Medical Imaging Modalities

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Outline

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2. Introduction
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Motivation

- The most direct (and invasive) way to see inside the human body is cut it open, that is, to carry out a surgical procedure (surgery).
- With medical imaging methods, we can see inside the human body in ways that are less invasive (or completely non-invasive).
- We can even see metabolic/functional/molecular activities which are not visible to the naked eye.

Goals

- Understanding sources of digital images in 3D medical imaging.
- Analisys of parameters in medical imaging and their counterpart in digital images.
- Advantages and disadvantages of each medical imaging modality.

Medical imaging applications

- Medical image data are used for different processes (or procedures), mainly clinical analysis and medical intervention (surgery):
  - Diagnosis
  - Therapy planning
  - Intraoperative navigation
  - Postoperative monitoring

Computed Tomography (CT)

- Computed Tomography (CT or CAT) combines multiple X-ray projections taken from different angles to produce **cross-sectional images** of areas inside the body. CT is used to evaluate different situations such as:
- Presence, location and size of tumors.
- Colon health (CT colongraphy).
- Pulmonary embolism and aortic aneurysms (CT angiography).

Magnetic Resonance Imaging (MRI)

- MRI uses radio waves and a magnetic field to create detailed images of organs and tissues. Very useful for diagnosis because it shows very effectively the differences between normal and diseased soft tissue. MRI is often used to evaluate:
- Blood vessels.
- Abnormal tissue.
- Breasts.
- Tendon and ligament tears.

Positron Emission Tomography (PET)

- PET is a nuclear imaging technique that provides physicians information about how tissues and organs are **functioning** and it is often used to evaluate:
- Neurological diseases such as Alzheimer and Multiple Sclerosis Cancer.
- Heart conditions.

Ultrasound

- Ultrasound uses high frequency sound waves to create images of the inside of the body by sending these waves and registering the returned echoes as images. It is often used to evaluate:
- Pregnancy.
- Abnormalities in the heart and blood vessels.

X-ray

- X-ray is the oldest and most commonly used form of medical imaging. X-ray modality sends X-ray beams through the body, which are absorbed in different amounts depending on the density of the material. X-ray are used form multiple situations such as:
- Broken bones.
- Location of swallowed objects.
- Lungs and blood vessels.

Medical imaging modalities we will use

(a) Computed Tomography (CT) example.

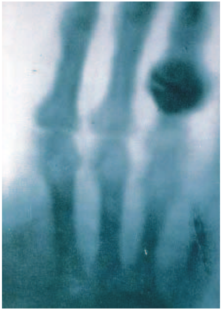
(b) Magnetic Resonance Imaging (MRI) example.

X-ray imaging. Introduction

- The discovery of X-rays by Wilhelm Konrad Röntgen in 1895 was the birth of medical imaging.
- This revolutionary tool "allows the doctors to visualize the body without surgery", hence interior parts of a body could be seen without actually cutting into it.
- X-ray images can show different intensity codifications, due to different recording techniques.

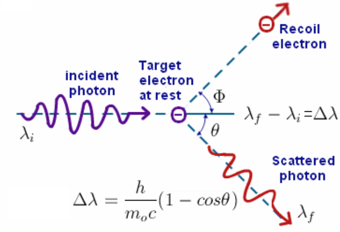
X-ray imaging. Introduction

- In the left image, low densities (e.g., air) are mapped to white, and high densities (e.g., bone) are mapped to dark.
- In contrast, the right image shows high densities in white, and low densities in black.



X-ray imaging. Physical phenomenon

- X-ray images are based on the attenuation of **X-ray quanta** travelling through the scanned object.
- The attenuation is based on two processes:
    - X-ray quanta are **absorbed** by the object that is hit.
    - X-ray quanta are **scattered** due to the so-called **Compton effect**.
- The Compton effect occurs between arriving photons and electrons at an atom, and actually **limits the contrast** and quality of X-ray images.



