Joint CI-JAI advanced accelerator lecture series

Imaging and detectors for medical physics

Lecture 1: Medical imaging

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Course layout

Day	AM 09.30 – 11.00	PM 15.30 – 17.00
Week 1		
6th June	Lecture 1: Introduction to medical imaging	Lecture 2: Detectors for medical imaging
7th June	Lecture 3: X-ray imaging	
8th June		Tutorial
Week 2		
13th June	Lecture 4: Radionuclides	
14th June	Lecture 5: Gamma cameras	Lecture 6: SPECT
16th June	Lecture 7: PET	
Week 3		
22nd June	Tutorial	

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Books

1. N Barrie Smith & A Webb
   Introduction to Medical Imaging
   Cambridge University Press

2. Edited by M A Flower
   Webb's Physics of Medical Imaging
   CRC Press

3. A Del Guerra
   Ionizing Radiation Detectors for Medical Imaging
   World Scientific

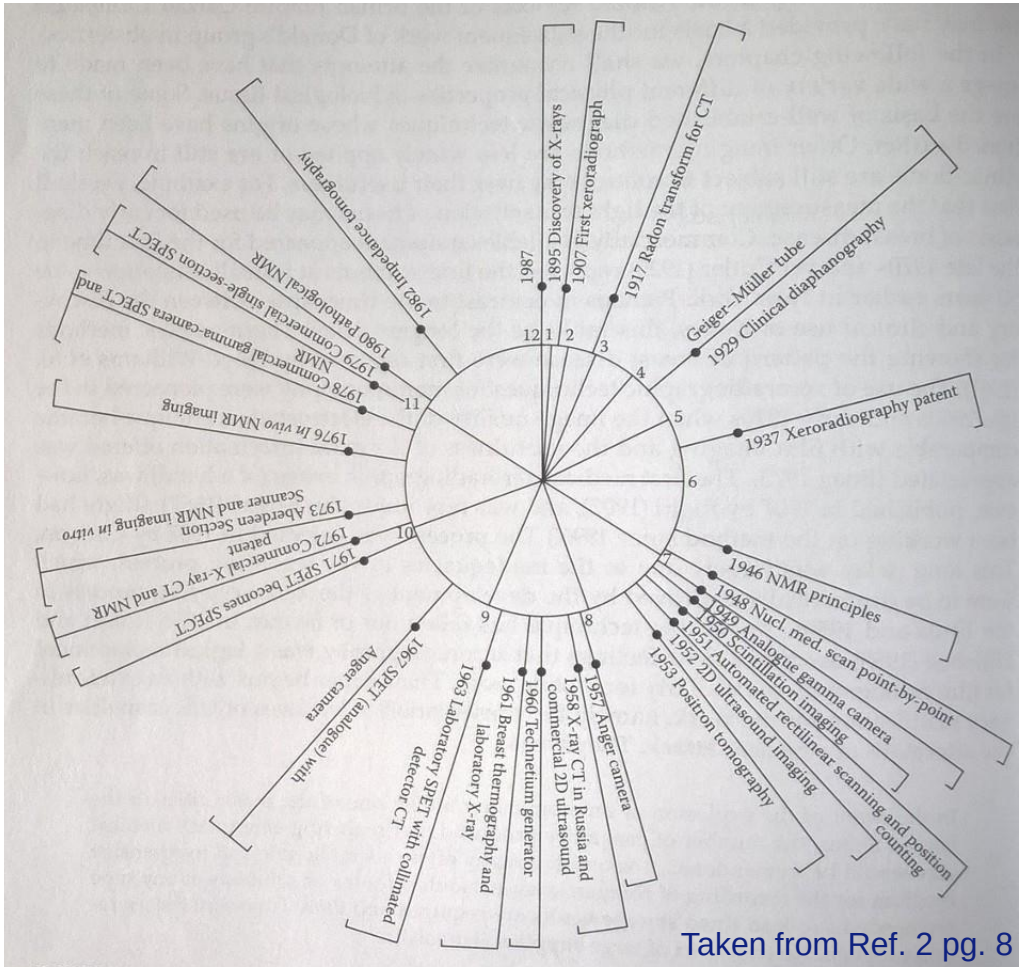
4. W R Leo
   Techniques for Nuclear and Particle Physics Experiments
   Springer-Verlag

Medical imaging: what is it?

