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Computed Tomography (CT)

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M. Kahl-Scholz, C. Vockelmann (eds.), *Basic Knowledge Radiology*,
https://doi.org/10.1007/978-3-662-66351-6_6

Computed tomography (CT) produces sectional images using X-rays. Since computer tomographs are available in almost all hospitals and radiology practices and the examination time is very short, CT is the method of choice in emergency diagnostics. The patient is exposed to radiation and the attenuation is determined. This produces images of different structures that are free of superimposition and allow spatial delineation in all planes. Organs and pathologies can thus be precisely assigned and their extent determined.

6.1 History

The history of computed tomography began in the early 1970s with Sir Godfrey Hounsfield, who developed the first computed tomograph. For this he received the Nobel Prize in 1979. Hounsfield received financial support from the record company EMI, which among others had the Beatles under contract. For this reason the first scanner was also called EMI scanner, with which skull CT's could be accomplished. Since computers were not well developed at that time, the resolution was low (matrix 80 × 80) and the examination time very long (about 10 min/image). However, it was possible for the first time to diagnose large brain processes without operating on the patient. Larger tumors and hemorrhages could be delineated and ventricular width assessed. Today, in honor of Hounsfield, the units of attenuation are given in **Hounsfield Units (HU).**

6.2 Design and Operation of A Computer Tomograph

The CT scanner itself consists of the **table** and the **gantry.** The gantry is the heart of the tomograph. The X-ray tube, aperture system, detector system, cooling system and mechanical elements are located under the cover. The entire gantry can be tilted horizontally up to ±30 °. In a CT, the tube-detector systems rotate around the patient with a weight of 2–3 t (in dual-source systems even 4–5 t). This creates immense centrifugal forces. The X-ray emitter of a CT is a rotating housing emitter. Here, the entire housing, i.e. anode and cathode, rotates around the patient.

X-rays are emitted continuously during the rotation. After penetrating the patient, the X-rays are detected on the opposite detector. Different tissue with different densities is located in the beam path. These density differences are registered or measured. This weakened radiation, which has penetrated the patient, is converted into electrical signals. Behind the detector system there is the DAS (= Data Acquisition System) to record the signals. These are passed on to the computer where the generation or reconstruction of the digital images takes place. Both - the power supply of the tube and the forwarding of the detector signals - are carried out via slip rings.

6.3 Investigation Techniques

6.3.1 CT Sequence

The first technique developed is sequential recording technique. It is also called “step and shoot”. Transversal/axial exposures are performed slice by slice. A table movement is necessary between two exposures. The amount of data to be reconstructed is small and can be done immediately. The examiner can therefore view the images directly. However, the disadvantage is the long examination time. Since the data acquisition is not continuous, there is a risk of not capturing the smallest details between two slices. There is no possibility of three-dimensional representation.

Nowadays, sequential CT is mainly used for interventions and prospectively triggered cardio-CTs. Even cranial CTs are still acquired sequentially in some cases today in order to avoid exposing the lenses of the eye, which are very radiation-sensitive structures, to the direct beam with a tilted gantry. However, modern equipment techniques are increasingly replacing this technique with spiral scans.

6.3.2 CT Dynamic

Dynamic CT images are also mainly taken using a sequential technique. However, only a selected slice position is continuously recorded. This makes it possible, for example, to perform flow measurements and thus to depict and assess physiological processes. These measurements can only be made with the aid of contrast media. The blood flow is displayed by the contrast medium, so that the kinetics are recorded and measured. This makes it possible, among other things, to make statements about organ perfusion or the cardiac output rate. The dynamic CT examination plays an essential role for acute stroke patients. Lysis therapy can be effective up to 4.5 h after the onset of the first symptoms; therefore, a patient with suspected stroke must undergo imaging as soon as possible. Computed tomography can detect the area of the brain that is poorly perfused by measuring the perfusion of the brain and identify the artery that should supply this area.

Another dynamic imaging technique is **bolus triggering**. The contrast agent accumulation in the focused vessel lumen is continuously measured at a selected slice position. If a preset and predetermined density (HU) is reached, the device starts automatically and acquires images of the desired region.

