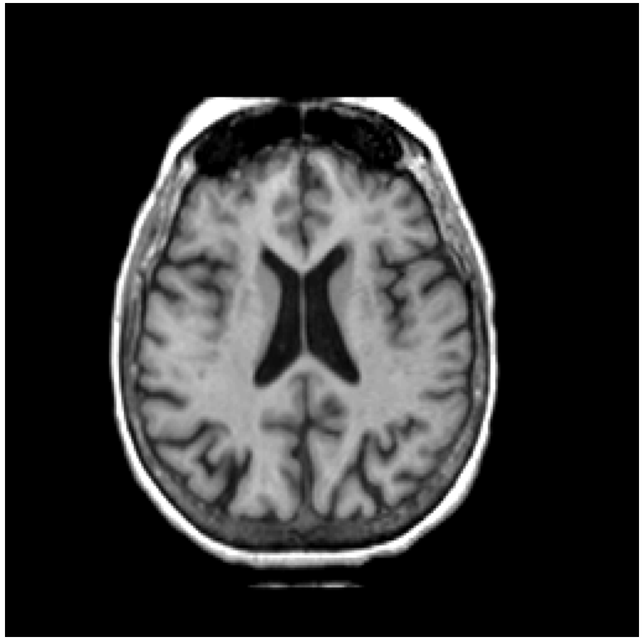


Magnetic resonance

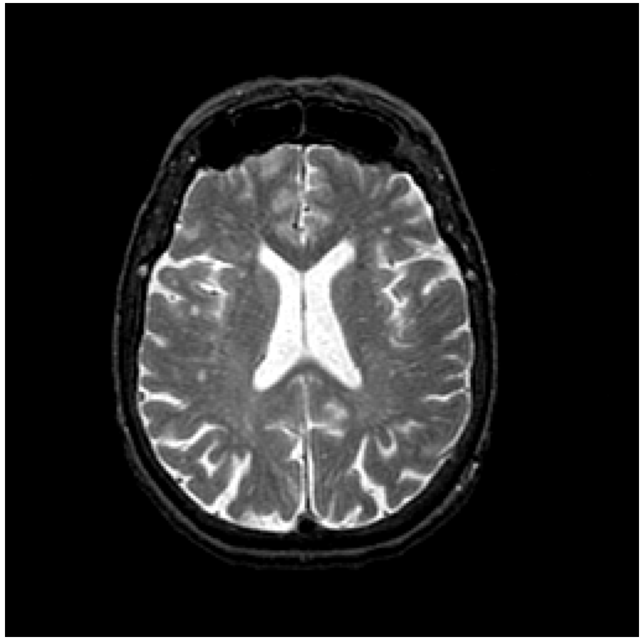
- MR Structural Imaging
- Flow Imaging
- Chemical Shift Imaging
- Spectroscopy
- Functional Imaging

Magnetic Resonance Imaging

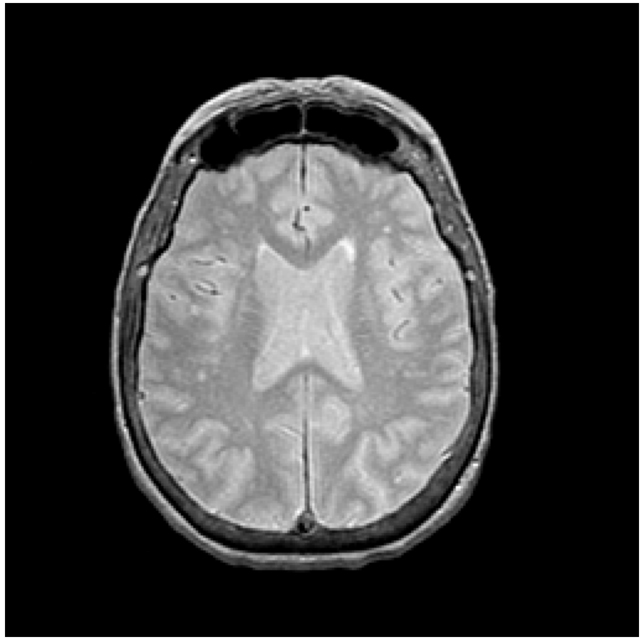
- Some examples of MR Images
  - MRI can provide **unprecedented contrasts** between various organs and tissues and the three-dimensional nature of imaging.



T1 Weighted



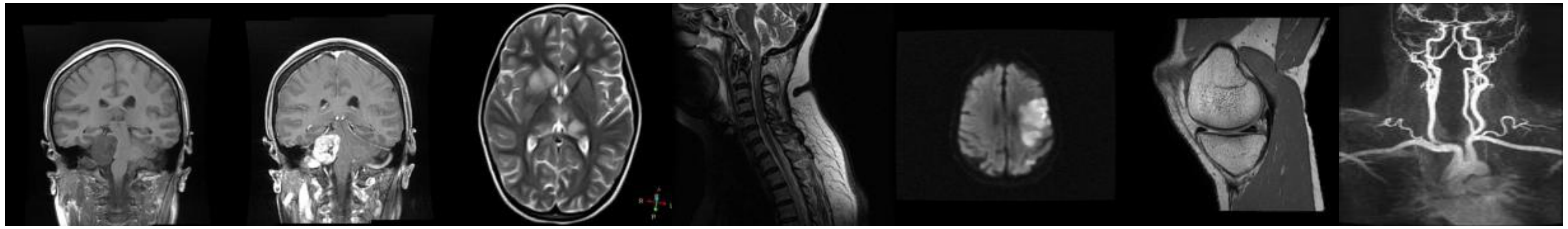
T2 Weighted



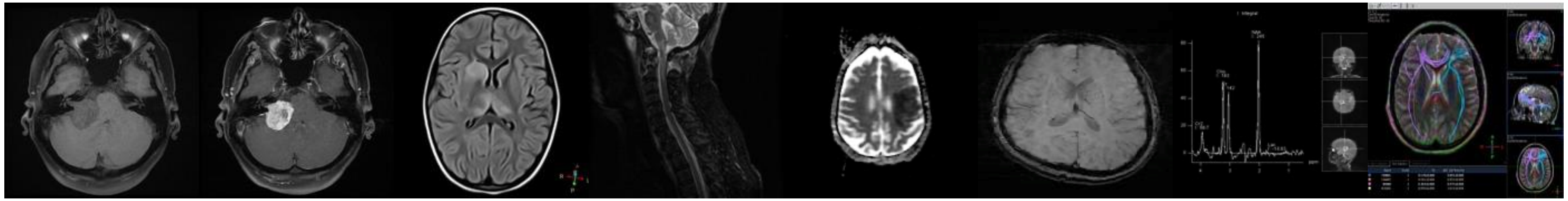
Spin Density Image

Magnetic Resonance Imaging

- Some MR Sequences
  - Three different parameters—spin density ρ, spin-lattice relaxation $\mathrm{T1}$, and spin–spin relaxation $\mathrm{T2}$ —determine the resonance signal.
  - Hence, different sequences can be developed for enhancing either of the parameters.