- "**Medical imaging** is the technique and process of creating visual representations of the interior of a body for clinical analysis and medical intervention, as well as visual representation of the function of some organs or tissues." – *Wikipedia*
- Used to:
  1. Diagnose the disease = diagnostic imaging
  2. Plan and monitor the treatment of the disease
- Clinical speciality: radiology & radiography + medical physics

Origins of medical imaging

Ref. 2 – Chapter 1



Taken from Ref. 2 pg. 8

Origins of medical imaging: some dates

Ref. 2 – Chapter 1

- 1895: X-ray discovery, Wilhelm C Röntgen
- 1931: invention of cyclotron, Ernest O Lawrence
- 1938: production of $^{99}Tc^{m}$ at cyclotron
- 1946: radioisotopes available for public distribution → nuclear medicine
- 1946: discovery of NMR, Felix Bloch and Edward M Purcell
- 1958 – 1967: SPECT images
- Early 1960s: first clinical PET images
- 1972: first CT machine, Godfrey N Hounsfield
- 1976: first MRI images
- 1978: first commercial SPECT systems

Medical imaging techniques

- Techniques not using ionising radiation:
  1. Ultrasound imaging (Ref. 1 – Chapter 4, Ref. 2 – Chapter 6)
  2. MRI (Ref. 1 – Chapter 5, Ref. 2 – Chapter 7)
  3. Infrared imaging (Ref. 2 – Chapter 8)
  4. Optical imaging (Ref. 2, Chapter 10)
- Techniques using ionising radiation:
  1. X-ray imaging: films, CT
  2. SPECT
  3. PET
  4. Scintigraphy (Ref. 1 – Chapter 3)

Basic physics concepts

See for ex. Ref. 4 – Chapters 1, 2, 3 and 4

- X-ray energy spectrum
- Interaction of photons with matter
  1. Photoelectric effect
  2. Compton scattering
  3. Absorption and attenuation
- Probability distributions: Gaussian, Poisson, etc.
- Radioactive sources
  1. Radioactive decay
- Dosimetric units

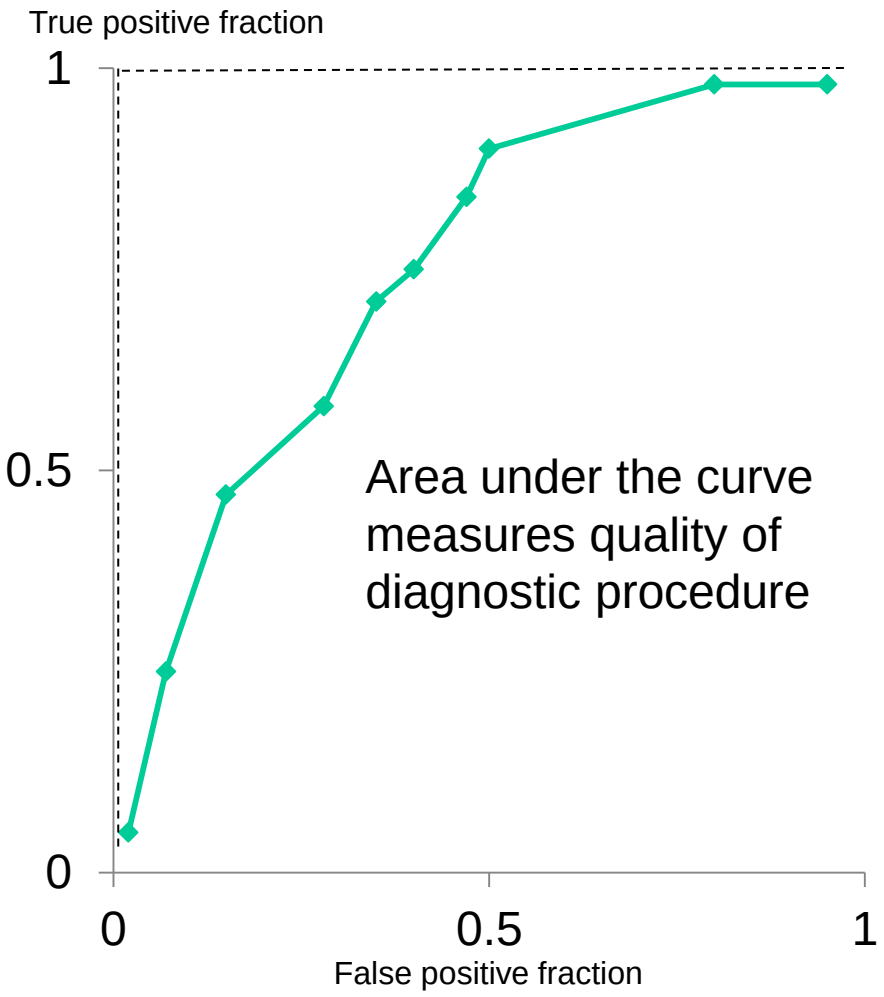
The receiver operating characteristic (ROC) curve

