
The Principles of Diagnostic Imaging

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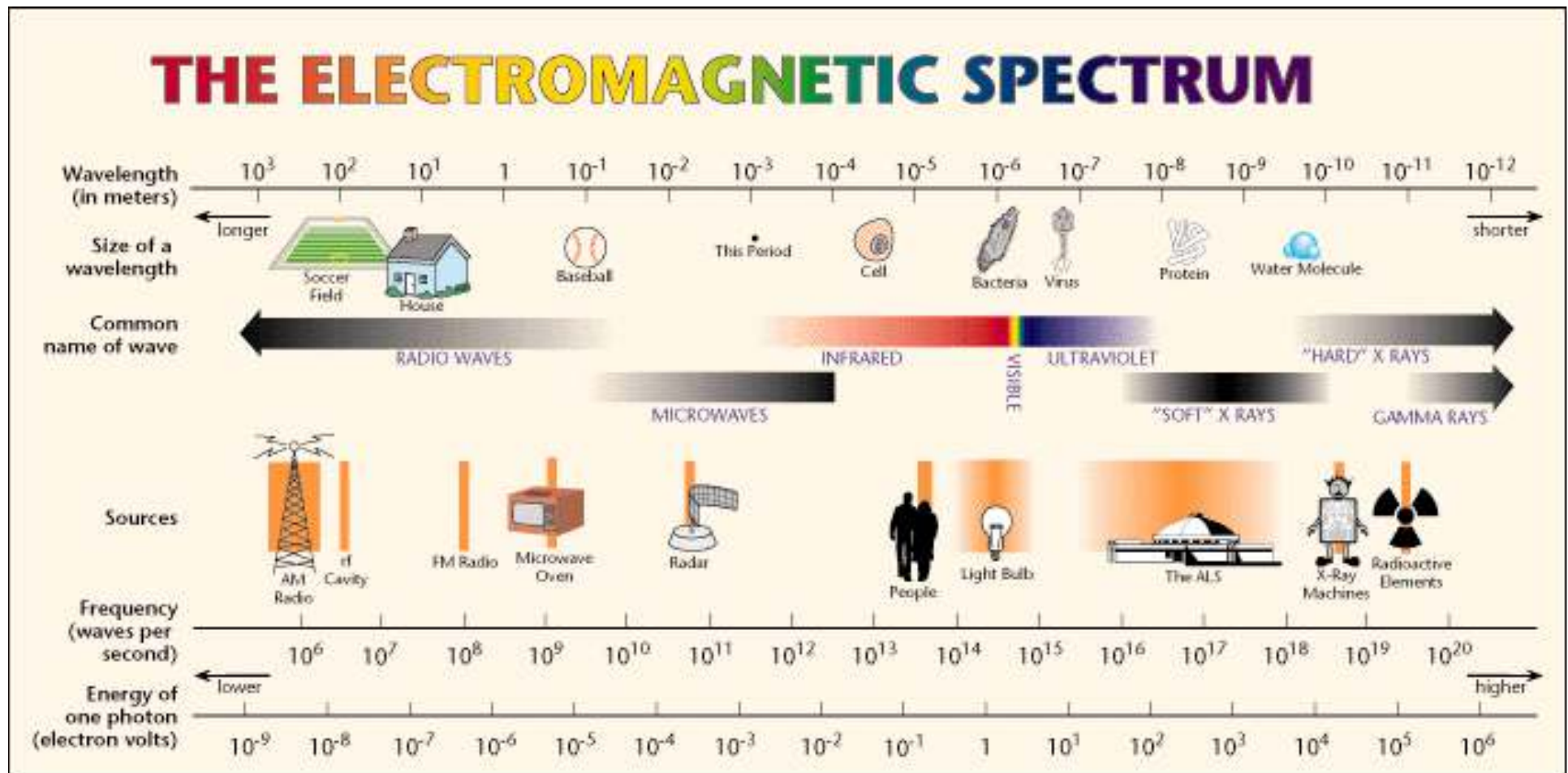
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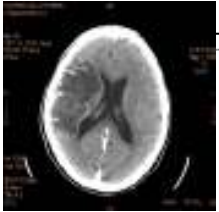
Objectives for this lecture

- To teach the basic principles of diagnostic imaging with
 - X-rays (planar and CT)
 - Magnetic Resonance
 - Ultrasound
 - Radionuclide (SPECT and PET)

Imaging employs electromagnetic radiation



Medical Imaging modalities



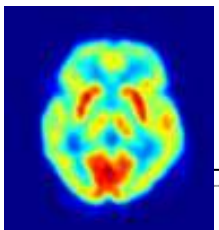
X-ray CT – (X-ray computed tomography) uses ionising radiation, source is external to the body. In some cases, contrast agents are injected. Anatomical images



MRI (Magnetic resonance imaging) – uses magnetic fields and radiofrequency pulses to produce anatomical images. In some cases, contrast agents are injected. Also, fMRI



US (Ultrasound imaging) – uses high frequency sound waves and the pulse echo effect (which is the basis of radar) to give anatomical information.

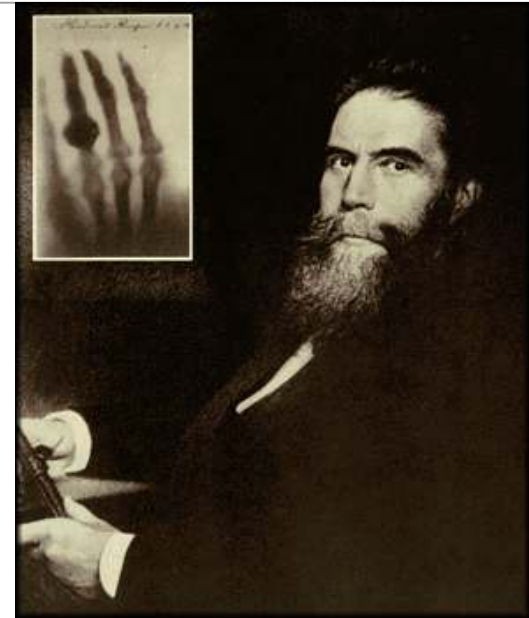


Nuclear medicine imaging – uses unsealed radioactivity to produce functional images

The beginnings of Radiology

November 1895 - Roentgen discovered X-rays

- when experimenting with cathode ray tubes in a darkened room, he noticed a faint fluorescent glow emanating from a plate he had left on the bench
- when he moved to pick it up, he was amazed to see the image of the bones from his hand cast onto the plates
- the prospects for x-ray diagnosis were immediately recognised but Roentgen refused to patent his discovery
- Won first Nobel Prize in Physics for his discovery - 1901



Planar - X-ray

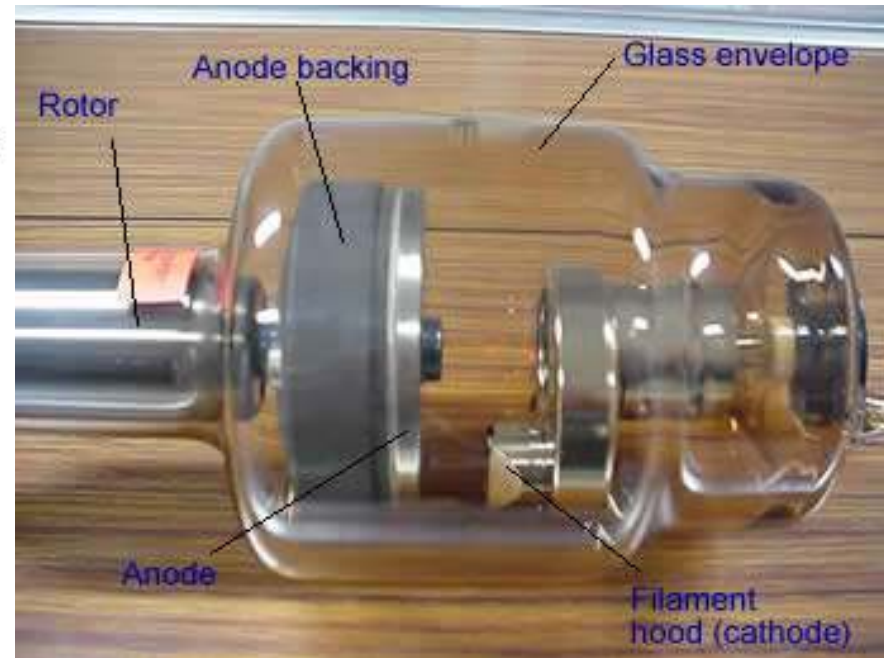
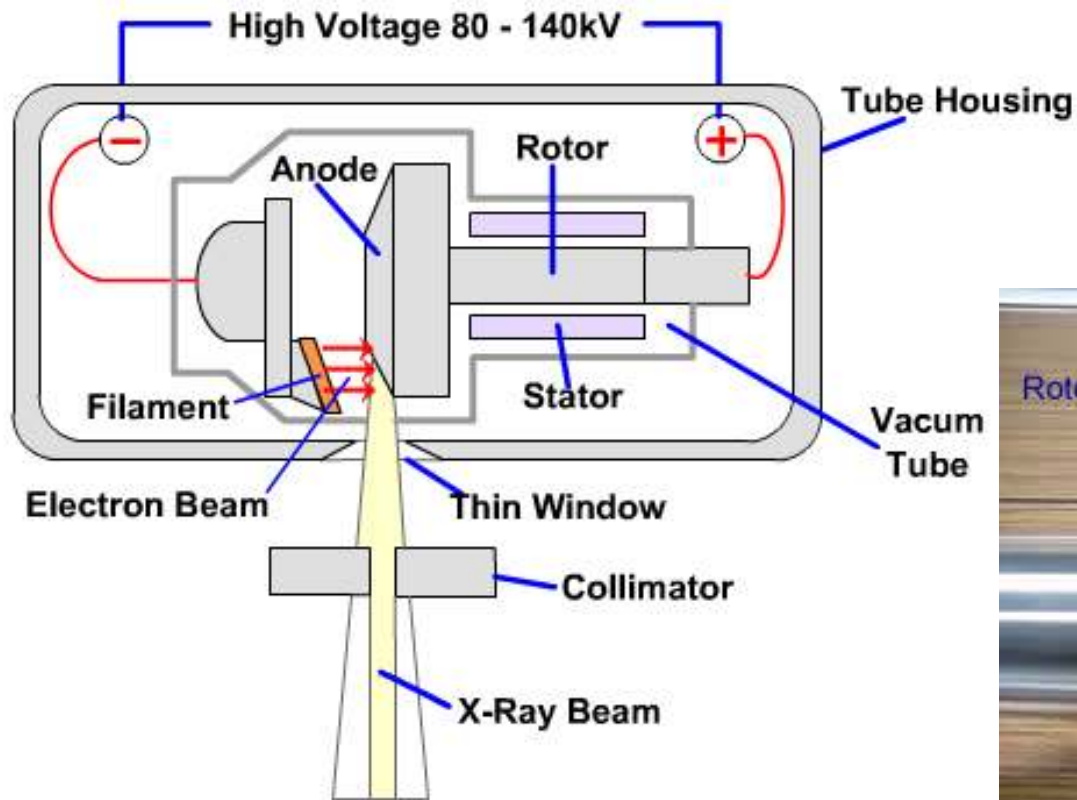


Early X-ray apparatus ~ 1920's

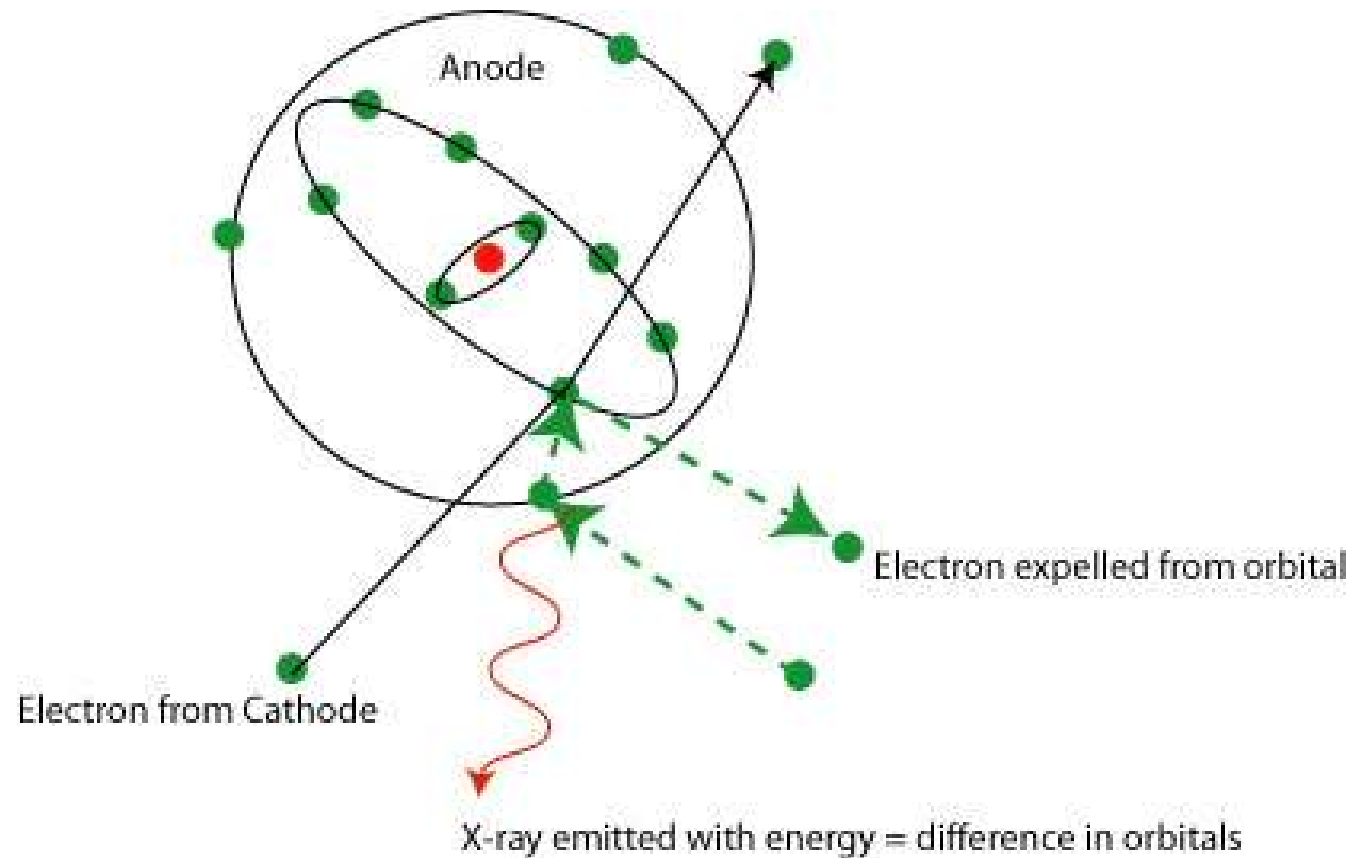
Modern direct capture Radiography



X-ray tube

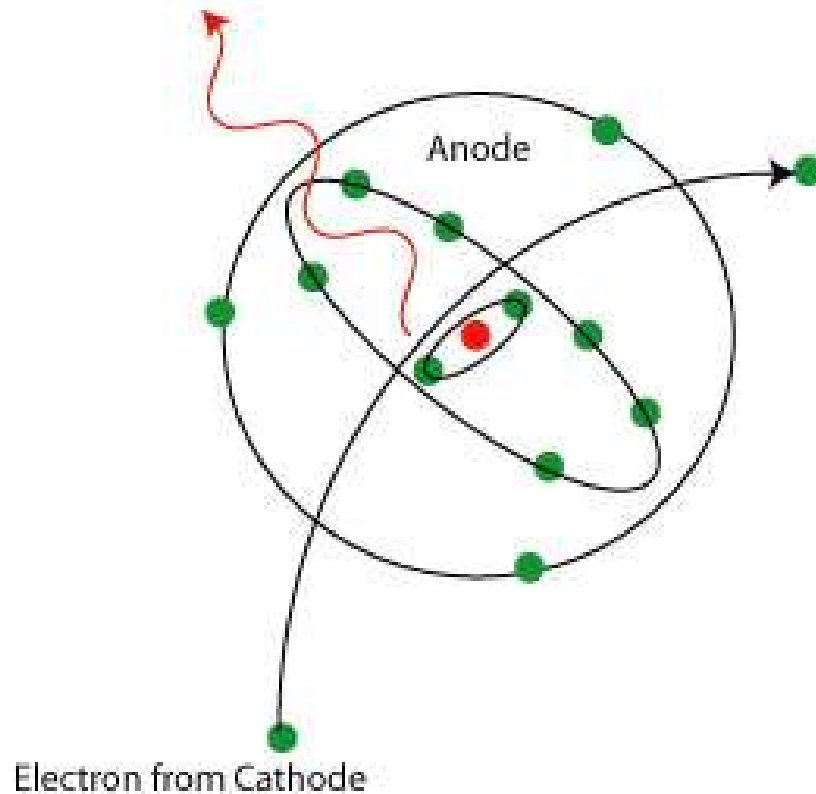


Production of characteristic X-rays



Production of Bremsstrahlung X-rays

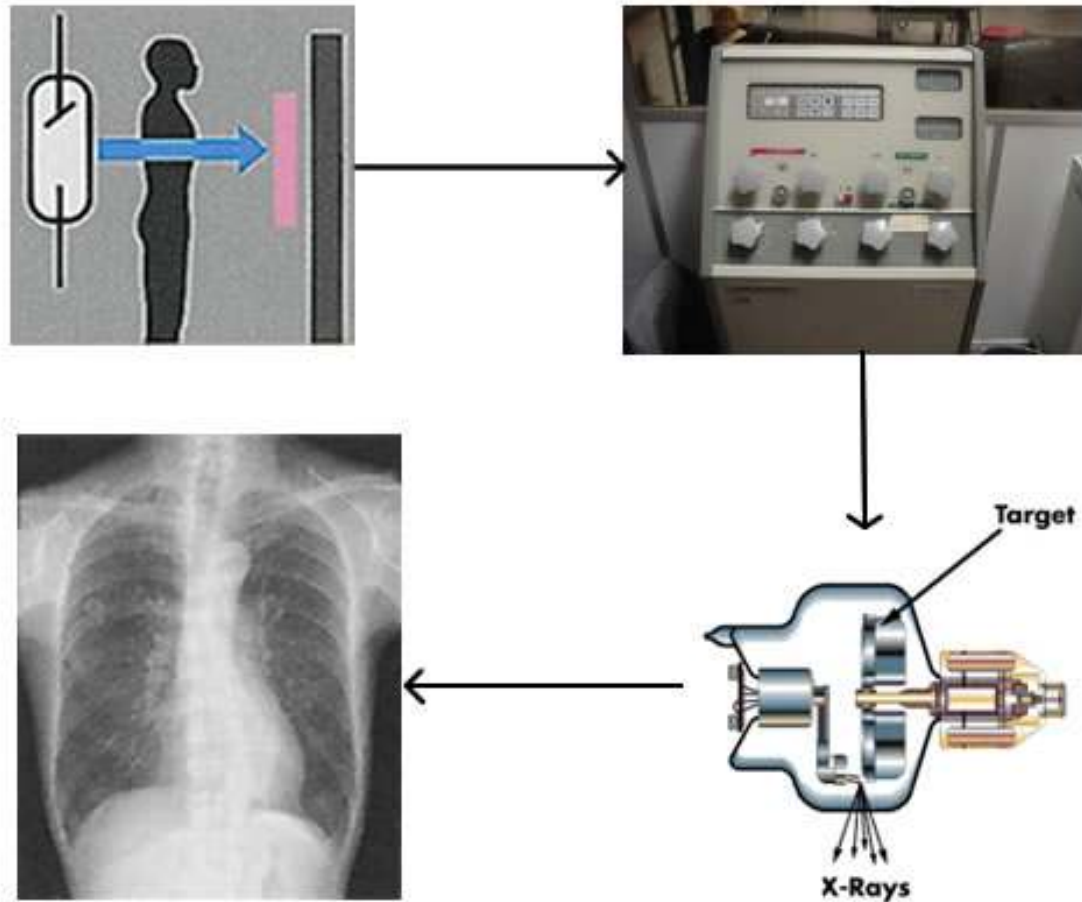
Bremsstrahlung (braking) radiation - wide spectrum of energy



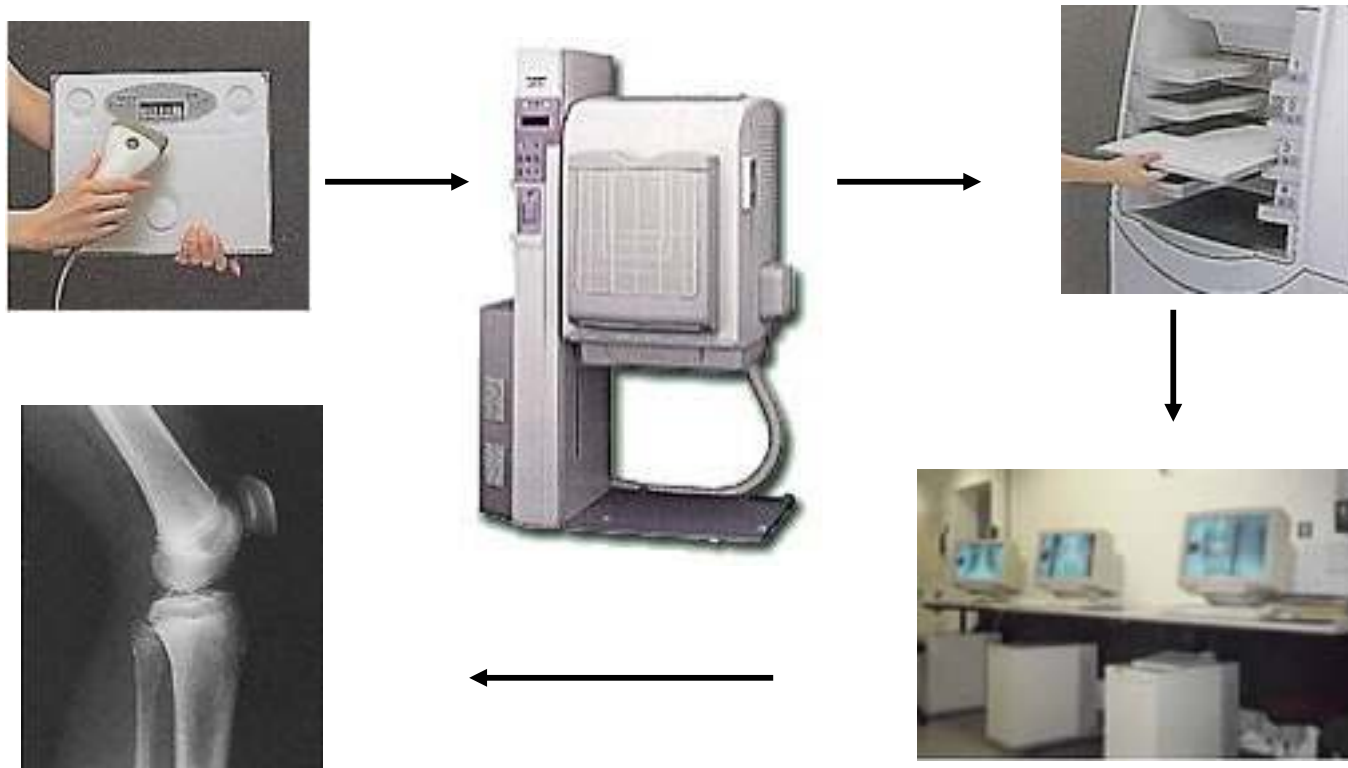
Process of Image Production

- X-rays produced
- X-ray photons are either: **Attenuated**, **Absorbed**, **Scattered**, **Transmitted**
- **air < fat < fluid < soft tissue < bone < metal**
- Transmitted X-ray photons (+some scatter) reaches the cassette and may interact with: Intensifying screens (produce light) or Film
- Latent image (i.e. undeveloped) produced which is then processed.