6.3.3 CT Spiral/CT Singleslice (SS-CT)

New possibilities were opened up by the introduction of spiral CTs in the early 1990s. Data acquisition was no longer “only” sequential, but also spiral, also called helical or helical. The patient is acquired throughout the volume with continuous table advancement and continuous tube rotation, and there are no data gaps. A detector array acquires the data. The region to be examined can be covered very quickly by spiral acquisition. This shortens the examination times to such an extent that the examination can be performed within one breathing phase. The amount of contrast medium can also be reduced automatically. The volume coverage is now seamless and allows the possibilities of overlapping reconstruction, so-called multiplanar reformation (2D) and 3D imaging.

6.3.4 CT Multislice (MS-CT)

In 1998, the first multislice CT came onto the market. It was a so-called “4-slice”, as four detector rows were available. With a tube rotation around the patient, four slices could be recorded directly. Thus a larger volume coverage took place. The volume acquisition was therefore faster, which shortened the examination times, which in turn led to a reduction in contrast medium. Another advantage of the multislices is the post-processing. By stringing together several detectors, an isotropic voxel geometry can now be achieved. Isotropic means that all edge lengths are of the same length. This is important for the 3D display, because it allows the step-free display of reconstructed images in all spatial planes without continuity interruptions.

> The smaller the voxels, the better the spatial resolution.

However, as the slice thickness decreases, the signal-to-noise ratio deteriorates and the radiation dose to the patient increases.

Detector Design

The introduction of the multi-line technique, in which several detector rings are placed opposite the X-ray source, allows the acquisition of several layers simultaneously. The detector lines do not have to have the same width. There are two types of detectors.

Adaptive Array Detector

In the "Adaptive Array Detector", the detector chambers become wider and wider towards the periphery. This leads to the possibility of interconnecting individual elements and lines. Thus, the option of different layer thicknesses exists.

Fixed Array Detector

With the "Fixed Array Detector" there are fixed sizes of detector elements per detector row. By selecting certain detector lines, the layer thickness can be determined.

6.3.5 CT Dual-Source (DS-CT)

In the DS-CT, there are two tubes in the gantry at a 90° angle with two associated, opposing detectors. The tubes work in parallel, but can be operated with different energies. The first tube has with 80 kV a lower voltage than the 2nd tube with 140 kV. Some manufacturers allow the use of different tube voltages with only one tube, this technique is called Dual-Energy.

Two images are created. The different tube current results in different attenuation values. Since the tube current is automatically adjusted, there is no increased radiation exposure. The acquisition time is very short due to two separate acquisition units. This is a distinct advantage for spatial resolution, especially for involuntarily moving organs such as the heart. However, the dual-source technique offers further possibilities and advantages:

- The two images with different energies can be added together to produce a "mixed image" equivalent to a 120 kV image.
- Iodine can be accurately detected and subtracted from both images, resulting in a "native" image, i.e. as if the examination had been performed without KM. Thus, separate native images are no longer necessary beforehand. It is used, for example, in liver and kidney diagnostics.
- As an alternative to the virtual removal of iodine information from the image, this information can also be color-coded, e.g. in the evaluation of myocardial ischemia, i.e. reduced blood flow to the heart muscle, or pulmonary perfusion, i.e. blood flow to the lungs.
- Besides iodine, other materials can also be differentiated and characterized by this so-called material decomposition, e.g. ureteral stones.

The use of different energies is also made possible in current device generations, depending on the manufacturer, by modulating the tube voltage or a special detector configuration ("double-layer detector").

6.4 Important Parameters in Spiral CT

6.4.1 Pitch Factor

The pitch describes the **relationship between table feed and detector width**. It is calculated with **p (pitch = table feed/number of simultaneously detected detector lines) x** slice **thickness.**

With a pitch = 1 the volume is recorded without gaps, with a pitch > 1 the data helix is pulled apart. Mathematically, one still obtains a complete data set with a lower image quality but also lower radiation exposure. With a pitch < 1 the volume is acquired overlapping. The pitch regulates the speed of the table feed and thus also the duration of the examination.

6.4.2 Collimation

Collimation describes how **thick or thin a slice** is selected along the *z*-axis, i.e. the longitudinal axis of the patient's body. Collimation is achieved by a system of apertures and detector elements. The **apertures** serve to focus the radiation and to reduce scattered radiation in front of the detector. The choice of collimation determines the activation of the detector rows and the detector elements. The detector **elements** have different sizes. The layer thickness is influenced by the choice of detectors and can subsequently be reduced to a maximum of the size of the smallest detector element.

