Medical Imaging Methods, in Brief

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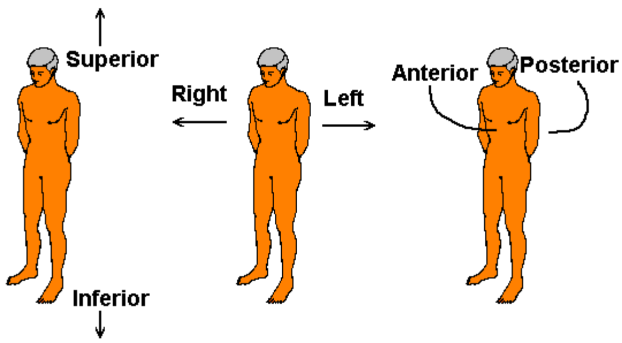
Slide 2: Lecture overview

1. Medical imaging coordinate naming
2. X-ray medical imaging
   - Projected X-ray imaging
   - Computed tomography (CT) with X-rays
3. Nuclear medical imaging
4. Magnetic resonance imaging (MRI)
5. (Ultrasound imaging covered in previous lecture)

Slide 3: Medical imaging coordinates

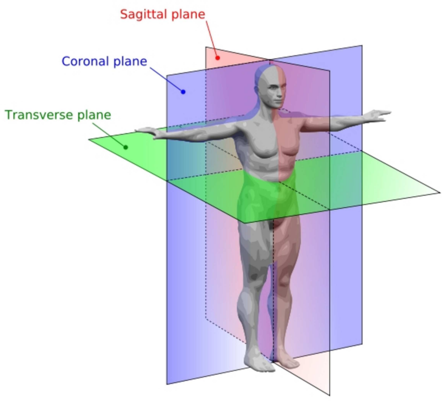
The anatomical terms of location

- Superior / inferior, left / right, anterior / posterior:



Note: left / right is seen from the view of the patient!

Slide 4: Medical imaging planes

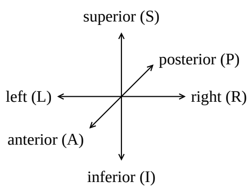


- Axial plane = transverse plane: perpendicular to the body long axis
- Sagittal: bisects the left from the right side [from new latin *sagitta* = arrow]
- Coronal: bisects the front from the back [from latin *corona* = crown]

Slide 5: Medical imaging planes

Coordinate system positive direction conventions

- 3 letters are used to indicate sequence and orientation of the (x, y, z) axes, *e.g.* "LSA" coordinates used in computed tomography (CT). Abbreviation letter codes:



S	superior	I	inferior
L	left	R	right
A	anterior	P	posterior

- "LSA" thus indicates:
  - x axis goes from left (L) to right
  - y axis goes from superior (S) to inferior
  - z axis goes from anterior (A) to posterior
- Other common coordinate system: "RPI".
- What has to be done before combining images in *e.g.* LSA coordinates with images in RPI coordinates?

Slide 6: Invasive / non-invasive

- Invasive imaging techniques:
  - Optics inside the body, *e.g.* endoscope [greek: *endo* = inside]

  - Open surgery
  - Cameras in minimally invasive surgery, *e.g.* "camera pills" in veins or digestive tract

- Non-invasive imaging (Medical imaging) considerations:
  - Planar projections vs. cross-sectional images
  - Static images vs. dynamic series of images ("film")

Slide 7: Classes of physical signals/processes

Non-invasive medical imaging: 4 different kinds of physical processes that generate signals:

- Ultrasound back-scattering / reflection
- X-ray transmission
- γ ray emission from radioisotopes
- Spin precession in magnetic fields

Slide 8: Imaging modalities

Method	**information carrier**	**note**
Ultrasound imaging	high-frequency pressure waves	backscattering / reflection imaging
X-ray imaging (projection radiography)	ionizing radiation	transmission imaging
Computed tomography: CT, C-arm		
Nuclear imaging: SPECT, PET		emission imaging
Magnetic resonance imaging (MRI)	nuclear spin precession	magnetic resonance imaging

Slide 10: X-ray medical imaging

- *Radiography:* use of ionizing electromagnetic radiation to view objects
- *Radiotherapy:* use of ionizing electromagnetic radiation to cure diseases (thus not an imaging modality)

Slide 11: X-ray medical imaging

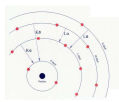
Brief historical retrospect

- Radiography started in 1895: discovery of X-rays by Wilhelm Conrad Röntgen (1845-1923, died from instetine cancer)
- First published picture using X-rays is of Anna Berthe Röntgen's hand in the paper "On A New Kind Of Rays" (*Über eine neue Art von Strahlen*)
- Awarded the first Nobel Prize in Physics (1901) *In recognition of the extraordinary services he has rendered by the discovery of the remarkable rays subsequently named after him*
- X-rays were put to diagnostic use very early, before the dangers of ionizing radiation were discovered

