Chapter 2

DIGITAL IMAGE ACQUISITION

Concepts

Concepts, Notions, and Definitions Introduced in this Chapter

- › *Imaging techniques:* X-ray, fluoroscopy and angiography, digital subtraction angiography, X-ray CT, CT angiography, MR imaging, MR angiography, functional MRI, perfusion MRI, diffusion MRI, scintigraphy, SPECT, PET, ultrasound imaging, optical coherence tomography, photography, optical and electron microscopy, EEG, and MEG.
- › *Reconstruction techniques*: filtered backprojection, algebraic reconstruction, EM algorithms
- › *Image artifacts*: noise, motion artifacts, partial volume effect, MR-specific artifacts, ultrasound-specific artifacts.

Imaging Aspects

- A major difference between most digital medical images and pictures acquired from photography is that depicted physical parameters in medical images are usually inaccessible for inspection.
- Infeasible to open the human body in order to verify whether a tumor volume measured in a sequence of CT images in some post treatment confirmation scan corresponds to the true volume.
- Fortunately, physical property depicted, its diagnostic value, and possible artifacts are usually well-known.
- The development of efficient analysis techniques often uses this knowledge as part of the domain knowledge in order to make up for the inaccessibility of the measured property.
- A physical property measured by an imaging device and presented as a picture must **meet three conditions in order to be useful**. **It has to penetrate the human body, it must not unduly interfere with it, and it must be meaningful for answering some medically relevant questions.**

Major Imaging Techniques

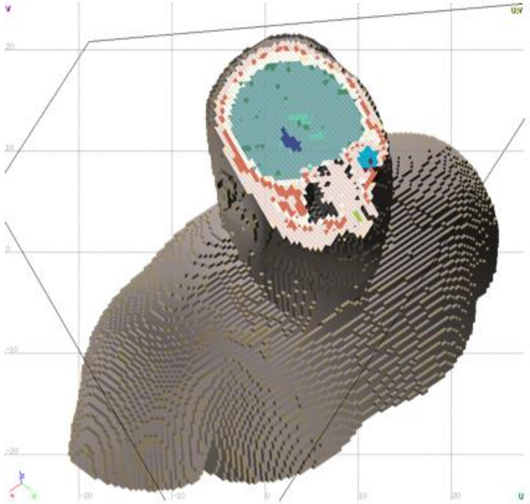
- With respect to digital imaging, **four major** and several minor imaging techniques meet these requirements. The major techniques are as follows:
- • **X-ray imaging** measures absorption of short-wave electromagnetic waves, which is known to vary between different tissues.
- • **Magnetic resonance imaging** measures density and molecular binding of selected atoms (most notably hydrogen which is abundant in the human body), which varies with tissue type, molecular composition, and functional status.
- • **Ultrasound imaging** captures reflections at boundaries between and within tissues with different acoustic impedance.
- • **Nuclear imaging** measures the distribution of radioactive tracer material administered to the subject through the blood flow. It measures function in the human body.

Image types

- Many of the imaging techniques come in two varieties: **Projection images** show a projection of the 3d human body onto a 2d plane and **slice images** show a distribution of the measurement value in a 2d slice through the human body.
- Slice images may be stacked to form a volume.
- Elements of a 2d picture are called pixels (picture elements), and elements of stacked 2d slices are called voxels.

1

PIXELs	VOXELs
picture elements	volume elements
tiny squares (2D)	tiny cubes (3D)
building blocks making up a slice	building blocks making up a chunk (many slices stacked together)

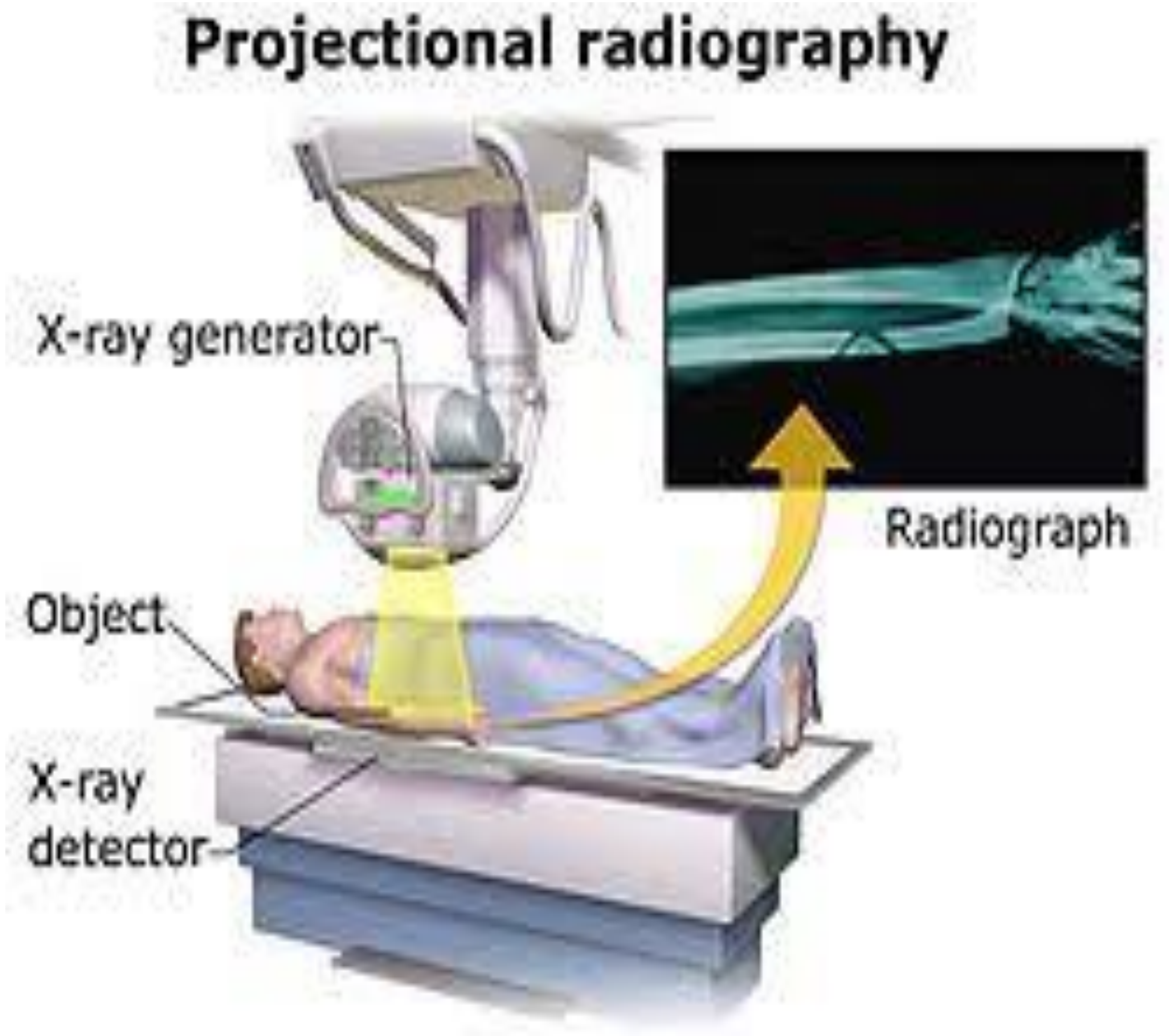


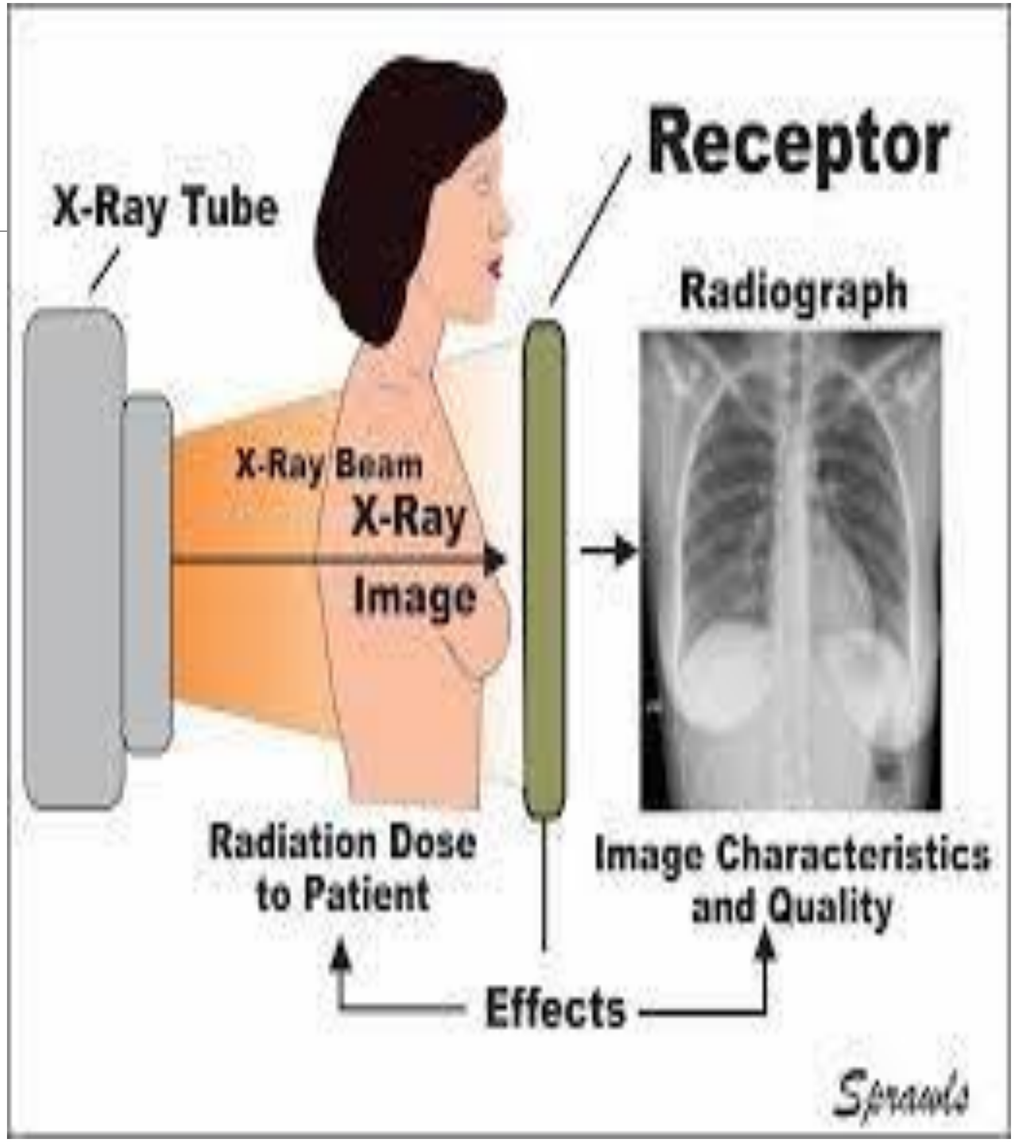
X-rays

- X-rays have been discovered in 1895 by Wilhelm Röntgen. He noticed an unknown kind of rays emitted by a cathode ray tube (CRT) which easily penetrated paper, aluminum, and many other materials but not a lead plate.
- For the first time in history, a technique allowed non-invasive insight into the human body.
- X-rays are electromagnetic waves with a wavelength above the visible spectrum. (10^{-8} to 10^{-11})
- Electromagnetic radiation has the characteristics of waves but is actually traveling as clusters of energy called **photons** with a given wavelength.
- The energy of a photon measured in electron volts (eV) is the energy that a single electron acquires when moving through a potential of 1 V.
- **The energy of a photon is characterized by its wavelength.** It is given by e=1.24/Lamda.

Exposure

- The energy of X-ray photons is sufficient to release electrons from an atom, a process -called **ionizing radiation.**
- X-rays are characterized by their **exposure**, i.e., the amount of charge per volume of air, which is measured in Roentgen (R).
- Exposure measures the energy of the radiation source, but it does not describe how much of the radiation is absorbed by a body under radiation.
- Absorption per unit mass is called **dose**, and it is measured in radiation absorbed dose (rad) or gray (Gy) with 1 Gy = 100 rad.
- **The ratio between exposure and dose varies with the X-ray energy and is often called the f-factor.**
- The f-factor at low exposure for hard tissues such as bone is much higher than for soft tissues and water.
- Hence, bone at low doses absorbs a significantly higher amount of radiation than soft tissues.


Projectional radiography
X-ray generator
Radiograph
Object
X-ray
detector


X-Ray Tube
Receptor
Radiograph
X-Ray Beam
X-Ray
Image
Radiation Dose
to Patient
Image Characteristics
and Quality
Effects
Sprawls