6.4.3 Tube Voltage (kV)

The tube voltage is applied between the cathode and anode and determines the penetration capability of the radiation through the matter. Values between 70 and 140 kV can be selected in steps, depending on the manufacturer. Higher kV values mean a hardening of the X-ray radiation, which means that it penetrates tissue types with higher absorption better and causes less scattered radiation. For examinations of the parenchyma, 120 kV tube voltage is usually selected, for CT angiographies (CT-A), i.e. vascular imaging, or bony examinations and examinations of children, 80 kV is usually selected. An increase in tube voltage has a disproportionate effect on the radiation dose. A change of the tube voltage from 100 kV to 140 kV with otherwise unchanged parameters leads to a 4-fold higher dose.

6.4.4 Tube Current-Time Product (mAs)

The tube current has a linear relationship to the radiation dose; doubling the tube current also doubles the radiation dose.

> The thicker the object being transmitted, the more mAs are required to ensure adequate image quality.

Since bone absorbs or scatters the radiation more, a higher tube current must also be used in body regions with more skeletal parts, such as the shoulder girdle or the pelvic skeleton. This is usually done using automatic dose modulation in order to obtain a homogeneous image quality of the examination (► Sect. 6.9.1).

6.4.5 Scan Time (S)

It indicates the actual examination time and depends on the scan distance, the pitch and the rotation time.

> The longer the scan time, the slower the examination and therefore the higher the dose.

For examinations that involve increased motion artifacts (thoracic CT with respiratory movements, abdominal CT with intestinal peristalsis and pulsation artifacts through the aorta), it is advantageous to select the scan time as short as possible. This can also reduce image blurring caused by involuntary patient movements.

6.4.6 z-sharp Technology

Spring focus, also called flying focal spot or double-z-sampling, is a novel technology. The electron path is deflected by an electromagnetic field so that two focal spots are formed on the anode. The distance between the two focal spots is half of the thinnest collimation selected, so there is an offset, but also an acquisition overlapping by half. With a 64-slice CT, double the volume coverage can be achieved, i.e. 128 slices can be acquired. The overlapping acquisition technique results in a higher spatial resolution, because the image information is added to the same slice.

6.5 Parameters for Image Reconstruction

6.5.1 Layer Thickness

The slice thickness in which the images are to be reconstructed can be chosen by the examiner. It can be minimally equal to the thickness of the smallest detector element and is determined by the choice of collimation.

6.5.2 Increment

The degree of overlap in the reconstruction of the individual slices is determined by the selection of the increment. An increment of 20–30% should be selected for further 3D post-processing.

6.5.3 Convolution Kernel, Reconstruction Filter or Algorithm

This is a computational algorithm that is used to highlight certain structures during reconstruction. The edges of the bony structures and lung structures in the lung window are emphasized with a sharp convolution kernel so that they can be precisely delineated and assessed. The smallest details are shown with sharp separation. In soft tissue imaging, i.e. parenchymal organs, a soft kernel is selected and the image is optically smoothed. The detail detectability of structures with small density differences is improved.

6.5.4 Windowing

The human eye has only a limited perception, even the best radiologist cannot distinguish significantly more than 60 gray values. Therefore, a narrowing down of the grey values is carried out with the help of windowing. The range of gray values depends on the region or organ to be examined, depending on where the focus lies. The focus is referred to here as “Center (C)”. The spectrum of gray values used is called “Window Width (WW)”. The Center is the “zero point” of the window. Thanks to this setting, one can refer to the density of the interested organs and delimit and judge them.

6.5.5 z-Interpolation

After or during a spiral acquisition, this measuring principle is carried out by software in the background and only enables the complete data acquisition. Due to a spiral, no complete 360° acquisition takes place. Data within a 360° rotation that lie outside an image plane are “copied” to an image plane, the z-axis, by z-interpolation. This is done by using a computational algorithm to calculate a second spiral that is 180° to the measured spiral. The scanned spiral and the calculated spiral together provide 360° coverage on a plane. Since the pixels have small distances to each other, this provides a good spatial resolution. In addition, the motion artifacts that occur due to the permanent table movement are eliminated. After the z-interpolation the next calculation is performed. The mean values of the image points are determined for image reconstruction/image calculation.

6.6 Image Formation

The patient is positioned isocentrically on the table, i.e. the object to be imaged is always in the center of the beam path during imaging and rotation. This is a very important point for dose control, spatial resolution and thus image quality. First, an overview image, a **topogram** or **scout**, is taken. With its help, the area to be examined is defined and delimited. The data acquisition is carried out with the preset parameters and the data is forwarded to the computer. After z-interpolation, the mean values of the image points are determined. This raw data forwarded to the computer, the attenuation values from all angles, is also called a **sinogram**. The result is a blurred image. The filtered back projection is necessary for a detailed recognizability.