Slide 12: Energetic electrons creating X-rays

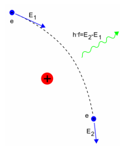
Characteristic radiation

- Energetic electron collides with and ejects K-shell electron
- K-shell "hole" is filled by electron from the L, M, or N shells
- Produces characteristic spectral lines corresponding to the energy differences between the shells

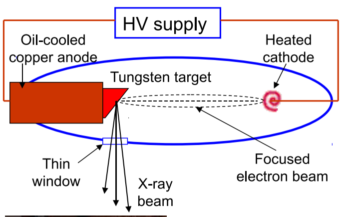


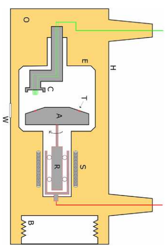
Bremsstrahlung (braking / deceleration radiation)

- Energetic electron interacts with nucleus of atom
- Deceleration causes loss of energy
- Continuous spectrum. Peaking @ anode-to-cathode potential



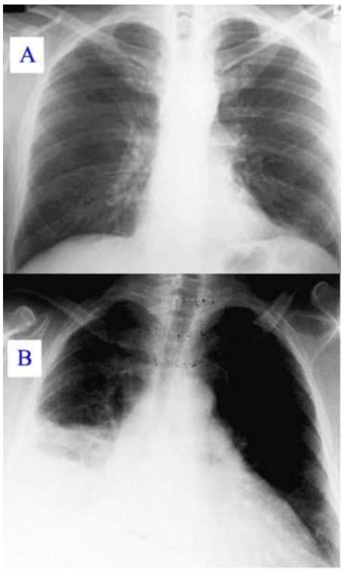
Slide 13: Conventional X-ray source





- Electrostatic lens to focus electron beam onto a small spot @ anode
- Anode designed to dissipate heat from focused electrons:
  - Mechanically spun to increase the area heated by the beam.
  - Cooled by circulating coolant.
- Anode angled to allow escape of some of the X-ray photons which are emitted essentially perpendicular to the direction of the electron current
- Anode usually made of tungsten (W) or molybdenum (Mo)
- Window designed for escape of generated X-ray photons

Slide 14: Image contrast



- Image contrast: caused by varying absorption in object
- Absorption depends on atomic number Z:
  - Metals distinguished from tissues
  - Bones distinguished by high Ca-content
- Absorption grows with Z^2 due to binding energy of inner electrons growing with Z^2
- Absorption thus depends on projected mass density:
  - Lungs and air passages form good contrast images by density difference
  - Higher water content (*e.g.*, pneumonia) easily detected

Slide 15: Projected X-ray transmission images

- Expose object to X-rays, capture "shadow"
- Produces a 2-D projection of a 3-D object
- "Shadow" may be converted to light using a fluorescent screen
- Image is then captured on either
  - photographic film
  - phosphorus screen to be "read" by laser
  - matrix of detectors (*digital radiography*)
- Projection radiography uses X-rays in different amounts and strengths depending on what body part is being imaged:
  - Hard tissues (bone) require a relatively high energy photon source
  - Soft tissues seen with same machine as for hard tissues, but with "softer" or less-penetrating X-ray beam

Slide 16: X-ray detectors

Ordinary photographic film

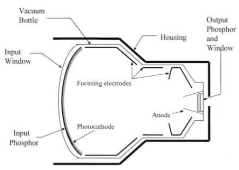
- Very inefficient, only 1–2% of radiation stopped
- Requires unnecessarily large X-ray dose to patient

Intensifying screens on both sides of film

- Phosphorus transforms x-ray photons into light photons
- Two types of luminescence
  - Fluorescence: emission within 10^{-8} s of excitation
  - Phosphorescence: emission delayed and extended
- Conversion efficiency: 5–20%

X-ray image intensifiers (XRIIs)

- Input window of aluminum or titanium
- X-ray photons absorbed by phosphorus
- Channeled toward photocathode



Slide 17: Mammography

- X-ray examination used in diagnostic screening for breast cancer
- Used by radiologist or surgeon before biopsy (removal of cells or tissue for examination), or lumpectomy (surgery to remove *e.g.* a tumor)
- Radiation used for mammography tends to have a lower photon energy than that used for bone and harder tissues
- Globally, breast cancer is the most lethal form of cancer for women (106 cases/year)
- US and Canada has highest incidence rate (100 per 100.000), but low mortality rate (19 per 100.000)
- Norway: incidence rate 75 per 100.000, mortality 16.1

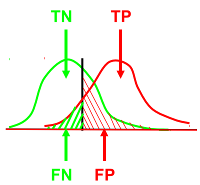
Slide 18: True / False positives / negatives

