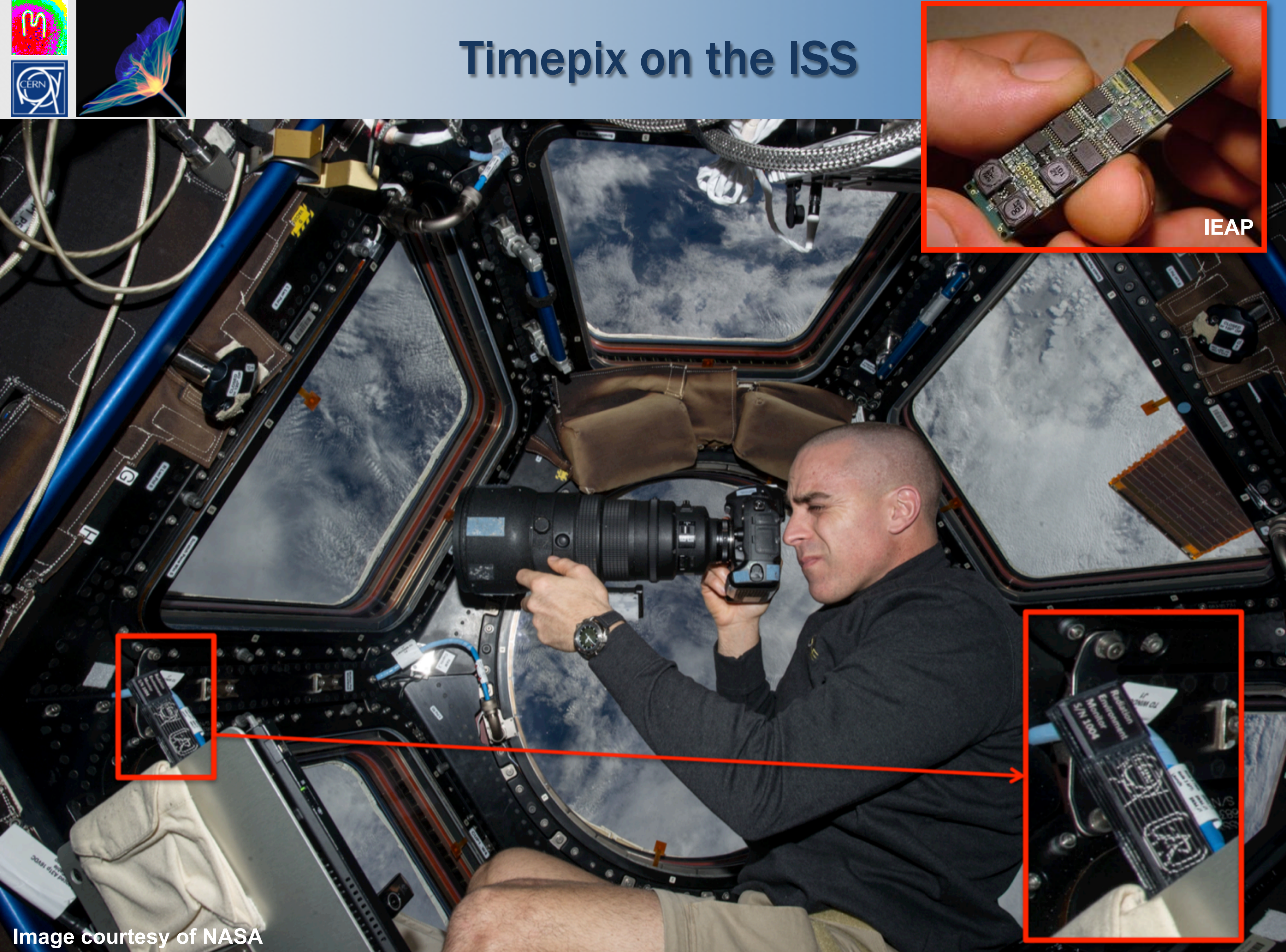
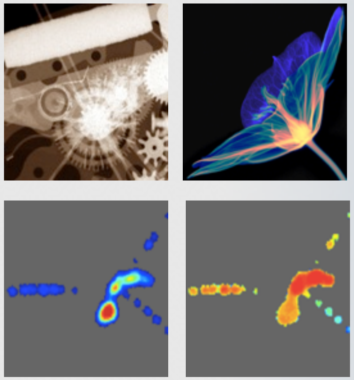

FITPix
Medipix/Timepix USB2.0 Interface
Patent pending
0354 v.2.3


IC1
MEDIPIX PROBE CARD
EP 680-1131-650-A
FITPix
Medipix/Timepix USB2.0 Interface

Timepix on the ISS





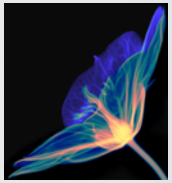
INTRODUCTION TO MEDICAL IMAGING

Winnie Wong

International School on Trigger and Data Acquisition Systems

Wigner Datacenter

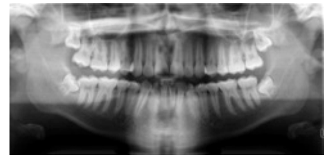
Budapest, 2014



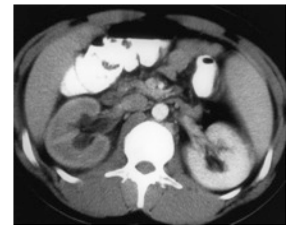
Outline

Overview of Medical Imaging Modalities:

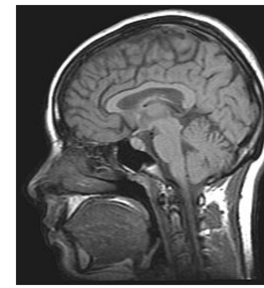
- Radiography



- Computed Tomography

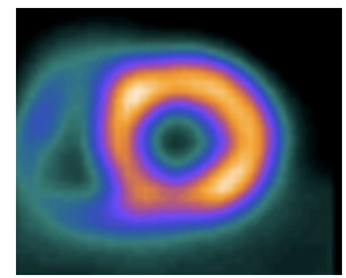


- (Magnetic Resonance Imaging)

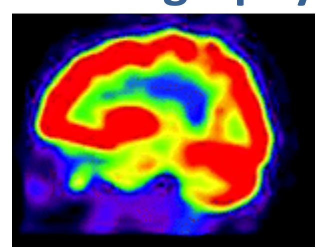


- (Ultrasound)

- Single Photon Emission Computed Tomography

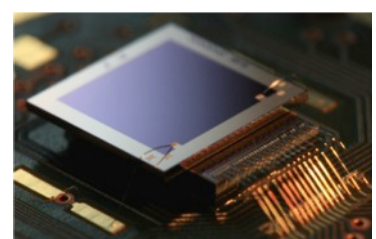


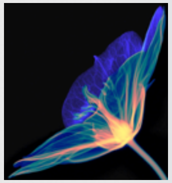
- Positron Emission Tomography



Informatics

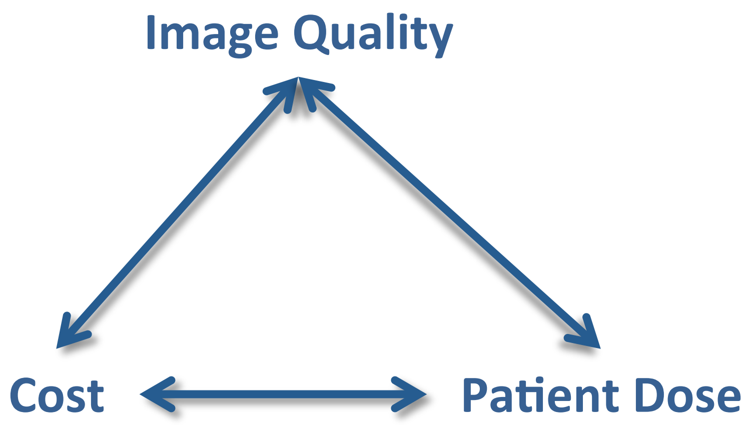
The Medipix Family of Hybrid Pixel Detectors





Imaging the Human Body

- Goal of diagnosis-oriented medical imaging is to view internal structures and/or understand the functions or organs ***inside*** the body
- Replace the need for many exploratory surgeries
- Used as a preventative tool as well as a curative tool
- Used to determine treatment and follow the progress of the treatment



The Electromagnetic Spectrum

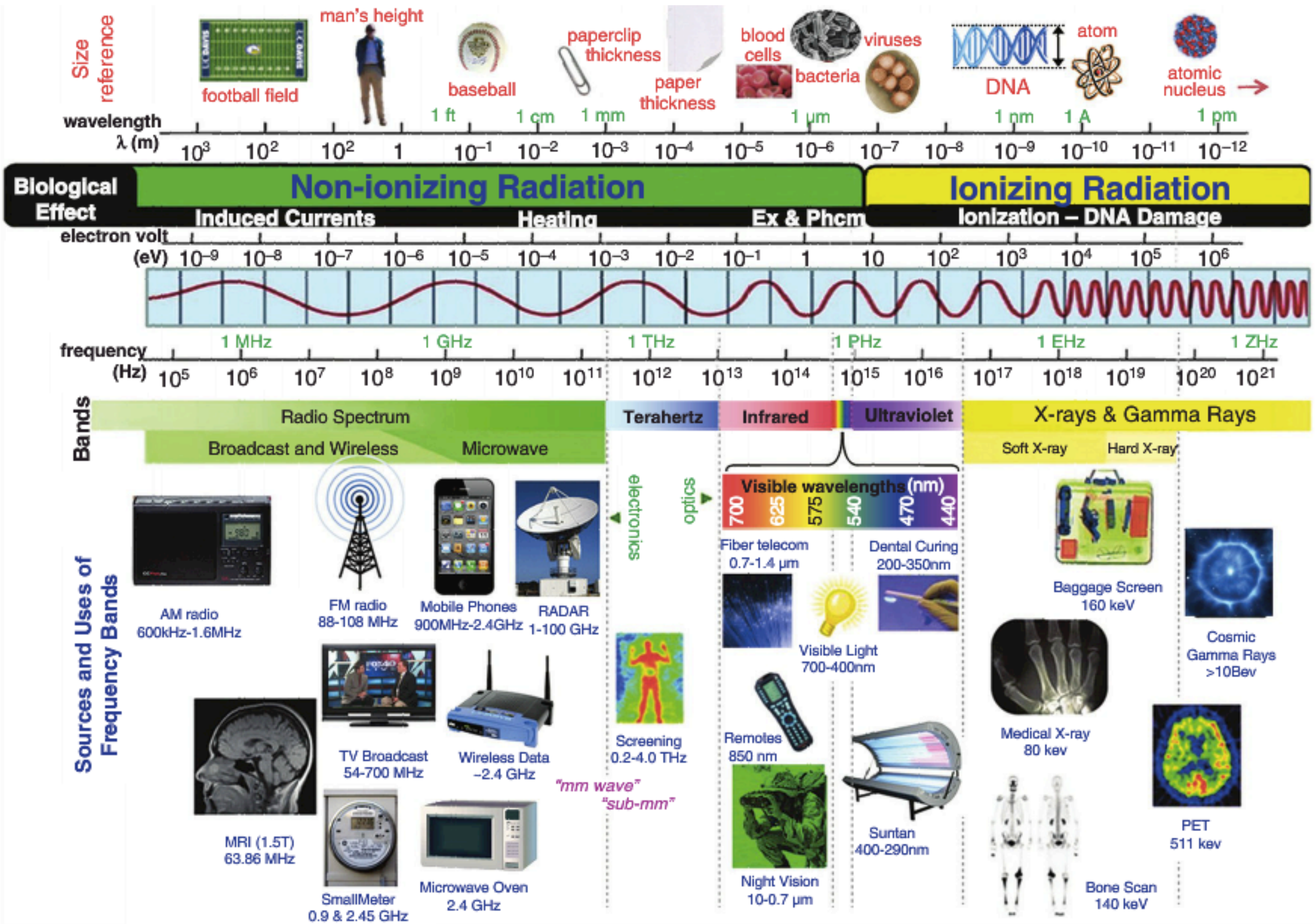
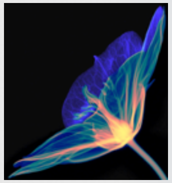


Image source: The Essential Physics of Medical Imaging (textbook)



Common Medical Imaging Modalities

Modality	Radiation Detected	Clinical Information	Cost	Exam Duration	Pros	Cons
Radiography	X-rays (transmission)	Anatomic structures (e.g broken bones)	< $100	Seconds	Quick, cheap, accessible, lower doses than CT	Radiation dose, anatomic noise from overlaying structures
Computed Tomography (CT)	X-rays (transmission)	Anatomic structures	$1000-$3000	Minutes (actual scan time is seconds)	Fast, great anatomic detail	Radiation dose
Magnetic Resonance Imaging (MRI)	RF	Anatomic structures (also some functional applications)	$1000-$4000	0.5 hour	No radiation, great soft tissue contrast	Not suitable for patients with metallic implants, patients can feel clausterphobic, long scan time, expensive
Ultrasound Imaging	High frequency sound waves		$100-$1000	10-15 minutes	No radiation, real-time, no side effects, good soft tissue resolution	Highly operator-dependent, limited applications
Single Photon Emission Computed Tomography (SPECT)	Gamma-rays (emission)	Functional (e.g. brain, heart)	$3500	Hours (actual scan time 30-40 minutes)	Lesion localisation, removal of out-of-focal plane data (compared to planar imaging)	Radiation dose, risk of allergic reaction to tracer, patient is radioactive (for a short time), poor spatial resolution (1 cm)
Positron Emission Tomography (PET)	Gamma-rays (emission)	Functional	$3000-$6000	2-4 hours (actual scan time 15-35 minutes)	Can distinguish between benign and malignant lesions, good spatial resolution for functional imaging	Radiation dose, risk of allergic reaction to tracer, patient is radioactive (for a short time), expensive

History of Radiography

- Discovery of X-rays by Wilhelm Roentgen in 1895
- First radiographic image of Bertha Roentgen's hand on December 22, 1895
- Nobel Prize in Physics in 1901

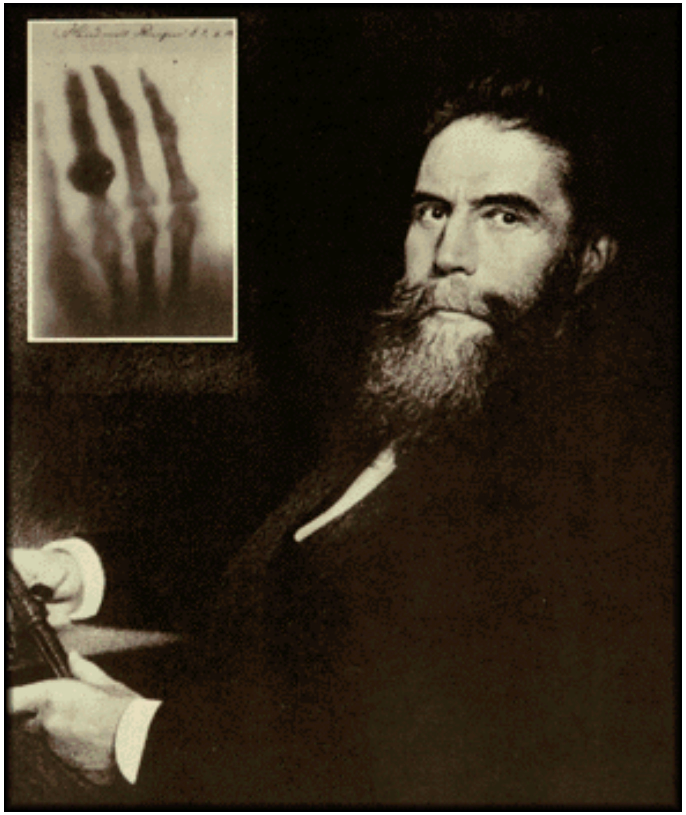
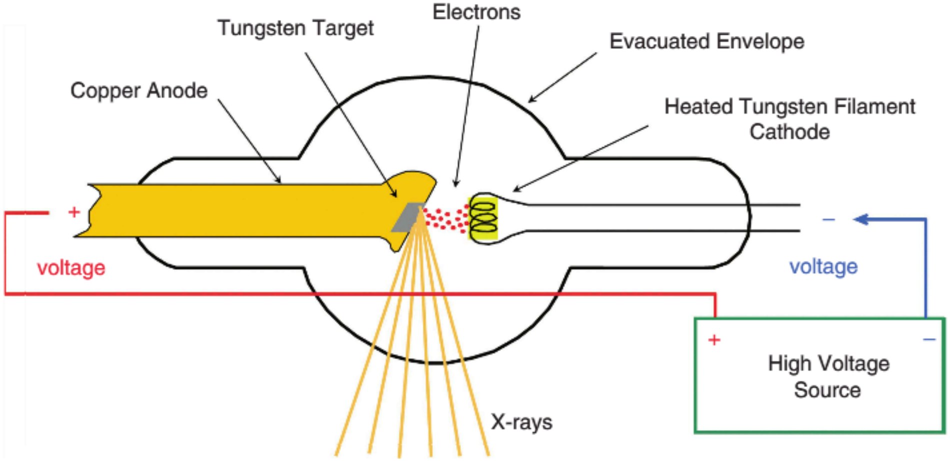
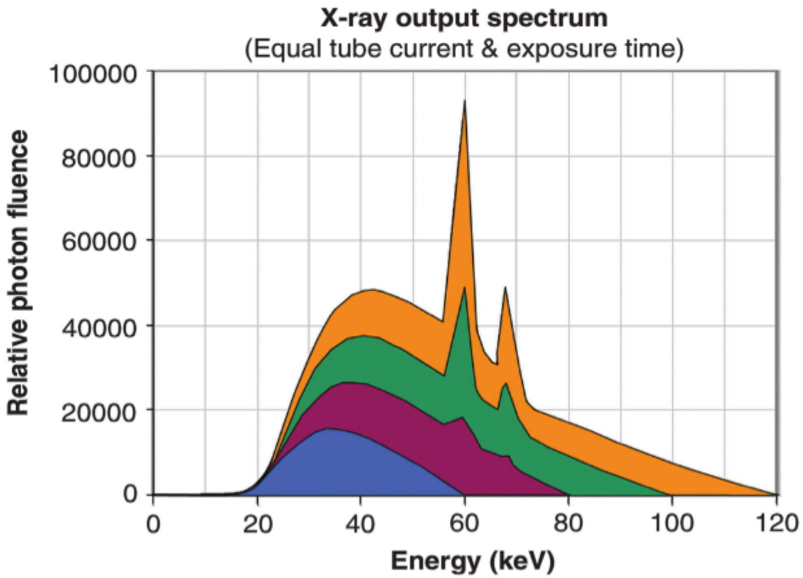