Diagnosis	Actual situation	
	Disease	Healthy
Disease	True positive	False positive
Healthy	False negative	True negative

$$Accuracy = \frac{N_{correct\ diagnoses}}{N_{total\ diagnoses}}$$

$$Sensitivity = \frac{N_{true\ positives}}{N_{true\ positives} + N_{false\ negatives}}$$

$$Specificity = \frac{N_{true\ negatives}}{N_{true\ negavites} + N_{false\ positives}}$$



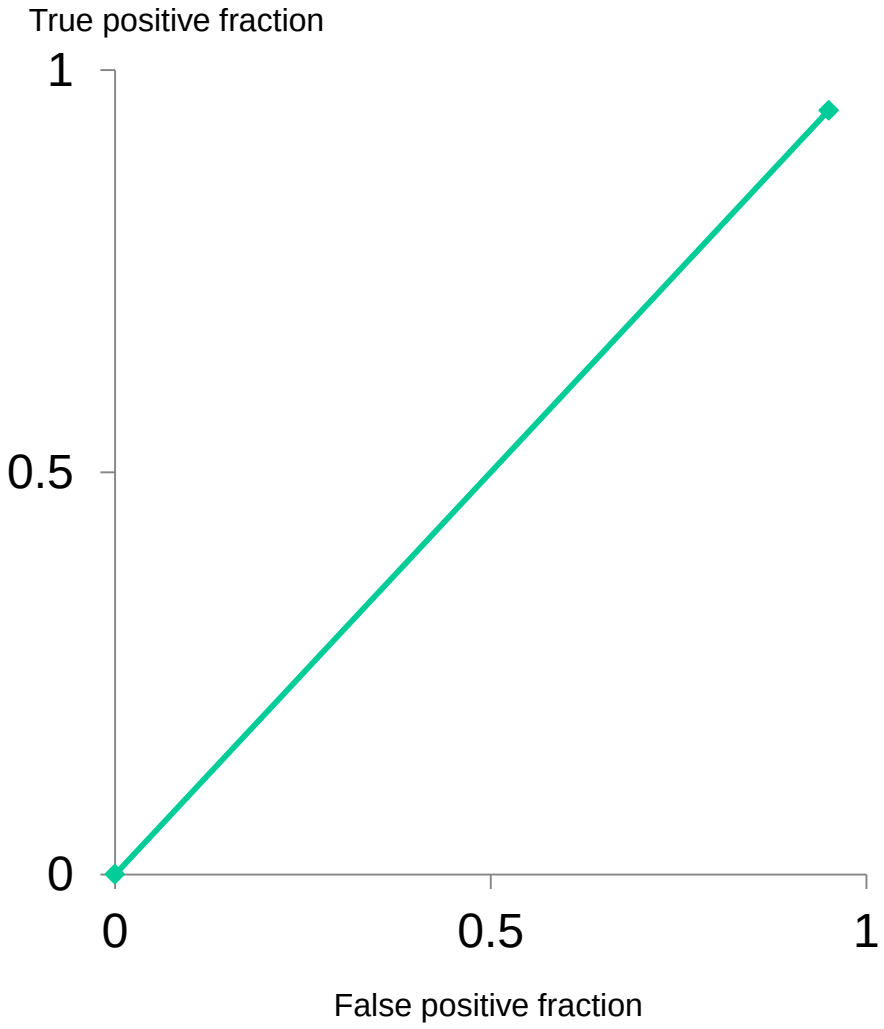
Exercise

Exercise

Draw the ROC curve for when trying to diagnose cardiac disease by counting the number of lesions in the brain

Solution

- Cardiac disease completely unrelated to brain lesions
- 50-50 chance of true positives and false positives irrespective of number of brain lesions found



Important parameters for all imaging techniques

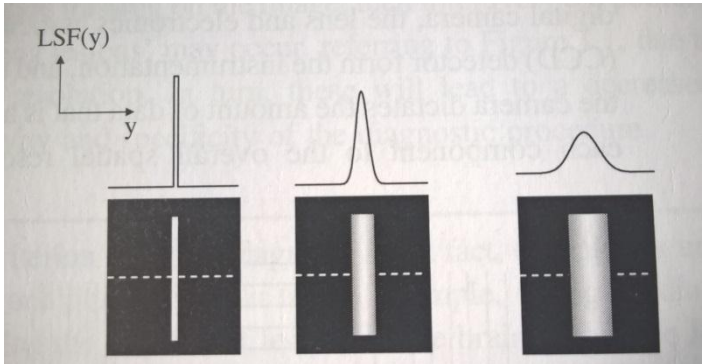
- Spatial resolution
- Signal-to-noise ratio, SNR
- Contrast-to-noise ratio, CNR

Spatial resolution

- Imaging systems not perfect → introduce blurring
  = no sharp edges → finite spatial resolution
- Spatial resolution determines:
  1. The smallest feature that can be visualised
  2. The smallest distance between two features so that they can be resolved and not seen as one
- Measures of spatial resolution / blurring:
  1. Line spread function (LSF) – 1D
  2. Point spread function (PSF) – 3D

Line spread function (LSF)