True positive (TP)
Patient with cancer and positive test

True negative (TN)
Healthy patient and get negative test

False positive (FP)
Healthy patient, but positive test

False negative (FN)
Patient with cancer, but negative test



Good to have: TP & TN   Bad to have: FP & FN

Slide 19: Sensitivity and specificity

Sensitivity

The dataset portion that tested positive out of all the positive patients tested: Sensitivity = TP/(TP+FN)

- The probability that the test is positive given that the patient is sick
- The higher the sensitivity, the fewer decease cases go undetected

Specificity

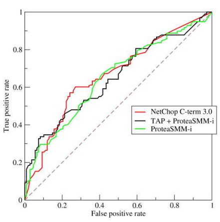
The dataset portion that tested negative out of all the negative patients tested: Specificity = TN/(TN+FP)

- The probability that a test is negative given that the patient is not sick
- Higher specificity means that a smaller percentage of healthy patients are labeled as sick

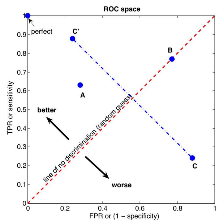
Slide 20: ROC curves

ROC = *Receiver operating characteristic*

- Plot of sensitivity vs. (1−specificity) for a binary classifier, as the discrimination threshold is varied
  Same as: true positive rate vs false positive rate [TP/(TP+FN) vs. FP/(TN+FP)]



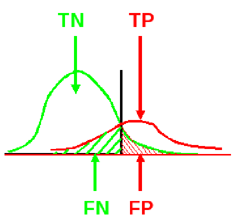
- Best possible method would give a point in upper left corner of plane
  - 100% sensitivity and specificity represents the perfect classification.
- Result equivalent to random guessing would lie on the diagonal.



Slide 21: Positive and negative predictive values

Positive predictive value (PPV)

The probability that a patient is sick, given that the result of the test was positive:
PPV = TP/(TP+FP)



Negative predictive value (NPV)

The probability that a patient is not sick, given that the test result was negative:
NPV = TN/(TN+FN)

- Assume a classifier with sensitivity = specificity = 0.99, and unequal class probabilities: P_N = TN+FP = 0.9, P_P =

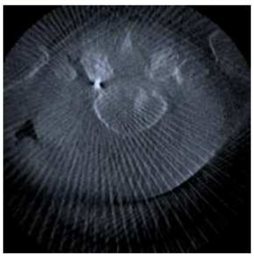
TP+FN = 0.1 ⇒ 92% probability of a positive result being correct (PPV=0.92), 0.1% probability of a negative result being wrong (NPV=0.999)

- For sensitivity = specificity = 0.9 (and same P_N, P_P as above), ⇒ 50% probability of a positive result being correct, but still only 1.2% chance of a negative result being wrong (PPV=0.5, NPV=0.988)

Slide 22: Fluoroscopy

- Provides real-time images
- X-ray source → patient → fluorescent → recorder
- X-ray image intensifier (XRII)
  - Cesium iodide phosphorus deposited directly on XRII photocathode
  - Output image approximately 10^5 times brighter than input image
    - flux gain (amplification of photon number) ≈ 100
    - minification gain (from large input onto small output screen) ≈ 100
  - quantum noise (small number of photons) limiting image quality
- Flat-panel detectors
  - increased sensitivity to X-rays, reducing patient radiation dose
  - Improved temporal resolution, reducing motion blurring
  - Improved contrast ratio over image intensifiers
  - Spatial resolution is approximately equal

Slide 23: C-arm



- A portable fluoroscopy machine that can move around the surgery table and make digital images for the surgeon
- A limited number of projections is often used to reconstruct a 2-D "slice" through the 3-D volume
- High density objects (*e.g.* a needle) or density gradients may create disturbing fan-shaped artifacts

Slide 24: Use of passive contrast agents

- Enhanced images may be made using a substance which is opaque to X-rays
- This is normally as part of a *double contrast technique*, using positive and negative contrast
- *Positive radiographic contrast agents:*
  - Iodine ($Z = 53$) can be injected into bloodstream
  - Barium ($Z = 56$)
- *Negative radiographic contrast agents:*
  - air and carbon dioxide (CO_2)
  - CO_2 is easily absorbed and causes less spasm
  - CO_2 can be injected into the blood, air can not!