Image source: www.accessexcellence.org

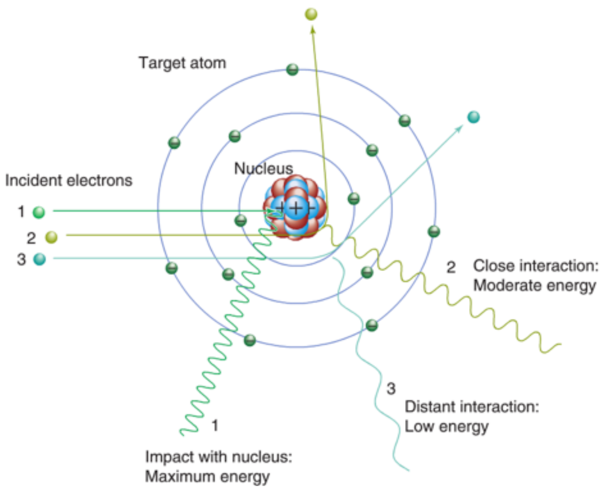
Image source: www.learningradiology.com

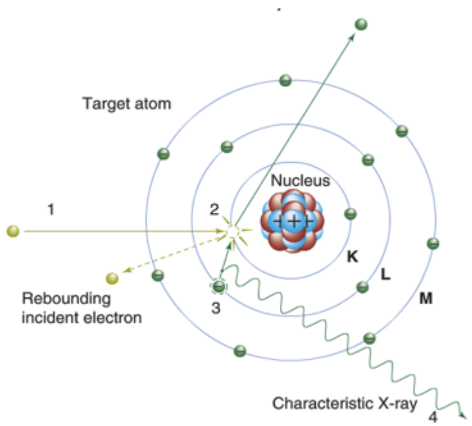
X-ray Production





1 eV ≡ energy of electron accelerated in 1 V E-field





Factors Affecting the X-Ray Spectrum:

- Anode target material
- Beam filtration

- Tube voltage (kVp)
- Tube current (mA)
- Exposure time (s)

Image source: The Essential Physics of Medical Imaging (textbook)

Radiography

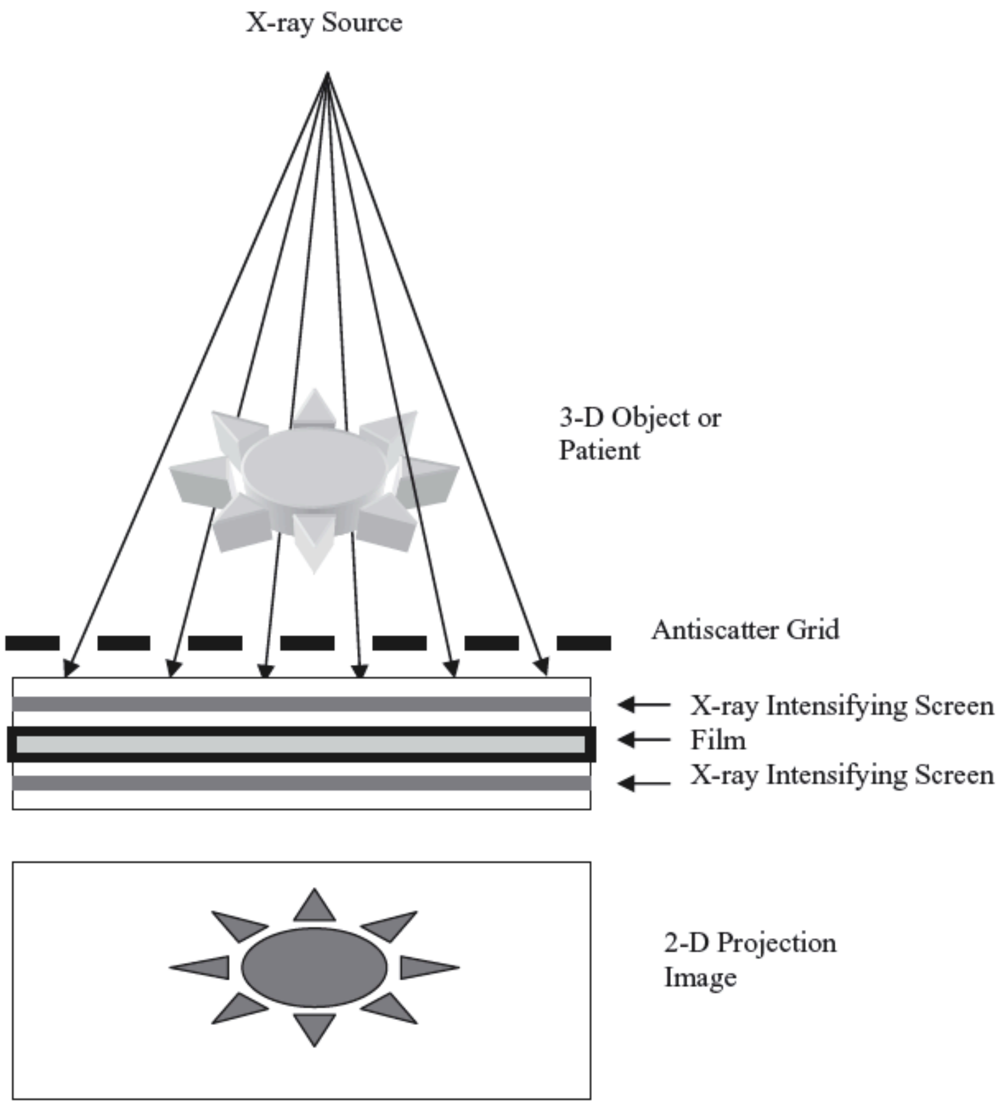


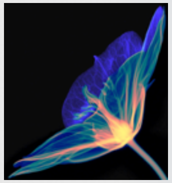
Image source: Medical Image Analysis (textbook)

Example energies:

55 kVp to image thin bones (e.g. wrist)

75-90 kVp to image spine (depending on size)

120 kVp to image lungs (less interaction with high density ribs)



"Typical" Doses

Single Exposure Exam	Average Effective Dose [mSv]
Chest (LAT)	0.04
Chest (AP)	0.02
Skull (AP)	0.03
Skull (Lat)	0.01
Pelvis (AP)	0.7
Thoracic Spine (AP)	0.4
Lumbar Spine (AP)	0.7
Mammogram (four views)	0.7
Dental (LAT)	0.02
Dental (panoramic)	0.09
DEXA (whole body)	0.0004
Hip	0.8
Hand or Foot	0.005
Abdomen	1.2

Data from: https://hps.org/documents/meddiagimaging.pdf

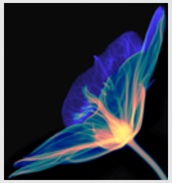
1 Gy = 1 J/kg (= 100 rad)

Absorbed dose D is measured in Gy

The quality factor (biological impact weighting factor) for photons, Q = 1

Dose equivalent, H [Sv] = D [Gy] x Q

Note: these numbers do not represent standards. They are just examples of typical values. Dose depends on many factors, including the size of the patient and the design of the machine.



Detectors in Radiography

Screen-Film Radiography

- Film with photosensitive emulsion sandwiched between two intensifying screens (scintillator crystals) that convert X-rays to visible light →indirect detection of X-rays

Computed Radiography (CR)

- Imaging plates coated with photostimulable phosphor (PSP) materials that store absorbed X-ray energy in charge traps in metastable energy states (caused by dopants in the material)
- Trapped charges are released when the PSP is stimulated by a red laser. Recombination of e^-/h^+ pairs causes emission of blue light, which is then read by a photomultiplier tube (PMT).

Digital Radiography (DR)

- CCD* or CMOS APS** or flat panel + scintillator crystal →indirect detection
- Flat panel + semiconductor (e.g. amorphous selenium) →direct detection

* CCD: Charge Coupled Device

**APS: Active Pixel Sensor

Dual Source Radiography

Logarithmic weighted subtraction to remove anatomic noise

$$DE(x,y) = \alpha + \beta \left[Ln\{(I_{HI}(x,y)\} - R\ Ln\{I_{LO}(x,y\}\right]$$

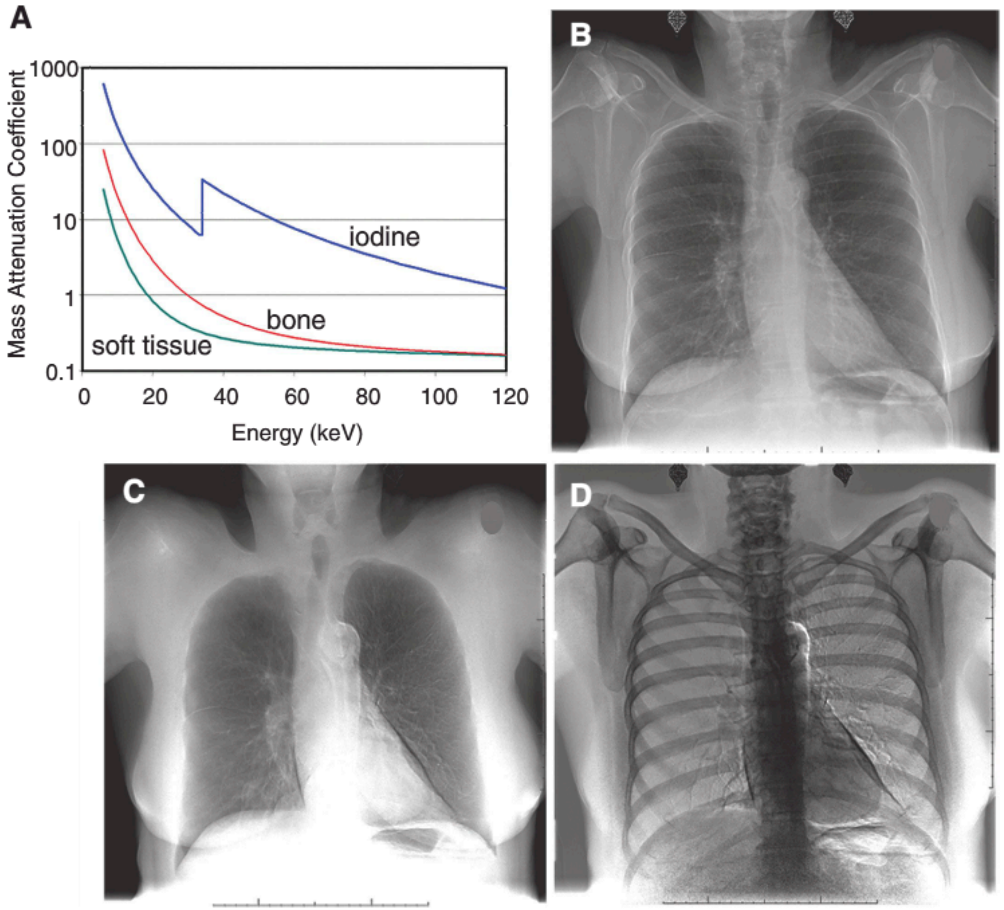


Image source: The Essential Physics of Medical Imaging (textbook)

A: Density-dependant mass attenuation coefficients of different tissues

- $Z_{iodine} = 53$
- $Z_{bone} \approx 13$
- $Z_{soft\ tissue} \approx 7.6$

B: 120 kVp radiograph

C: Soft tissue-only image (bone subtracted out)

D: Bone (and metal) image (soft tissue subtracted out)

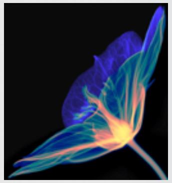
History of Computed Tomography (CT)

- Nobel Prize in Physiology or Medicine 1979 jointly awarded to Allan Cormack and Godfrey Hounsfield "for the development of computer assisted tomography"

Image source: www.nobelprize.org

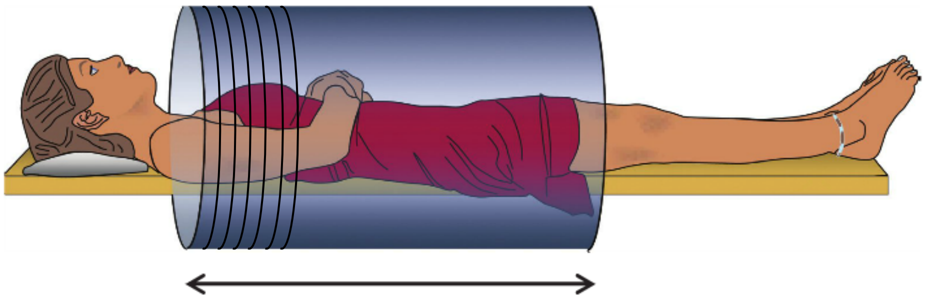
- CT was the first medical imaging modality to require computers
- First patient scanned on October 1, 1971
- First CT scanner in clinical use was the EMI Mark 1
  - 80 x 80 pixels of 2.4 x 2.4 mm^2
  - 3 bits (i.e. 8 shades of grey) per pixel
  - A scan took ~4 minutes and image reconstruction ran overnight

Image source: bjr.birjournals.org



CT Basics

- In radiography, a 2D image is taken of a 3D object → overlapping structures
- Greek *tome* ("cut") or *tomos* ("part" or "section") and *graphein* ("to write")



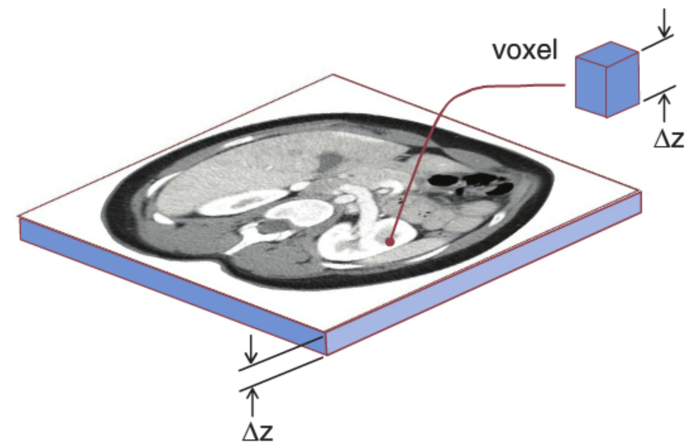
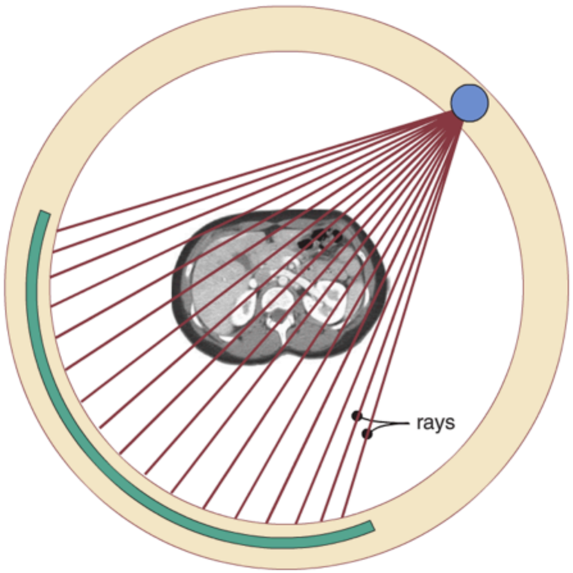
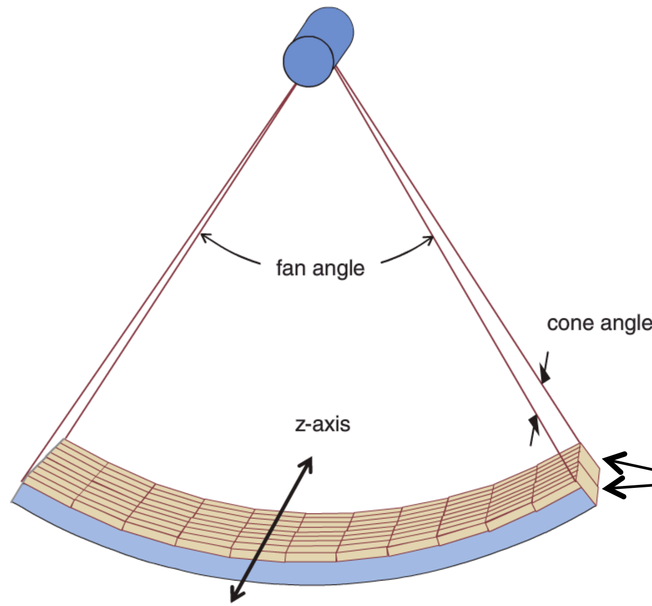


