U O W

INSPYRE 2018

Dr. Alessandra Malaroda
malaroda@uow.edu.au

UNIVERSITY
OF WOLLONGONG
AUSTRALIA

https://www.surrey.ac.uk/events/20170425-medical-physics-talk

CENTRE FOR MEDICAL RADIATION PHYSICS

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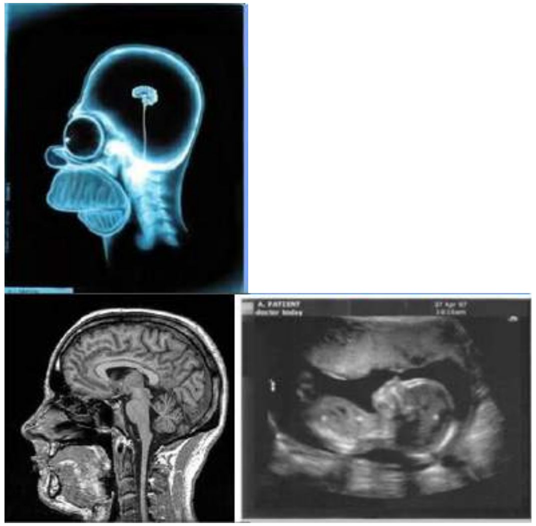
physics and medicine

Looking inside people:
by using X-rays, magnetic resonance and ultrasound



https://www.surrey.ac.uk/events/20170425-medical-physics-talk

Understanding physiology:
Positron Emission Tomography imaging

http://www.phas.ubc.ca/medical-physics

γ -ray vision

using radiation
to peek inside bodies

Alex Malaroda
School of Physics & Centre for Medical Radiation Physics
University of Wollongong
malaroda@uow.edu.au

CENTRE FOR MEDICAL RADIATION PHYSICS

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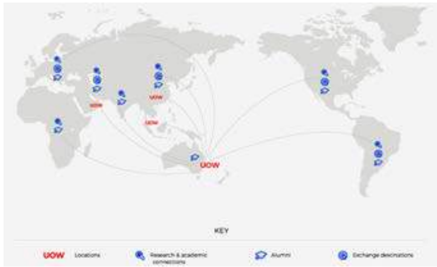
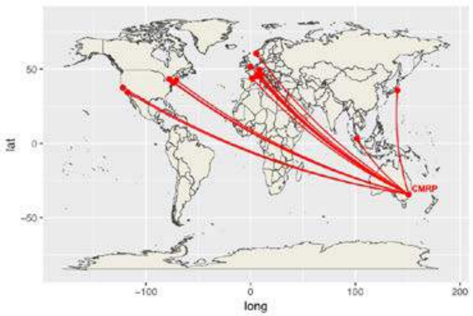
University of Wollongong &
Centre for Medical Radiation Physics

UOW:

- top 2% universities in the world
- 3 international sites/partners: Dubai, Hong-Kong, Singapore
- Undergraduate and postgraduate program in physics and in medical radiation physics



CMRP:
Largest medical physics group in Oceania and south-east Asia



Collaborators:
NASA
Brookhaven National Labs (USA)
Rutherford Labs (UK)
CERN (Switzerland)
INFN, Laboratori di Frascati (INFN)

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PROFUMERIE

Dalla *strada costiera* to the *great pacific drive*

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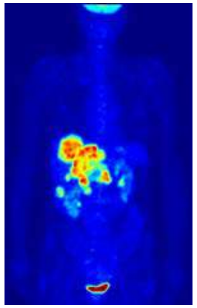
Where Modern Physics Meets Medicine

- Historic background and the discovery of the X-rays
- Modern physics and medicine
  - Production of photons: X-rays and Radioactivity
  - The physics of the photons
- From X-ray projections to conventional tomography to computed tomography
- Emission tomography
  - *The gamma camera*
  - *Single photon emission tomography*
  - *Positron emission tomography*



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5th Solvay international conference on Electrons and Photons (1927)

front row

Irving Langmuir, Max Planck, Marie Curie, Hendrik Lorentz, Albert Einstein, Paul Langevin, Charles-Eugène Guye, C.T.R Wilson, Owen Richardson.

middle row

Peter Debye, Martin Knudsen, William Lawrence Bragg, Hendrik Anthony Kramers, Paul Dirac, Arthur Compton, Louis de Broglie, Max Born, Niels Bohr.

back row

Auguste Piccard, Émile Henriot, Paul Ehrenfest, Édouard Herzen, Théophile de Donder, Erwin Schrödinger, JE Verschaffelt, Wolfgang Pauli, Werner Heisenberg, Ralph Fowler, Léon Brillouin.

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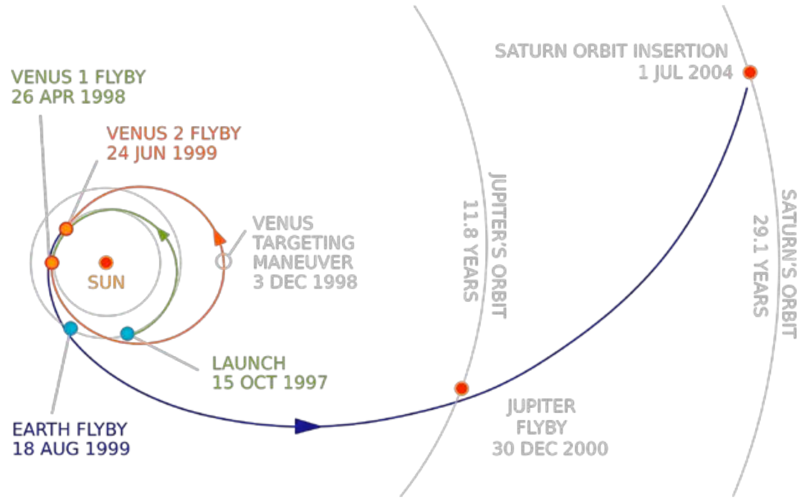
WHY MODERN PHYSICS?

Classical physics works

Cassini interplanetary trajectory



https://saturn.jpl.nasa.gov/resources/1776/

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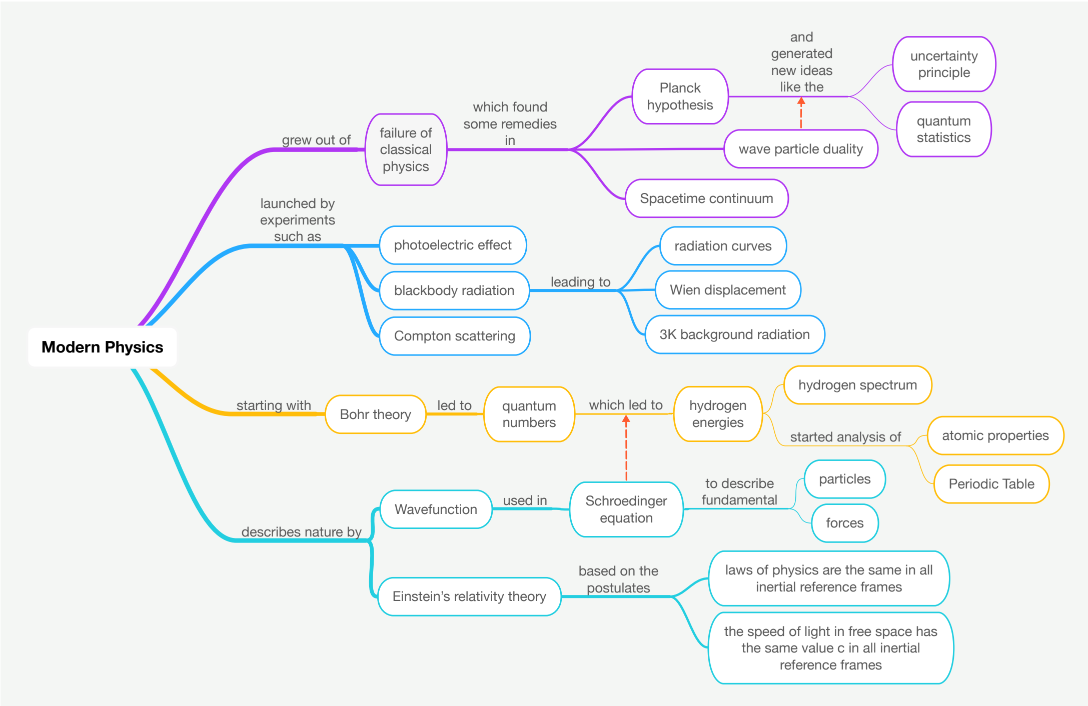
Modern Physics



Adapted from http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

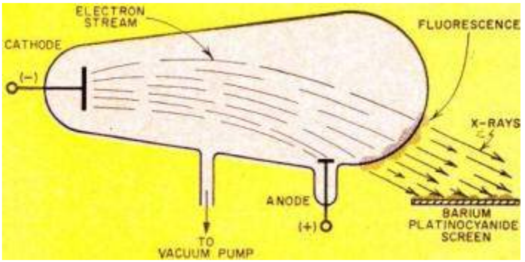
The discovery of the X-rays

1895

First X-ray: Roentgen's wife hand

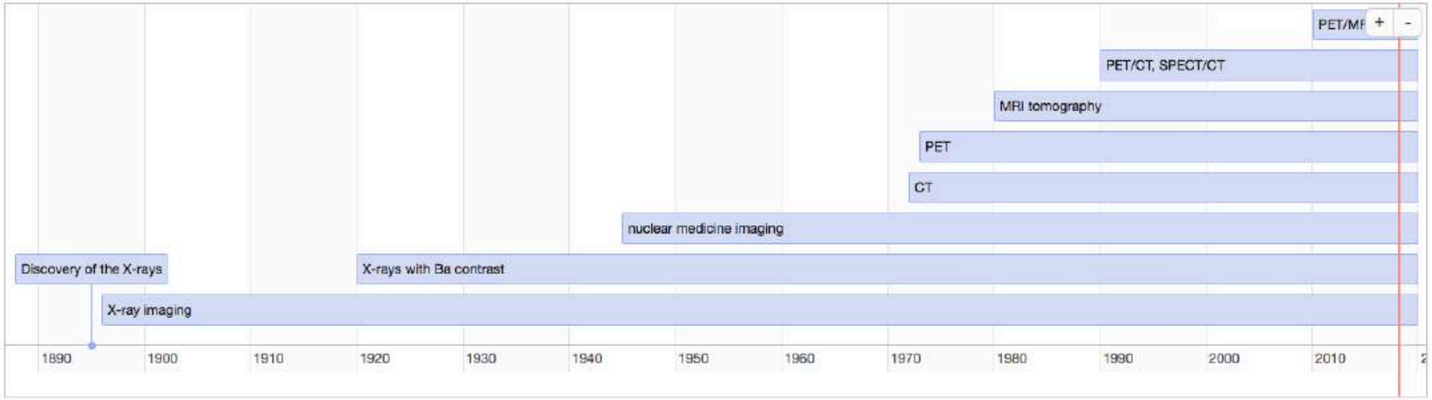
http://www.awesomestories.com/asset/view/First-X-ray-1895-Anna-Bertha-Roentgen-s-Hand

Roentgen observed highly penetrating radiation while studying cathode rays in tubes evacuated of air.



http://www.rfcafe.com/references/popular-electronics/x-rays-october-1960-popular-electronics.htm