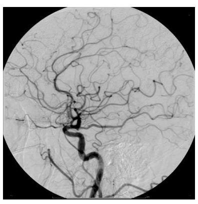
Slide 25: Angiography

Used to visualize the inside of blood vessels and organs.Ancient greek: *angeion* = "container", *grapho* = "I write"

- Blood has the same X-ray density as surrounding tissue
- An iodine-based contrast is injected into the bloodstream and imaged as it travels around
- Angiography used to find:
  - Aneurysms (abnormal blood-filled swellings of an artery or vein, resulting from a localized weakness in the wall of the vessel)
  - Leaks
  - Thromboses (blood-clots that form and cause obstruction of the blood vessel), etc
- The X-ray images may be:
  - Still images, displayed on a fluoroscope or film
  - Video sequences (25–30 frames per second)
- Retinal angiography: commonly performed to identify vessel narrowing in patients with *e.g.* diabetic retinopathy and macular degeneration [*retina* = light sensitive tissue lining the eye inner surface, *macula* = yellow spot near retina center responsible for central vision]

Slide 26: Digital subtraction angiography

- Angiography images: made while injecting contrast medium into the bloodstream
  - Image includes all overlying structures besides the blood vessels
  - Useful for determining anatomical position of blood vessels



- To remove distracting structures, a mask image of the same area is acquired before the contrast is administered

- An image intensifier (fluoroscopy) is used, producing images at a $1 - 6$ frames per second rate, subtracting all subsequent images from the original "mask" image in real time
- Hence the term "digital subtraction angiography" (DSA).
- DSA is being used less and less, being taken over by CT angiography, which is less invasive and less stressful

Slide 27: Reconstruction from projections

- A 3-D object distribution can be mapped as a series of 2-D projections
- With a sufficient number of projections the mapping process can be inverted and the 3-D distribution reconstructed from the projections
- If the projection axes lie in a plane, the reconstruction may be carried out one slice at a time
- Then the inversion is simpler and may be done using a Fourier method
- To avoid a large matrix, a Maximum Likelihood (ML) method is used and the solution is found by iteration
- Mathematical foundation presented by Johann Radon in 1917

Slide 28: Computed Tomography (CT) history

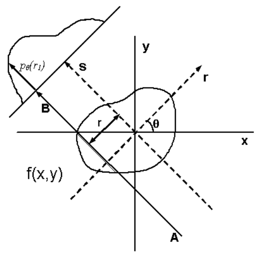
- CT as an imaging technique was described by Cormack in 1963
- The first clinical implementation made by Hounsfield in 1972
- 1971 prototype made 160 parallel readings in 180 angles, with each scan taking 5 minutes
- Image reconstruction from these scans took 2.5 hours
- Hounsfield and Cormac shared the 1979 Nobel Prize

Slide 29: Reconstruction radiography

- CT uses X-rays
- Instead of a 3-D cone beam, they are collimated to travel in a 2-D "fan–beam"
- A 2-D projection of a cross section of the body is detected by a large number of detectors
- Repeated for many orientations as the X-ray tube and the detectors rotate around patient
- An image of the cross-section is then computed from the projections

Slide 30: Tomographic reconstruction

- Data series collected: integrals at position r, across a projection at angle θ
- Repetition for various angles
- Total attenuation given by line integral:



$$p_\theta(r,\theta) = \int_{A \to B} \mu(x(s), y(s))\mathrm{d}s,$$

where all points on the line $A \to B$ satisfy $r = x\cos\theta + y\sin\theta$, so

$$p_\theta(r,\theta) = \int_{-\infty}^{\infty} \mu(x,y)\delta(x\cos\theta + y\sin\theta - r)\mathrm{d}x\mathrm{d}y.$$

- This is the *Radon transform* of the 2-D object
- *Projection-slice theorem*:
  - Infinite number of projections ⇒ perfect object reconstruction
  - Inverse Radon transform ⇒ estimate of object function $\mu(x,y)$
  - Unstable with respect to noisy data.
  - Stabilized and discretized version: *filtered back-projection algorithm*
- In-depth theory: `http://www.slaney.org/pct/pct-toc.html`, ch. 3

Slide 31: 3 different CT modalities

- A *single-slit CT* is the simplest:
  - Gives a single axial-plane image
  - In axial "step and shoot", the table is moved between each slice
- In *helical CT*, the X-ray tube and the detectors rotate, while the patient is moved along an axis through the center of rotation:
  - Rapidly acquires 3-D data
  - Slightly lower z-axis resolution than "step and shoot"
  - May tilt detector $\pm 30°$ relative to the axis of rotation
- In *multislice CT*, several rows of detectors gather a cone of X-ray data, giving a 2-D projection of the 3-D patient
  - With 1-3 revolutions per second, near real-time 3-D imaging is possible, with translation speeds up to 20 cm per second

Slide 32: CT advantages

- CT eliminates superimposition of structures outside ROI
- Small differences in physical density can be distinguished
- CT data can be viewed as images:
  - in an axial plane
  - in a coronal plane
  - in a sagittal planes
  - (multiplanar reformatted imaging)
- CT angiography avoids invasive insertion of an arterial catheter and guidewire
- CT colonography is as useful as a barium enema x-ray for detection of tumors, but may use lower radiation dose [*Enema:* procedure of introducing liquids into the rectum and colon via the anus, barium: used as a contrast agent]