X-ray imaging. Physical phenomenon

- The absorption depends on the denser the current part of that object is and the thickness of the object to be passed.
- The X-ray quanta are generated by electrons accelerated through an electric field. When these electrons hit the target material (the anode), the kinetic energy is transformed into heat (approximately 99%) and X-ray quanta.
- The target material is often tungsten, which exhibits characteristic X-ray energies that are appropriate for imaging bones.
- For other applications such as mammography, where soft tissue is imaged, other target materials are required, for example molybdenum.

X-ray imaging. X-ray types

- The speed (and hence the energy) of the electrons depends on the strength of the electric field that accelerates the electrons.
- If the generating voltage is larger than 100 kV, we speak of **hard beam X-rays**; otherwise, we speak of **soft beam X-rays**.
- If **hard beam X-rays** are used to generate X-ray quanta, the **scattering effect** dominates the interaction with the object and the quanta are only **absorbed in very dense material**.
- In medical imaging, this is exploited for the representation of **bone structures**.

X-ray imaging. X-ray types

- **Soft beam X-rays** result predominately in **absorption**; hence, this can be used for the representation of **soft tissue**.
- This technique, however, results in more energy intake by the tissue itself, which in turn leads to more tissue damage.
- Therefore, soft beam X-rays are more harmful than hard beam X-rays.

X-ray imaging. Density as brightness

- A film behind the patient **records the X-ray attenuation**.
- The varying brightness of the film is a result of the interactions of X-rays with the different tissue types that have been passed.
- Tissue types that absorb a large fraction of X-ray intensity lead to a low density of radiographs and appear bright.
- Skeletal structures exhibit the highest absorption rates and are therefore the brightest structures.

X-ray imaging. Model of Intensity decay

- The resulting intensity I depends on the thickness of the material that is passed, as well as on a coefficient μ that characterizes the attenuation S.
- The initial intensity I_0 drops exponentially with increasing distance d.

$$I(d) = I_0 \cdot e^{-\mu d} \tag{1}$$

- The product $\mu \cdot d$ characterizes the attenuation S.

X-ray imaging. Model of Intensity decay

- When X-ray imaging is used, different tissue types are involved, which leads to the approximation of the attenuation S as a sum of different materials with individual attenuation coefficients μ_i and a certain distance d_i.

$$S = \sum_i \mu_i \cdot d_i \tag{2}$$

- **Note**: The elements (pixels) of an X-ray image characterize the whole pass of the radiation through the body and produce a weighted average value of X-ray attenuation, therefore merely the silhouettes of objects and structures are recognizable.

X-ray imaging. Model of Intensity decay

- Since individual X-ray images cannot be used to accurately localize structures, as a consequence, X-ray images are often generated in two different imaging planes.

X-ray imaging flavours

- Images generated by X-rays are typically provided as digital image data. The necessary digitalization can basically be achieved in two ways.
  - If they are recorded on film material, they need to be scanned afterwards ("**computed radiographs**").
  - The X-ray images can be directly recorded digitally by a detector array ("**direct radiograph**").

X-ray imaging. Digital Mammography

- A special example of digital X-ray images is digital mammography, where digital X-ray images of the female breast are acquired.
- It is often essential to compare the current mammography (from two viewing angles) with previous images to evaluate the progress of suspicious regions over time.
- Mammography images can be processed computationally to improve their interpretation. Be carefull with the specialist.
- A problem of mammography is that it requires soft beam X-rays, which in turn increase the potential tissue damage of the patient.

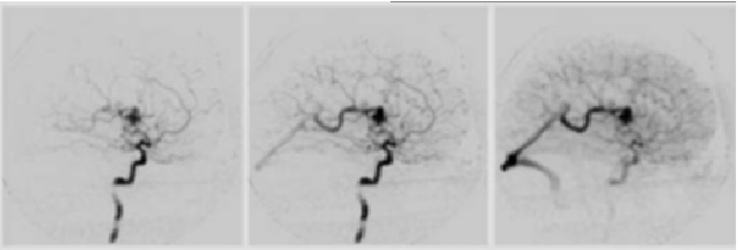
X-ray imaging. Angiography

- Angiography is an imaging technique in which an X-ray picture is acquired **to display the inner open space of blood-filled structures**.
- The resulting X-ray image is called an **angiogram**.
- Angiography is employed to depict arteries; the most widespread applications are:
  - **Cerebral angiography**. Depiction of blood vessels inside the brain.
  - **Coronary angiography**. Depiction of the coronary vessels around the heart.