Producing a Radiograph



Digital images



Direct Capture Radiography

- Direct capture Imaging System
- No Cassettes
- Amorphous Silicate used as detector material
- Similar to digital simulator/ treatment setup



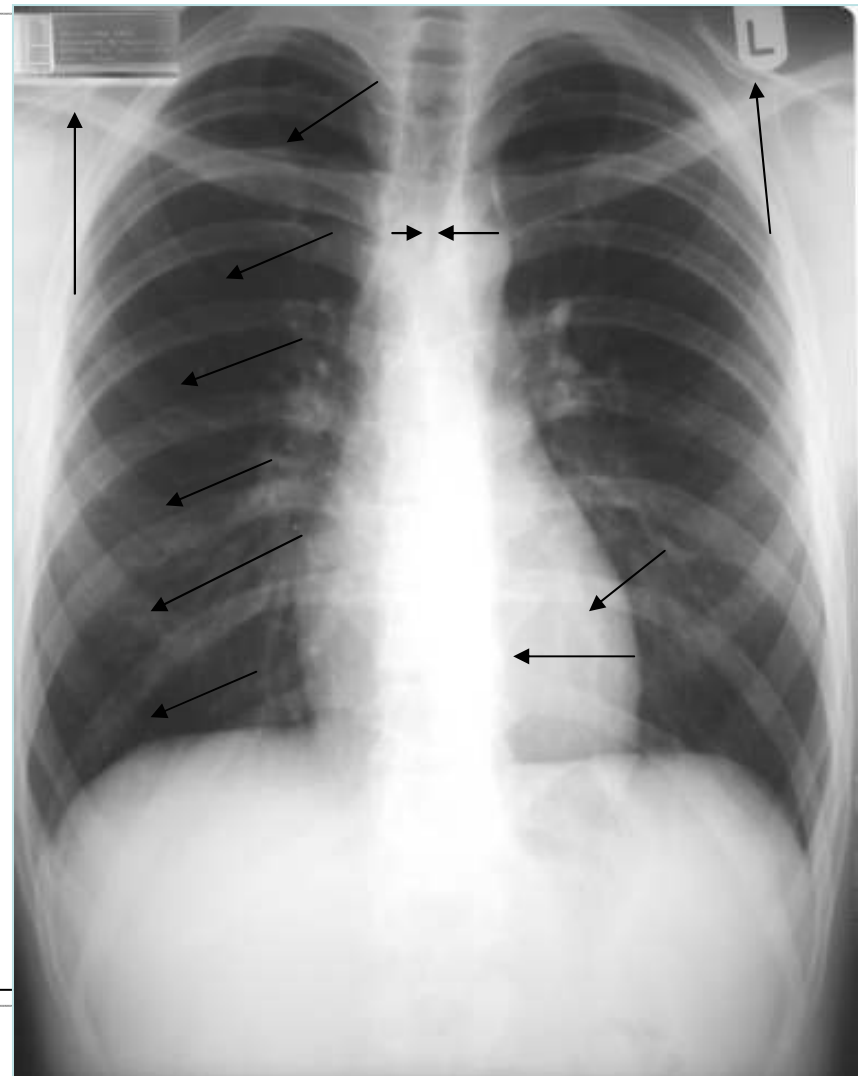
Factors affecting Radiograph

- Scatter
- Distance
- Movement
- kVp and mAs settings

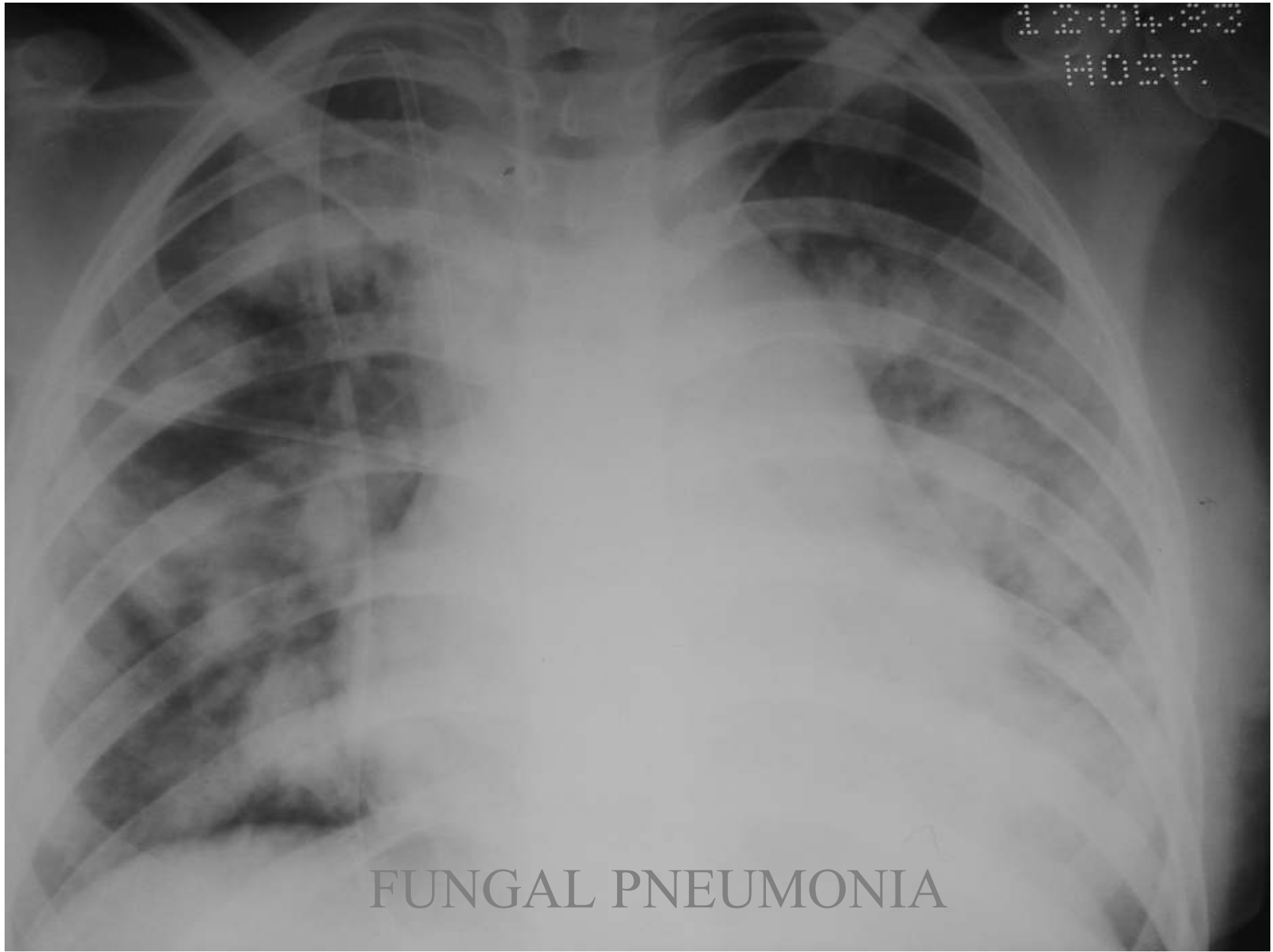


The normal CXR

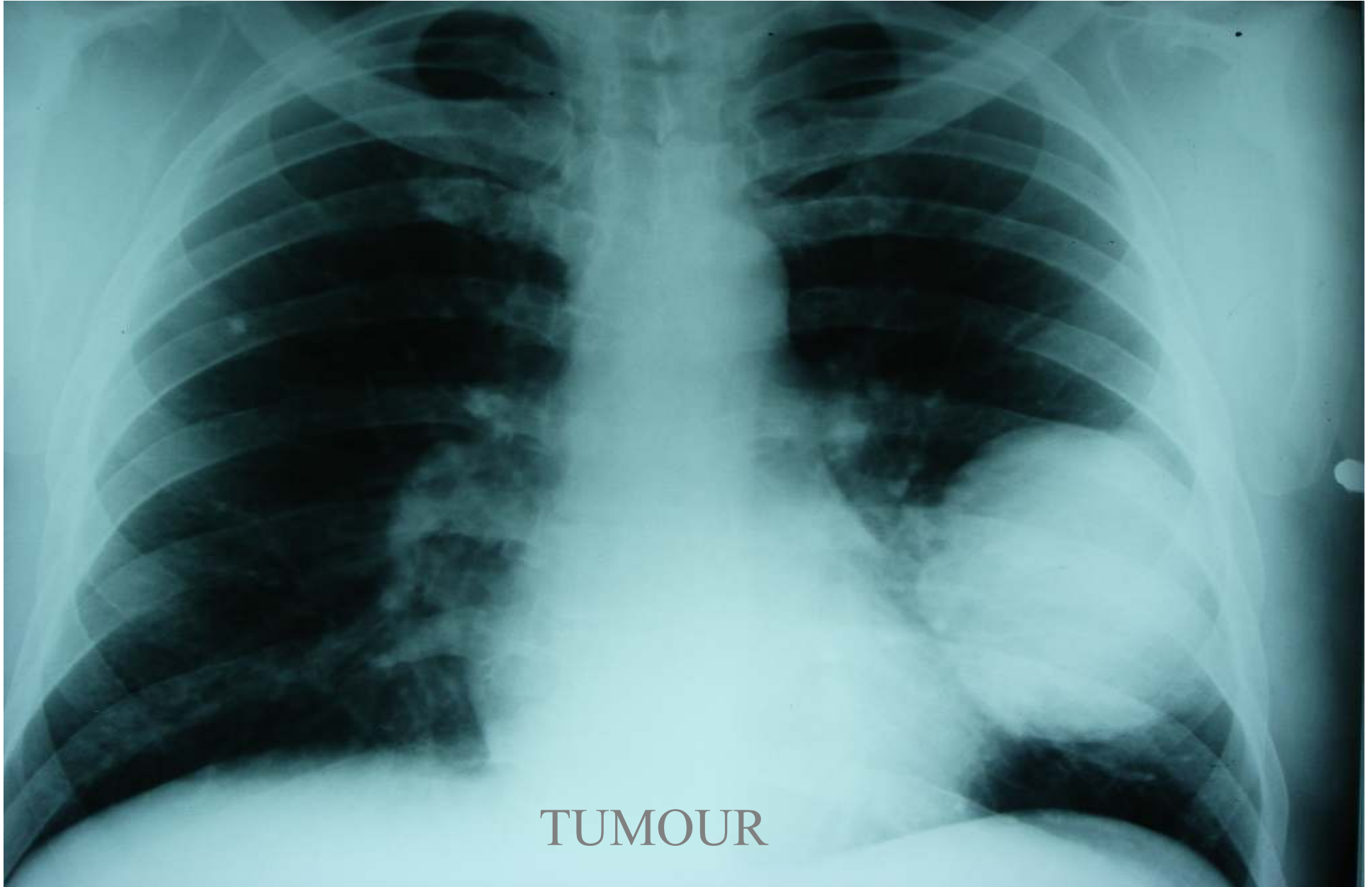
- First of all is the film *technically adequate* ?
 - Correct area imaged ✓
 - Inspiratory effort ✓
 - Penetration ✓
 - Rotation ✓
 - Annotation ✓



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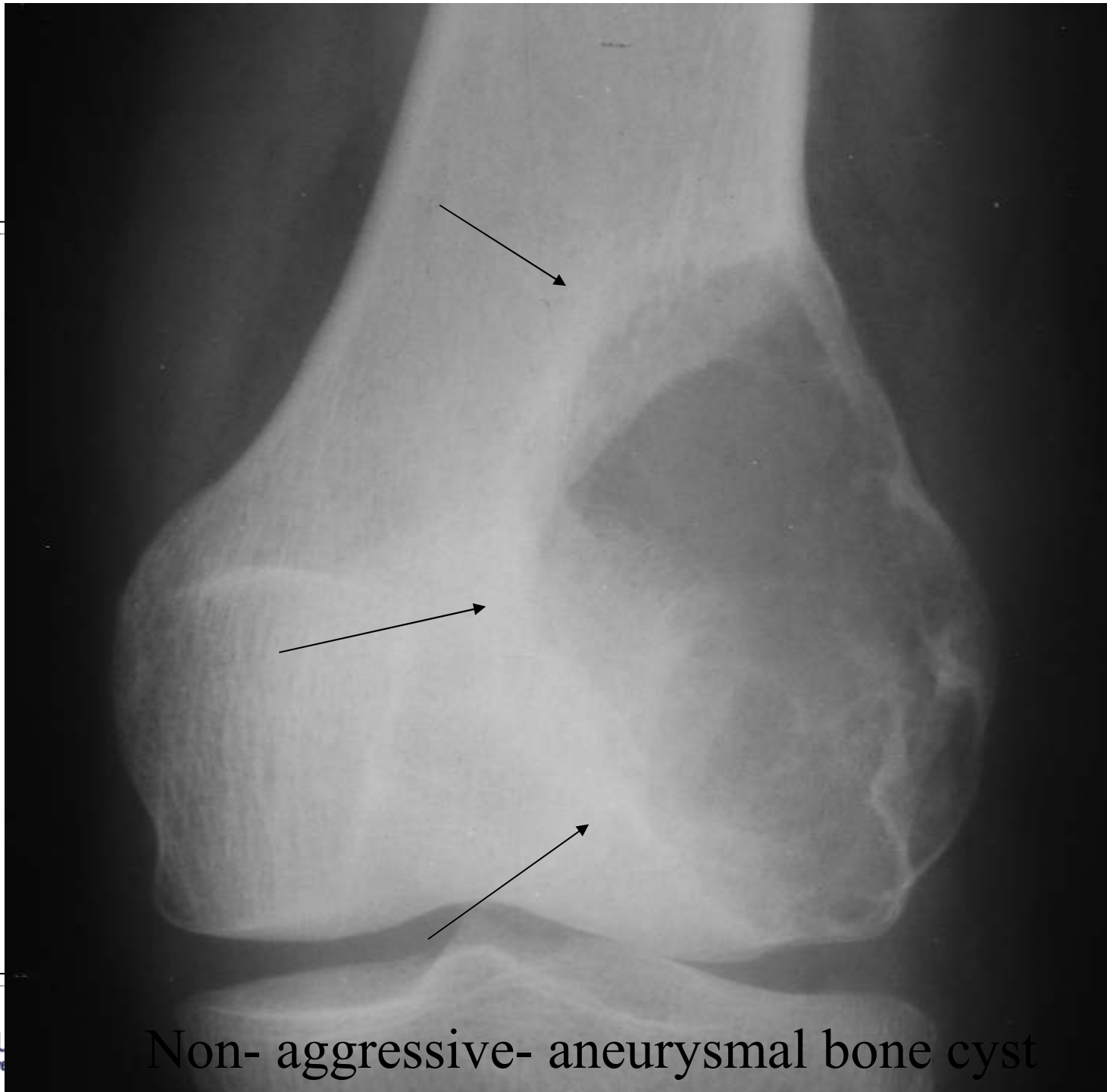
FUNGAL PNEUMONIA