T1 T1 C+ T2 T2 DWI PD MRA

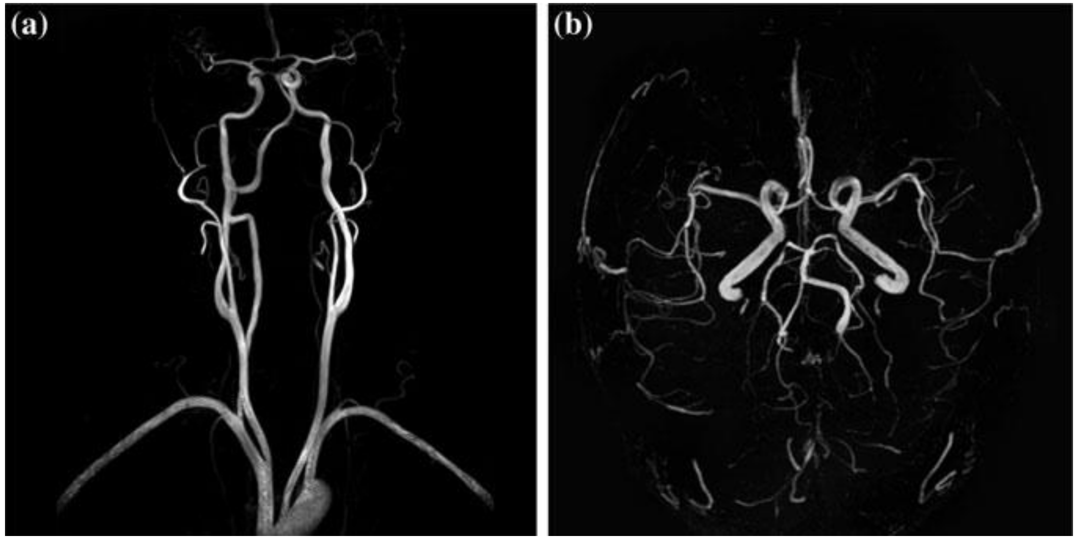


T1 fat sat T1 C+ fat sat FLAIR STIR ADC SWI MR spectroscopy MR Tractography

https://radiopaedia.org/articles/mri-sequences-overview

Magnetic Resonance Imaging

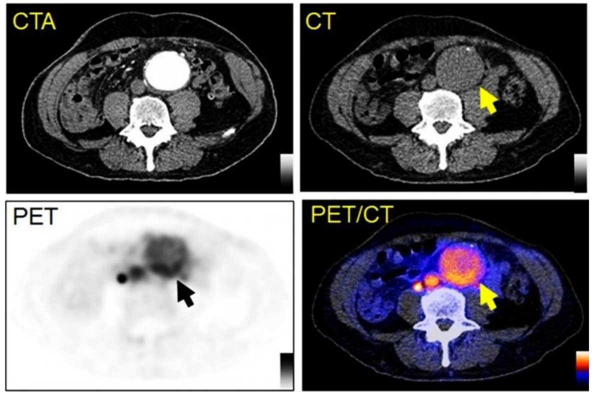
- **MR Angiography**
  - Contrast-enhanced angiography uses gadolinium, an agent that causes altering in the T1 relaxation time.
  - Phase contrast imaging is an MRI technique that can be used to visualize moving fluid. Spins that are moving in the same direction as a magnetic field gradient develop a phase shift that is proportional to the velocity of the spins.



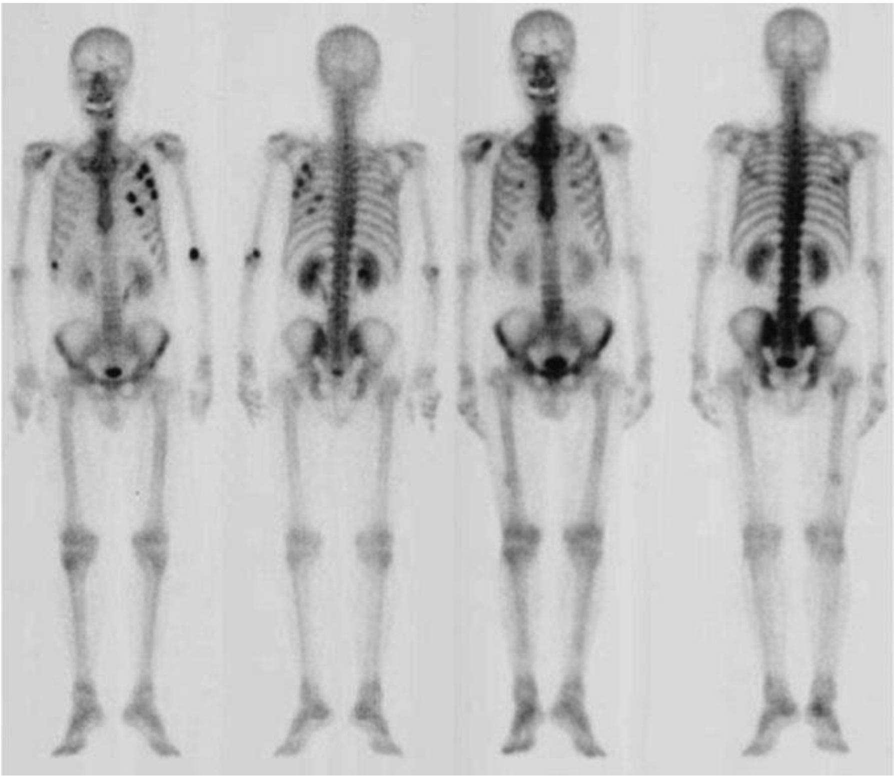
gadolinium-enhanced MRA   phase-contrast MRA

Nuclear Imaging

- Scintigraphy, which measures a projection of tracer distribution with a geometry similar to projection X-ray imaging.



64Cu-DOTA-ECL1i PET/CT image of a patient with an abdominal aortic aneurysm.

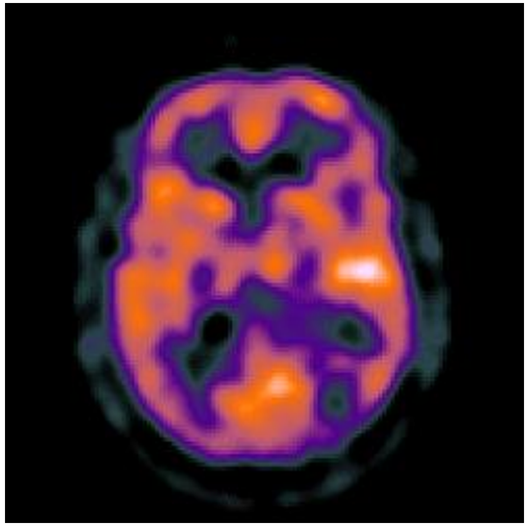


Bone scintigraphy

Mado et al. (2006)

Nuclear Imaging

- SPECT (Single Photon Emission Computed Tomography), which is a reconstruction from projections of tracer material producing a 3D material distribution.
- Radioactive materials are administered into the body and are selectively taken up in a manner designed to indicate a specific metabolism or disease.