Image source: The Essential Physics of Medical Imaging (textbook)

CT Basics



fan beam projection



Multi-detector CT (MDCT)

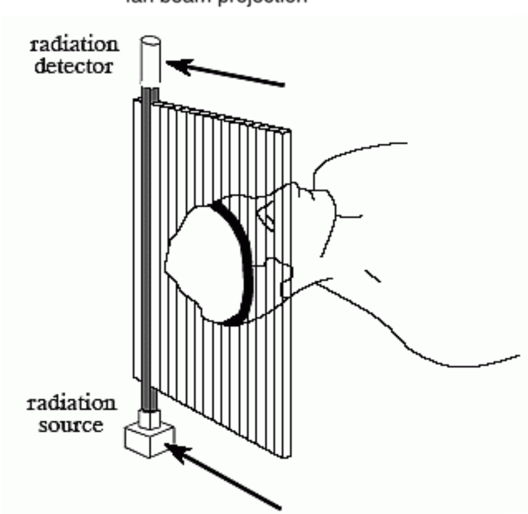
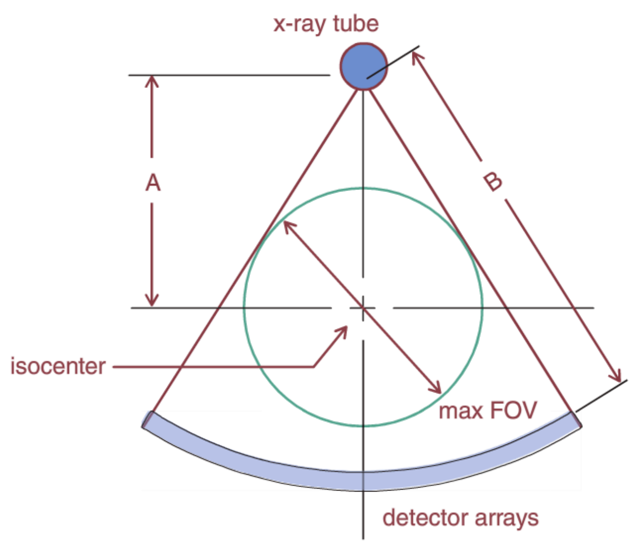


Image source: www.dspguide.com



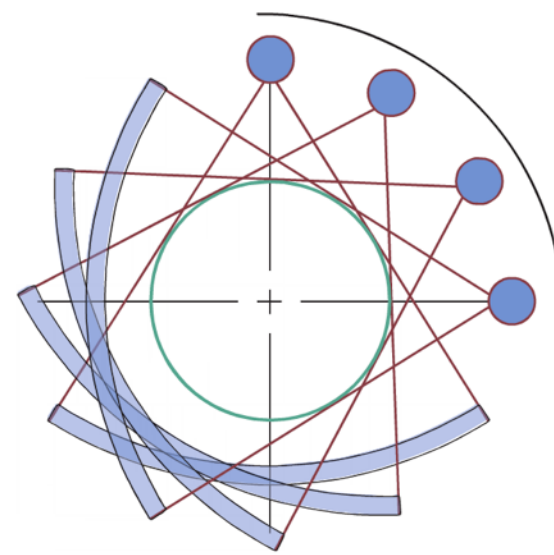
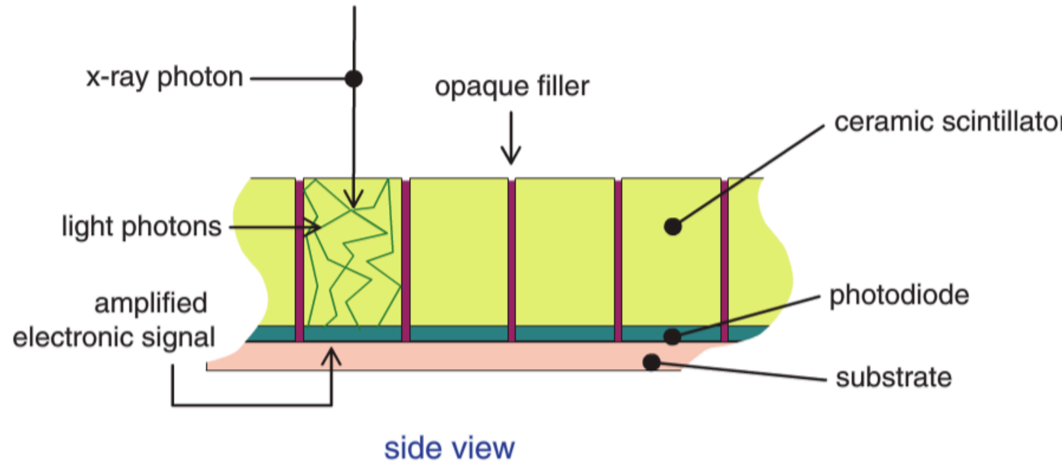


Image source: The Essential Physics of Medical Imaging (textbook)

CT Detectors

- Indirect detection with high-density scintillation crystals
- The opaque fillers reduce optical crosstalk



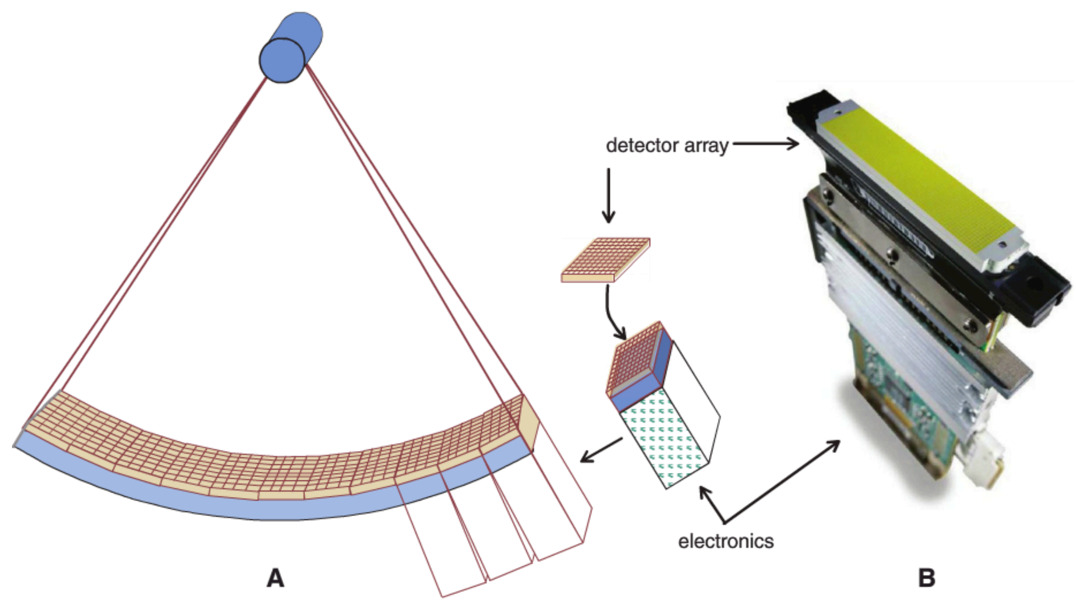
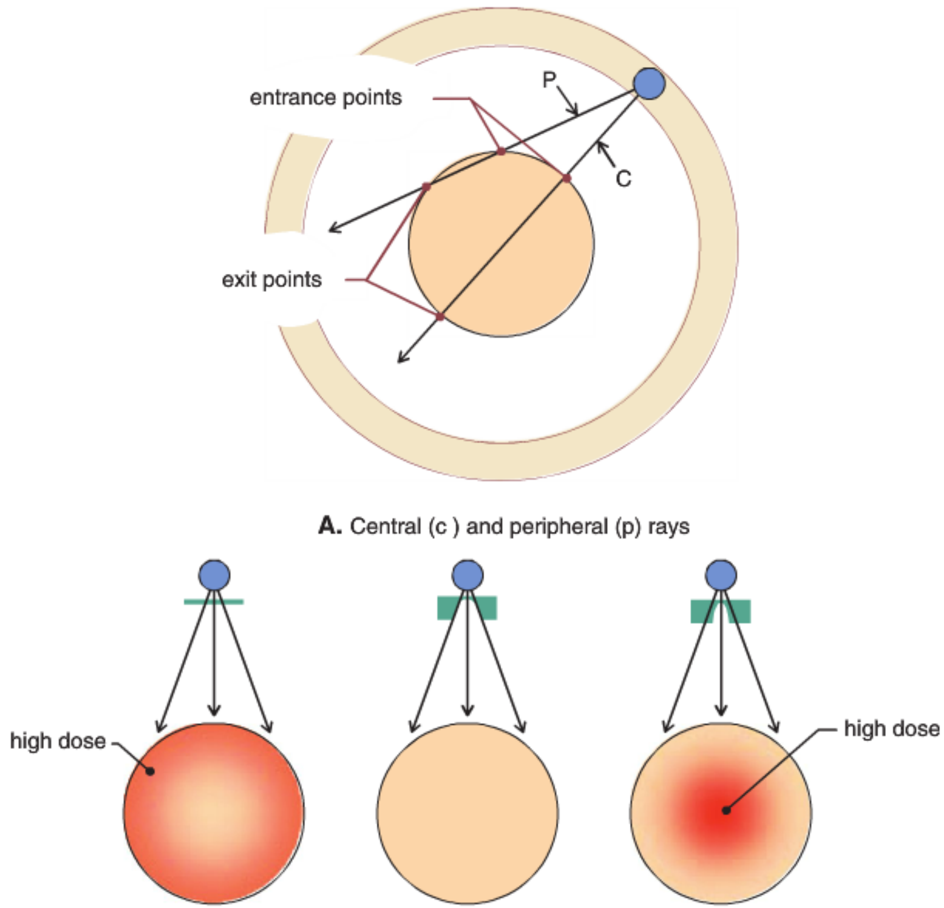


Image source: The Essential Physics of Medical Imaging (textbook)

Beam Shape

- **Bow tie filters used to shape beam for homogeneous dose distribution in thickness of body**



A. Central (c) and peripheral (p) rays

B. no bow tie **C.** ideal bow tie **D.** Small bow tie

Image source: The Essential Physics of Medical Imaging (textbook)

Inside the Gantry

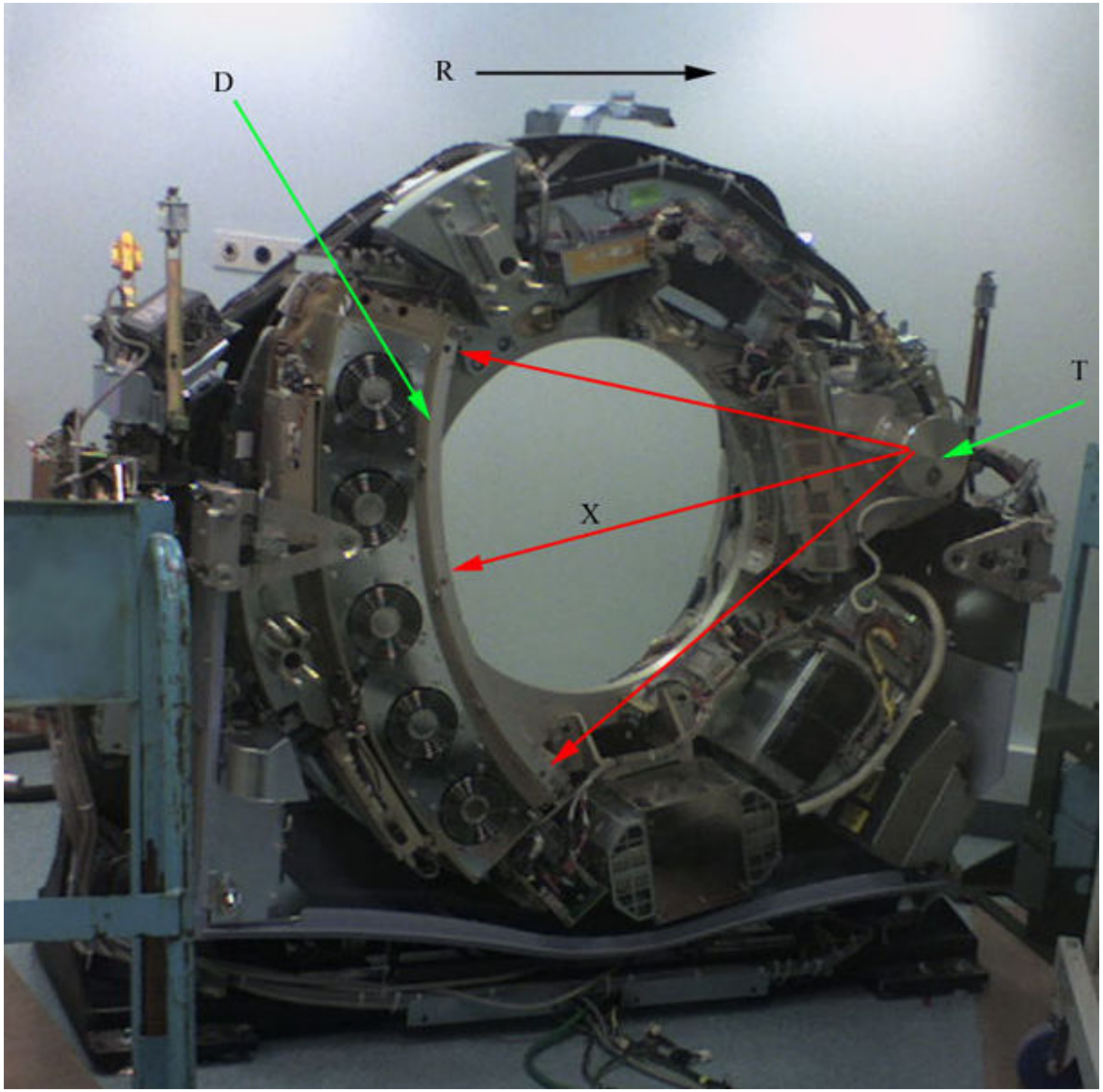


Image source: wikipedia.org

T: X-ray tube
X: X-ray beam
D: Detectors
R: Ganry rotation

The Houndsfield Unit

The (12-bit) "CT Number" (grey scale value) stored in a processed CT image is given in Houndsfield Units (HU):

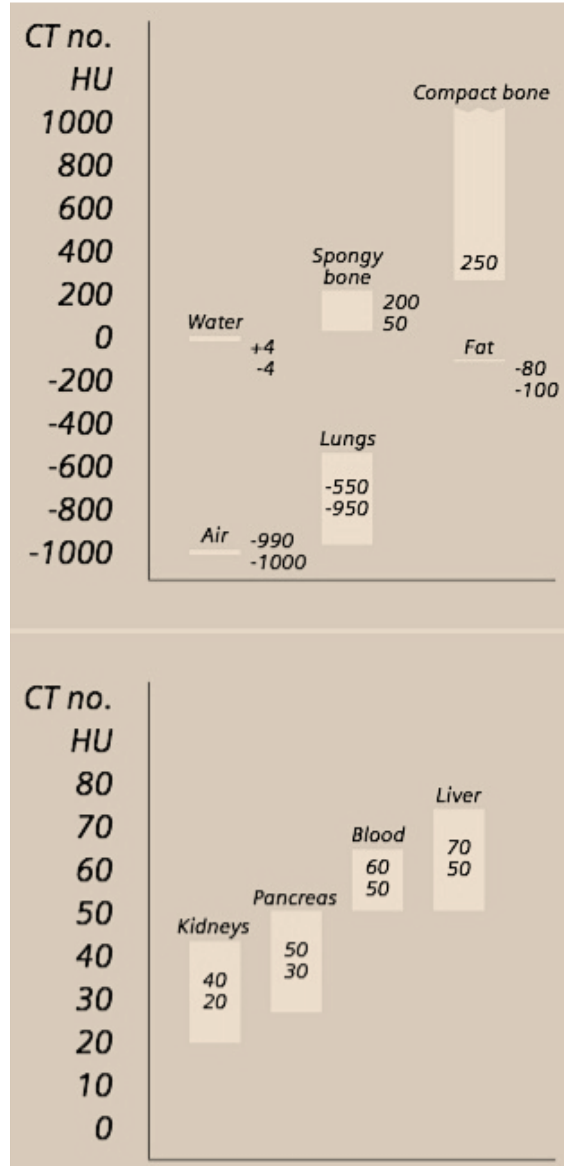
$$HU(x,y,z) = 1000\,\frac{\left(\mu(x,y,z) - \mu_w\right)}{\mu_w}$$

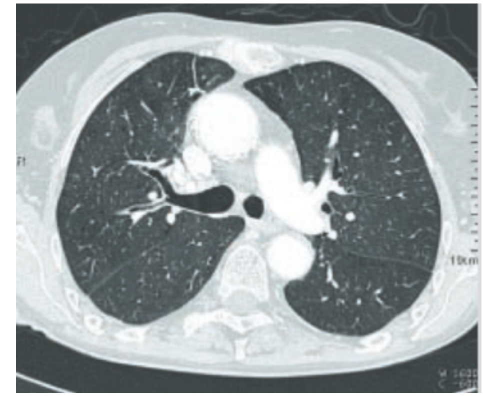
$\mu(x,y,z)$: average linear attenuation coefficient for a voxel of tissue in the patient at the location (x,y,z)

μ_w: linear attenuation coefficient of water for the X-ray tube setting

Note: The HU scale depends on the X-ray tube setting. The figure here shows the HU values for one example setting.