X-ray Generation

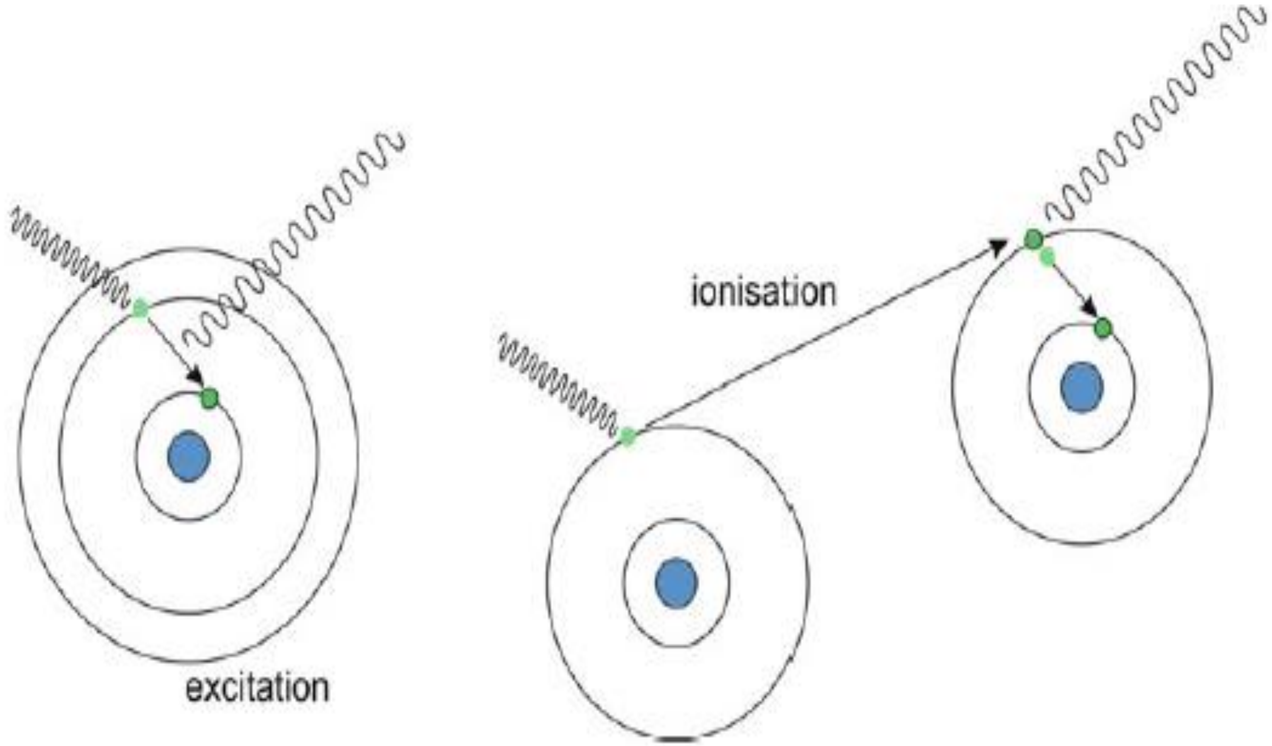
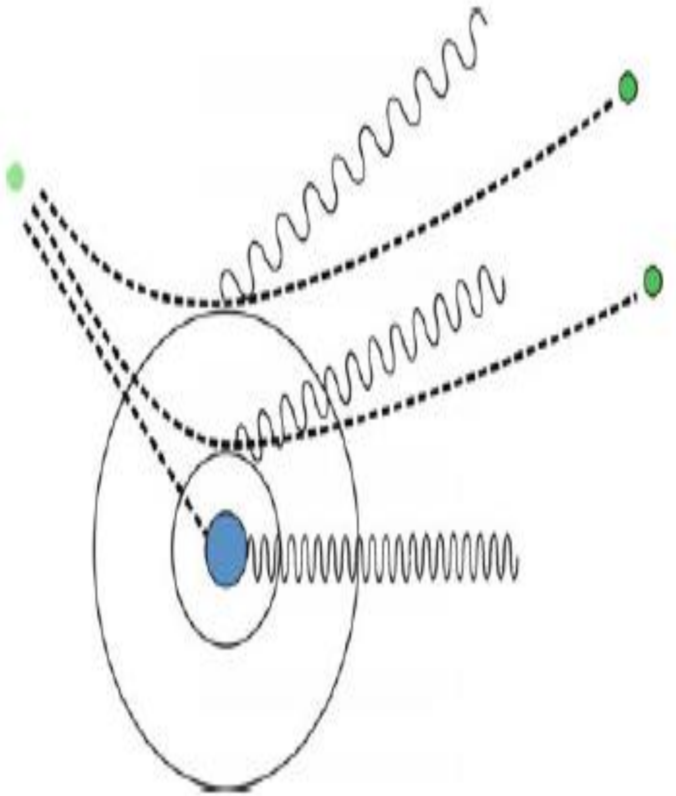


Fig. 2.4 X-ray generation by excitation and ionization. In excitation, external energy pushes an electron from an outer shell to an inner shell. Excess energy is released as X-rays. The ionization process is similar, except for the fact that excitation happens indirectly by an electron that is released from an outer shell of a different atom

Fig. 2.5 Polychrome radiation is a result of a passage of an electron. The frequency of the released radiation depends on the extent to which the electron loses its energy



X-ray Attenuation

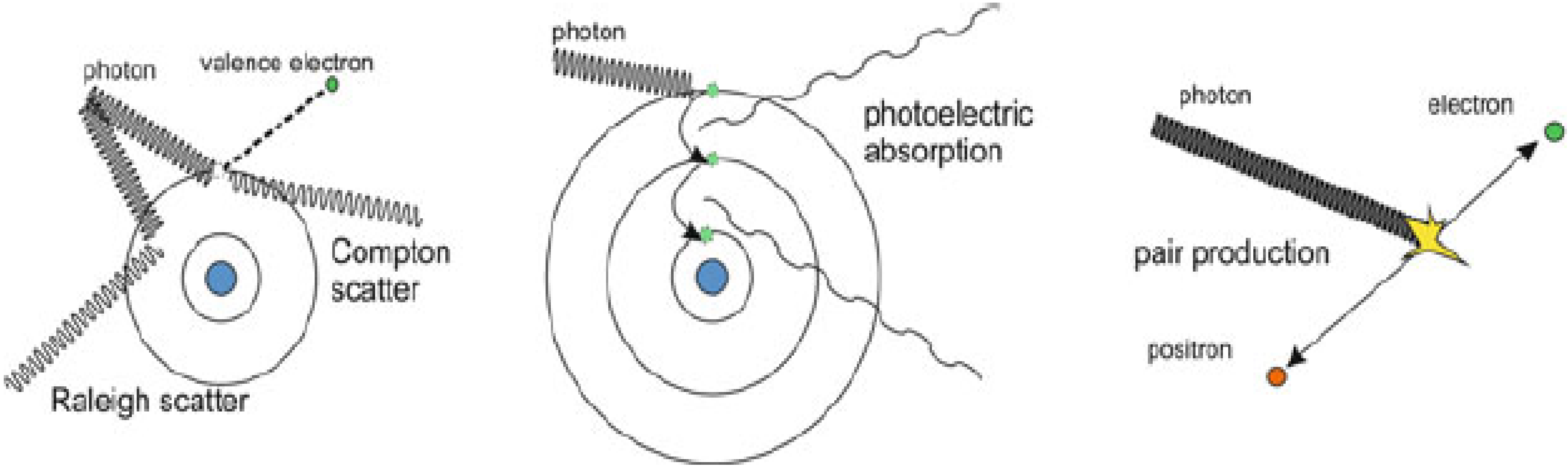


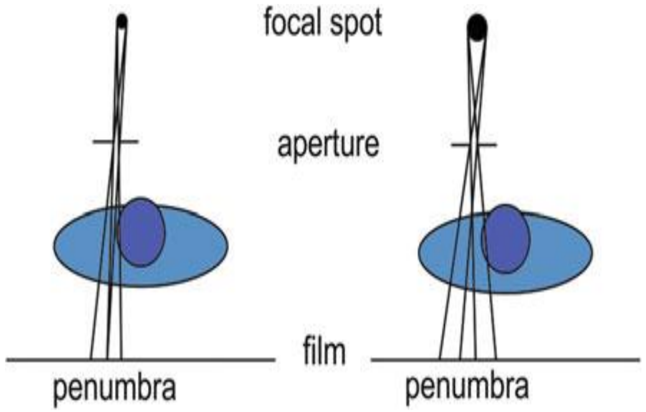
Fig. 2.6 Four kinds of X-ray attenuation exist. Rayleigh and Compton scatter causes noise in the image since the scatter direction is random. Photoelectric absorption produces the X-ray image, since the released energy is too low to be detected. The energy levels used in X-ray imaging do not produce pair production

X-ray Imaging

- Diagnostic equipment for X-ray imaging consists at least of a cathode ray tube **emitting X-rays and a receptor with the patient placed between emitter and receptor.** The receptor may be a film, an image intensifier, or a flat panel detector with the latter two producing digital images.

- The measured intensity for a monochromatic beam at a location (x, y) on the receptor is then

$$I_{\mathrm{out}} = I_{\mathrm{in}} \cdot \exp\left(- \int_{s_0}^{s_1} \mu(s) \mathrm{d}s \right)$$



- the focal spot of an X-ray source covers a finite area leading to a loss of resolution due to penumbrae.

- Regular X-ray CRTs have a focal spot with a diameter of 1 mm, fine focus CRTs have one with 0.5 mm diameter, and microfocus CRT has a 0.2-mm-diameter focal spot.

Imaging Receptors

- Of the **three types of receptors,** **analogue film** is the oldest and still the most widespread. Film may be digitized, but receptors such as image intensifiers and flat panel detectors are preferred if computer-assisted post-processing is desired.

- **An image intensifier** produces a visible image from X-rays in a similar fashion than a conventional CRT. X-rays are turned into visible light on a phosphor screen in a vacuum tube, which is then converted into electrons by a photocathode.

- The image intensifier was originally invented for **creating a visible signal without the need to use and develop film.** It has the additional advantage of enabling transmittance of the electronic signal and its digitization through an A/D converter.

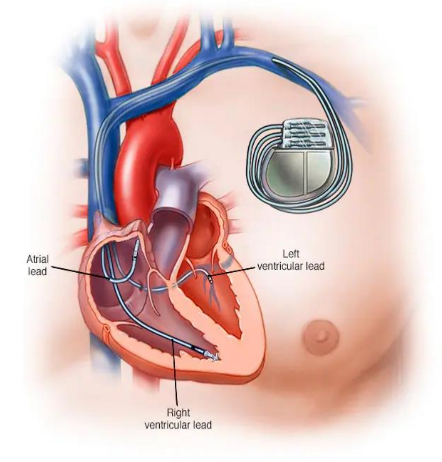
- Images from an image intensifier suffer from a number of artifacts of which the following three are relevant for post-processing: Vignetting, Pincushion distortion and S-distortion.

A completely digital receptor for X-rays is the **TFT flat panel detector** which has been developed in recent years. A flat panel detector combines a flat panel scintillator, which turns X-rays into visible light with a detector that transforms the light into an analog electric signal which may then be digitized.

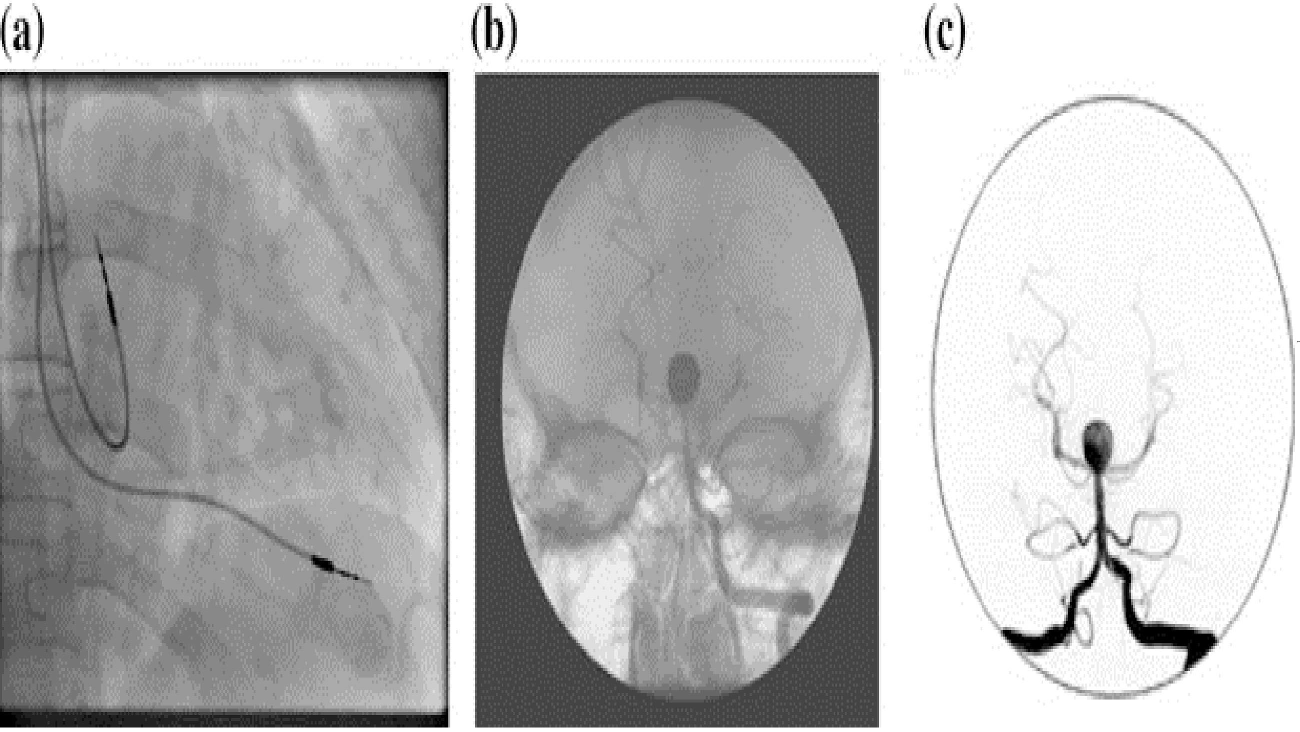
X-ray Imaging

- The **blackening curve**, which measures the dependency of incident radiation on the receptor and the intensity of the resulting images, has a larger interval of linear increase for flat panel detectors and image intensifiers than for film. This decreases the likelihood of an accidental overexposure or underexposure.
- The spatial resolution in digital radiography is still lower than that of film.
- An advantage of digital radiography using either a TFT detector or an image intensifier is that the **operator may choose the spatial resolution.**
- If imaging at a lower resolution is sufficient for some diagnostic purpose, this can be achieved by analog or digital integration over several pixels of the image. Since integration reduces noise, the signal-to-noise ratio increases without having to increase exposure and, consequently, dose.

Fluoroscopy and Angiography



- Fluoroscopy is a specific kind of X-ray imaging to visualize moving or changing objects in the human body . Examples for using diagnostic fluoroscopy are as follows:
- • to follow the **heartbeat for detecting abnormal behavior**;
- • to follow the course of a contrast agent through the colon in order to **detect potential abnormalities such as a tumor**; and
- • to image **cardiac or cerebral blood flow** by using a contrast agent.
- Most of today's fluoroscopic imaging devices produce digital images and enable the creation of X-ray films as well.
- Fluoroscopic imaging devices are not necessarily static. When mounted on a C-arm, they can be rotated around the patient for producing projections along arbitrary directions.
- Fluoroscopic imaging is used for diagnosis and supports surgical interventions. It is an attractive imaging technique for the latter because images can be produced during the intervention.


(a)
(b)
(c)


Artis zeego

Fluoroscopy and Angiography

- **Fluoroscopic imaging of the vascular system using a contrast agent is called angiography**
- Angiographic images show anatomy with blood vessels enhanced through the contrast agent. Angiographic images can be acquired in real time and can be used to guide a surgical intervention.
- angiographic image acquisition systems can also be used to **reconstruct 3d images from a sequence of projection** from different angles.
- Anatomic information from all other structures can be removed when an image is subtracted, which was made prior to giving the contrast agent. Although it is possible—and has been done—to do the subtraction mechanically using film, it is **now done on digital images**. The technique is called **digital subtraction angiography.**
- DSA images from cerebral blood flow are affected to a much smaller extent by motion artifacts from heartbeat and patient motion.
- Some research work on non-rigid registration between the two images in DSA has been reported, but as far as we know, none of this has reached maturity.

Mammography

- **Bremsstrahlung** is the major influence in most X-ray tubes with the exception of X-ray tubes for mammography using mammography tubes.
- The purpose of mammography is to detect small non-palpable lesions in the female breast. This requires a much higher image quality than normal X-ray imaging with respect to contrast and spatial resolution.
- Mammography tubes use a material molybdenum, which produces an almost monochrome X-ray with peak energies around **17–19 keV.**
- For the breast, however, the use **of low energy beams increases contrast between subtle differences of different tissues.**
- Digital mammography with its potential for post-processing has received much attention, have numerous advantages. They can be easily distributed and accessed in a hospital network. The dynamic range of digital detectors (about 1000:1) is much higher than that of film (40:1). Digital mammograms can be created using currently available TFT flat panel detectors, but owing to the need for a high resolution, the development of techniques reaching an even better resolution is still an active research field.