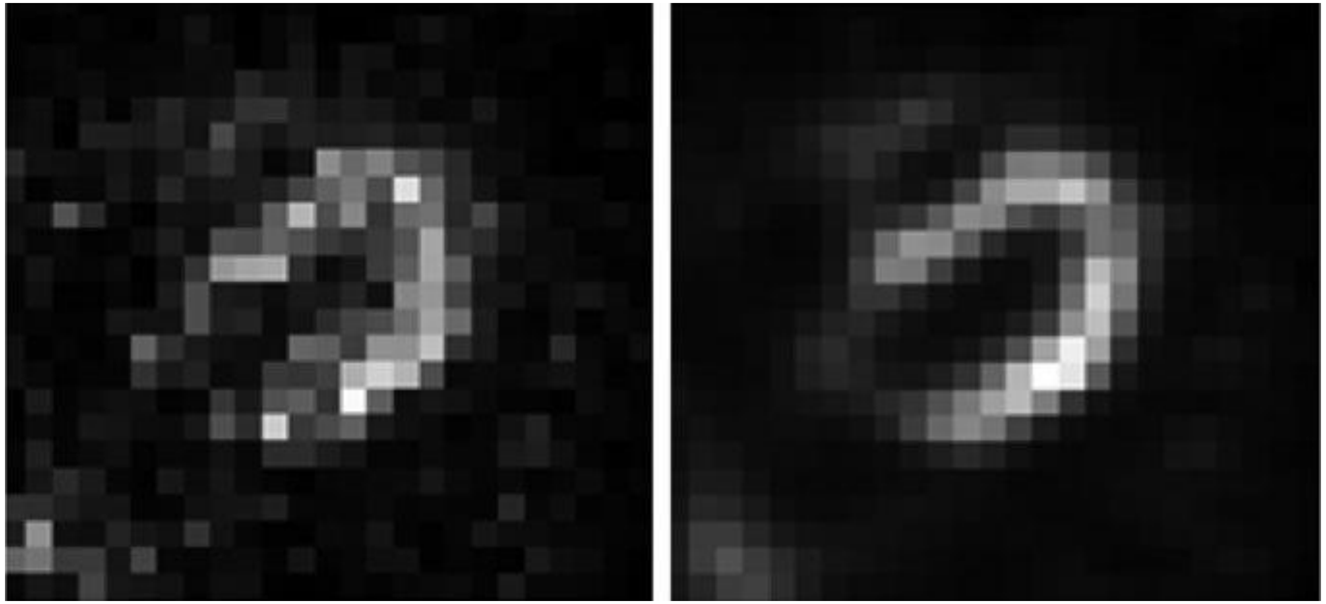


$^{99m}T_c$ (140 keV) SPECT Image

Nuclear Imaging

- In SPECT imaging, gamma rays are emitted from these materials absorbed by the tissue or body, which then becomes a radioactive source. External detectors are used to reconstruct images of the radioactive source.

Two-plane SPECT imaging system
used in cardiac imaging



SPECT image of the left ventricle,
reconstructed w/o and w/ attenuation correction.

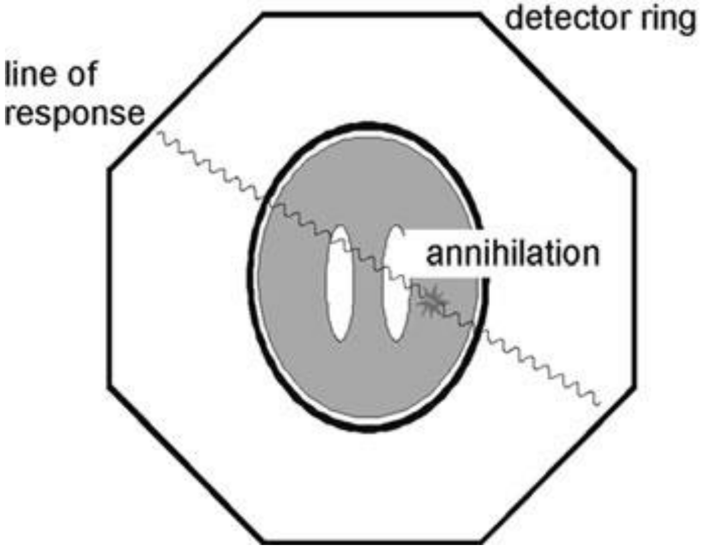
Anna Celler, Department of Radiology, University of British Columbia, Vancouver

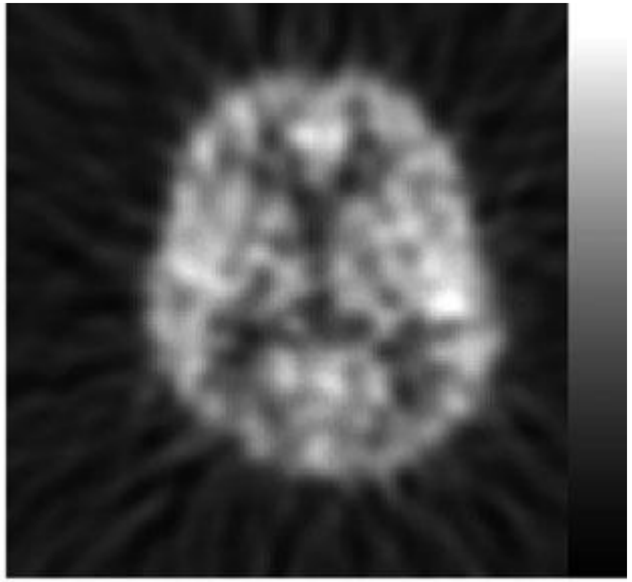
Nuclear Imaging

- PET (Positron Emission Tomography), which is a tomographic technique as well but uses different tracer materials that produce positrons.
- In PET imaging, the radioactive pharmaceuticals which decay by emitting positrons are administered into the body.
- When these radioactive materials are taken up by the body, positrons are emitted which, after losing some energy through kinetic motion, annihilates with the free electrons of the biomaterial within the body.
- The annihilation results in the emission of two photons, which travel in almost opposite directions and escape from the body to be detected by external detectors. This is called the coincidence detection.

Nuclear Imaging

- Radiation of positron–electron annihilation is measured and reconstructed.





Schematic view of a PET scanner (left) and resulting image of measured activity in the brain

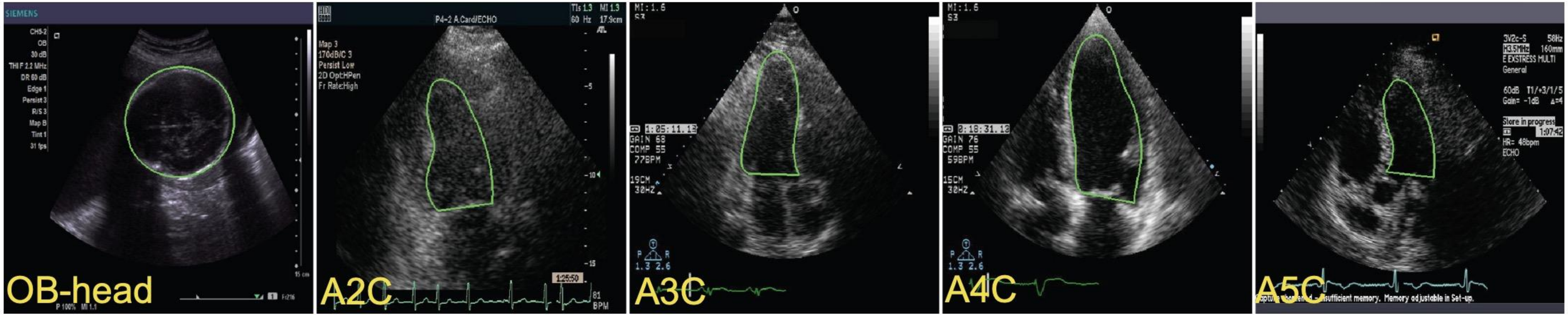
Ultrasound Imaging

- **Ultrasound**
  - An ultrasound reflection signal is created using a transducer which acts as sender and receiver of ultrasound waves.


Ultrasound equipment

Ultrasound Imaging

- An ultrasound *A-scan* sends a single wave with known direction into the body and records the amplitude of reflections as a function of travel time between sending and receiving the signal.
- Ultrasound (US) images (so-called B-scans) are created from a planar fan beam of differently rotated A-scans.