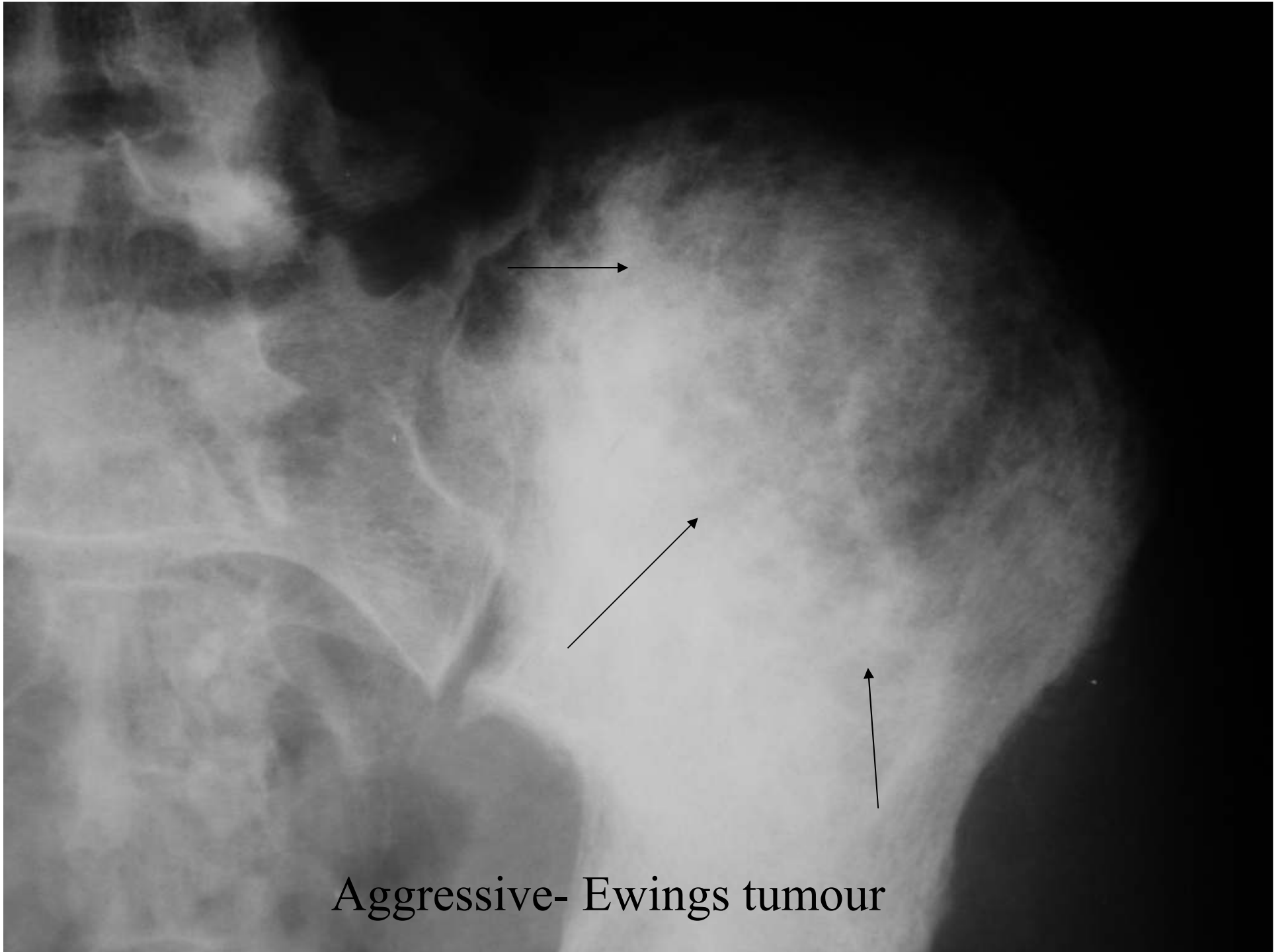
TUMOUR

Aggressive- fibrosarcoma



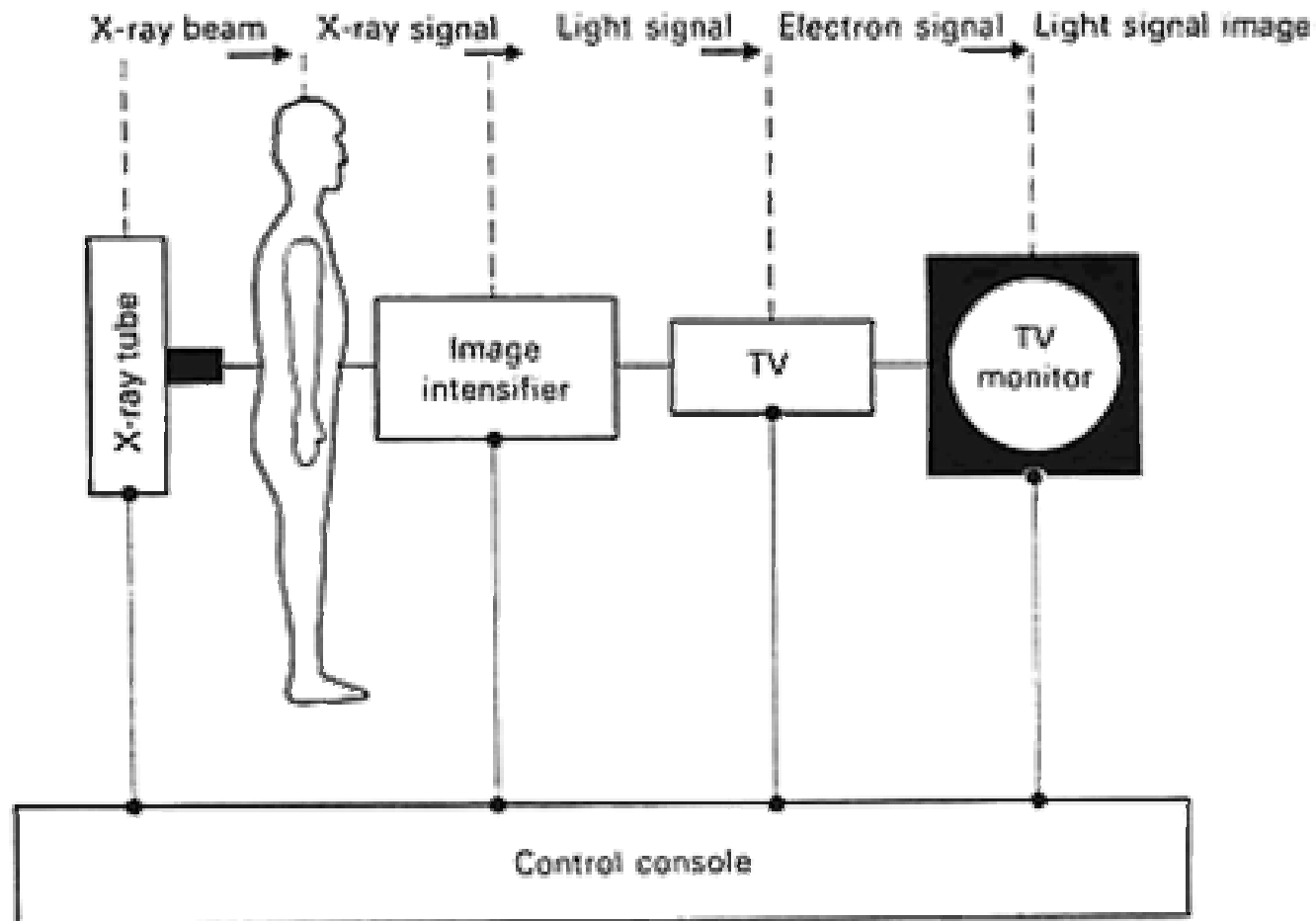


Non- aggressive- aneurysmal bone cyst

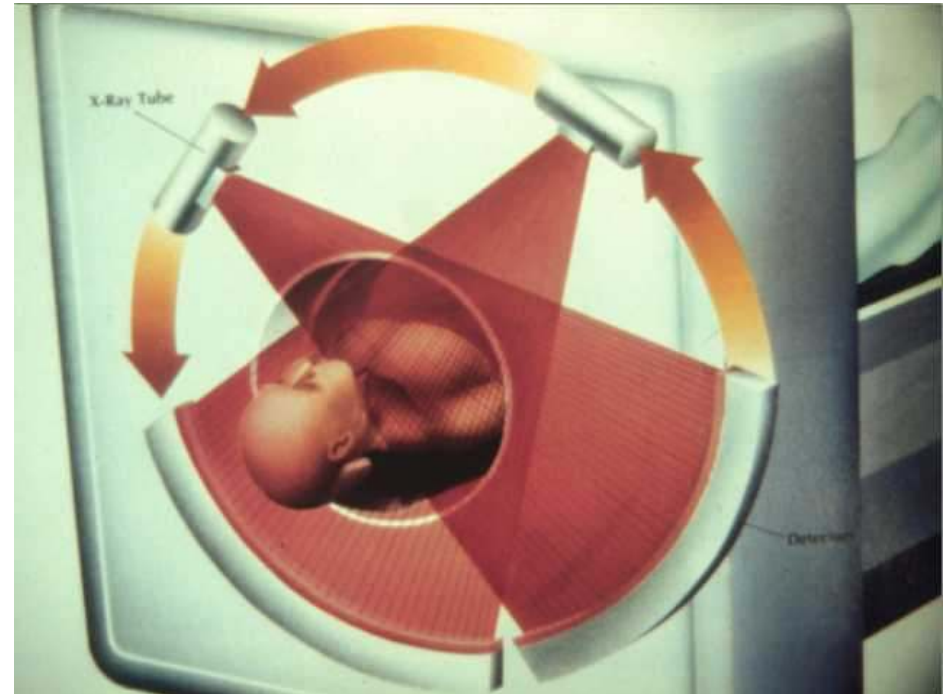


Aggressive- Ewings tumour

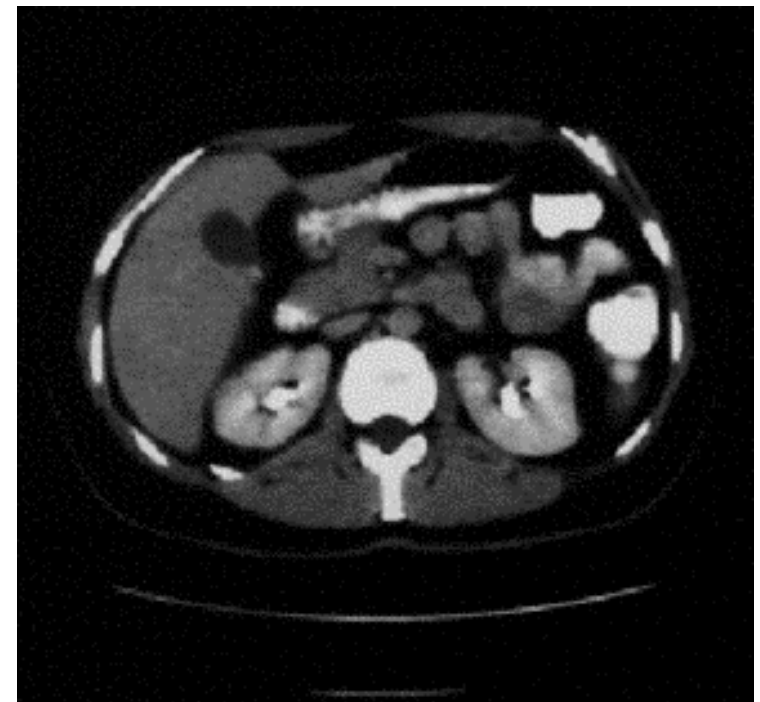
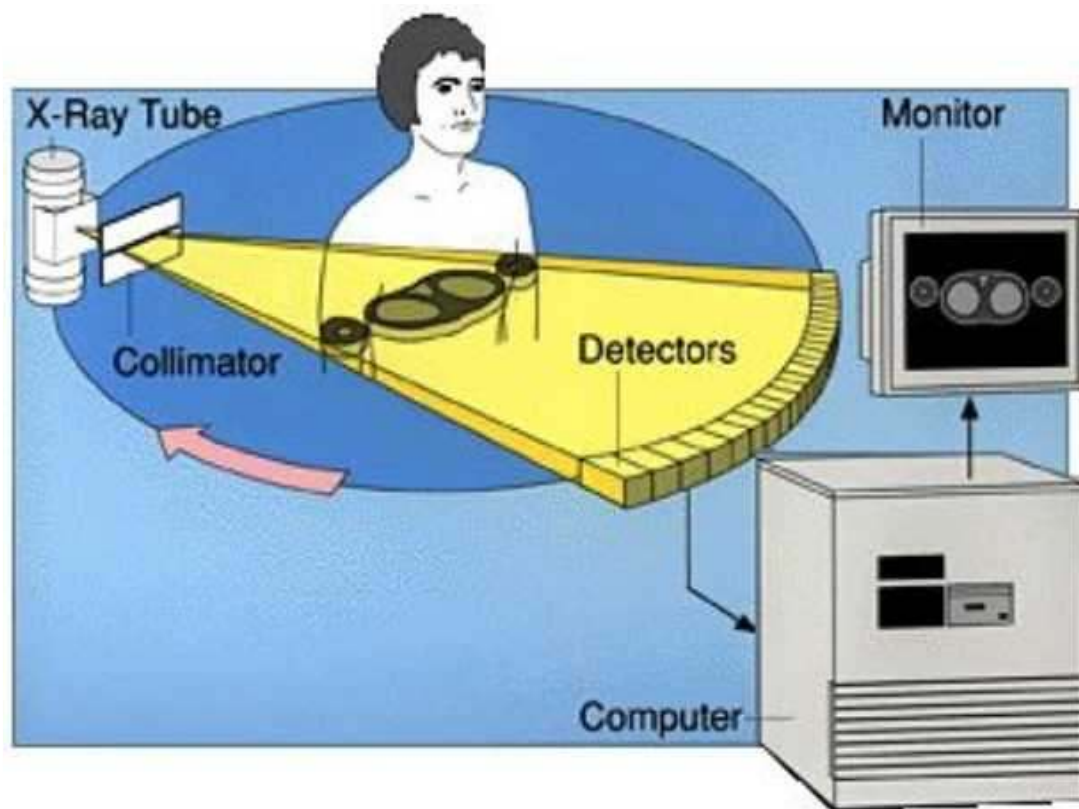
Fluoroscopy



Computerised X-ray Tomography



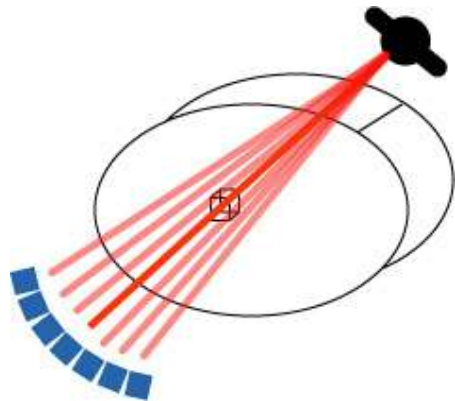
Computerised X-ray Tomography



CT numbers

Linear attenuation coefficient μ
= Fraction of energy absorbed

$$\text{CT number} = \frac{\mu_{\text{voxel}} - \mu_{\text{water}}}{\mu_{\text{water}}} \times 1000$$



Tissue	approx CT number
dense bone	1000
Muscle	50
white matter	45
grey matter	40
Blood	20
CSF	15
Water	0
Fat	-100
Lungs	- 200
Air	- 1000

Radiation doses

- | | |
|-------------------------|----------|
| • CT head | 2.5 mSv |
| • CT chest | 8 mSv |
| • CT abdomen | 10 mSv |
| • CT pelvis | 10 mSv |
| • chest radiograph PA | 0.02 mSv |
| • abdomen radiograph AP | 0.7 mSv |
| • pelvis radiograph AP | 0.7 mSv |

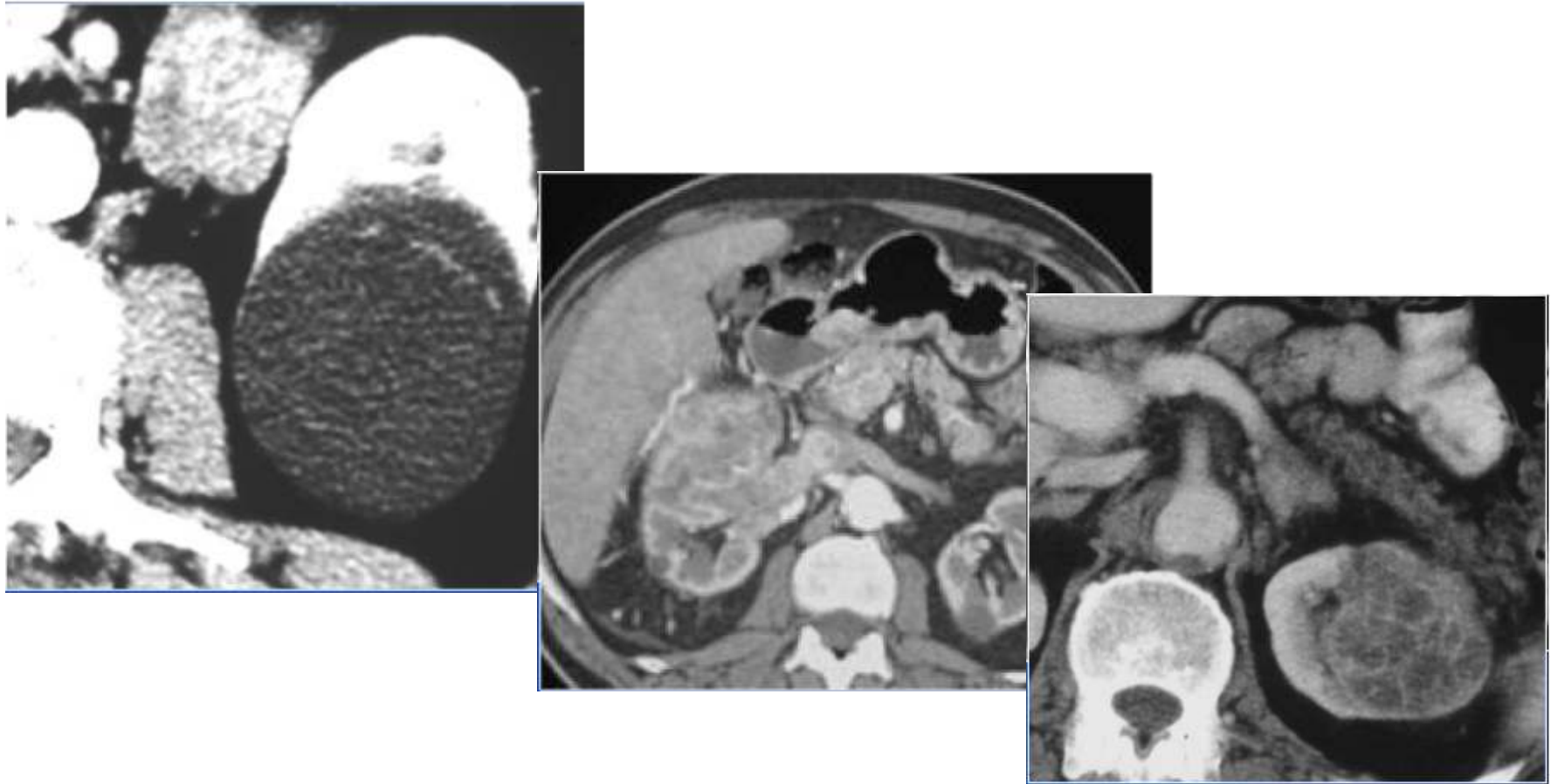
X-ray Contrast Agents

- substances with high atomic numbers have high density which is useful for X-ray contrast. Appear bright white in X-ray exams
- e.g. Barium (atomic number 56) causes considerable attenuation of X-rays compared with the soft tissues of the body (used for barium meals and barium enema's for diagnosis in the gastrointestinal tract) (Barium sulfate - inert) used mainly for plain radiographs
- Salts of iodine (atomic no. 53) are used as water soluble CT contrast agents. Can be injected intravascularly or into any cavity, sinus or tract. Can also give an indication of function e.g. filtration by the kidney. Can be toxic- allergic side effects.

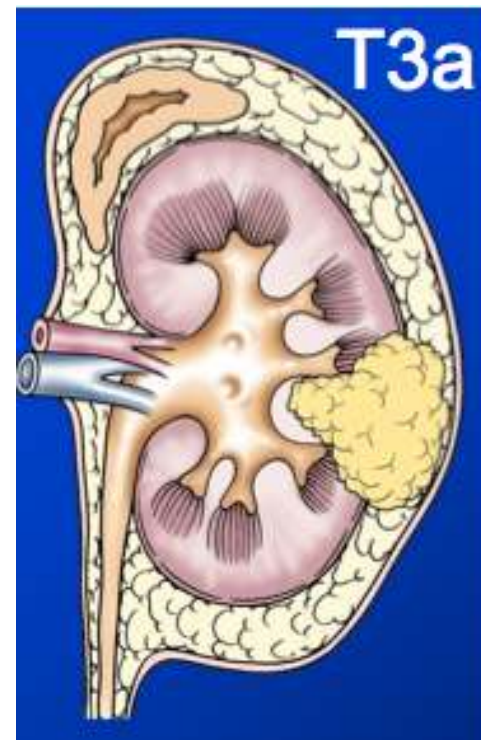
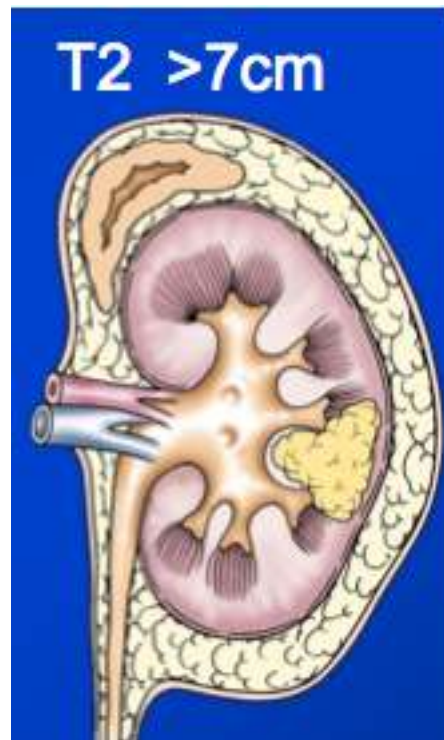
Applications of Imaging in Cancer