- Measured by imaging a single thin line or set of lines



Taken from Ref. 1 pg. 6

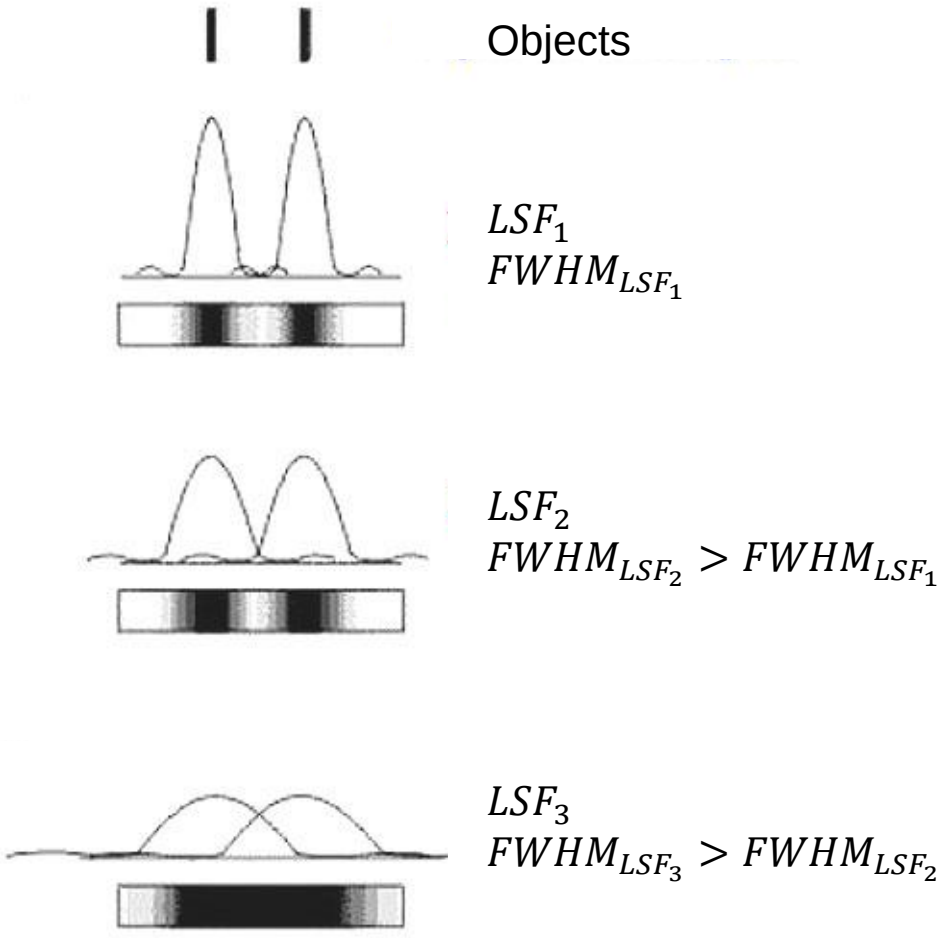
- For many imaging systems LSF is a Gaussian:

$$LSF(y) = \frac{1}{\sqrt{2\pi\sigma^2}} exp\left(-\frac{(y-y_0)^2}{2\sigma^2}\right)$$

σ = standard deviation

$$FWHM = \left(2\sqrt{2\ln 2}\right)\sigma \cong 2.36\sigma$$