Image Reconstruction for Computed Tomography

- Images from X-ray attenuation are projection images. Structures are projected on top of each other.
- High attenuating objects such as bone may hide other objects.
- Tomography (from the Greek “tomos” = cut, slice) attempts to create an image of one or more slices through the body. A set of slices provides a detailed 3d distribution of X-ray attenuation per volume unit.
- The name computed tomography (**CT, also called CAT = computed axial tomography**), emphasizes that these images are not acquired directly by some clever imaging device but are computed from projection measurements.
- Computed tomography goes a different way. It produces a digitized solution of the inverse Radon transform from projections in a slice without interference from other slices .
- The inversion is computed numerically from projections by the imaging computer.

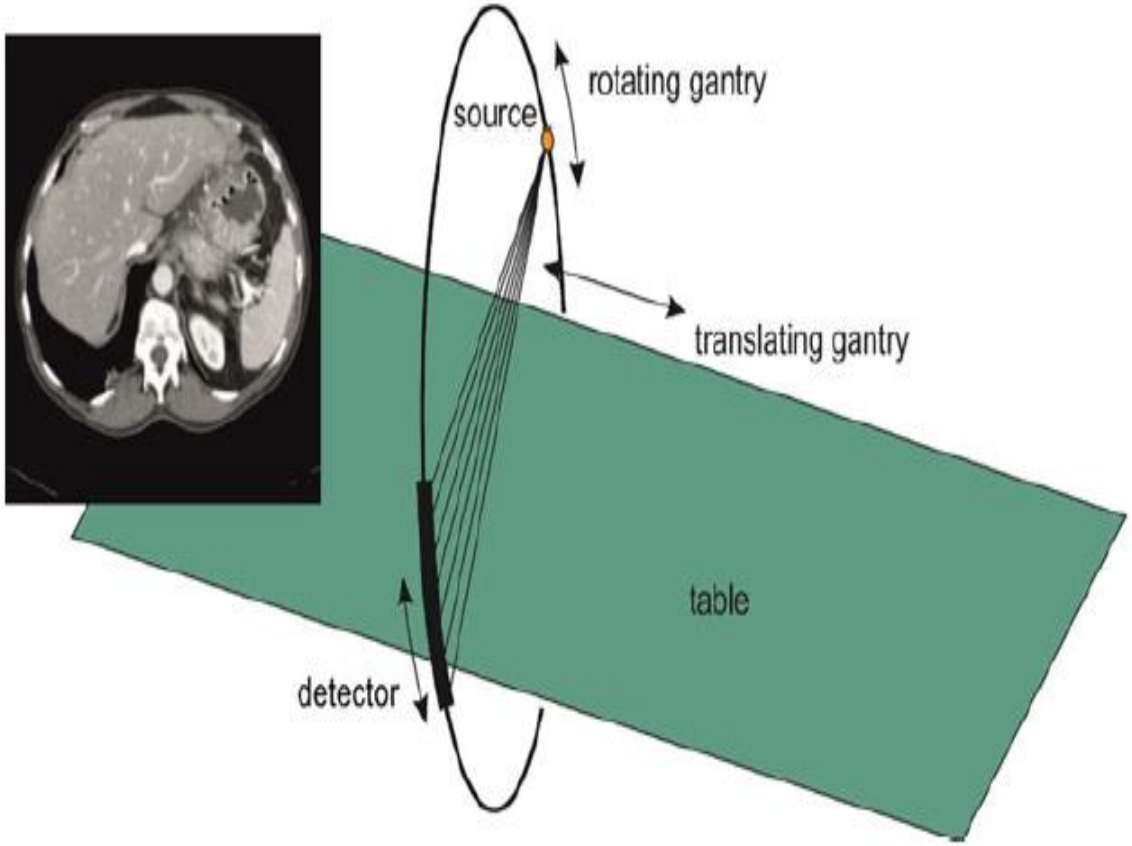


Fig. 2.13 Schematic view of CT image generation. The patient is placed on a moveable table. A CT image is a slice that is reconstructed from multiple projections taken from different angles. A sequence of CTs is created from translating the table and repeating the image acquisition procedure

Fig. 2.14 An X-ray CT scanner (Siemens Somatom, image with kind permission by Siemens Sector Healthcare, Erlangen, Germany). Image acquisition takes place in the doughnut-shaped gantry that houses X-ray source and detector rings (which, in this system, can be tilted). The patient is moved through the gantry while slices of CT images are acquired

Hounsfield Unit

- Attenuation coefficients are normalized for making the result independent of imaging parameters such as beam energy. **The scale is called Hounsfield scale.**
- Normalization is based on the attenuation of water and air:

$$\mathrm{HU}(\mu) = 1000 \cdot \frac{\mu - \mu_{\mathrm{Water}}}{\mu_{\mathrm{Water}} - \mu_{\mathrm{Air}}}$$

- Thus, air has −1000 HU and water has 0 HU. Hounsfield units for different tissue types are given in Ta

Table 2.1 Hounsfield units of different tissues

Air	Fat	Water	Blood	Muscle	White matter	Gray matter	CSF	Bone
−1000	−100	0	30–45	40	20–30	37–45	15	>150

Note Air, water, and bone are well differentiated, while contrast between different soft tissues is low

Contrast Enhancement in X-ray Computed Tomography

- Contrast agent used in fluoroscopic imaging or angiography is used in X-ray CT as well.
- Instead of showing a time-varying function such as in fluoroscopy, **use of a contrast agent in X-ray CT enhances structures which are otherwise difficult to differentiate.** A major application is the depiction of vessels.
- CT angiography or CTA works similar to ordinary X-ray angiography with the difference that images are not projections .The 3d nature of CTA images allows quantitative analysis by direct measurement on the image.
- however, that CTA requires a higher exposure to X-rays than X-ray angiography. Compared to subtraction angiography (a reconstruction from DSA), CTA provides information about soft tissues not visible in DSA.
- On the other hand, the intensity of vessels filled with contrast agent is similar to that of bone, making it difficult to separate vessel structures close to the skull from bone structures.

Image Analysis on X-ray-Generated Images

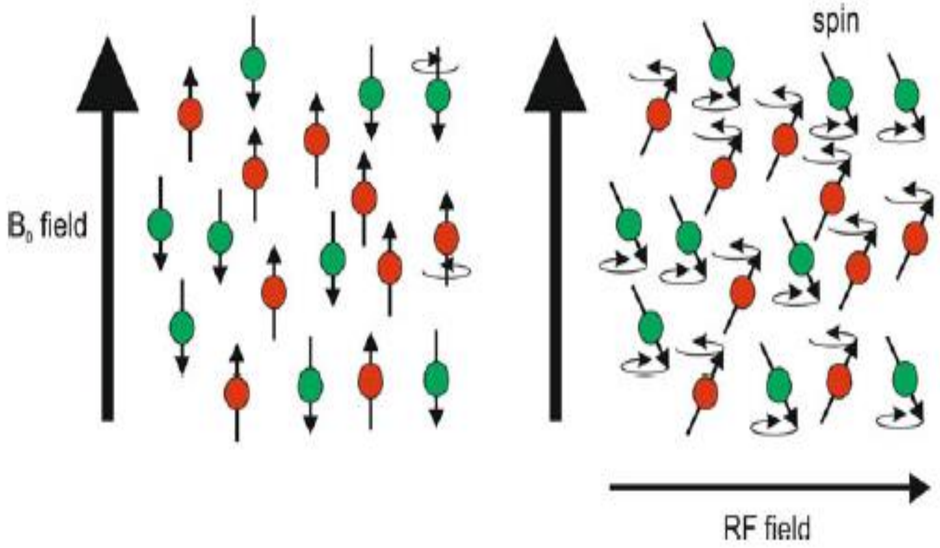
- **Radiographs have a high spatial resolution** which supports the detection of small lesions such as microcalcifications in mammography, potentially cancerous nodules in lung scans or small stenoses in angiography. The signal is bright for dense structures and dark for low attenuation objects.
- As the image is a projection, no assignments between absolute brightness value and tissue type can be made. Distance measurements are not possible.
- Over- or underexposure (for digitized film) may reduce the contrast, and images may be blurred due to motion or the size of the focal spot.
- Recognition of small objects may be hindered by the fact that structures hide other structures in the projection. Projection may also cause a very convoluted appearance of larger objects.
- Creating tomographic images reduces or removes some of the problems above, which is one of the reasons for the sudden increase in computer-assisted analysis methods in medicine
- CT Images have a lower spatial resolution than radiographs, which is why radiographs may still be preferred if diagnosis requires high resolution images.

Magnetic Resonance Imaging

- Protons and neutrons of the nucleus of an atom possess an angular momentum which is called spin.
- These spins cancel if the number of subatomic particles in a nucleus is even. Nuclei with an odd number exhibit a resultant spin which can be observed outside of the atom. **This is the basis of magnetic resonance imaging (MRI) .**
- In MRI, spins of nuclei are aligned in an external magnetic field. A high-frequency electromagnetic field then causes spin precession that depends on the density of magnetized material and on its molecular binding. The resonance of the signal continues for some time after this radio signal is switched off. The effect is measured and exploited to create an image of the distribution of the material.
- **The resonance effect has been used in MR spectroscopy for** quite some time.

MRI Vs CT

- Magnetic resonance imaging almost exclusively **uses the response of the hydrogen nucleus** which is abundant in the human body. Variation in hydrogen density and specifically its molecular binding in different tissues produces a much better soft tissue contrast than CT.
- MRI has some further advantages if compared with X-ray CT:
- • MRI does not use ionizing radiation.
- • Images can be generated with arbitrary slice orientation including coronal and sagittal views.
- • Several different functional attributes can be imaged with MRI.
- In summary, MRI is a remarkably versatile imaging technique justifying an extended look at the technique.



MRI Basics

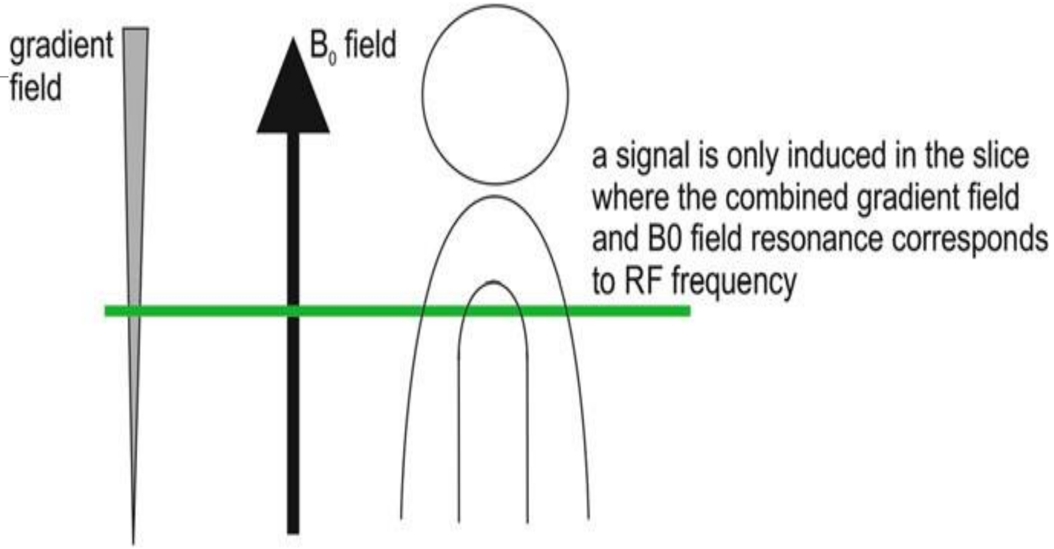
- To produce a resonance image, spins of all nuclei of the body are aligned in a static magnetic field B0. The strength of the magnetic field is measured in Tesla (T) or Gauss (10,000 Gauss = 1 T).
- Today's MR imaging devices for human full body imaging operate with field strengths between 1 and 3 T.
- A precession of spins around an axis parallel to the B0 field can be induced by a radio signal. The effects of parallel and antiparallel precessing spins cancel. Given that the hydrogen atom possesses the highest sensitivity of all atoms and that the temperature cannot be increased arbitrarily, the only way to increase the signal is to increase the magnetic field. **This is the reason for the exceptionally high magnetic fields that are applied in MRI (for comparison, the strength of the earth magnetic field is 0.00003–0.00006 T).**
- If spins are aligned in the external B0 field, their angular momentum, i.e., their spin frequency ω, depends on the strength of B0 and an atom-specific gyromagnetic constant c:

$$\omega = \gamma B_0$$

- The frequency x is called **Larmor frequency**. The gyromagnetic constant for water is 42.58 MHz/T which translates into a spin frequency of 63.87 MHz for an MRI scanner with a static field with 1.5 T.

MR Imaging

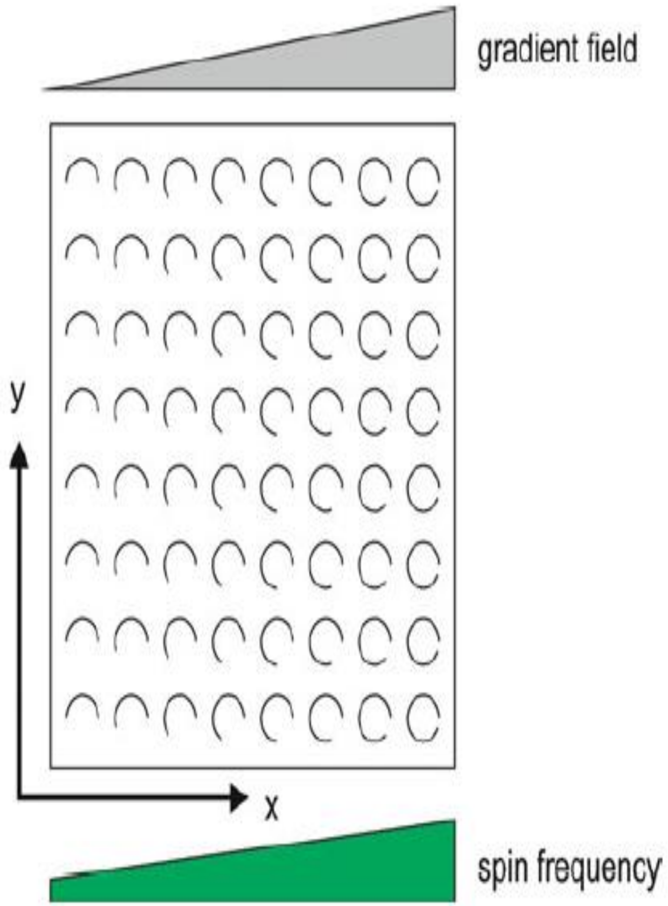
- Extending the MR technique for creating an image is due to the work of **Mansfield and Lauterbur.**
- The dependency of excitability of a proton on the frequency of the HF field is used for the necessary localization.
- If, before applying the HF-field, a linear gradient field in z-direction is overlaid to the B0 field, the magnetic field strength will linearly increase in direction of z. Protons will spin with a frequency that depends on their location in z.
- If an HF field is applied whose frequency range corresponds to spin frequencies of protons in a slice with z1 < z < z2, only those protons will be excited and produce a resonance signal. **The process is called slice selection.**



MR Imaging

- In order to localize protons within a slice, a similar technique is applied while reading the signal.
- If a linear gradient field in x-direction is applied during observation of the resonance signal, the recorded signal will contain a range of frequencies (see Fig. 2.24). The process is called **frequency encoding.** The gradient is called readout gradient.
- The technique produces a projection of spin densities along y onto the x-axis.
- Having obtained the data, an image could be reconstructed by **filtered backprojection.** This was the first technique for reconstructing MR images.