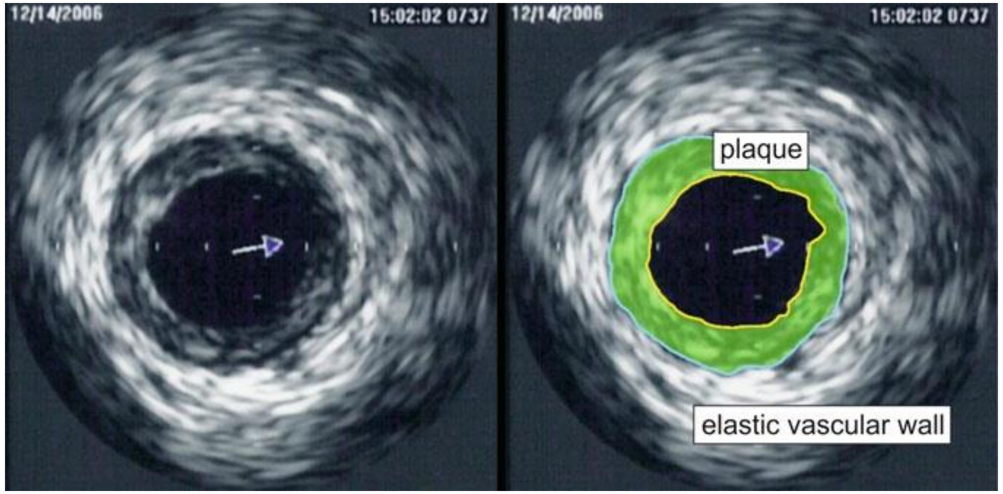


Examples of ultrasound images

Chen, et al. Anatomical Structure Detection and Segmentation from Ultrasound Images. MICCAI 2016.

Ultrasound Imaging

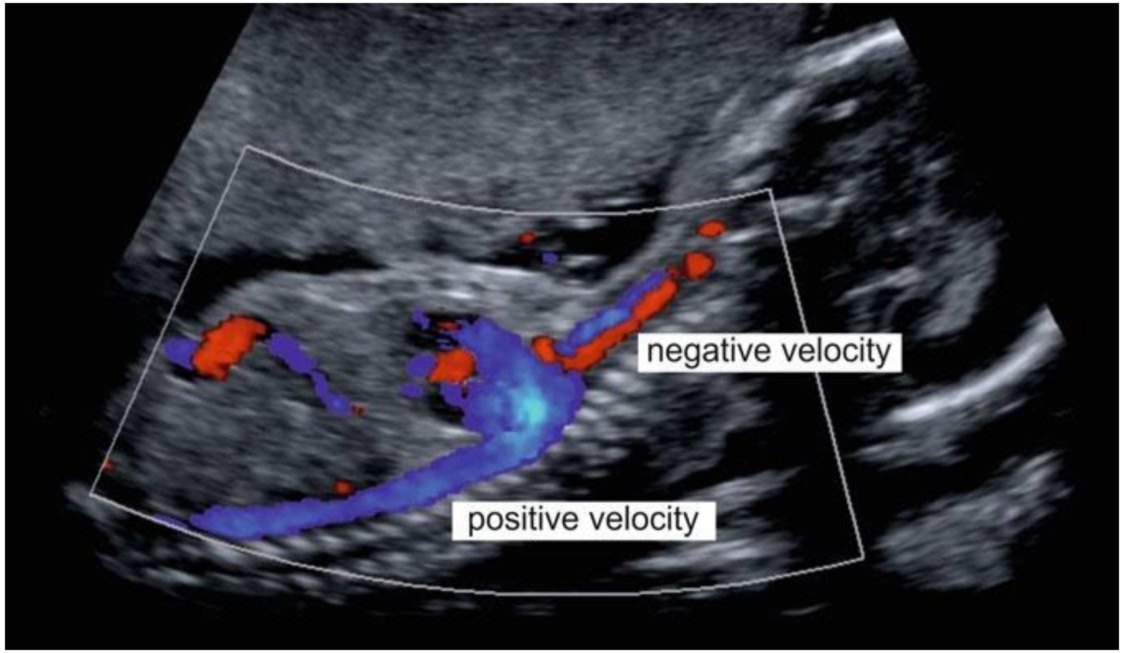
- Ultrasound imaging (also called *sonography*) happens in real time and is able to show motion of the organs being imaged.
- Ultrasound imaging of internal organs is only possible if they are not hidden by bone, since bone causes total reflection of incident sound waves.
- In ultrasound imaging, air causes excessive attenuation and therefore cannot be used to study some anatomical structures, such as lungs.



Intravascular ultrasound image of the carotid artery

Ultrasound Imaging

- Doppler imaging is a specific technique using the Doppler effect for estimating the speed and direction of moving objects (such as blood) in the ultrasound image.

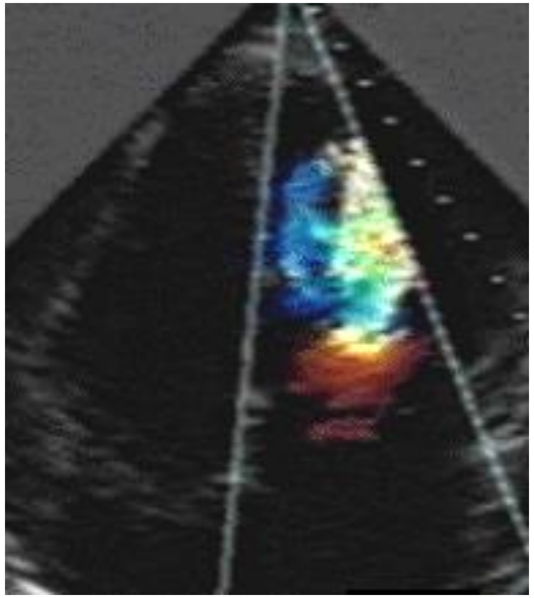


Doppler sonography uses the Doppler effect to depict blood velocity

Ultrasound Imaging

- The main advantage of ultrasound imaging is its **non-invasive** nature and capability of providing excellent information for imaging objects **immersed in fluids**.

B-Mode Imaging of Heart

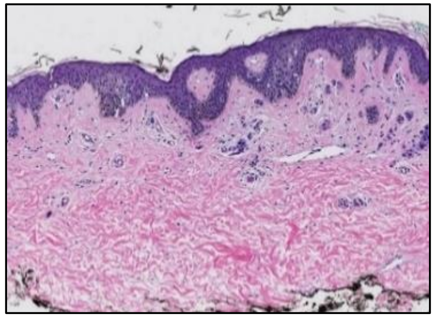


Doppler Imaging of Beating Heart

Microscopy Imaging

Optical Microscopy

- Optical microscopes can analyze living structures of sizes larger than approximately 200 nm.
- After an image from a machine shows possible cancer, physicians perform a biopsy.
- Pathologists look at the biopsy, traditionally on a slide under a microscope.
- Microscopic images can be used for cell counting, shape analysis of cells, and differentiation of tumors.



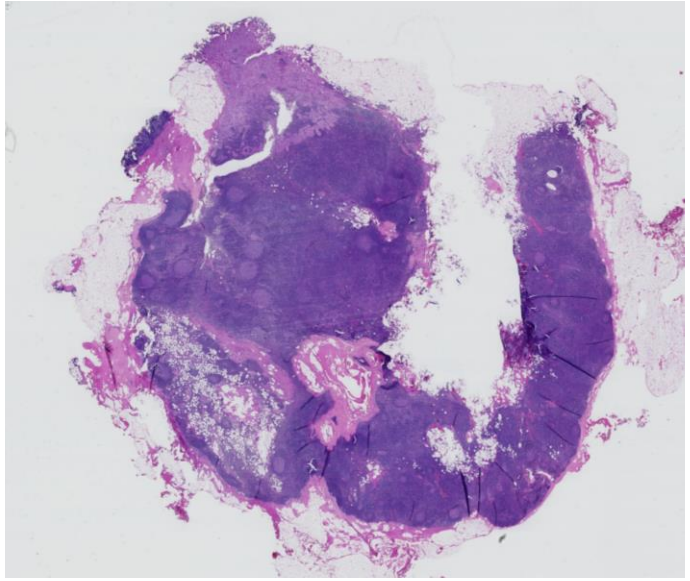
Microscopy Imaging

Digital Pathology

- Philips obtained FDA approval in 2017 for use of whole slide digital images, beginning a new era for pathologists.