Slide 33: CT disadvantages

- CT is a moderate to high radiation diagnostic technique:
  - Improved radiation efficiency ⇒ lower doses
  - Higher-resolution imaging ⇒ higher doses
  - More complex scan techniques ⇒ higher doses
- Increased availability + increasing number of conditions ⇒ large rise in popularity
- CT constitutes 7% of all radiologic examinations (UK)
- Contributed 47% of total collective medical X-ray dose
- Overall rise in total amount of medical radiation used, despite reductions in other areas

Slide 34: Contrast agent disadvantages

A certain level of risk associated with contrast agents

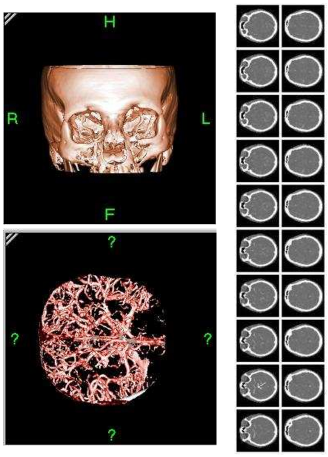
- Some patients may experience severe allergic reactions
- Contrast agent may also induce kidney damage (nephropathy):
  - If normal kidney function, contrast nephropathy risk negligible
  - Risk is increased with patients who have:
    - preexisting renal insufficiency (= kidney failure)
    - preexisting diabetes
    - reduced intravascular volume.
  - For moderate kidney failure, use MRI instead of CT
  - Dialysis patients do not require special precautions:
    - little function remaining
    - dialysis will remove contrast agent.

Slide 35: 3-D surface / volume rendering

- *Surface rendering:*
  - Threshold value chosen by operator (*e.g.* corresponding to bone), or a threshold level set using edge detection algorithms
  - From this, a 3-dimensional model can be displayed
  - different thresholds and colors may represent: bone / muscle / cartilage [Norwegian: *brusk*]
  - interior structure of each element is not visible in this mode
  - will only display surface closest to viewer
- *Volume rendering:*
  - transparency and colors are utilized
    * bones could be displayed as semi-transparent
    * one part of the image does not conceal another

Slide 36: Rendering examples

- Slices of a cranial CT scan (extreme right).
- Blood vessels are bright due to injection of contrast agent.
- Surface rendering shows high density bones.
- Segmentation removes the bone, and previously concealed vessels can now be demonstrated.

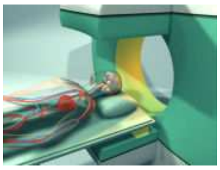


Slide 38: Nuclear medical imaging

- We need to generate contrast by local activity
- We inject a radioisotope carried by a molecule which is absorbed differentially according to local metabolic rate
- Most of the radiation from the decay should escape the body without attenuation or scatter
- Half-life of decay should match duration of procedure
- SPECT involves high patient dose, poor spatial resolution, and exceptional contrast
- PET solves most of SPECT's shortcomings, but procedure is more complex and expensive

Slide 39: Single photon emission computed tomography (SPECT)

- Mostly used for study of blood-flow, by injection of a radiopharmaceutical into the bloodstream. May otherwise ingest or inhale the radiopharmaceutical
- Image obtained by gamma camera is a 2-D view of 3-D distribution of a radionuclide
- SPECT imaging is performed by using a gamma camera to acquire multiple 2-D image
- Tomographic reconstruction yields 3-D dataset
- From this dataset we may show thin slices along any chosen axis similar to MRI, CT, PET



Slide 40: Choice of radioactive isotope

- Radiation from decay should escape body:
  - eliminates alpha radiation
- Minimal scattering to make sharp images:
  - eliminates beta radiation
- Energy deposition should be minimal:
  - eliminates gamma emission below 70 keV
- Half-life to match duration of procedure
- Short half-life to minimize radiation dose $\Rightarrow$ radioactive isotope w/ gamma half-life $\approx 10^3$ s, energy $\approx 10^5$ eV $\Rightarrow$ ^{99}Tc (Technetium), produced by β decay of ^{99}Mo (Molybdenum), produced in neutron-induced fission of ^{235}U, or produced by neutron absorption by ^{98}Mo

Slide 41: SPECT cameras

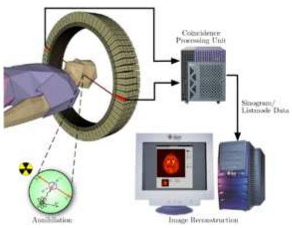
- SPECT images are collected by pinhole gamma camera rotating around patient
- Projections are acquired at defined points during the rotation, typically every 3-6 degrees
- A full 360° rotation gives optimal reconstruction:
  - 15 – 20 seconds / projection
  - Total scan time: 15–20 minutes
- Multi-headed gamma cameras $\Rightarrow$ faster acquisition:
  - Dual-head camera give 2 projections simultaneously
  - Triple-head cameras with 120 degree spacing are also used