The evolution of medical imaging



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The physics of imaging

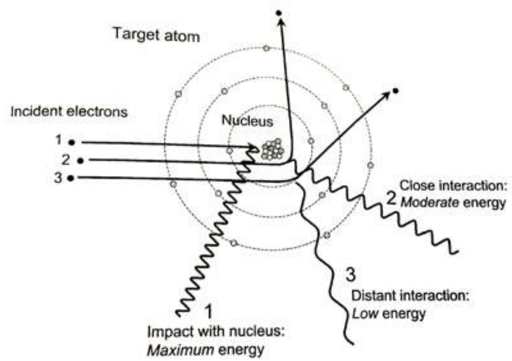
1. Electrons decelerating in a material emit photons
   - X-rays are produced through the Bremsstrahlung effect

2. Unstable nuclei emit particles in order to become “stable”:
   - Gammas, electrons, positrons, alpha particles

3. Photons interacting in a material can be:
   - Absorbed (photoelectric effect)
   - Deflected (change direction) but not losing energy (Rayleigh scatter)
   - Change direction, lose energy and free electrons (Compton scatter)
   - Pair production

Bremsstrahlung: production of photons

- Charged particles decelerated by the electric and magnetic field of a nucleus lose kinetic energy, which is converted into emission of photons (x-rays)
- The emitted photons can have energies between 0 and the maximum kinetic energy of the incident charged particle



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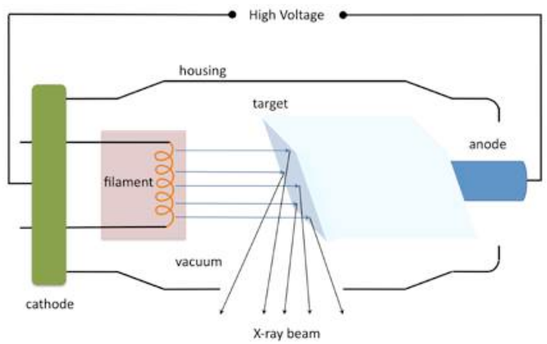
Production of x-rays

- x-rays are produced by the deceleration of electrons in a target material (Bremsstrahlung):
- electrons are emitted by a filament (tungsten) heated at 2000 °C and accelerated towards a target (e.g. aluminium, tungsten or copper), the electrons are decelerated within the target and bremsstrahlung and characteristics (for the target material) x-rays are produced.
- The x-ray beam is than collimated (pre-patient collimation).
- The x-ray produced by an x-ray tube is a poly-energetic (polychromatic) beam with energies between 0 up to kVp keV.
- The kVp (kilovolt peak) is the maximum voltage applied across the x-ray tube and determines the maximum energy of the electrons impacting on the tube target and the maximum energy of the x-ray emitted.



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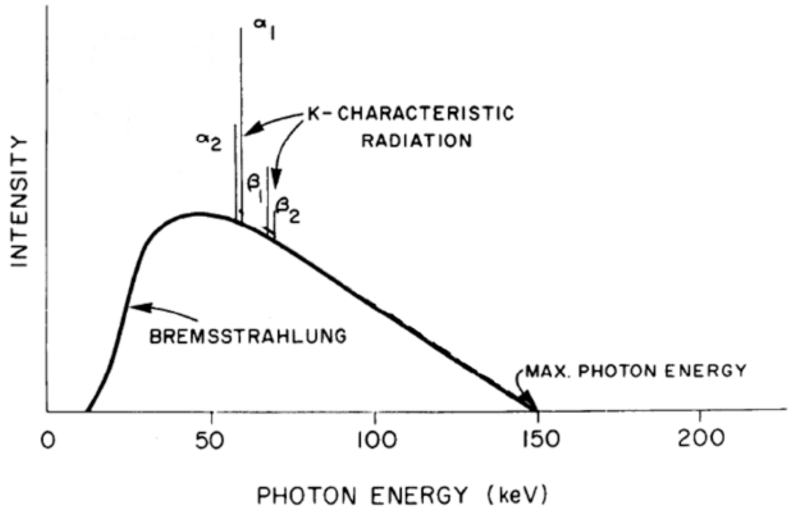
Production of X-rays

- x-rays are produc
(Bremsstrahlung)
- electrons are emit
accelerated towar
electrons are dec
characteristics (fo
- The x-ray beam is
- The x-ray produce
beam with energi
- The kVp (kilovolt p
tube and determir
the tube target an



The spectrum of bremsstrahlung and K-characteristic radiation

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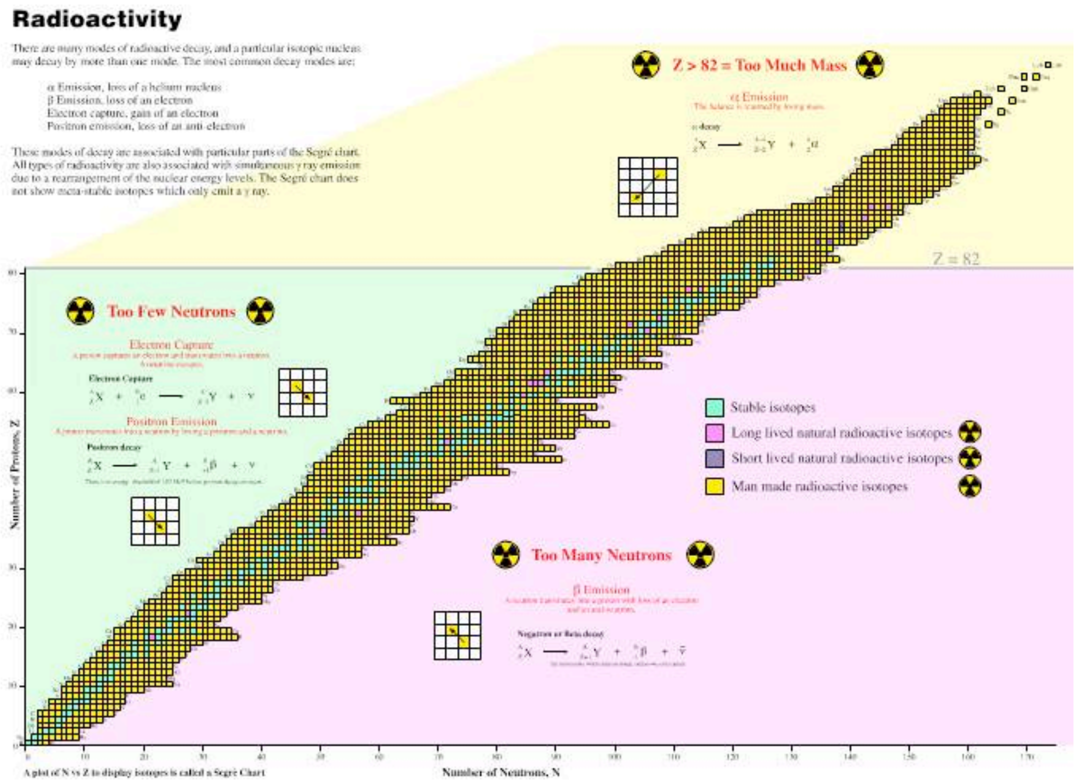
Unstable nuclei: radioactivity



- Gamma emission
  too much energy
- Alpha emission:
  too much mass
- Electron emission:
  too many neutrons
- Positron emission:
  too few neutrons

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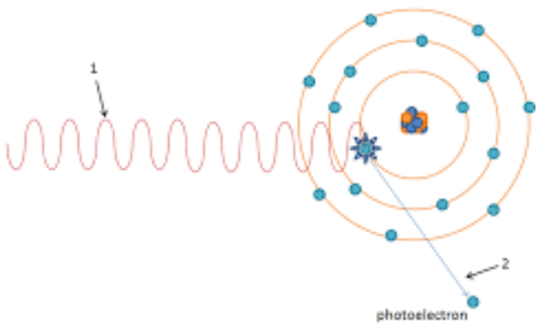
Photons interaction with matter

- Photoelectric effect
- Scatter:
  - Coherent
  - in-coherent scatter
- Pair production: e^{-} - e^{+}

Photoelectric effect



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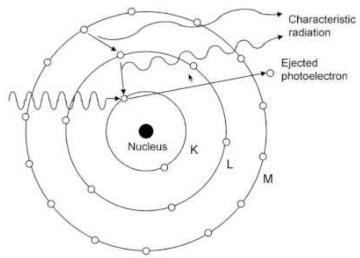
Photons interaction with matter

- Characteristic X-rays

- Scatter:
  - Coherent
  - in-coherent scatter

- Pair production: e^- - e^+

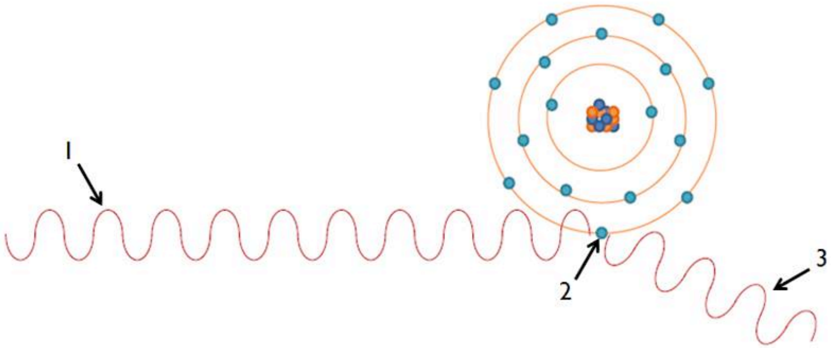


Photons interaction with matter

- Photoelectric effect
- Scatter:
  - Coherent
  - in-coherent scatter
- Pair production: e^- - e^+

Coherent scattering

(Thompson scattering)



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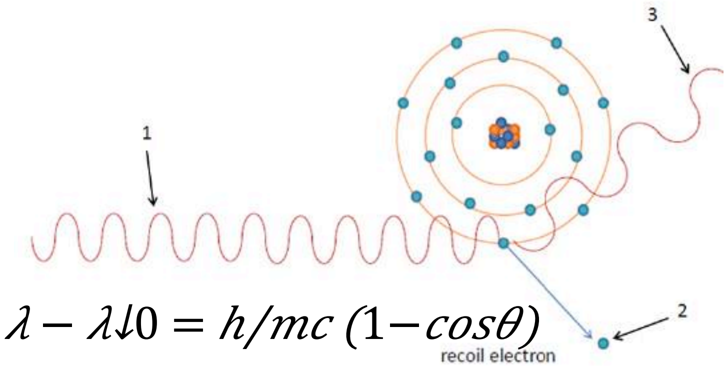
Photons interaction with matter

- Photoelectric effect
- Scatter:
  - Coherent
  - in-coherent scatter (Compton)
- Pair production: e^{-} - e^{+}

Compton scattering



$$\lambda - \lambda_0 = h/mc\,(1-\cos\theta)$$

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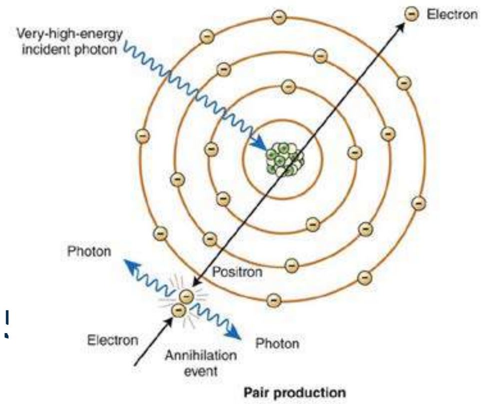
Photons interaction with matter

- Photoelectric effect
- Scatter:
  - Coherent
  - in-coherent scatter
- Pair production: e^- e^+

  $E_\gamma \geq m_{e^-} c^2 + m_{e^+} c^2 = 2m_{e^-} c^2 = 2 \cdot$

  (E_γ in medical imaging ~ 80-200 keV)