Microscope

Digital pathology scanner

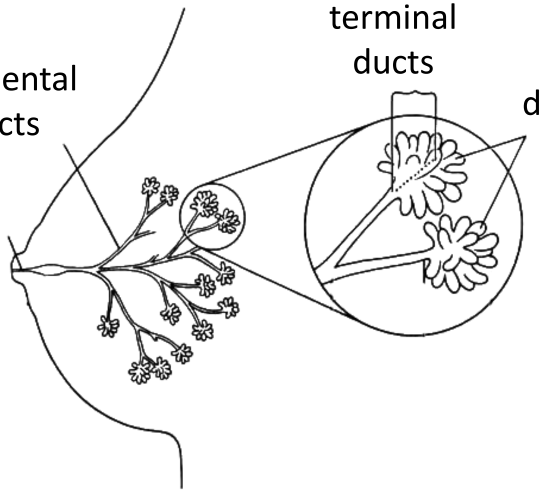


Examples of whole sliding images (WSI)

Microscopy Imaging

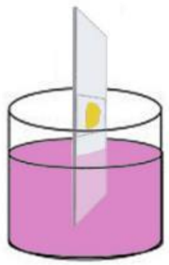
Digital Pathology

- Medical diagnosis of cancer.



female breast

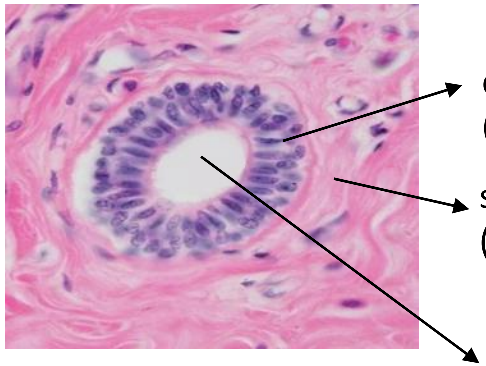
tissue specimen



H&E staining

glass slide

whole slide imaging

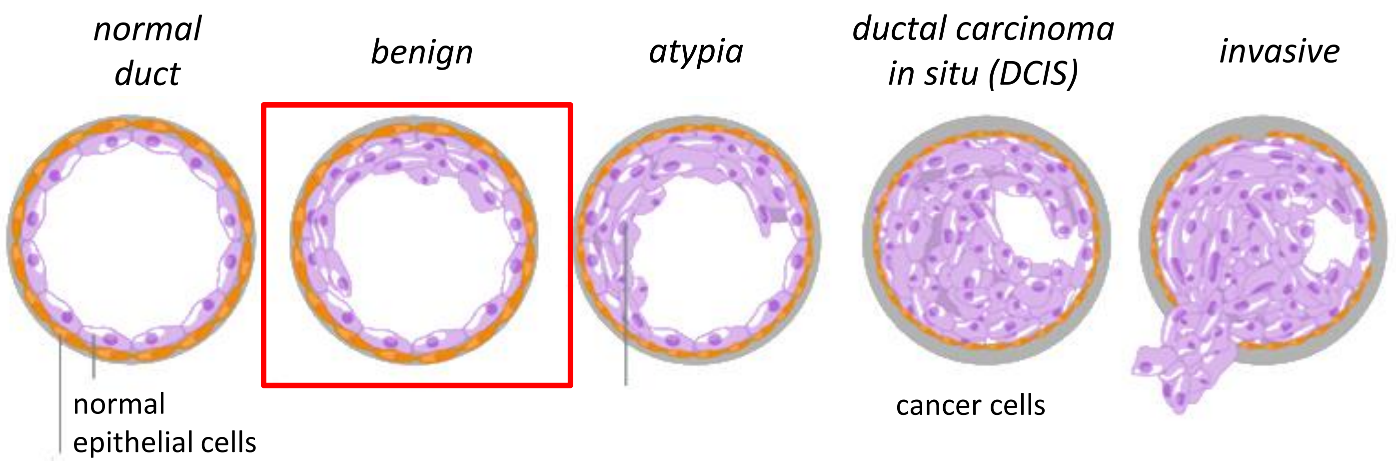


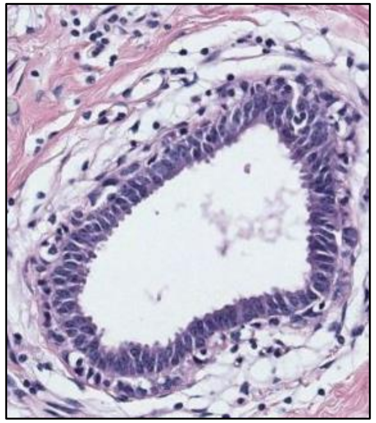
a duct

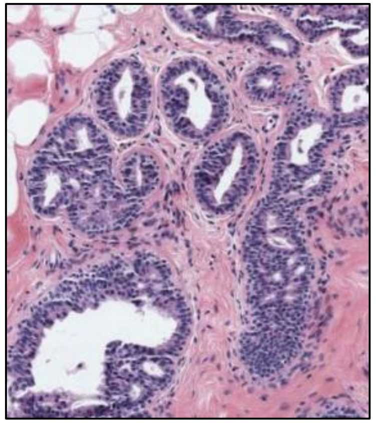
Microscopy Imaging

Digital Pathology

- Breast histopathology




columnar cell change

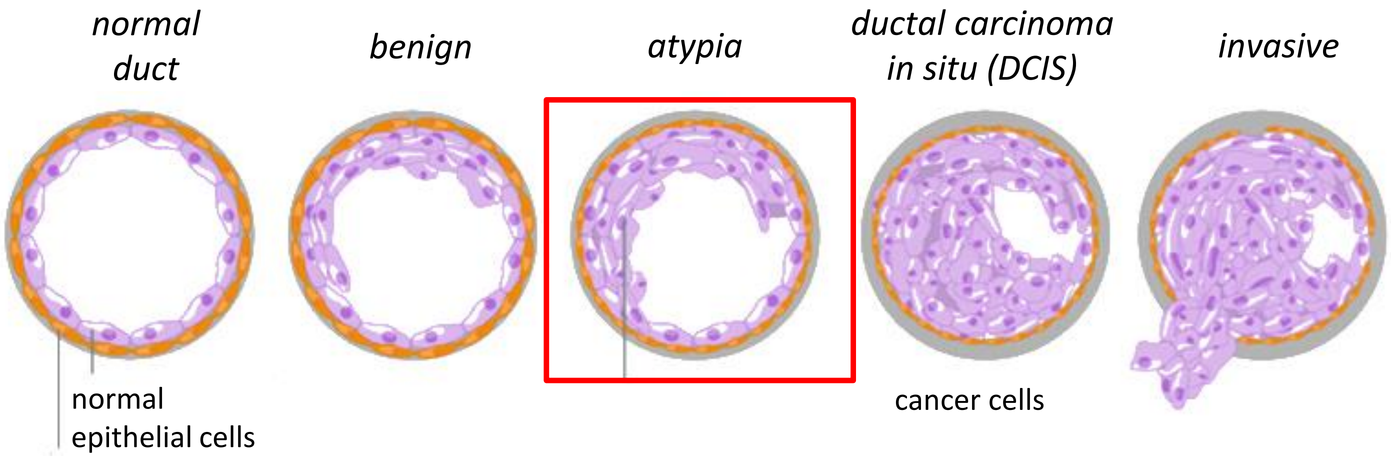

usual ductal hyperplasia

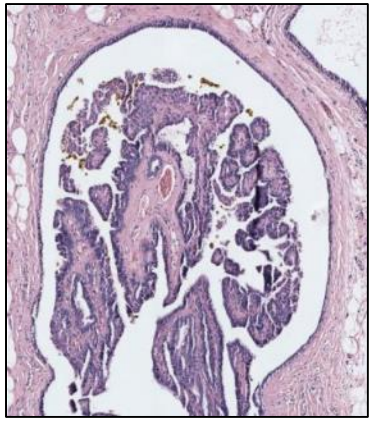

intraductal papilloma

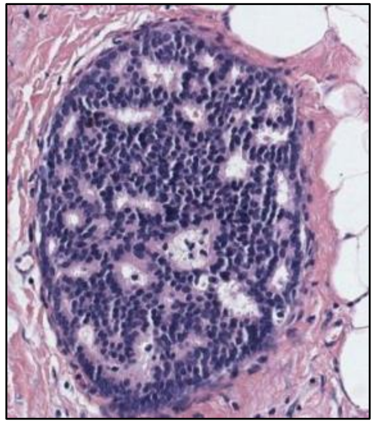
Microscopy Imaging

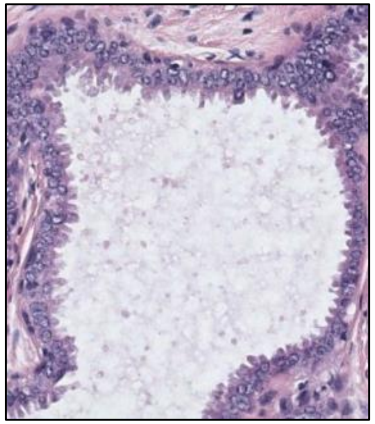
Digital Pathology

- Breast histopathology