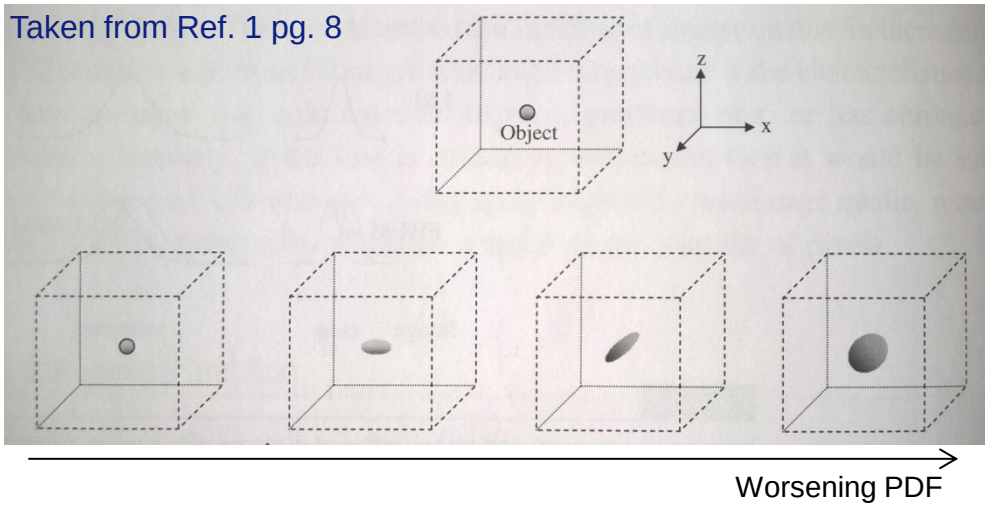
LSF and spatial resolution



- Two structures can be resolved if:
  $d > FWHM_{LSF}$ $d > 2.36\sigma_{LSF}$
  d = distance between two structures
- The narrower LSF = smaller $FWHM \rightarrow$ the smaller the distance between two structures that can be resolved → better spatial resolution

Point spread function (PSF)