Fig. 2.24 Frequency encoding of the signal is done by a gradient field in the *xy*-plane. It causes spins to rotate with different frequencies at readout time so that atoms can be associated with lines orthogonal to the gradient field



k-space Imaging

- Today’s scanners employ a different technique, which is called **k-space imaging** (k-space is frequency space).
- K-space imaging generates the image function in frequency space directly through measurements.
- we apply another linear gradient in y-direction prior to making the measurement, spin frequency will increase along y and the spins will dephase. The gradient is called **phase encoding gradient.** It is applied just long enough in order to diphase spins between 0 and 2π for the range of y-values between y0 and ymax.
- After switching off phase encoding, frequency encoding is applied and the obtained signal is transformed into frequency space.
- In other words, we have produced the real-valued part of the next line in k-space of the Fourier transform in u-direction. The imaginary part is computed by weighting the signal with the corresponding sine wave.
- The measurement is repeated with phase encoding for the remaining lines in k-space. Once the k-space is filled, the image is generated by transforming it back into the spatial domain.

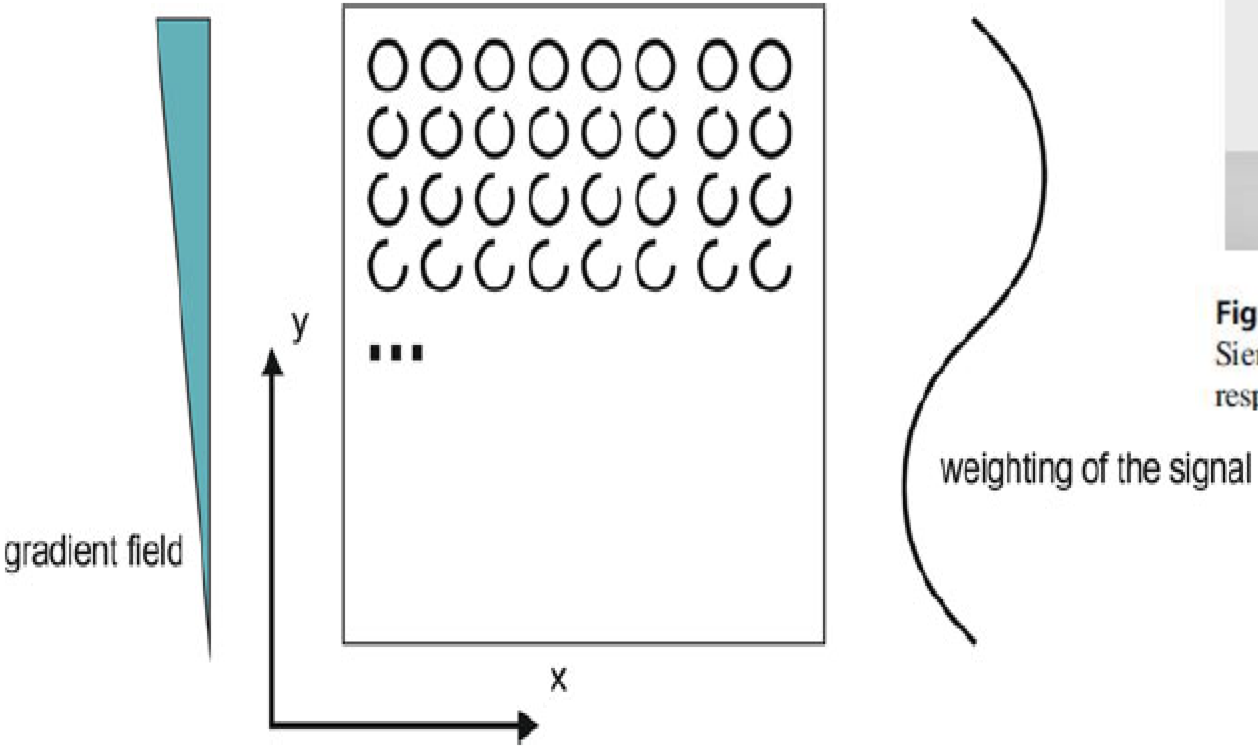


Fig. 2.25 Gradient field for each phase encoding causes a controlled dephasing which acts as a weighting of the observed signal with a cosine function. Phase encoding is done before readout, and the phase encoding gradient is switched off before readout

Fig. 2.26 Gantry of an MR imaging device (Magnetom Avanto, with kind permission from Siemens Sector Healthcare, Erlangen, Germany). Images can be produced at arbitrary angles with respect to the gantry by producing appropriate slice selection gradients

MRI Imaging Vs CT

- Image equipment looks similar to CT .However, the gantry in which the B0 field is produced is usually **smaller than a CT gantry**.
- Image planes need not to be perpendicular to the direction of the B0 field, since gradients may be generated in arbitrary directions. **It is a major difference compared to CT imaging.**
- Also, a variety of different images may be produced form the same patient showing different aspects of the resonance signal.
- **Three different parameters—spin density ρ, spin-lattice relaxation T1, and spin–spin relaxation T2—determine the resonance signal.**
- Hence, different sequences can be developed for enhancing either of the It changes the appearance of different tissues in images (e.g., water and fat is bright in T2 images and tissue is darker, while the opposite is true for a T1 image).
- A normalized scale such as the Hounsfield units of CT does not exist.

Some MR Sequences

- T1 and T2 time constants cannot be measured directly because signal strength is always influenced by proton density and because field inhomogeneities (the T2* decay) hide the T2 effect. **T2-enhanced images can be generated by the spin echo sequence.**
- The sequence uses a clever mechanism to cancel out T2* effects. It consists of a 90° impulse which tilts spins into the xy-plane followed by a sequence of 180° impulses producing spin echoes. Usually, a single echo will be taken as image.
- The time between 90° impulse and the echo impulse is called echo time TE. The time between two measurements is called repetition time TR. Short TE (20 ms) and long TR (2000 ms) will produce a proton-density-weighted image. Using a shorter repetition time (TR = 300–600 ms) will produce a T1-weighted image because T1 relaxation is generally longer than 200–600 ms. A long TE (>60 ms) and a long TR (2000 ms) produce a T2-weighted image.
- The **inversion recovery sequence** is another sequence used in MRI. It produces an image that is strongly influenced by the T1 time constant. In inversion recovery, a 180° impulse is followed by a 90° impulse. The time between the two impulses is called TI or inversion time.

MR imaging

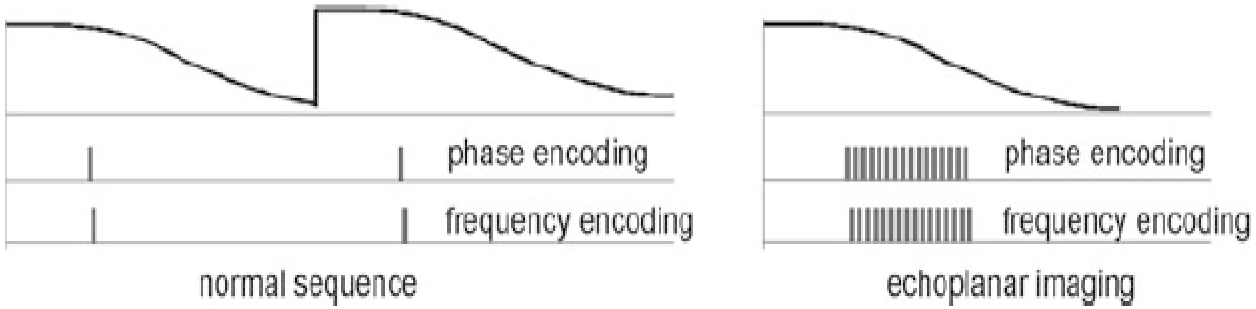


Fig. 2.28 Main difference between normal encoding and a fast imaging sequence is that in fast imaging, several to all encodings are done during a single excitation of the resonance signal

- MR images of the head created by imagining sequences like the ones above, usually have a slice thickness of 1–3 mm and 256*256 voxels in a slice. Body MR images usually have 512*512 voxels per slice.
- **Data acquisition times using either of the sequences are longer compared to CT imaging**.
- In the early 1980s, acquisition times have been a serious drawback. Since the 1990s, a wealth of fast imaging sequences has been developed. **Gradient echo imaging was one of the first techniques to speed up imaging time.**

Turbo spin echo sequences make several measurements at a time. This is done by applying a sequence of several phase shift gradients during a single echo and reading the signal after each phase shift. all lines are acquired from a single excitation (RARE—Rapid Enhancement with Relaxation Enhancement) so that an image can be acquired within time TE. **RARE is a variant of an older sequence known as Echo Planar Imaging (EPI)**, a term which simply refers to acquiring the complete k-space in a single resonance experiment.

Artifacts in MR Imaging

- Ultrafast sequences such as EPI produce images in less than 100 ms. There are problems:
- The **chemical shift** of protons (and any other nuclei) is caused by magnetic shielding from electrons in the molecular environment. It depends on the molecular binding of protons and causes a material-dependent deviation of spin frequency. The difference is particularly apparent for protons in water, as compared to those in fat.
- Chemical shift is present in all non-shift-corrected images but is pronounced in EPI (RARE) images where the offset may amount to 8–10 pixels. At 3-mm voxel size, this is an offset of about 2.5 cm.
- **Ghosting** appears because of inaccuracies in the phase encoding. Ghosting may also happen in regular imaging if the patient has moved in phase encoding direction between acquisitions.
- **Shading** is due to variation in attenuation of the RF signal and an inhomogeneous magnetic field. It causes differences in the resonance signal according to location.
- Artifacts from noise and PVE are similar to CT imaging. **Metal artifacts** from paramagnetic materials causes signal deletion.

MR Angiography

- MR angiography (MRA) exists with and without using contrast agents.
- Contrast-enhanced angiography uses gadolinium, an agent that causes a strong decrease in the T1 relaxation time. Gadolinium-enhanced vessels can be imaged with a T1-weighted sequence that saturates all other tissues while highlighting vessels.
- **The resulting contrast is so high that the images look similar to DSA images but without the necessity of subtracting a null image**. Vessels may be depicted even if they are smaller than a voxel because of the partial volume effect.
- MRA images come as a true 3d volume, but they are often displayed as **maximum intensity projection images (MIP).**
- MIP is simple and fast and produces images similar to digital subtraction angiograms.

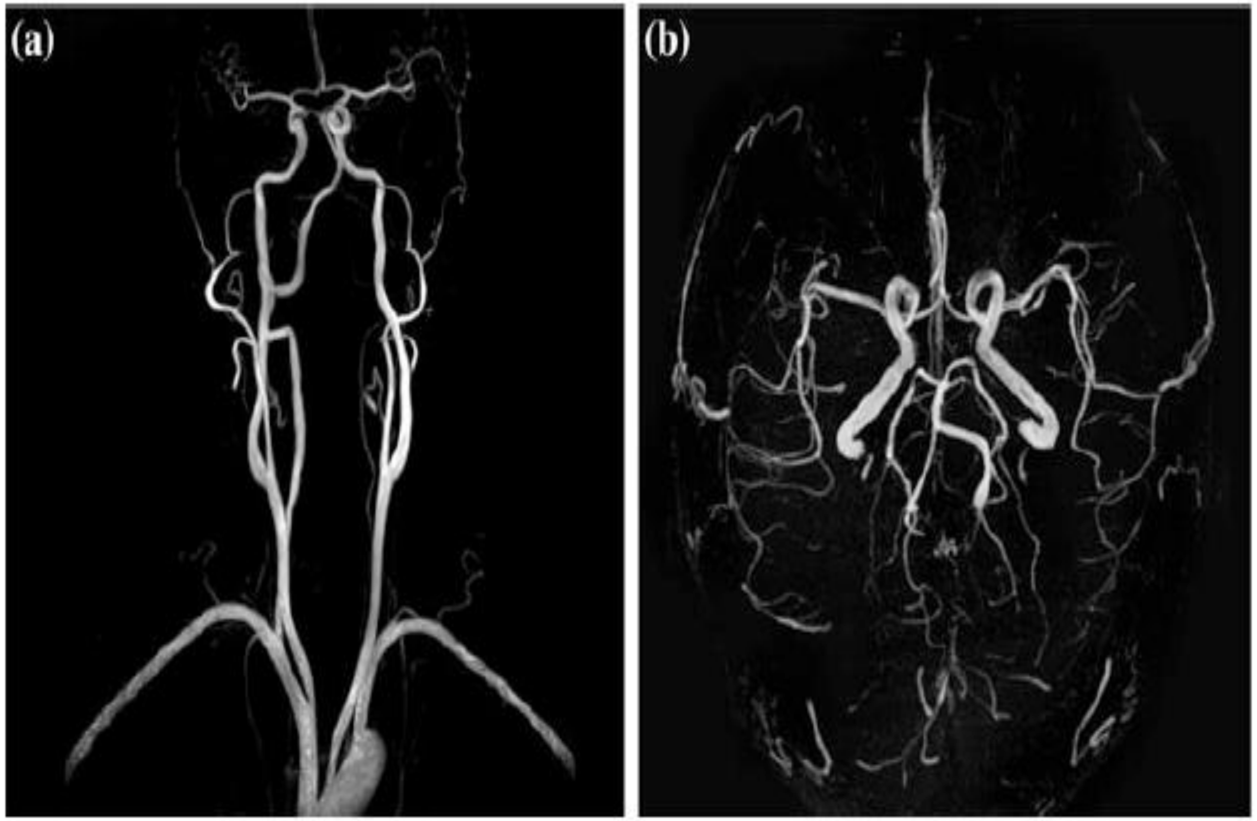


Fig. 2.29 Maximum intensity projections of gadolinium-enhanced MRA (*left*) and phase-contrast MRA (*right*). While using gadolinium, contrast agent produces images with better resolution, phase-contrast imaging is noninvasive and has the potential for computing vessel velocities (images from Siemens Sector Healthcare with permission)

BOLD Imaging

- Blood supplying the brain carries oxygen via hemoglobin. Oxygenated haemoglobin is diamagnetic such as all the other tissues, but deoxygenated hemoglobin is paramagnetic causing a small, local distortion of the magnetic field.
- The distortions change the measurable signal which can be made visible. **The technique is called Blood Oxygen-Level Dependency (BOLD) Imaging.**
- Since brain activity is associated with energy supply through oxygenated hemoglobin, **BOLD imaging may be used to image brain activity**.
- The ability for measuring functional activity truly differentiates MRI from CT imaging and has put MRI in competition with Nuclear Medicine Imaging techniques such as PET.
- Gradient echo imaging with low angles is particularly sensitive to inhomogeneities and is often used in **functional MRI (fMRI).**

BOLD Imaging

- During image acquisition, a subject is asked to perform a task (e.g., listen to sound) for some time and then refrain from performing it.
- Potential correlation between intensity changes in the images and the "action"–" no action" sequence is computed for every voxel in a post-processing phase.
- An interesting alternative to use the BOLD effect is **resting-state BOLD imaging**, where no task is given to the subject.
- The aim of this analysis is to detect potential correlations between different regions of the brain.
- Despite of the complexity of processing the functional data, **fMRI is popular and currently the only technique to measure cortical activity** at a spatial resolution under 3 mm.