Typical CT number range:
-1024 to +3071



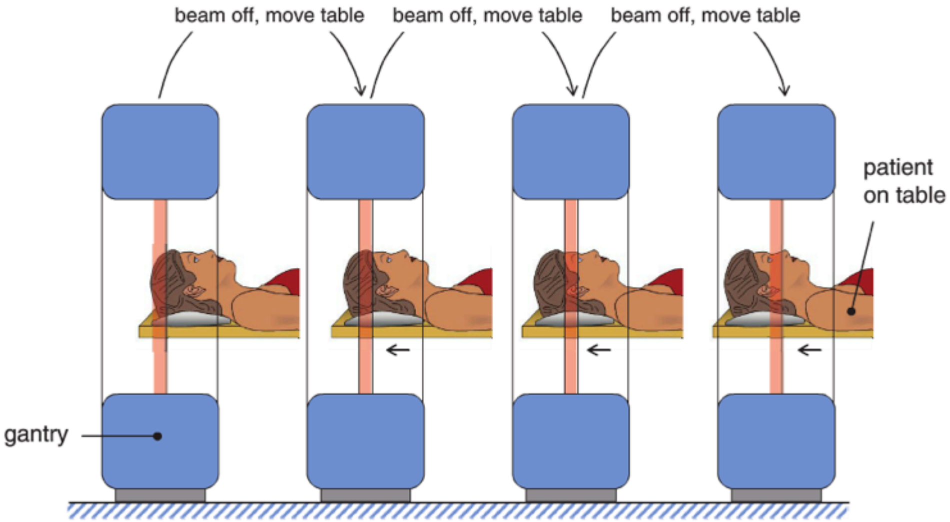


Lung window

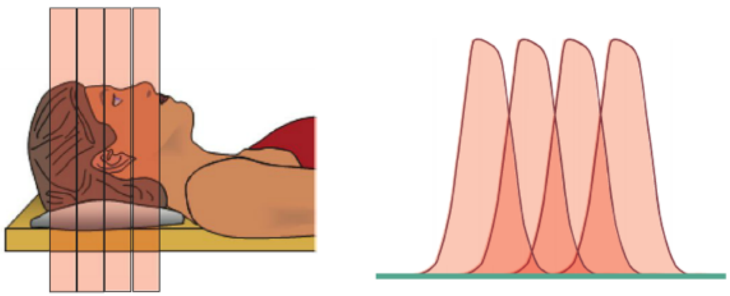
Soft tissue window

Image source: http://www.medical.siemens.com

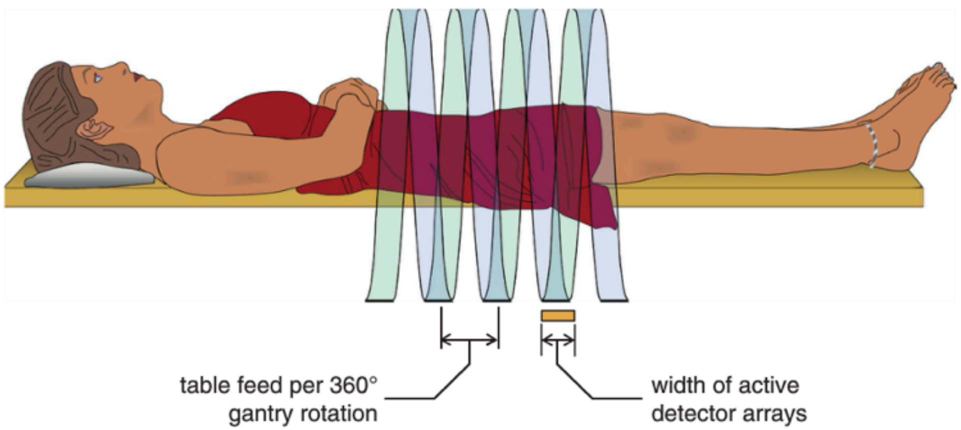
Axial versus Helical Scans



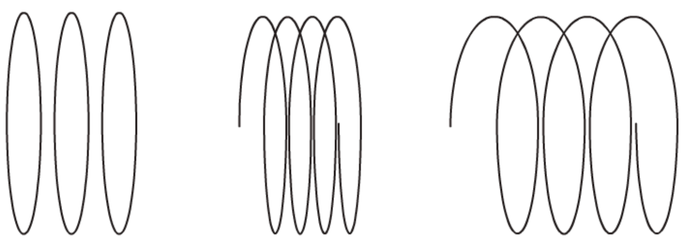
Axial or Sequential CT Acquisition



A. contiguous axial imaging **B.** dose overlap between scans



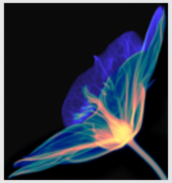
Helical or Spiral CT Acquisition



A. axial / sequential **B.** low pitch helical / spiral **C.** high pitch helical / spiral

$$dose \propto \frac{1}{pitch}$$

Image source: The Essential Physics of Medical Imaging (textbook)



"Typical" Doses

Recall:

Single Exposure Exam	Effective Dose (mSv)
Chest (LAT)	0.04
Chest (AP)	0.02
Skull (AP)	0.03
Skull (Lat)	0.01
Pelvis (AP)	0.7
Thoracic Spine (AP)	0.4
Lumbar Spine (AP)	0.7
Mammogram (four views)	0.7
Dental (LAT)	0.02
Dental (panoramic)	0.09
DEXA (whole body)	0.0004
Hip	0.8
Hand or Foot	0.005
Abdomen	1.2

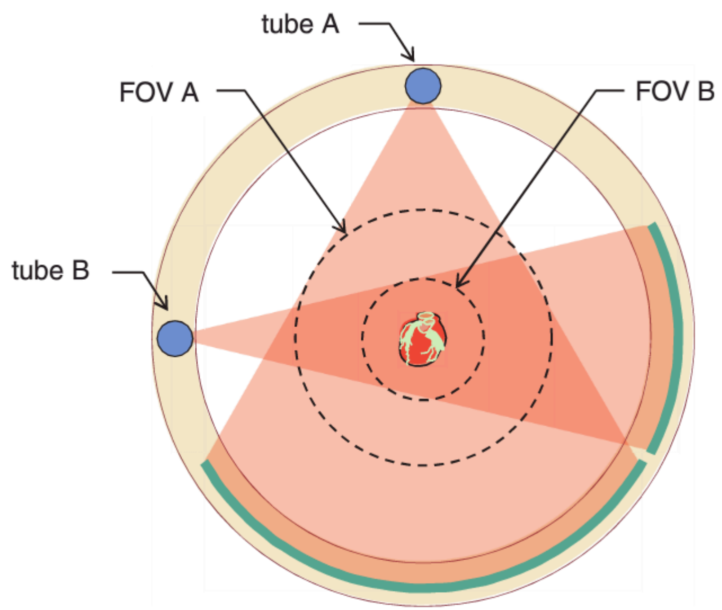
Complete Exams	Effective Dose (mSv)
Intravenous Pyelogram (kidneys, 6 films)	2.5
Barium Swallow (24 images, 106 sec, fluoroscopy)	1.5
Barium Enema (10 images, 137 sec. fluoroscopy)	7.0
CT Head	2.0
CT Chest	8.0
CT Abdomen	10.0
CT Pelvis	10.0
Angioplasty (heart study)	7.5
Coronary Angiogram	4.6

Data from: https://hps.org/documents/meddiagimaging.pdf

Global average background radiation = 2.4 mSv/year
Swiss average background radiation = 2.8 mSv/year

Dual Energy CT

- Similar concept to dual energy radiography
- Can be done by either:
  - Switching a single source (e.g. between 80 kVp and 140 kVp), or
  - Using two sources (note: tube B has a smaller FOV due to the gantry geometry)



dual source CT

Image source: The Essential Physics of Medical Imaging (textbook)

Tomographic Image Reconstruction

Pre-processing includes:

- Corrections for bow tie filter (reference images taken in air)
- Detector gain variation correction
- Interpolation of data to compensate for dead pixels
- Scatter correction
- Adaptive noise filtering
- Logarithmic transformation to account for exponential nature of X-ray attenuation
  - Projection image becomes linear sums of the attenuation coefficients along the X-ray path (through the patient)

Image reconstruction:

- Simple back-projection (suffers from 1/r blur)
- Filtered back-projection
  - Corrects 1/r blur, can be done in the frequency domain – Fourier Transforms
- Iterative back-projection
  - Computationally-intensive (mostly used in SPECT which has less raw data)
  - Can model X-ray spectrum, focal spot blur, etc.
  - Better final image quality than filtered-back projection – dose reduction

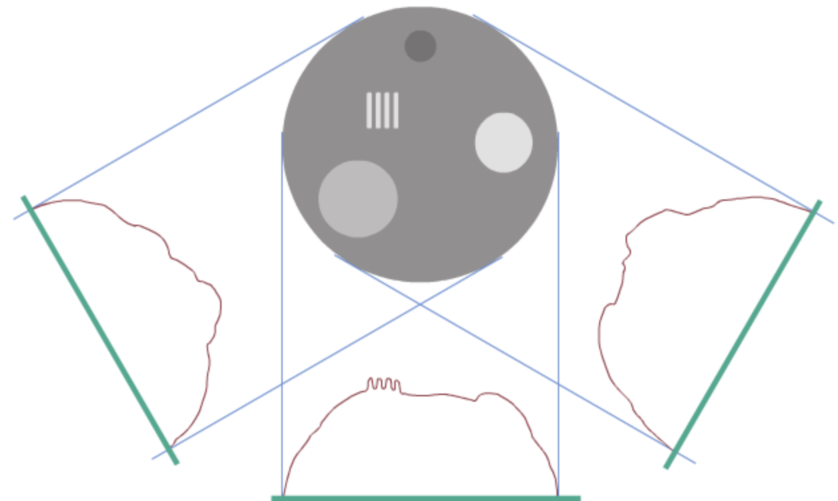
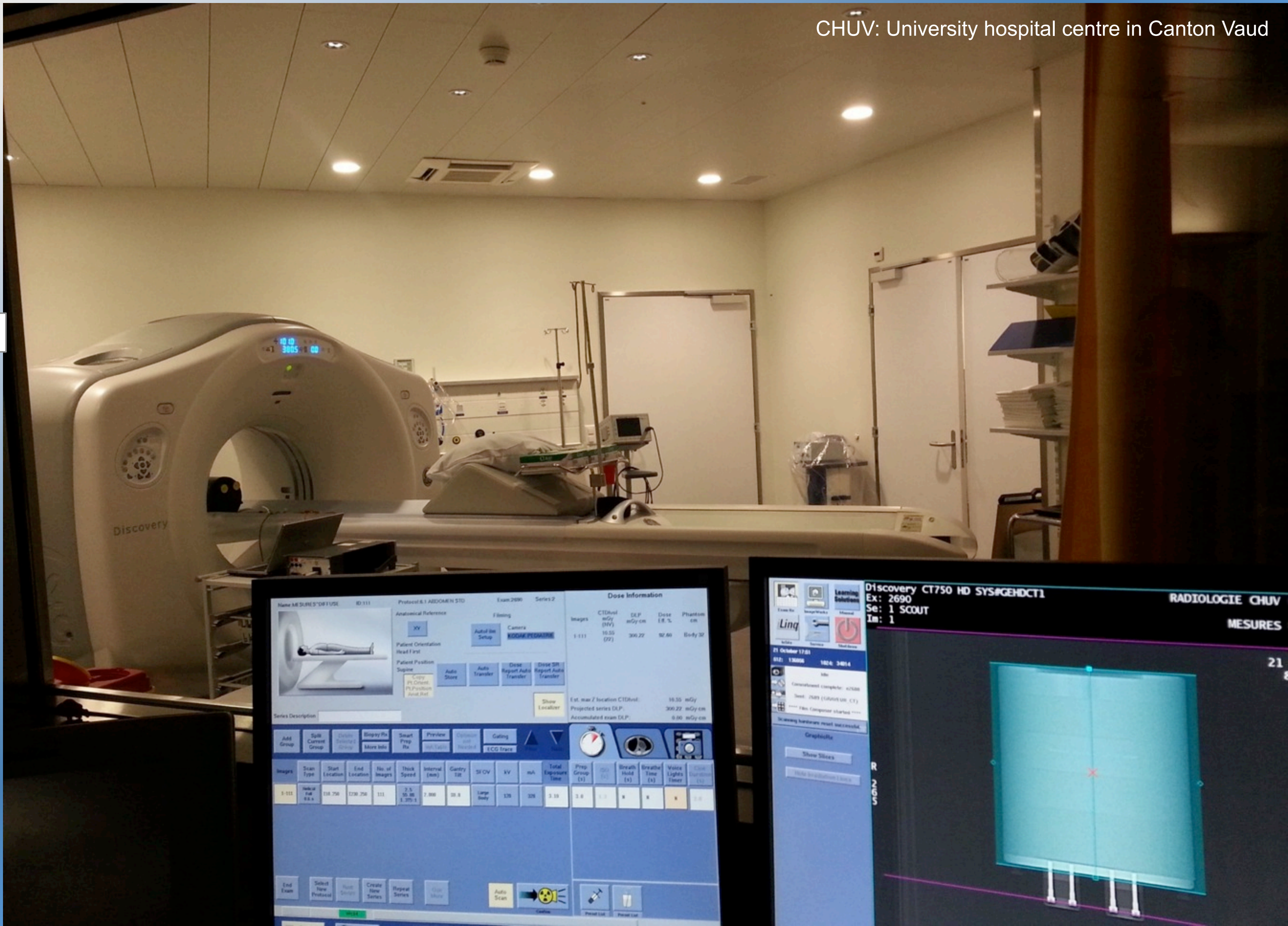


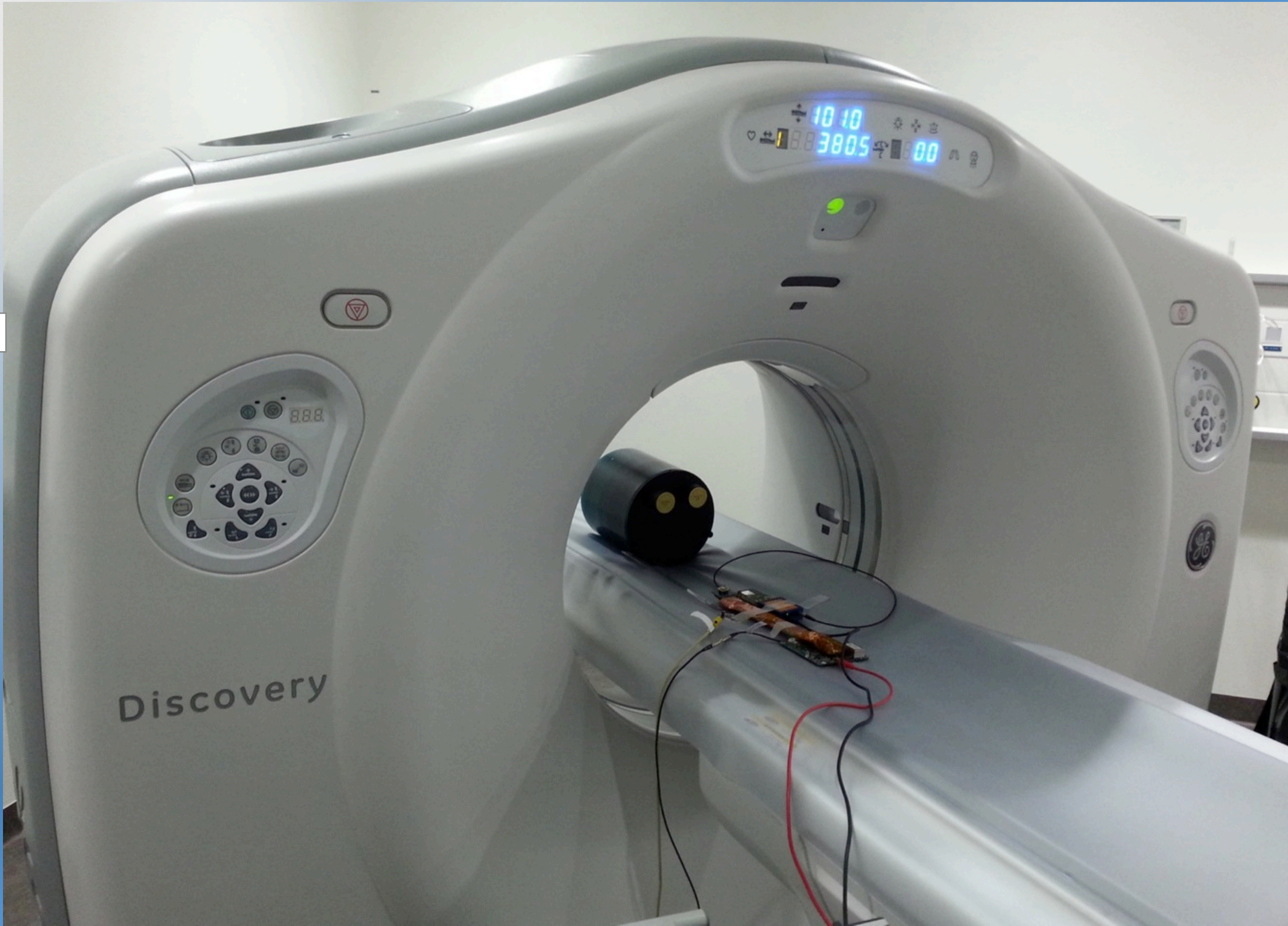
Image source: The Essential Physics of Medical Imaging (textbook)