X-ray imaging. Digital Subtraction Angiography

- **DSA** tracks the blood flow through contrast agent for obtaining an enhanced imaging.
- In order to maximize the representation of the blood vessels, a “mask image” of the object before injecting the contrast agent is taken.
- During the contrast-enhanced phase, this mask image is subtracted from acquired images, thus leaving only the changing parts of the images, which in case of a DSA is typically a blood vessel tree.

X-ray imaging. Digital Subtraction Angiography



X-ray imaging. Rotational X-ray

- Rotational X-ray is based on DSA. Hence, most of the associated applications are angiography applications (**rotational angiography**).
- Rotational X-ray acquires a series of X-ray images while rotating around the subject to be scanned.
- To generate volumetric datasets, a series of up to 132 X-ray projections are taken from a rotation range of 200 degrees around the scanning object.
- In contrast to CT, rotational X-ray is using a full array of up to 1024^2 detectors, which allow the measurement of a full cone of rays.

X-ray imaging. Rotational Angiography

- Very high resolution
- Isotropic datasets
- Good reconstruction quality (for selected organs, such as bones and contrast agent enhanced blood vessels)
- A high data acquisition speed of up to 13 seconds for a full scan.

Computed Tomography. Introduction

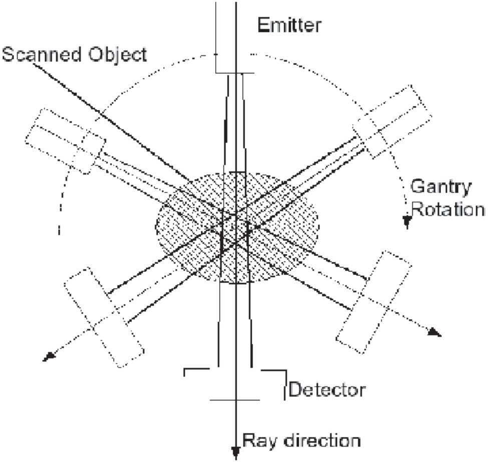
- The introduction of **X-ray computed tomography** (CT) in 1968 by Godfrey Hounsfield provided for the first time a **volumetric representation of objects**.
- CT data represents a series of individual X-ray images that are composed into one volume dataset.
- These X-ray images are acquired by an emitter/detector system that rotates around the object to be scanned.
- Each X-ray image represents an intensity profile measured by the detectors.

Computed Tomography. Introduction

- From the intensity profiles of a full rotation, the **slice image** of the scanned object is computed based on the **Radon transform**, which essentially is based on the **Fourier theorem**.
- Afterward, the table on which the scanned object is positioned will be moved forward and the **next image slice** of the object will be acquired.

Computed Tomography. Introduction

- Illustration of how computed tomography works



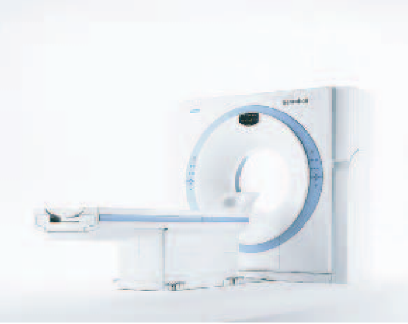
Computed Tomography vs. X-ray

Localization of anatomical structures. While X-ray images superimpose the X-ray absorption values of many tissues along a ray, CT records X-ray attenuation for small volume elements independently.

Sensitivity. X-ray images are not able to distinguish different soft tissues such as liver (hígado) and pancreas, whereas CT image data discriminate these tissues. The contrast between soft tissues, however, is small with CT data. Better soft tissue contrast is achieved with MRI data.