- Diagnosis
- Staging
- Monitoring response
- Detection of recurrence

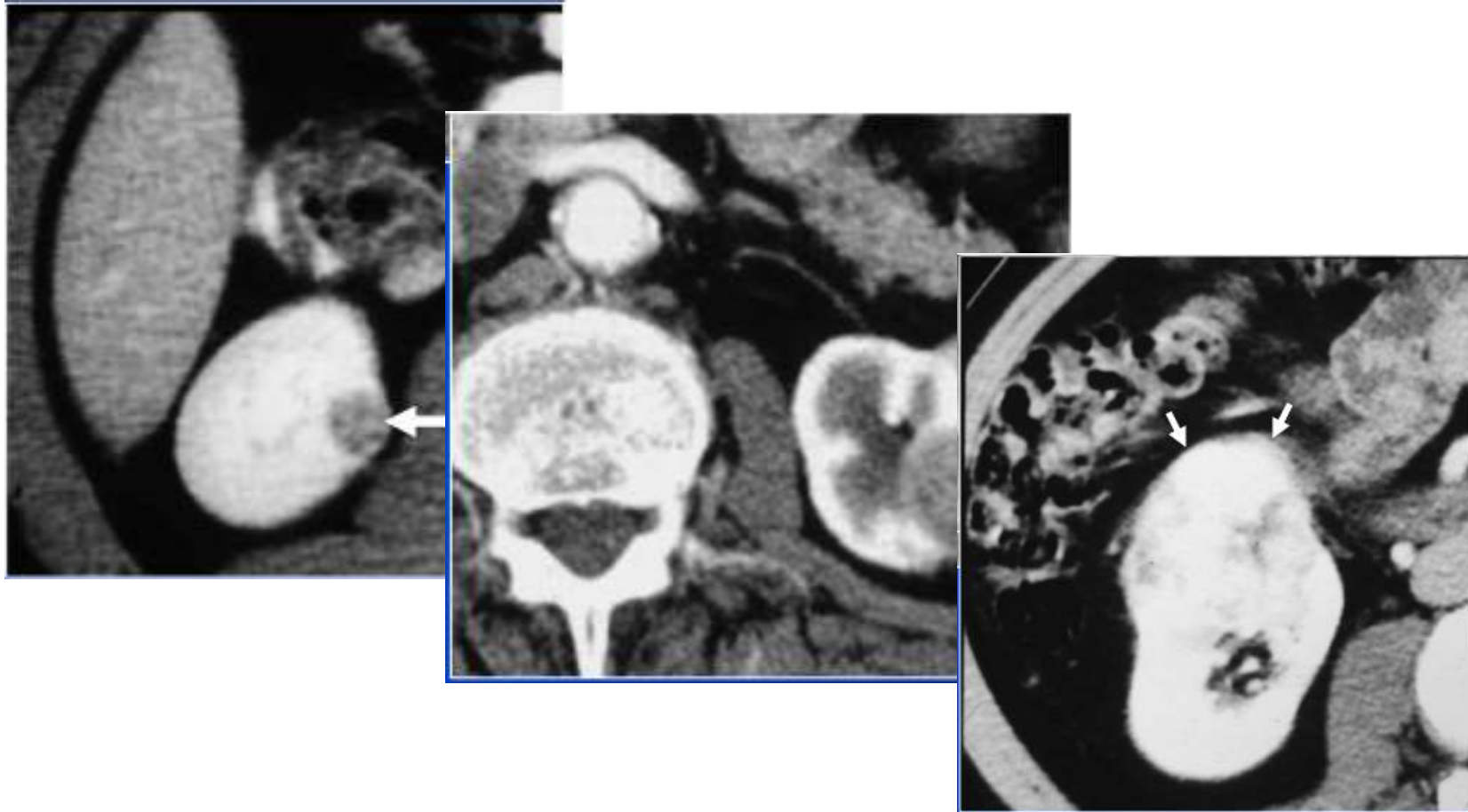
Diagnosis



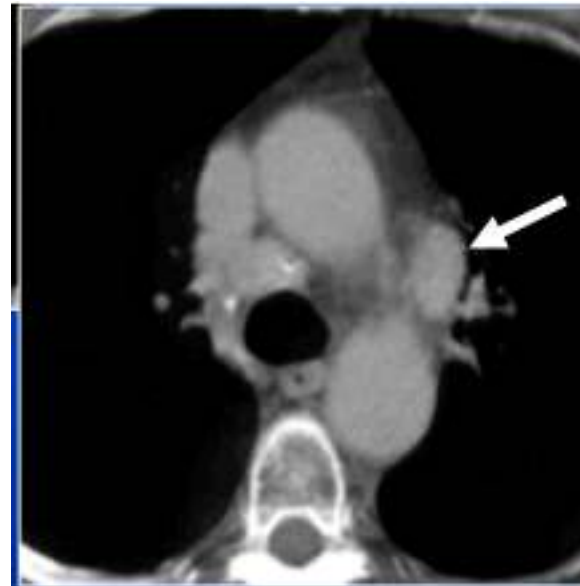
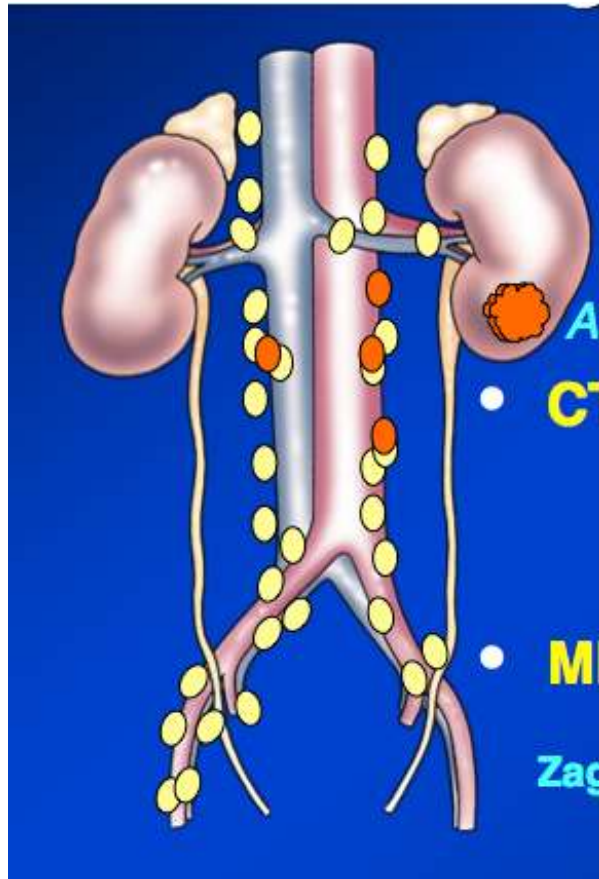
Staging – local spread



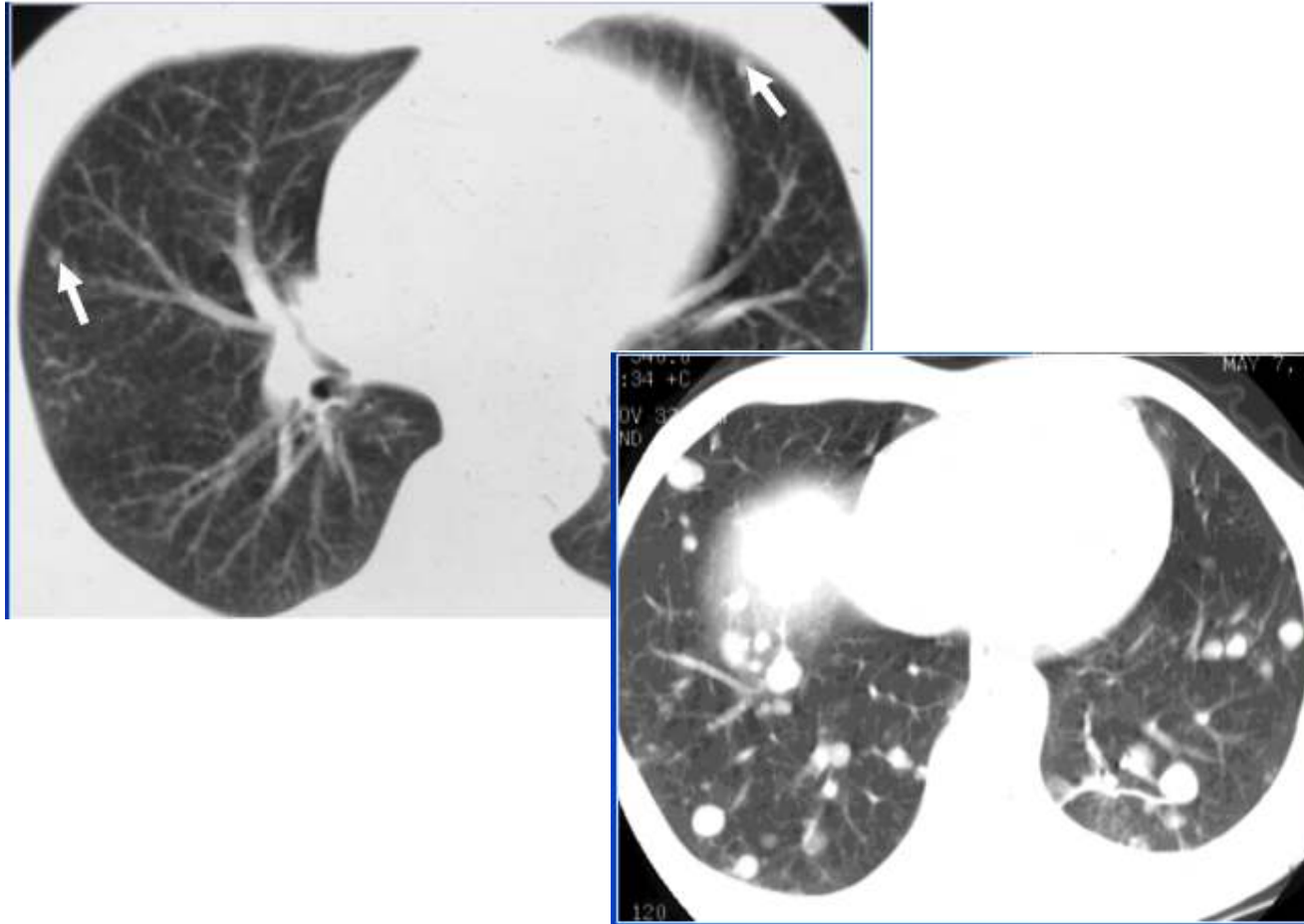
Staging – local spread



Staging – lymph nodes



Staging – distant spread



Magnetic Resonance Imaging

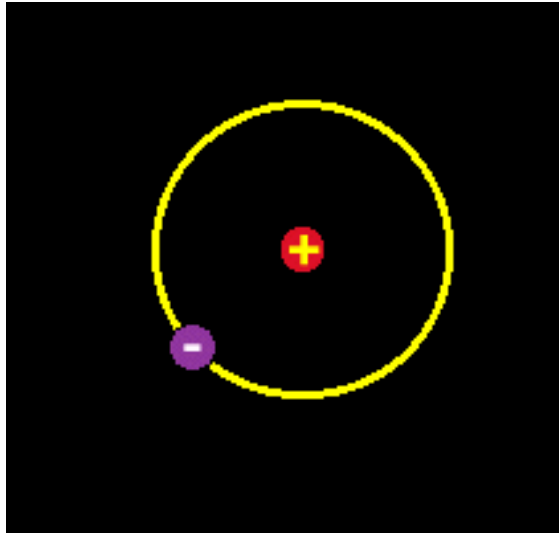
- The newest imaging modality
- Principle used in spectroscopy since 1950s
- First human scan 1977
- Adopted for clinical use ~ 1988
- Approximately 300 in the UK (compared with approximately 500 CT scanners - which have been around since 1971!)

Magnetic Resonance Imaging

- MRI gives superior soft tissue discrimination compared with CT: large differences in signals emitted from different soft tissues



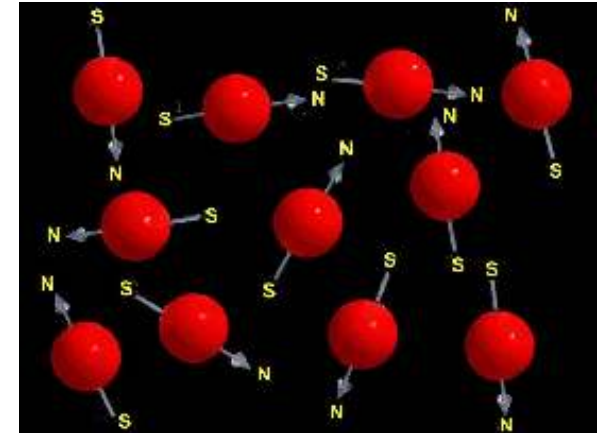
Principle of MRI



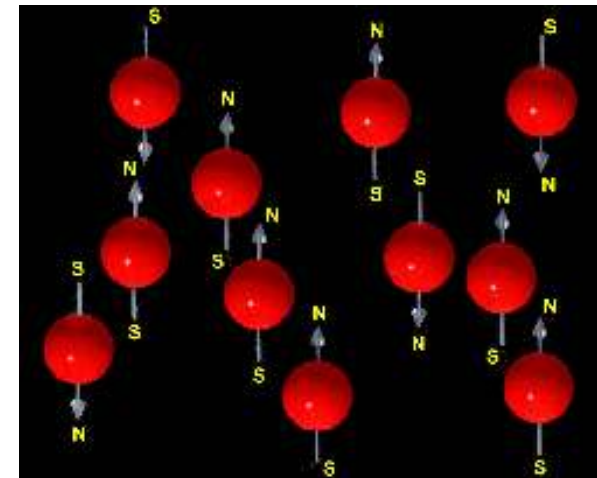
The spinning single proton in a hydrogen atom creates a magnetic field and each hydrogen atom acts like a tiny magnet

Principle of MRI

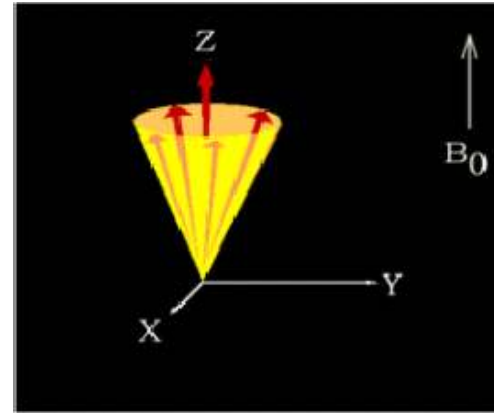
In the absence of an external magnetic field Hydrogen nuclei magnetic moments are randomly oriented and have a **net magnetization** of zero.



In the presence of an external magnetic field hydrogen protons align themselves in one of two directions, **parallel** or **anti-parallel** to the net magnetic field producing a net magnetic field (Mo)



Precession



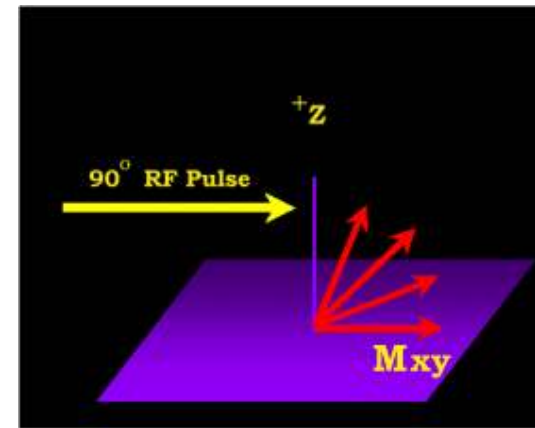
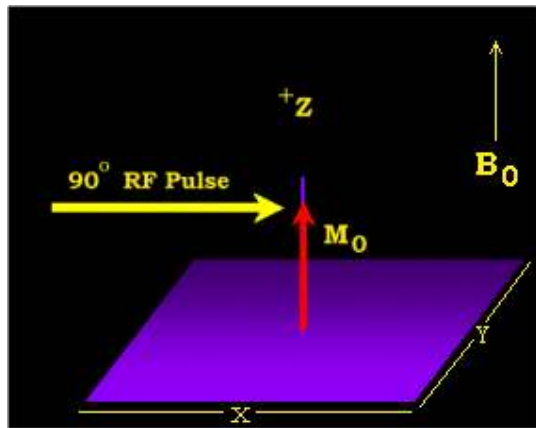
The hydrogen atoms are not still but ‘wobble’ or ‘precess’ like a spinning top in the direction of the external magnetic field

Larmor (or precessional) frequency (ω_0) = $B_0 \times \gamma$

Where B_0 is the magnetic field and γ is the ‘gyromagnetic ratio’

Resonance

If an RF pulse at the Larmor frequency is applied to the nucleus of an atom, the protons will absorb some energy and alter their alignment away from the direction of the main magnetic field .



As well as changing direction the protons also begin to precess ‘in phase’ resulting in a net magnetic moment transverse to the external field which induces a current and is detected in the transiever coil

Principles of MRI

When the RF is switched off, the protons:

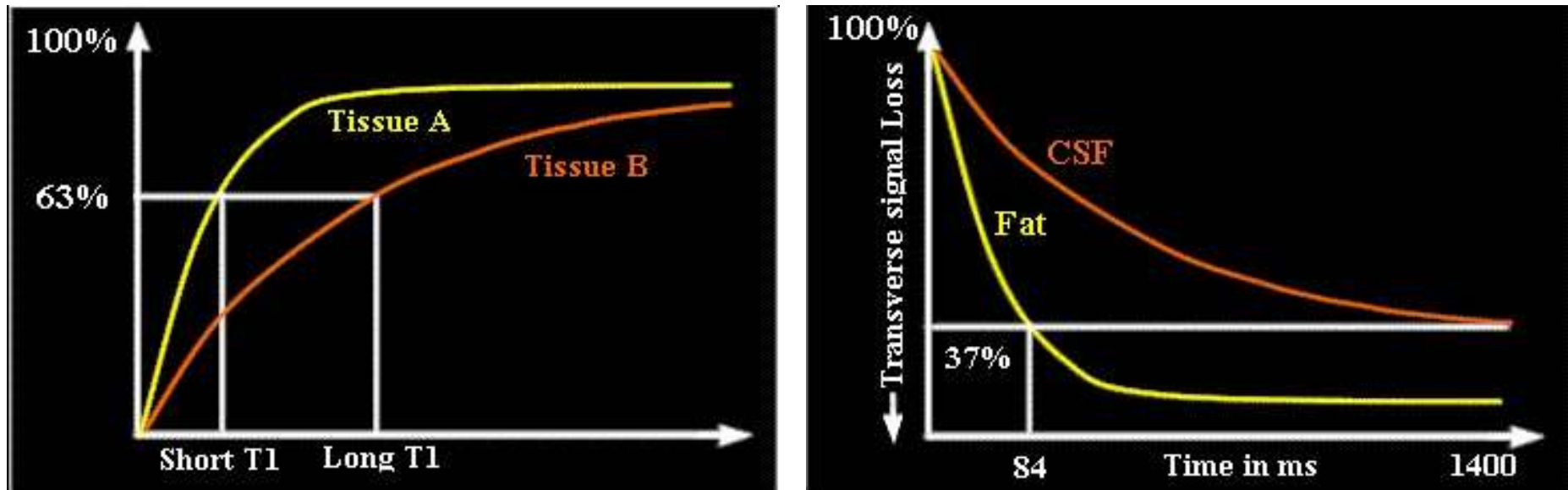
1. Give up the energy they have absorbed and start to return to their previous direction
2. Start to precess out of frequency

With the result that

- Longitudinal magnetization gradually increases - called **T1 recovery**
- Transverse magnetization gradually decreases - called **T2 decay**

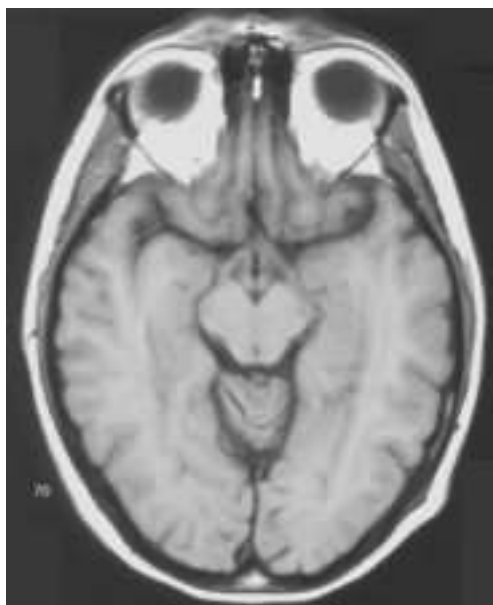
T1 and T2

The rate at which these processes occur vary from tissue to tissue

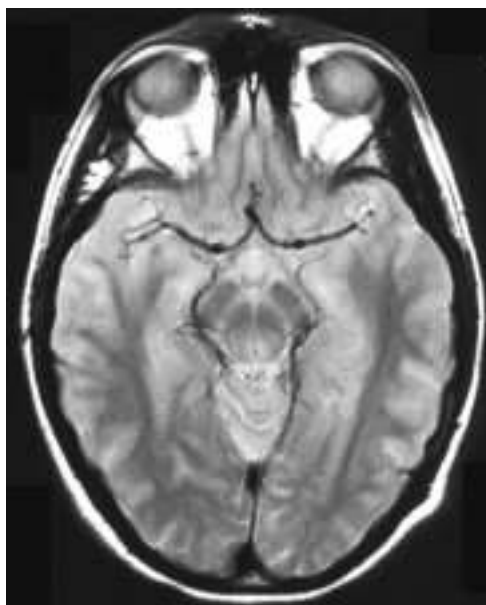


Imaging Parameters

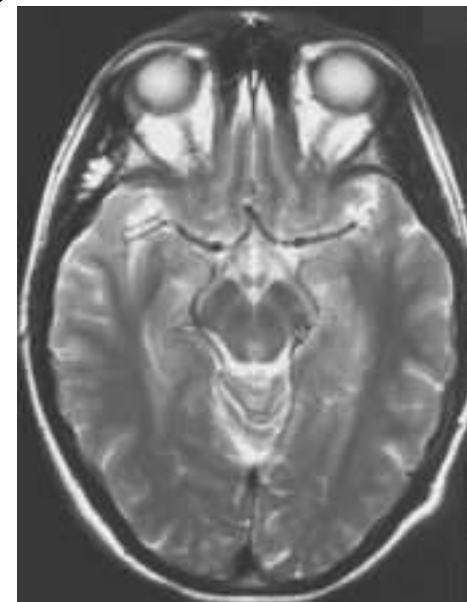
The duration, repetition, timing and amplitude of RF pulse sequences are varied to produce signals which can be analysed in different ways in order to ‘weight’ the image.