6.6.1 Filtered Back Projection

The main role here is played by the selected convolution kernel. Depending on the convolution kernel, the edge emphasis is enhanced by means of mathematical algorithms. For this purpose, a negative filter is assigned to each voxel in the edge region. After subtraction of filter and measurement data, the edge region is signal-free. This results in edge accentuation and sharper imaging and delineation. The choice of a stronger edge emphasis increases the image noise.

6.6.2 Iterative Reconstruction

This computational process plays an important role in modern computed tomography. It is used for noise reduction, which means that all examinations are performed with a lower dose. Noise had previously greatly affected images with lower doses and degraded image quality. With iterative reconstruction, the noise is "calculated away" and the image impression remains the same. In the best case, a **dose reduction of 50–60%** is achieved, depending on the examination region and object.

The noise or better signal-to-noise ratio (SNR) is the quality criterion of CT images. It is measurable and should be between 12–15 HU. The measurement is made in the peripheral area of the CT image, outside the object, practically in the air.

> The less radiation is incident, the fewer X-ray quanta hit the detector elements. This increases the noise and the poorer the image quality.

So more radiation is needed, the tube current must be increased. It is important to know that there is an exponential relationship between the mAs and the noise. So to halve the noise, a fourfold of mAs must be used.

6.6.3 Hounsfield Scale

The density values of individual structures and objects in computer tomographic examinations are measured and an image is calculated from them. The different density values are displayed in different grey scales. These scaled values are called Hounsfieldunits (HU) after the inventor of the CT. The reference values for water and air were set at room temperature. For water the value is 0 HU, for air −1000 HU. Bone, although not a reference value, is still important and ranges from +1000 to +3000 HU.

The spectrum of the Hounsfield scale ranges from −1024 to 3071 HU. The human eye cannot differentiate this amount of grey levels. That is why the window technique was introduced.

6.6.4 Window Technology

The window technique is used to limit the number of gray values (Fig. 6.1). The setting and narrowing down refers to the HU of the object of interest and is done by the

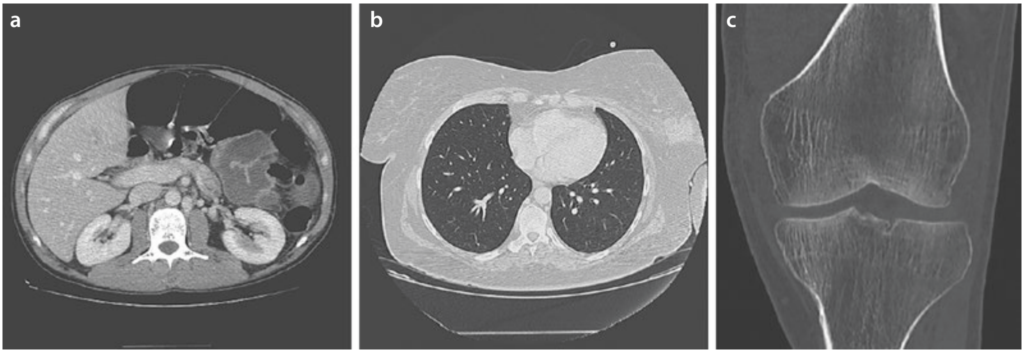


Fig. 6.1 **a** Soft tissue window. **b** Lung window. **c** Bone window

combination of Center (C) and Window Width (WW). The center, also called window location, sets the center of the window width (WW). It is approximately at the density value of the object of interest. The Window Width, also called Window Width or just Window, specifies the range of gray values that will be used to differentiate the structures. It determines the distribution of gray values from white to black.

6.7 Post-Processing

This refers to the post-processing of the acquired data in 2D or 3D representations. These are not used for primary diagnosis, but can be used for better visualization. The object can be viewed in all planes and at any angle. The calculation should be done using very thin, axial slices and there should be an overlap, i.e. the increment should be chosen at least 20% smaller than the slice thickness. This avoids a step-like representation (step artefacts) of the object.

6.7.1 2D Representation

- **Multiplanar Reconstruction (MPR)**

This post-processing is a standard part of every examination. The axially acquired data are displayed coronally and sagittally (Fig. 6.2), so that the findings can be made in all planes. The curved MPR is a special form of MPR. Objects that are not straight can be displayed straight thanks to this method. This is used, for example, in vascular examinations in order to better visualize the course.