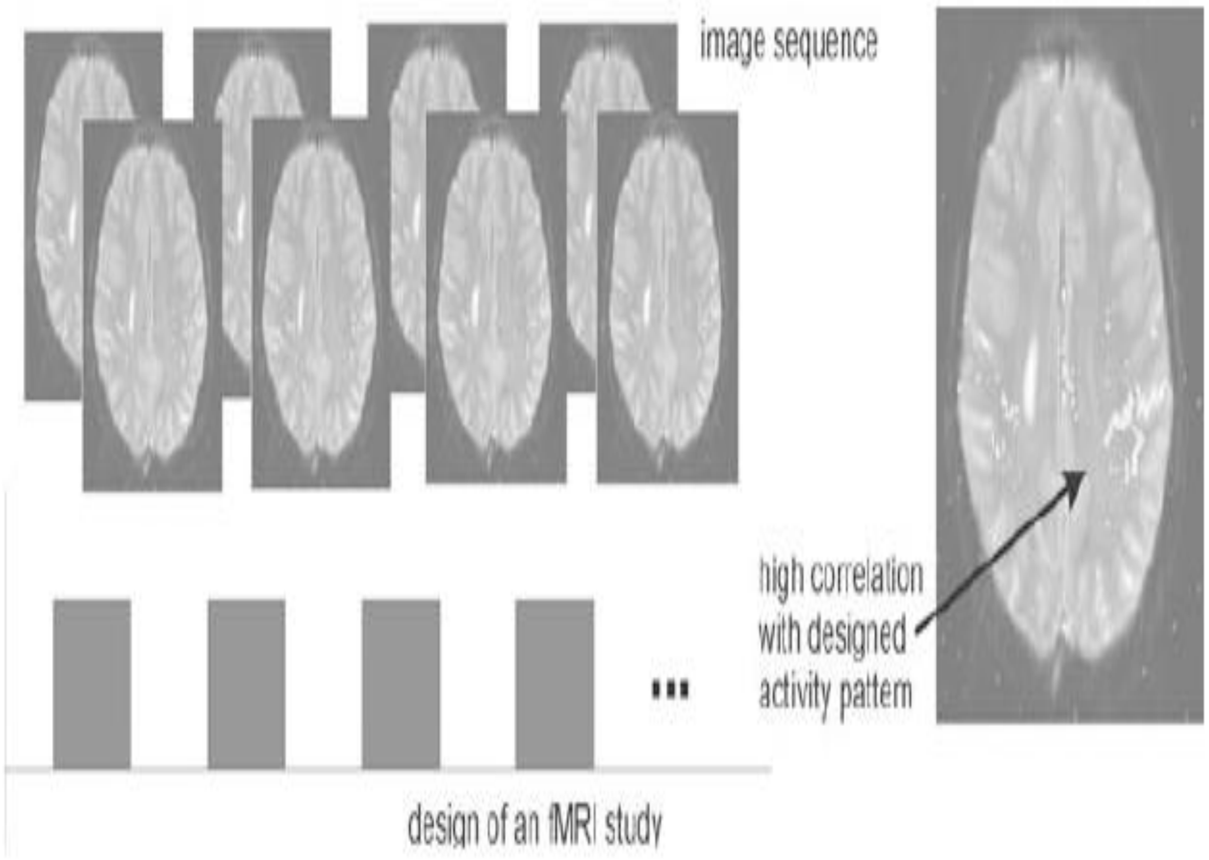
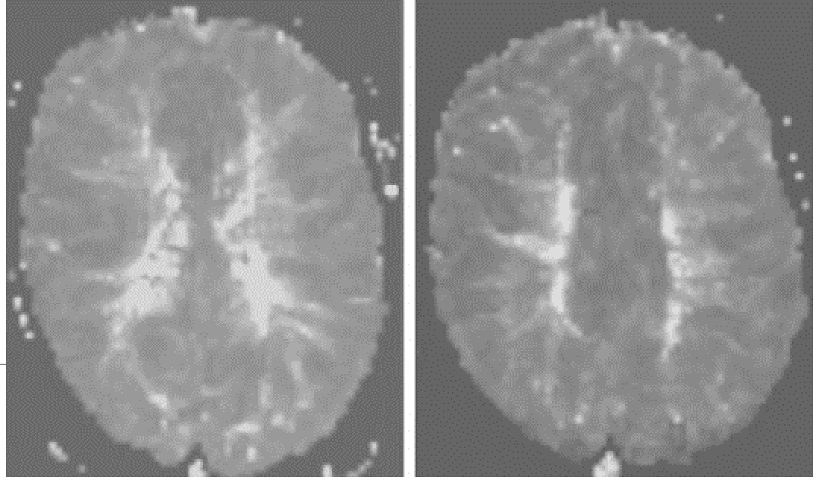


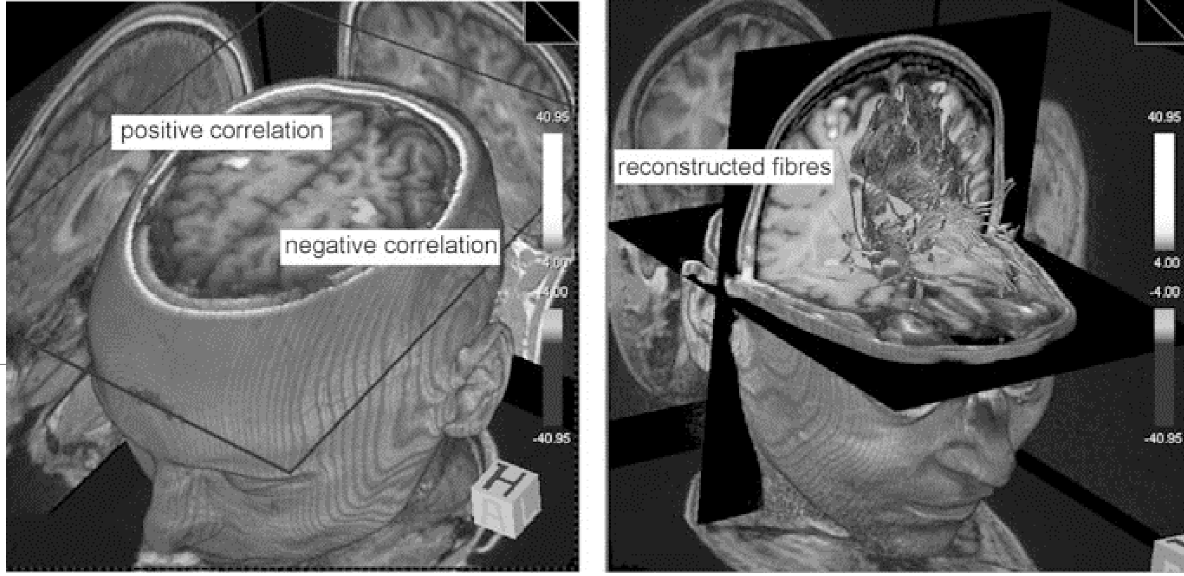
Fig. 2.31 A simple fMRI sequence consists of a sequence of images taking during a time in which a task is either on or off. Locations of which intensity changes correlate with the task design are then emphasized

Perfusion Imaging



- **Gadolinium may be used to measure perfusion in MRI.** Gadolinium not only reduces the T1 time but also shortens the T2 time (and with this the T2* time). The change in T2* is related to the amount of gadolinium. Since this is related to the amount of blood passing through the volume of tissue, **Gadolinium-caused T2* contrast predicts blood perfusion.**
- The main application of perfusion imaging is the depiction of parameters such as the **relative cerebral blood volume (rCBV), relative cerebral blood flow (rCBF),** and the **mean transit time (MTT)** in the brain , perfusion imaging for tumor analysis in the female breast , and perfusion imaging in cardiac imaging for rest and stress studies .
- Echo planar imaging with a gradient echo sequence is one of the sequences that are fast enough and sensitive to T2*.
- An indication for performing cerebral perfusion imaging is the diagnosis of regions affected by a stroke.
- Diffusion imaging can demonstrate the central effect of a stroke on the brain, whereas perfusion imaging visualizes the larger “second ring” delineating blood flow and blood volume.

Diffusion Imaging



- Measuring the diffusion coefficient of isotropic diffusion is called **diffusion imaging** .
- A change of the value of the diffusion coefficient may indicate, for instance, the breakdown of cells in the brain after a stroke.
- **Diffusion tensor imaging (DTI)** relates to the measurement of a tensor that describes anisotropic diffusion.
- The knowledge of local fiber direction from DTI is used for **fiber tracking** in the brain , which—together with fMRI—may be used to infer configuration of regions of different brain functions.
- Reconstructing connections between different brain regions using fiber tracking is known as **MR tractography.** The result of a reconstruction of all connections between brain regions is part of the **connectome** of the human brain. Integrating information about the connectomes of different subjects in the attempt to analyze generic building blocks of humans is known as **connectionism**.

Image Analysis on Magnetic Resonance Images

- There are a number of parallels between MRI and X-ray CT such as the reconstruction of a true 3d volume with good spatial resolution. **Many analysis methods being developed for X-ray CT are in principle appropriate for analysis and measurement in MR as well**. There are differences:
- The much **better contrast for soft tissue** enables separation of soft tissues by means of the reconstructed image intensity. However, there is no standardization of the image intensity with respect to the entity which has been measured.
- A T2-weighted image may look different depending on the kind of sequence used, on the type of scanner, and on measurement parameters such as repetition time or echo time.
- Artifacts from shading in a study with known acquisition parameters hinder defining a mapping between tissue type and image brightness within this study.
- Noise in MR imaging can be a problem if an analysis tool requires the mapping of a tissue type to a small range of brightness values, such as in direct volume rendering visualization or in threshold segmentation.
- Local homogeneity is not given if the size of image details reaches the limits of spatial resolution.
- Accidental removal of such details by noise reduction is critical in MRI, since detection of small objects is often an objective of applying MRI because of its good soft tissue contrast.

Ultrasound

- Sound waves will be reflected at boundaries between materials of different acoustic impedance. An ultrasound wave sent into the human body will be reflected at organ boundaries.
- The locus of reflection can be reconstructed if the speed of sound in the material through which the wave travels is known (Szabo 2004). For most soft tissues this speed is around 1500 m/s.
- An ultrasound reflection signal is created using a transducer which acts as sender and receiver of ultrasound waves.
- Frequencies for diagnostic ultrasound range between **1 and 20 MHz.**
- High frequency waves attenuate faster than low-frequency waves and do not penetrate the body as good as low-frequency waves.

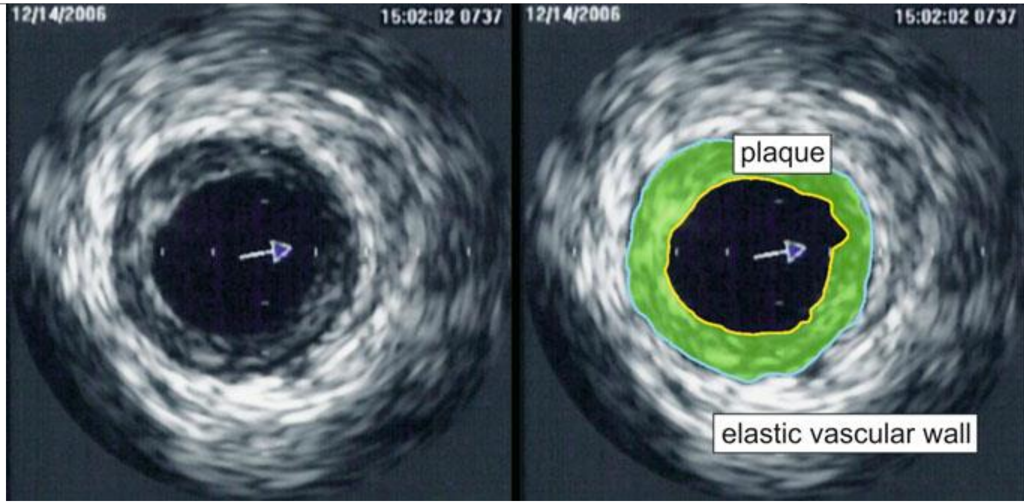
Ultrasound

- An **ultrasound A-scan** sends a **single wave** with known direction into the body and records the amplitude of reflections as a function of travel time between sending and receiving the signal.
- It is a one-dimensional probe into the body showing tissue boundaries and other boundaries between regions with different acoustic impedance.
- **Ultrasound (US) images (so-called B-scans**) are created from a planar fan beam of differently rotated A-scans.
- Amplitudes are mapped to gray values for creating the image. They may also be acquired as 3d images with this fan beam rotating around a second axis perpendicular to the first axis of rotation.