papilloma w/atypia

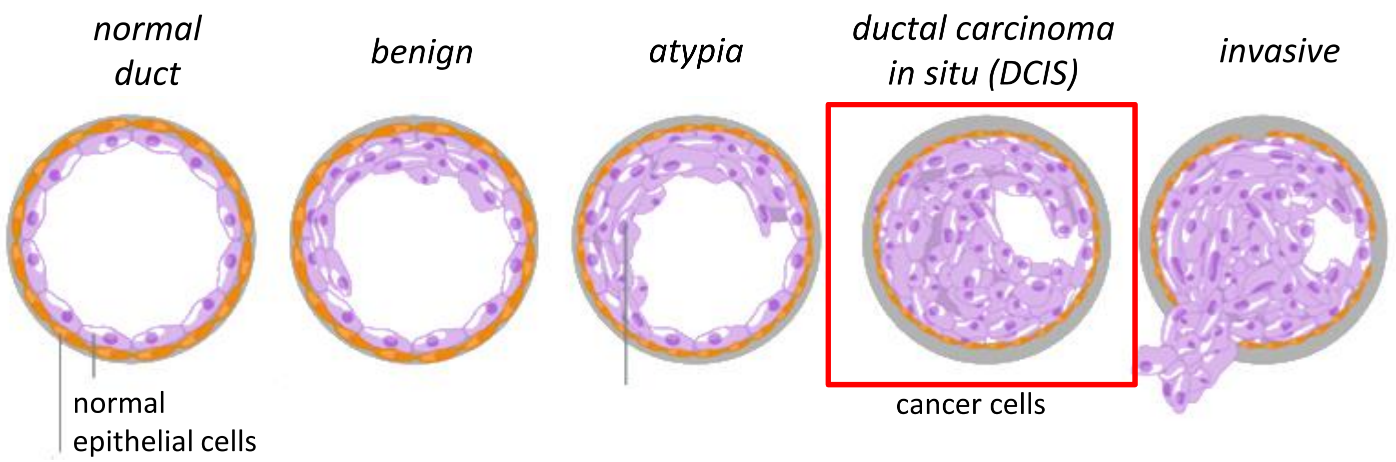

atypical ductal hyperplasia

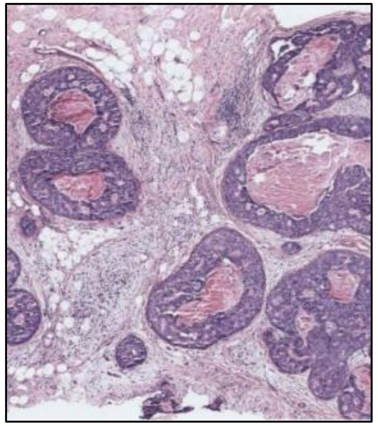

flat epithelial atypia

Microscopy Imaging

Digital Pathology

- Breast histopathology



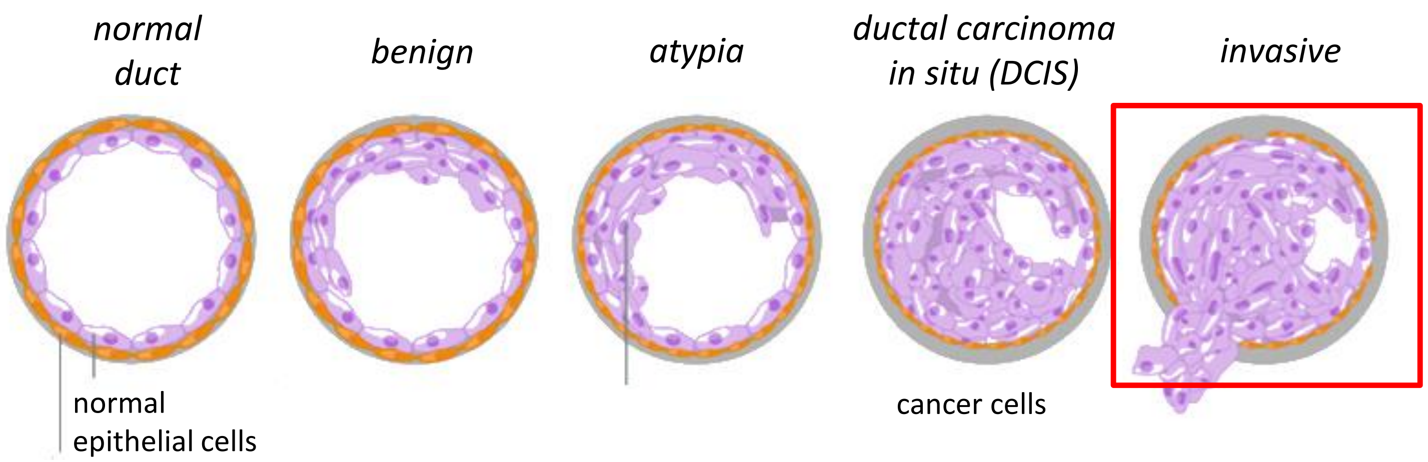


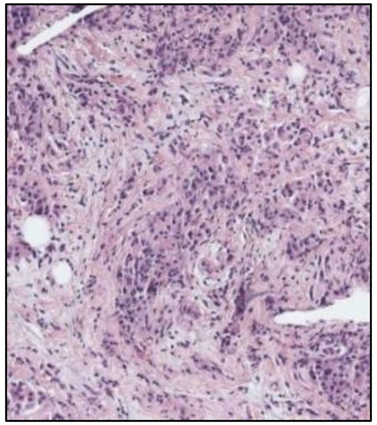
ductal carcinoma in situ (DCIS)

Microscopy Imaging

Digital Pathology

- Breast histopathology





invasive carcinoma

Microscopy Imaging

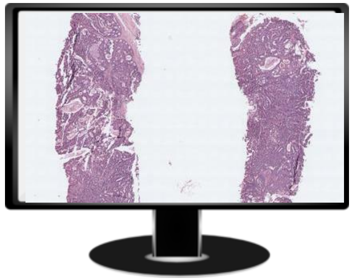
Digital Pathology

- Labelling

pathologist
(n=87)

age
years in practice
cases per week
affiliation
lab size
education
pathology perception

assessment
(n=5,220)



participant ROI*
participant diagnosis
viewport log

confidence score
difficulty score
borderline diagnoses

diagnostic outcome

ROI identification*
diagnostic agreement
efficiency

case
(n=240)