CT Scatter Measurements at CHUV

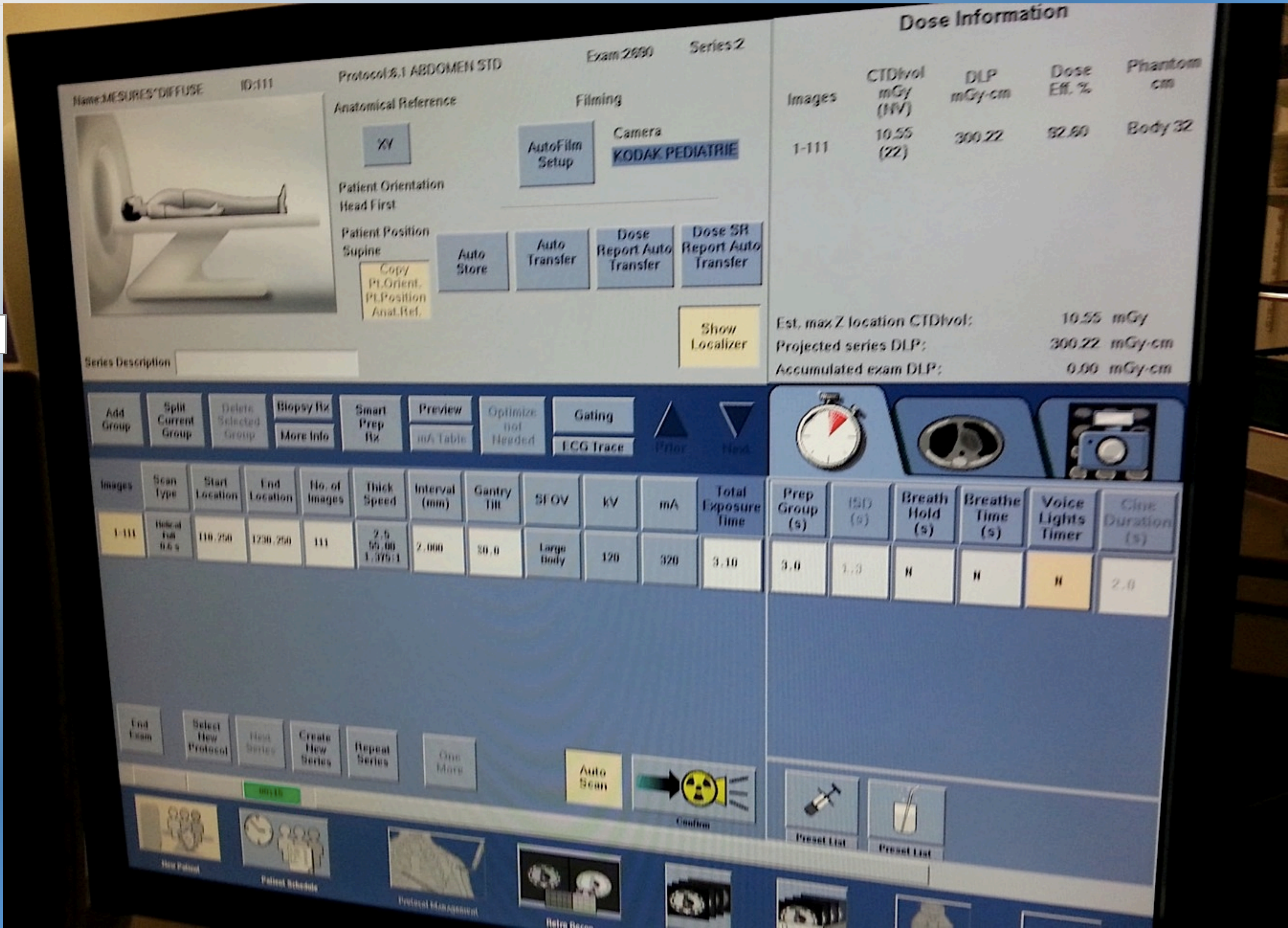


CHUV: University hospital centre in Canton Vaud

CT Scatter Measurements at CHUV



CT Scatter Measurements at CHUV



Radiography

CT

MRI

Ultrasound

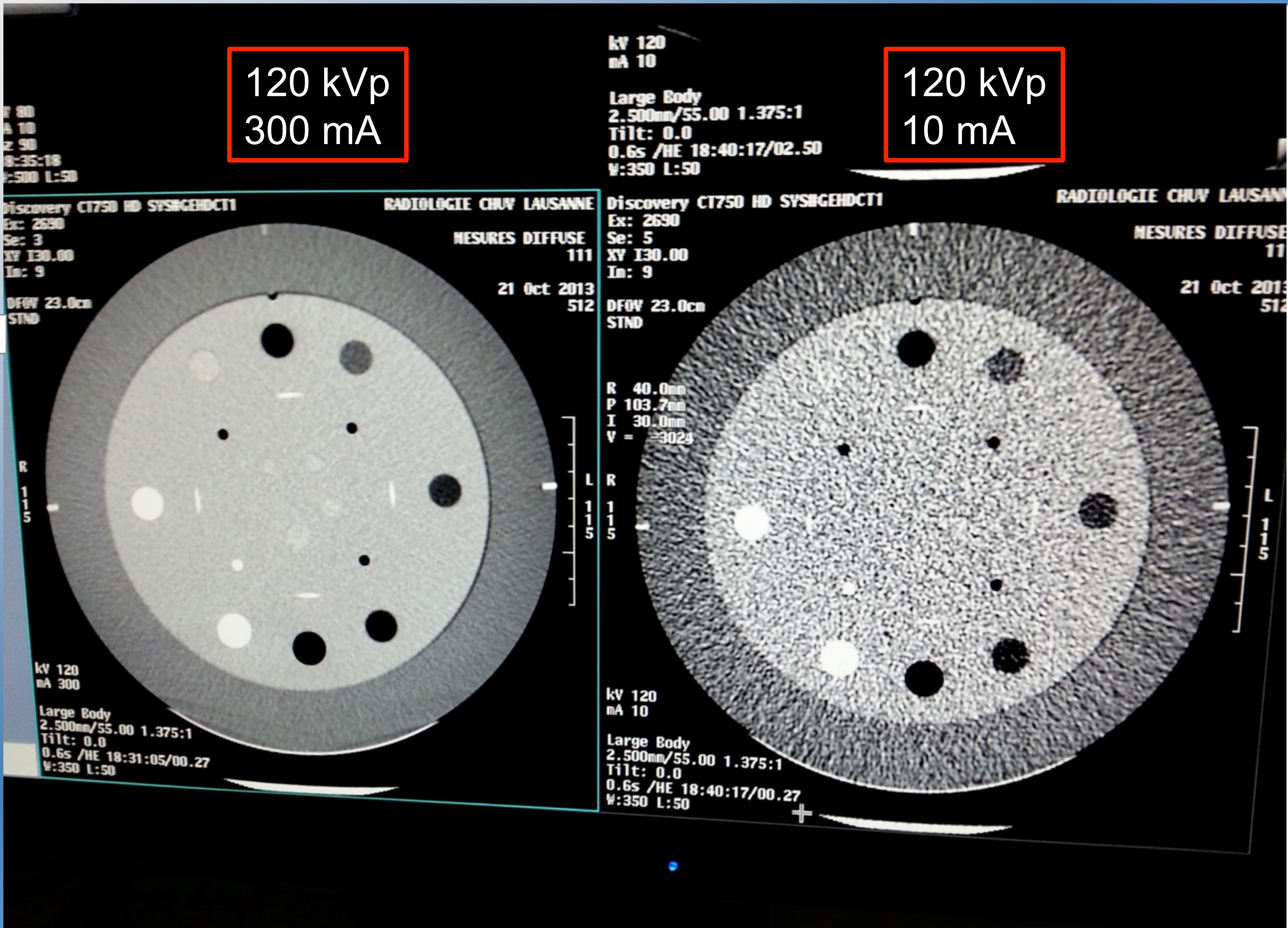
SPECT

PET

Informatics

Medipix

CT Scatter Measurements at CHUV



Magnetic Resonance Imaging

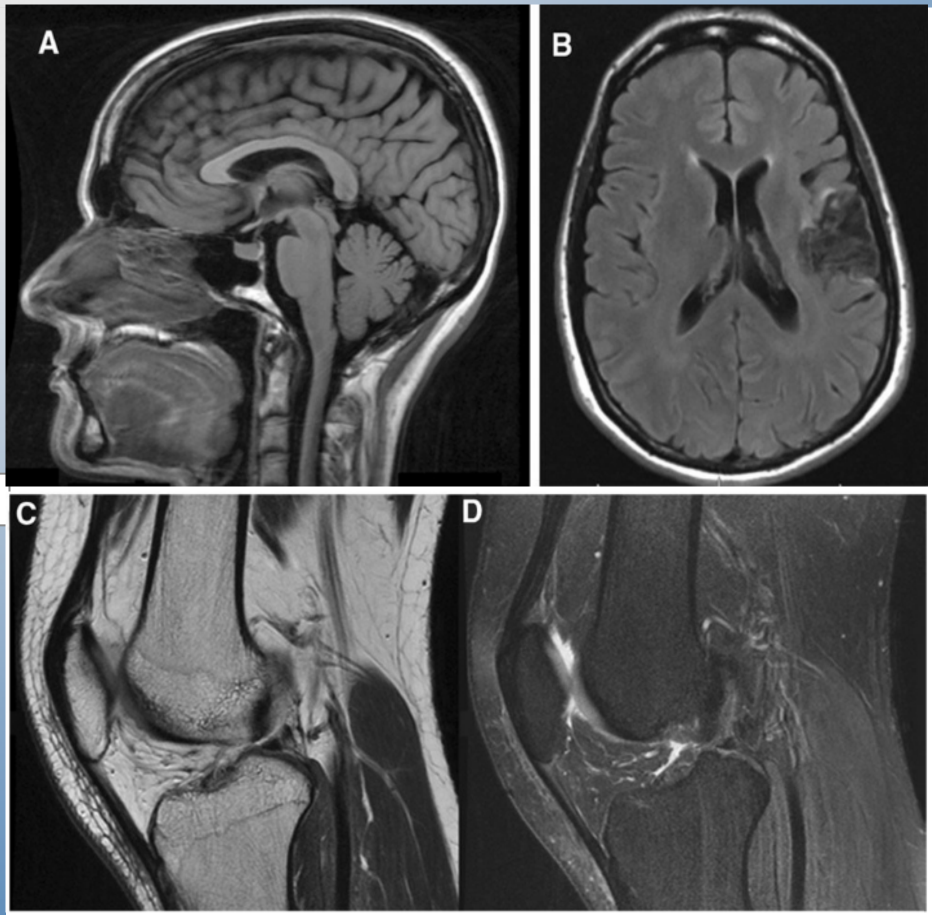


Image source: The Essential Physics of Medical Imaging (textbook)

- Tomographic imaging, competes with CT in many clinical applications
- Based on the nuclear magnetic resonance properties of the proton (i.e. nucleus of hydrogen)
  - 10^{18} protons/cm^3 of tissue
- Proton has a magnetic moment. When placed in a strong magnetic field, it precesses (wobbles) about its axis and absorbs 64 MHz RF energy
- Patient is placed in the 1.5 T magnetic field and surrounding antenna coils send an RF pulse
- Protons in the patient absorb the RF wave energy and after a time, re-emit the RF waves. The time depends on the spatially-dependent magnetic properties of the tissue.
- Antennae detect the emitted RF waves
- The proton resonance frequency is proportional to magnetic field strength, so the machine can determine spatial information by vary the magnetic field strength as a function of position
- Position of each signal from the patient is determined by its frequency and phase

Functional MRI (fMRI)

Brain activity determined by monitoring blood flow

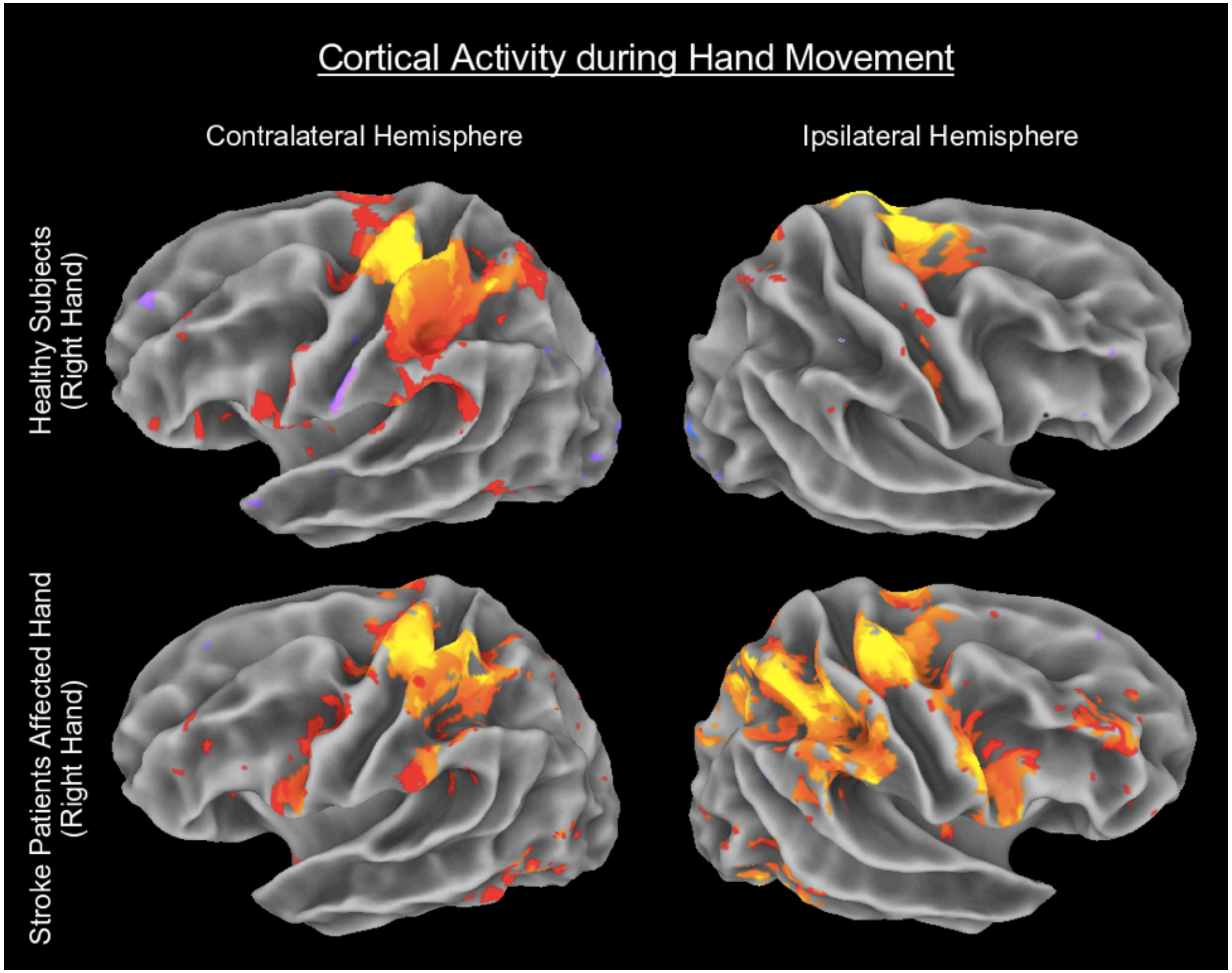


Image source: www.martinos.org/neurorecovery/technology.htm

Ultrasound

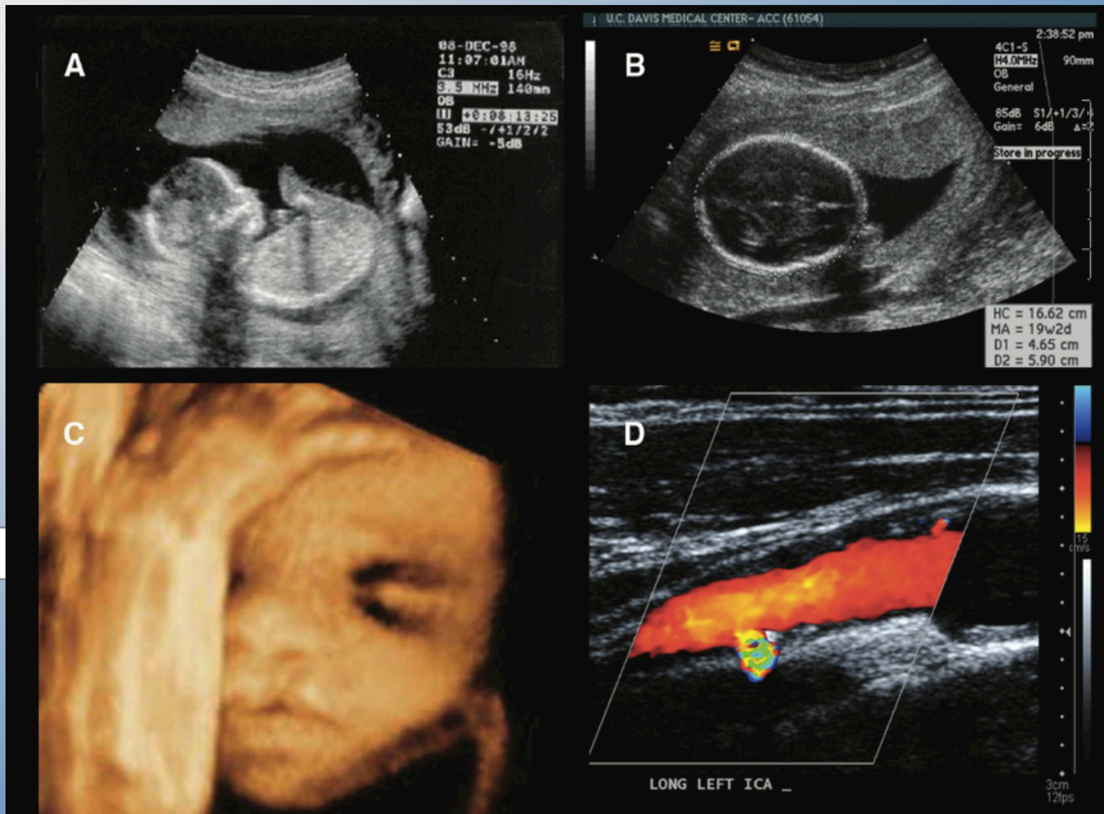


Image source: The Essential Physics of Medical Imaging (textbook)