Quantitative measurements. Since the X-ray absorption is computed with high accuracy for individual volume elements, it is possible to analyze CT data quantitatively (e.g., osteoporosis).

Computed Tomography. Machine and example image



Principle of CT data generation

- The major differences are different **projection reconstruction algorithms** and the **emitter and detector architecture** (data acquisition).
- The first commercial generation of CT scanners used small angle fan beams and multiple detectors to scan two neighboring rotational projections at the same time.
- The required scanning time needed for a sufficient reconstruction is 10 to 60 seconds, up to several minutes per slice.
- The radiation was emitted at fixed time intervals and was measured by the detectors.

Principle of CT data generation

- The next improvement increased the fan beam angle and the number of detectors to cover the whole object, thus the translating movement became unnecessary and reduced the scanning time to about five seconds per slice.
- Currently, the state-of-the-art systems are **spiral or helical CT**, where the emitter/detector system rotates permanently around the object, while the object is moving continuously in a perpendicular direction to acquire a full data volume.

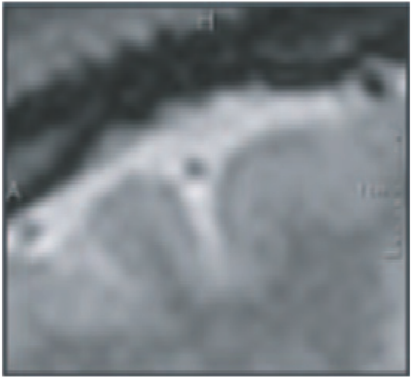
Parameters of CT scanning

- Datasets acquired by a CT scanner can be described by their **spatial resolution**, composed of the **number of slices**, the **number of pixels per slice**, and the **voxel distances**.
- **Note**: The typical definition of resolution only describes how much detail can be represented in an image (or volume). In medical imaging, resolution also includes the **voxel distance** and therefore also describes (to some extent) the acquisition accuracy (sampling interval).
- The number of pixels in one slice is also referred to as **image matrix**; an image matrix of 512x512 simply describes an image slice of that resolution.
- If we have a CT dataset with an image matrix of 512x512 and 300 slices, we have a **volume dataset** with the resolution 512x512x300.

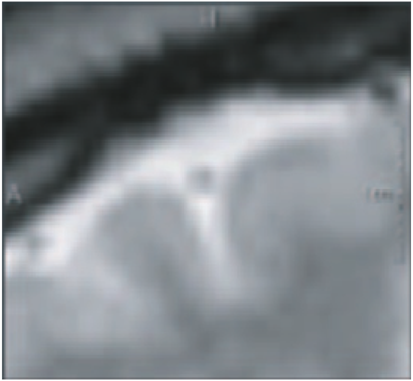
Parameters of CT scanning

- The distances between the voxels are differentiated into the **slice distance** (out-of-plane) and **pixel distance** (in-plane).
- A dataset with a slice distance different than the pixel distance is described as an **anisotropic dataset**, while equal distances constitute an **isotropic dataset**.
- The resolution of the data has an influence on the noise level: data with **higher resolution** are **noisier** if the radiation dose remains the same.
- The dose of radiation also influences the image quality. With a **higher dose of radiation**, a **better signal-to-noise ratio** is achieved.

Parameters of CT scanning



(a) Noisy high resolution image (512x512 matrix).

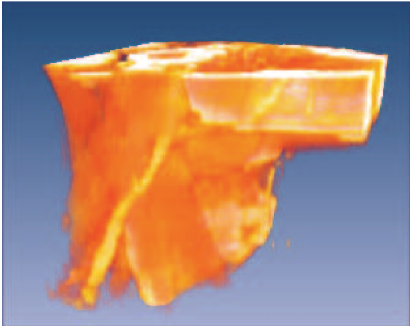


(b) Low resolution image (256x256 matrix).