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Attenuation of a photon

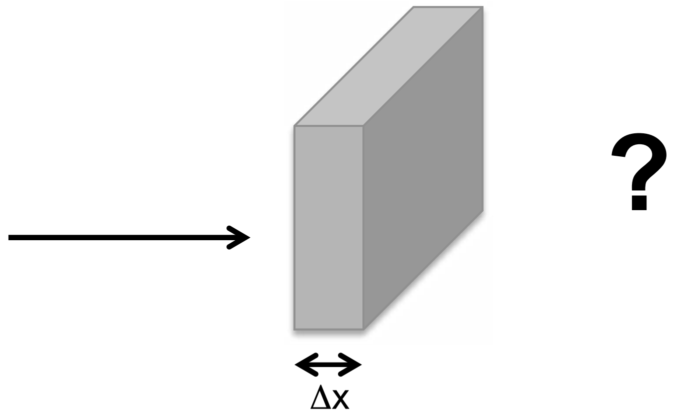
The photon can:

- Be transmitted with no interaction
- Be absorbed (photo-electric effect)
- Get scattered:
  - without losing energy (coherent scatter)
  - Losing energy (Compton scatter)
- Produce an $e^- e^+$ pair

Which one of these processes is the most probable?

depends on the *cross-section* of each process

which depends on the: energy of the photon and the material of the target



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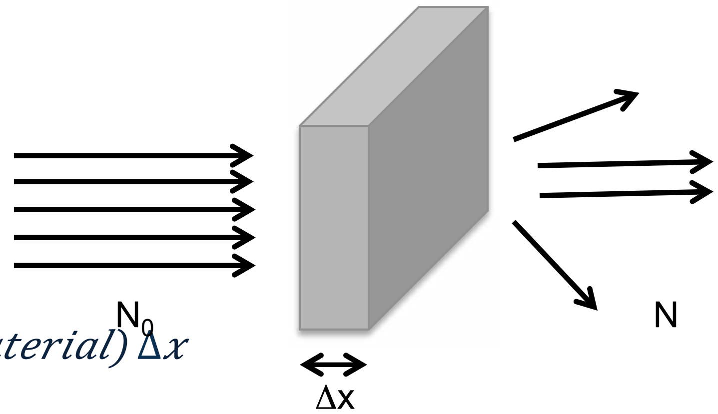
Attenuation of photons

- A number N_0 of photons incident to an object can undergo photoelectric effect, scatter (coherent, Compton) or pair production (if E > 1.02 MeV)



$$N - N_0 = \Delta N = -N_0\ \mu\, \Delta x \quad \Rightarrow N = N_0\, e^{-\mu(E,\, material)\, \Delta x}$$

- The probability of N transmitted photons is proportional to the linear attenuation coefficient μ of the material

$$\mu = \mu_{photoelectric} + \mu_{scatter} + \mu_{pair\ production}$$

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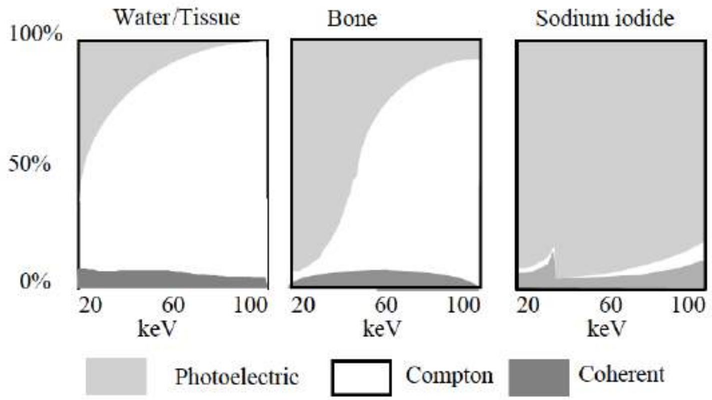
Photon interaction modes

Relative importance of photon interaction modes for tissue, bone and NaI for incident photon of energies between 20 and 100 keV



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(projection) radiography

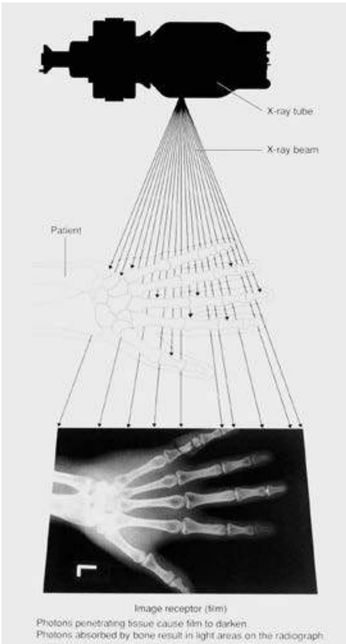

FIGURE 1–8. Relative positions of x-ray tube, patient, and film necessary to make the radiograph shown. Bones tend to stop diagnostic x-rays, but soft tissue does not. This results in the light and dark regions that form the image.

- The image is a given by the number of photons transmitted through the object
- The transmission depends on the material traversed:
  - attenuation coefficient of bone > attenuation coefficient of soft tissue
  - attenuation coefficient of soft tissue > attenuation coefficient of air

➔ more photons attenuated by bone than soft tissue

In order to form an image, enough photons needs to be transmitted onto the film/detector

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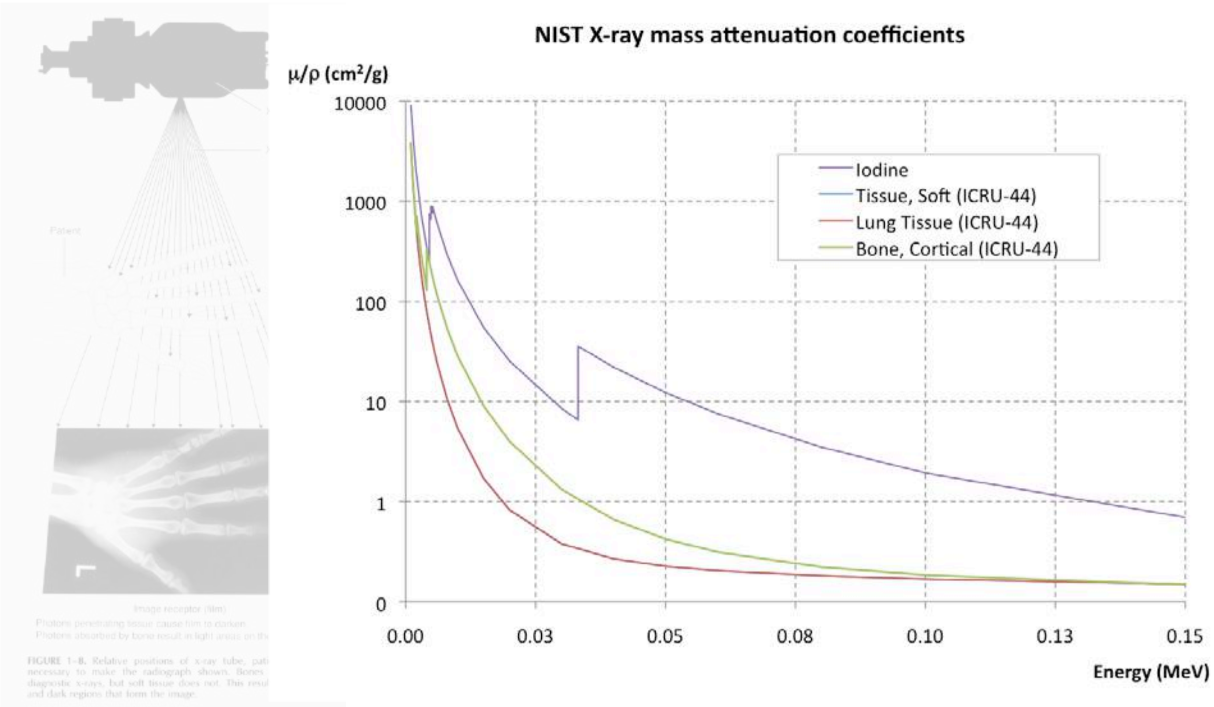
(projection) radiography



itted through the

ficient of soft tissue

sue

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mammography

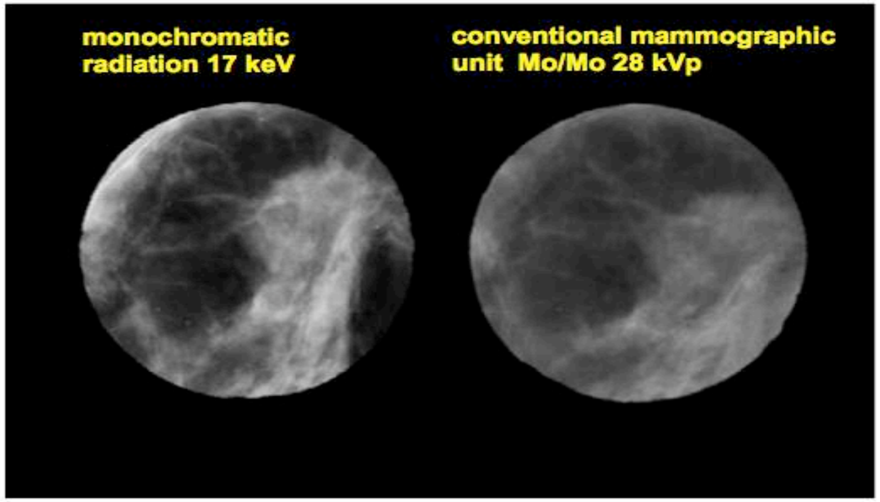
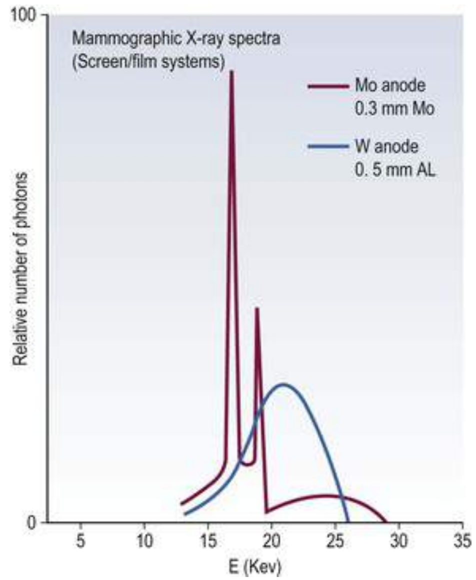


Fig. 3 – Confronto fra una mammografia monocromatica (sinistra) con una tradizionale (destra).



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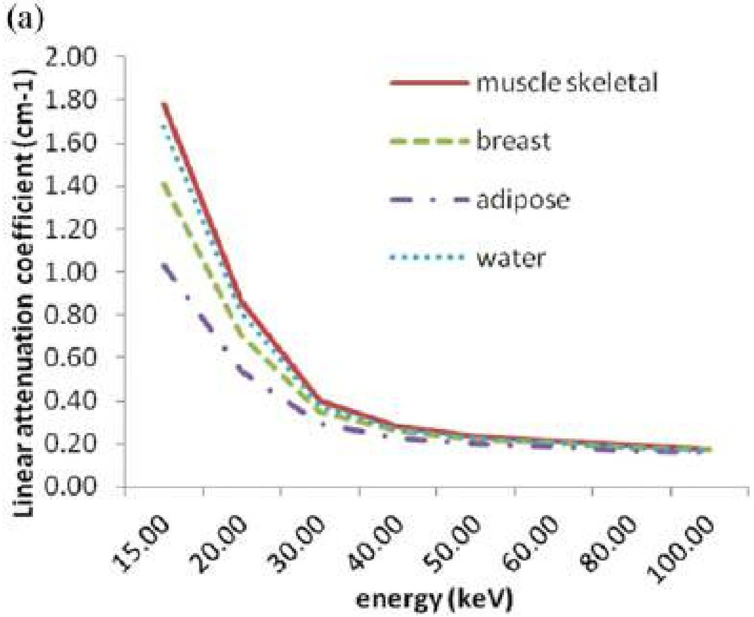
mammography

Fig. 3 – Confronto fra una mammografia monocromatica (sinistra) con una tradizionale (destra).



