Medical imaging

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)

Medical imaging coordinates

The anatomical terms of location

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

  ![Diagram showing medical imaging coordinates]

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

Medical imaging planes

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

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”)

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
- \(\gamma\) ray emission from radioisotopes
- Spin precession in magnetic fields

Imaging modalities

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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

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 radiation” or “deceleration radiation”):
  - Energetic electron interacts with nucleus of atom
  - Deceleration causes loss of energy
  - Continuous spectrum, peaking at anode-to-cathode potential
Conventional X-ray source

- Electrostatic lens to focus electron beam onto a small spot on the 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

Image contrast

- Image contrast is 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

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
  - photographic film, or
  - a phosphorus screen to be “read” by laser, or
  - a 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

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

Sensitivity and specificity

- If a patient has cancer, and the classification result is positive; the patient is a true positive (TP).
- If the classifier fails to identify the patient’s cancer, we have a false negative (FN).
- Healthy patients that get a negative test are true negatives (TN).
- Healthy patients that get a positive test are false positives (FP).
- Sensitivity is the portion of the data set that tested positive 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 is the portion of the data set that tested negative 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

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.

Positive and negative predictive values

- The positive predictive value gives the probability that a patient is sick, given that the result of the test was positive: PPV = TP/(TP+FP)
- The negative predictive value gives 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: \( P_N = \frac{\text{TN+FP}}{0.9}, \quad P_P = \frac{\text{TP+FN}}{0.1} \)
  \( \Rightarrow \) 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),
  \( \Rightarrow \) 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)
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

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!

Angiography

Used to visualize the inside of blood vessels and organs.
Ancient greek: angiēn = "container", graphe = "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]

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
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

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

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

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 the patient
- An image of the cross-section is then computed from the projections
Tomographic reconstruction

- Data series collected: integrals at position $r$, across a projection at angle $\theta$
- Repetition for various angles
- Total attenuation is given by line integral:
  $$ p_\theta(r, \theta) = \int_{A \to B} \mu(x(s), y(s)) \, ds, $$
  where all points on the line $A \to B$ satisfy $r = x \cos \theta + y \sin \theta$, so
  $$ p_\theta(r, \theta) = \int_{-\infty}^{\infty} \mu(x, y) \delta(x \cos \theta + y \sin \theta - r) \, dx \, dy. $$
- This is the Radon transform of the 2-D object
- Projection-slice theorem:
  - Infinite number of projections $\Rightarrow$ perfect object reconstruction
  - Inverse Radon transform gives 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](http://www.slaney.org/pct/pct-toc.html), ch. 3

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 $\pm 30^\circ$ 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

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 plane
  - (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

CT disadvantages

- CT is a moderate to high radiation diagnostic technique:
  - Improved radiation efficiency $\Rightarrow$ lower doses
  - Higher-resolution imaging $\Rightarrow$ higher doses
  - More complex scan techniques $\Rightarrow$ higher doses
- Increased availability + increasing number of conditions $\Rightarrow$ 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
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.

3-D surface / volume rendering

- Surface rendering:
  - Threshold value chosen by operator (e.g. corresponding to bone), or a threshold level is set using edge detection algorithms
  - From this, a 3-dimensional model can be displayed
  - different thresholds and colors may represent:
    bone / muscle / cartilage (brusk in Norwegian)
  - 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

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.
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

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

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
  - radioactive isotope with gamma half-life \( \approx 10^3 \) s, energy \( \approx 10^5 \) eV
    - \( ^{99}\text{Tc} \) (Technetium), produced by \( \beta \) decay of \( ^{99}\text{Mo} \) (Molybdenum), produced in neutron-induced fission of \( ^{235}\text{U} \), or produced by neutron absorption by \( ^{98}\text{Mo} \)

SPECT cameras

- SPECT images are collected by rotating pinhole gamma camera around the 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 per projection
  - Total scan time of 15–20 minutes
- Multi-headed gamma cameras give faster acquisition:
  - Dual-head camera give 2 projections simultaneously
  - Triple-head cameras with 120 degree spacing are also used
SPECT reconstruction