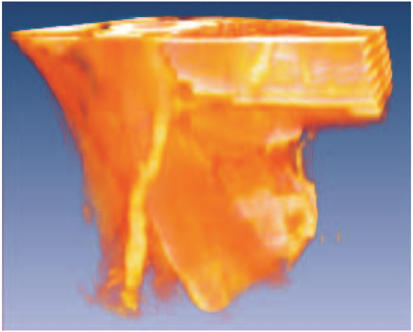
Parameters of CT scanning

- A slice in a volumetric dataset from a scanned resource does not represent an infinitesimally thin data slice; it represents a specific area of the image matrix times the **slice thickness**.
- The rotating emitter/detector system of a CT scanner is called the **gantry**. The **tilt** of the gantry defines also the tilt of the image slices.
- Since most CT datasets are of anisotropic spacing, it can be useful to adapt the gantry tilt to the target organ of an examination, e.g., to ensure optimal sampling of the respective organ structures.
- Therefore, the **gantry tilt** is an additional parameter of CT scanning.

Parameters of CT scanning: Gantry tilt



(a) A gantry tilted dataset.



(b) The same dataset but warped.

Hounsfield Units

- The computed intensity value represents the densities of the scanned object. In medical imaging, these intensity values are normalized into **Hounsfield units** (HUs).
- This normalization maps the data range into a 12-bit range (in fact, packed in 16 bits (2 bytes)), where the intensity of water is mapped to zero and air is mapped to -1000.

$$HU = \frac{\mu - \mu_{H_2O}}{\mu_{H_2O}} \cdot 1000 \tag{3}$$

Hounsfield Units

- The table below lists Hounsfield density values for different organs and tissue types.

Tissue type	Hounsfield value interval
Air	-1000
Lung tissue	$[-900, -170]$
Fat tissue	$[-220, -30]$
Water	0
Pancreas	$[10, 40]$
Liver (hígado)	$[20, 60]$
Heart	$[20, 50]$
Kidney (riñon)	$[30, 50]$
Bones	$[45, 3000]$

Magnetic Resonance Imaging

- Magnetic resonance imaging (**MRI**) is based on different properties of human tissue in a (strong) magnetic field. In particular, the occurrence of **hydrogen nuclei** (just one proton) in human tissue is exploited for image generation.
- They can be considered as small dipole magnets aligning themselves either parallel or anti-parallel along a strong external magnetic field.
- This difference between parallel and anti-parallel results in a **net magnetization**.
- To **measure this magnetization**, a magnetization component perpendicular to the magnetic field must be generated.

Magnetic Resonance Imaging

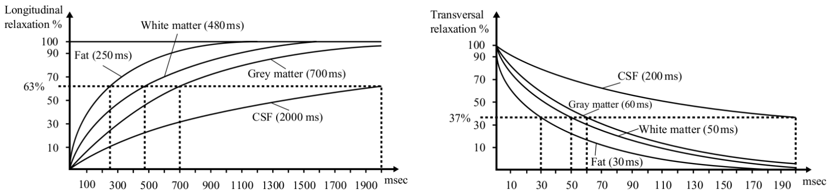
- This pulse forces all the protons to spin synchronously, or in **phase**, and increasingly to flip into the antiparallel orientation of higher energy, until the number of parallel protons is equal to the number of antiparallel oriented protons.
- After the stimulation of the protons, they slowly release the received energy, **dephase**, and realign with the magnetic field.
- The device measures two times: $T1$ and $T2$.

Magnetic Resonance Imaging: $T1$ and $T2$

- The **transversal relaxation** is an exponential decay. The time required for a 63% decay $(1 - 1/e)$ relaxation is called $T2$ and is in the order of a few milliseconds.
- The **longitudinal relaxation** has a logarithmic increase. The time until 63% of the original magnetization is restored is called $T1$ and is in the order of a second.
- $T1$ largely depends on the material (tissue), its structure, and its surrounding tissue. Since water has a long $T1$ and $T2$ relaxation time, tissue that contains a large ratio of water will also have a long $T1$ and $T2$ time.