- **Maximum Intensity Projection (MIP)**

In MIP, the structures with the highest density in each slice are determined and displayed in an enhanced form. This method is usually not used in the axial images, but is intended for coronal and sagittal images. The axial datasets are the ones relevant to the findings. The slice thickness is usually chosen thicker than in MPR, because the accumulation of the denser structures leads to higher intensity and representation of the same. Areas of application include thoracic CT in the lung window (Fig. 6.3) or all vascular examinations.

- **Minimum Intensity Projection (minIP)**

In this case, the highest density is not determined and amplified (MIP), but the lowest. The rest of the principle is the same as for the MIP. The representation of the chochlea can be done, for example, with this projection.

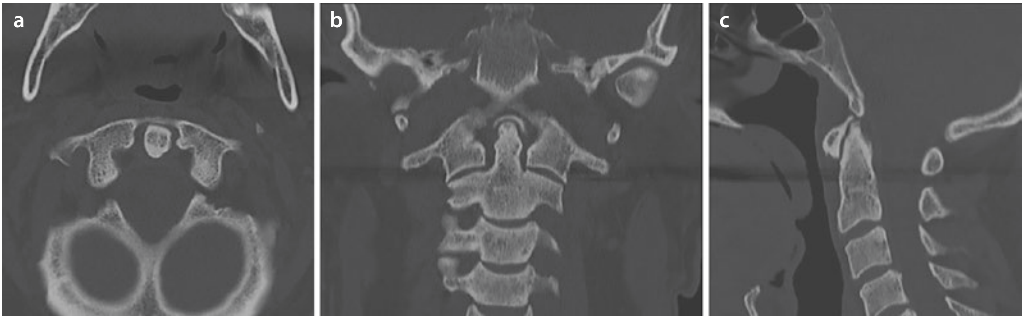


Fig. 6.2 **a** Axial layer plane. **b** Coronal MPR. **c** Sagittal MPR

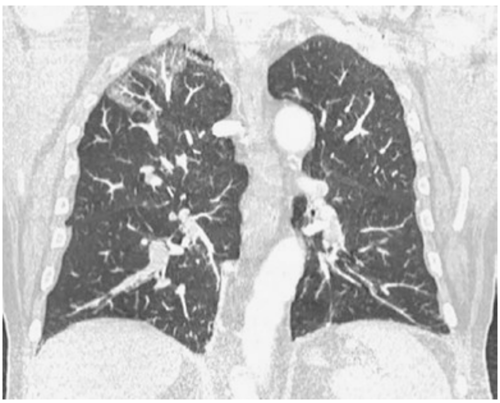


Fig. 6.3 MIP in the lung window

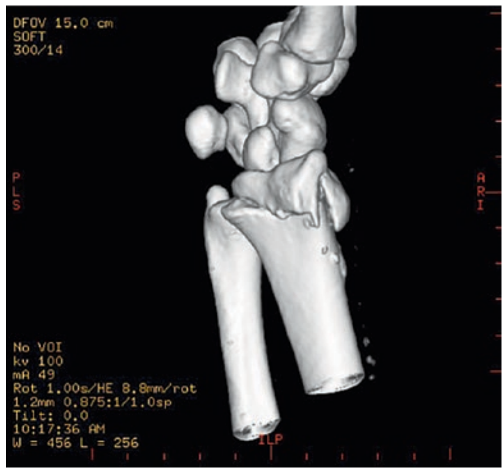


Fig. 6.4 SSD of the distal forearm bones and wrist joint

6.7.2 3D Representation

Shaded Surface Display (SSD)

The 3D surface representation can be used for surgical planning. It restricts the representation of a bone surface (Fig. 6.4) to certain Hounsfield values above a threshold value. Under certain viewing angles and a hypothetical light source, which the computer uses for shading, the surfaces appear plastic.

Volume Rendering (VR)

This is a color assignment and transparency of the individual CT values (Fig. 6.5).

Furthermore, it is possible to measure distances and angles as well as to carry out calcification of vessels or bone density measurements.