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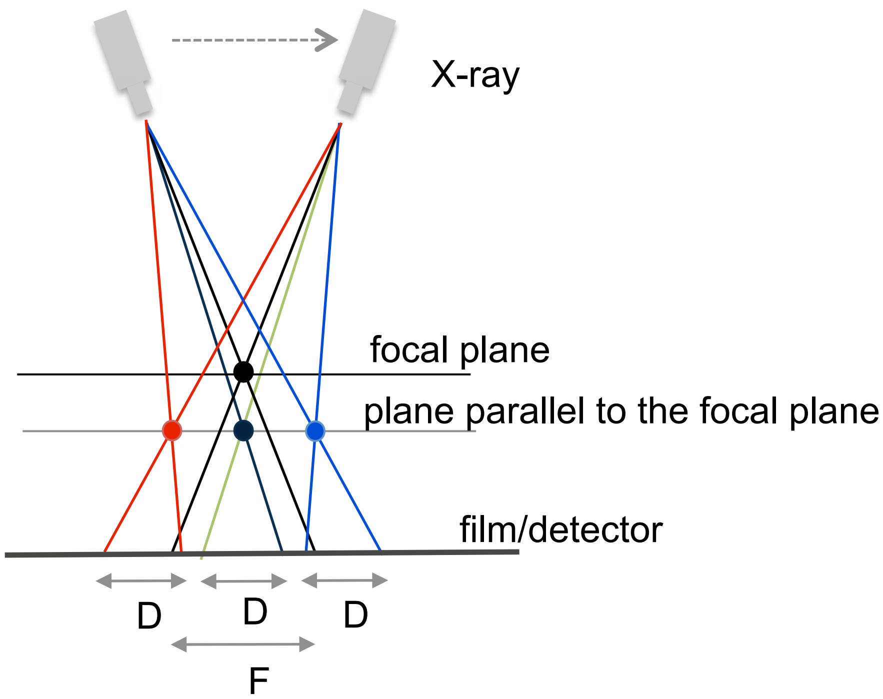
Conventional tomography



Moving the detector with speed

$$v_{detector} = \frac{H-h}{h} v_{Xrays}$$

Objects outside the focal plane will be blurred

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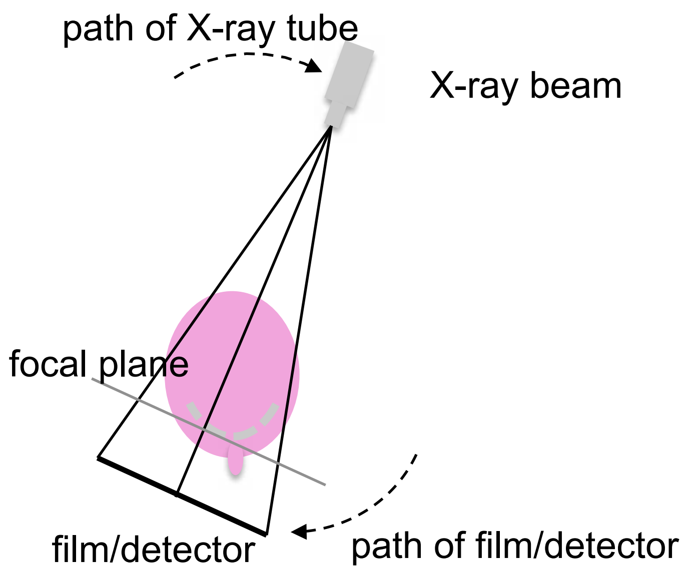
Dental panoramic

- developed in 1933
- first commercial machine in 1950s



http://www.hamamatsu.com/jp/en/hamamatsu/newsroom/advertisements/nature/0807ccd/en.html

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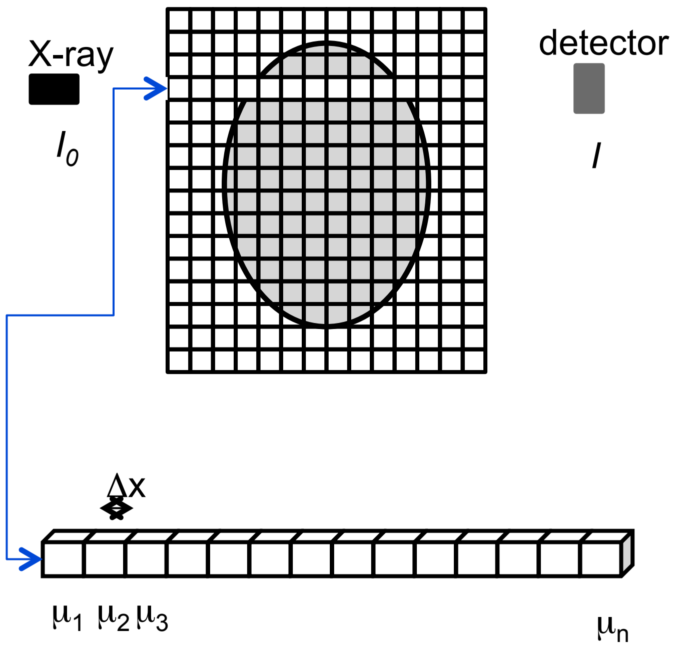
3D X-ray images



I_0 intensity of produced X-rays, I intensity of detected X-rays.
I is the number of photons not attenuated in the object.

Beer's Law:

$$I = I_0 e^{-\int_a^b \mu(x)\,dx} \quad \Rightarrow \quad -\ln\left(\frac{I}{I_0}\right) = \int_a^b \mu(x)\,dx$$

μ material's attenuation coefficient, depends on X-ray beam energy and materials the photons pass through

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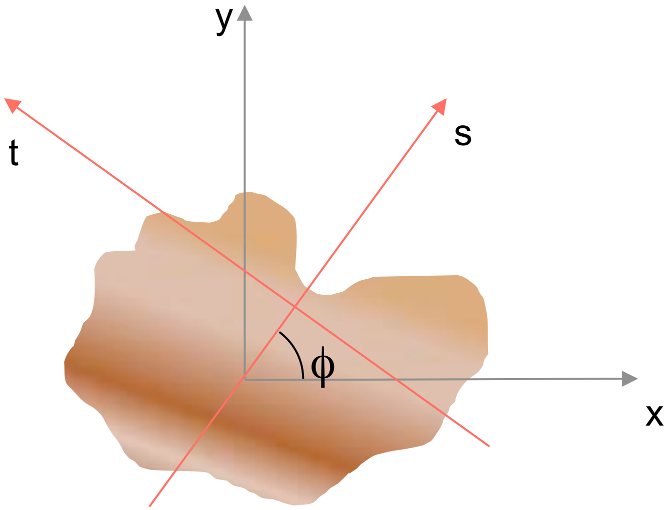
Radon transform (1917)

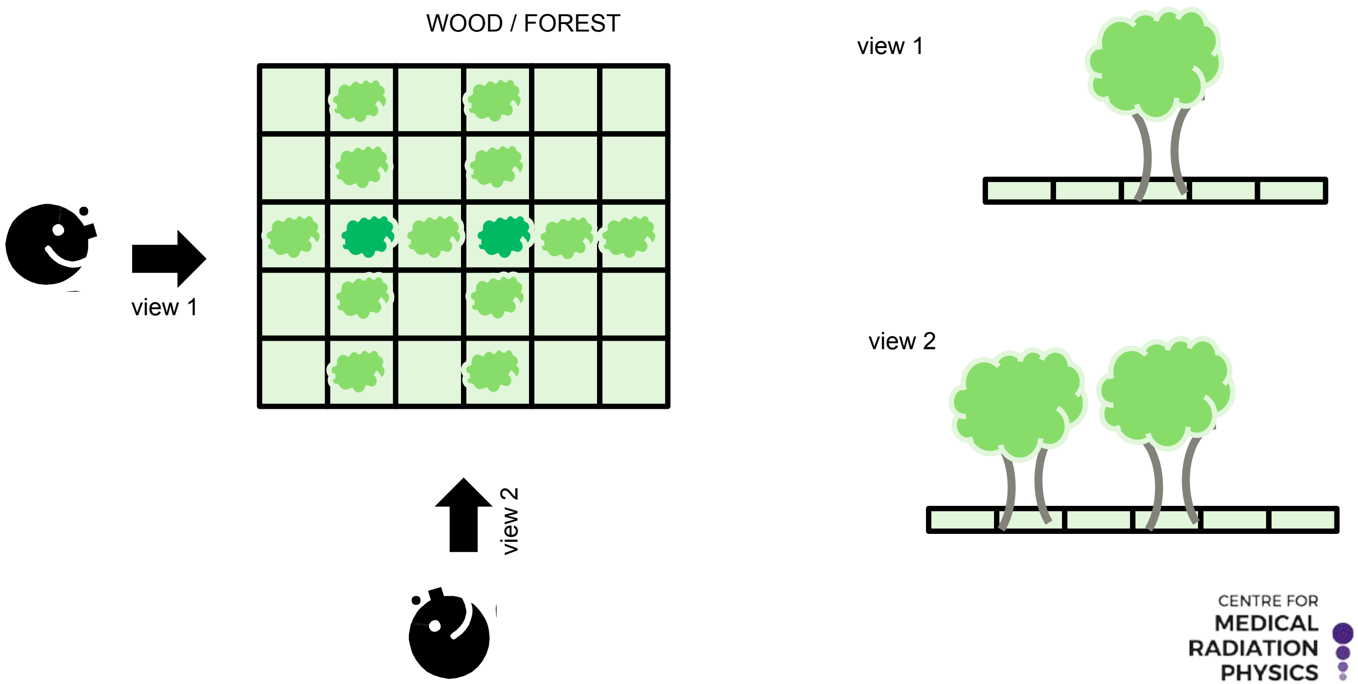


Radon proved that a 2D function f can be "reconstructed" from the line integrals around the function ($-\infty \le s \le +\infty$ and $0 \le \phi \le 360^o$) by inverting the operator Radon transform R:

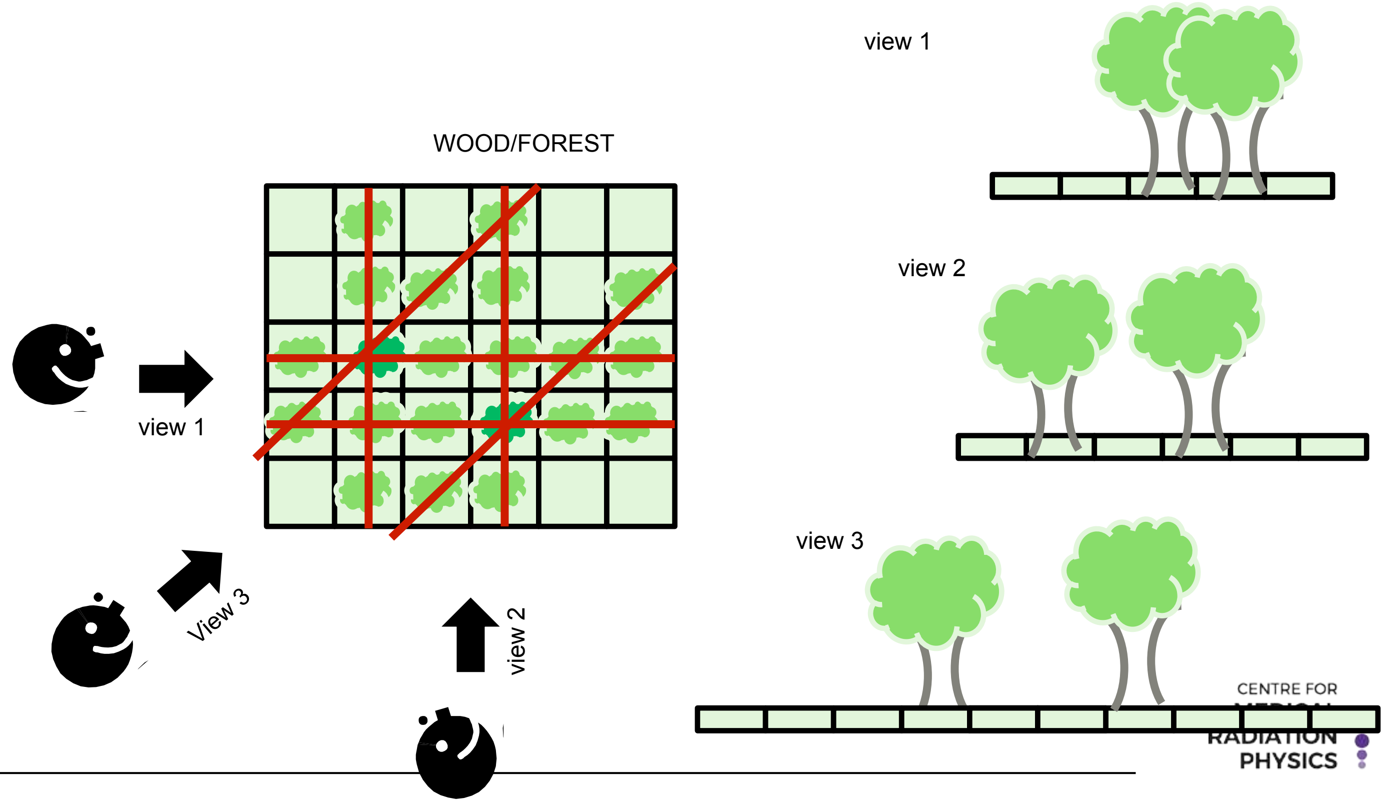
$$p(s,\phi)=R[f(x,y)]=\int^{t(s,\phi)} f(t)dt$$

$$f(t)= R^{-1} [p(s,\phi)]$$

Backprojection - 0



Backprojection - 0



The 1st CT

Ambrose and Hounsfield,
Br J Radiol (1973) 46, 1016

Computerized transverse axial scanning (tomography): Part I. Description of system

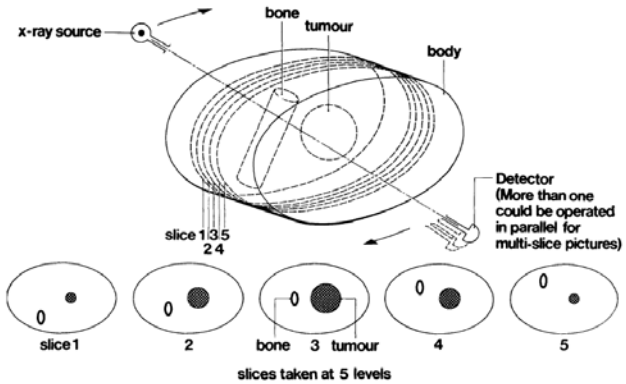
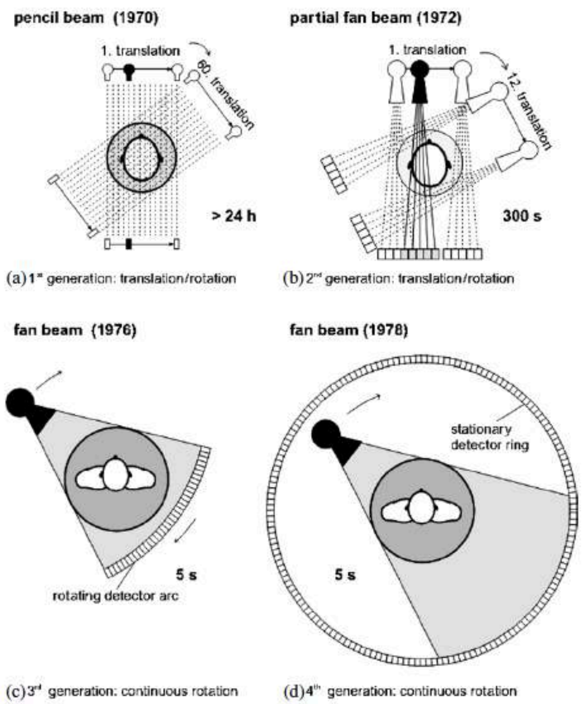


Fig. 1.
Computerized transverse axial techniques on a body containing bone and tumour.

Evolution of CT technology



from Kalender; Phys Med Biol (2006) 51; R29

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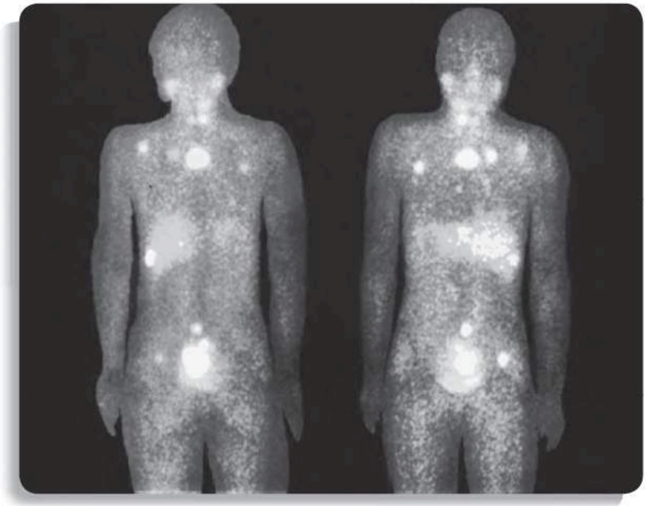

Radioactive isotopes have proven to be valuable tools for medical diagnosis. The photo shows gamma-ray emission from a man who has been treated with a radioactive element. The radioactivity concentrates in locations where there are active cancer tumors, which show as bright areas in the gamma-ray scan. This patient's cancer has spread from his prostate gland to several other locations in his body.

Alex Malaroda, UOW

Dr Erin McKay, St George Hospital (Kogarah, Australia)

NUCLEAR MEDICINE IMAGING

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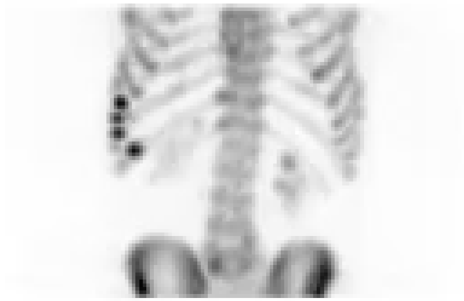
Radioactivity in medicine

- Unstable nuclei (radionuclides) decay to stable states emitting particles:
  - Gamma rays, electrons, positrons, alpha particles

- Radionuclides can be attached to pharmaceuticals or molecule that can follow a physiological or biochemical process

Bone scan

- ^{99m}Tc methylene diphosphonate (MDP) is taken up by fast growing osteoblast cells
- ^{99m}Tc is a metastable radionuclide: it decays emitting photons with energy
- 140 keV
- Increased uptake of MDP in areas of inflammation, fractures or cancer (primary or metastases)



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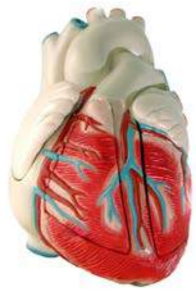
Cardiac studies: gated blood pool

- ^{99m}Tc pertechnetate is injected to label red blood cells
- amount of blood in the heart at different beating phases can be measure



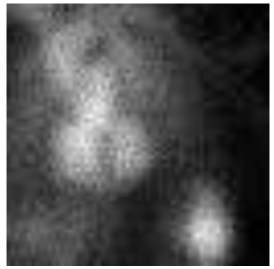


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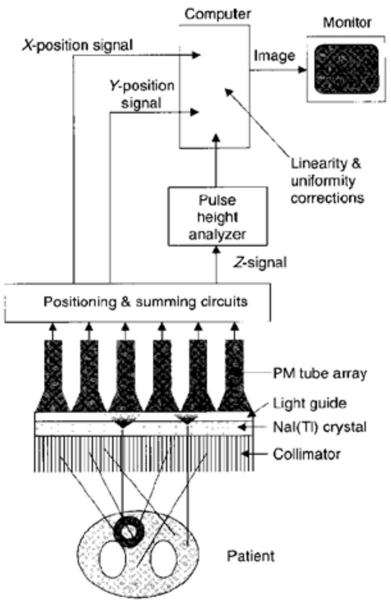
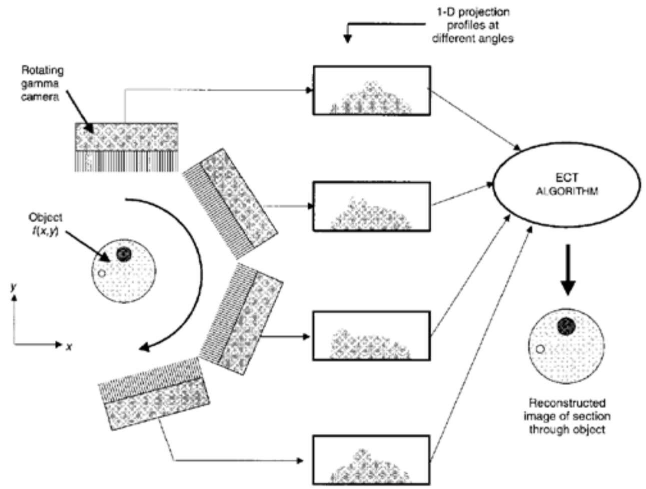
Image acquisition

Planar imaging



3D imaging
Single Photon Emission Tomography - SPECT



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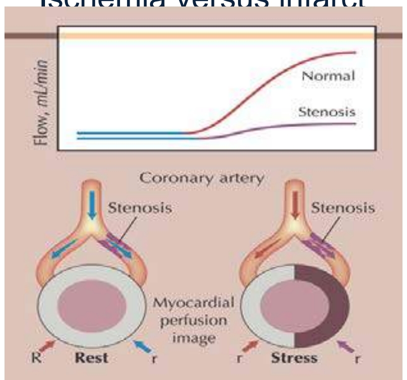
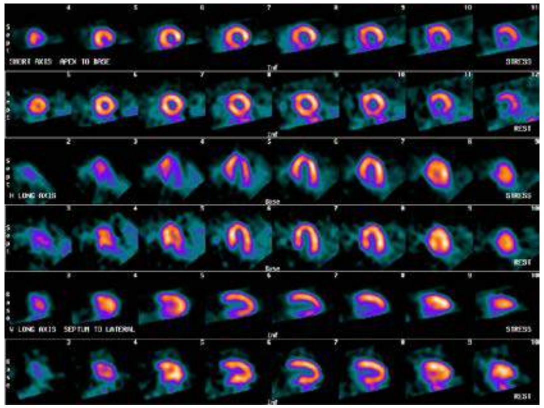
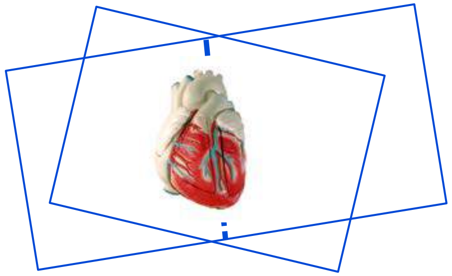
Myocardial perfusion