Slide 42: SPECT reconstruction

- Low-resolution images (64×64 or 128×128 pixels)
- Pixel sizes: 3–6 mm
- Reconstructed images compared to planar images:
  - lower resolution, increased noise, reconstruction artifacts
- Uneven distribution of nuclides may also cause artifacts
- Attenuation ⇒ underestimation of activity with depth
  - Modern SPECT equipment integrated with X-ray CT scanner
    - CT images are attenuation map of tissues
    - Incorporated into the SPECT reconstruction to correct for attenuation
  - Co-registered CT images provide anatomical information

Slide 43: Positron emission tomography (PET)

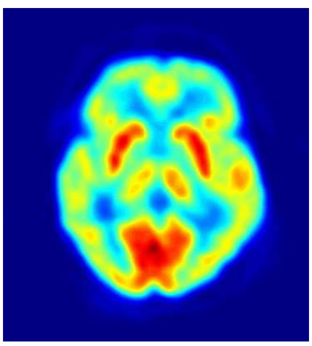
1. A sugar (fluorodeoxyglucose, FDG) containing radioactive ^{18}F is injected
2. During decay, isotope emits positron
3. Positron annihilates with an electron
   ⇒ pair of γ photons moving in opposite directions



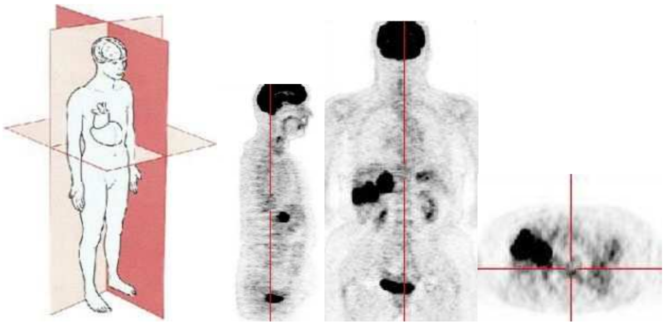
- Gamma photons are detected by scanning device
- Only simultaneous pair of photons used for image reconstruction

Slide 44: PET examples

Maximally intensity projection of typical full-body 18F: (GIF animation file `PET-MIPS-anim.gif`) *PET scan of the human*

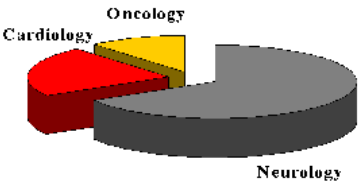
brain: 

Slide 45: Orthogonal PET slices

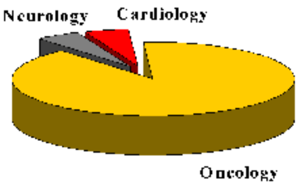


Slide 46: Shift in PET application areas

Main PET areas in the 1990s



Main PET areas today:

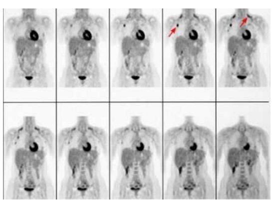


- *Cardiology:* disorders of the heart and blood vessels
- *Oncology:* tumors (cancer), neurology: the nervous system

Slide 47: Oncology: lung case

- Traditionally: lung masses evaluated with X-rays, CT, and, more recently, MR. To determine malignancy: biopsy have been performed
- Now: PET can determine malignancy

55F, diagnosed w/ stage III "lung non-small cell carcinoma" (NSSC)



PET findings: Increased uptake of FDG in several lung nodules ⇒ recurrent tumour indication. Also found: abnormal uptake in the *cervical lymph nodes* (neck lymph nodes)

Slide 48: PET benefits

- Principal benefit: sensitivity to imaging metabolic activity
- Spatial information:
  - better than SPECT, worse than CT or MRI
- PET images may be fused with X-ray CT
  - on the patient
  - at the same time
  - in the same machine

  ⇒ functional + anatomical image

Slide 49: PET limitations

- PET scanning uses short half-life isotopes: ^{11}C (~20 min), ^{13}N (~10 min), ^{15}O (~2 min), and ^{18}F (~110 min)
- Timing and logistical limitations restrict clinical PET to ^{18}F
- Frequent recalibration of remaining dose of ^{18}F needed
- Ethical limitations to injecting radioactive material:
  - short-lived radionuclides minimize radiation dose
  - in cancer therapy, risk from lack of knowledge therapy response may be much greater than the risk from due to PET radiation
- Isotopes must be produced in a cyclotron ⇒ high costs