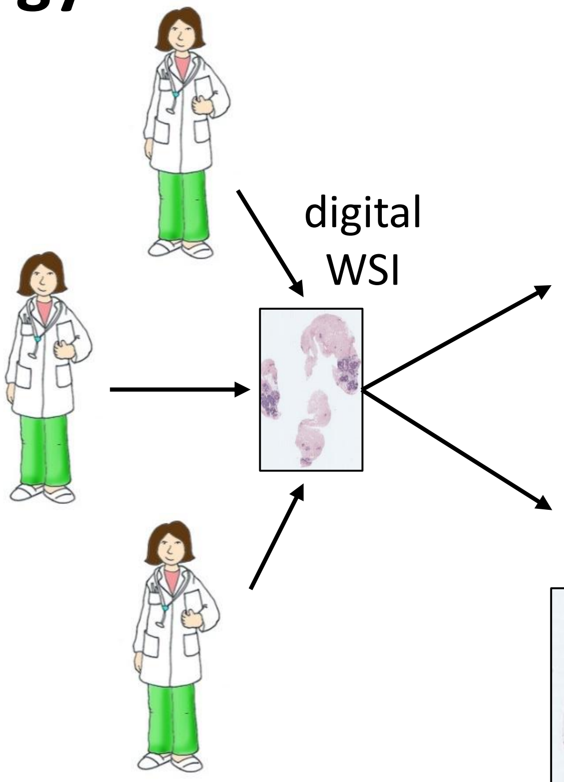
digital WSI
consensus ROI
consensus diagnosis

biopsy type
breast density
patient age

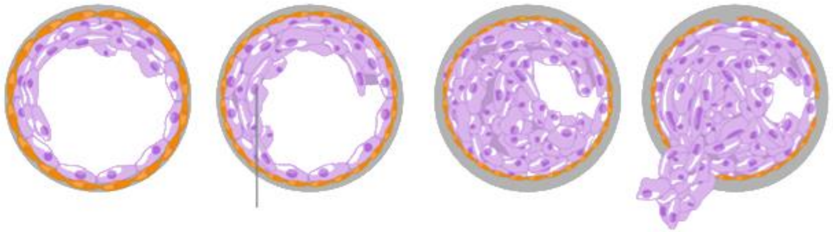
Microscopy Imaging

Digital Pathology

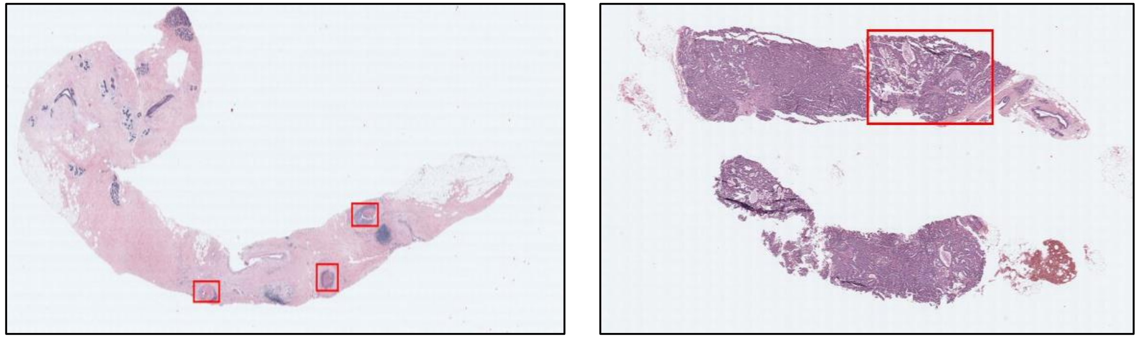
- Labelling



3 world experts



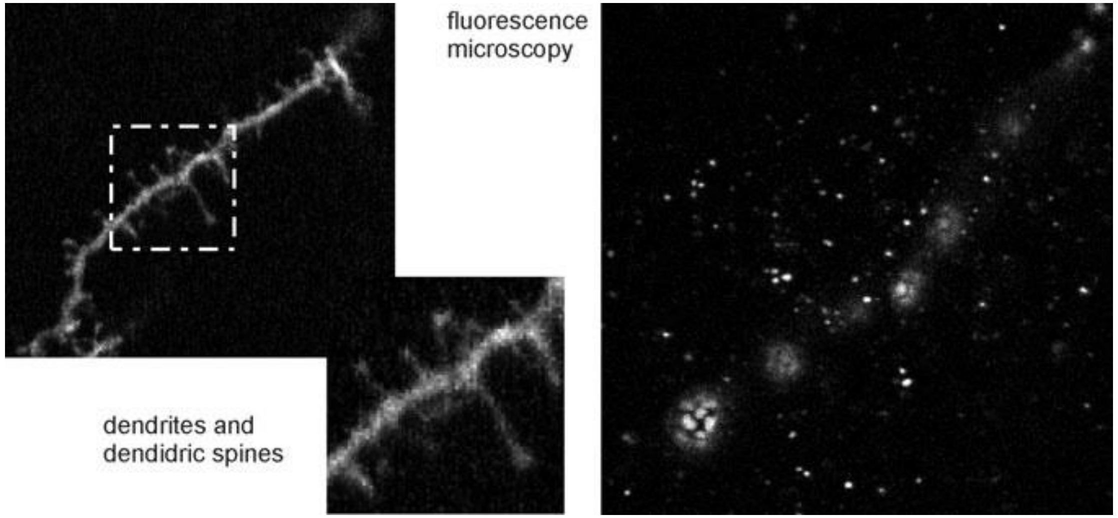
Consensus Diagnosis	*benign*	*atypia*	*(DCIS)*	*invasive*
# Cases	*60*	*80*	*78*	*22*
Consensus ROIs	*102*	*128*	*162*	*36*



Microscopy Imaging

Fluorescence Microscopy

- Instead of using reflection and absorption, the signal is generated by the fluorescence response of the living material to incident laser light.



Dendritic spine (left) and fluorescence microscopy (right) of the synapses of drosophila larvae