Magnetic Resonance Imaging: $T1$ and $T2$

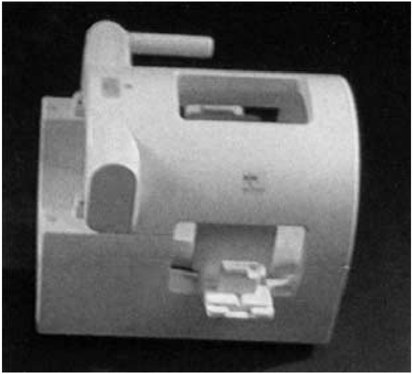
- The actual measured volumetric information is the proton density σ, which needs to be reconstructed at the specific voxels.
- The figure shows the relaxation curve for different brain tissue and the corresponding $T1$ and $T2$. The different times are due to different densities of hydrogen protons in different tissue types; cerebrospinal fluid has the highest water content, at 97%. Gray matter and white matter have, respectively, an 84% and 71% water content.



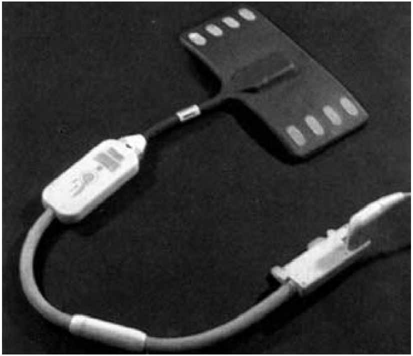
Magnetic Resonance Imaging

- MR imaging is performed in a ring magnet that is large enough to enclose the whole patient.
- Inside this magnet, gradient coils are embedded in such a way that magnetic field gradients in three orthogonal directions (x, y, and z) can be generated.
- The coils used for the MR image acquisition are very different, depending on which body region is to be imaged.

Magnetic Resonance Imaging



(a) A head coil.



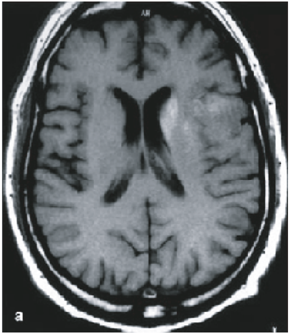
(b) Flexible surface coils.

Parameters of MRI scanning

- The large potential parameter space of MRI leads to a high number of imaging protocols that emphasize different functional or physiological properties of the tissue.
- An MRI examination often contains a variety of five or more different MRI scans.
- As an example of imaging possibilities, we are just going to consider the parameters $T1$ and $T2$.

Parameters of MRI scanning

- The figure compares $T1$- and $T2$-weighted images acquired for neuroradiological diagnosis. While $T1$-weighted acquisition sequences (left) **emphasize tissue signals**, $T2$-weighted acquisition sequences (right) **emphasize fluid signals**.



(a) T1-weighted

(b) T2-weighted

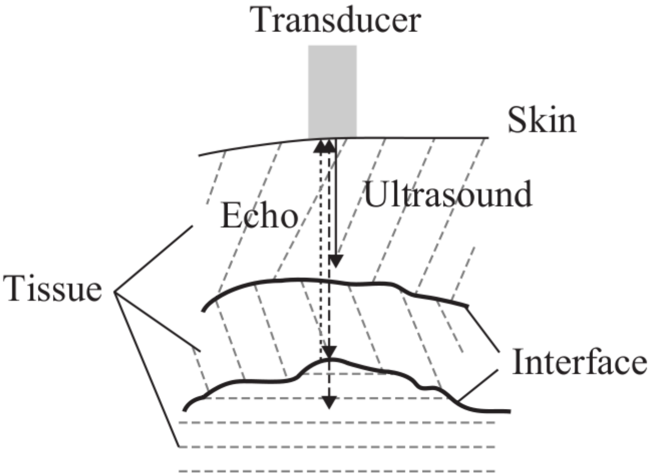
CT vs MRI data

- MRI data, in general, have a lower resolution compared to CT image data (the in-plane resolution/pixel distance is often between 1 and 2 mm, and the slice distance between 2 to 5 mm).
- CT and MRI are rather complementary: MRI—since it depends on a sufficient water content—does not produce a good quality signal for skeletal structures, whereas CT is less appropriate (and sometimes completely insufficient) to discriminate soft tissues.
- Compared to CT data, MRI is able to provide a high soft tissue contrast.
- CT data can often be understood by the referring physician, whereas MRI data are carefully commented upon by radiologists.