T1 weighted



Proton density weighted



T2 weighted

Signal intensities on T1

High: Fat, bone marrow, contrast agents

Intermediate: Soft Tissues

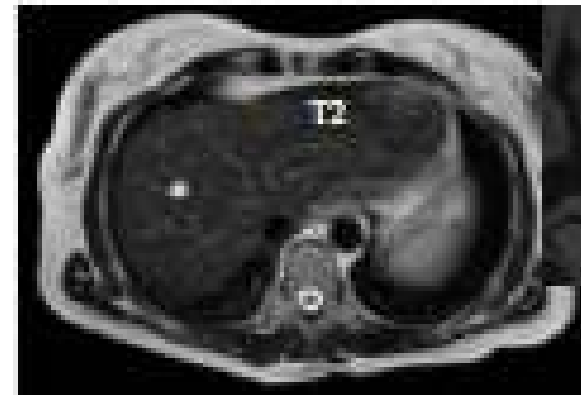
Low: Water (urine, CSF)



Signal intensities on T2



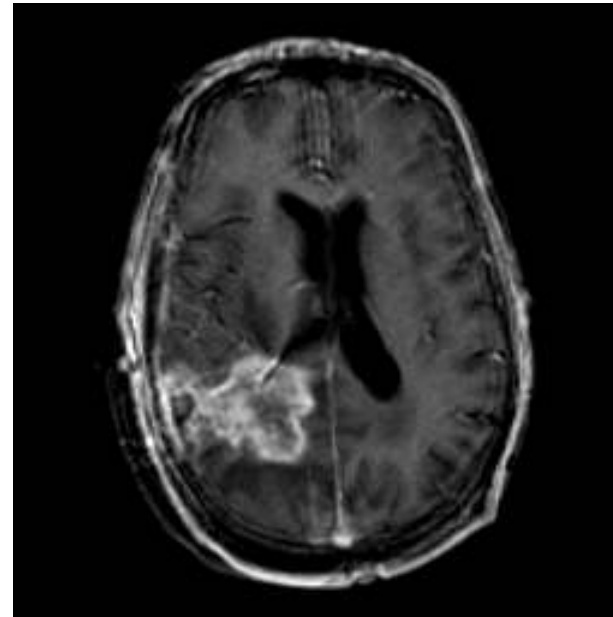
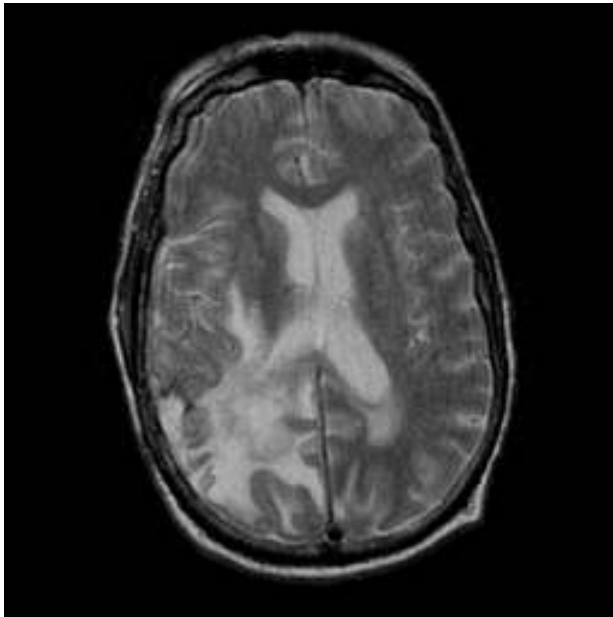
ssue



MR contrast agents

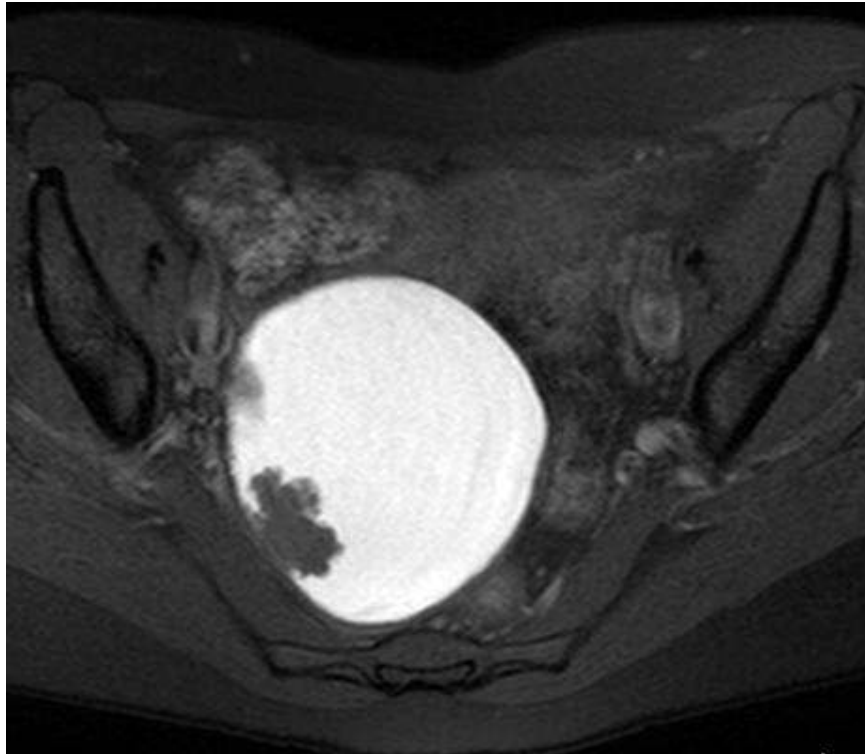
The most common contrast agents are Gadolinium chelates (DOTA, DTPA, DO3A etc) which interact with the water molecules in its vicinity to produce white areas in T1 weighted images

T2

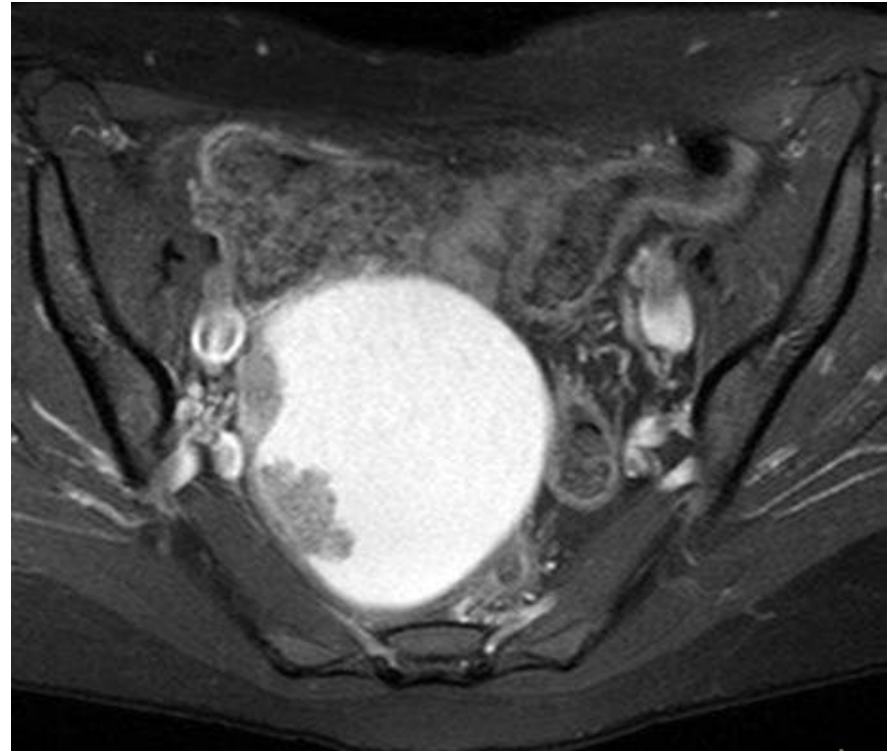


T1 +Gd

Ovarian Cancer within endometrial cyst

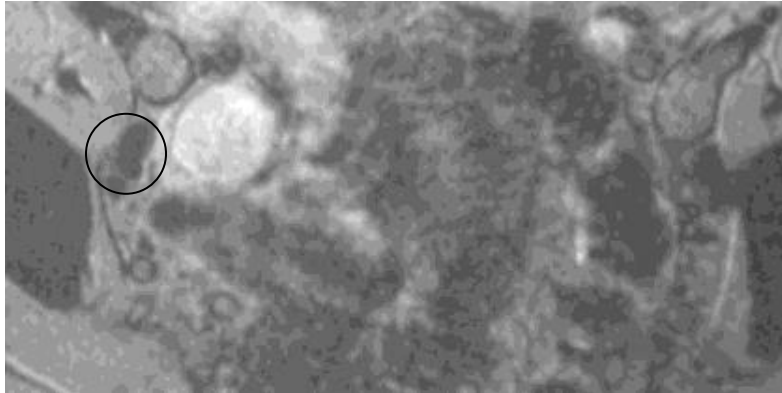
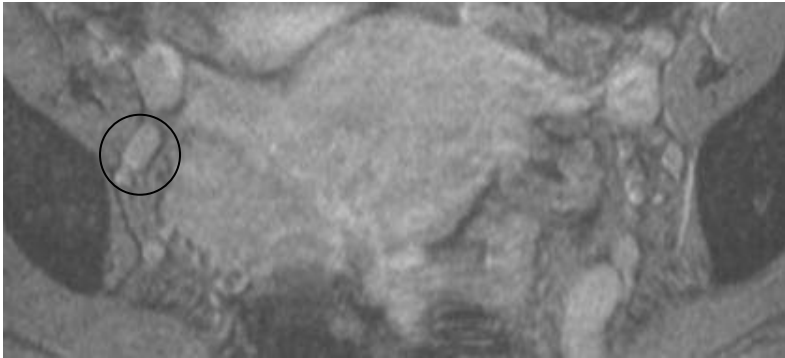


Pre -Gd



Post Gd

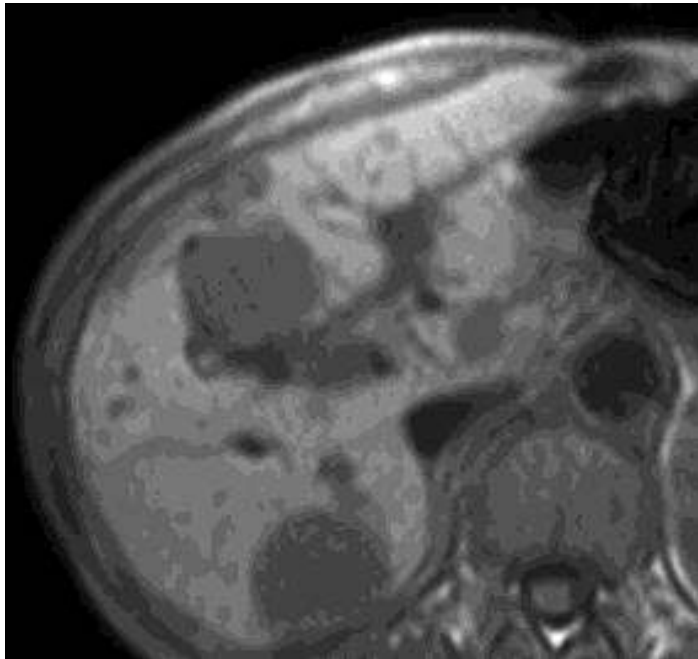
Iron-oxide particles-darken on T2



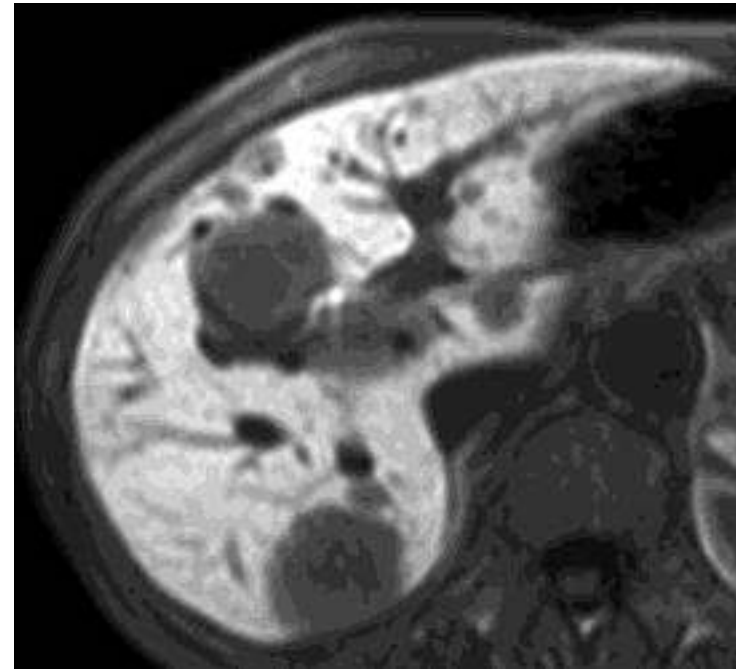
Malignant

Benign

Mn-DPDP – brightens liver on T1



T1



T1 + 'Teslascan'

Manganese(II)-dipyridoxal diphosphate (Mn-DPDP)

Magnetic resonance spectroscopy

- allows examination of individual molecules within a sample
 - MRS can be used to study the biochemical nature of disease
 - looks at concentrations of different substances in tissue to identify disease
 - e.g. brain spectra can give concentrations of N-acetyl aspartate (NAA), creatine/phosphocreatine and choline. In patients with temporal lobe epilepsy, the levels of NAA are reduced and the levels of creatine/phosphocreatine and choline are increased in the diseased lobe
 - e.g. lipid concentration can be used to grade tumours
-

Ultrasound imaging

- **Ultrasound imaging** is based on the pulse-echo principle, which is also the basis of radar
- It only came into use as a medical imaging technique after WW2 during which fast electronic pulse technology was developed
- first 2-D ultrasound scan in a living subject (of a myoblastoma in the leg) was carried out in 1951
- 1961 - first scan of pregnant abdomen



Diagnostic ultrasound

- Ultrasound imaging uses ultra-high-frequency sound waves (3-10 MHz). Human hearing - 20 to 20 000 Hz
 - a **Piezoelectric** transducer (a "crystalline" material such as quartz that changes shape when an electric current is applied creating sound waves and when struck by sound waves creates electrical currents)
 - ultrasonic waves are emitted by the transducer and travel through human tissues at a velocity of 1540 m s^{-1} . When the wave reaches an object or surface with a different texture or acoustic nature, a wave is reflected back
 - these echoes are received by the apparatus, changed into electric current and a 2-D image is produced
 - more than 20 frames can be generated per second, giving a smooth, real-time image
-

Diagnostic Ultrasound

- The stronger the returning signal, the more white it will be on the grey-scale image (*hyperechoic* = white or light grey e.g. fat containing tissues)
- *hypoechoic* = dark grey (e.g. lymphoma, fibroadenoma of the breast)
- pure fluid gives no echoes, appearing black (*anechoic*) leading to *acoustic enhancement* of tissues distal to e.g. gallbladder and urinary bladder
- *acoustic shadow* is the opposite effect where tissues distal to e.g. gas containing areas, gallstones, renal stones receive little sound and thus appear as black



Jackson Memorial
08/19/02 4:20:17 PM

adm

7656767

MI 0.8

TIs 0.0

3.5C

Fetal Echo



B
0- Frq 5.0 MHz
- Gn 50
- E/A 0/3
- Map C/O
- D 16.0 cm
- DR 72
- FR 15 Hz
▲ AO 100 %

5-

▲

▲

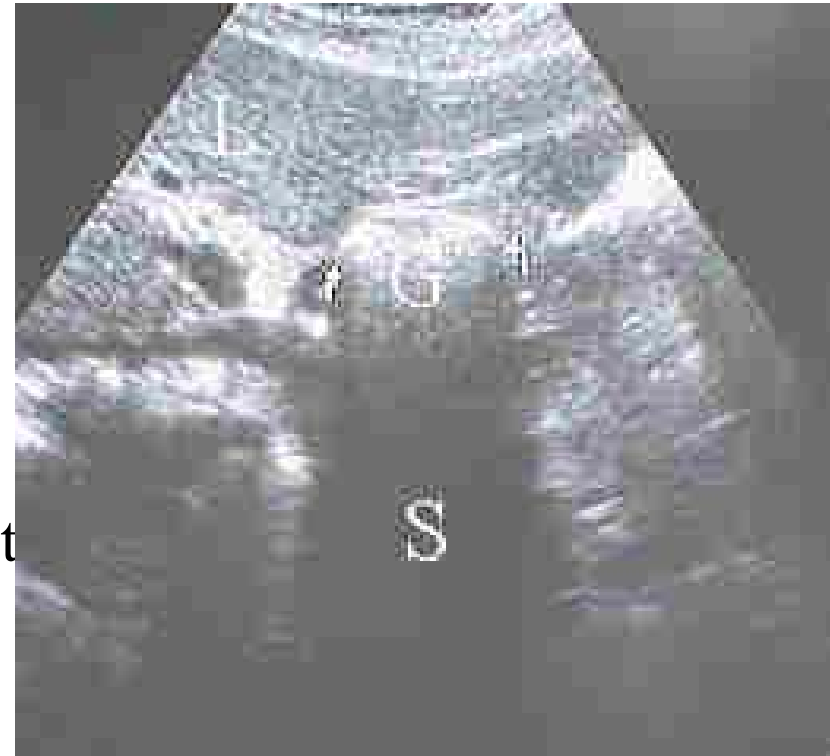
10-

15-

16 WEEK FETUS

Ultrasound - disadvantages

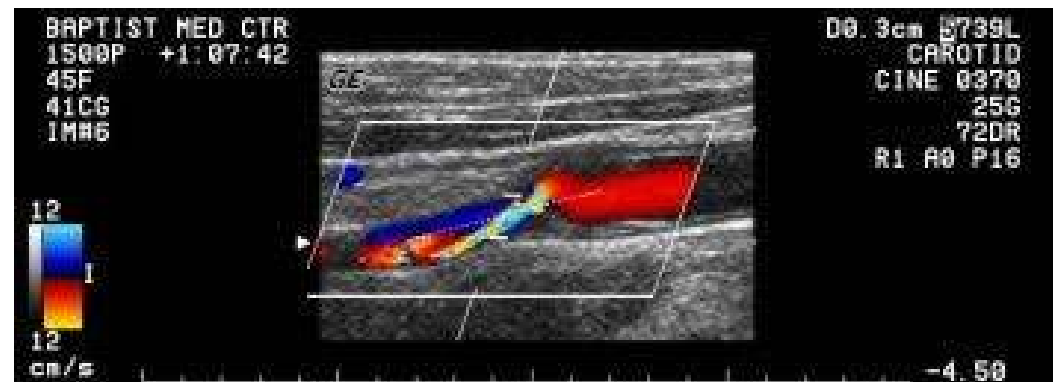
- interactive modality, operator dependent
- ultrasound waves are greatly reflected by air-soft tissue and bone-soft tissue interfaces, thus limiting its use in the head, chest and musculoskeletal system



Ultrasound image of gallstone (G) causing acoustic shadow (S). L = liver

Doppler Ultrasound

- **Doppler effect:** the influence of a moving object on sound waves
- object travelling towards listener causes compression of sound waves (higher frequency)
- object travelling away from listener gives lower frequency
- flowing blood causes an alteration to the frequency of the sound waves returning to the ultrasound probe, allowing quantitation of blood flow
- Colour Doppler shows blood flowing towards the transducer as red, blood flowing away as blue - particularly useful in echocardiography and identifying very small blood vessels



Nuclear Medicine

.....the clinical application
of 'unsealed' radioisotopes
or 'radiopharmaceuticals'

The discovery of Radioactivity

- In 1896, Henri Becquerel discovered that uranium (and its salts) emitted radiation
- 2 years later, Pierre and Marie Curie showed that uranium rays were an atomic phenomenon characteristic of the element, and not related to its chemical or physical state.
- They called this phenomenon “radioactivity”
- Becquerel and the Curies shared the Nobel Prize for Physics - 1903

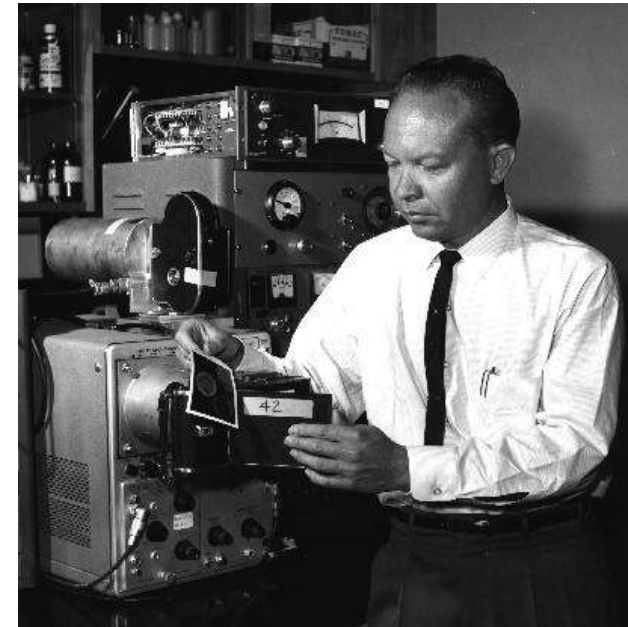


-
- In 1931, Ernest Lawrence invented the cyclotron and it became possible to produce artificial radioisotopes
 - ^{99m}Tc was first produced by a 37 inch cyclotron in 1938
 - the first nuclear medicine scan (^{131}I -thyroid) was carried out in 1948 (point by point)



Ernest Lawrence

-
- planar imaging using an Anger camera - 1957
 - 1967 SPET with Anger camera (rotating the patient on a chair in front of the camera)
 - 1978 - first commercial gamma-camera-based SPECT systems
 - The beginnings of PET (the technique of counting gammas from positron annihilation) had come about in 1951 and images were produced in 1953
-



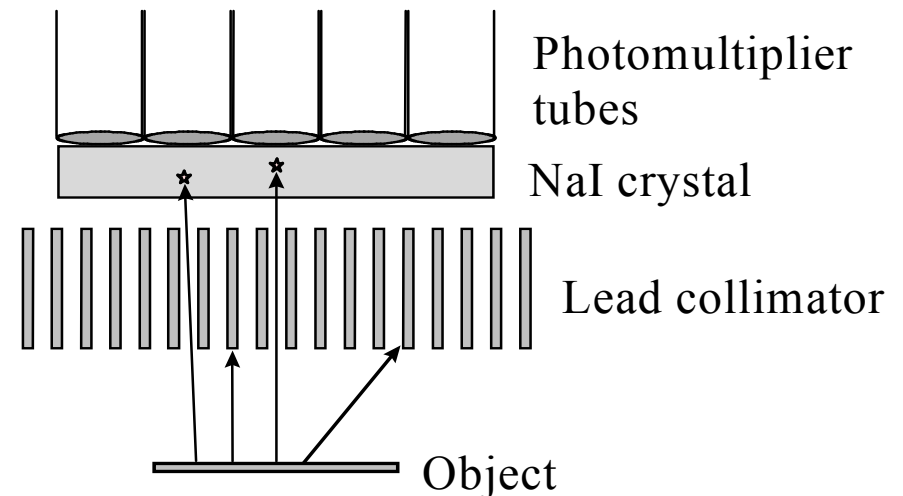
Hal Anger with his invention, the scintillation camera

Nuclear Medicine Imaging

- Three types of emissions from radioactive isotopes: α particles, β particles and γ -rays (also some associated X-rays)
- only γ -rays are useful for radioisotope imaging (high energy photons)
- In radioisotope imaging, source is inside the body (X-ray CT – source is external).