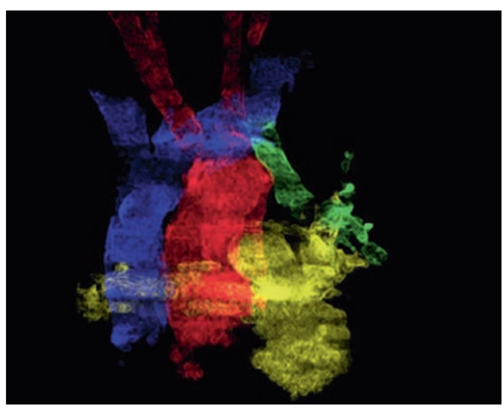


Fig. 6.5 VR of the vessels in the upper thoracic region

6.8 Artifacts

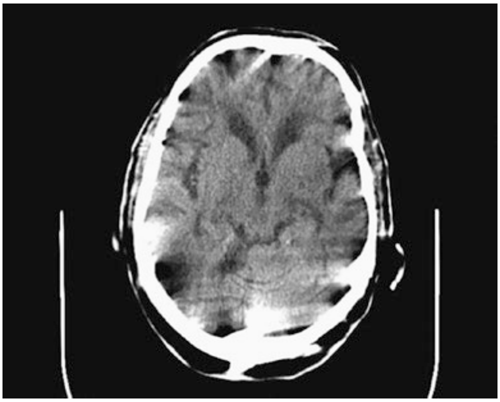
Artifacts are image disturbances that can reduce the assessability of the images or even prevent them altogether. Different types of artifacts are distinguished, which can occur both patient-based and physical-technical.

6.8.1 Movement Artefact

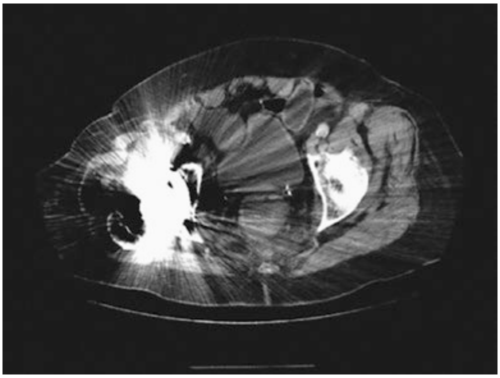
This image disturbance (◘ Fig. 6.6) is caused by movement of the patient, such as breathing. It can be either voluntary or involuntary. The patient may need to be sedated briefly for the examination.

6.8.2 Pulsation Artefact

These occur involuntarily, such as the heartbeat, vascular pulsations or the peristalsis of the intestines.



◘ **Fig. 6.6** Cranial CT with motion artifacts



◘ **Fig. 6.7** Metal artefacts due to implanted hip TEP

6.8.3 Metal Artifact

Metal in the examination field causes detail obliteration (◘ Fig. 6.7). Therefore, all removable metal parts should be removed from the examination region before the examination. If a metal part cannot be removed, e.g. in the case of hip TEP, a higher tube voltage can be selected directly in order to reduce the artefacts.

6.8.4 Partial Volume Effect/Partial Volume Effect

This effect occurs when two adjacent objects in a layer show massive density differences (◘ Fig. 6.8). In this case, the mean value of the measured attenuation values is converted into a gray value for the image display. This can be prevented by choosing thinner layers.

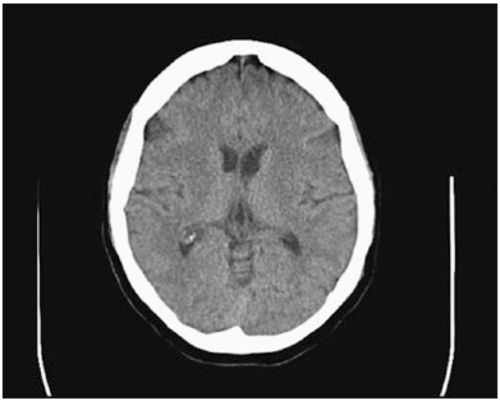


Fig. 6.8 Incised sulcus right frontotemporal

Fig. 6.10 Exceeding the measurement field in a patient with a large abdominal wall hernia