Ultrasound B-scan of the abdomen

Ultrasound Imaging

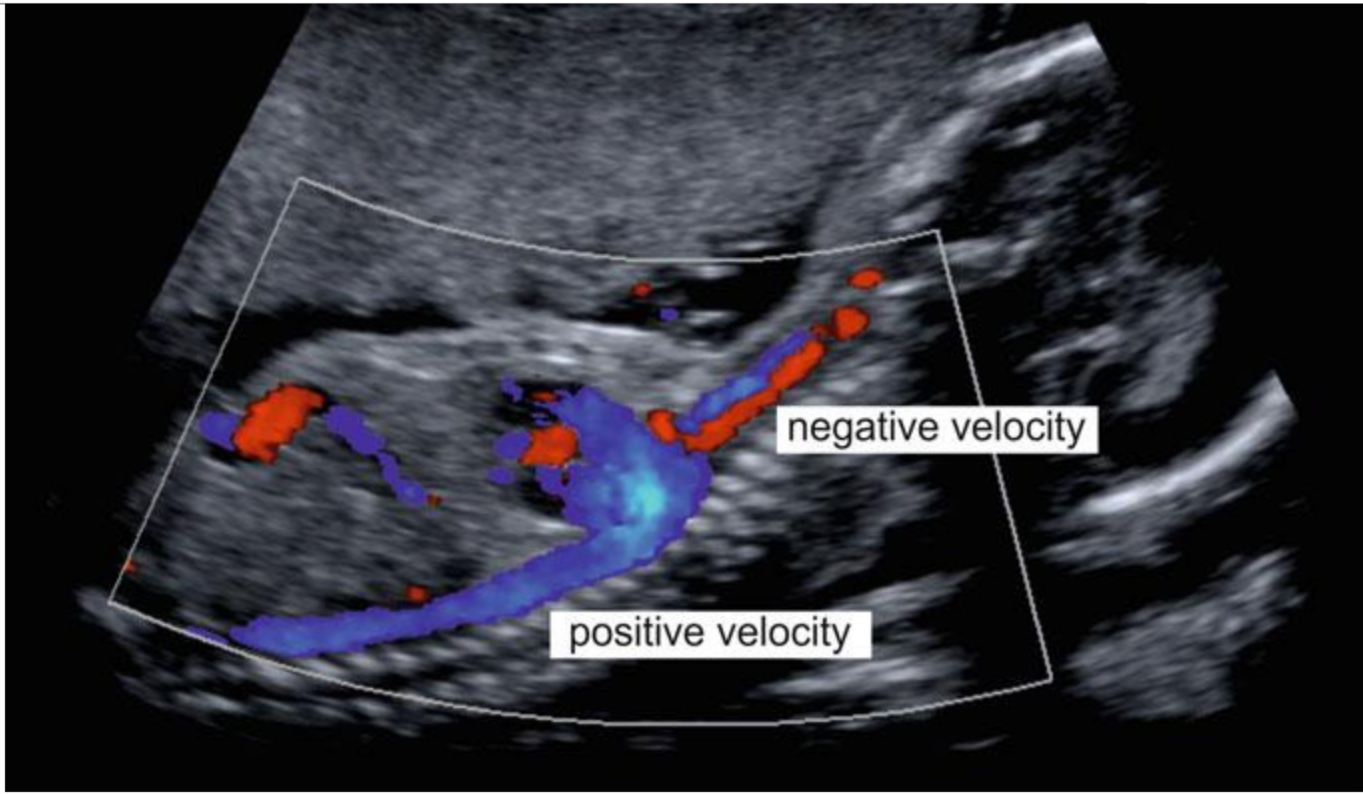
- Ultrasound imaging (also called **sonography**) happens in real time and is able to show motion of the organs being imaged. Ultrasound imaging of internal organs is only possible if they are not hidden by bone, since bone causes total reflection of incident sound waves.
- Organs to be imaged include **liver, gallbladder, pancreas, kidneys, spleen, heart, and uterus**.
- Heart imaging may also be carried out by putting the ultrasound device (a transducer sending and receiving sound waves) into the esophagus.
- Similarly, in **transrectal ultrasound (TRUS) imaging**, the device is placed into the rectum for imaging the prostate.
- **Intravascular ultrasound (IVUS)** is another technique for imaging organs from within. In this case, the ultrasound device is mounted on a catheter that is inserted into the artery for imaging and quantifying calcifications



Intravascular ultrasound image of the carotid artery clearly shows a difference between the elastic vascular wall and the plaque

Doppler imaging

- Doppler imaging is a specific technique using the **Doppler effect** for estimating the speed and direction of moving objects (such as blood) in the ultrasound image.
- It is used for **diagnosing effects of vessel blockages or changes of blood flow due to stenosis.**
- Doppler sonography uses the Doppler effect to depict blood velocity.
- The color-coded depiction of velocity differentiates between different flow directions and velocity.



FUS Imaging

- Ultrasound has also been used in **image-guided therapy**. If the sound waves are focused at some point, the energy will increase at this point (**focused ultrasound— FUS).**
- The most obvious application of this effect is the **thermal ablation of tumors**, where FUS is used to overheat tumor cells while leaving the remaining tissue intact.
- Temperature change induced by FUS can be visualized using MRI. If region selection is verified, the tumor cells are destroyed by a short, focused ultrasound impulse. Besides tumor ablation, FUS may also be applied for inducing mechanical effects (e.g., moving stones in the gallbladder) or to stimulate growth.
- FUS has been applied in various body regions (e.g., brain, prostate, abdominal organs), but requires substantial support prior and during the intervention.

Artifacts of US Imaging

A number of effects cause artifacts in an ultrasound image:

- Sound waves are attenuated just as electromagnetic waves in X-ray imaging.
- Absorption turns wave energy into heat.
- The wave may be scattered or refracted.
- Interference and a diverging wave cause further deterioration.

- Absorption causes a decrease in amplitude with increasing depth. The decrease is exponential with an unknown absorption coefficient of the tissue. It is usually corrected by assuming constant absorption throughout the tissue.
- Interference, scatter, and refraction of and between waves lead to the typical speckle artifacts in ultrasound images. It is a non-linear, tissue-dependent distortion of the signal.
- Tissues and tissue boundaries that reflect or attenuate a high amount of the incoming sound energy produce an acoustic shadow behind the tissue. Materials that attenuate little of the incident energy lead to signal enhancement in tissues behind this material.

Image Analysis on Ultrasound Images

- Ultrasound is **noninvasive and inexpensive**. Hence, it is widely used as a diagnostic tool.

- The artifacts, underlying assumptions for imaging may adversely influence measurements in quantitative analysis:
  •Localization in ultrasound imaging assumes that the **speed of sound in the material** is known. It is usually taken as a constant value of average speed of sound in soft tissue and causes signal displacement depending on deviation from average.

- • Refraction which has not been accounted for may lead to a further displacement error.

- • Organ boundaries may cause mirror echoes or multiple echoes which appear as false boundaries in the image. Mirror echoes appear behind the true boundary.

- Multiple echoes appear between transducer and boundary.

- • False, hyperbola-shaped boundaries may be caused by low-frequency lateral oscillation of the sound wave.

- • Motion artifacts lead to wave-like distortions of boundaries.

- • Acoustic shadowing may hide parts of tissues, and fluid-induced signal enhancement may lead to a position-dependent signal increase.

- • Absorption decreases the signal-to-noise ratio with respect to the distance from the transducer.

Nuclear Imaging

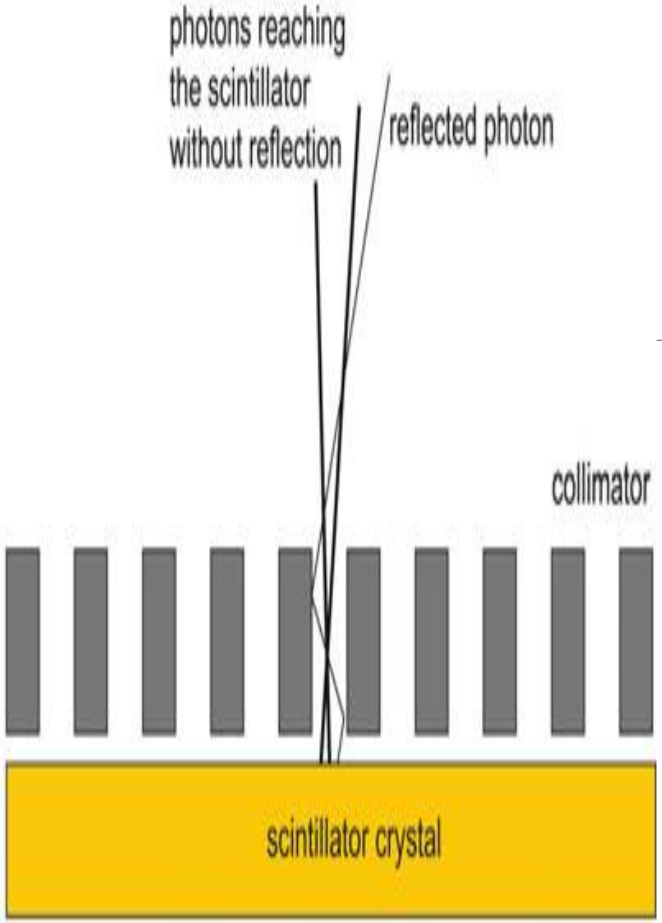
- Nuclear imaging measures the distribution of a radioactive tracer material and produces images of function in the human body.
- The tracer material is injected intravenously prior to image acquisition and will distribute through blood circulation.
- Distribution is indicative to perfusion of organs in the body.
- Examples for applications are measurements of brain activity, perfusion studies of the heart, diagnosis of inflammations due to arthritis and rheumatism, or the detection of tumor metastases due to increased blood circulation.
- Images are created from measuring photons sent by the tracer material through the body.
- Spatial resolution in nuclear imaging is lower than for the procedures described above, since tracer concentration is very low as to not to interfere with the metabolism.
- Sensitivity of imaging techniques in nuclear medicine is high, since detectors are able to measure a signal from few photons.

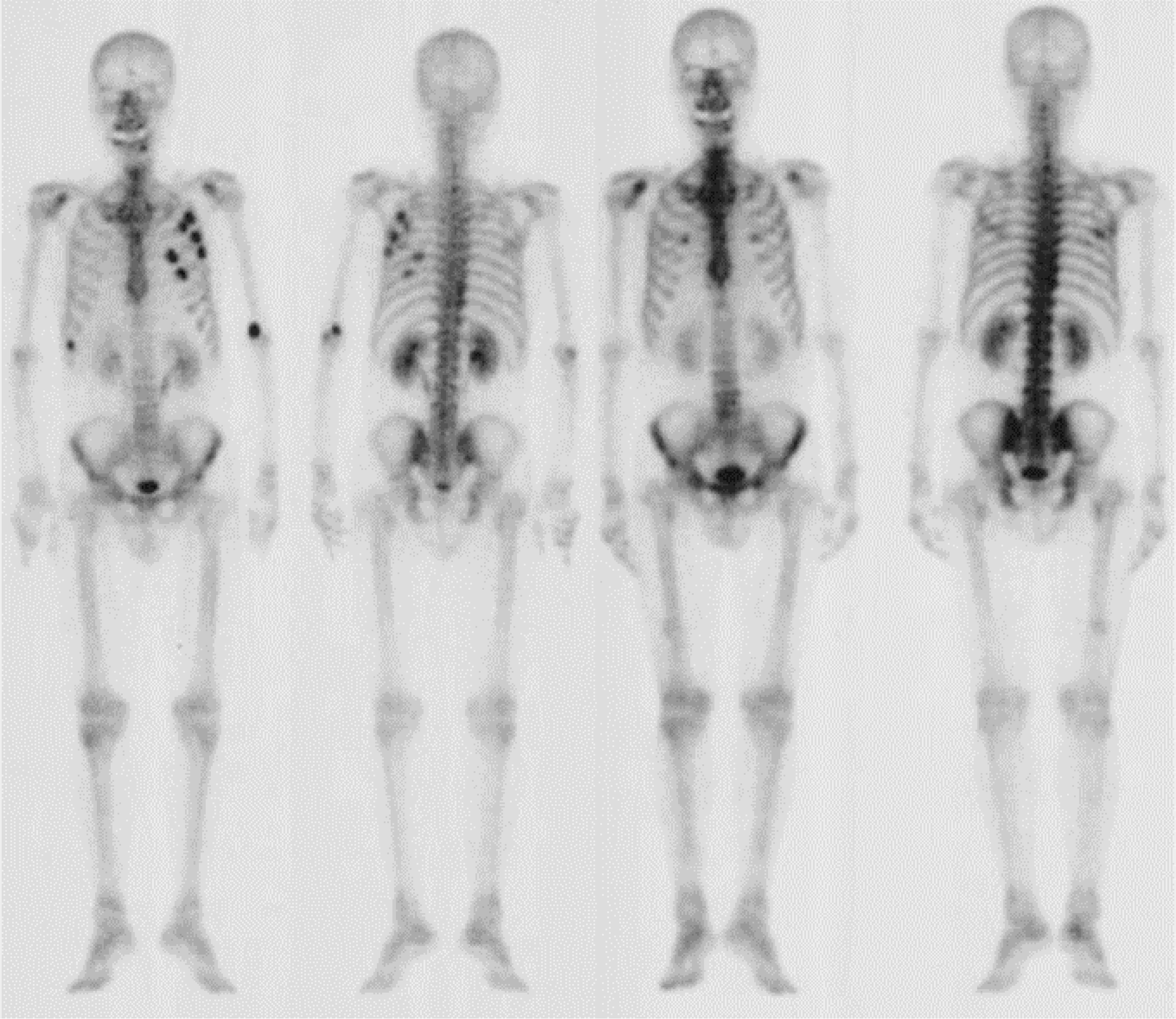
Major imaging techniques

- Major imaging techniques in nuclear medicine are as follows:
- • **Scintigraphy,** which measures a projection of tracer distribution with a geometry similar to projection X-ray imaging.
- • **SPECT (Single Photon Emission Computed Tomography)**, which is a reconstruction from projections of tracer material producing a 3d material distribution.
- • **PET (Positron Emission Tomography),** which is a tomographic technique as well but uses a different tracer materials that produce **positrons**. Radiation of positron–electron annihilation is measured and reconstructed.

Scintigraphy

- For creating a scintigram, a molecule carrying the radioactive atom 99Tc (Technetium-99) is applied.
- Photons emitted by tracer radiation are measured by a gamma camera [also written as c-camera and sometimes called Anger camera].
- The camera consists of a collimator that restricts measurements of photons to those who hit the detector approximately at a 90° angle, a scintillator crystal that turns incident radiation into visible light, and photomultipliers for amplifying the signal.
- Collimator causes the image to be an approximate parallel projection of photons from tracer material in the body onto the image.
- Collimator characteristics limit the spatial resolution and contrast of the scintigram.