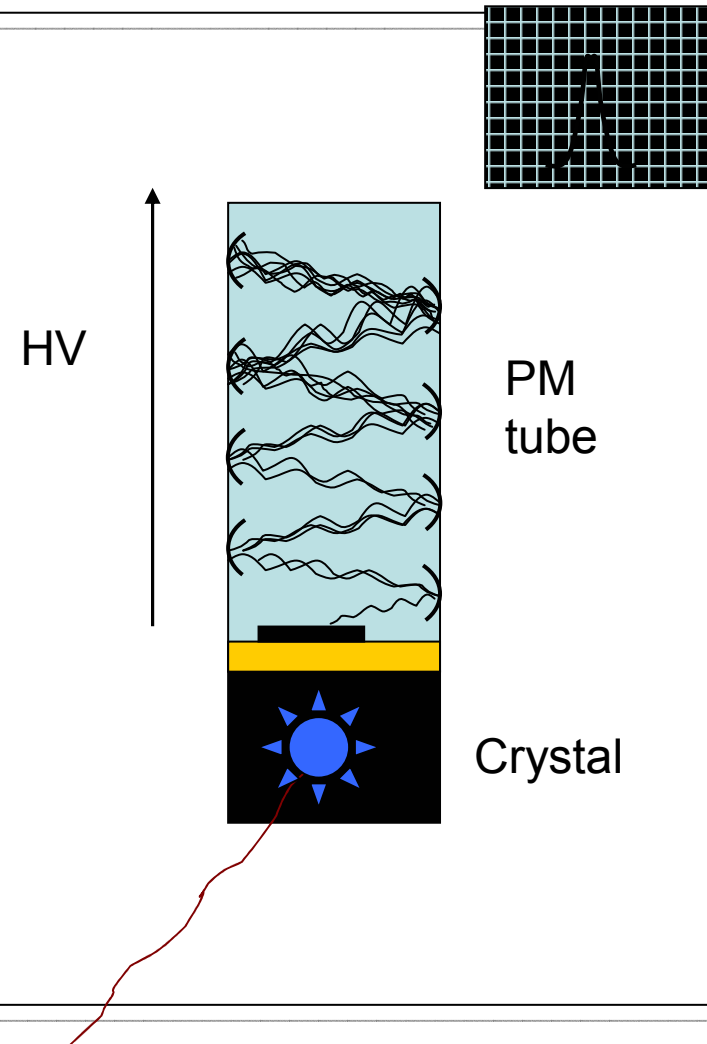
Nuclear Medicine

- Radiolabelled tracer (**Radiopharmaceutical**) is administered
- γ -rays (high energy photons) emitted by the radioisotope are detected outside the body on a '**Gamma camera**'
- Lead 'collimators' are used to absorb scattered γ -rays
- γ -rays impinge on sodium iodide crystals (dense enough to stop the photons) and converted into light which is detected by photomultipliers.



Photon Detection

- photon is converted by scintillation crystal to flash of light
- Crystal is coupled to Photomultiplier Tube
- Photocathode converts light to electron.
- Electron avalanche leads to electronic pulse



Gamma-camera Principle



Patient

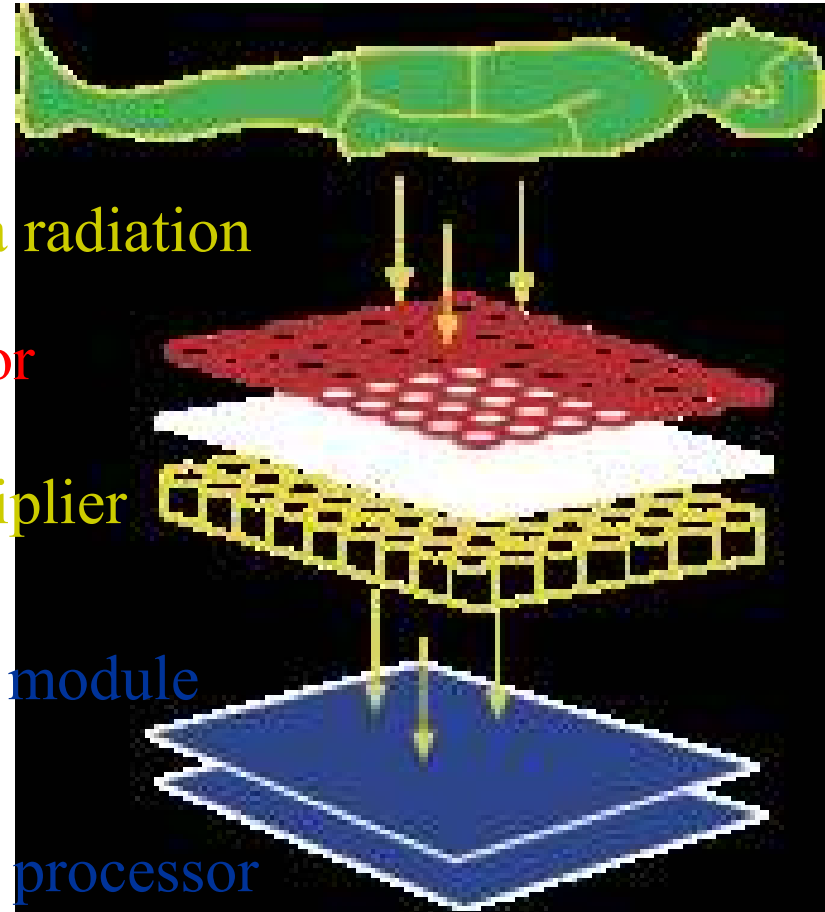
Gamma radiation

Collimator

Photomultiplier

Acquisition module

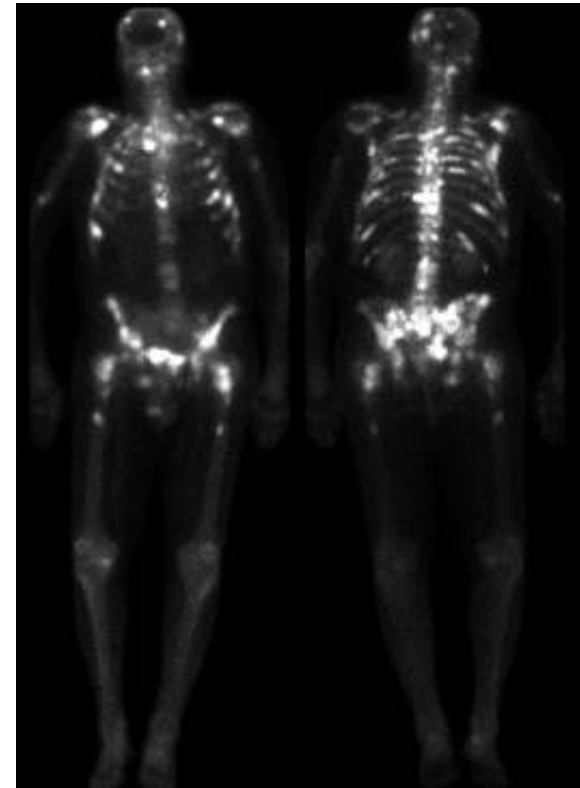
Image processor



Functional Imaging



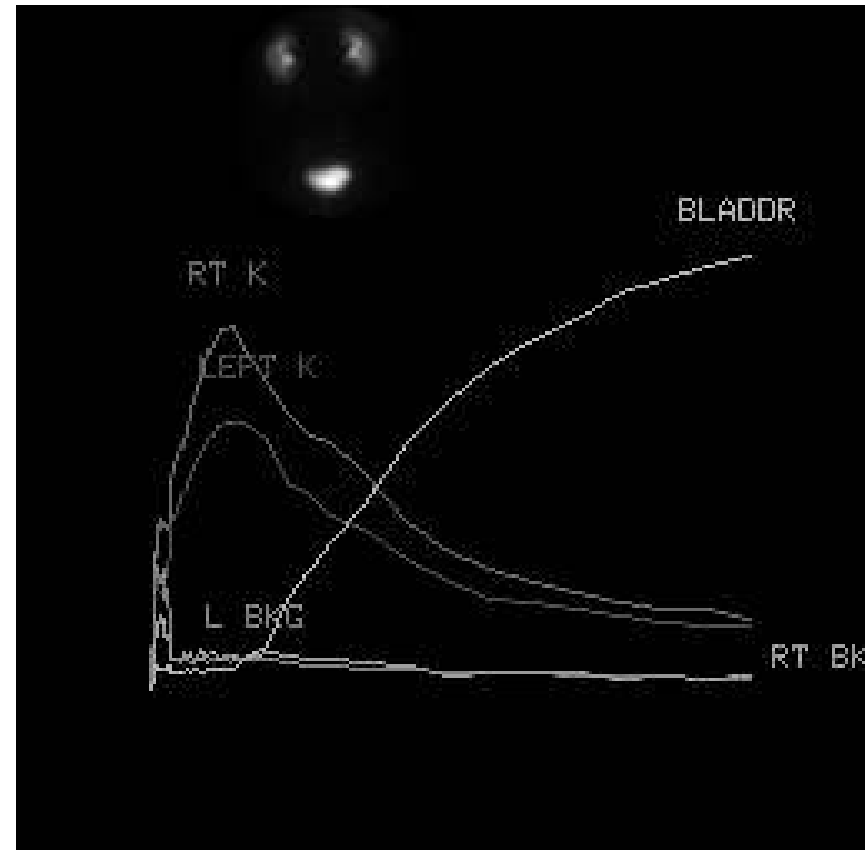
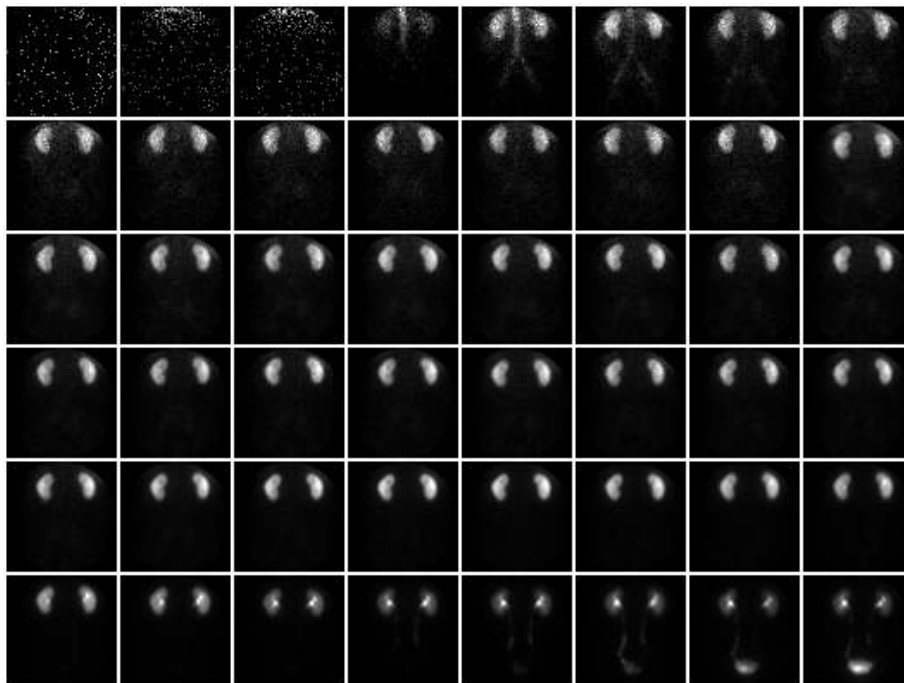
Normal distribution of bone function

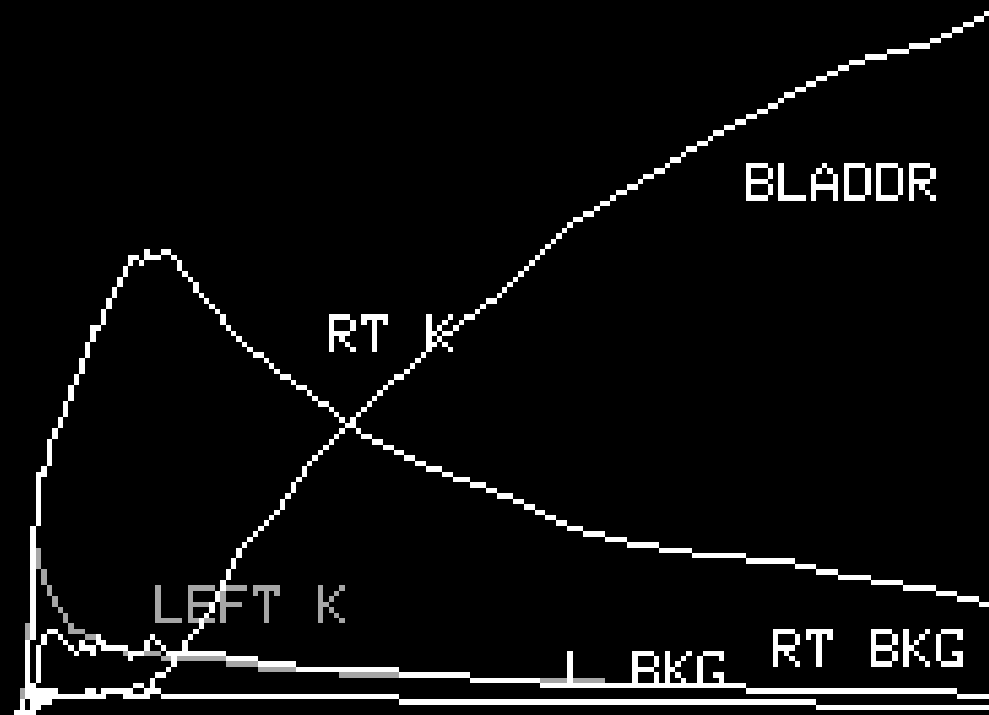
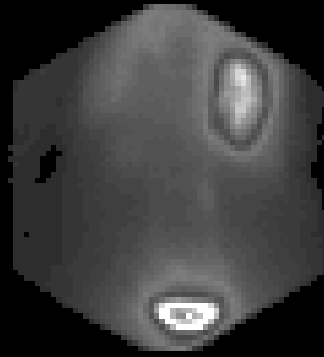


Abnormal distribution

Quantitative

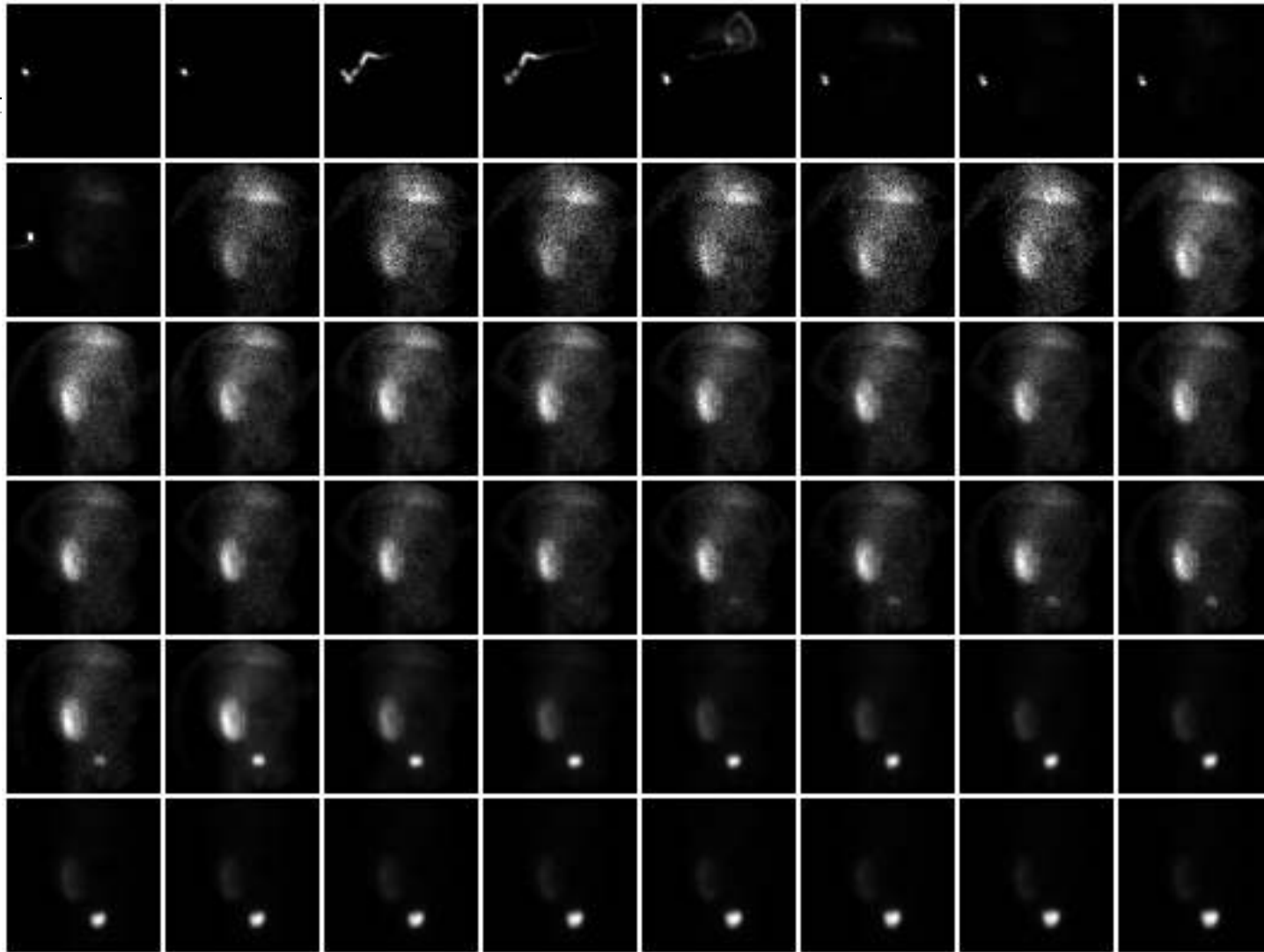
Dynamic acquisition





Renogram with absent Left kidney function

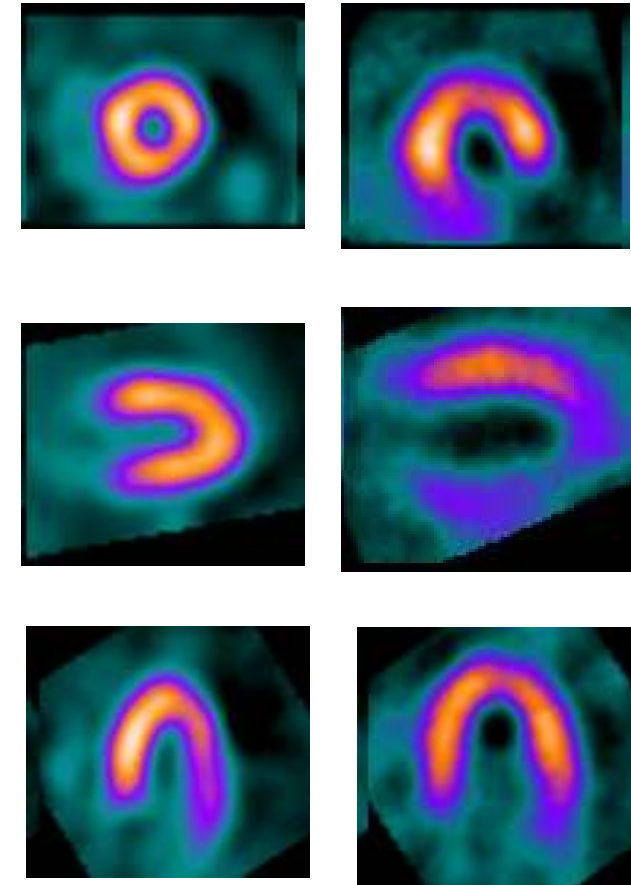
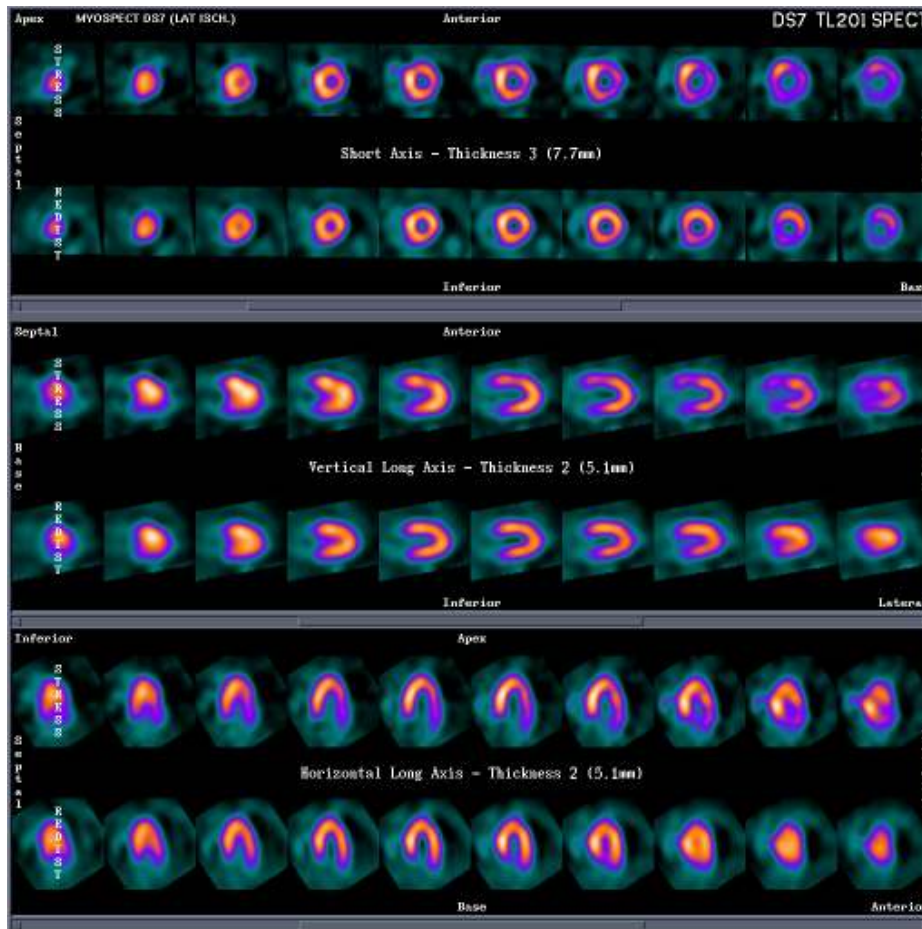
Dynamic MAG-3 kidney transplant study