- Ultrasound is another form of tomographic imaging
- A transducer in contact with the patient's skin generates a short pulse of sound, which travels into the tissue
- Echoes are created by reflection of the sound waves by internal structures in the body
- An array of multi-element transducers scan through a sector
- Ultrasound is reflected strongly by interfaces, so is useful for surfaces and internal structures of abdominal organs
- Ultrasound is also commonly used to image a fetus since there is no ionising radiation
- Not useful to image interfaces between air and tissue (e.g. lungs) or bone and tissue (e.g. brain)
- In Doppler ultrasound, the Doppler effect is used to measure the motion of blood

Check on demo

Single Photon Emission Computed Tomography

- SPECT is the standard for many nuclear medicine exams
- Patient is administered a radionuclide tracer that emits gamma rays
- E.g. ^{99m}Tc (140.5 keV γ-rays, 28-33 keV X-rays),
  ^{125}I (35.5 keV γ-rays)
- Path/location of tracer concentration is imaged e.g. iodine tends to concentrate in the thyroid, so we can use an iodine-based tracer to image thyroid cancer and its metastases
- SPECT often used in brain and cardiac imaging

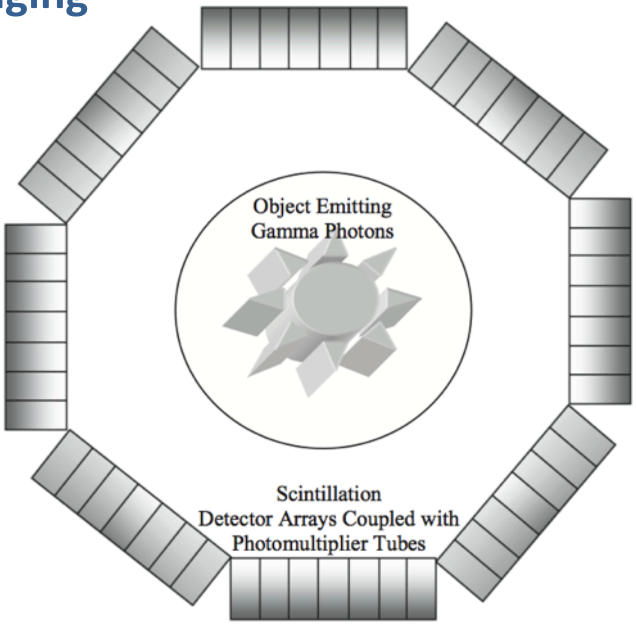


Image source: Medical Image Analysis (textbook)

Body Contouring in SPECT

C

D

E

F

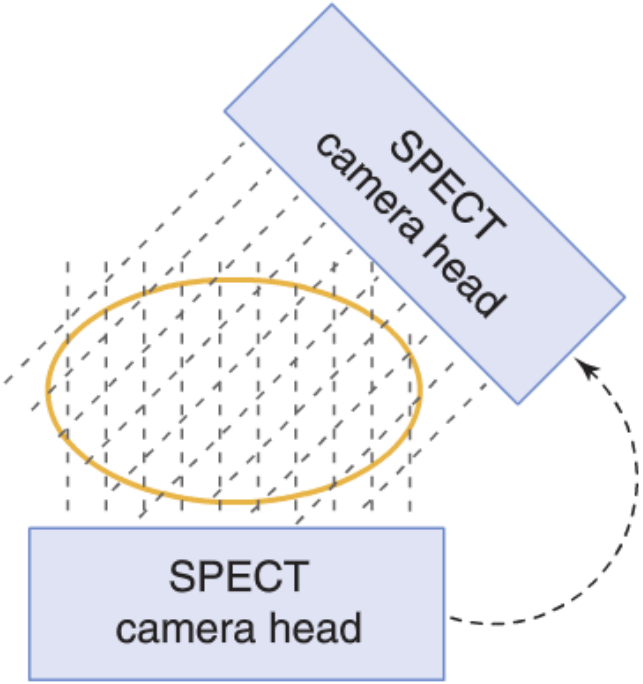


Image source: The Essential Physics of Medical Imaging (textbook)

The Scintillator Camera

Scattering of photons in patient tissue is a problem in every modality dealing with photons. Collimators (a.k.a. anti-scatter grids) are placed in front of the detector to select parallel rays.

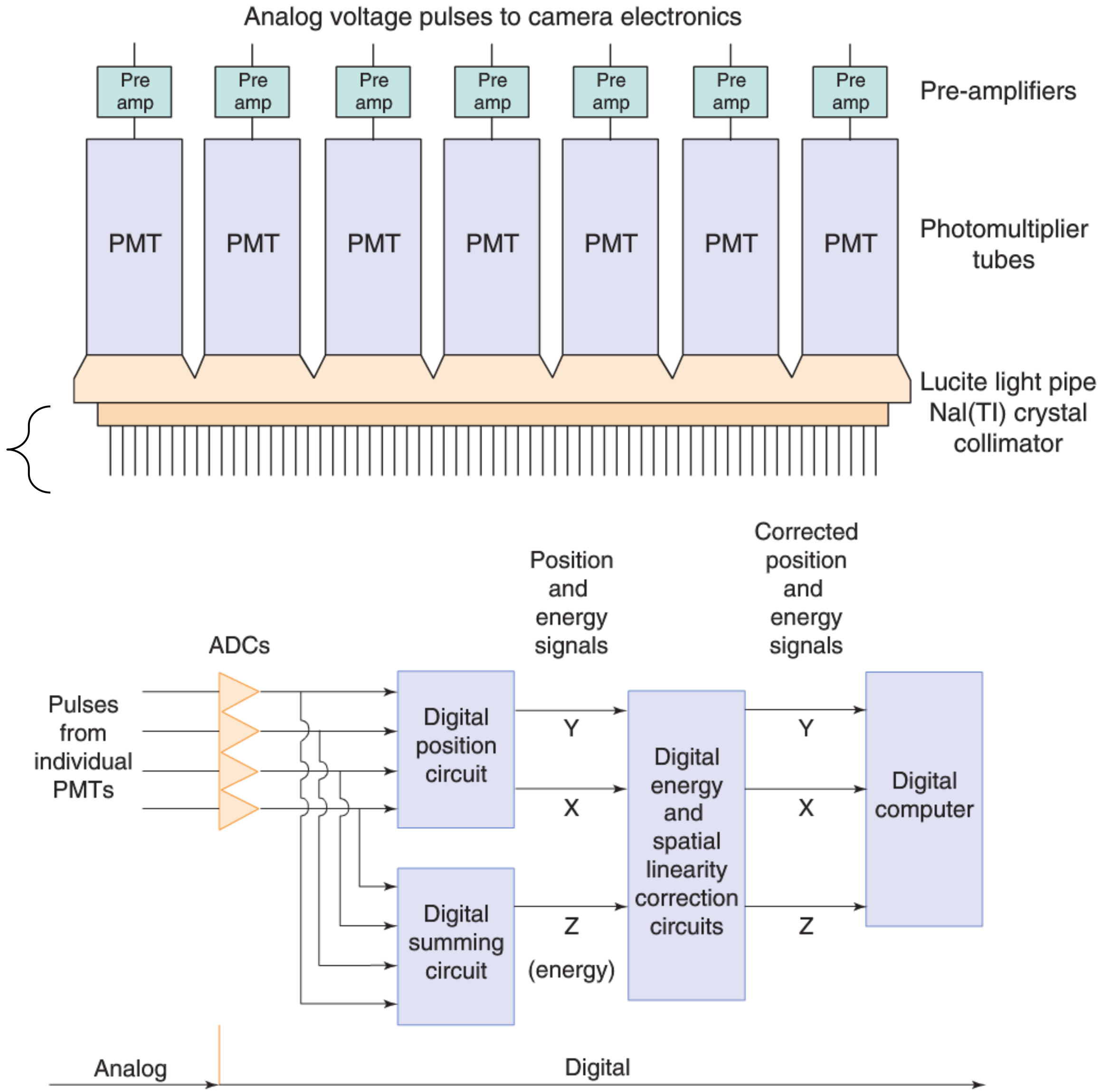


Image source: The Essential Physics of Medical Imaging (textbook)

SPECT Images

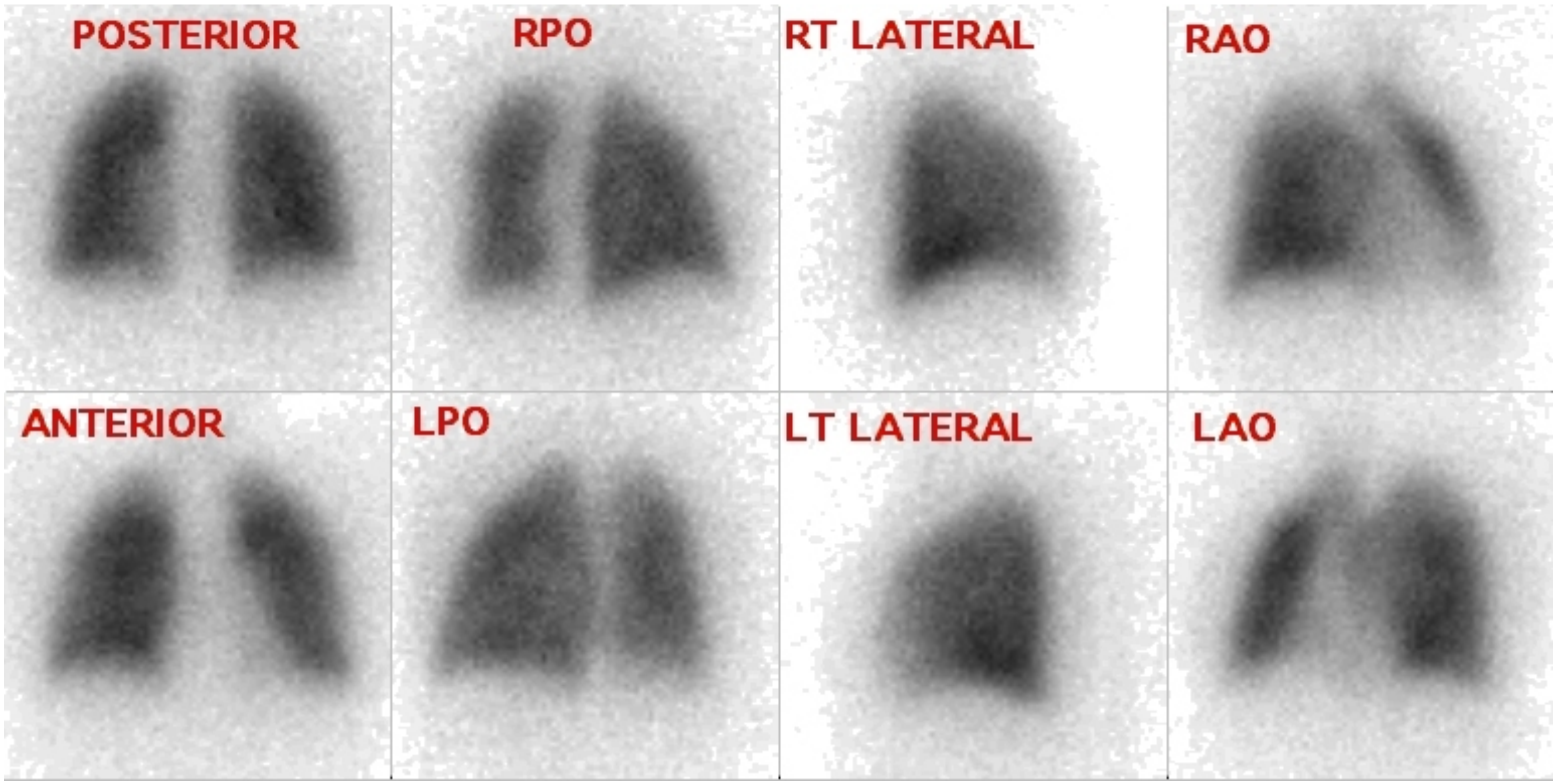


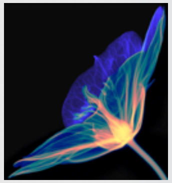
Image source: www.nuclearimaging.com.au/lung_spect.htm

Positron Emission Tomography

Radiography
CT
MRI
Ultrasound
SPECT
PET
Informatics
Medipix

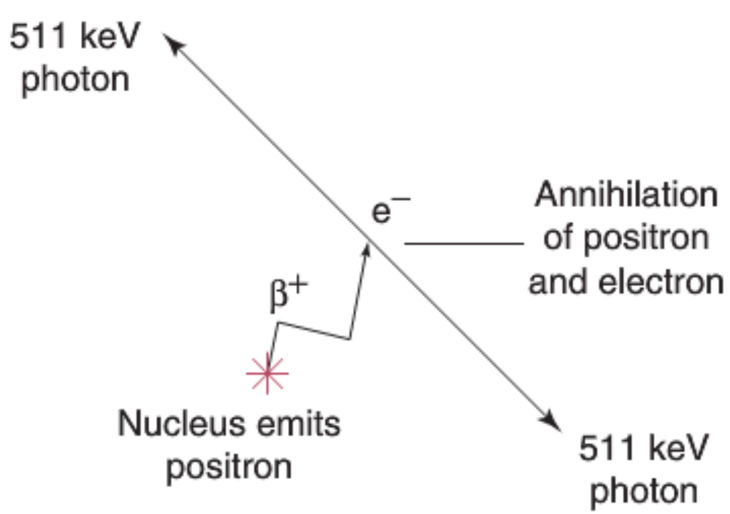
Image source: The Essential Physics of Medical Imaging (textbook)

- The patient is administered a solution containing glucose molecules labelled with a radionuclide
  - Glucose concentrates in regions of high metabolism
  - Malignant (tumour) cells have higher rates of metabolism than normal tissue
    - Effective for oncological applications, particularly for imaging prostate cancer



Positron Emission Tomography

- The most commonly used tracer is ^{18}F-2-fluoro-2-deoxy-d-glucose (FDG)
- Positrons (i.e. β^+) are emitted from the ^{18}F decay
- The interaction of β^+ with an e^- (from the surrounding tissue) results in annilhilation, which creates two γ photons of 511 keV emitted in opposite directions
  - ACD: annihilation coincidence detection
- A ring of PMT detectors surrounding the patient detects and reconstructs coincident pairs of γ-rays separated by 180°
  - Need position, time and energy information



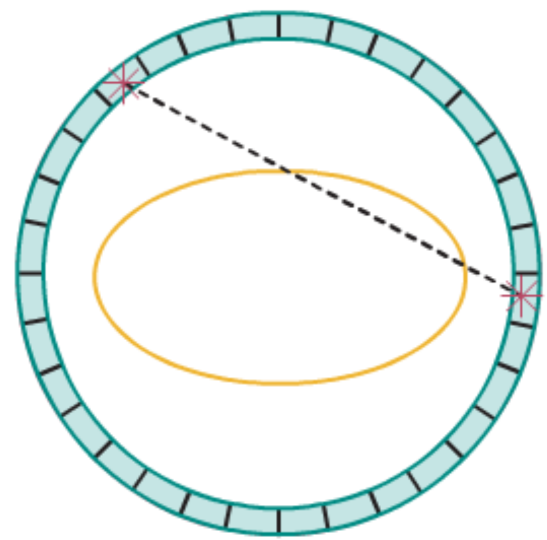


Image source: The Essential Physics of Medical Imaging (textbook)