- Takes into account the spatial resolution may become poorer with depth in the body → 3D
- PSF describes image of a point source



$$I(x,y,z) = O(x,y,z) * h(x,y,z)$$

3D image — 3D object — convolution — 3D PSF

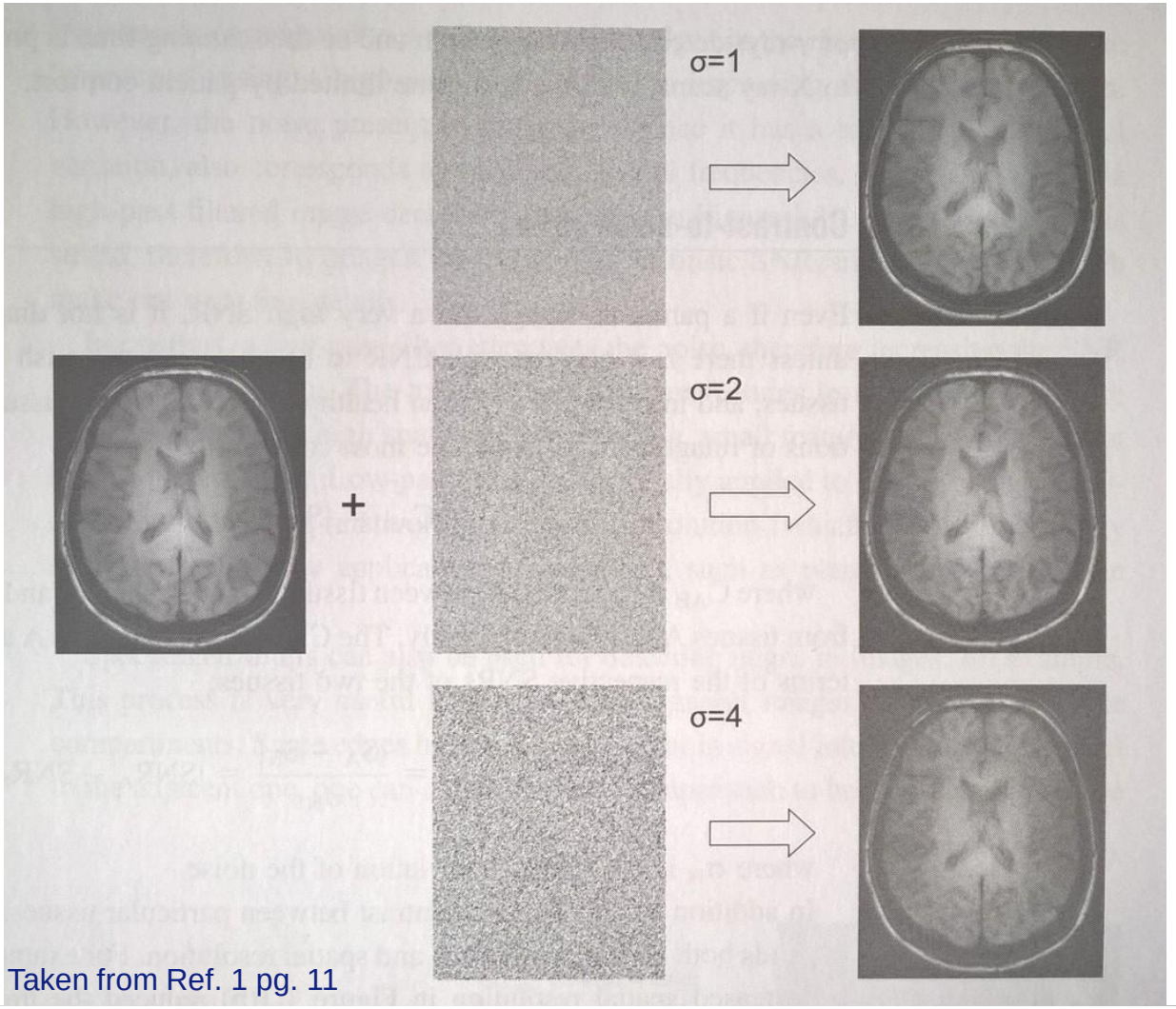
Signal-to-noise ratio SNR

- Noise = random signal superimposed on top of real signal → mean value zero → standard deviation σ_N
- Sources of noise different for different imaging modalities
- Signal-to-noise ratio SNR:

$$SNR = \frac{Signal}{\sigma_N}$$

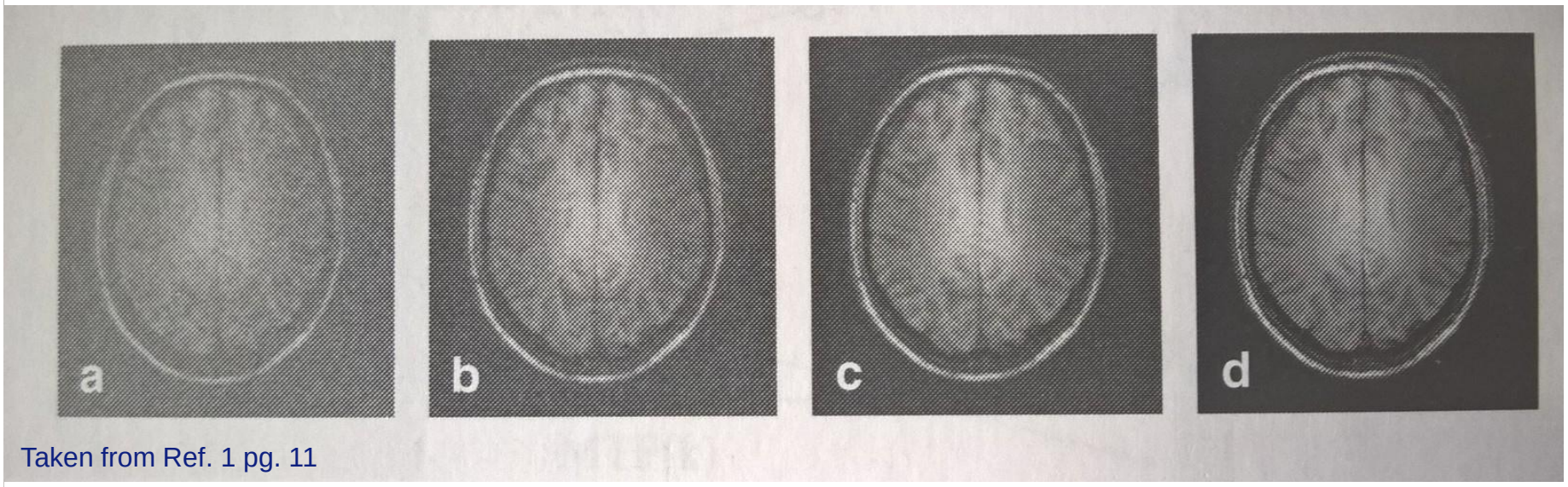
- The higher SNR the better the image:
  - Maximise signal = when designing imaging systems
  - Average signal acquired over repeated scans

Example of effect of noise: MRI scan



Taken from Ref. 1 pg. 11

Example of averaging the signal: MRI scan



Taken from Ref. 1 pg. 11

a. One scan
b. Average of two identical scans
c. Average of four identical scans
d. Average of 16 identical scans

Contrast-to-noise ration CNR

- Ability to distinguish between different tissues = between healthy and pathological tissues
- Contrast-to-noise ratio CNR_{AB} between tissues A and B:

$$CNR_{AB} = \frac{C_{AB}}{\sigma_N} = \frac{|S_A - S_B|}{\sigma_N} = |SNR_A - SNR_B|$$

$S_A, S_B =$ signals from tissues A and B

$C_{AB} =$ contrast between tissues A and B

$\sigma_N =$ standard deviation of noise

- The higher CNR_{AB} the better the image

Dose

- $Absorbed\ dose\ D(Gy) = \frac{radiation\ energy\ E(J)}{kg\ of\ tissue}$
- $Mean\ absorbed\ dose\ D_{T,R}\ in\ mass\ m_T\ of\ tissue\ T\ from\ amount\ of\ radiation\ R$

$$D_{T,R} = \frac{1}{m_T} \int_{m_T} D_R\, dm$$

- $Equivalent\ dose\ H_T(Sv) = \sum_R w_R D_{T,R}$ with $w_R\ radiation\ weighting\ factor$