Slide 51: Magnetic resonance imaging (MRI)

- Non-invasive method, based on nuclear magnetic resonance
- First utilized in physical and chemical spectroscopy
- 1971: Different relaxation times of tissues and tumors
- 1971: MRI first demonstrated on test tube samples
- 1973: first image published
- 1977: first image of human published

Slide 52: MRI history

- 1952: Bloch and Purcell: Nobel Prize for discovering Nuclear magnetic resonance (NMR)
- 1975: Ernst: MRI using phase and frequency encoding, and Fourier Transform
- 1977: Mansfield: developed the echo-planar imaging (EPI) technique
- 1987: Dumoulin: magnetic resonance angiography (MRA)
- 1991: Ernst: Nobel Prize in chemistry for pulsed Fourier NMR and MRI
- 1992: functional MRI (fMRI) developed [imaging of changes in blood flow in the brain]
- 2003: Lauterbur and Mansfield: Nobel Prize for discoveries in MRI

Slide 53: MRI basics

- Nuclei of hydrogen atoms (protons) align either parallel or antiparallel a strong static external magnetic field $\vec{B}_0$
- Electromagnetic RF wave at resonance frequency υ transmit in a plane perpendicular to the magnetic field.

  $$\upsilon = \gamma |B_0|, \tag{1}$$

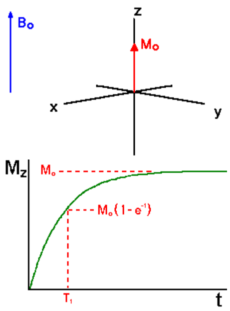
  γ: gyromagnetic ratio. For hydrogen: $\gamma = 42.58$ MHz / T
- Puts nuclei in non-aligned high-energy state
- As protons return to alignment, they precess
- Precession generates new RF signal, picked up by antenna

Slide 54: Image formation

- To excite only protons in selected body parts: gradients added $\Rightarrow$ spatial variation of $\vec{B}_0(\vec{r})$ $\Rightarrow$ only selected parts of object resonate at the transmit RF υ
- Tomographic methods to generate 2-D images (back-projection etc.)
- Stronger gradients permit faster imaging or higher resolution
- Faster switching of gradients permits faster scanning. Limited by safety concerns over nerve stimulation
- Typical resolution: $\sim$1 mm^3

Slide 55: The T_1 process

- At equilibrium:
  - Magnetization vector $\vec{M}$ of the protons lies along the $\vec{B}_0$: equilibrium magnetization $\vec{M}_0$
  - M_z: longitudinal magnetization
  - No transverse magnetization M_x or M_y.

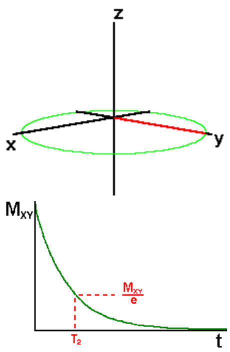


- Time constant T_1: describes how M_z returns to equilibrium: *spin-lattice relaxation time*

$$M_z = M_0 \left(1 - e^{-t/T_1}\right)$$

- T_1: time to reduce difference between the longitudinal magnetization M_z and its equilibrium value M_0 by a factor of e

Slide 56: The T_2 process



- T_2: describes return to equilibrium of the transverse magnetization, M_{xy}: *spin-spin relaxation time*

$$M_{xy} = M_{xy0} e^{-t/T_2} \qquad (2)$$

- T_2, T_1 processes occur simultaneously
- Always: $T_2 \leq T_1$
  - $M_{xy} \rightarrow 0$ as $t \rightarrow \infty$,
  - $M_z \rightarrow M_0$ as $t \rightarrow \infty$

Slide 57: MRI contrast agents

- T_1 / T_2 images don't always show anatomy/pathology. May be enhanced by injection of contrast agents
- Most common: *paramagnetic contrast agents*
  - Appear extremely bright on T_1-weighted images
  - High sensitivity for detection of vascular tissues (*e.g.* tumors)
  - Permits observation of brain perfusion (*e.g.* in stroke).
- *Super-paramagnetic contrast agents* (*e.g.* iron oxide nanoparticles):

  - Appear dark dark on T_2-weighted images
  - Used for liver imaging: normal liver tissue holds back agent. Scars and tumors lets it in.