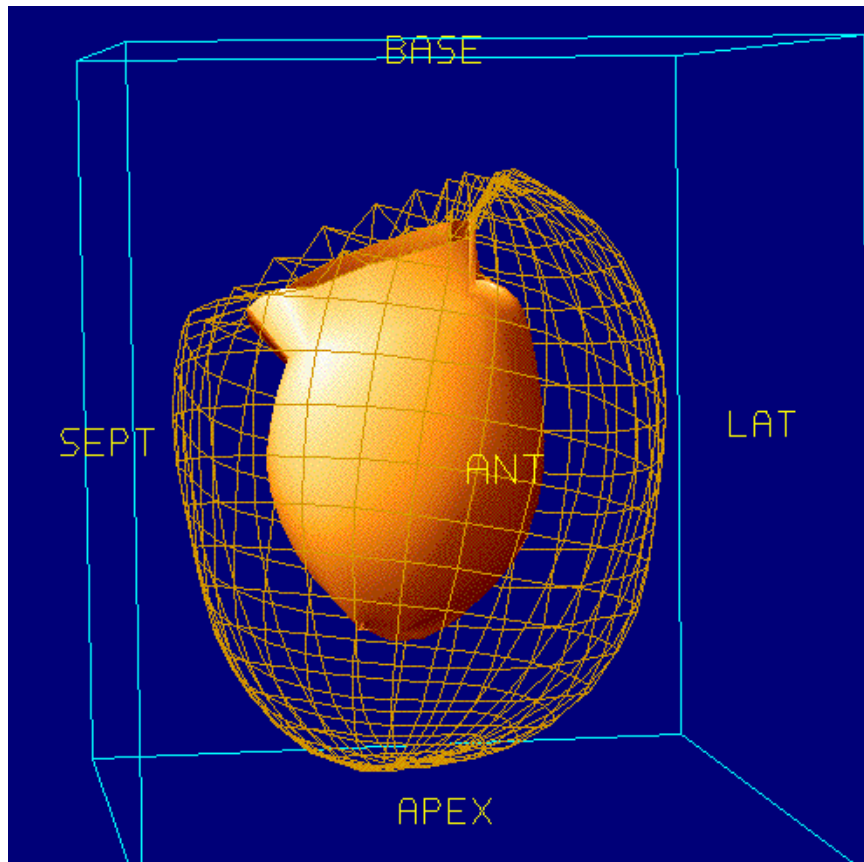
Tomographic acquisition (SPECT)



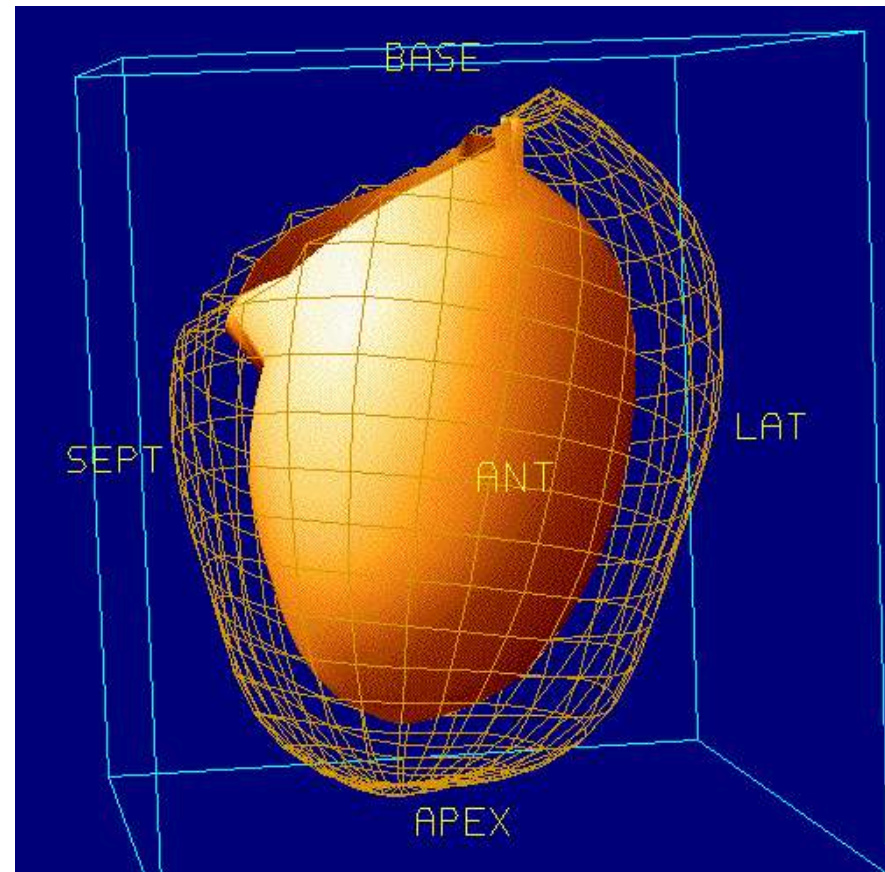
Myocardial perfusion



3-D Rendering

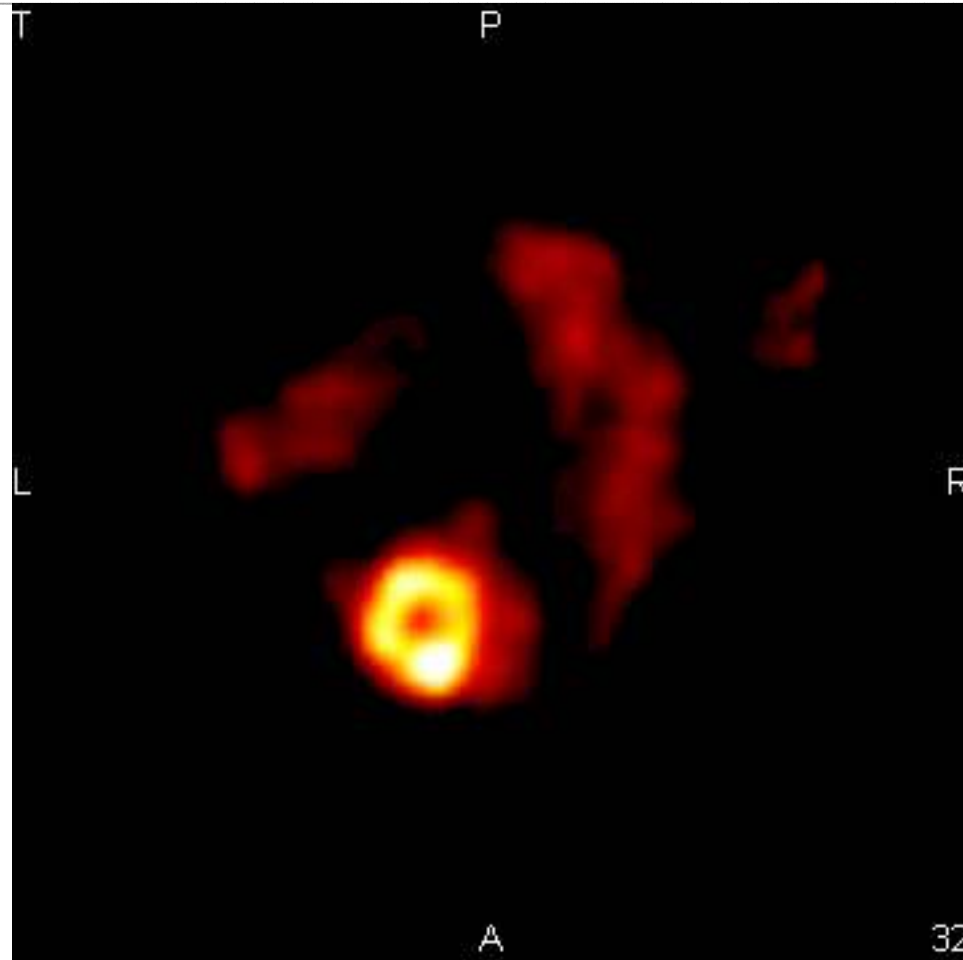


SYSTOLE

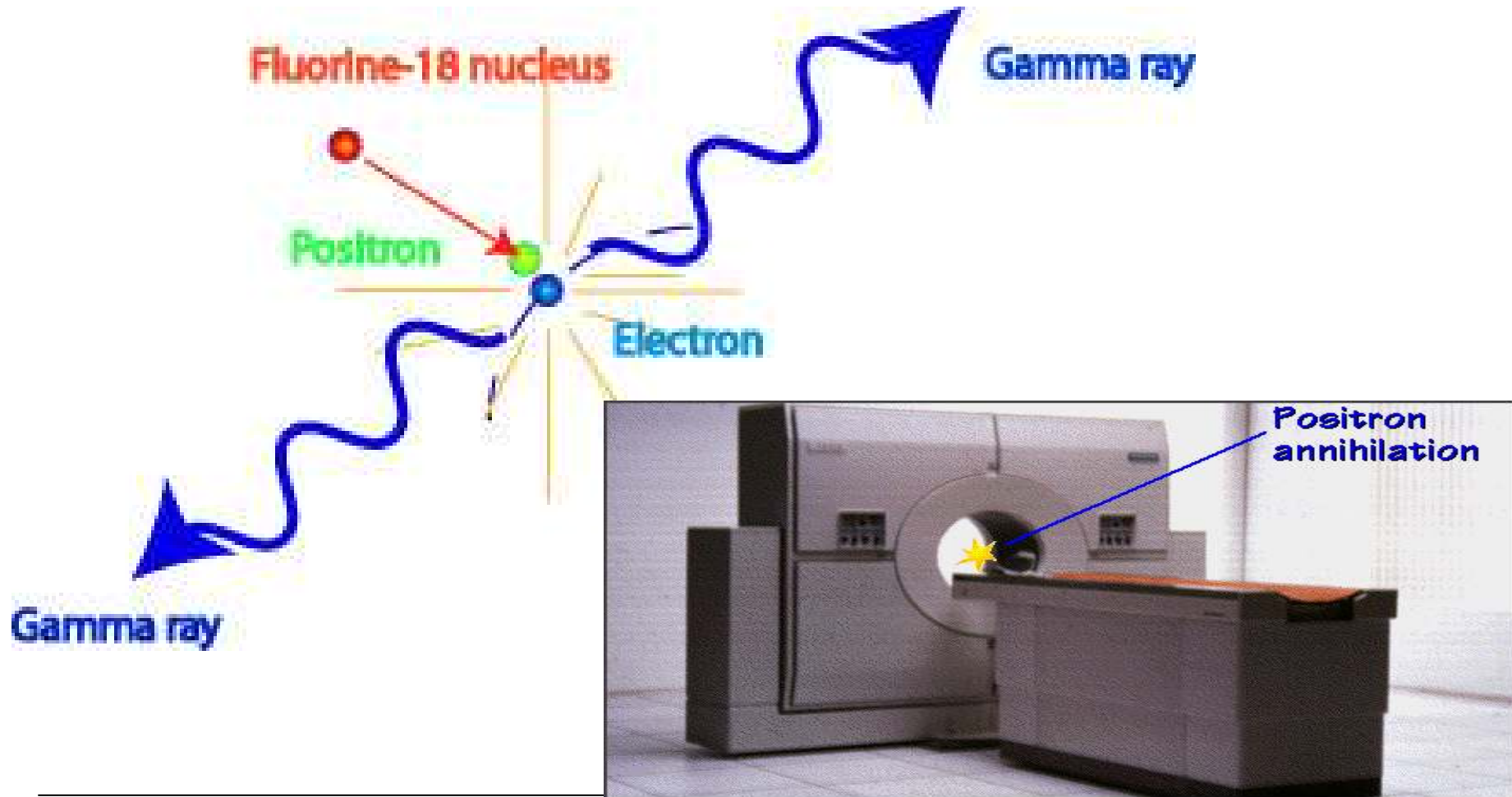


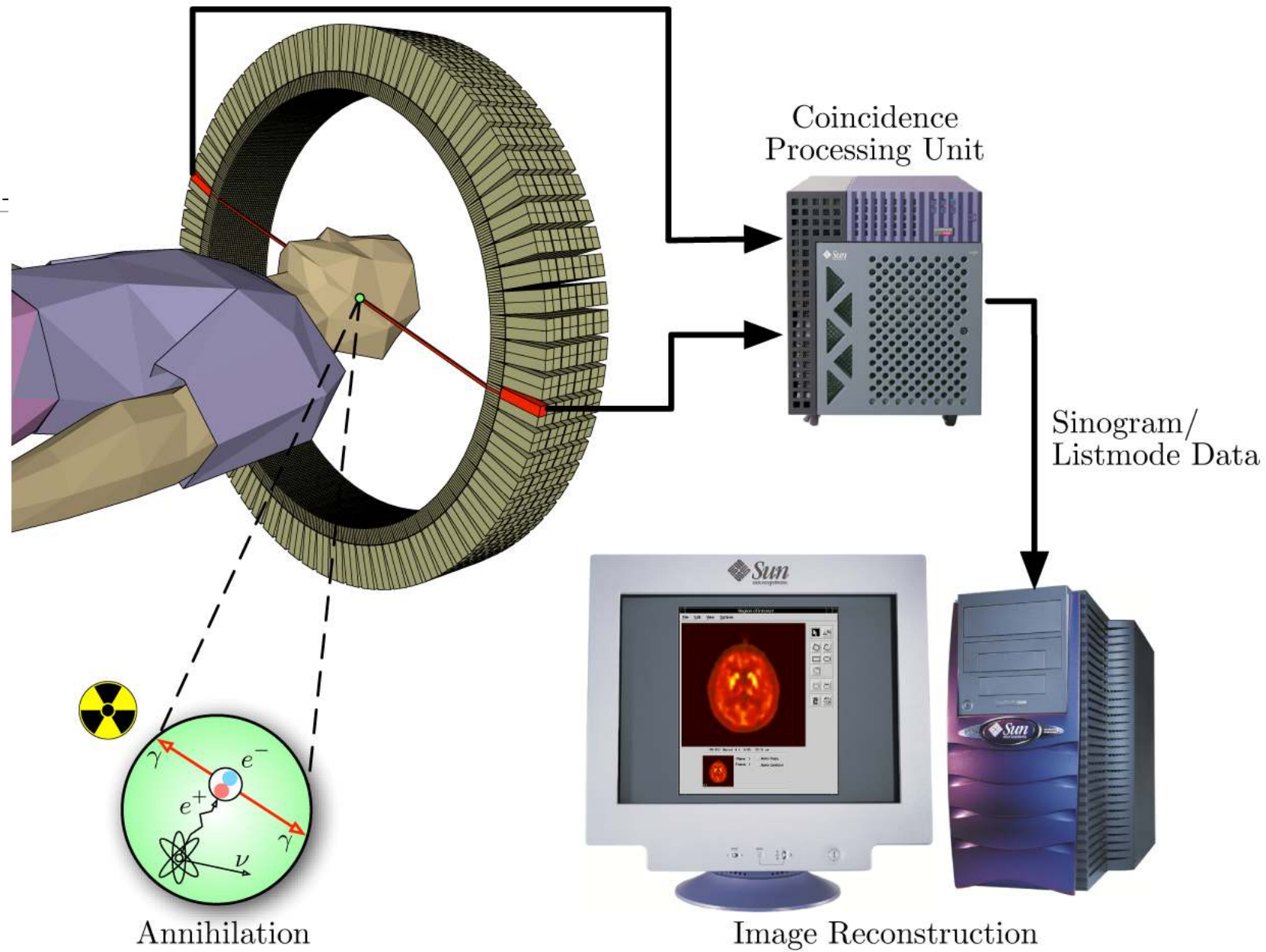
DIASTOLE

Beating mouse heart

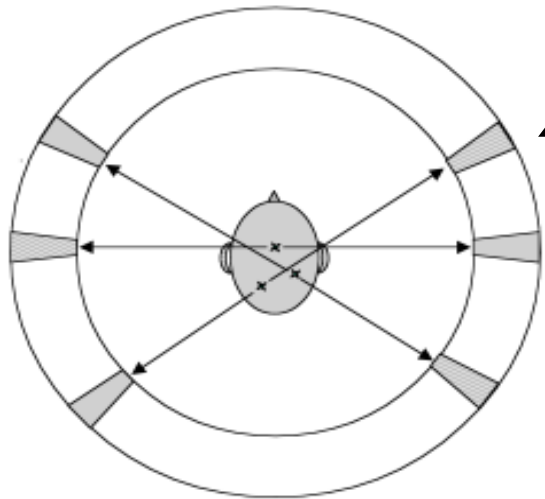


Positron Emission Tomography (PET)





PET coincidence detection

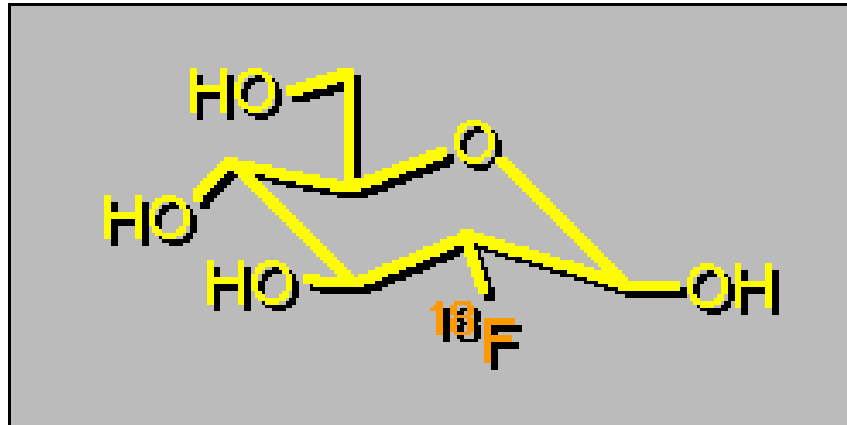


bismuth germanate (BGO) or

Lutetium Oxyorthosilicate (LSO) crystals

- No collimators
- High sensitivity
- Picomolar concentrations
- Absolute quantification (moles per microlitre)

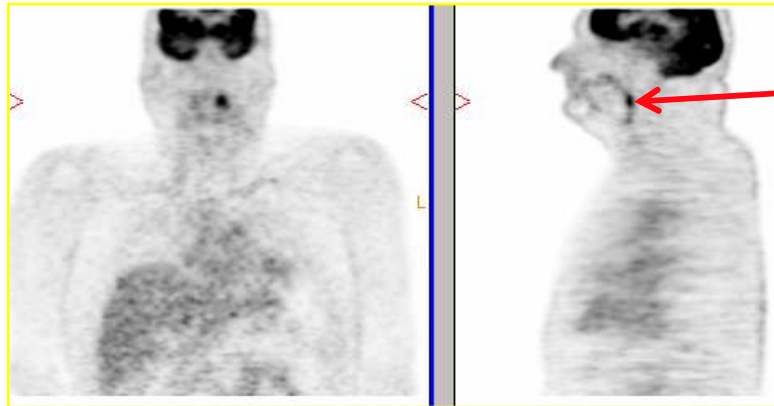
Fluorodeoxyglucose -FDG



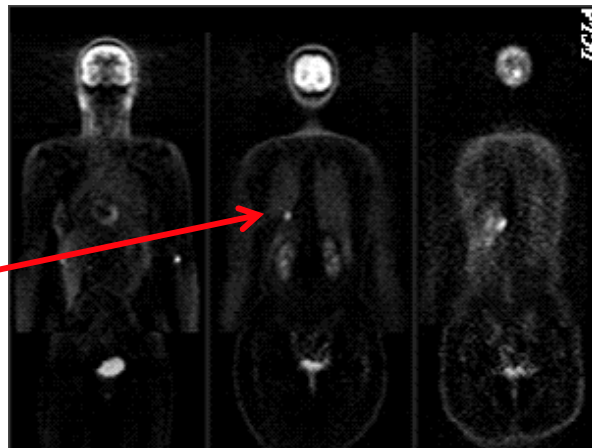
- Substrate for glucose transporters
- undergoes phosphorylation
- No further metabolism