Attenuation of Emission Photons

- In photon transmission modalities, the attenuation of X-rays through the tissue can be estimated
- In photon emission modalities (i.e. planar nuclear imaging, SPECT, PET), a transmission source need to be included to characterise attenuation in the patient
  - Used for attenuation correction during reconstruction
  - Source can be an external gamma source or X-rays
- For a 20-cm path in soft tissue, ~15% of annihilation photon pairs escaping tissue without interaction

$$(e^{-\mu x})\cdot(e^{-\mu(d-x)}) = e^{-\mu d}$$

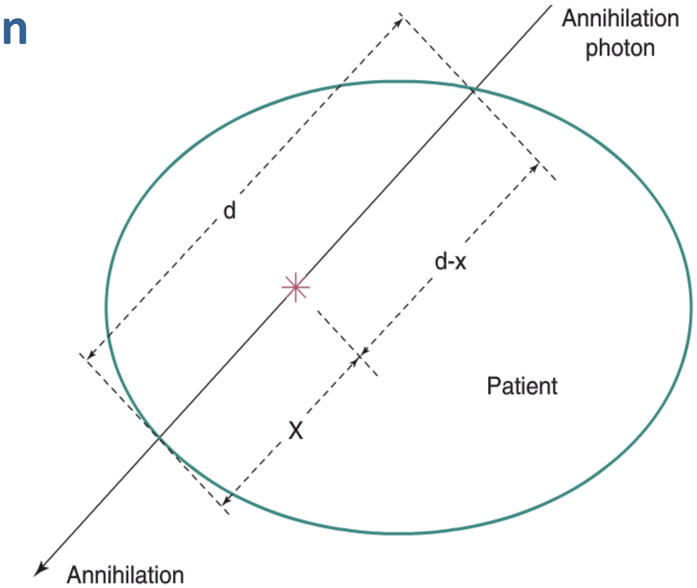


Image source: The Essential Physics of Medical Imaging (textbook)

- CT data used for:
  - Patient alignment
  - Attenuation correction in PET data reconstruction
  - Anatomic information (if CT doses high enough for diagnosis quality)

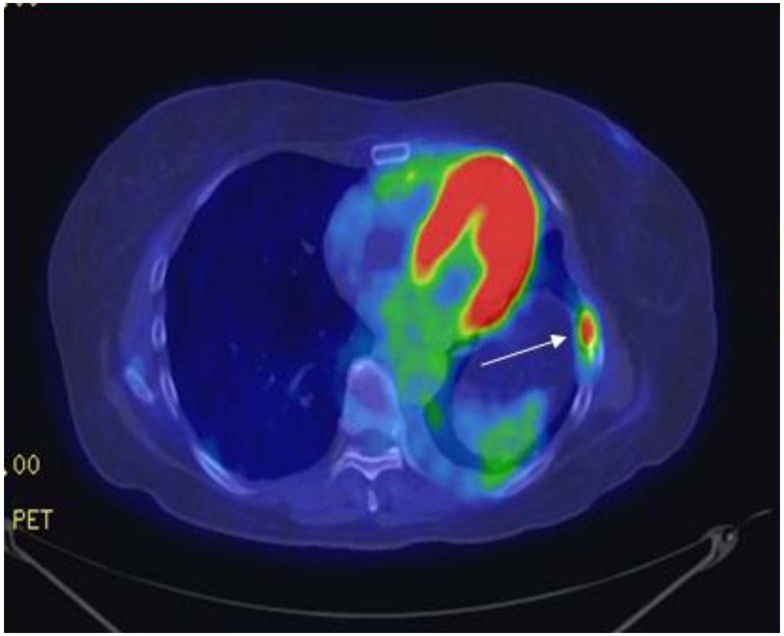


Image source: http://cancergrace.org

Other Combined Modalities

PET/MRI

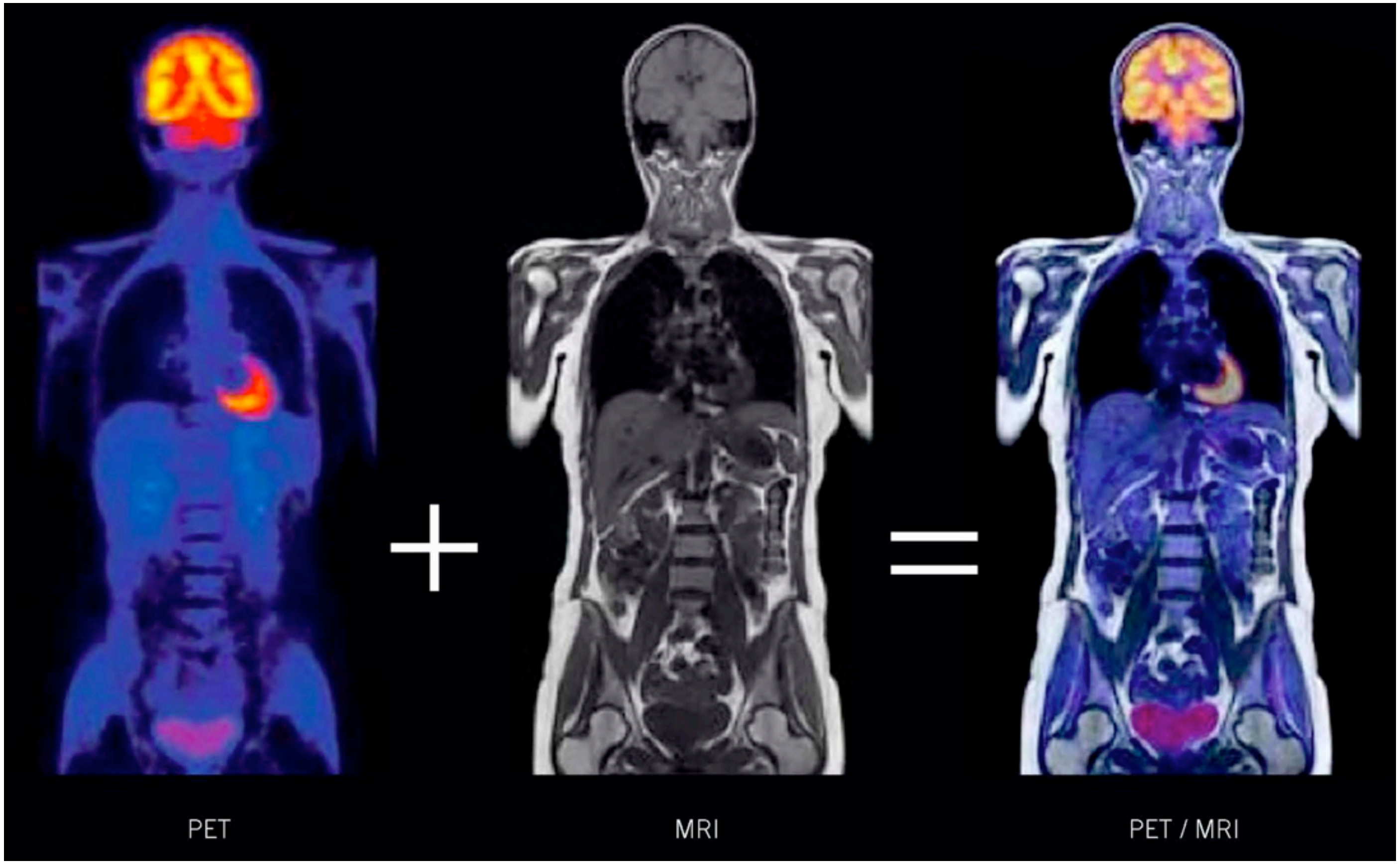


Image source: stonybrookmedicine.edu/imaging/pet-mri

Other Combined Modalities

SPECT/CT

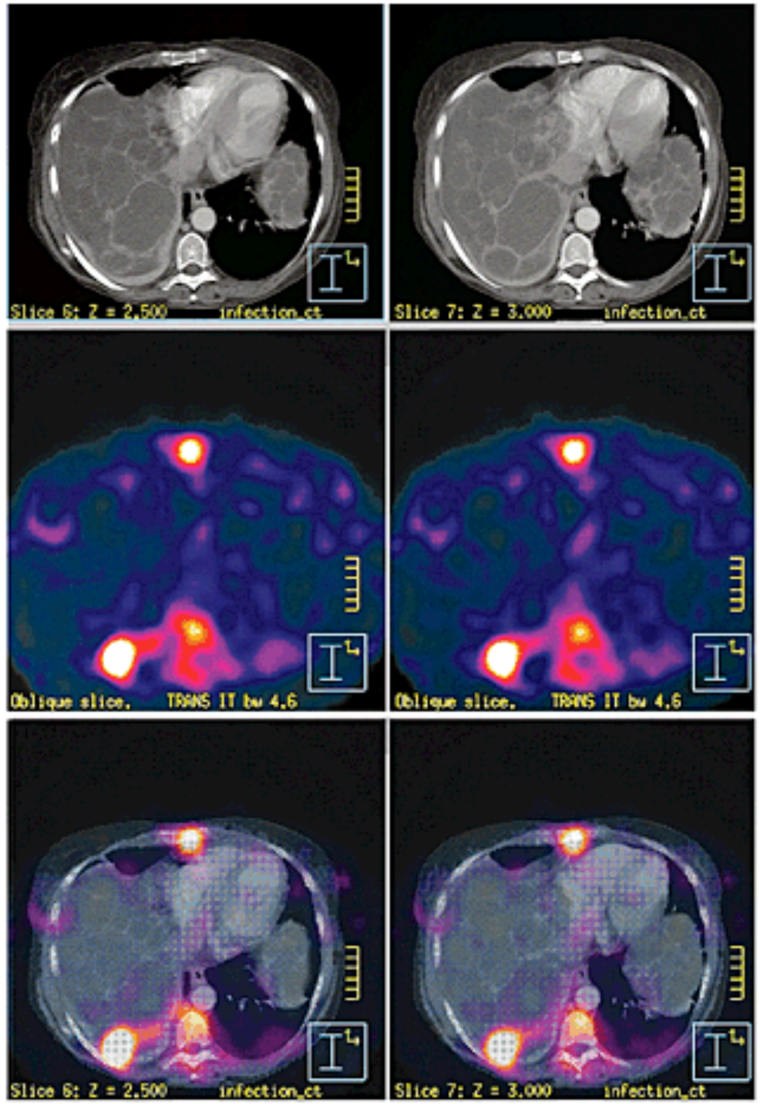


Image source: pubs.acs.org

Other Combined Modalities

SPECT/MRI

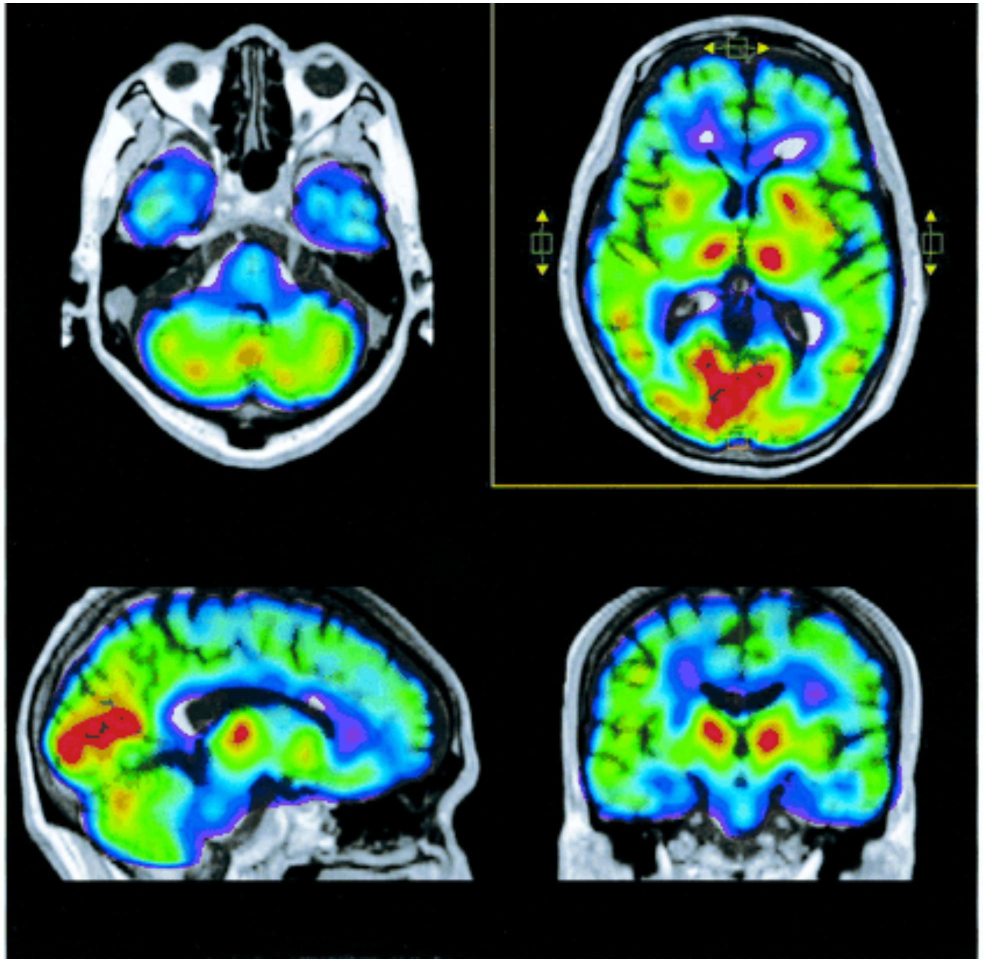
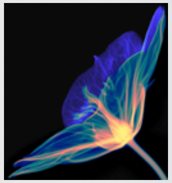


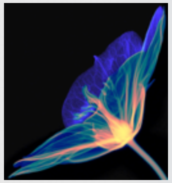
Image source: stonybrookmedicine.edu/imaging/pet-mri



Data Formats

Modality	Pixel matrix format	Pixel word size/dynamic range [bits/pixel]
Digital radiography Fuji CR chest (200 µm) Trixell DR (143 µm)	 2140 x 1760 3000 x 3000	 10-12 12-16
Digital fluoroscopy	512^2 or 1024^2	8-12
Mammography GE-24x31 cm (100 µm) Hologic-24x29 cm (70 µm)	 2394 x 3062 3328 x 4096	 12-16
X-ray CT	512^2	12
MRI	64^2 or 1024^2	12
Ultrasound	512^2	8
Scintillation camera planar	64^2 or 128^2	8 or 16
SPECT	64^2 or 128^2	8 or 16
PET	128^2 or 336^2	16

We can estimate data rates of some of the modalities, but these are highly dependent on system configuration and body part being imaged. E.g. in MDCT, we can assume 4, 8, 16, or 64 slices, a fan angle of 60°, pixels of the order of a few hundred µm, and 0.5 s per gantry rotation.



The DICOM Standard

- DICOM = Digital Imaging and Communications in Medicine
- Define a vendor-neutral set of standards to:
  - Track personal information, imaging machine settings, diagnosis results/opinions, etc. for better (more accurate) patient care
  - Viewable by radiologist consulting from offsite
- A set of medical imaging industry standards, e.g.
  - Data storage formats (.dicom is an image file extension) with image information but also database on the patient imaging history
    - Headers containing information object definitions (IOD)
    - Also annotations or notes from consulting radiologists, etc.
  - Communications protocols
  - Compression
  - Security

Picture Archiving and Communication System (PACS)

- PACS are hardware/software products specifically for the transmission, viewing, processing, and storage (including redundancy) of medical imaging data
- Each imaging department in a large hospital might have a local mini-PACS

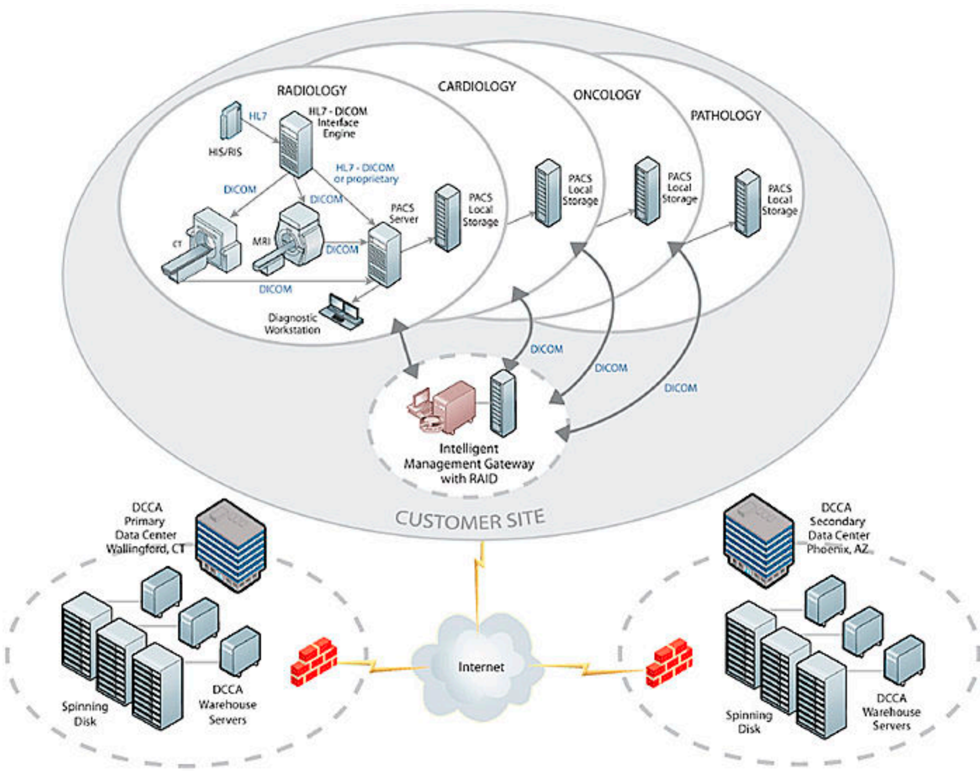
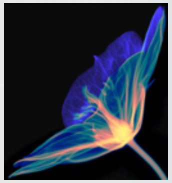