- Images have low resolution (64×64 or 128×128 pixels)
- Pixel sizes ranging from 3–6 mm
- Reconstructed images compared to planar images:
  - lower resolution, increased noise, reconstruction artifacts
- Uneven distribution of nuclides may also cause artifacts
- Attenuation gives 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

Positron emission tomography (PET)

- A sugar (fluorodeoxyglucose, FDG) containing radioactive $^{18}$F is injected
- During decay, isotope emits positron
- Positron annihilates with an electron ⇒ a pair of gamma photons moving in opposite directions
- Gamma photons are detected by scanning device
- Only simultaneous pair of photons are used in the image reconstruction

PET examples

Maximally intensity projection of typical full-body $^{18}$F:
(GIF animation file PET-MIPS-anim.gif)

Orthogonal PET slices
Shift in PET application areas

Main PET areas in the 1990s:

- Cardiology
- Oncology
- Neurology

Main PET areas today:

- Cardiology
- Oncology
- Neurology

[cardiology: dealing with disorders of the heart and blood vessels, oncology: with tumors (cancer), neurology: the nervous system]

Oncology: lung case

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

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

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

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

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
Magnetic resonance imaging (MRI)

- Non-invasive medical imaging 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

MRI basics

- Nuclei of hydrogen atoms (protons) align either parallel or antiparallel a strong static external magnetic field $B_0$
- Electromagnetic RF wave at resonance frequency $\nu$ transmit in a plane perpendicular to the magnetic field.
  $$\nu = \gamma |B_0|.$$  \hspace{1cm} (1)
- $\gamma$: gyromagnetic ratio. For hydrogen: $\gamma = 42.58 \text{ MHz} / \text{T}$
- Puts nuclei in non-aligned high-energy state
- As protons return to alignment, they precess
- Precession generates new RF signal, which is picked up by an antenna

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]
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Image formation

- To excite only protons in selected parts of body: gradients are added to get variation of $\vec{B}_0(x)$ in space ⇒ only selected parts of object, resonate at the transmit RF frequency $\nu$
- Tomographic methods are utilized 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: $\sim 1 \text{ mm}^3$

The $T_1$ process

- At equilibrium:
  - Magnetization vector $\vec{M}$ of the protons lies along the $\vec{B}_0$: equilibrium magnetization $M_0$
  - $M_z$: longitudinal magnetization
  - No transverse magnetization $M_x$ or $M_y$.
- The time constant $T_1$ describes how $M_z$ returns to equilibrium. Called spin-lattice relaxation time:
  \[ M_z(t) = M_0 \left( 1 - e^{-t/T_1} \right) \]
- $T_1$: the time to reduce the difference between the longitudinal magnetization $M_z$ and its equilibrium value $M_0$ by a factor of $e$

The $T_2$ process

- $T_2$: describes return to equilibrium of the transverse magnetization, $M_{xy}$, called spin-spin relaxation time:
  \[ M_{xy}(t) = M_{xy0} e^{-t/T_2} \]
- $T_2$, $T_1$ processes occur simultaneously
- Always: $T_2 \leq T_1$
  - $M_{xy} \rightarrow 0$ as $t \rightarrow \infty$,
  - $M_z \rightarrow M_0$ as $t \rightarrow \infty$

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 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
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 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 changes in blood-flow in the brain. Hemoglobin: diamagnetic when oxygenated, paramagnetic when deoxygenated ⇒ magnetic resonance signal of blood is different depending on oxygenation level

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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

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Magnetic resonance spectroscopy (MRS)

- **MRI shows the location of a tumor**
- **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

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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”
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) to decrease
  ⇒ Decreased sensitivity

Current density imaging (CDI)

- CDI is used for mapping of current pathways through tissue:
  - Electrical currents generate local magnetic fields
  - Such magnetic fields affect the phase of the magnetic dipoles during an imaging sequence
  - CDI uses phase information from images to reconstruct current densities within the object

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