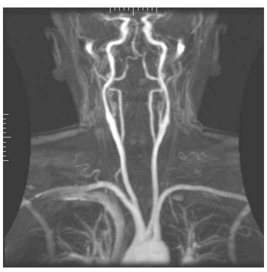
- *Diamagnetic contrast agents:*
  - Barium sulfate for use in gastrointestinal tract

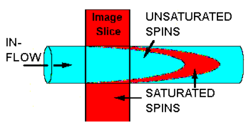
Slide 58: MRI modes

- *Standard MRI*: Including several different pulse sequences (time-series of different RF pulses to manipulate M)
- *Echo-planar imaging (EPI)*: Each RF excitation excitation: followed by a train of gradients with different spatial encoding ⇒ rapid data collection ⇒ less motion artifacts
- *MR spectroscopy*: Images other nuclei besides H: *e.g.* P (phosphorus), Na (sodium), F (fluorine)
- *Functional MRI (fMRI)*: Measures change in blood-flow in the brain. Hemoglobin: diamagnetic when oxygenated, paramagnetic when deoxygenated ⇒ magnetic resonance signal of blood is different depending on oxygenation level

Slide 59: MR angiography (MRA)

- MRA used to image blood vessels to evaluate for:
  - Stenosis: abnormal narrowing
  - Aneurysms: localized, balloon-like blood-filled bulge (most commonly in arteries)
- Techniques used are *e.g.*:
  - Injection of paramagnetic contrast agents
  - "Flow-related enhancement": Stationary tissue: has been in imaging plane for long time ⇒ not fully "relaxed" before next RF excitation ⇒ responds differently than "fresh" blood that just entered the imaging plane

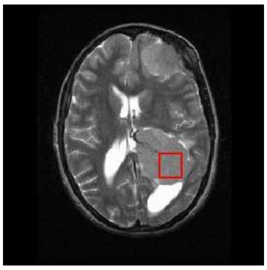




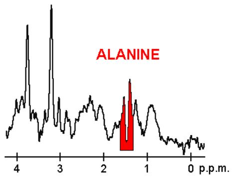
Slide 60: Magnetic resonance spectroscopy (MRS)

- MRI shows the location of a tumour
- MRS indicates how how aggressive (malignant) it is

- MRS can be tuned to different chemical nuclei, *e.g.* H (hydrogen), P (phosphorus), Na (sodium), F (fluorine)
- MRS used to investigate
  - Cancer (brain / breast / prostate)
  - Epilepsy, Parkinson's, and Huntington's (a neurodegenerative genetic disorder)



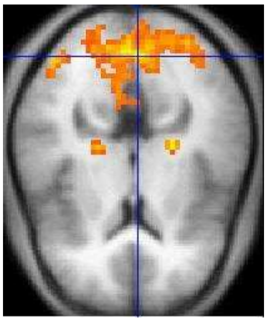
- *MRS example*: [University of Hull, Centre for Magnetic Resonance Investigations]
  5 mm thick axial MRI brain slice (tumor at bottom right)
  Red box: region of interest for MRS



- Proton MRS spectrum from marked region of interest:
  Red peaks correspond to alanine, generally only seen in meningiomas

Slide 61: Functional MRI (fMRI)

- Changes in brain activity linked to:
  Changes in blood flow and blood oxygenation
- Active nerve cells consume oxygen carried by hemoglobin
- Hemoglobin is:
  - Diamagnetic when oxygenated
  - Paramagnetic when deoxygenated



⇒ MR signal of blood depends on level of oxygenation ⇒ "Blood-oxygen-level dependent (BOLD) contrast"

Slide 62: Intraventional MRI

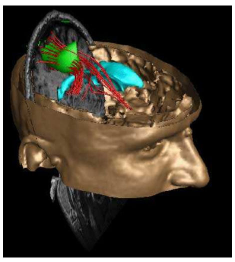
- MRI scanner used to simultaneously guide minimally-invasive procedure:
  - Strong magnetic radiofrequency field present
  - Quasi-static fields generated
    ⇒ Non-magnetic environment, instruments, and tools required
- Open magnet gives surgeon better access to patient (see image)

⇒ Often implies lower field magnets (∼0.2 T) ⇒ Decreased sensitivity

Slide 63: Current density imaging (CDI)

Used for mapping electric current pathways through tissue

1. External current is applied during MRI session
2. Electrical currents generate local magnetic fields
3. Such magnetic fields affect the phase of the magnetic dipoles during an imaging sequence
4. CDI uses phase information from MRI to reconstruct current densities within the object



[Data courtesy of NYU Medical Center]

Slide 64: MRI vs. CT

- CT: differentiates high Z tissue (bone, calcifications) from carbon based flesh
- MRI: best suited for non-calcified tissue

- CT: may be enhanced by contrast agents containing high atomic-number atoms (*e.g.* iodine, barium)
- MRI: Contrast agents have paramagnetic / diamagnetic properties

- CT: utilizes only X-ray attenuation to generate image contrast
- MRI: a variety of properties that may generate image contrast

- CT: usually more available, faster, much less expensive
- MRI: generally superior for tumor detection and identification

- MRI: best if patient is to undergo examination several times
- CT: if repeated, may expose the patient to excessive ionizing radiation