Image source: http://www.medicalexpo.com

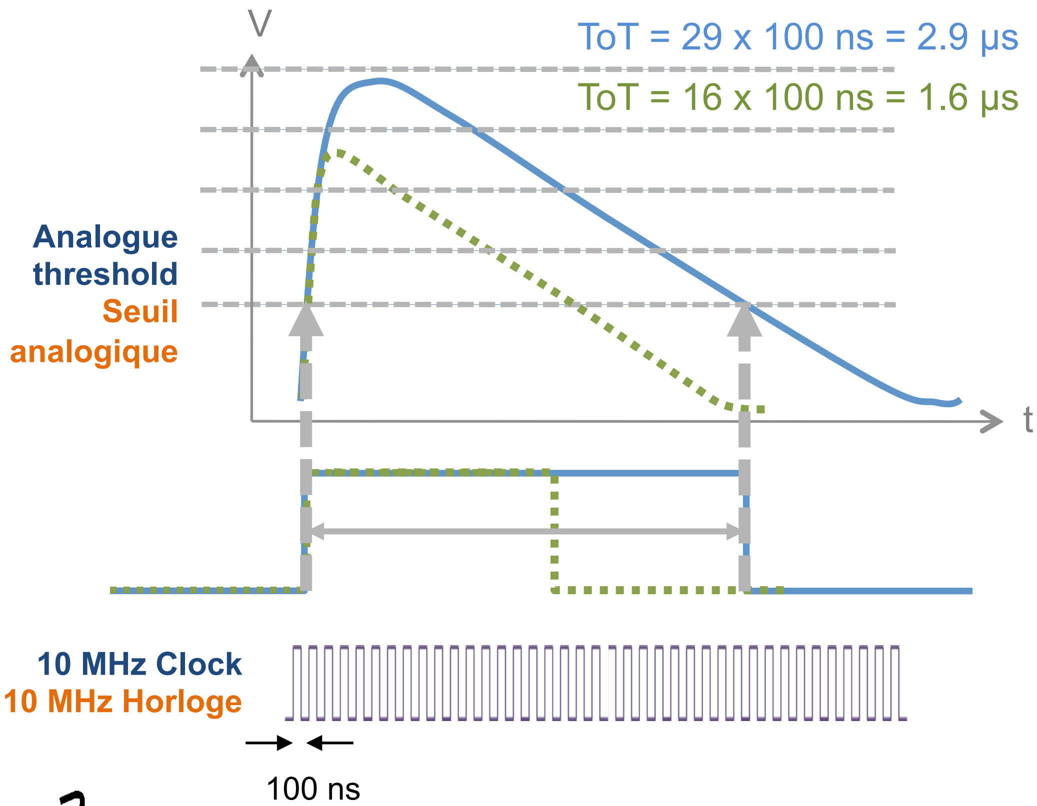
- A lot of web technologies used (e.g. web servers, web browsers)
- Idea is that radiologists from off-site can access the files
- Also considers displays optimised for medical image viewing

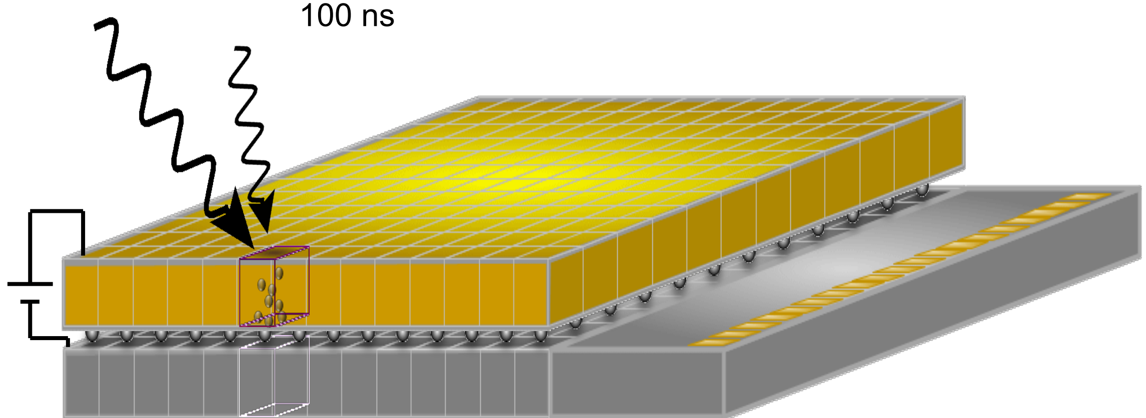
The Medipix Family of Detectors

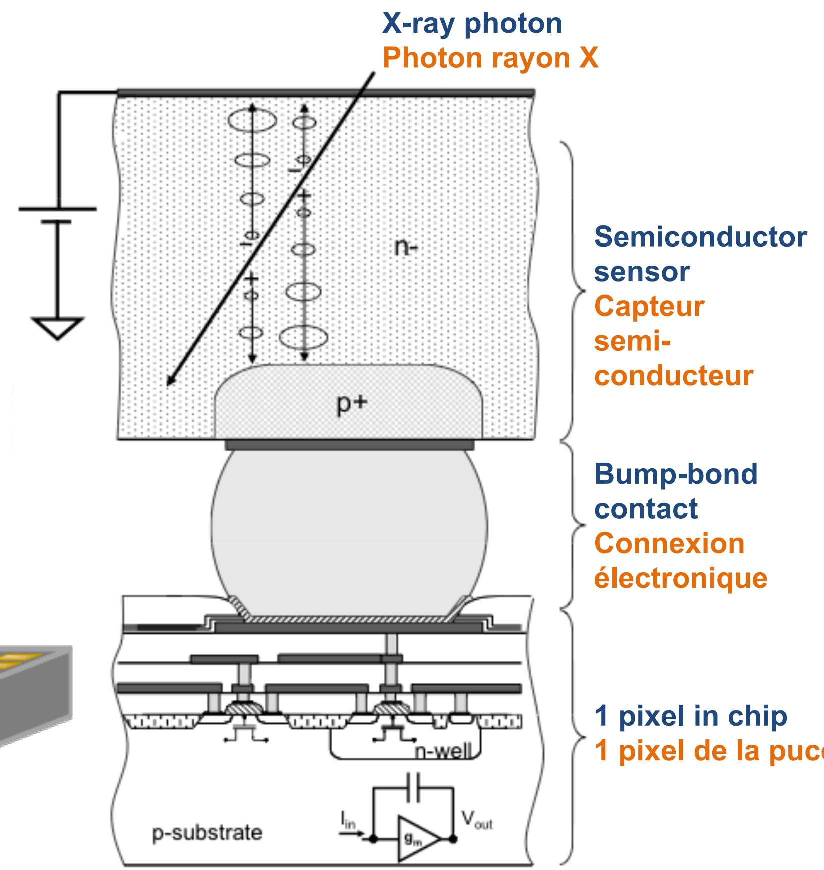


Photon Counting

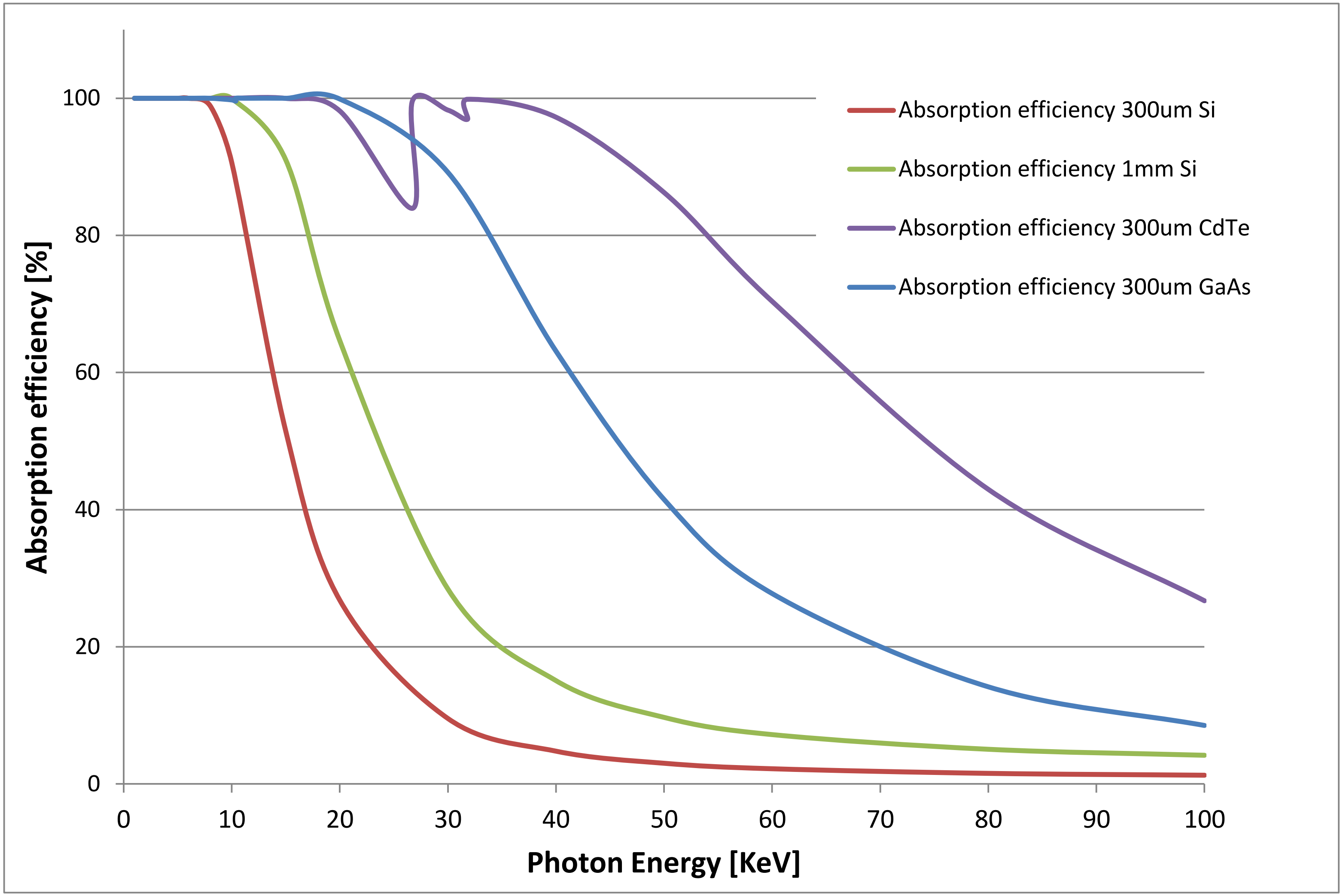
Photon counting **Le comptage de photons**	**E.g. Medipix2, Medipix3**
Time over threshold (ToT) **Temps sur le seuil (ToT)**	**E.g. Timepix, Dosepix, CLICpix Timepix3**



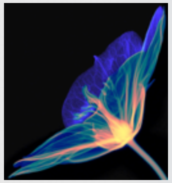




Absorption Efficiency in Semiconductor Sensors



Slide courtesy of R. Ballabriga



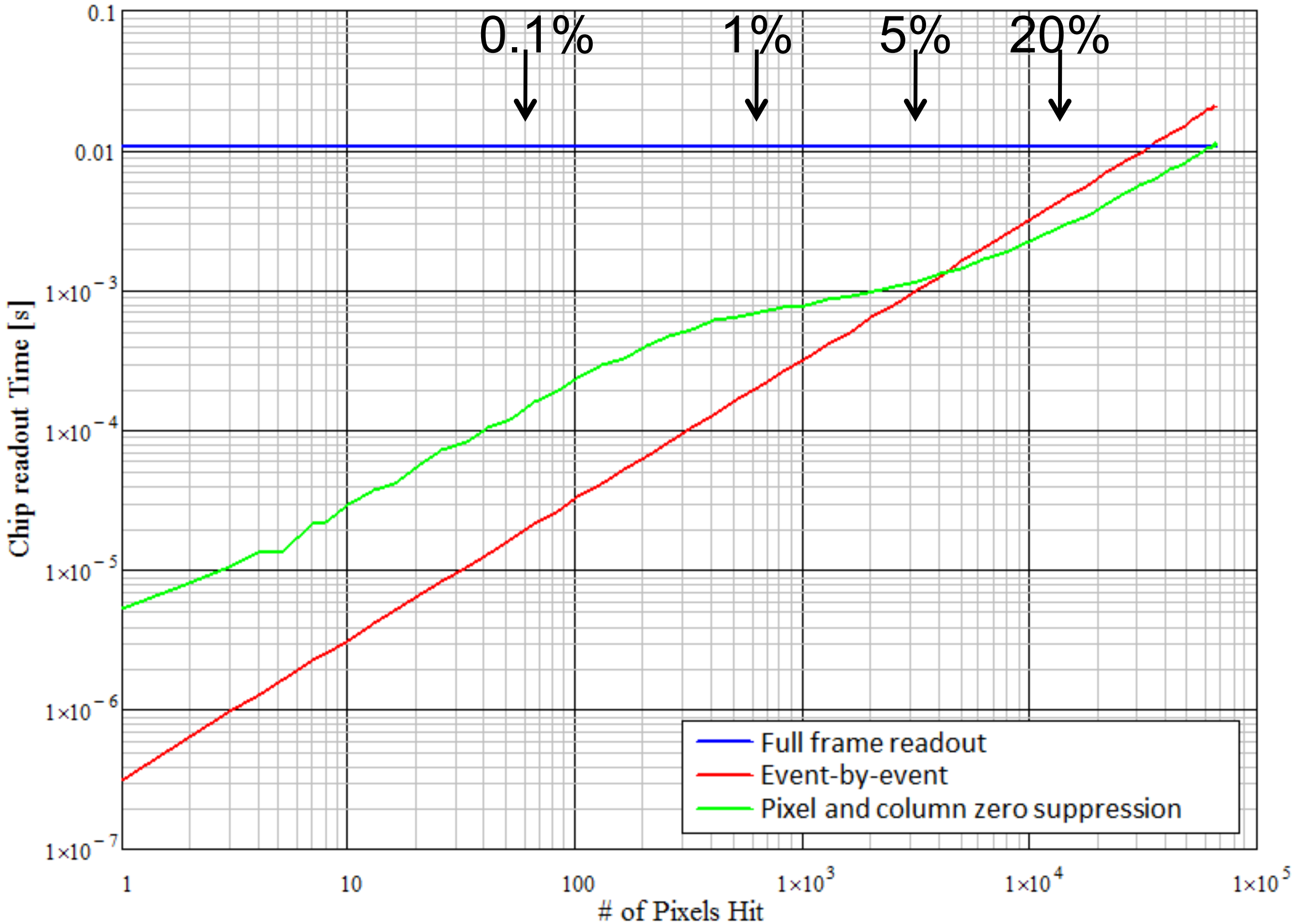
Different Readout Formats

- Full frame (e.g. 256 x 256 pixels per detector) e.g. Medipix2, Medipix3, Timepix
  - Serial
  - 32-bit parallel port
- Continuous read-write e.g. Medipix3
- Rolling shutter e.g. Dosepix
- (Region of Interest) – ROI readout, e.g. in CMOS APS – not in any Medipix chips but useful for imaging

Less for imaging and more for particle tracking (sparse data in frames):

- Zero compression e.g. Timepix3
  - Data push algorithm where the data is encoded in a 48-bit packet that includes the pixel address, ToT counter value and ToA counter value –read out only pixels with data
- Zero suppression e.g. CLICpix
  - Column-wise boolean hit flag

Readout Speed (power) versus Data Occupancy



Similar to:
Medipix3
Timepix3
~CLICpix

Simulation with 100MHz clock, 256x256 pixel matrix, 16 bits/pixel, randomly distributed hits.
Full frame: 256x256x16 bits are read out.
Event-by-event: at each pixel hit, 16bits for the pixel address and 16bits of content are read out.
Zero suppression: columns and pixels not containing data are skipped.

Slide courtesy of M. De Gaspari

Suggested Reading

Textbooks on medical imaging:

J. Bushberg et al., The Essential Physics of Medical Imaging, 3rd Ed., 2012.

L. Hanzo et al., Medical Image Analysis, 2011.

Resources on DICOM and PACS:

DICOM homepage (with downloadable standards): http://medical.nema.org

O. Pianykh, Digital Imaging and Communications in Medicine: a Practical Introduction and Survival Guide, 2008.

Comparing modalities:

http://www.diffen.com/difference/Category:Diagnostics

Some of the Medipix readout systems:

http://aladdin.utef.cvut.cz/ofat/others/RUIN/ (this page includes schematics)

http://www.nikhef.nl/pub/experiments/atlas/pixel/Medipix/

http://quantumdetectors.com/merlin/