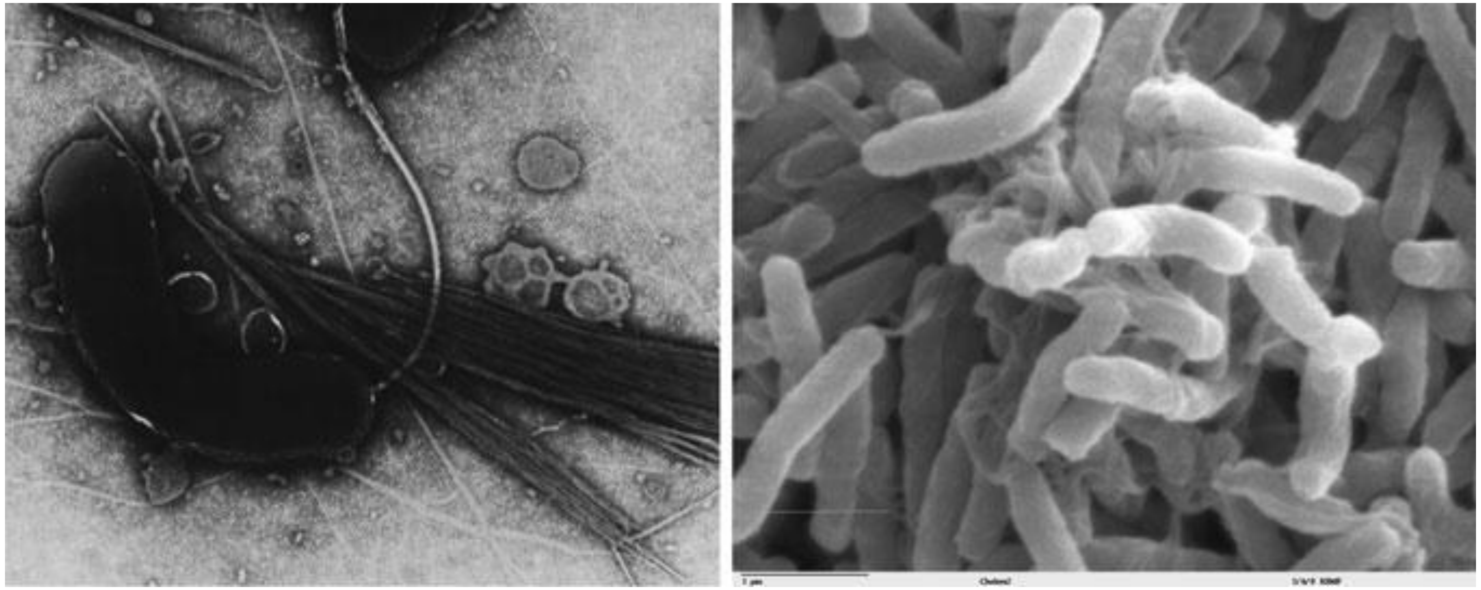
Fluorescence microscopy

Bachmann et al. (2004)
https://www.leica-microsystems.com/solutions/life-science/fluorescence/

Microscopy Imaging

Electron Microscopy

- Electron microscopy uses the detection of electrons instead of light for image acquisition.

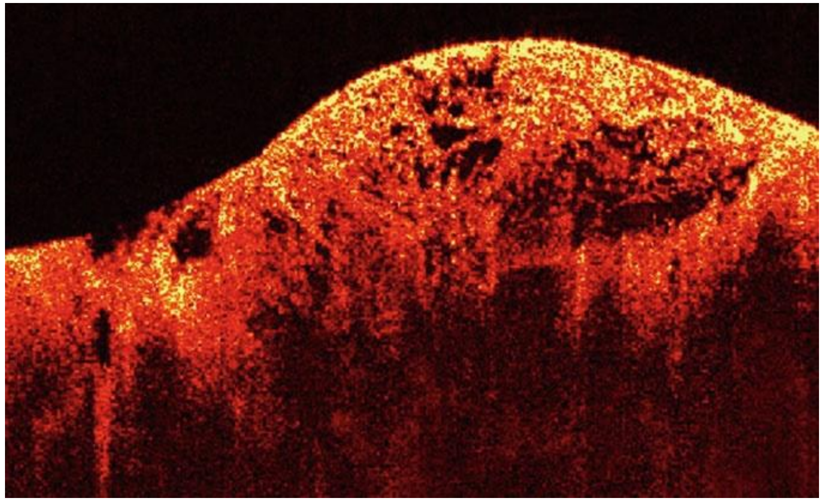


Transmission (left) and scanning (right) electron microscopies of cholera bacteria.

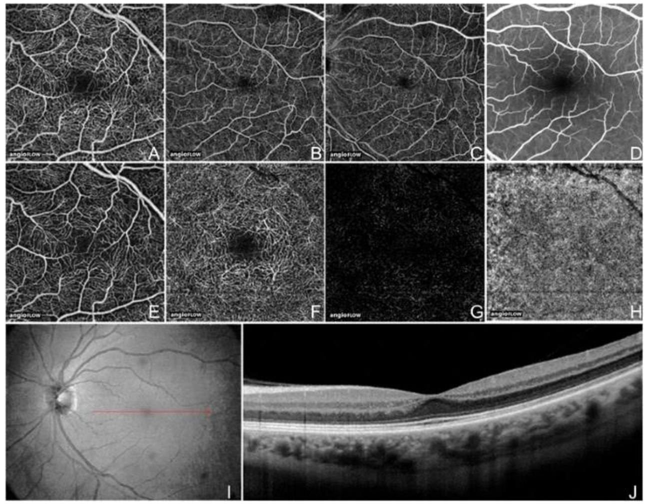
Dartmouth Electron Microscope Facility, Dartmouth College

Other Imaging Modalities

- Optical Coherence Tomography (OCT)
  - A light wave is sent into the probe, and reflections in the tissue are measured.
  - OCT can perform high-resolution cross-sectional imaging and analysis of structural changes in the eye during disease progression.
  - One of the main applications of OCT is ophthalmology.



OCT of a muscle tumor

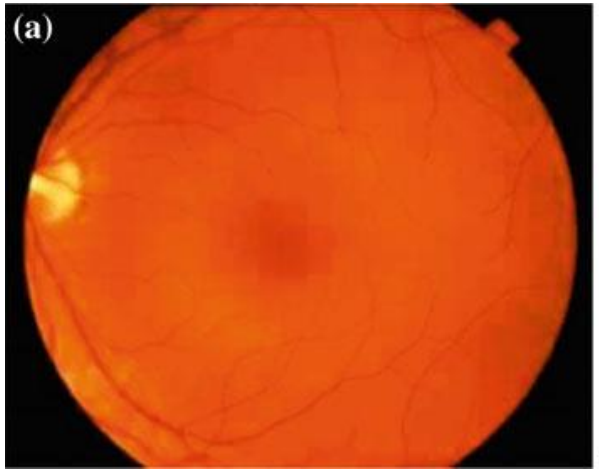


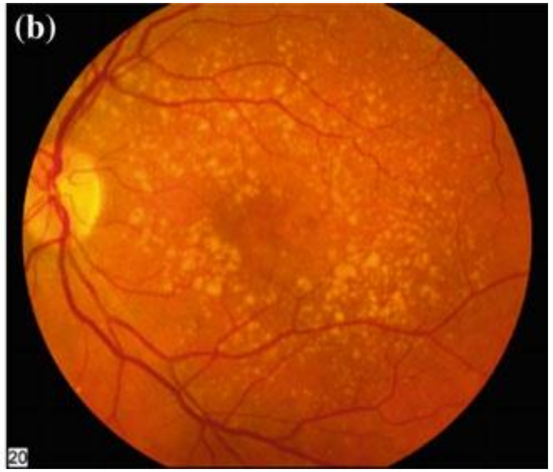
OCT Angiogram Fields of View and Segmentation Layers on Angiovue.

Image courtesy of Dr. Stephen Boppart, University of Illinois at Urbana-Champaign

Other Imaging Modalities

- Photography
  - Retina photography (a) ad (b)
  - Diagnosis and staging of skin tumor (c) or burn scars (d)





National Eye Institute http://www.nei.nih.goy
https://en.wikipedia.org/wiki/Scar

Other Imaging Modalities

- 3D Mesh: Allows for 3D head images of young children since the image acquisition is very fast.

3dMD 12-Camera Stereo System

3D Mesh from 3dMD

Trends and Challenges

- There are multiple imaging modalities, each with its own characteristics.

Which imaging modality should doctors choose?

- New medical imaging modalities are keeping developed, e.g., function-related oncology imaging, portable device, etc.

- Large-scale medical imaging data lies in the IT storage system of hospitals. How to wake them up and mine their values?

- Deep learning enables powerful analytical tools by leveraging the big medical imaging data.

Summary

- Background of MIA
- Medical Imaging Modalities
  - X-ray Imaging
  - Magnetic Resonance Imaging (MRI)
  - Nuclear Imaging
  - Ultrasound Imaging
  - Microscopy Imaging
  - Other Imaging Modalities
- Trends and Challenges