- ^{99m}Tc sestamibi distributes in the myocardium proportionally to the myocardium blood flow

- Ischemia versus infarct







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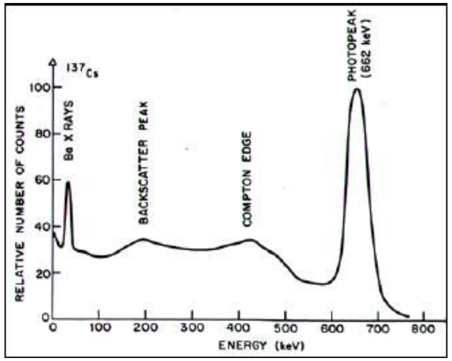
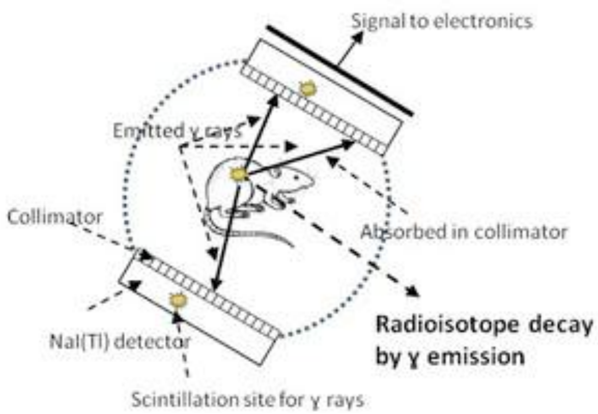
Considerations in image formation

- Radionuclide decays with time and redistribute within the body during the imaging
- Photons travel through the patient and within the detector
  - They get absorbed and scattered





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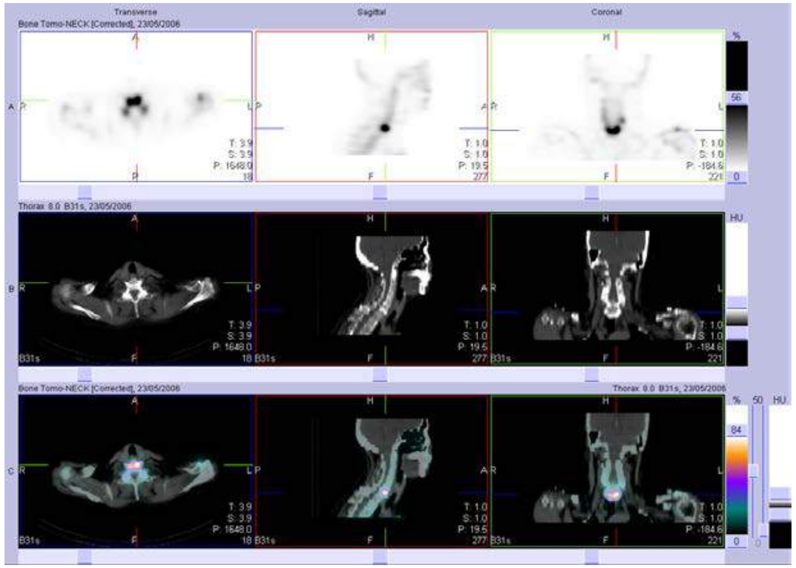
SPECT/CT



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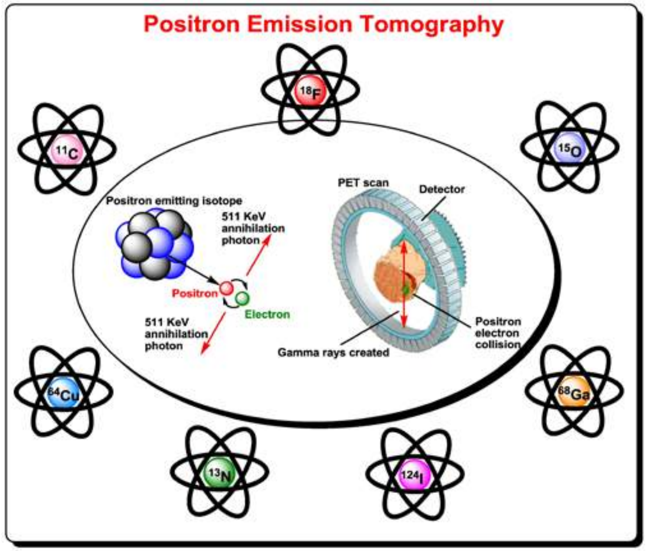
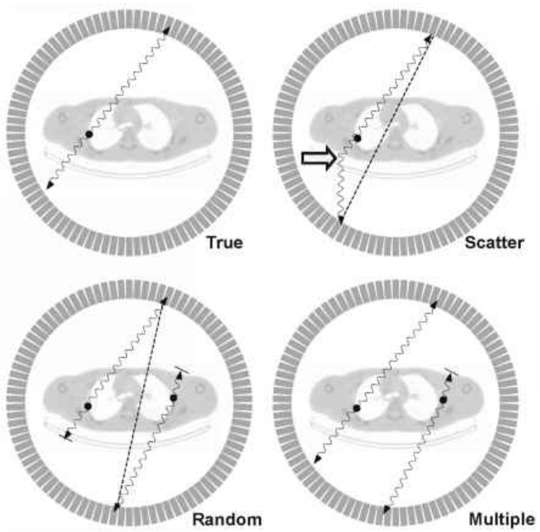
Positron Emission Tomography





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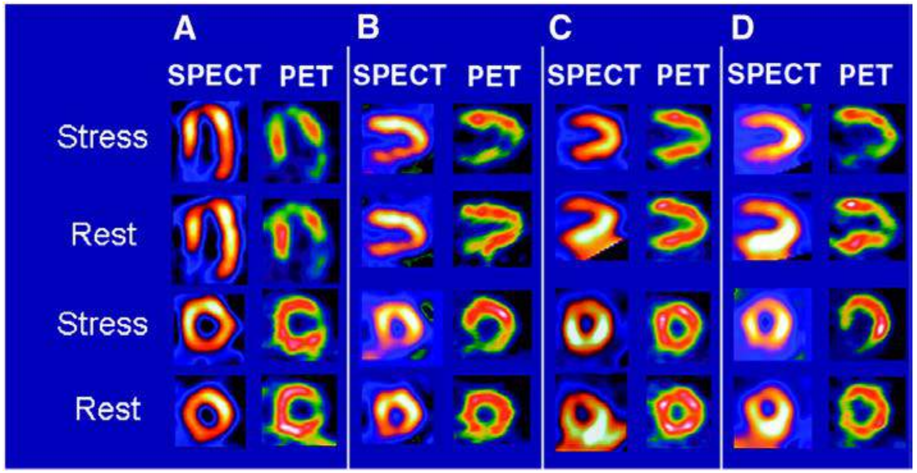
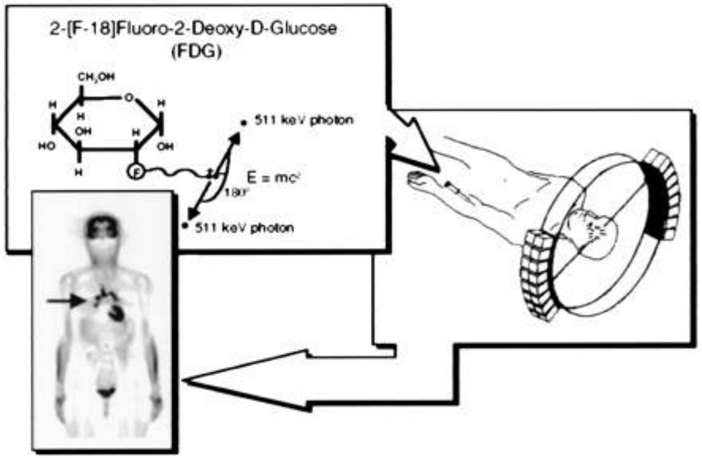
^{18}F-FDG imaging

[18]F-flourodeoxyglucose





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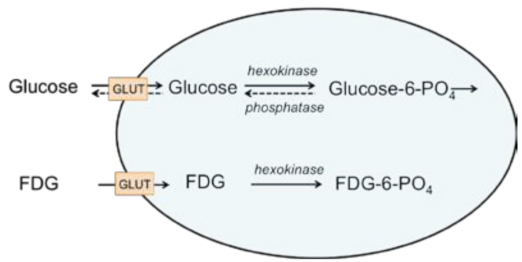
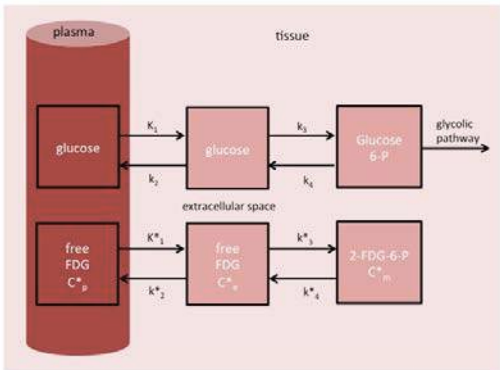
Glucose metabolism

- FDG is a glucse analogue, used by cells like glucose
- FDG-PET scans can be used to measure the cellular *metabolic rate of glucose* (MRGc)





$$MRGlc = k_1^* \, k_3^* / k_2^* +$$

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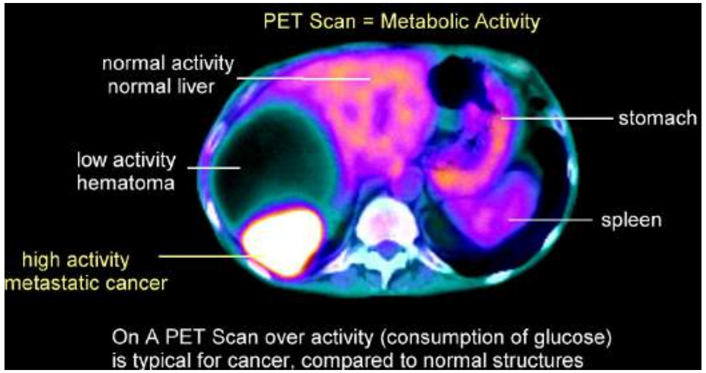
Why glucose metabolism?



http://www.aboutcancer.com/pet_scan.htm

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Segmentation of lung lesions on 4D-PET/CT images for radiation therapy treatment planning