Ultrasound

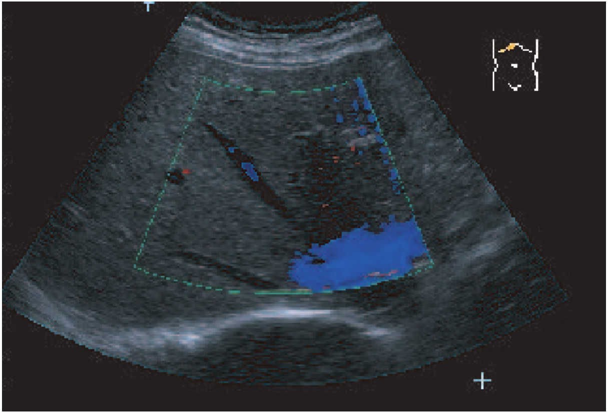
- Ultrasound scanning is based on sound waves emitted at very high frequencies (more than 20 kHz, 1 to 15 MHz) from the ultrasound probe (”transducer”) into the respective body part.
- The waves are partially reflected if they hit an interface between two tissue types.
- The reflected waves are recorded by sensors located next to the sound sources.
- Similar to sonar, the reflections of these sound waves are received by the transducer and used to generate the respective images.

Ultrasound



Ultrasound

- Ultrasound image depicting vessels in the human liver.



3D Ultrasound

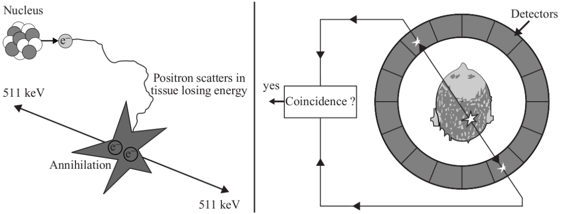
- Some ultrasound scanning devices allow also 3D image acquisition by acquiring and accumulating multiple scans while tracking the movement of the ultrasound probe
- 3D ultrasound is acquired either by a parallel scanner—resulting in axis-aligned images—or by rotation around a swivel (pivot).
- Depending on the chosen acquisition technique, different side effects must be considered; the rotational scan leads to a curvilinear organization of the data, while the parallel scan leads to an average gray value that differs from slice to slice.
- Freehand acquisition of 3D ultrasound data acquires a volumetric dataset that can provide additional views that are not available in 2D. In particular, the latter difference is similar to the difference between CT and X-ray.

Positron Emission Tomography (PET)

- Positron emission tomography (PET) is a nuclear medicine imaging technique. PET scans generate 3D images of functional processes, such as metabolistic activity.
- A short-lived radiopharmaceutical substance (**radiotracer**) is injected and traced throughout the body to its target area. At the target area, the substance is processed by the metabolism and the radioactive isotope decays, which emits positrons.
- If a positron interacts with an electron, it annihilates (destroys completely, which in turn generates two gamma photons (rays) in opposite directions (180 deg). These photons are then measured by the detector array of the PET scanner.

Positron Emission Tomography (PET)

- Principle of PET data acquisition.