Dose damage

Radiation effects	Description	Probability
Deterministic	Cellular damage that leads to loss in tissue function	- Dose threshold[1] - Zero or low at low doses below threshold - Climbs rapidly to unity above threshold
Stochastic	Cells are not killed but undergo genetic mutations → cancer	- No dose threshold - Increases with the dose - In the low dose region non negligible and higher than for deterministic effects

[1]The doses in imaging procedures are usually below this threshold

Effective dose

- Some tissues are more sensitive to radiation dose than others
- Tissue weighting factor w_T = fraction of total stochastic radiation risk

$$\sum_T w_T = 1$$

- $Effective\ dose\ E = \sum_T w_T H_T$

Tissue weighting factors

Tissue / organ	Tissue weighting factor[1]
Gonads	0.2
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Chest	0.05
Bladder	0.05
Liver	0.05
Thyroid	0.05
Oesophagus	0.05
Average (brain, small intestines, adrenals, kidney, pancreas, muscle, spleen, thymus, uterus)	0.05
Skin	0.01
Bone surface	0.01

[1] For the gonads = risk of hereditary conditions, for all others organs = risk of cancer

Multimodality imaging

Ref. 2 – Chapter 15

- Multimodality imaging (MMI) obtains information from combination of image data
- Main use = visualisation = localise functional data within body anatomy for same patient
- Made possible by:
  1. Increasing computer power easily accessible
  2. Merging different imaging modalities: hybrid scanners
  3. Multidisciplinary teams

MMI: image registration

- Image registration = align image data sets to achieve spatial correspondence for direct comparison
  - Images from different modalities
  - Images from same modality at different times
  - Images with standardised anatomy's atlases

1. Images produced already aligned → nothing to be done
   - Set-up parameters identical for all scans
2. Images not already aligned → image transformation
   - Rigid-body registration
   - Non-rigid registration

MMI: rigid-body registration

- Image transformation:

$$p_i' = \boldsymbol{R}(\boldsymbol{S}\boldsymbol{p_i''}) + \boldsymbol{T} + \zeta_i \quad i = 1 - N$$

p_i', p_i'' = two 3D point sets

$\boldsymbol{R}$ = 3x3 rotation matrix

$\boldsymbol{S}$ = 3x3 scaling matrix (diagonal)

$\boldsymbol{T}$ = 3x1 translation vector

ζ = 3x1 'noise' or 'uncertainty' vector

- 9 parameters to be determined:

  3 scaling factors + 3 angles + 3 translation factors

MMI: Classification schemes

Mainly used with rigid-body registration:

1. Point Matching
   - Based on a landmark that can be considered as point
   - Minimum 3 non-coplanar points needed, accuracy increases with number of points
   - Anatomical points accurate, functional data less accurate
2. Line or Surface Matching
   - Lines or Surfaces obtained from external frames or internal anatomy
3. Volume Matching
   - Derived from voxel information
   - Various algorithms being developed

MMI: non-rigid-body registration

See for ex. W R Crum, T Hartkens and D L G Hill “Non-rigid image registration: theory and practice”, Brit. Journ. Rad. 77 (2004), S140–S153

- Anatomy not rigid (apart some bony structures) → errors
- Elastic registration takes into account:
  1. Movement between different scans
  2. Motion during the scan
- Various methods developed
- Less commonly used due to high complexity and pitfalls of warping image data unrealistically

MMI registration accuracy

- Aim = one-to-one spatial correspondence between each image's element
- Potential primary sources of errors:
  1. Definition of features used
  2. Accuracy and robustness of algorithm used
  3. Accuracy of image transformation
  4. Differences in anatomy or image parameters
- Absolute accuracy impossible to determine, only relative accuracy between different registration methods