FDG shows increased tumour uptake



Head and Neck



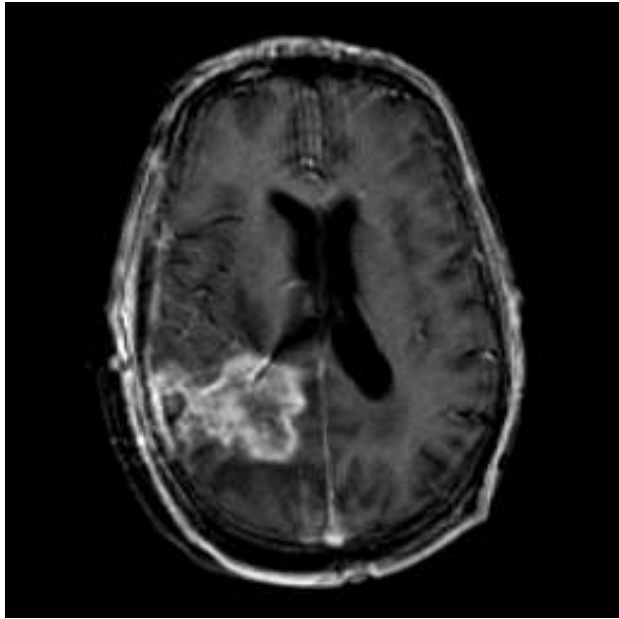
Lung cancer



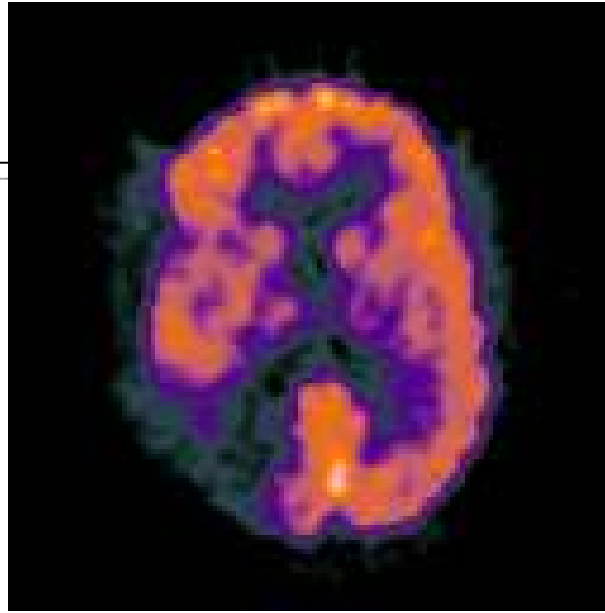
Primary Breast Carcinoma



FDG-whole body PET showed increased glucose metabolism, highly suspicious for metastatic breast carcinoma. Fine-needle aspiration revealed metastatic adenocarcinoma. NOTE: MRI is negative



Gd contrast MRI



FDG-PET

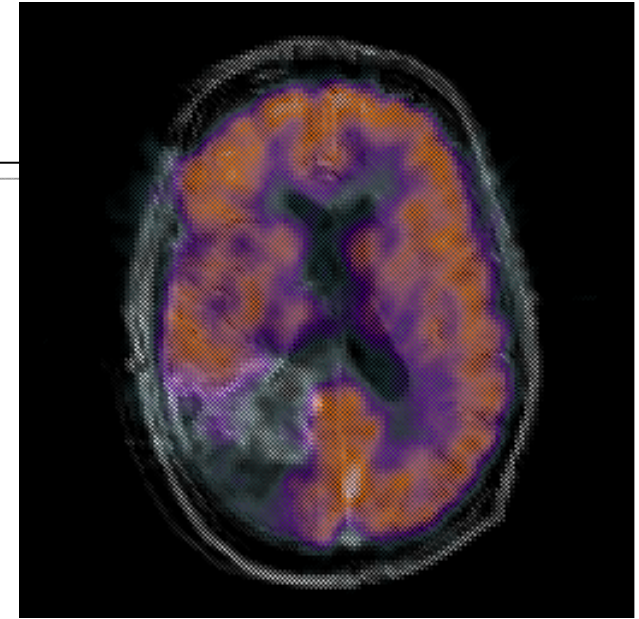
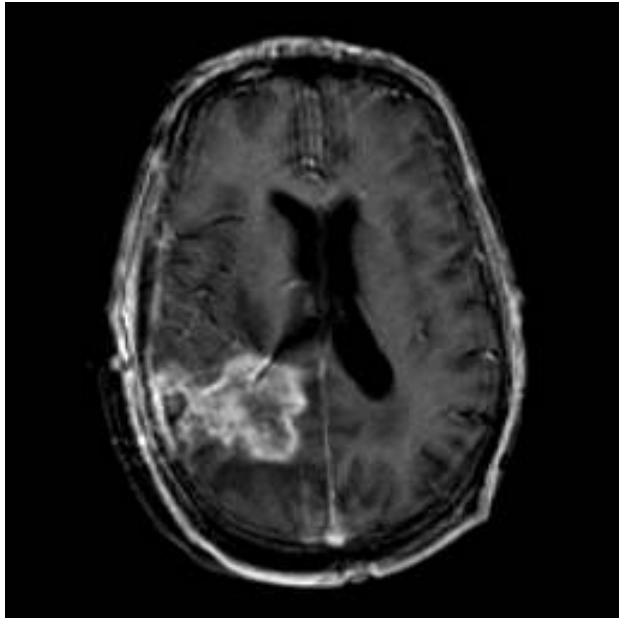
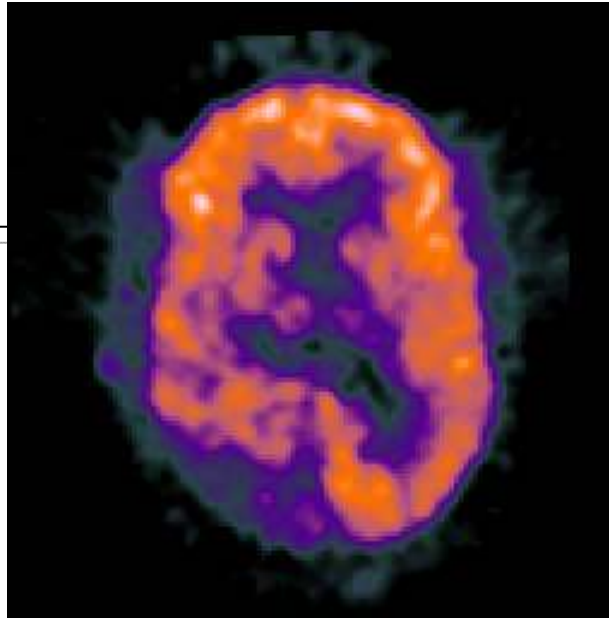


Image overlay

Glucose metabolism is very low on the first PET study



Gd contrast MRI



FDG-PET

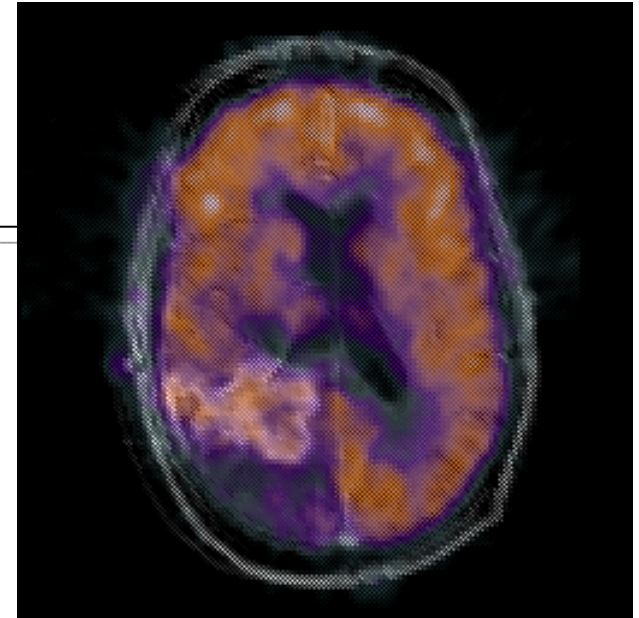
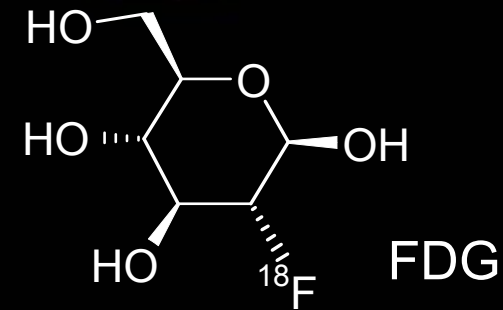
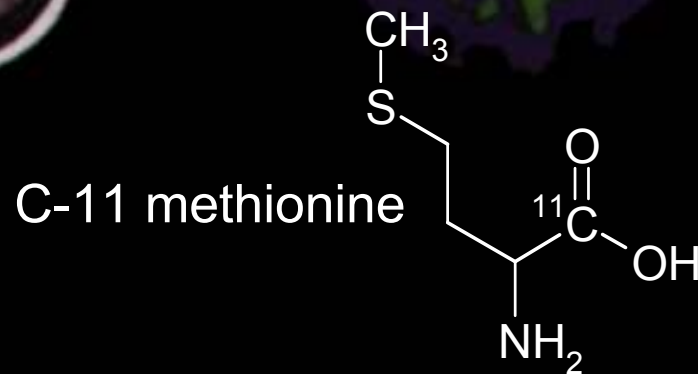
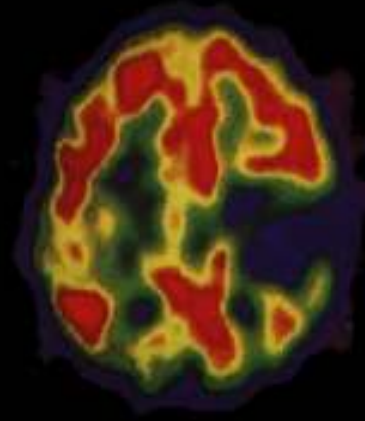
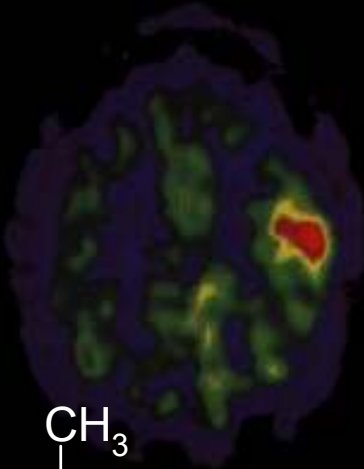
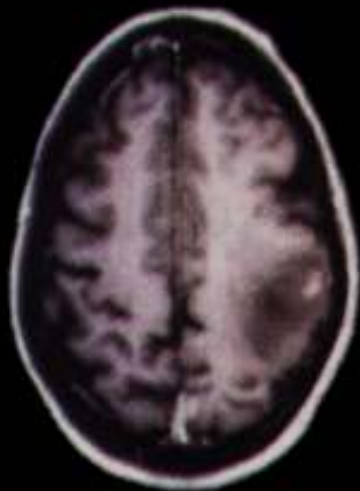


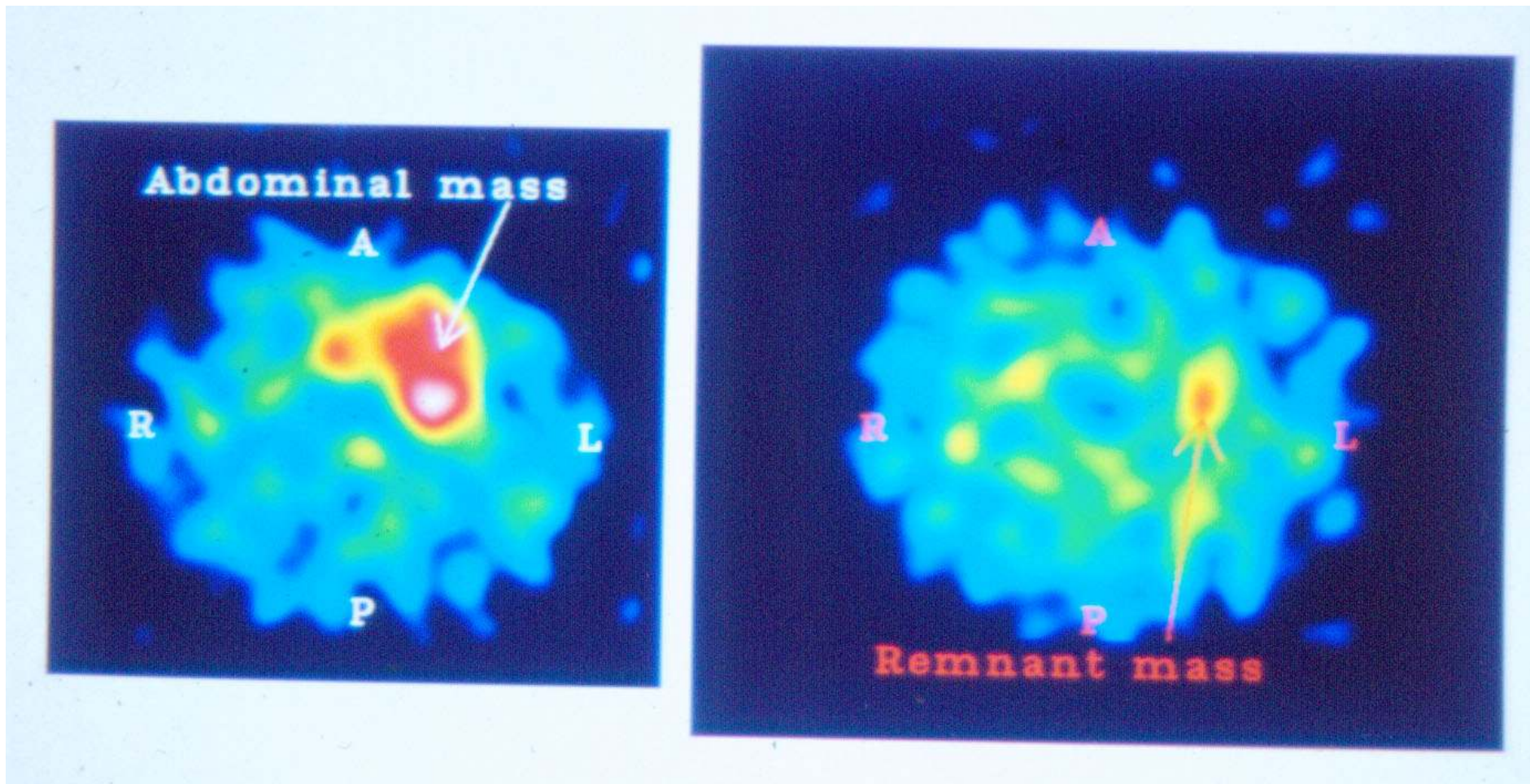
Image overlay

FDG-PET uptake has increased three months later.
This suggests tumor recurrence, and effectively rules out radiation necrosis.

Biologically relevant radionuclides

From Kaschten *et al.*, JNM, 39 (1998), 778





Comparison of PET and SPECT

Biological isotopes can be used for PET

High sensitivity (arising from coincidence detection) and better image resolution

Collimators essential for SPECT (much of signal is lost)

Attenuation correction in PET is simple - in SPECT it is v.complex

PET can be quantitative

Fast - detector ring in PET collects much more of the signal and no need for gantry rotation

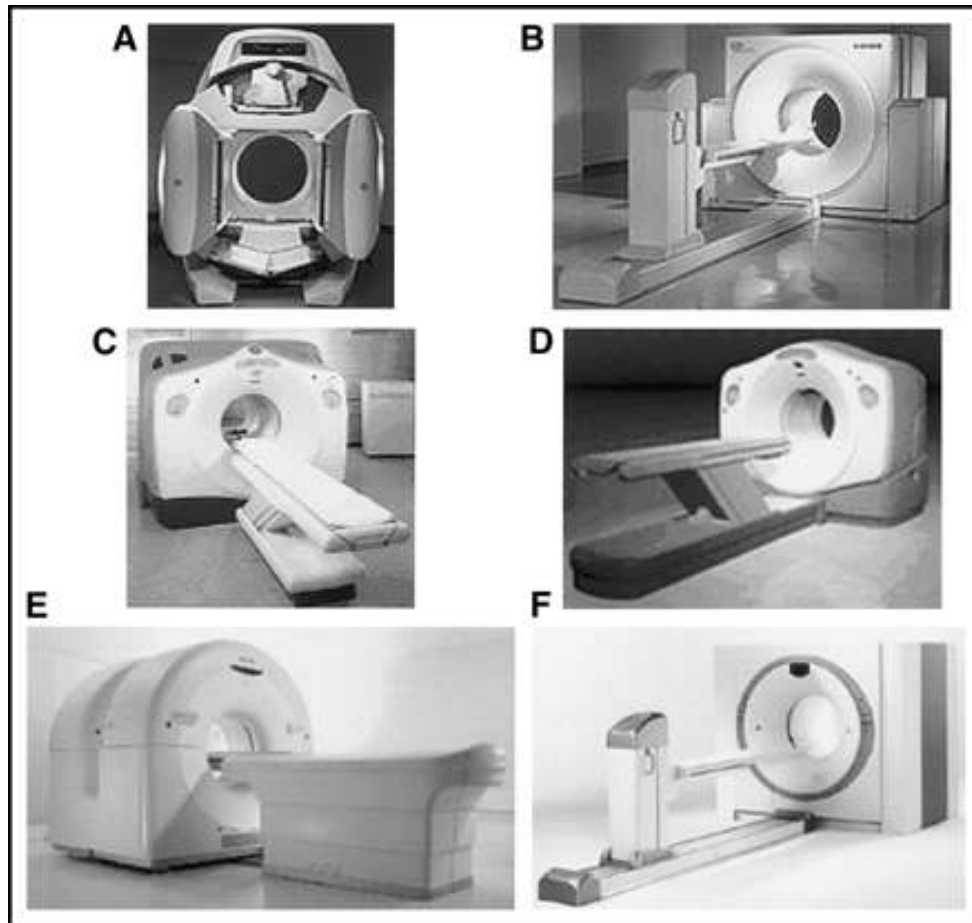
However

SPECT is much more commonplace and is cheaper than PET

Access to a local cyclotron essential in PET

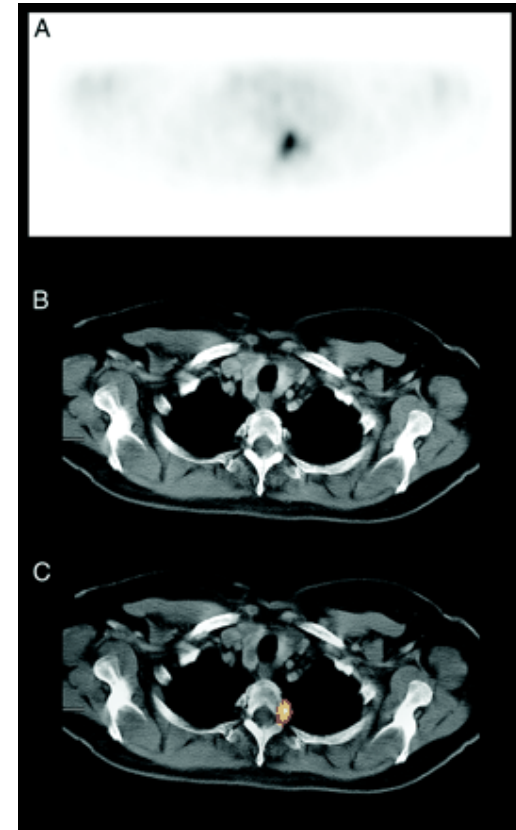
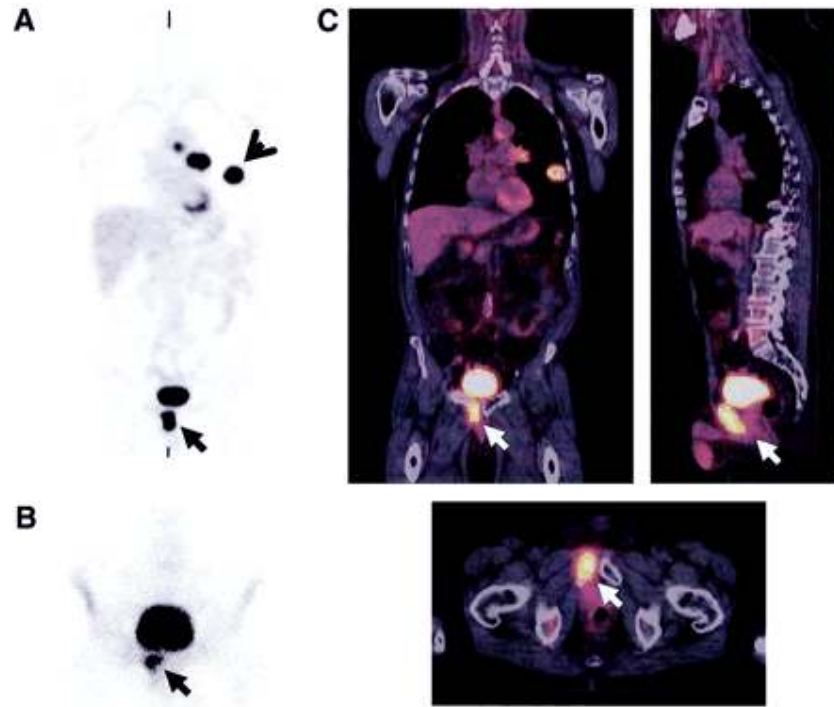


PET-CT - The best of both worlds



Combines functional
information from PET
with anatomical
location provided by
CT

PET-CT



PET/CT shows an area of increased uptake in the left nasopharynx and physiologic increased uptake inferior oral cavity and tongue.