Timia Osman

Supervisors: Alessandra Malaroda, Anatoly Rozenfeld, Bruce McBride, Simon Downes

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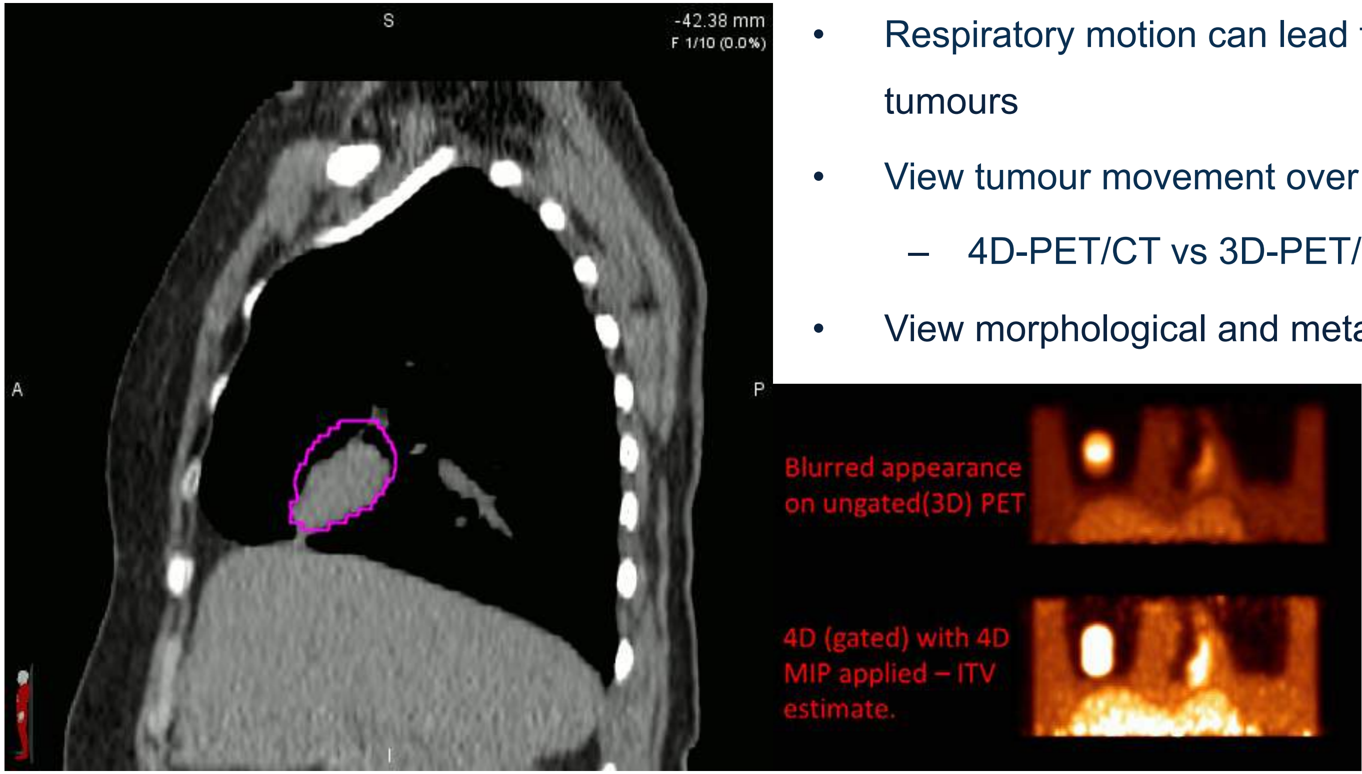
Introduction: Imaging



- Respiratory motion can lead to incorrect delineation of lung tumours
- View tumour movement over time
  - 4D-PET/CT vs 3D-PET/CT
- View morphological and metabolic information

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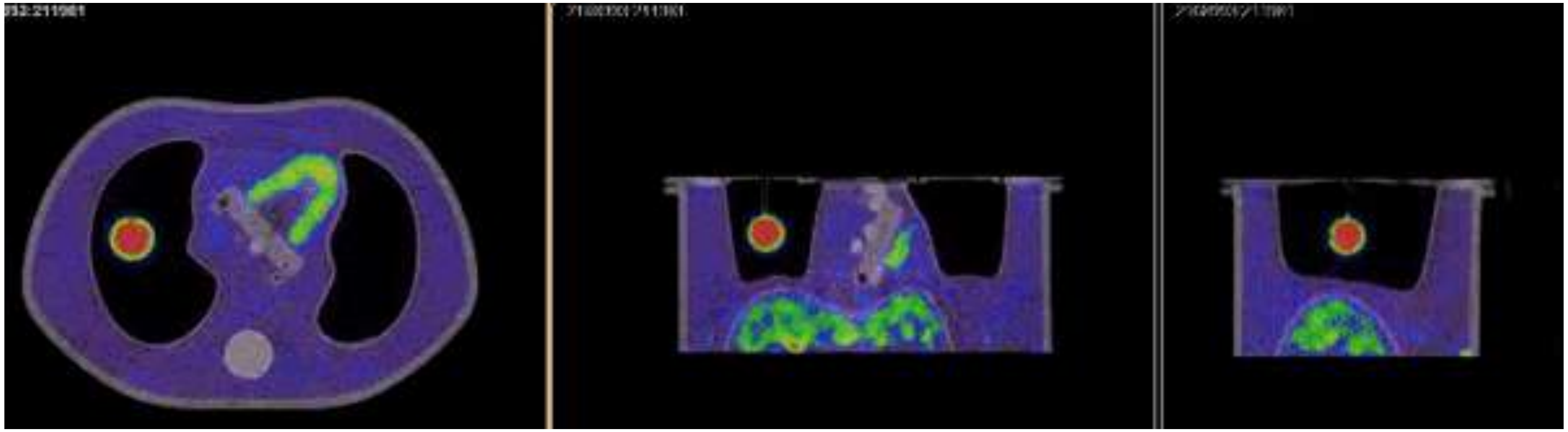
http://uthealth.utoledo.edu/centers/cancer/radiation-oncology/services/lung-cancer.html

Introduction



4D-PET/CT anthropomorphic phantom data set

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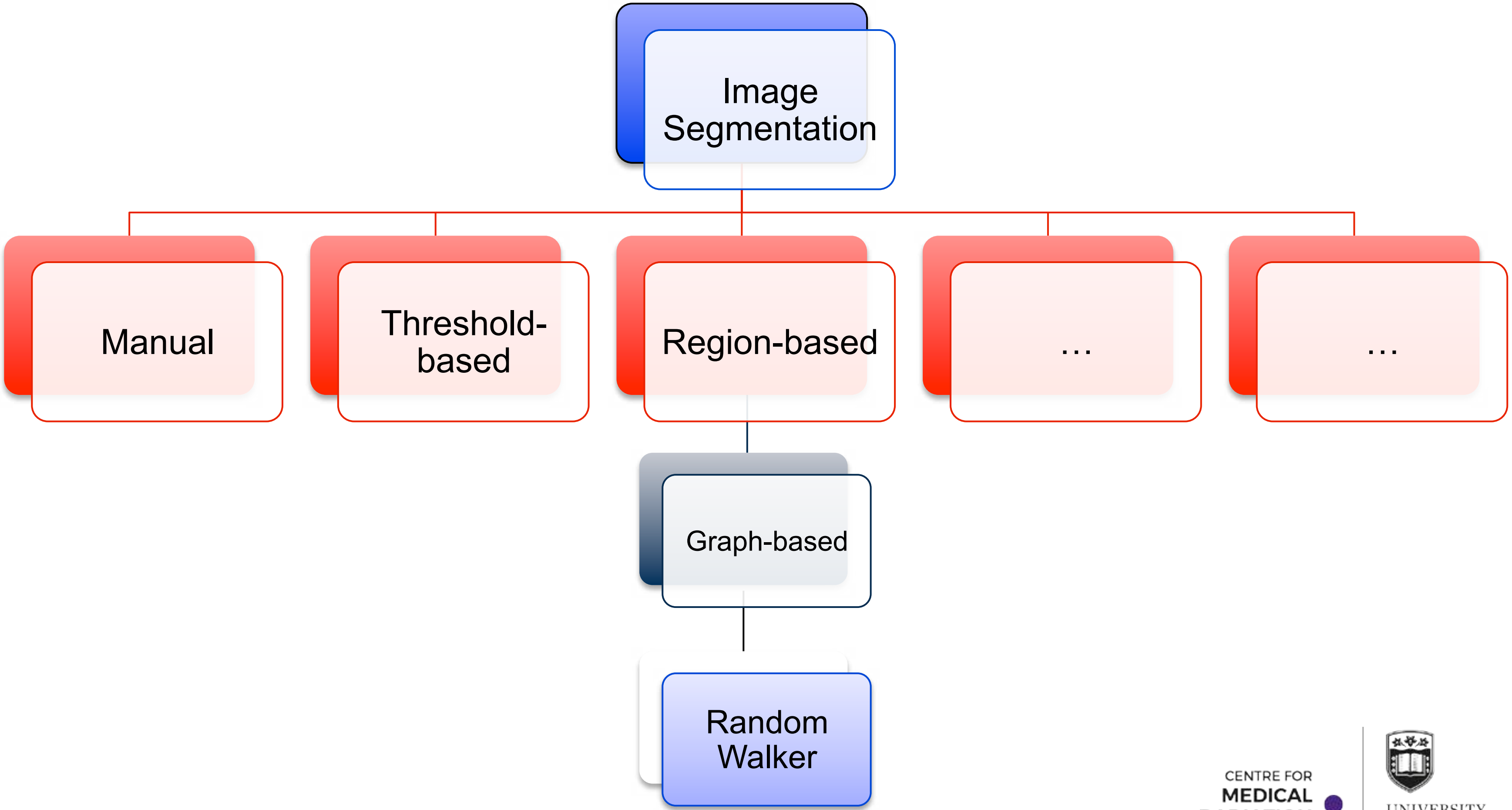

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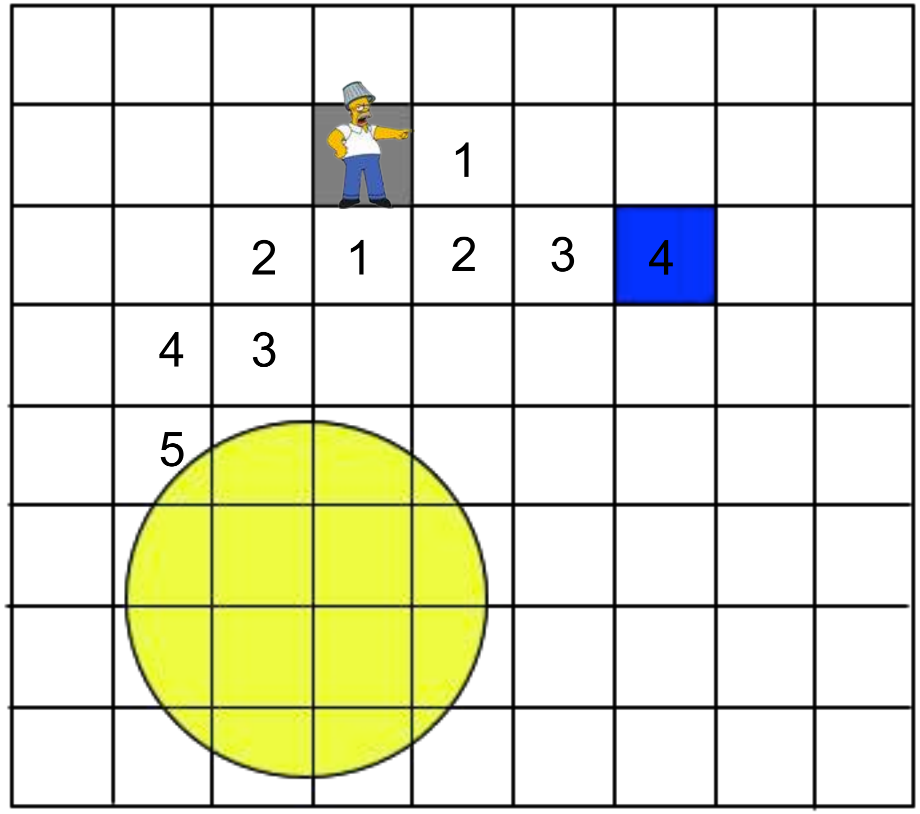
Random walk intuition