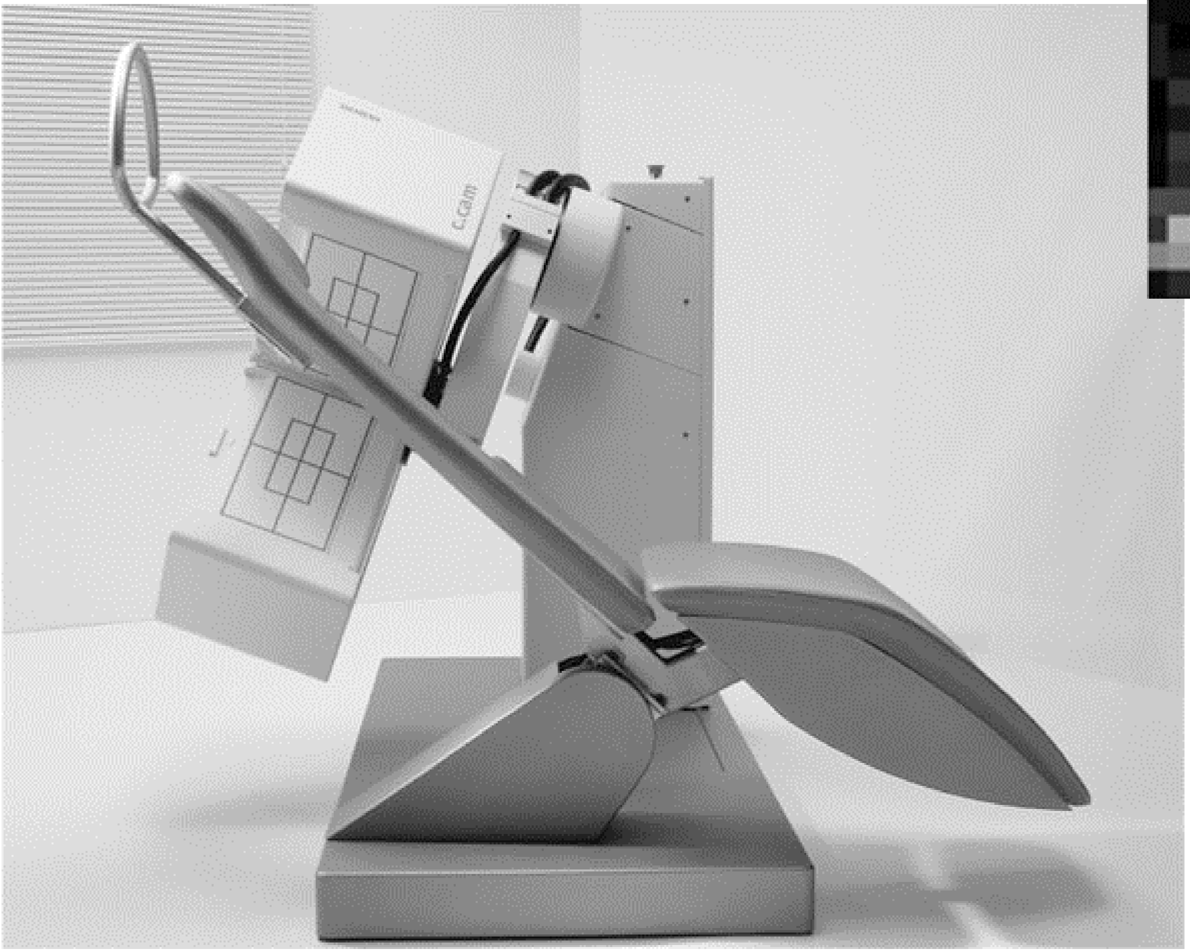


Bone scintigraphy (in this case a before- and after-treatment bone scintigraphy

Single Photon Emission Computed Tomography (SPECT)

- SPECT uses projection images from the gamma camera in order to create an image of the radioactive tracer distribution.
- Images without attenuation correction can be reconstructed by FBP yielding a spatial resolution of approximately 3–6 mm side length of a pixel. Image sizes vary between 64* 64 and 128 * 128 voxels per slice with 25–35 slices to be reconstructed.
- Acquisition of SPECT images can be carried out by a single rotating gamma camera. However, modern systems use **3-head cameras** for capturing three projections at a time.
- Acquisition time for a single projection is about 15–20 s which amounts, for a 3-head system, to total acquisition times between 5 and 10 min.
- **Scatter in SPECT decreases contrast and causes noise in the image**.
- Artifacts due to motion during image acquisition cause blurring of the data.
- Major application fields for SPECT imaging are imaging of ventricular perfusion and ejection fraction of the heart, scans of lungs, kidneys, liver, and bone for tumor detection, and brain perfusion studies.

Two-plane SPECT imaging system used in cardiac imaging



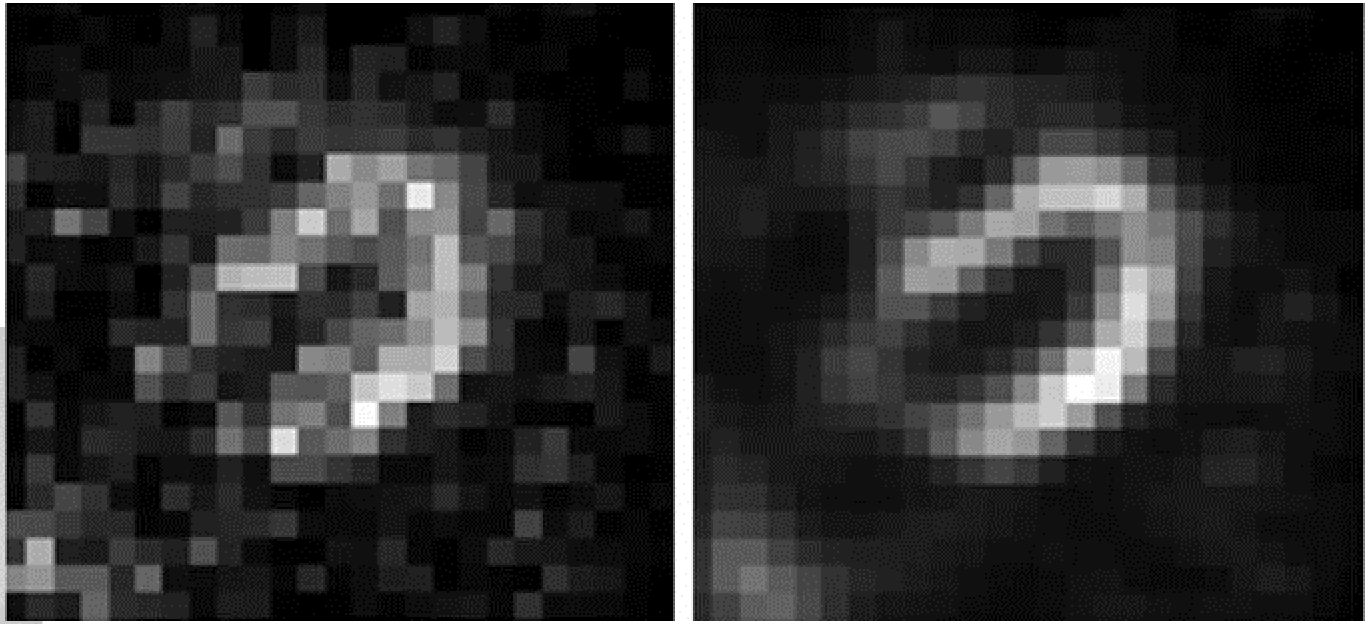
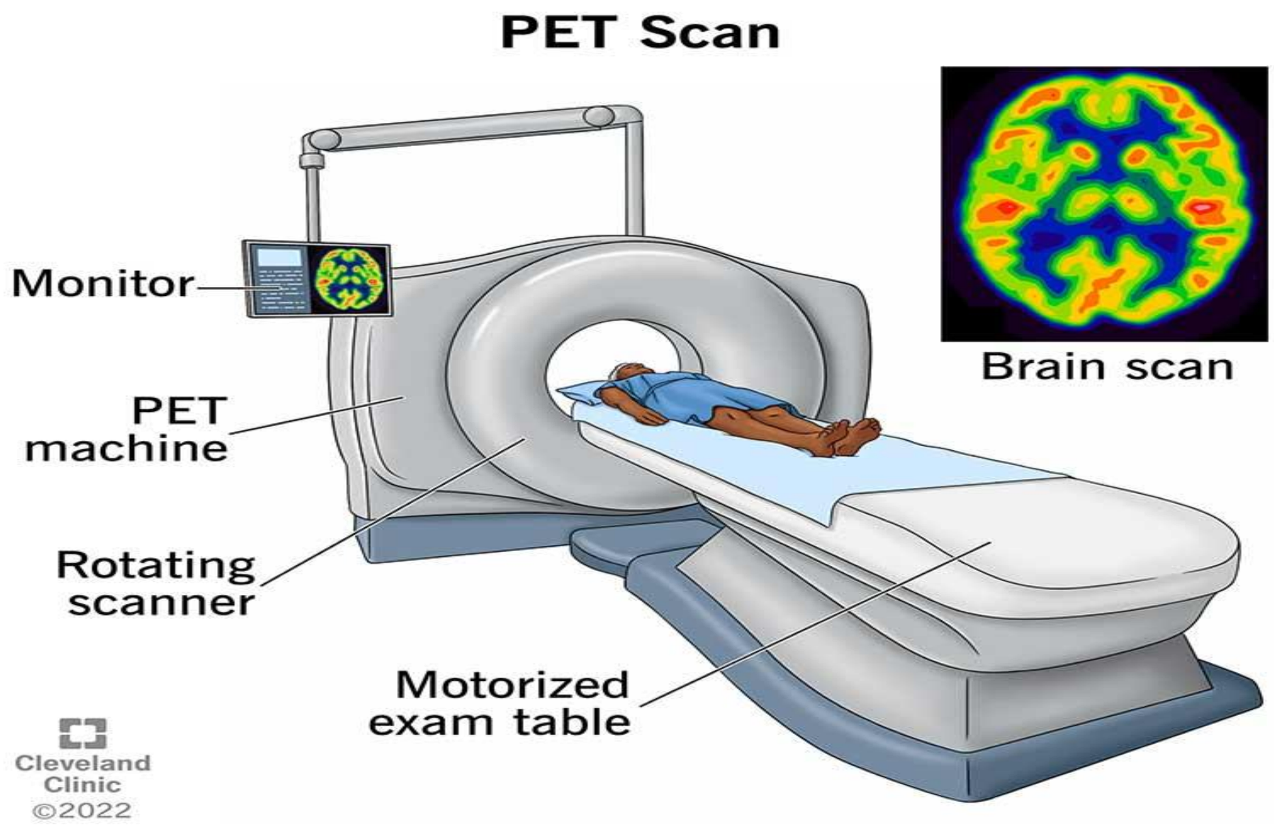


Fig. 2.47 SPECT image of the left ventricle. The two images are not smoothed in order to reveal their true spatial resolution. The left image was reconstructed without, and the image on the right with attenuation correction

Positron Emission Tomography (PET)

- PET uses positron emitters for producing the image .Radioactive isotopes of atoms such as oxygen or fluoride emitting positrons are administered to the human body.
- If distributed in the body, emanating positrons annihilate if they meet an electron and produce two photons that are emitted in near-opposite direction. Photon energy is 511 keV. Events are measured by a detector ring and do not require collimators.
- An annihilation event is registered if two photons are detected at nearly the same time (within nanoseconds). The event is attributed to a location on a line connecting the two detection sites. This line is called **line of response (LOR).**
- PET is an expensive technique if compared to SPECT because positron-emitting isotopes have a short half-life and need to be generated in a cyclotron in close neighborhood to the PET scanner.
- The scanning technique is demanding requiring a fixed detector ring that is capable of analyzing events according to synchronicity of measurement. Image quality of PET is better than SPECT.
- One of the many uses of functional imaging using PET is to observe brain activity using an oxygen isotope as a tracer.
- applications for PET imaging are the analysis of tumor metabolism in oncology or the tracing of labeled neuro-receptors in psychiatry.


PET Scan
Brain scan
Monitor
PET machine
Rotating scanner
Motorized exam table
Cleveland Clinic
©2022

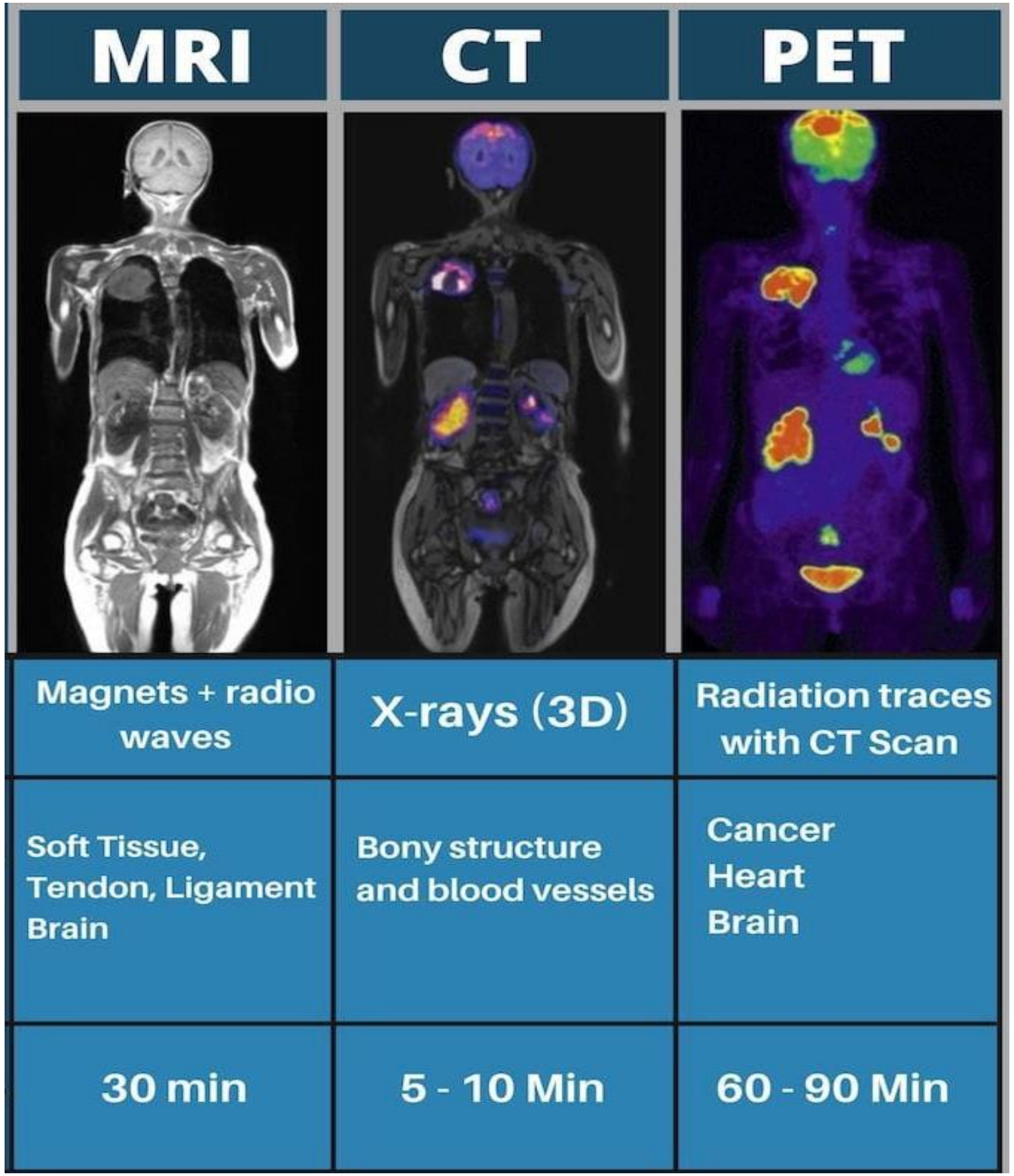

MRI
CT
PET
Magnets + radio waves
X-rays (3D)
Radiation traces with CT Scan
Soft Tissue, Tendon, Ligament Brain
Bony structure and blood vessels
Cancer Heart Brain
30 min
5 - 10 Min
60 - 90 Min

Image Analysis on Nuclear Images

- Images come as projection images as well as slice images.
- Signal strength in the images depends on the amount tracer given and the individual metabolism.
- Quantitative measurements based on intensity are usually a comparison of activity between two regions because the absolute intensity value at some location depends on external factors.
- The image quality, i.e., resolution and signal-to-noise ratio, is poor because of the low number of photons contributing to an image and because of restrictions from image acquisition.
- Analysis often requires correlating the functional signal with anatomy.