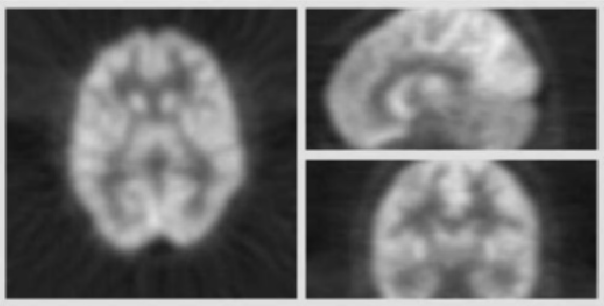


Positron Emission Tomography (PET)

- The spatial resolution of a PET image dataset is significantly lower than CT and MRI data.
- The pixel size equals 1–2 mm for neuroimaging and 2–3 mm for other parts of the body.
- Nuclear medicine images can be superimposed with computed tomography (CT) or magnetic resonance imaging (MRI) to produce special views, a practice known as **image fusion** or **co-registration**.

Positron Emission Tomography (PET)

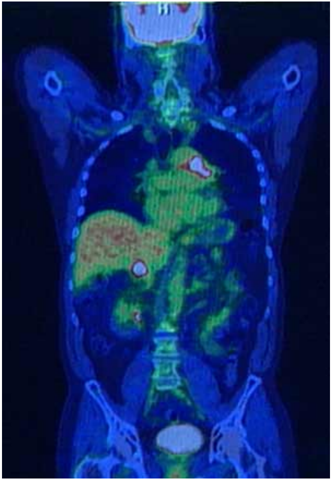
- Orthogonal slices of PET data.



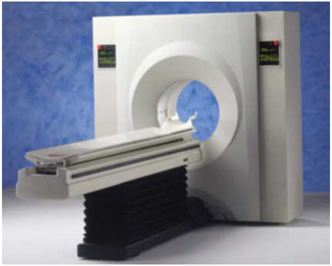
Positron Emission Tomography (PET)

- Due to the low resolution of PET image data, it is often combined with CT or MRI data to enhance the low resolution functional data with high resolution morphological data of the respective body parts.
- This requires the alignment (**registration**) of the generated volumetric datasets. This registration, however, is quite difficult, since the scanned patient has to be moved to another scanner and by the different resolutions of CT/MRI and PET image data
- One of the proposed solutions for this situation is the development of **combined PET/CT scanner** and the recently introduced imaging technology **PET/MRI**.

Positron Emission Tomography (PET)



(a) PET/CT image.



(b) Positron Emission Tomography (PET) equipment.

Single-Photon Emission Computed Tomography (SPECT)

- Single-photon emission computed tomography (SPECT) scanning is based on gamma cameras that acquire multiple images of the 3D distribution of a radiopharmaceutical.
- The technique requires delivery of a gamma-emitting radioisotope (a radionuclide) into the patient, normally through injection into the bloodstream.
- Emissions from the radionuclide indicate amounts of blood flow in the capillaries of the imaged regions. In the same way that a plain X-ray is a 2D view of a 3D structure, the image obtained by a gamma camera is a 2D view of 3D distribution of a radionuclide.

Single-Photon Emission Computed Tomography (SPECT)

- SPECT imaging is performed by using a gamma camera to acquire multiple 2D images (**projections**), from multiple angles. A computer is then used to apply a tomographic reconstruction algorithm to the multiple projections, yielding a 3D dataset.
- To acquire SPECT images, the gamma camera is rotated around the patient. Projections are acquired at defined points during the rotation, typically every 3–6 degrees. In most cases, a full 360-degree rotation is used to obtain an optimal reconstruction.

Single-Photon Emission Computed Tomography (SPECT)

Single-Photon Emission Computed Tomography (SPECT)

- In contrast to PET, SPECT is more limited in terms of spatial and temporal resolution, and more limited with respect to the effects that can be monitored.
- The advantage is SPECT tracers decay more slowly than PET tracers, thus allowing the examination of longer-lasting metabolistic functions.
- Typically, the voxel spacing is between 4 and 7 mm, and a typical SPECT image slice consists of 64x64 or 96x96 pixels. Images are provided either as gray scale images or as pseudo-colored images.
- Like PET, SPECT imaging has been recently integrated with CT imaging in a combined scanner.

Single-Photon Emission Computed Tomography (SPECT)

- Left: slice in the middle of the data set at the beginning of the time sequence. Right: the same slice four minutes later.