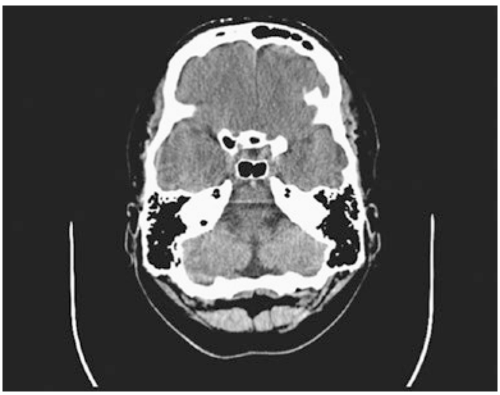


Fig. 6.9 Hardening artefact in the area of the brain stem

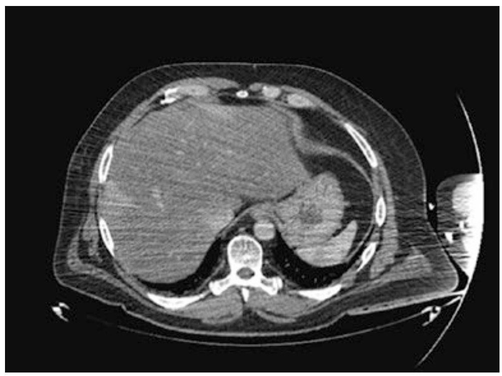


Fig. 6.11 Photon starvation artefact when the patient's left arm cannot be elevated

6.8.5 Hardening Artefact

This artefact is caused by hardening of the radiation as it passes through excessively dense tissue. It occurs, among other things, when examining the rock bones and causes artefacts in the adjacent brain tissue (Fig. 6.9). This artefact can be reduced by thinner collimation.

6.8.6 Measuring Field Overrun

Objects that protrude beyond the measuring field lead to artefacts in the edge area and cannot be assessed beyond this (Fig. 6.10).

6.8.7 Photon Starvation Artefact

This occurs when the amount of radiation is too small and can lead to fringe artefacts (Fig. 6.11). It often occurs in patients who cannot raise their arms above their head. When the arms are positioned next to the body, these artefacts occur at the liver. This form of positioning results in an increased demand for dose in the lateral beam path. Positioning the arms on the patient's abdomen counteracts this and the liver can be imaged almost artefact-free.

6.8.8 Ring Artefact

If individual detector rings deviate, ring-shaped artifacts will appear in the image. If a calibration does not solve this problem, the examination with the device must be stopped and the service technician must be contacted.

6.8.9 Line Artifact

Failure of individual detector elements and/or channels will cause black lines to appear across the acquired image. The acquisition must be stopped immediately and the manufacturer notified.

6.9 Radiation Protection Measures and Dose Reduction

Before performing a CT scan, the indication should first be reviewed. If an examination is justified, it must be considered whether alternative imaging with comparable informative value is possible without radiation exposure and how radiation exposure can be minimized. This is particularly true when examining infants, toddlers, and adolescents. Radiation reduction can be achieved by preset programs on the CT:

6.9.1 Dosage Modulation

First, a dose adjustment to the anatomy, shape and size of the patient can be made. During the acquisition of the topogram with the patient in isocentric position and during the acquisition, the required dose is determined. The measured values are compared with the target values of the average patient of 70/75 kg and the mAs are adjusted simultaneously. Thus, the radiation is individually adjusted. The application of lead covers e.g. on thyroid gland and eye lenses can lead to an increased dose exposure depending on the type of dose modulation.

6.9.2 Adaptive ECG Pulsing

ECG pulsing is used in cardio-CT and also in CT angiographies of the ascending aorta. Here, the patient is connected to an ECG. The examination always takes place in the same cardiac phase. In this phase, the acquisition takes place with 100% dose, outside of which a reduction down to approx. 4% takes place. The image quality and the spatial resolution are thus maintained. Unnecessary repetitions are avoided.

6.9.3 Avoidance of Overranging

For the calculations in spiral acquisitions, it is usually necessary to include half a revolution before and after the examination field. With asymmetric collimators, which close before and after the actual scan, this excess radiation is eliminated. This leads to a dose reduction of up to 25%.

6.9.4 Iterative Reconstruction

For some years now, iterative reconstruction has been used in image calculation in addition to or as an alternative to filtered back projection, by means of which image noise can be "calculated away". This reduces the necessary dose of a CT examination considerably by up to 70%. Iterative reconstruction is somewhat reminiscent of Sudoku for advanced students. Ultimately, through repeated trial and error, the computer calculates until it has the best value for each voxel in the image to achieve the attenuation measured at the detector.

Practice Questions

1. What kind of artifacts do you know that affect image assessability?
2. What is the difference between sequence CT and spiral CT?
3. Which detector types in multislice CT do you know? How do they differ?

Solutions ► Chap. 27