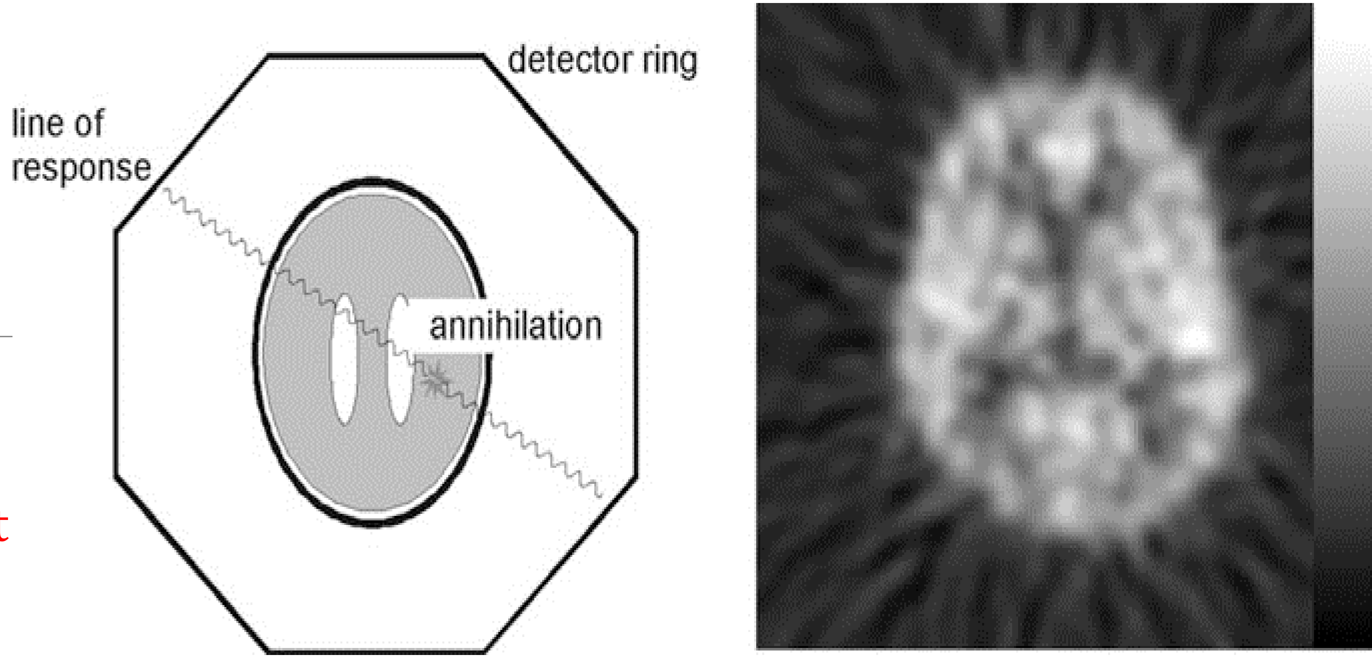


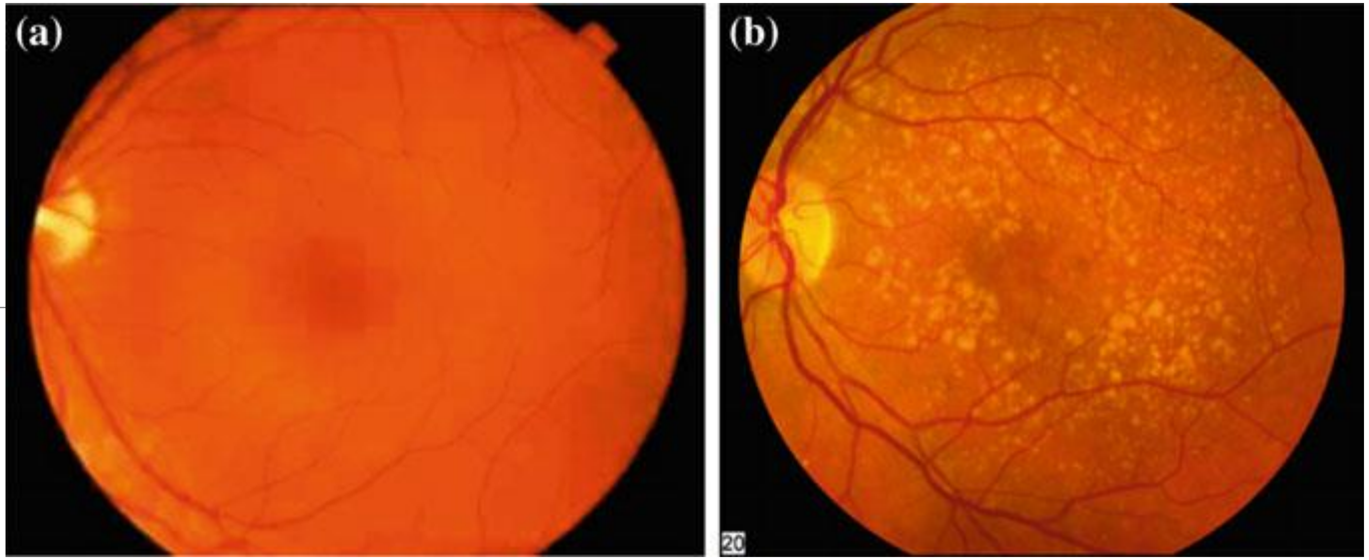
Fig. 2.48 Schematic view of a PET scanner (left) and resulting image of measured activity in the brain

Other Imaging Techniques

- quite common in clinical practice— are not often subject to image analysis methods. Reasons are that at present most of them are diagnosed quite satisfactorily by inspection by a human expert.
- **Optical Coherence Tomography:** The principle of optical coherence tomography (OCT) bears similarities to ultrasound imaging.
- **A light wave (and not a sound wave) is sent into the probe, and reflections in the tissue are measured.**
- Instead of the time delay (as in ultrasound), OCT uses the interference between the reflected wave and a wave reflected before the probe as measure to find the depth of reflection.
- The wave is generated by amplitude modification. The phase difference allows computing the depth for all depth differences smaller than the wavelength.
- One of the main applications of OCT is ophthalmology, e.g., for analyzing the optic nerve and the retinal nerve fiber layer.
- Another application field is dermatology. OCT imaging enables assessment of inflammatory and bullous skin diseases and differential diagnosis for some tumors.

Photography

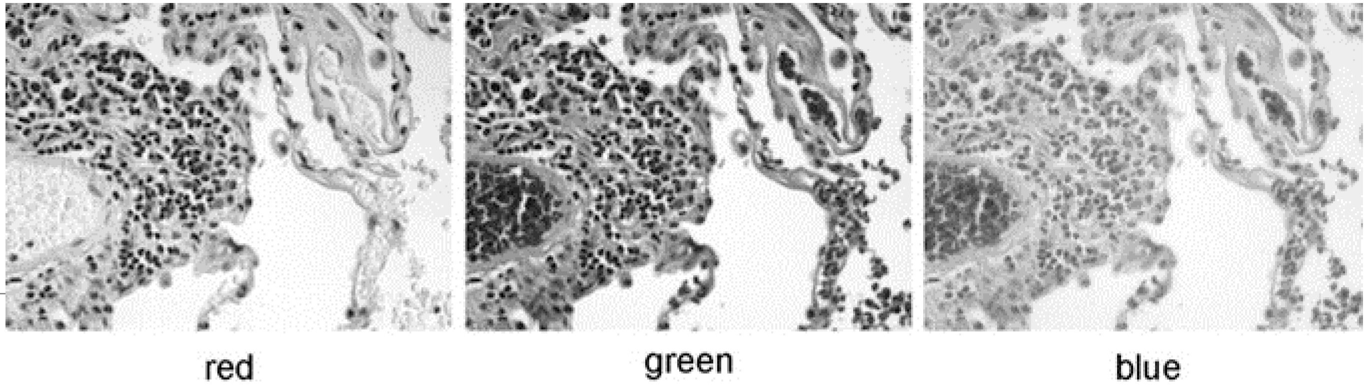
- An example for diagnosis using photography is the depiction of vascular processes in retina photography
- The retina is the only location in the human body where vessels are visible on the surface.
- Another application is the diagnosis and staging of skin tumors or burn scars .
- A photographic image is a projection of some opaque surface, so that similar rules with respect to measurement and analysis apply as for X-ray projection images.
- Digital photographs are usually high-quality and high-resolution color images.

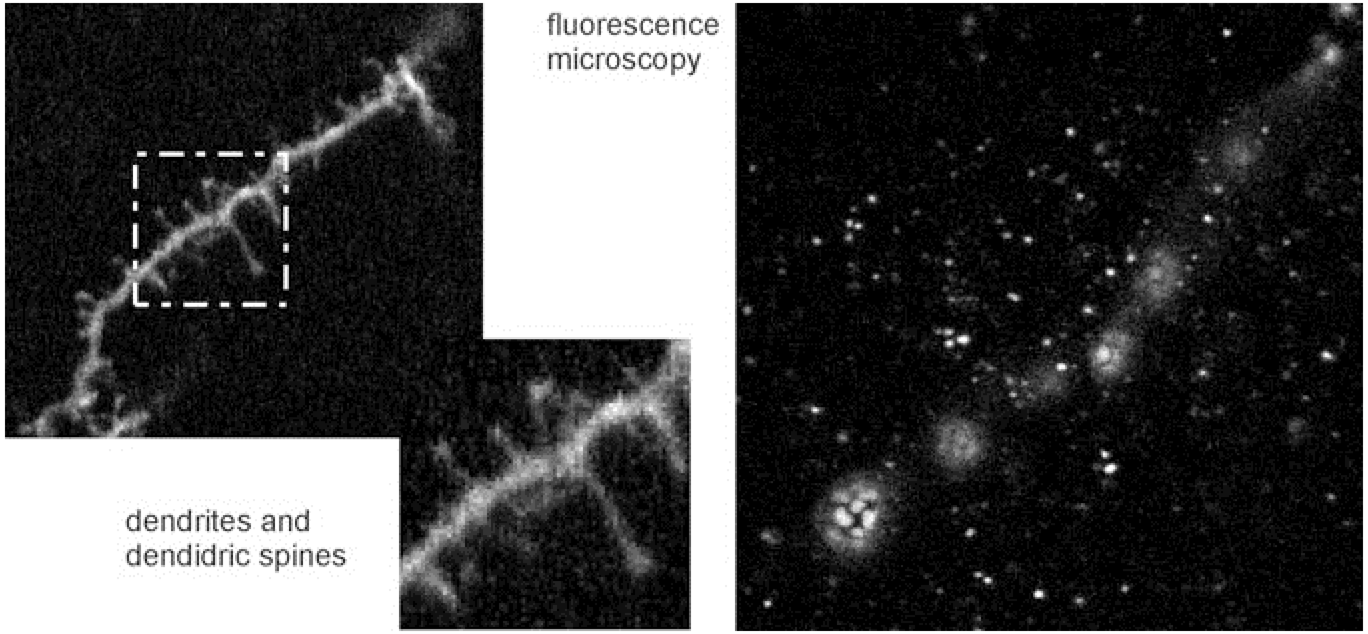


Examples of retina photography (in the printed version, color of the original images has been mapped to gray levels): a retina of a normal and b degeneration of the macula

Optical Microscopy

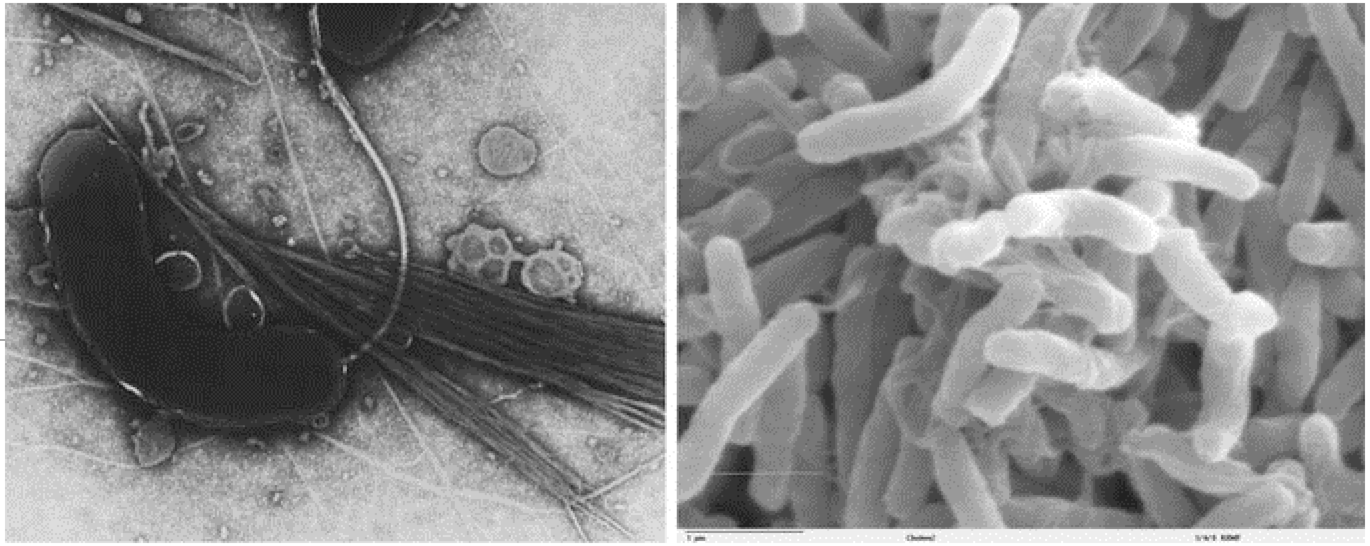
- Optical microscopes in medical imaging are able to analyze living structures of sizes larger than approximately 200 nm.
- Microscopic images are often used for diagnosis of pathology in tissue specimen on the cell level.
- Images are color images or gray-level images with good contrast and signal-to-noise ratio.
- A variant of cell microscopy is fluorescence microscopy. Instead of using reflection and absorption, the signal is generated by the fluorescence response of the living material to incident laser light.
- Microscopic images are good quality high- to very high-resolution images, may suffer from blurring due to defocusing.





Electron Microscopy

- Electron microscopy uses the detection of electrons instead of light for image acquisition.
- Since their wavelength is much smaller than that of light, the achievable resolution is substantially higher.
- The first electron microscopes produced transmission images (transmission electron microscopy—TEM) where a beam of electrons is transmitted through an ultrathin specimen, interacting with the specimen as it passes through it.
- Scanning electron microscopy (SEM) produces images of a sample by scanning it with a focused beam of electrons.



Transmission (left) and scanning (right) electron microscopies of cholera bacteriae. The resolution of the TEM is much higher than that of the SEM showing a single bacterium, whereas numerous bacteriae are depicted in the SEM.

EEG and MEG

- For creating an electroencephalogram (EEG), a number of electrodes (16–25) are placed on the scalp to detect electrical impulses caused by brain activity.
- The impulses are amplified and represent an array of brain activity curves indicating function of the human brain.
- Brain activity happens in gray matter, which—for the most part—is close to the scalp.
- Hence, EEG provides a brain map of functional Activity.
- A magnetoencephalogram (MEG) measures a similar effect than EEG through the magnetic field of neural brain activity

An EEG consists of a set of time signals that are acquired from different locations on the head surface.