- Steps to bkg seed = 4
- Steps to tumour seed = 7

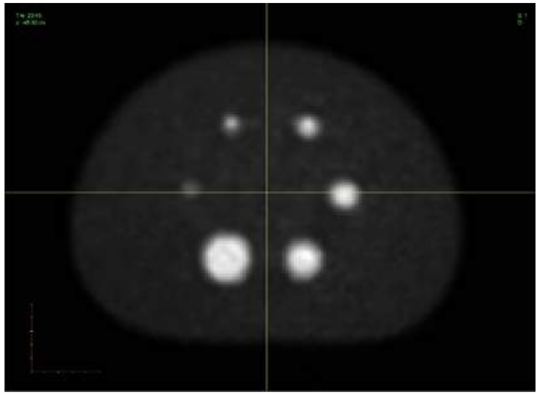
∴ $prob_{bkg} > prob_{tumour}$

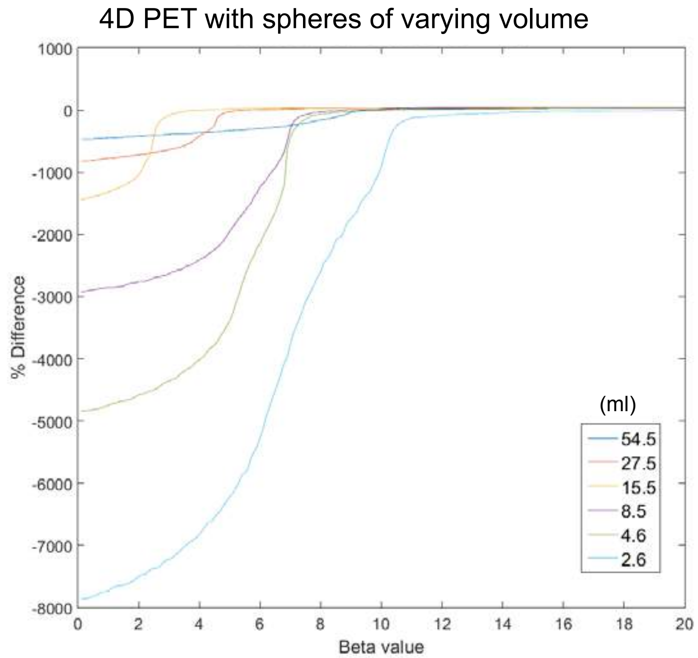
- However, there is more fancy maths involved

Beta parameter and the effect on the volume

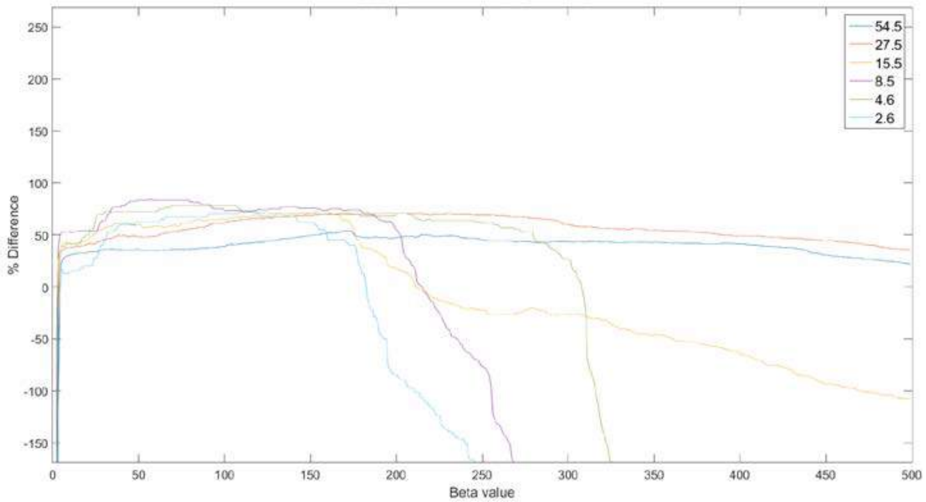
$$w_{ij} = exp\left(-\beta \frac{(I_i - I_j)^2}{d(\mathbf{i},\mathbf{j})}\right)$$

Weighting equation

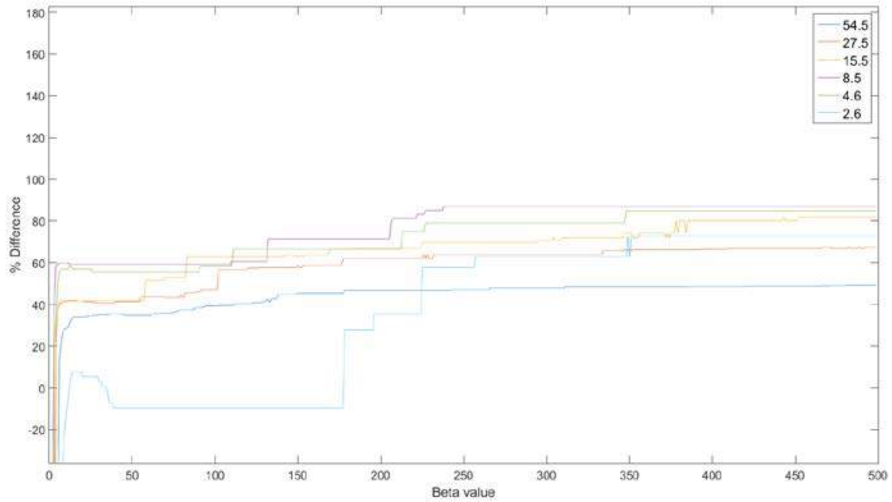




2D vs 3D Random Walk



2D RW on 4D PET with SBR = 9:1



3D RW on 4D PET with SBR = 9:1

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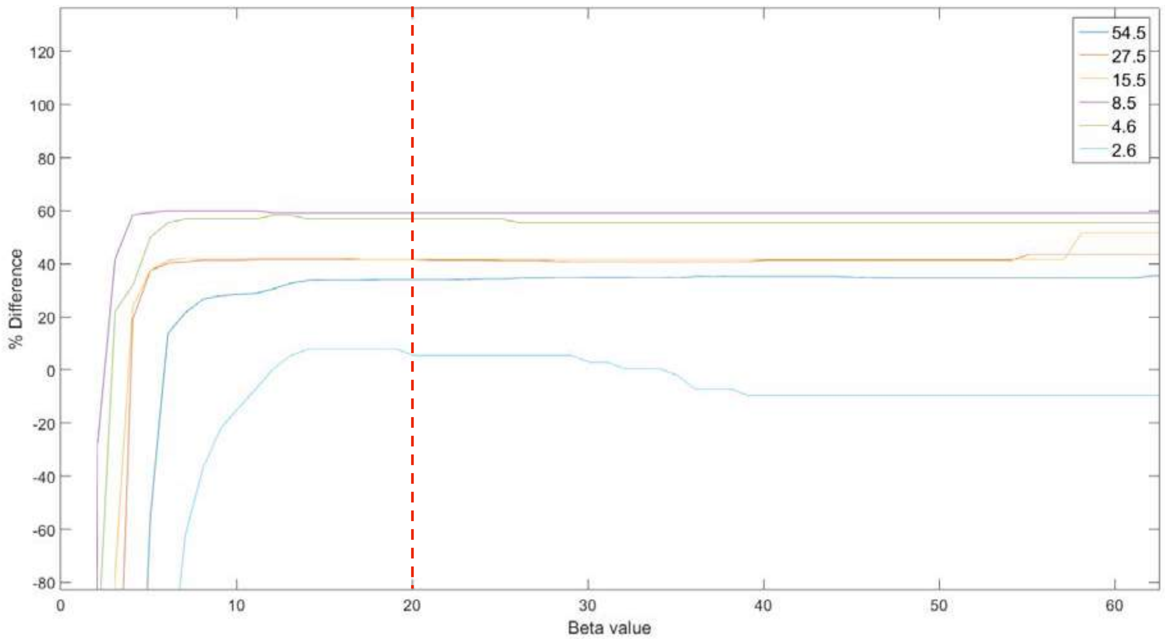
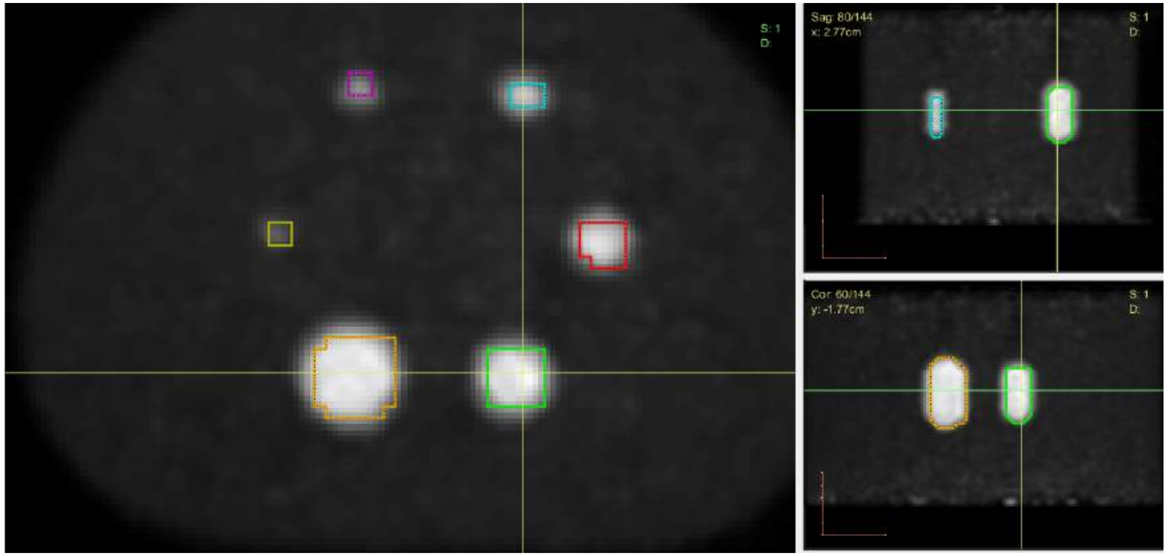
3D RW



4D PET with SBR = 9:1

3D RW with Beta set to 20



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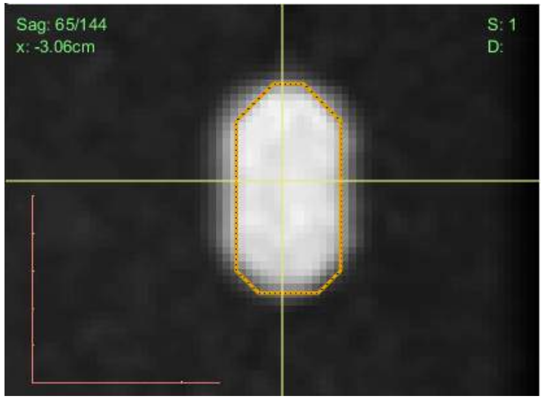
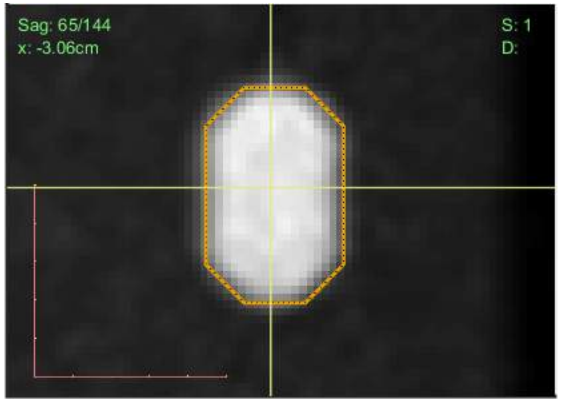
Comparison with thresholding

True Volume (mL)	RW with optimised β (mL)	RW with β = 20 (mL)	Adaptive Threshold Volume (mL)	40% Fixed Threshold Volume (mL)
54.5	54.4	35.9	47.2	49.3



RW with β = 20 Contour



Adaptive Thresh Contour

Conclusion / Future work

- Random Walk can be used for the segmentation of 4D-PET/CT moving lung tumours
- There is still work to do in improving image segmentation
  - 2D RW and gradient analysis
  - 3D RW and region growing

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